

# Assessment of Gomti River Basin with Special Reference to Environmental Flows Requirements

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*Dedicated To  
My Beloved Parents*



## **DECLARATION**

I hereby declare that the thesis titled “**Assessment of Gomti River Basin with Special Reference to Environmental Flows Requirements**” has been carried out by me under the supervision of **Dr. Venkatesh Dutta** in the Department of Environmental Science at Babasaheb Bhimrao Ambedkar University, Vidya Vihar, Raebareli Road, Lucknow. The thesis is an outcome of my original research work. I further declare that the content of this thesis did not form a basis for the award of any previous Degree or Diploma to this or any other University/Deemed University.

Also, I undertake that the thesis is essentially free from all kinds of plagiarism and the sources used in this study have been duly acknowledged.

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## **CERTIFICATE**

This is to certify that the thesis titled “**Assessment of Gomti River Basin with Special Reference to Environmental Flows Requirements**” submitted by **Ms. Urvashi Sharma** is an original research work and has not been previously submitted in part or full for the award of any other Degree or Diploma to this or any other University.

The thesis submitted to Babasaheb Bhimrao Ambedkar University, Lucknow satisfies all the requirements as stipulated in the Doctor of Philosophy (Ph.D.) Regulations-1999, as amended in 2008/2010//2013 and it is fit for submission and evaluation for the award of the Doctor of Philosophy of the University

Supervisor

Date:

Head of the Department

## PREFACE

The human interventions in the riverine systems have altered the natural flow regimes significantly by reducing the available flow and disturbing the variable flow regimes characteristic to the rivers. Approximately, more than 60% of rivers are reported to be fragmented by hydrological alteration throughout the world. As a result, ecological services, socially valued diversity of native species and healthy ecosystems are getting degraded or completely lost. Further, increasing pollution load and compromised flow is severely affecting the combined functional integrity and resilience of the rivers. The understanding of 'riverine ecosystems' has gradually proceeded towards the study of 'environmental water allocation' or 'environmental-flows' requirements of the rivers.

This research work has been carried out to assess the e-flow requirements of the Gomti River. The first objective of this study is to divide the river into homogenous zones to identify the environmental-flows sites on the river stream. The second objective is to assess the e-flow for River Gomti. Based on the detailed review and the available data, a multi-step methodology is used for e-flows assessment. The third objective is to identify the indicator species and assess the e-flows for indicator species. The fourth objective is to assess the e-flow for socio-cultural needs.

The results of the study indicate the ecological flow requirements are much higher than what hydrological methods are recommending. This study stresses upon the uniqueness of every river system that should be considered for assessing e-flows. The thumb rule to address the uniqueness is by maintaining the riverine flow near to the natural flow regime as much as possible. The water resource management should focus on the long term ecological sustainability of freshwater ecosystems rather than short term economic goals.

This study also emphasizes the fact that in the initial phase of any e-flows assessment study, it is hard to predict the accuracy or the suitability of a method for a particular study area. A combination of ecological and hydrological methods would be best suited for recommending e-flows for the long term sustainability of a riverine ecosystem. This study also recommends to take a bottom-up approach where tributaries can be managed first and subsequently, the main channel can be approached. The flow in River Gomti and many other major tributaries of Ganga can be restored to achieve a better outcome of River Basin Management plans for the entire basin.

**Urvashi Sharma**

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*Chapter 1*  
*Introduction*



## **1 Introduction**

Rivers are an integral part of human civilization. The most primitive life forms originated in the water. Along with being the most significant repository of inland freshwater resources, rivers are home to the most valuable and threatened ecosystem on the Earth (Wohl *et al.*, 2015). In the initial development plans, land development agencies conceptualized rivers as simple channels functioning as the conveyance of water and sediments from the upstream to the downstream region. In the early developmental phase of mankind, rivers found their importance for transportation, agriculture and energy generation. Later on, the associated ecosystem services and economic benefits from the rivers were recognized that enhanced the dependency and usefulness of maintaining healthy river systems. Ecosystem services can be categorized as provisioning, regulating, supporting and cultural services (Wohl, 2018). River provisioning refers to the products obtained from the complex riverine ecosystems processes, including continuous profitable fisheries and fertile alluvial soil. The ecological processes such as floods are regulated to control damage that may be caused due to flooding each year (MEA, 2005; Wohl, 2018). Supporting ecosystem services are the services essential for the production as well as the maintenance of other ecosystem services (De Groot *et al.*, 2002; Wohl, 2018). The supporting ecosystem services include nutrient accumulation in the form of plant products, nutrient recycling by micro-organisms and micro-invertebrates in the channel and its floodplains. Cultural ecosystem services are the non-physical benefits derived from riverine ecosystems and their associated landscapes.

Rivers carry nutrients, sediments, energy downstream and finally empty themselves into larger water bodies. In this process, rivers maintain the water cycle, transport sediments, nutrients and provide habitat and food to living organisms,

including humans. In due course of time, humans have developed more understanding and technology to harness greater benefits from the riverine resources. Rapid development and simultaneous increase in water demands have resulted in the construction of water storage structures, diverging canals and over modification of natural riverine systems. The significant outcomes of water resource development projects are the construction of large dams and weirs, flood control structures, urban water supply projects and flow controls adequate for navigation in the rivers (Dyson *et al.*, 2003; Arthington, 2012). These human interventions in the riverine systems have altered the natural flow regimes significantly by reducing the total flow and disturbing the variable flow regimes characteristic to the rivers. Approximately more than 60% of rivers are reported to be fragmented by hydrological alteration throughout the world (Kingsford and Thomas, 1995; Reyes-Gavilan *et al.*, 1996; Pringle and Scatena, 1999; Dauble and Geist, 2000; Kingsford, 2000; Revenga *et al.*, 2000; Joy and Death, 2001; Revenga *et al.*, 2005; Poff, 2016). These anthropogenic alterations have changed the geomorphology, hydraulics and hydrology of rivers (Brandt, 2000; Poff *et al.*, 2007). As a result, ecological services, socially valued diversity of native species and healthy ecosystems are getting degraded or completely lost. They are the critical factors in providing ecological goods and services to the humans (Karr, 1991; Dynesius and Nilsson, 1994; Poff *et al.*, 1997; Dudgeon, 2000a, Dudgeon, 2000b; Richter *et al.*, 2003; Bradford, 2008; Dutta *et al.*, 2011; Dutta *et al.*, 2015). The destruction of natural riverine habitats is leading to the loss of aquatic and riparian biodiversity, benthic biota, riparian vegetation, crocodiles and molluscs (Ward, 1976; Armitage *et al.*, 1987; Nilsson, 1996; Dudgeon, 2000a; Dudgeon, 2000b, Dutta *et al.*, 2018). Further, we not only over-extract water from rivers; we are also dumping a large amount of untreated wastewater, solid wastes and other

domestic, agricultural and industrial wastes back into the rivers. Consequently, increasing loads of pollutants and compromised flow severely affect the combined functional integrity and resilience of the rivers (Poff *et al.*, 1997; Acreman and Ferguson, 2010; Acreman *et al.*, 2015).

With the increasing understanding of the fragile riverine ecosystems and its importance to humanity, various mitigation measures have been taken by the scientists and planners to restore the altered river systems. The construction of large dams allows storing water during the monsoon season and delivers it in the non-monsoon season to downstream or off-stream. The growing off-stream needs, over-allocation of flow, increasing effects of consecutive droughts and pollution are also major threats that impact the fragile riverine ecosystems. The researchers, scientific communities and other stakeholders have come to an agreeable viewpoint that freshwater biodiversity and the associated riverine ecosystem services can be improved and maintained by sustaining the variability of natural flows or flow nearly comparable to the natural flows. The outcomes of the riverine research have stressed upon letting the water flow to mimic the natural variability near to the natural conditions to achieve the best ecological conditions in a river basin. This understanding of ‘riverine ecosystems’ gradually proceeded towards the more comprehensive terms such as ‘environmental water allocation’ or ‘environmental-flows.’ For the very first time during Brisbane declaration (2007), the term environmental-flows was defined as “the quality, quantity and timing of water flows required to sustain freshwater, estuarine ecosystem and the human livelihoods’ well-being that depend on the ecosystem” (Acreman and Ferguson, 2010). This definition was further modified in 2018 to incorporate the importance of social and cultural values in e-flow management (Arthington *et al.*, 2018). The modified framework

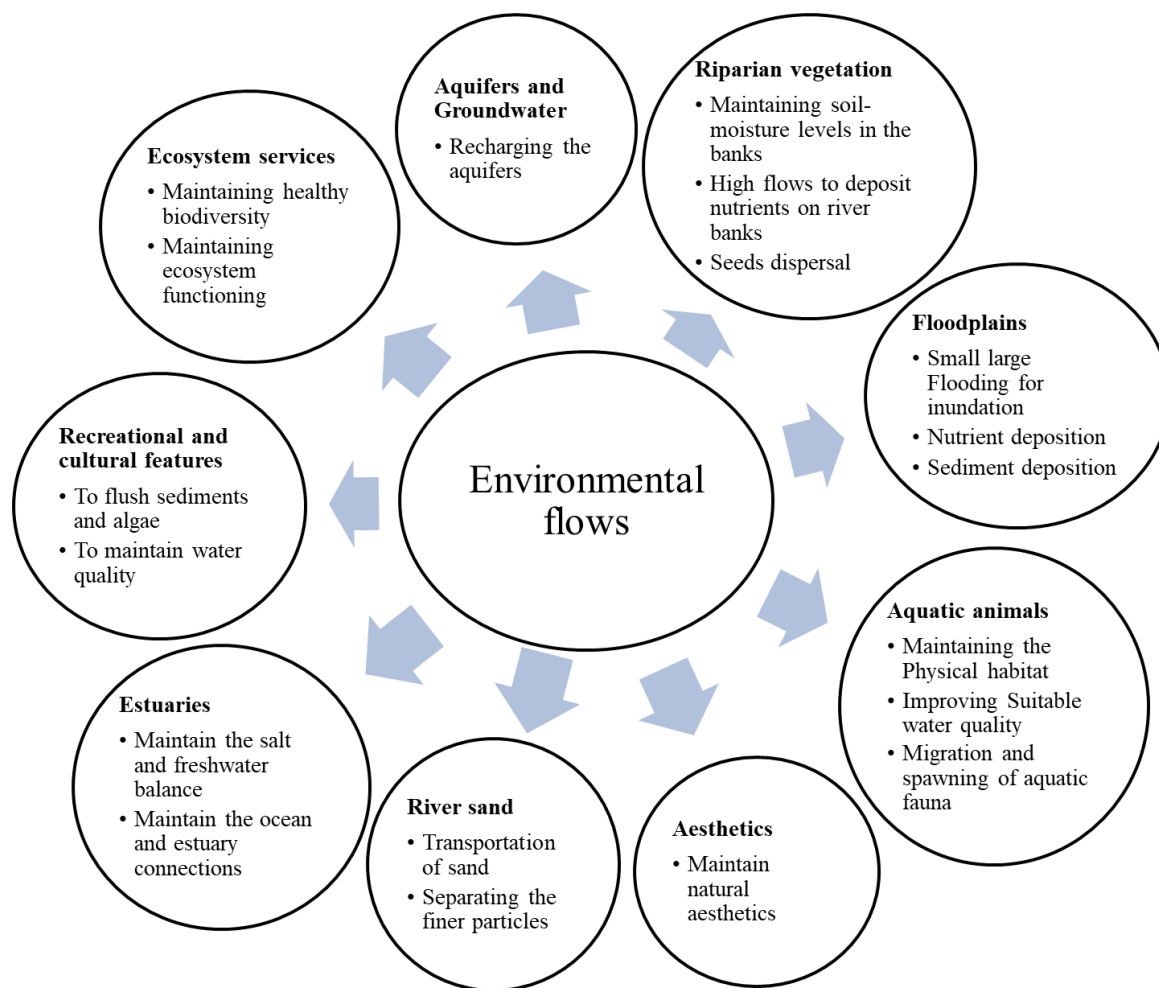
defines e-flows as “the quantity, timing and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods and well-being.” Other attempts made to define the e-flows were based on personal understanding of the researchers and requirements of water flow which are summarized as follows (Table 1.1):

**Table 1.1:** Definition of e-flows given by different organizations

<b>Organization</b>	<b>Definition of e-flows</b>	<b>Reference</b>
World Bank	“The quality, quantity and timing of water flow required to maintain the components, functions, processes and resilience of aquatic ecosystems which provide goods and services to people.”	Richard and Hirji (2003)
IUCN	“The water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated.”	IUCN (2011)
Conservation Gateway	“The quantity and timing of water flow required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people.”	Conservation Gateway (2010)
International Rivers Organization	“Quantity, timing, and quality of water flows below a dam, to sustain freshwater and estuarine ecosystems and the human livelihoods that depend on them.”	International Rivers Organization (2014)

The initiation of environmental flow assessment (EFA) methodologies in the USA occurred in the 1940s. However, the real progress started in the 1970s (Tharme, 2003). Insufficient documents were available to describe the route of the establishment of EFA methodologies in other parts of the world. The EFA processes earned popularity in other parts of the world, such as Australia, England, New Zealand, South Africa, Brazil, Czech Republic, Japan and Portugal, during 1980s.

However, a large portion of the world was still unacquainted with the EFA processes and their importance in water resource development (Poff and Matthews, 2013). The developing nations like India, Nepal, China, Sri Lanka and Iran incorporated using EFA processes only during the early 21<sup>st</sup> century. Since the beginning of the EFA processes, around 220 methodologies have been reported from 44 countries (Tharme, 2003; Shokoohi and Hong, 2011). The scientific communities are putting continuous efforts in improving the existing EFA methods, as well as developing new and more reliable methods (Stalnaker and Arnette, 1976; Wesche and Rechar, 1980; Morhardt and Altouney, 1986; Estes and Orsborn, 1986; Loar *et al.*, 1986; Kinhill Engineers, 1988; Reiser *et al.*, 1989; Arthington and Pusey, 1993; Growns and Kotlash, 1994; Karim *et al.*, 1995; Tharme, 1996; Jowett, 1997; Dunbar *et al.*, 1998; Arthington and Zalucki, 1998a; Arthington and Zalucki, 1998b; Arthington, 1998a; Arthington, 1998b; Mahoney and Rood, 1998; King *et al.*, 1999; Tharme, 2000; King *et al.*, 2003; Tharme, 2003; Black *et al.*, 2005; Poff *et al.*, 2010; Sanderson *et al.*, 2011; Cluer and Thorne, 2014; Martin *et al.*, 2015; and Horne *et al.*, 2019). Flow is the principal variable in maintaining the stream morphology and protecting riverine features, including aquatic animals, riparian vegetation, ecosystem services, estuaries, aquifers, surface water interactions, recreational, aesthetic value and cultural features as well as the overall functioning of the environment. However, the emphasis is not given on the ecological and social components of the rivers and their associated functions while recommending the e-flows (Figure 1.1).



**Figure 1.1:** The ecological and social components of the river and their associated functions Source: Sharma (2019)

**Table 1.2:** The value of river functions with an example of environmental flow requirements

Feature	Explanation of value	Example of environmental flow requirements
Aquatic animals	The angling fish, rare water birds, small aquatic life are the crucial base for the higher food chain. The freshwater fishes are an essential source for the associated population	Flows are required to maintain healthy riverine habitat, acceptable water quality, facilitate the migration of fish and maintenance of small floods for spawning
Riparian vegetation	Stabilize river banks, provide food and firewood for riparian population and habitat for	Flows to maintain soil-moisture levels in river banks, nutrient deposition and seed distribution

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<b>Feature</b>	<b>Explanation of value</b>	<b>Example of environmental flow requirements</b>
	animals and prevents the nutrient and sediment losses from human activities in the river catchment	is favored by high flows
River sand	Used as construction material	The river flows transport sand and separates the finer particles from it
Estuaries	Act as spawning and nursery areas for marine fishes	Flows to maintain salt/freshwater balance requirements and ocean connection to stabilizes estuary
Aquifers and Groundwater	Acts as the source of water in lean period of flow as well as maintain the perennial nature of rivers	Flows to recharge the aquifers
Floodplains	Support fishery and flood-recession agriculture for the riparian population	Floods to inundate the floodplain once in a year and large floods to stabilize the flood plains should occur after every few years
Aesthetics	The sound of water running over rocks, the smells and sights of a river with trees, birds, and fish	Sufficient flow is required to maximize natural aesthetic features
Recreational and cultural features	The water games such as river rafting and cliff jumping are promoted and done in clean water with rapids, clean pools for holy rituals ceremonies, or bathing. Natural beauty is appreciated by anglers, birdwatchers, photographers and aquatic animals	Adequate flows for sediment, algae flushing and also to maintain water quality
Ecosystem	The aquatic ecosystems need to	Flows to sustain biodiversity and

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<b>Feature</b>	<b>Explanation of value</b>	<b>Example of environmental flow requirements</b>
services	be maintained well so they can regulate associated essential ecosystem processes such as water purification, flood attenuation and controlling	ecosystem functioning
Overall environmental protection	Minimize the anthropogenic impacts to conserve the natural systems for future generations	Some or all the types mentioned above contribute to the overall environmental protection

Source: Sharma (2019)

Understanding of surface water and groundwater interactions are crucial in maintaining the e-flows in the river streams. It has been well documented that many perennial rivers have become intermittent in past years (Gleick, 2003; Datry *et al.*, 2014). Water appropriation and climate change are also aggravating this problem (Jenkinsc, 1968; Larned *et al.*, 2010; Doll and Schmied, 2012). The level of river flow is directly connected to the groundwater table present beneath it (Owen, 1991). The effects of increase in groundwater pumping within a few hundred meters of a river are visible over a small period, i.e., in a year or two. This phenomenon is composed of two components, an interception and induced recharge. Thus, the groundwater-fed perennial rivers might turn into intermittent rivers in low flow seasons when the water table is low (Parkin *et al.*, 2007). A river is said to be gaining or losing river based on the hydraulic connection, river stage elevation and groundwater head. A losing river is when it is recharging the aquifers in the post-monsoon season. A gaining river is when it is receiving the flow in the form of base flows during lean flow seasons. Over-abstraction results in the decreased groundwater head below the base of the river. Thus, the connection between the river and the groundwater breaks and the loss

of water from the river does not correspond to an increase in the groundwater head further. It is well understood and documented that baseflow plays a crucial role in maintaining the riverine variable flow regimes (De Graaf *et al.*, 2019).

### **1.1 E-Flows in India**

The rapid development phase in developing countries is putting high stress on their valuable natural resources. The problems due to overexploitation and over-dependence of natural resources are becoming critical. Developing nations are still struggling for the implementation of sustainable development strategies, natural resource management plans and robust policy targets. Thus, it is utmost necessary for the developing nations that they judiciously use their natural resources and decrease their dependency on them. It is critical to have robust and well-studied resource management plans to ensure sufficient flows in the rivers. Water as a natural resource is considered inexhaustible. However, it is facing the highest exploitation throughout the world. Globally freshwater resources are getting polluted, overexploited and freshwater demands are increasing with each passing day. Thus, freshwater sources should be protected and managed well. Developed nations have gone through the stages of water resource development, where they have developed controlling structures on their water bodies to store water and harness hydro-energy (WCD, 2000; Bandyopadhyay *et al.*, 2002). The adverse effects of these ambitious projects started to appear on the indigenous biodiversity and river ecosystems, after the commencement of these large projects of water diversions (Pandit and Grumbine, 2012; Grumbine and Pandit, 2013).

In India, many river development projects are under construction or in their planning phase. India is a land of the vast networks of the rivers over which people

depend for their socio-economic and cultural needs. Physiologically all these river systems are characterized by significant seasonal variation in their discharges due to seasonal rainfall and extended dry periods (Bandyopadhyay, 2012). The Indian mainland has 19 major (Amarasinghe *et al.*, 2004), 45 medium, and 120 minor rivers grouped on the basis of their origins, into Himalayan and peninsular rivers and east-flowing or west-flowing based on the direction of flow (Rao, 1975). The plain-fed rivers have different flow requirements in comparison to the snow-fed Himalayan rivers. Studies have reported that intermittent rivers accumulate higher quantity of organic matter and has higher nutrient transformation than perennial rivers (Austin *et al.*, 2006; Corti and Datry, 2012; Datry *et al.*, 2018). Thus the productivity potential of the intermittent rivers is comparatively higher than the perennial (Datry *et al.*, 2014). The natural drying and re-watering process in the groundwater-fed rivers act as an evolutionary process that increases the overall biological, physiological and ecological trait diversity (Datry *et al.*, 2014). The snow-fed rivers carry high amount of sediments, rock minerals and large boulders from the mountains. The plain-fed rivers mainly accumulate organic material and leaf litter debris from the riparian vegetation (Brintrup *et al.*, 2019). It gets transported from upper reaches to the downstream regions along with sediments during monsoon season. The changing land use pattern, inefficient agricultural practices, growing urban and industrial water demand and high energy demand are putting stress on the river system. As a result, several rivers are under stress and their ecosystems have got fragmented (Richter and Thomas, 2007). As per the National Water Policy-2002, water allocation for ecosystem is the fourth priority and water allocation and demand assessment for sustaining river ecosystems is not mentioned (NWP, 2002; NWP, 2012). Water for

the maintenance of river health and its ecosystem has been kept in the end while allocating the flow for all other developmental processes (Standford and Anputhas, 2006). The overall water demand in India is estimated to increase at a rapid rate of 62.95%, from 656 Km<sup>3</sup> in 2010 to 1069 Km<sup>3</sup> in 2050 (Thatte *et al.*, 2009).

Increasing water demand, weak demand and supply management of water resources, pollution, increasing population, water-intensive agricultural practices and rapid industrialization in India are putting stress on its riverine ecosystems. The river channels are left with very less water to maintain its ecosystems due to over-abstraction for meeting the ever-increasing freshwater demands. In past few years, studies have been done to evaluate the e-flows requirements of river systems in India. However, the river basin management plans are still lacking in integrating the e-flows requirements in planning and development processes. India is an ecologically and culturally diverse country. The requirements and availability of river water are not same at all the places (CISMHE, 2007). The concept of maintaining the ‘minimum desirable flow’ in the river channel is often considered as the e-flows for the Indian rivers (Durbude, 2014). However, it cannot work for all water bodies as each water body has a distinct natural flow regime (Acreman and Ferguson, 2010). There is an advantage of being at a time where ongoing studies can learn from past mistakes and success stories in developing EFA frameworks suitable for Indian rivers.

In this background, this study was conducted on Gomti River Basin, a sub-basin of Ganges to assess the environmental flows (e-flows) requirements of the river Gomti. The study has the following objectives:

1. Homogeneous zonation of River Basin for identification of environmental-flows sites

2. To determine the preferred environmental flows for River Gomti
3. To assess and make recommendations on the flow requirements for indicator species
4. Socio-cultural mapping and E-flows need



*Chapter 2*  
*Review of Literature*



## 2 Review of Literature

### 2.1 Natural Flow Regimes and Ecological Functions

The water quality, sediment transport, food-supply systems and biotic relations are the vital determining factors for a healthy flowing river. Also, the primary factor for maintaining a river and its associated ecosystems is the flow regime (Poff *et al.*, 1997; Bunn and Arthington, 2002; Dyson *et al.*, 2003). The concept that the natural flow regime of a river is vital in maintaining the riverine resistance and resilience has been widely accepted (Poff *et al.*, 1997). Any modification in the natural flow regimes can result in disturbed ecological processes (Table 2.1).

**Table 2.1:** Flow components and ecological responses to flow alterations on aquatic organisms

Flow components	Primary alteration	flow	Ecological response on aquatic organisms
Magnitude	Stabilization of flow indicates loss of extremely high and low flows and other flow regimes	of flow	Loss of flow-sensitive species, reduction in diversity, alteration in assemblages and dominant taxa, reduction in abundance and increase in exotic species
	The greater magnitude of extremely high and low flows		Life cycle disturbance, decreased species richness, alteration in the assemblages and relative abundance of aquatic organisms
Frequency	A decrease in the frequency of peak Flows	in the	Reduced and a seasonal reproduction, diminution, and deracination of indigenous fishes, reduction in the richness of endemic and sensitive aquatic species, and decrease in the habitat availability for young fishes
Duration	A decrease in the duration of the flood plain inundated		Diminution of the richness of young fish, change in juvenile fish assemblage patterns, loss of riverine floodplain

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Timing	A shift in peak flow timing	Alteration in diversity and assemblage structure of the aquatic taxa, disruption of spawning grounds, decrease in overall reproduction and recruitment
	Increased predictability	Disruption of spawning cues decreased reproduction and recruitment, alteration in assemblage structure
Rate of change	Reduced variability	Stagnancy in the aquatic habitat, increase in the microbial population and increase in abundance of some micro-invertebrate

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Thus the e-flows assessment methodologies were developed to restore the existing flows to the natural or nominal flow regimes present in the rivers before the disturbances (Poff and Matthews, 2013).

## **2.2 Ecological Functions**

Ecological functions are the outcome of biological, physical and chemical processes interacting at different levels that form complex ecosystems. The activities included in ecological processes are nutrient cycling, predator-prey relationships and movement of sediment and water. The unique interaction among these ecological processes shapes the associated ecological features such as morphology and temperature of stream, the composition of biological communities as well as sediment size and distribution (Fischenich, 2003; Kumar and Jayakumar, 2020). Thus, it is imperative to protect ecological functions and biotic communities within a given system to carry out different phases of their life history (Kumar and Jayakumar, 2020). Disturbances in ecological functions intimidate the vitality and health of organisms within the biological system. Humans are also a component of the biological system. Therefore, it is crucial to protect ecological functions for

maintaining human health and wellbeing (Fischenich, 2003; Acreman and Ferguson, 2010).

The ecosystem services, security of social and economic goods such as fish, medicines, timber and protection from natural disasters such as flooding can be done by protecting the ecological functions (Acreman and Ferguson, 2010). Several categories of ecological functions within riverine ecosystems are distinct that are outlined as follows (Table 2.2) (Fischenich, 2003).

**Table 2.2:** Categories of ecological functions supported within the riverine ecosystems

<b>Ecological functions</b>	<b>Categories</b>	<b>Functions</b>	<b>Importance</b>	<b>Reference</b>
Hydrological Functions	Surface water storage	<ul style="list-style-type: none"> <li>• Deliver attenuation of high flow events, backwater areas, the release of water and maintenance of baseflow during low flow periods</li> <li>• Maintenance of baseflow</li> </ul>	<ul style="list-style-type: none"> <li>• Reduction of high flows: provides relief to aquatic ecosystems from physical stress caused due to the turbulence and velocity of high flows</li> <li>• Backwater areas: provide low-velocity habitat, refuge areas during high flow period, increase contact time for biogeochemical processes</li> <li>• It will sustain longitudinal connectivity which will make waterways available for organisms to migrate and provide in-stream habitat during low flows or no flows periods</li> <li>• Also, it will maintain soil moisture during low flow or no flow periods</li> </ul>	Fischenich, (2003); Thorpe <i>et al.</i> , (2006)
	Hydrodynamic balance processes	<ul style="list-style-type: none"> <li>• Range of flow conditions</li> </ul>	<ul style="list-style-type: none"> <li>• It includes flow magnitude, frequency, timing, duration and rate of change of flows, an essential factor in maintaining aquatic ecosystems</li> <li>• Allow seasonal access to floodplains and wetlands for instream organisms, acts as a nursery habitat for several species and can significantly alter local biogeochemistry</li> <li>• It also acts as a cue to move into the next phase of their life histories such as spawning, egg hatching, rearing, reproduction and migration</li> </ul>	Junk <i>et al.</i> , (1989); Poff <i>et al.</i> , (1997)

Ecological functions	Categories	Functions	Importance	Reference
		<ul style="list-style-type: none"> <li>• Lateral and longitudinal variability</li> </ul>	<ul style="list-style-type: none"> <li>• It creates heterogeneous physical habitat conditions that lead to habitat complexity and increased biodiversity</li> </ul>	Ward, (1989)
Groundwater-Surface Interaction	Groundwater storage and upwelling	<ul style="list-style-type: none"> <li>• The dominant source of baseflow</li> <li>• Groundwater upwelling</li> </ul>	<ul style="list-style-type: none"> <li>• These interactions regulate stream temperature, moderately low and high flow, increase the processing of nutrients and the exchange of chemicals and provide flow pathways between the channel and subsurface</li> <li>• It sustains refugial pools that may be critical to the survival of aquatic species during low flow</li> <li>• Processing of nutrients and decomposition of organic matter is also dependent on the quantity and quality of the groundwater flux in a stream</li> </ul>	Bovee <i>et al.</i> , (1998); Fischenich, (2003); Piggot <i>et al.</i> , (2005); Boulton and Hancock, (2006)
Geomorphic Functions	Include sediment erosion, transport and deposition	<ul style="list-style-type: none"> <li>• Flow pathways between the channel and subsurface</li> <li>• Affect the quality of water</li> </ul>	<ul style="list-style-type: none"> <li>• Provide routes for the movement of organisms and provide habitat for species that have adapted to take advantage of the unique characteristics that the flow pathways provide</li> <li>• Suspended sediment increases turbidity which affects light penetration, photosynthesis and biogeochemical processes, as well as some nutrients such as phosphorus, can bind to sediments and be eroded, transported and deposited</li> <li>• Contribute to the succession of aquatic and riparian habitats</li> </ul>	Huebner and Vinson, (2004) Withers and Jarvie, (2008)
	Determine the morphological	<ul style="list-style-type: none"> <li>• Spatial and temporal distribution and size of</li> </ul>	<ul style="list-style-type: none"> <li>• Formation of point bars, scour pools, islands, pool-riffle sequences and oxbows</li> </ul>	Thorpe <i>et al.</i> , (2006); Acremen

Ecological functions	Categories	Functions	Importance	Reference
	characteristics of the riverine landscape	channel substrate and geomorphic features	<ul style="list-style-type: none"> <li>• They create habitat complexity and increase the aquatic biodiversity, thus making the system more resistant to natural and anthropogenic disturbance</li> <li>• Provides ecosystem services to society such as flood control</li> </ul>	and Ferguson, (2010)
Biogeochemical Functions	Maintenance of the biological structure and critical biogeochemical processes	<ul style="list-style-type: none"> <li>• The presence of diverse communities of native species with appropriate age class and life form distribution as well as genetic diversity</li> <li>• Occur within the soil zone, the groundwater zone and the river channel</li> </ul>	<ul style="list-style-type: none"> <li>• Important as organisms will interact with each other to create and maintain healthy aquatic ecosystems, organisms will interact through predator-prey relationships or by providing structural habitat for other organisms, such as that created by downed woody debris or beaver damming</li> <li>• Important chemical variables include acidity, amount of total dissolved solids, amount of dissolved oxygen, and nutrient levels. Maintenance of appropriate ranges of water quality variables is necessary as organisms native to a particular environment within the aquatic ecosystem function optimally within a specific range of these variables</li> <li>• Maintaining appropriate ranges of water chemistry can control the spread of pathogens and viruses within a system</li> <li>• Benefit society by maintaining clean, aesthetically appealing watercourses for recreational enjoyment as well as a potential source of drinking water</li> </ul>	Larson <i>et al.</i> , (2001); Thorpe <i>et al.</i> , (2006)  Fischenich, (2003)

There is another categorization of ecological functions done based on factors such as connectivity, water quality, sediment transport, channel and floodplain morphology and biological requirements (Table 2.3).

**Table 2.3:** Summary of critical ecological functions of ‘river flows’

<b>Flow Need(s)</b>	<b>Rationals</b>
<b>Connectivity</b> (Vannote <i>et al.</i> , 1980; Ward and Stanford, 1995; Jungwirth <i>et al.</i> , 2000; Bradford, 2008)	
Longitudinal Connectivity	<ul style="list-style-type: none"> <li>● Prevent disruption of the food web and allow for migration and access to refugia</li> </ul>
Lateral Connectivity	<ul style="list-style-type: none"> <li>● Sustain floodplains and riparian wetlands</li> <li>● Access to complex biophysical floodplain habitats</li> <li>● Maintain nutrient dynamics</li> <li>● Recruit woody debris</li> </ul>
Vertical Connectivity	<ul style="list-style-type: none"> <li>● Maintain hyporheic interaction</li> </ul>
<b>Water Quality</b>	
Stream temperature	<ul style="list-style-type: none"> <li>● Maintain preferred range for the community of aquatic organisms</li> <li>● Prevent negative effect on DO</li> </ul>
Fulfill objectives for water quality	<ul style="list-style-type: none"> <li>● Maintain DO concentrations</li> <li>● Flush down the by-products of metabolism</li> <li>● Achieve biodegradation, nutrient transformation and dilution of related to wastewater effluent discharges</li> </ul>
<b>Sediment Motion</b> (Kondolf and Wilcock, 1996; Church and White, 2006)	
Maintain the sediment transportation capacity	<ul style="list-style-type: none"> <li>● Maintain a balance between deposition and erosion to sustain natural evolution of channel and morphology of floodplains</li> <li>● Replenish the substrates for habitat and spawning areas for fish and benthic organisms</li> </ul>

<b>Flow Need(s)</b>	<b>Rationals</b>
Flushing flows	<ul style="list-style-type: none"><li>• Sustain the quality and character of substrates material (e.g., prevent suffocation of biota and allow removal of metabolic waste)</li><li>• Scour encroaching vegetation</li></ul>
<b>Channel and Floodplain Morphology</b> (Whiting, 1998; Whiting, 2002)	
Maintain planforms (natural meander amplitude and wavelength, braiding and sinuosity)	<ul style="list-style-type: none"><li>• Maintain sediment transport capacity</li><li>• Maintain aquatic habitat</li></ul>
Maintain profile, spacing, and sequences of features	<ul style="list-style-type: none"><li>• Hydraulic biotype (e.g., riffles, runs, pools, cascades, backwaters and side channels) are integral habitat</li></ul>
Maintain the cross-sectional shape of the channel	<ul style="list-style-type: none"><li>• Maintain capacity of the channels</li><li>• Maintain thalweg structure for longitudinal connectivity in the channel</li><li>• Maintain wetted perimeter for the production of food</li><li>• Maintain bank structure for habitat provision and channel stability</li></ul>
Maintain floodplain morphology	<ul style="list-style-type: none"><li>• Maintain the diversity of floodplain habitats</li></ul>
<b>Biological Requirement</b> (Gregory <i>et al.</i> , 1991; Imhof <i>et al.</i> , 1996)	
Maintain stream hydraulics and unique features	<ul style="list-style-type: none"><li>• Conditions for the habitat specialists should be maintained, e.g., groundwater discharge zones for Brook Trout, basking sites for turtles</li></ul>
Maintain moisture levels for riparian vegetation	<ul style="list-style-type: none"><li>• Riparian vegetation governs the bank morphology, controls light and water temperature as well as it provides a source of organic matter</li></ul>

Source: Adapted from Bradford (2008); Beaton (2012)

### **2.3 Environmental Flow Assessment (EFA) Methodologies**

Around 220 EFA methodologies have been developed and applied throughout the world (Shokoohi and Hong, 2011). The EFA methodologies are essential in assessing the e-flows to maintain the critical riverine ecological functions (Poff *et al.*, 1997). EFA or instream flows assessment is the science of determining the flow regime required to sustain specific features of an aquatic ecosystem (Poff *et al.*, 1997; King *et al.*, 1999). The e-flows assessment methodologies have evolved from straight forward generic methods to robust, site-specific holistic methods. Based on chronological evolution, e-flows assessment methodologies have been categorized into four generations, as shown in Table 2.4.

**Table 2.4:** Evolution of e-flows assessment methodologies from simple models to holistic methodologies

Generation	Time-period	Site-specific	Multiple targets	ecological	Hydrology into EFA Pragmatism	Integrated management	basin	Incorporating social frameworks	Incorporating future climatic scenarios
1 <sup>st</sup>	1970-1990	Tennant method, R2 Cross method, Idaho method, FDC <sup>1</sup> , Wetted Perimeter	IFIM <sup>2</sup> , WUA <sup>3</sup>		PHABSIM <sup>6</sup>	RCHARC <sup>7</sup>			
2 <sup>nd</sup>	1991-2000	Median annual FDC	Expert panel method, IHA <sup>4</sup> , RVA <sup>5</sup>			BBM <sup>8</sup> , DRIFT <sup>9</sup> , RAISON software	IQQM <sup>10</sup> ,		
3 <sup>rd</sup>	2001-2010	Tessmann method	Smakhtin method, Recruitment Box Model, Stochastic matrix modeling, Numerical modeling, Response curves	structured or modeling,		DHRAM <sup>11</sup> , Fuzzy method-Bayesian modeling, vegetation-flow guild framework, ELOHA <sup>12</sup>	mixture Riparian response		
4 <sup>th</sup>	2011-2019					WFET <sup>13</sup>		Social preference incorporated in ELOHA	REFDSS <sup>14</sup>

Source: Author's elaboration. <sup>1</sup>Flow Duration Curve, <sup>2</sup>Instream Flow Incremental Methodology, <sup>3</sup>Weighted Usable Area, <sup>4</sup>Indicator of hydrological alteration, <sup>5</sup>Range of Variability Analysis, <sup>6</sup>Physical Habitat Simulation Model, <sup>7</sup>Riverine Community Habitat Assessment and Restoration Concept, <sup>8</sup>Building Block Methodology, <sup>9</sup>Downstream Response to Imposed Flow Transformations, <sup>10</sup>Integrated water quantity and quality simulation model, <sup>11</sup>Dundee Hydrological Regime Alteration Method, <sup>12</sup>Ecological limits of hydrologic alteration, <sup>13</sup>Watershed Flow Evaluation Tool, <sup>14</sup>Raison software environmental flows decision support system

### **2.3.1 1<sup>st</sup> Generation EFA Models**

In 1976, Tennant designed the first in-stream flow model named ‘Montana Method’ or ‘Tennant Method’ although the Tennant method was officially not applied in Montana (Tennant, 1976). The method recommends flows in terms of Average daily discharge or Mean annual flow (MAF) based on trend analysis of the relationship between river condition, amount of flow in the river and effect on fish habitat. In this method, 10% of the MAF is recommended to maintain a minimum instantaneous flow that ensures survival of most aquatic life; 30% MAF is recommended to sustain suitable habitat; 60-100% of the MAF is recommended to maintain excellent habitat; 200% MAF is recommended for ‘flushing flows’ in the river stream. This method has few limitations, such as ecologically important variable flow and extreme flow conditions are not taken into consideration while recommending flows. Also, this method neglects the timing of the flow while recommending the e-flows for a particular area. Stalnaker and Arnette (1976) developed the ‘Wetted Perimeter’ method. This method is a transect based site-specific method that finds its use in e-flow analysis, but it does not suitably represent the aquatic habitat. The wetted perimeter-discharge relationship can be derived from the survey of the discharge level at different sites on the channel cross-section. The transects are often placed only at the places where there are riffles or at the sites where fish passage is likely to be restricted. There are multiple methods available to model the relationship, such as Manning ‘n’ equation (Gordon *et al.*, 1992) and computer-based programs (Grant *et al.*, 1992). The breakpoint in the wetted perimeter-discharge relationship graph has been used to define the minimum or optimum flow requirements for fish rearing or food production in a stream in the US and Australia (Collings, 1972; Cochnauer, 1976; Nelson, 1980; Richardson, 1986). As

per the Oregon Department of Fish and Wildlife, 50% of the maximum wetted perimeter is recommended at the riffles as e-flows (Stalnaker and Arnette, 1976). Otherwise, it will lead to exposure and unproductiveness of the riffle area, diminution in fish due to stream bank cover reduction, fish overcrowding, and water quality deterioration. Tennant (1976) and Gippel and Stewardson (1998) used this method for defining the minimum flow requirements of Wyoming and Montana streams and Starvation Creek and Armstrong Creek of Melbourne catchment, respectively. Clemens Herschel in 1880 first used the Flow Duration Curve Analysis (FDCA) (Foster, 1934). However, FDCs were studied and developed precisely by many workers (Foster, 1934; Mitchel, 1957; Fennessey and Vogel, 1990; Vogel, 1994). It is a hydrology-based methodology and displays the relationship between discharge and the percentage of time that it exceeded (based on the daily, weekly, monthly time interval of stream-flow variable analysis). Booker and Snelder (2012) observed and analyzed FDCs of 379 gauging stations located across New Zealand indicated that predictive capabilities are different between methods and through the exceedance of the percentiles. They also emphasized that the mixed-effects approach is the most parsimonious method for estimating FDC at un-gauged sites. Bovee (1982) introduced 'Instream Flow Incremental Methodology' (IFIM) based on Flow duration curve (FDC) (Bovee *et al.*, 1998; Tharme, 2003). The U.S. Fish and Wildlife Service used this method for determining the suitability of habitats to streamflow of different magnitudes and frequencies (Orth and Maughan, 1982; Gordon *et al.*, 1992; Stalnaker *et al.*, 1996). As per Gore and Nestler (1988) it was considered to be most refined, scientifically and legally defensible methodology existing for quantitatively assessing EFRs for rivers among the ecologists throughout the world (Reiser *et al.*, 1989; Bullock *et al.*, 1991; King and Tharme, 1994; Jowett and Richardson, 1995). In this

method, transect based hydraulic analysis was performed to evaluate simple habitat conditions (e.g. depth, velocity) connected with varying levels of flow. In the following years, it has also been adapted for the calculation of instream flows for benthic invertebrates (Gore, 1987; King and Tharme, 1994), instream biota downstream of hydropower projects (Gore *et al.*, 1989; Gore *et al.*, 1990a), riparian vegetation (Bovee and Milhous, 1978; Bovee, 1982), wildlife (Gore *et al.*, 1990b), flushing flows (Reiser *et al.*, 1989) and for maintenance of water quality (Armour and Taylor, 1991) in countries like Alaska, Canada, Britain and Wales. The e-flows assessment of peaking hydropower and sediment flushing is possible using the modifying IFIM methodology. Further, the outputs from habitat simulation methodologies can be linked to the water quality and temperature models to get more holistic e-flows assessment methodology. In the case of Physical Habitat Simulation Model, PHABSIM done by Williamson *et al.* (1993), IFIM is integrated with models of biological populations, biological response models and complex suitability criteria to increase its potential for ecological prediction (Gore *et al.*, 1990a; Williamson *et al.*, 1993; Stalnaker *et al.*, 1994). PHABSIM comprises two sets of procedures composed of hydraulic simulation and habitat simulation. These simulations use around 240 computer programs that contain five different hydraulic and five habitat simulation models. The results of the simulation procedures are interconnected to produce an output of Weighted Usable Area (WUA) versus discharge, indicating the losses or gains in habitat. The combination of depth, velocity, substratum and the cover as a function of discharge are used to quantify the losses and gains for the target species, life stages, or species assemblages of concern. Environmental flows are recommended based upon breakpoints on the WUA-discharge curves.

‘Riverine Community Habitat Assessment and Restoration Concept’ (RCHARC) is another variant of the IFIM approach. It was first applied in the Missouri River (USA) by Nestler *et al.*, (1994). It resulted in the concept that the spatial distribution and abundance of stream features like depth and velocity at a place gets affected by human interventions like damming and channelization. The limitations of transect-based models are that they assume a stable channel, characterization of habitat is in limited terms such as depth and velocity. The performance of these models improves when the habitat requirement of the modeled species at different life stage are known.

### **2.3.2 2<sup>nd</sup> Generation EFA Models**

The New South Wales departments of Fisheries and Water Resources developed the expert panel method (Swales *et al.*, 1994; Swales and Harris, 1995). It was the first multidisciplinary, panel-based EFAs approach employed in Australia (Arthington, 1998a). The eminent scientists (Growth and Kotlash, 1994; Tharme, 1996; Dunbar *et al.*, 1998; Arthington, 1998a; Tharme, 2000) reviewed this method aimed at the overall river ecosystem health rather than the health of the single component. Although the “suitability of stream flows for the survival and abundance of native fish is taken as the primary criterion of the suitability of the discharge as an environmental flow” (Swales and Harris, 1995). A panel of experts in aquatic ecosystems and river management is constituted. They make the interpretations based on multiple trial flow releases from an impoundment, at study sites located downstream to the impoundments. Thus, recommendations were made for the selected site. This method was first used to recommend EFRs for six tributaries of the Murray-Darling system. To recommend e-flows, two panels composed of multidisciplinary members were constituted. It included a freshwater fish ecologist,

riverine invertebrate ecologist and fluvial geo-morphologist. This method is widely used in parts of Britain, Germany and Switzerland.

In 1994, Vogel pointed out the problems in daily streamflow based interpretation method as highly unreliable as daily streamflow data are highly skewed, resulting in biased product-moment ratios. Vogel (1994) introduced a new 'Median Annual FDC' method to streamflow analysis that allows the user to derive confidence intervals, recurrence interval and quartile estimation procedure for FDC in a non-parametric framework.

Richter *et al.* (1996) developed an Indicator of hydrological alteration (IHA) based on magnitude, frequency, timing, duration and rate of change in flow components of the natural flow regime. The initial flow management targets have 32 hydrological parameters as the base of the e-flows assessment. Richter *et al.* (1997) developed the Range of Variability Approach (RVA) with the use of IHA methods to develop a hydrological method with a primary objective to protect the natural ecosystem by releasing the set benchmark flows in the river. The starting point in RVA is to either measure or synthesize daily streamflow values from a period where the degree of human perturbations to the hydrological regimes was negligible. In the RVA method, the range of variation lies in +/-1 standard deviation from its mean or between 25th -75th percentiles. The relative change in the frequency of pre- and post-impact on IHA values that fall into the default range of variation were calculated. These relative changes are considered as the hydrological alteration in the RVA (Yang *et al.*, 2014).

Some desktop-based systems were also designed, such as IQQM and RAISON. Young *et al.* (2000) used RAISON software to design a decision support system (DDS) in Murray–Darling Basin, Australia. This method is flexible in its approach and works on the data derived from other e-flows assessment

methodologies. The flexibility in the software design is the most promising salient feature for the decision support system. The DSS cannot be used to model the details of river hydrology or hydraulics; instead, it uses the output from other models to do the ecological modeling. The DSS provides a range of tools that benefits users in evaluating the scenario-based results as well as provide the supporting information and explanations to elucidate the ecological modeling (Young *et al.*, 2000).

King and Tharme (1994) and King (1996) introduced the Building Block Methodology (BBM). Tharme and King (1998) and King and Louw (1998) systematically described this methodology. BBM originated way back in the 1990s, and several workshops preceded the on-ground application of this method in the management of the Luvuvhu River and Sabie-Sand River in South Africa. The South African Department of Water Affairs and Forestry (DWAF), after attending these workshops, realized the need for legal regulation for quantifying the requirement of water for river maintenance. Thus, in the new National Water Act (No. 36 of 1998) of South Africa, the environmental flow was allocated for maintaining river ecosystems in the form of Ecological Reserves (King *et al.*, 2008). The methodology is under continuous development and has been applied regularly in South Africa, Australia, India and other parts of the world (Arthington and Lloyd, 1998; WWF, 2012; WWF, 2013). It is a holistic method used in environmental flow management. It is a tool to organize and structure the data and acquired knowledge to provide useful output. The output received is a modified flow regime, which is quantified explicitly in terms of space and time to the study area. Recently, a study has been done based on BBM methodology in the upper Ganga basin by WWF-India (WWF, 2012) as well as on the Kumbh Mela-2013 (WWF, 2013). DRIFT methodology has evolved from BBM (Brown and King, 1999). It is a scenario-based approach involving the collection of massive data from all the disciplines to describe the biophysical and socio-economical

impacts of the modification in the present flow patterns on the ecosystem. It consists of four modules, first is the biophysical module which addresses the changes occurring in the ecosystem in association with changing river flow. Second is socio-economic module that links the riparian people to the river based on their requirements of river resources and their health-related impacts. In the third module, scenarios are built based on future river flow scenarios and their impacts on the riparian peoples. The fourth is an economic module, and it deals with the compensation and mitigation cost. DRIFT is also accompanied by two exercises that are not part of it but run parallel with the study. Firstly, a macro-economic assessment of the broader implication of each scenario. Secondly, the public participation process in which the level of acceptability of each scenario by the people other than subsistence users (King *et al.*, 2003). This method has been developed in semi-arid and developing regions. It was used for studying the impact of Lesotho Highlands Water Project, South Africa.

### **2.3.3 3<sup>rd</sup> Generation EFA Models**

In this category, the methods developed from 2001 to 2010 have been grouped. Black *et al.*, (2005) developed the Dundee Hydrological Regime Alteration Method (DHRAM) to classify river flow regime alteration for the European Community Water Framework Directive (EC-WFD). In this method, the Indicators of Hydrologic Alteration approach is used to classify the risk of damage to instream ecology. The daily mean flow time-series data is used to represent the impacted and un-impacted situations due to any anthropogenic hydrological impact (such as abstractions, impoundments, or flow augmentation) at the selected site. In this method, a synthetic series of daily mean flows can be generated using the Micro Low Flows computer package. A pair of Scottish case studies demonstrate its ability to classify regime alteration and mapping, which is of considerable value to river basin

managers. In Australia, the first continental-scale classification of hydrological regimes was presented by Kennard *et al.* (2010). It incorporates 120 matrices to describe the ecologically relevant characteristics of the natural hydrologic regime based on discharge data for 830 stream gauges. A continuous-time series of mean daily discharge data were used to calculate the matrices, and classification was undertaken using a fuzzy partitioning method – Bayesian mixture modeling. They classified distinctive flow regimes into 12 classes based upon different seasonal discharge patterns, degree of flow stability (i.e., degree of change of flow in perennial to intermittent flow), variation in flood magnitude and frequency and additional aspects of flow predictability and variability. They emphasized that the hydrological spatial variations are determined by complex interactions among geology, climate, vegetation and topography at different temporal and spatial scales. In this work, the decision tree was also developed to determine the natural flow-regime class membership of other stream gauges as per their vital environmental and hydrological characteristics. This classification system is beneficial in understanding the flow-ecological relationships in Australia. Subsequently, the management efforts were aimed at prescribing environmental flows for river restoration and conservation.

Merritt *et al.* (2010) developed a riparian vegetation-flow response guild framework for the prediction of vegetation response to changing environmental conditions. They propose to organize riparian plants into non-phylogenetic groupings of species with shared traits that are related to components of the hydrologic regime. Thus a probabilistic response curve was prepared with hydrologic attributes of a specific class of river. Similar models based upon the relation between the riparian vegetation and flow regimes attributes were developed at an individual scale, population-scale and community scale. Some of the models are the recruitment box model, stochastic structured or matrix modeling, numerical modeling and response

curve, respectively (Mahoney and Rood, 1998; Lytle and Merritt, 2004; Smith *et al.*, 2005; Griffith and Forseth, 2005; Friedman *et al.*, 2006). Researchers have also used the Bayesian Network (BN) method in decision-making tools for environmental flows assessment (Hart and Pollino, 2009; Stewart-Koster *et al.*, 2010). Stewart-koster *et al.* (2010) used the BN method in south-east Queensland, Australia to address the specific river restoration goals based upon the prioritization of flow as well as catchment restoration options. They also incorporated the cost of restoration in this model (Ames *et al.*, 2005). Shenton *et al.* (2011) developed an e-flows Bayesian Network (BN) model by linking four flow components with an ecological model to predict the spawning and recruitment of two native fish species, the Australian Grayling and River Blackfish in lower Latrobe River in Victoria, Australia. In this method the essential flow components were linked to an ecological model. Thus the prediction for the flow requirements of two important fish species, Australian Grayling and River Blackfish, were made in highly regulated and flow-stressed Latrobe River in Victoria, Australia (WGCMA, 2005). Chan *et al.* (2012) used the BN models to assist the decision making process on e-flows required to keep the Daly River ecological healthy (Northern Territory, Australia). The abundance of two fish species namely barramundi (*Lates calcarifer*) and sooty grunter (*Hephaestus fuliginosus*) is considered as ecological indicator endpoints for the model. They also tried to model the impact of groundwater abstraction of river flow depending on the distance of bore from the river. Gyftodimos and Flach (2002) made an extension to the BN that can include additional information on the structure of the domains of variables, termed it as Hierarchical Bayesian Networks (HBN). BN methods are found very useful for reasoning under uncertainty. HBN is more expressive as the node in it may correspond to an aggregation of multiple simpler types. Webb *et al.* (2015) incorporated the available knowledge from literature, experts, and monitoring

data in the Bayesian hierarchical model. All these elements were used to quantify the relationship between flow variation and ecological response. Studies have found that these parameters are important in predicting the ecological response to the flow restoration works (Webb *et al.*, 2018).

Richter (2010) introduced the Sustainable Boundary Approach (SBA) based on the sustainable boundary concept of Postel and Richter (2003). It is not an EFA method instead of a concept that can be applied to other EFA methodologies to determine the sustainable boundaries for setting up quantitative water management goals. Approaches similar to SBA have been applied in other parts of the world, such as ‘percent-of flow’ approach used in Southwest Florida Water Management of natural streamflow at the time of withdrawal (Flannery *et al.*, 2002). A similar type of formula for water supply plan was developed and applied in the city of Charlottesville and Albemarle Country in Virginia (U.S.) by the Rivanna Water and Sewer Authority (RWSA). In this plan, the importance was given on natural inflow to determine the amount of water that can be store for water supply and how much water is needed to be released from the reservoir to maintain adequate environment flows downstream (Richter, 2007). Poff *et al.* (2010) devised a new framework for setting regional environmental flow standards, the ecological limits of hydrologic alteration (ELOHA). It is an amalgamation of multiple existing hydrologic techniques and e-flow methods that are already in use at various levels to provide general regional flow management. This approach is flexible and allows water-resource managers, scientists, and stakeholders to evaluate and combine the available scientific information into ecologically centered and socially acceptable targets for the management of e-flows. The existing database on hydrology and ecology from many rivers in a user-defined region was synthesized to develop scientifically defensible and empirically testable relationships among the flow alteration and associated

ecological responses. This relationship sets the base for the socially driven process of developing flow standards specific to a region. Initially, the ‘hydrologic foundation’ of baseline and current hydrographs was set using hydrologic modeling for the river and stream. Then, a set of ecologically relevant flow variables were used to classify the river segments into a few distinctive flow regime types that are expected with different ecological characteristics. In the next step, these rivers can be sub-classified as per significant geomorphic features that outline hydraulic habitat features. In a further step, the aberration in the current flow conditions from the baseline-condition flow is resolute. In the final step, river specific flow alteration–ecological response relations were developed. These relations were grounded on a combination of existing hydro-ecological literature, field studies and expert knowledge across gradients of hydrologic alteration. This process is robust and multi-dimensional in approach but is devoid of social methods with practical guidelines for integrating social preferences into e-flows management problems.

#### **2.3.4 4<sup>th</sup> Generation EFA Models**

The most advanced and latest group of methodologies has been developed in the past five years. Specific EFAs cannot keep pace with the rate and geographic extent of water resource development. To meet the requirements of the regional basin, Sanderson *et al.* (2011) developed a Watershed Flow Evaluation Tool (WFET) to assess the flow-related ecological risk at a regional scale in Colorado, USA. This method has four steps:

- (i) Modeling natural and developed daily streamflows,
- (ii) Analyzing the resulting flow time series,
- (iii) Describing relationships between river attributes and flow metrics (flow–ecology relationships), and

- (iv) Mapping of flow-related risk for trout, native warm-water species, and riparian plant communities.

This method is cost-effective, applicable for large areas, but has limitations with active channel changing rivers as well as data deficient study areas. It is a promising method to evaluate the impacts of future climate change and water development scenarios on the river ecosystem. Bark *et al.* (2012) emphasized the need to account for multiple and diverse social and cultural values of people for aquatic ecosystem management. In 2015, Jackson *et al.* developed an EFA methodology to incorporate the water requirements of indigenous people as well as their knowledge into EFA. He applied this study to the Murray-Darling Basin, Australia. In this method, the priority was the problems due to humans and natural systems. Akhbari and Grigg (2015) developed Agent-based modeling (ABM), a tool to develop integrated human-environmental models. They used three models system, i.e., a watershed simulation model, an optimization model, and a behavioral simulation model for the development of a conflict management tool. This method was applied in the San Joaquin River (SJR) watershed, California, to create a hydrologic-environmental-human interface to support powerful decision-support tools to manage conflicts and make informed, practical decisions in water resources management.

In 2015, Martin *et al.* worked on incorporating the social preference into ELOHA that was earlier developed by Poff *et al.*, (2010). This method is developed to prioritize river basin conditions and to rank river segments so that hydro-ecological and social, environmental flow needs of the rivers can be combined. This method was used to recommend the e-flows for the Yampa-White River basin, Colorado. Survey-based stakeholder preferences were collected. The importance of five criteria recognized as socially valued substitutions of freshwater management in the river basin was estimated using the analytic hierarchy process. The prioritization of basin

river segments was done using the analytical methods for multi-criteria assessment to incorporate the preference information with the results obtained from the ELOHA application. This method simplifies the ways for stakeholder negotiation and future environmental flow policy analyses. This extension widens the framework's approach and is beneficial in planning environmental flow policy and management in other river basins. Maloney *et al.* (2015) developed the Riverine Environmental Flow Decision Support System (REFDSS) for the Upper Delaware River, USA. This tool evaluates competing-flow situations and other variables on instream habitat. This model can integrate a large set of spatially explicit data to synthesize the modeled discharge values for three different management scenarios. This method was developed to enable the adjacent evaluation of different flow management scenarios and their effects on potential habitat availability (Kelly *et al.*, 2015). It supports the managers in recommending the best flow scenarios for the study area.

Tharme (2003) has divided EFA into five major categories depending upon the date, time, and resources requirements:

1. Hydrological Methods,
2. Hydraulic Rating Methods,
3. Habitat Simulation Methods,
4. Holistic Methodologies and
5. Combined methodologies

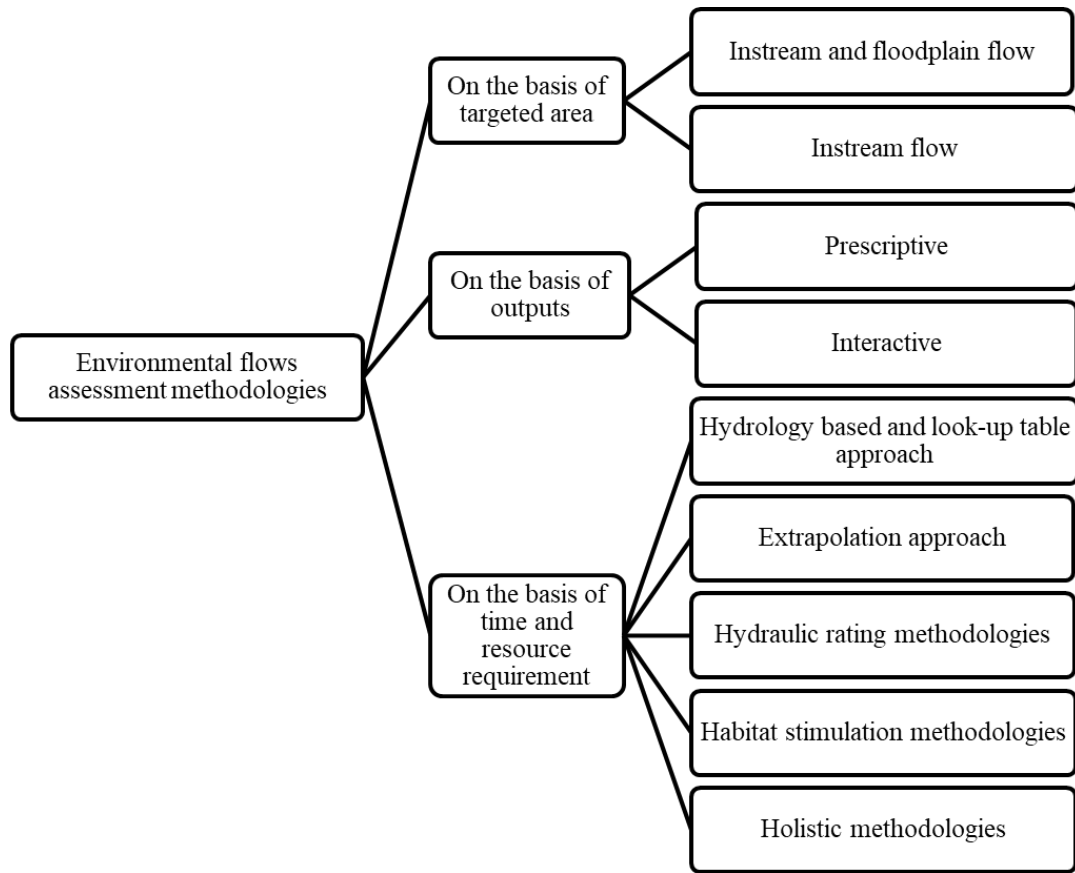
The limitations and benefits of the categories mentioned above are outlined as follows (Table 2.5).

**Table 2.5:** General requirements and limitations of each type of E-Flows assessment methodology

<b>Assessment Type</b>	<b>Requirements</b>	<b>Time required for analyses</b>	<b>Costs</b>	<b>Confidence required</b>	<b>Examples</b>	<b>Limitations</b>	<b>Benefits</b>
Hydrological Models	Hydrology	1 Day	Low	Low	<ul style="list-style-type: none"> <li>• Tennant,</li> <li>• FDC Analysis,</li> <li>• Aquatic base flow,</li> <li>• RVA,</li> <li>• Percentage of flow</li> </ul>	<ul style="list-style-type: none"> <li>• The ecologically critical extreme flow conditions and timing of flow are not incorporated</li> <li>• Challenging to implement in data deficient situations</li> <li>• Expertise required to set-up, run and interpretation of the output of the models</li> </ul>	Simple, rapid, inexpensive, can be used as a component of holistic methodologies
Hydraulic Rating	Hydrology/ Hydraulics	1 Week	Intermediate	Low	<ul style="list-style-type: none"> <li>• Wetted perimeter</li> </ul>	<ul style="list-style-type: none"> <li>• The detailed hydrological and hydraulic study is not included, it relies on the oversimplistic assumption that the health of a given aquatic ecosystem component is dependent on one hydraulic variable or a small group of hydraulic variables that are measured</li> <li>• Results are only given in minimum flows requirements to sustain given habitat variables</li> <li>• It does not consider other aspects of a natural flow regime such as timing, duration, rate of change and frequency</li> <li>• The relationship between discharge and</li> </ul>	A relatively simple, cost-effective method, provides a more explicit link between discharge and ecology, incorporates ecological information related to physical habitat requirements at various discharges

Assessment Type	Requirements	Time required for analyses	Costs	Confidence required	Examples	Limitations	Benefits
Habitat Simulation	Hydrology/ Hydraulics/ Ecology	Months	High	Fairly high	<ul style="list-style-type: none"> <li>•Habitat simulation methods,</li> <li>•Instream flow incremental methods</li> </ul>	<p>hydraulic parameters of concern is hard to attain,</p> <ul style="list-style-type: none"> <li>•The stage-discharge relationship to the actual flow regime, the hydraulic relationship is limited in spatial resolution to the cross-sections thus tricky to expand to out of channel ecosystem components such as riparian vegetation</li> <li>• The river channel is assumed to be stable, and characterization of the habitat is limited in terms of depth and velocity</li> <li>• Data-intensive and data collection and model simulation can be time-consuming</li> <li>•In the absence of real-time data availability, significant expertise is required to run and make interpretation of the model output</li> <li>• Does not incorporate broader aspects of the riverine landscape</li> <li>•Does not account for long-term changes in river morphology</li> <li>•There is a need for further research, testing and validation to improve confidence in the modeled output</li> </ul>	It provides a relatively scientific and defensible flow assessment by enabling the evaluation of multiple scenarios for various species and life stages, can readily be incorporated into holistic methodologies

Assessment Type	Requirements	Time required for analyses	Costs	Confidence required	Examples	Limitations	Benefits
Holistic	Hydrology/ Hydraulics/ Ecology/ Geomorphology/ Social/Water Quality	Months / Years	High	High	<ul style="list-style-type: none"> <li>•BBM,</li> <li>•DRIFT,</li> <li>•EPAM,</li> <li>•ELOHA</li> </ul>	<ul style="list-style-type: none"> <li>• Hard to implicate, long procedures as well as information gaps in every fundamental aspect of aquatic biology of large plain areas</li> <li>• Lack of connection among the social and livelihoods processes in EFA and framework</li> <li>• Rely heavily on expert opinion, expert opinion can be subjective, non-transparent, and inconsistent and has been perceived to be biased by stakeholders in case experts are employed by regulatory authorities or developers</li> </ul>	They allow the ability to construct flows that sustain a wide array of riverine landscape components into the EFR. They also allow flexibility based on time and resources and can have strong ties to the natural flow regime.
Combined methodologies	Hydrology/ Hydraulics/ Ecology/ Geomorphology/ Social/Water Quality/ Expert opinions	Months /Years	High	High	<ul style="list-style-type: none"> <li>•REFDSS,</li> <li>•Social preference incorporated in ELOHA</li> </ul>	<ul style="list-style-type: none"> <li>• Lack of data to develop the baseline conditions for the streams</li> <li>• Availability of field experts and many times expert opinions can be subjective, non-transparent, and inconsistent and are perceived to be biased in the cases when experts are employed by stakeholders when regulatory authorities or developers</li> </ul>	Multiple methods can be brought together to address specific problems



**Figure 2.1:** Classification of e-flow assessment methodologies based on their targets, output and requirements (Source: Sharma, 2019)

Developing a regional-specific holistic model to recommend e-flows requires a large group of field experts, as shown in Table 2.6.

**Table 2.6:** Requirement of field experts in e-flow assessment

S.No.	Field expert	Responsibility
1	Hydrologist	To describe the river flow, how it was in the past and how it has got changed as well as how it is changing
2	Geohydrologist	To predict the location and height of the water table and changes in subsurface flow, to understand baseflow contribution in e-flows assessment
3	Hydraulic modeler	To study the surface flows and simulate hydraulic conditions
4	Sedimentologist and fluvial	To study and predict the channel response to the changed hydraulic conditions such as in-filling or

S.No.	Field expert	Responsibility
	geomorphologist	flushing of pools, changes in mobility, loss or gain of flood-terrace deposits, sedimentation or scouring of riffles and size-sorting of different-sized bed particles and the accumulation or loss of muddy deposits within the active channel
5	Water-quality specialist	To predict the change in concentrations of nutrients and dissolved solids and their effects on the chemical and thermal regime of the river stream
6	Vegetation specialist	Describes the expected biotic responses of any change in the river channel and flows by predicting how each vegetation zone might change location, width, or some other characteristic, as well as the response of individual plant species
7	Fish ecologist	They predict the changes in fish communities such as any shifts in abundances and condition of the fishes and community composition and they also assess the flow needs of iconic species
8	Plankton specialist, amphibians, reptiles, water birds, semi-aquatic species specialist	They predict and report any change in these communities due to changes in biotic or abiotic factors

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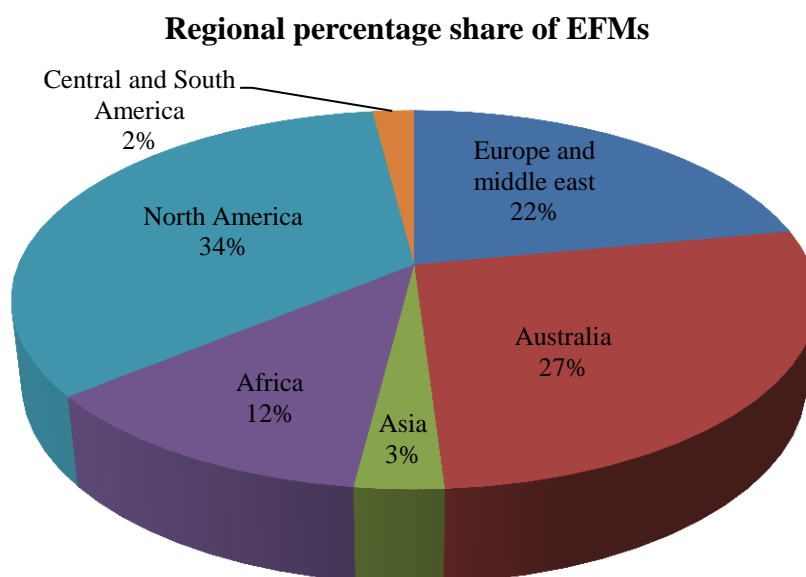
Source: King and Brown (2006); Dutta *et al.* (2019)

#### **2.4 Environmental Flows Assessment Round the Globe**

Western Europe and the USA were the pioneers in the development and application of e-flows assessment methodologies for sustainable water resource management (WCD, 2000; Tharme, 2003; Acreman and Dunber, 2004, Dutta *et al.*, 2019). The whole world was classified into six sub-continent, namely Europe and the Middle East, Australia, Asia, Africa, Central and South America and North America. Out of all the continents, the highest percentage of studies based upon hydrological

Methodologies were reported from Europe and North America a total of 38% and 26%, respectively (Tharme, 2003). In further studies, it was found that in the past few years the hydrological methodologies are gaining popularity in developing nations (Babu and Kumara, 2009; Durbude, 2014; Bhattacharjee and Jha, 2014). They are also gaining importance as a component of holistic approaches. These methodologies have a limited approach and apply to a small region only. These are the target-based method mainly focused on maintaining the minimum flow requirements of a single species. The highest number of applications of hydraulic rating methodologies were reported from North America, with a share of 76% of all studies reported, followed by Europe and Australia. The concept of maintaining the multiple ecological targets essential for sustaining the ecosystem first started in Australia (Arthington *et al.*, 1992; Thoms, 2000) than in South Africa (King and Tharme, 1994). Maximum studies using habitat simulation methodologies were reported from North America followed by Africa and Latin America. Australia and Africa are considered leaders in the development and application of holistic methodologies. However, the concept of ecological consideration for environmental flow assessment developed parallel in New Zealand (Biggs, 1990) and Australia (Hughes, 1987; Hughes and James, 1989). The absence of any study based on such methodologies in North America emphasizes on the limitation of the approach of these methodologies to the native regions (Dutta *et al.*, 2019). The highest studies of e-flows assessment were reported from Europe, i.e. 39% and 57%, of e-flows studies using the Combined EFMs and other approaches, respectively. However, these methodologies had little or no exposure in South and Central America (Dutta *et al.*, 2019). At present, the development and application of new and modifications in the existing methods were reported mainly from Australia (Martin *et al.*, 2015), South Africa (King and Brown, 2018), and

Europe (Acreman *et al.*, 2014). A cumulative assessment is done to understand the percentage share of different regions based on the applications of EFA methodologies (Figure 2.2). Australia is leading in the development and implication of EFM methodology. The incorporation of new concepts and development of new methodologies for e-flows assessment are from Australia, Europe, South Africa and North America. However, the Asian countries and other developing nations of the world are still using the hydrological and hydraulic methodologies and continuously progressing in understanding the available e-flows methodologies to suit their river systems.

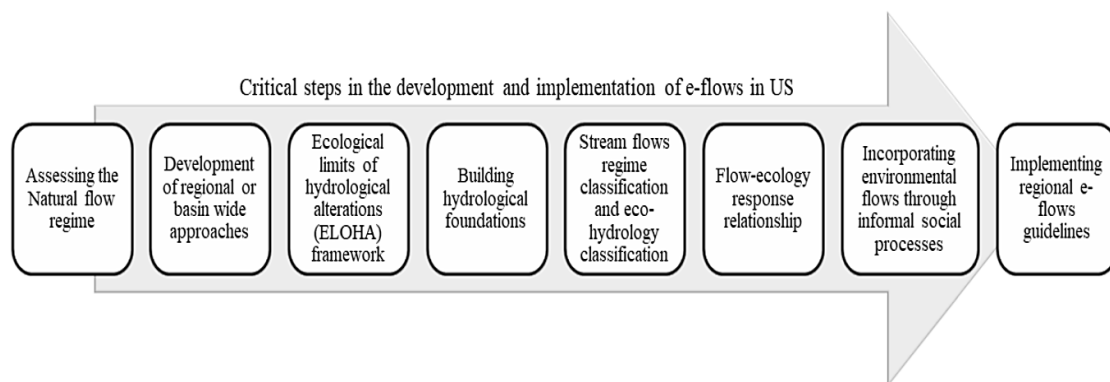


**Figure 2.2:** Regional percentage of EFMs applied in different parts of the world (Source: Dutta *et al.*, 2019)

If we see the critical steps in the development of the E-Flows assessment methodologies in different regions of the world, we can easily demarcate paths chosen regionally to get the desired flow results. In South Africa and the United States, several methods were developed for e-flows assessment and which are still in the process of refinement. In South African, Hydrological, Hydraulic Rating and Habitat

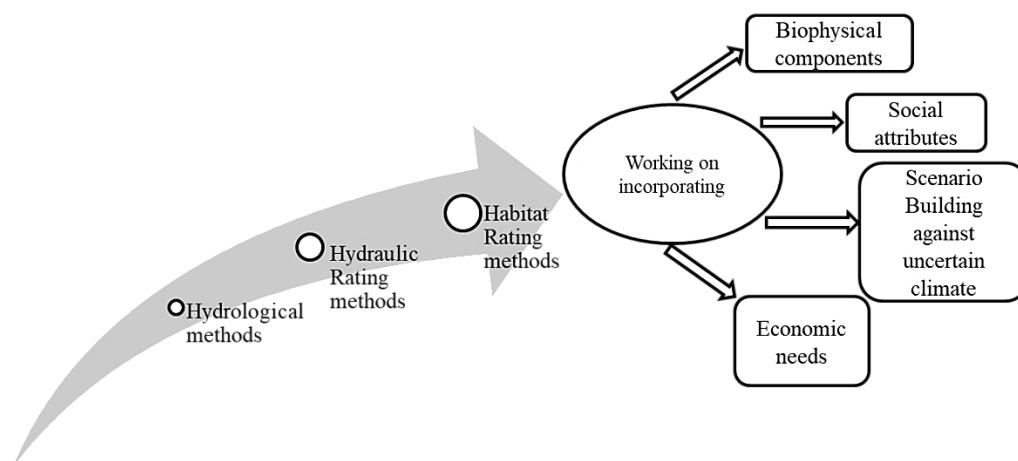
Rating methods are in use for the e-flows recommendation, yet these methods are unable to come to the point of delivering satisfactory results in managing the health of riverine systems (King and Brown, 2006; King and Brown, 2018).

Further improvements are in process to incorporate the biophysical components, scenario-based approaches, economical and social attributes. In the United States, various EFA methods have suggested and implemented the e-flows through strict guidelines on a regional basis (Poff *et al.*, 2007; Poff *et al.*, 2010; Sanderson *et al.*, 2012; Poff and Matthews, 2013; Poff *et al.*, 2017). Critical steps in expansion and application of e-flows assessment in the USA has been shown in Figure 2.3 below:



**Figure 2.3:** Critical steps in expansion and application of e-flows assessment in the United States (Source: Sharma, 2019)

If we see the evolution of E-flows assessment methodologies in South Africa, the already existing methodologies: Hydrological, Hydraulic Rating, and Habitat-Rating methods were not providing the desired level of confidence for credible e-flows assessment (Figure 2.4). Their scientists were looking forward to incorporating four bases in their analysis, i.e., biophysical components, social attributes, scenario building against uncertain climate, and economic needs into e-flows assessment processes.



**Figure 2.4:** Evolution of e-flows methods in South Africa and future desired inputs (Source: Sharma, 2019)

## 2.5 Environmental Flows Assessment in India

India being a developing nation is at a crucial stage where a lot of water management infrastructure projects are getting constructed. The present situation in India is comparable to as it was in North America and Western Europe during the mid-twentieth century. Large river basins all around the world are under stress due to proposed and under-process dams like Mekong Basin, Ganga Basin, Nile, Indus, Yellow, Amu and Syr Darya, Rio Grande and Colorado. Southeast Asia has more than 80 dams under construction (Ziv *et al.*, 2012), the Himalayas in India is home to more than 300 dams (Grumbine and Pandit, 2013) and the Andes has more than 150 dams (Finer and Jenkins, 2012) which are resulting in drought-like conditions in the lower basin areas of the rivers (Poff and Matthews, 2013). In developing countries, little attention has been paid on the assessment of environmental water demand. After independence, India is witnessing rapid development in the form of urbanization, intensification of agriculture and industrialization, which has affected the rivers in multiple ways. Although most of the Indian rivers are highly regulated or in the process of regulation, still very limited or no efforts have been made in assessing the

EFR. The first National Workshop on Environmental Flows held at New Delhi in March 2005 brought a significant interest in the concept of EFs among national agencies and research institutions and revealed their lack of clarity regarding EFs. The significant problems prevailing in developing countries in EFA were highlighted, such as not incorporating and interpreting existing knowledge of aquatic ecosystem components (e.g., fish) and flow-ecology relationships in quantifying the e-flows requirements. There are few studies for e-flows assessment done in India which has been summarized in the table below (Table 2.7).

**Table 2.7:** List of e-flows assessment studies reported in India

S.no.	Location	Methodology used	Recommended e-flows	Recommendations	Reference	
1	Cauvery River	Hydrological methods, EMC-FDC Tennant and modified Tennant method or Tessman method	Index Sites Belus Hadige Akkihebal Kollega Maintenance flow (cumecs) 5.32 20.79 12.24 91.22	<ul style="list-style-type: none"> <li>• Minimum flow in the river channel should be maintained to sustain the riverine ecosystems</li> <li>• A lookup table might not be appropriate for Indian conditions</li> </ul>	Durbude, (2014)	
2	Upper Ganga Basin	Building Methodology	Block Sites Kaudiyala Kachla Bithoor Maintenance flows as % of MAR 72% 45% 47%	Drought year flows as % of MAR 44% 18% 14%	<ul style="list-style-type: none"> <li>• Site-specific e-flows</li> <li>• Can be applied to other rivers</li> </ul>	WWF-India, (2012)
3	Mahanadi River	Tennant method, RVA (Range of Variability Analysis) and IHA (Indicators of hydrologic Alterations)	<ul style="list-style-type: none"> <li>• Minimum (low) flow should be higher than that of 7-day minimum projected by the RVA analysis</li> <li>• For maintaining excellent habitat conditions: MAF for the month of Oct-Mar (4.93-161.91 cumec) and Apr-Sept (62-1186.5 cumec) based on the data from 1978-2010 years</li> </ul>	<ul style="list-style-type: none"> <li>• Low flow is defined as 10% of the total flow based upon the Montana method, the 7-day minimum flow based upon RVA analysis, and low flow is less than 10% of the total annual flow</li> <li>• Results suggest that Tennant method is not applicable for this basin</li> </ul>	Bhattacharjee and Jha, (2014)	
4	Alaknanda and	Hydrological method, Look up	Index Table • 2% to 15% of MAR is recommended as Maximum and minimum e-flows respectively	<ul style="list-style-type: none"> <li>• No seasonal flow recommendations were</li> </ul>	AHEC, (2011)	

S.no.	Location	Methodology used	Recommended e-flows	Recommendations	Reference	
	Bhagirathi	and Q90-Q95 method			made to address river variability <ul style="list-style-type: none"> <li>The study does not address the cumulative impacts of current power projects</li> </ul>	
5	Alaknanda and Bhagirathi	Building Block Methodology and Rating Method	Environment Management Class, based on flow requirements for two species Golden mahseer ( <i>Tor putitora</i> ) and snow trout ( <i>Schizothorax richardsonii</i> ) The Mahseer and snow trout zone No fish zone only for the lean season Other dry zones	E-flows recommendations were made to maintain 'C' 21.8% of Mean Seasonal Flow 14.5% of the Mean Seasonal Flow 20% of the monthly average flow from Nov-Mar 25% of the monthly average flow in Oct-Apr 30% of the monthly average flow from May-Sept	EMC approach is based on two species, only the Golden mahseer and snow trout In conducting a holistic study they missed on socio-economic and cultural impacts The objective setting is not very clear	Rajvanshi <i>et al.</i> , (2012)
6	Brahmani and Baitarani River	Flow Duration Curve approach	<ul style="list-style-type: none"> <li>FDCs were computed for 1-day, 7-day and 30-day mean</li> <li>The 7Q10 FDC was recommended e-flows for drought years or low flow periods and 7Q100 FDC was found appropriate for good precipitation years</li> </ul>	<ul style="list-style-type: none"> <li>The 7Q10 of FDC yearly mean is beneficial in:</li> <li>Protecting or regulating water quality from wastewater discharges or waste load allocations</li> <li>Protection of Habitat during drought conditions</li> </ul>	Jha <i>et al.</i> , (2008)	

S.no.	Location	Methodology used		Recommended e-flows	Recommendations	Reference
7	Sone River (Maikalsut)	Global Environmental Flow Calculator (GEFC), desktop software by the International Water Management Institute (IWMI) based on Flow Duration Curve (FDC) approach	Sites Indrapuri Barrage	Flows as % of MAR 5.16% and 2-5 % wetted perimeter	<ul style="list-style-type: none"> <li>• Chronic criteria for aquatic life</li> <li>• A local extinction flow</li> <li>• 7Q100 is not a common practice</li> <li>• 18.9% of MAR is required to restore the stretch from Critically Modified (F) to Moderately Modified Class (C)</li> <li>• 34.2% of MAR will be required to maintain this stretch in Slightly Modified Class (B)</li> </ul>	Jha <i>et al.</i> , (2014); Joshi <i>et al.</i> , (2014)
8	Kumbh Mela (Sangam) in Allahabad	Building Methodology	Block Kumbh Mela	Water depth:1.2 m for the entire duration and a stage of 73.53±0.11 m Flow: 225 cumecs (7,950 cusecs) Surface width: 175 m Special bathing days: depth of 1.5 m, a stage of 73.83±0.11 m Flow: 310 cumecs (10,950 cusecs).		WWF-India, (2013)
9	Bhadra River	Tennant method	8,855 Tennant Management Class (TMC) 26,565 TMC 53,129 TMC	Poor flow at 10%  Moderate flow at 30% Excellent flow 60%	Downstream to the Bhadra reservoir <ul style="list-style-type: none"> <li>• 10 times the flow was above the excellent flow conditions</li> <li>• 12 times flow was meeting the poor conditions</li> <li>• 10 times flow was above</li> </ul>	Babu and Kumara, (2009)

S.no.	Location	Methodology used		Recommended e-flows		Recommendations	Reference
10	Upper Ganga reaches up to Rishikesh town	The modified version of BBM, integrating ecological and geomorphological parameters with hydraulic analysis	Sites Ranari U/s Devprayag D/s Devprayag Rudraprayag U/s Rishikesh	Dry period flow as % of Natural flow	Wet period flows as % of Natural flow	Moderate flow conditions <ul style="list-style-type: none"> <li>To sustain the rivers present method only quantifies the lower bound water flow rates as required water flows</li> <li>Does not specify flow requirements off low components such as sediment transport</li> <li>The dams and barrages have affected the natural flows as unnatural high flows were recorded during the dry period</li> <li>In the wet period, the presently available flow is significantly less than the natural flow. However, it is higher than the e-flows</li> <li>The recommended flow will be able to fulfill the bare minimum eco-geomorphological conditions. Still, these river stretches are significantly impacted and vulnerable to future damages</li> </ul>	Tare <i>et al.</i> , (2017)

S.no.	Location	Methodology used	Recommended e-flows				Recommendations	Reference
11	Narmada	Lookup Tables	WCD	UK Q95	75% of	MAF	<ul style="list-style-type: none"> <li>The Lookup Tables are not appropriate to recommend EFR</li> <li>The Tenant method gives comparatively more choices to recommend EFR than Lookup Tables</li> <li>Tessman method appears to be more acceptable out of all and recommending EFR on monthly basis</li> <li>The results are based on hydrological data only thus further investigations are necessary to recommend flow to fulfill the ecological needs of the river</li> </ul>	Dubey <i>et al.</i> , (2013)
			10%	(Cumec)	Q95	(Cumec)		
			MAF		(Cumec)			
			(Cumec)					
			Sandia	50.6	73.5	55.03		
		Barman	39.79	52.5	42.8	397.87		
		Manot	9.2	0.56	0.42	92		
		Dindori	4.05	1.2	0.71	40.5		
		Tennant Method	Apr-Sept (cumec)		Oct-Mar (cumec)			
			excellent	Good	excellent	Good		
			habitat	habitat	habitat	habitat		
Sandia	253.05		202.44	151.83	101.22			
Barman	198.935	159.15	119.36	79.57				
Manot	58.7	46.96	35.22	23.48				
Dindori	20.25	16.2	12.15	8.1				
Tessman method	A fixed percentage of MMF is recommended as e-flows for all the sites based upon the Tessman method's thumb rules							
12	Krishna River	Range of variability Approach (RVA), Desktop Reserve Model (DRM) and Global Environmental Flow Calculator (GEFC)	<ul style="list-style-type: none"> <li>DRM method recommends the intermediate value obtained using the three methods to preserve the riverine ecosystem in the downstream regions of the river,</li> <li>The flow allocated was 23.11% of mean annual flow (MAF) which is equal to 9378 Million Cubic Meter (MCM)</li> <li>The GEFC is allocating 22% of MAF</li> <li>The RVA method is allocating 31.04% of MAF</li> </ul>			<ul style="list-style-type: none"> <li>Reservoir operation policy results in alteration of flow in July</li> <li>In the absence of reliable environmental information hydrological indicators can be used for assessment of EFR</li> <li>The operations of the new reservoirs can fulfill human water needs without disturbing EFR</li> </ul>	Kumar and Jayakumar (2018)	

S.no.	Location	Methodology used	Recommended e-flows	Recommendations	Reference
13	Indian Sundarban	Holistic Building Block Methodology (BBM): Three distinctive blocks namely Hydro-Morphology, Ecology and Socio-Economy, Ecological indicators are Ganges Dolphin ( <i>Platanista gangetica</i> ), Sundari tree ( <i>Heritiera fomes</i> ) and Hilsa fish ( <i>Tenualosa ilisha</i> )	<p>Bhagirathi-Hugli requires additional water for:</p> <ul style="list-style-type: none"> <li>• Hilsa migration: 150-427 cumec in monsoon months and 850-1127 cumec in post-monsoon months</li> <li>• Dolphin movement: 327-486 cumec in pre-monsoon months and dry season, and 227-386 cumec in post-monsoon months</li> </ul> <p>Ichhamati river requires additional water for:</p> <ul style="list-style-type: none"> <li>• 743cumec in pre-monsoon and dry season and 543cumec in monsoon months and 443 cumecs in post-monsoon months to maintain navigation</li> </ul> <p>Sundarban ecosystem requires 1700 cumec to reduce the salinity level from 30ppt to 14ppt in the dry and pre-monsoon months</p>	<ul style="list-style-type: none"> <li>• The in-stream flow requirements surpass the presently available flow</li> <li>• The modified BBM is a useful approach for a sensitive eco region like Sundarban</li> <li>• The methodology can be further improved to incorporate other hydro-morphological, ecological and socio-economic components</li> <li>• The regeneration of <i>Heritiera fomes</i> and migration and breeding of Hilsa and Gangetic Dolphin are getting impaired due to unavailability of freshwater</li> <li>• The e-flows estimates done are highly generalized which do not reflect the dynamic hydrologic condition of Sundarban</li> </ul>	Hazra <i>et al.</i> (2015); Bhadra et al. (2016)

Source: Compiled from various sources, Sharma (2019)

## **2.6 Problems of Intermittent and Low-Flow Rivers**

Intermittent rivers and low-flow rivers are different from the perennial rivers. Here, the term ‘low-flow rivers’ refer to the rivers that do not receive their continuous flow from snow melts, and they are either seasonal or groundwater-fed rivers characterized by the low and sluggish flow. Intermittent rivers can be dry in dry seasons or even for a few consecutive years (Chevallier *et al.*, 2010). These rivers receive flow from the rainwater in monsoon periods and through baseflow from the groundwater in lean flow periods. These rivers constitute about 30% of the total discharge and length network of the global rivers (Tooth, 2000; Datry *et al.*, 2014). Even in a perennial river system, most of the low order streams are prone to flow intermittency thus, total global intermittent and low flow rivers network increases (Lowe and Likens, 2005; Datry *et al.*, 2014). Many larger perennial river systems are turning into intermittent due to over-abstraction of groundwater and intensive irrigation from canals withdrawing water from these rivers is resulting in reduced river flow and turning them into intermittent rivers (Rushton, 2002; Kirk and Herbert, 2002).

These rivers have been misunderstood as species-poor and intermittent dry channels were looked as biologically inactive with no associated ecological services (Poff and Ward, 1989; Stanley *et al.*, 1997). However, Datry *et al.* (2014) presented an argument based upon studies by Williams (2006) and Warfe *et al.* (2011) that natural drying and rewetting cycles occurring in the intermittent rivers serve as an evolutionary cue thus increasing the overall biological, physiological and ecological diversity. The dry phase increases the local and regional biodiversity (Steward *et al.*, 2012; Leigh and Datry, 2017), accumulates high organic matter (Corti *et al.*, 2011) which gets transported to the downstream region during the onset of a wet period

(Corti and Datry, 2012; Datry *et al.*, 2014). Surface water persistence and an increase in flow duration in intermittent rivers show an association with the high biodiversity of aquatic invertebrates and fishes (Leigh *et al.*, 2016; Datry *et al.*, 2017; Datry *et al.*, 2018). Intermittent rivers are becoming endangered ecosystems due to a lack of adequate management practices and proactive policies and legislatures (Datry *et al.*, 2014, Datry *et al.*, 2017). The potential ecosystem services, a cooperative association of biodiversity and nutrient cycles of the intermittent rivers are not appropriately studied. It urges and points out a significant gap in the global river basin management practices.

### **2.7 Problem Identification in E-Flows Estimation**

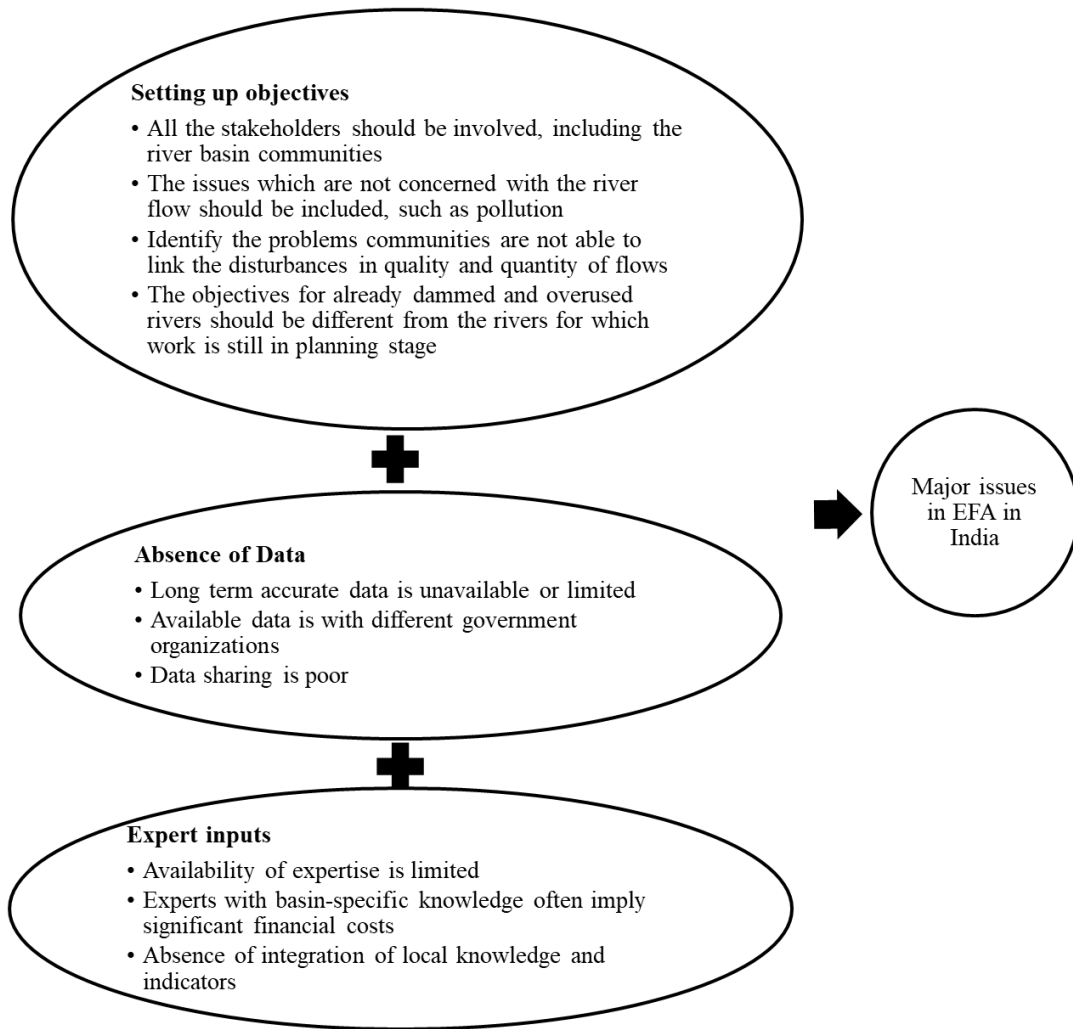
In India, the first National Water Policy was drafted in 1987 for the planning, development and management of water resources. It was later amended in 2002 and 2012. In the first National Water Policy (NWP, 1987), the focus was to protect the environment and rehabilitate the project-affected people and livestock, public health from the consequences of water impoundment and dam safety. With time, new problems and challenges came up and further in 2002 and 2012 (NWP, 2002; NWP, 2012), improvements were made to address issues like water resource planning and watershed management strategies. The emphasis was laid on hydrological perspectives, soil conservation, catchment area treatment, conservation of forest, increase in forest cover and construction of check dams. However, the effect of water storage, water abstraction, diversion and river basin encroachments was not given much attention.

Water in India falls in the Concurrent list; thus, power is considered by both the Central and State government. When it comes to having a State Water Policy, out of 29 States and seven Union Territories, only 14 States have their water policies to

manage the state water resources. Out of all the state policies, only Assam state has a mention of ‘water allocation for river life, flood management, wetland and water body restoration, watershed area management and environmental water allocation strategies.’ Goa State water policy has put special attention on the ecological sustainability of Western Ghats. Both National and State water policies have not incorporated the ecological and environmental water requirements.

Other problems include lack of on-ground implementation of environmental laws and regulations incorporating the environment impact assessment of river valley projects. India’s National environmental impact assessment (EIA) rules notified in 1994 with particular concern for threatened and endangered species, protected areas and other biodiversity concerns that have been poorly managed. On-ground application and strict implementation of these laws are still lacking and their implication remains uncertain (Dudgeon, 2000a; Dudgeon, 2000b). Slight attention has been paid to ecological evaluation and proper implementation of EIA processes in large-scale water development projects in India (Bandyopadhyay and Gyawali, 1994; Singh, 2006; Agrawal, 2010; Pandit and Grumbine, 2012)

The other problems in the assessment and recommendation of e-flows in India include setting relevant objectives. There is no single correct method for e-flows assessment and it ultimately depends on the social and political needs from a river (O’Keeffe and Le Quesne, 2009; Anantha *et al.*, 2017). The absence of real-time and accurate data is another big problem and the data available is not shared by different departments. The most crucial part is to have experts from all fields such as hydrology, hydraulics, geology, ecology, fishery, economics and water quality. In the event of unavailability of such experts, getting the expert advice would incur significant financial costs (Anantha *et al.*, 2017). Noteworthy issues in conducting e-flows assessments in India are listed in the flow diagram (Figure 2.5).



**Figure 2.5:** Major issues identified in e-flows assessment in India (Sharma, 2019)

## **2.8 Future Directions for Water Resource Management and E-Flows Estimation**

In India, e-flows assessment practices are in the initial phase and the water resources development practices are increasing at high speed. Thus it is a crucial time that both the aspects of development and management of water resources should be taken forward at the same pace. The management and e-flows assessment of riverine systems should not only quantification the flow requirements; it should also focus on the protection of riparian areas, headwater and associated floodplains. The baseline information on the biodiversity and ecosystem services of rivers and water bodies should be collected rigorously and at regular intervals. It will create a robust

ecological data for e-flows assessment. The rivers should be protected for their ecological, social and cultural standards similar to free-flowing rivers. It can be achieved by enacting and strict on-ground implementation of policies and laws targeted to maintain an '*Aviral*' (continuous) and '*Nirmal*' (clean) rivers devoid of flow-obstructions and polluting infrastructure projects. Conjunctive management of water resources should be explored to prevent riverine systems from excess pressure due to increasing anthropogenic water demands. The water storage capacity of the river basins should be increased by increasing the availability of inland water bodies, identifying the sites for groundwater recharge and increasing the opportunities for rainwater harvesting. With state of the art technologies, wastage of the potable water resources should be brought close to the minimum. In the process of e-flows recommendation, the minimum flow should not be confused with e-flows. Both the terms are not synonyms. The minimum flow recommendations can fulfill the flow requirements to attain the short term goals. However, to maintain the long term sustainability of river ecosystems, the needs of ecology that require variable flow regimes should be taken forward.



*Chapter 3*  
*Methodology*



### **3 Methodology**

#### **3.1 Study Area**

Gomti River is a groundwater-fed perennial River. It is one of the important tributaries of the river Ganges in northern India, Uttar Pradesh (U.P.). It originates from 'Fulhar Jheel' in Madho Tanda at an elevation of about 162 m (28°36'46" N 80°07'01" E) near Pilibhit town, (U.P.). Fulhar Jheel is a natural lake situated around 50 km south of the Himalayan foothills (Singh *et al.*, 2004). The river Gomti flows through the central and eastern part of the U.P., covering a total distance of about 941 Km and drains into the river Ganga at Kaithi near Varanasi. The catchment area of the Gomti basin is 31009 km<sup>2</sup>. This river basin covers 14 districts partially or fully (Table 3.1), flowing through both rural and urban areas. Lucknow, Sultanpur, and Jaunpur are the three major urban settlements on the banks of the river. Kathna, Sarayan, Reth, Luni, Kalyani, and Sai are the major tributaries of the river Gomti (Table 3.2). River Gomti has sluggish flow throughout the year except for the monsoon period, when it receives a maximum discharge due to rainwater runoff. The river turns intermittent at some places due to a shortage of flow in the summer months (Apr-Jun), while in monsoons, it does flood occasionally.

Gomti River flows near the district boundary of Hardoi and Sitapur as well as Sultanpur and Pratapgarh. Barabanki district has the maximum share of the river's length in its territory, followed by Jaunpur and Lucknow. The river has 27 major and minor confluences, including rivers and drainage outlets, into the river. The identification of the points of the confluence of all the drains with the mainstream was done (Table 3.2). These drains bring freshwater and pollution into the river's main channel through its main tributaries.

**Table 3.1:** District wise length of the Gomti River

<b>District(s)</b>	<b>Length of the river in (km)</b>	<b>Area falling in Gomti Basin in Km<sup>2</sup></b>
Pilibhit	30.03	894
Shahjahanpur	68.18	974
Kheri	85.12	2230
Hardoi and Sitapur	160.82	3572 (Hardoi) and 3076 (Sitapur)
Unnao	0	1856
Lucknow	98.75	2538
Barabanki	129.67	2960
Raibareli	0	3577
Faizabad	57.87	228
Sultanpur and Pratapgarh	163.18	3466 (Sultanpur) and 2878 (Pratapgarh)
Jaunpur	112.5	2230
Varanasi	10.39	492
Ghazipur	24.98	38
<b>Total</b>	<b>941.49</b>	<b>31009</b>

**Table 3.2:** Confluence points of all major and minor tributaries of River Gomti

<b>S.No</b>	<b>Tributary Name</b>	<b>District</b>	<b>Length (km)</b>	<b>Place of Confluence</b>
1	Gachai River	Pilibhit	14.90	28°29'42.16"N 80°5'15.91"E
2	Joknai River	Shahjahanpur	52	28°12'22.09"N 80°10'14.99"E
3	Bhainsi River	Shahjahanpur	41	28°5'17.69"N 80°12'10.10"E
4	Chuha Nala	Kheri	44	27°44'30.64"N 80°16'0.14"E
5	Andi Nala	Hardoi	10	27°30'53.23"N 80°20'18.79"E

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S.No	Tributary Name	District	Length (km)	Place of Confluence
6	Kathina River	Sitapur	176	27°28'23.89"N 80°23'29.62"E
7	Chitwa Nala	Sitapur	12	27°24'12.75"N 80°26'52.56"E
8	Gharera Nala	Hardoi	18	27°21'34.27"N 80°27'12.27"E
9	Sarayan River	Sitapur	274	27°11'58.67"N 80°47'20.88"E
10	Nakha Nala	Lucknow	10	27° 3'5.23"N 80°50'39.06"E
11	Akraddi Nala	Lucknow	19	27° 1'0.81"N 80°49'12.53"E
12	Behta River	Lucknow	134	26°56'8.03"N 80°51'25.45"E
13	Kukrail River	Lucknow	20	26°51'34.00"N 80°58'0.75"E
14	Loni River	Lucknow	2	26°48'59.66"N 81°0'30.53"E
15	Asaina Nala	Lucknow	6	26°50'15.02"N 81°5'36.15"E
16	Reth River	Barabanki	103	26°46'5.03"N 81°11'20.70"E
17	Kalyani River	Barabanki	190	26°41'33.77"N 81°35'49.73"E
18	Arahi Nala	Amethi	28	26°35'0.70"N 81°39'10.61"E
19	Betwa River	Barabanki and Faizabad border	19	26°35'17.18"N 81°42'9.59"E
20	Kandu Nala	Amethi	69	26°25'26.41"N 81°49'29.95"E
21	Gobaria Nala	Sultanpur	23	26°17'2.04"N

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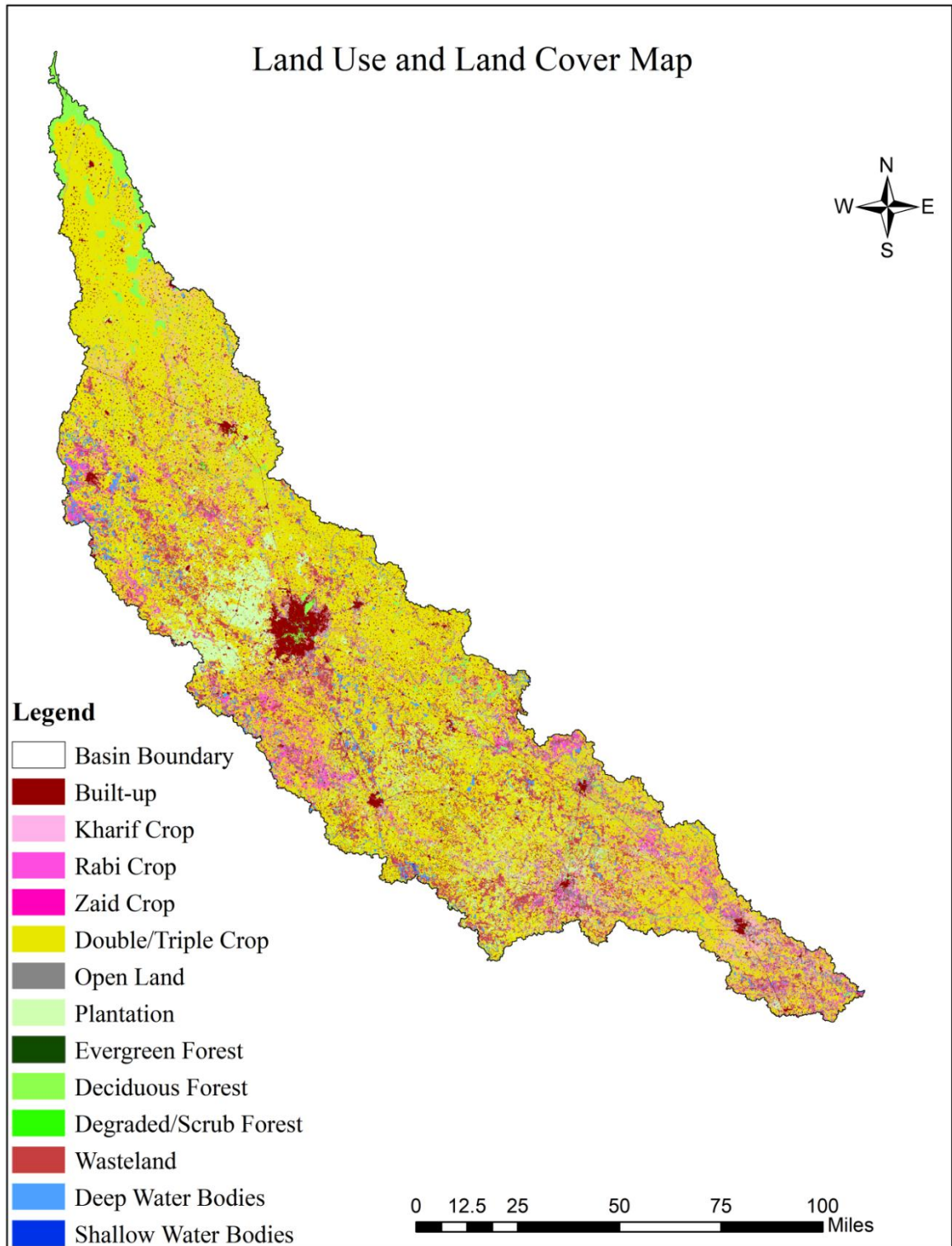
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S.No	Tributary Name	District	Length (km)	Place of Confluence
				82° 3'48.71"E
22	Sewai Nala	Jaunpur	31	25°57'46.55"N 82°32'23.89"E
23	Pili River	Jaunpur	95	25°51'6.47"N 82°35'24.40"E
24	Sewai Nala	Jaunpur	31	25°42'9.36"N 82°46'33.88"E
25	Balohi Nadi	Jaunpur	11	25°40'42.38"N 82°48'20.82"E
26	Sai River	Jaunpur	695	25°39'7.76"N 82°48'7.69"E
27	Nand River	Varanasi	47	25°37'21.43"N 82°57'15.65"E

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### 3.2 Land Use and Land Cover Pattern in the Basin

The land use and land cover pattern of the river basin were studied to identify the types of land use in the basin. A land-use land cover map was prepared for the year 2008 using the LISS III data acquired from the Bhuvan website (Bhuvan, 2015) to identify the land use patterns in the basin has been shown in Figure 3.1, 3.2 and Table 3.3.

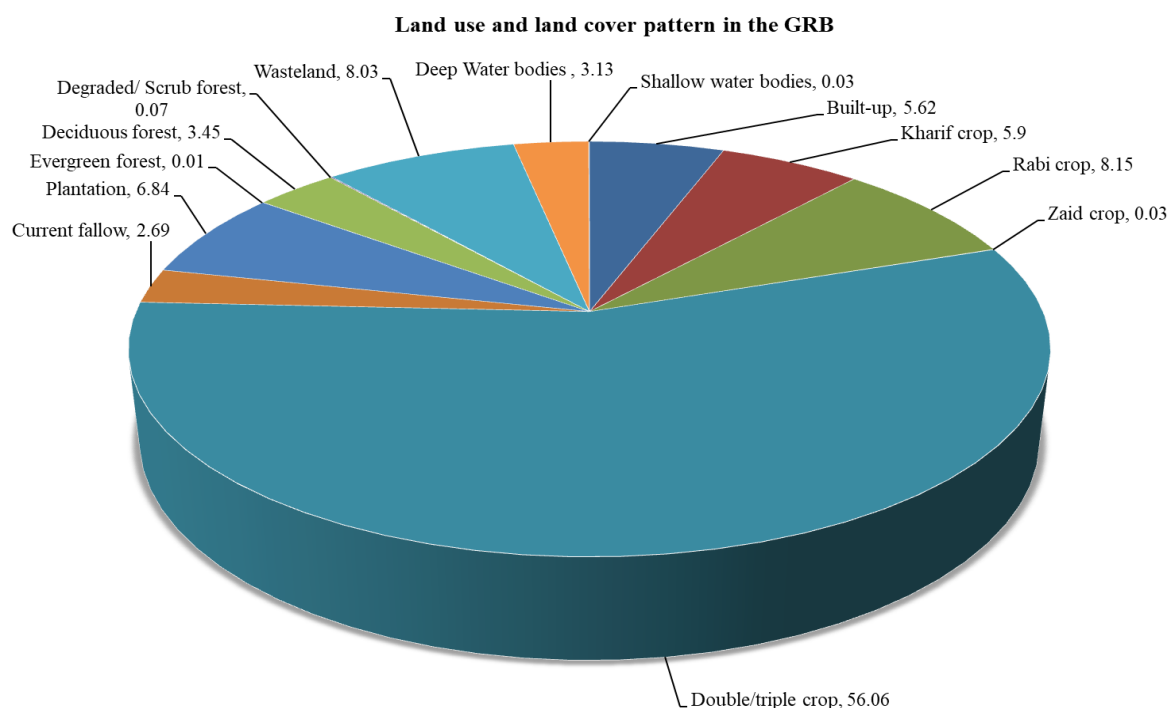


**Figure 3.1:** Land use and land cover pattern of Gomti River Basin (LISS III satellite image of 2008)

**Table 3.3:** Land use and land cover pattern in the Gomti River Basin (GRB)

Field	Area in Km <sup>2</sup>	Percentage share in Basin
Built-up	1743.014	5.62
Kharif crop only	1828.539	5.90
Rabi crop only	2527.707	8.15
Zaid crop only	8.799616	0.03
Double/triple crop	17384.9	56.06
Current fallow	833.6241	2.69
Plantation	2119.563	6.84
Evergreen forest	2.119936	0.01
Deciduous forest	1068.777	3.45
Degraded/ Scrub forest	21.97709	0.07
Wasteland	2489.783	8.03
Deep Water bodies	970.5042	3.13
Shallow water bodies	9.696512	0.03

Source: LISS III satellite image of 2008 (Bhuvan, 2015)



**Figure 3.2:** Percentage share of the land use and land cover pattern in the GRB

### 3.3 Morphometric Analysis

Shuttle Radar Topography Mission (SRTM)-90m Digital elevation database was acquired from the Consortium of International Agricultural Research Centers- Consortium for Spatial Information (CGIAR-CSI, 2017) for the year 2007 at 90m resolution. Resourcesat-1/Resourcesat-2: LISS III Satellite images were acquired from Bhuvan for the years 2008 and 2013 (Bhuvan, 2015).

**Table 3.4:** Major morphometric parameters of Gomti River

<b>Morphometric parameters</b>	<b>Symbol/Formula and units</b>	<b>Results</b>
Basin Area	A (Km <sup>2</sup> )	31009 Km <sup>2</sup>
Basin perimeter	P (Km)	1844 Km
Basin length	Lb (Km)	476.8 Km
Elongation ratio (Re)	$\frac{2 \sqrt{A/\pi}}{Lb}$	0.416
Form factor (Rf)	A/Lb <sup>2</sup>	0.136
Sinuosity index	Channel length/down valley length	1.97
Drainage density	Lu/A	0.165
Bifurcation ratio	Nu/Nu+1	2.32

Nu=Stream number, Lu=Stream Length

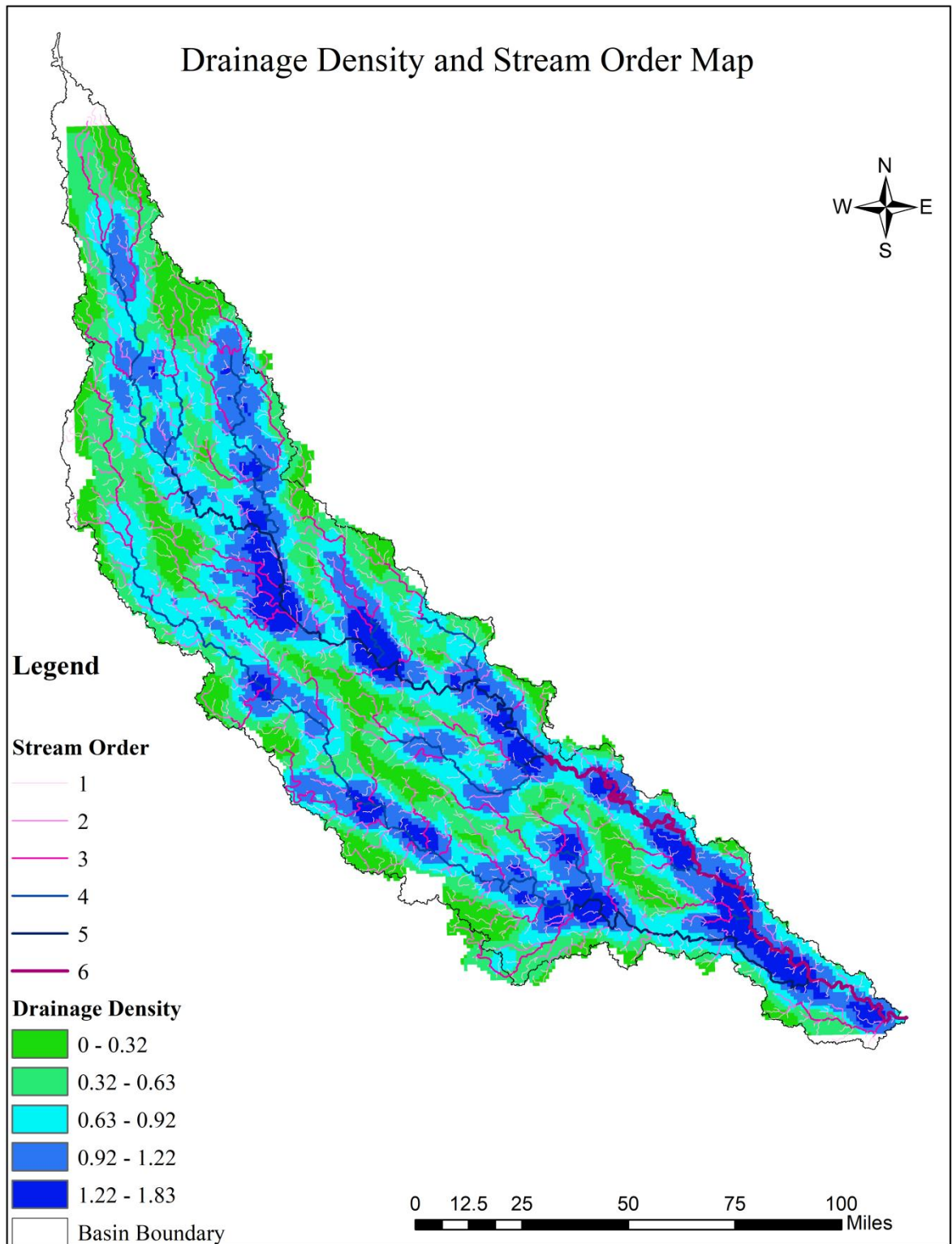
The elongation ratio varies from 0.6 to 1 for most of the basin, wherein a value less than 0.5 indicates a more elongated basin (Table 3.4). The elongated basin is efficient in the discharge of runoff as concentration time is less in the basin. The elongation ratio of 0.416 indicates moderate relief and slope for GRB (Table 3.5). The form factor is a dimensionless quantitative expression of the drainage basin. The low-value of form factor indicates a relatively flat peak of flow in that basin for a longer duration (Nag and Chakraborty, 2003). The sinuosity index calculated for the river is 1.97, which indicates a meandering river.

**Table 3.5:** Elongation ratio ranges

<b>S. No.</b>	<b>Value</b>	<b>Feature</b>
1	0.9-1.0	circular
2	0.8-0.9	oval
3	0.7-0.8	Less elongated
4	0.7-0.5	Elongated
5	>0.5	More elongated

Source: Shukla *et al.* (2014)

Bifurcation ration is the ratio between the number of streams of one order and those of the next-higher order in a drainage network. It is a dimensionless unit of significance in drainage basin analysis as it states the links to the hydrological regime of a watershed under topological and climatic conditions. It helps in interpreting the shape of the basin and deciphering the runoff behavior. It varies from 2 to 3 or 4 that is for flat or rolling drainage basins to mountainous or highly dissected drainage basins, respectively. It also emphasizes the flood proneness of a basin as higher the value of bifurcation ratio lesser will be the time taken for discharge to reach the outlet, therefore, resulting in higher peak discharges in a basin. A higher bifurcation ratio leads to a greater probability of flooding. Higher bifurcation ratio also puts forward the chances of being highly tectonically activeness of that area. The bifurcation ratio has a positive correlation with drainage density. A drainage density map is presented below in Figure 3.3, and a T-diagram of the Gomti river and its tributaries is presented in Figure 3.4.



**Figure 3.3:** Drainage density and stream ordering in Gomti River Basin (GRB)

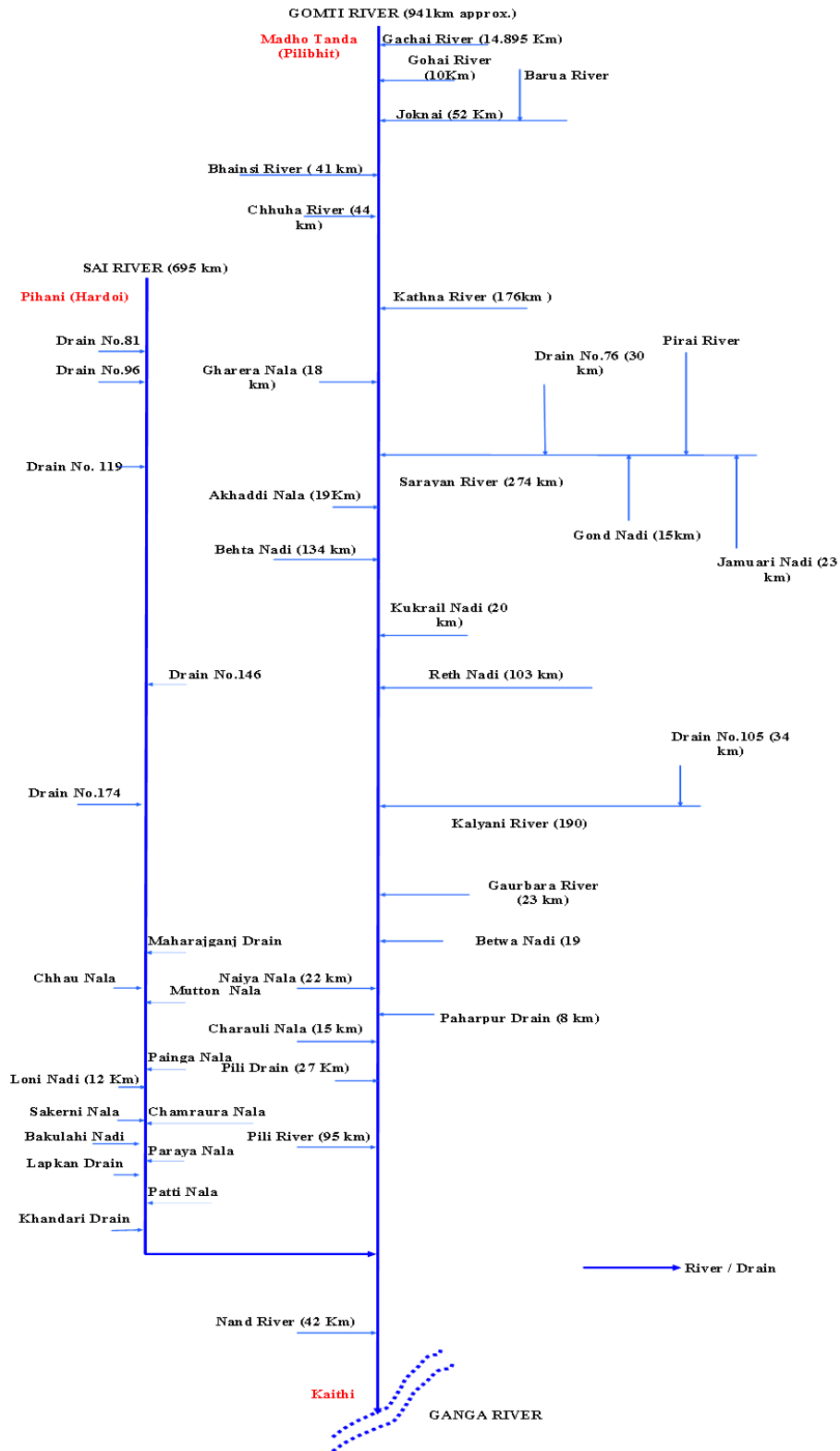


Figure 3.4: T-diagram of the Gomti River and its tributaries

### **3.4 Overview of the Methodology**

Tropical rivers of the Indian sub-continent are very dynamic with a diverse pattern of flow and physical properties. This framework is designed to recommend e-flows requirements for GRB based on several EFA methodologies. This method is a multi-step process, including extensive hydrological, hydraulic, water quality, ecological, and socio-cultural analysis. The steps of the designed framework are as follows and shown in Figure 3.5:

1. Monitoring and assessment of the baseline conditions
  - a. This step includes the baseline surveys and analysis of hydrological, hydraulic, water quality, ecological, and socio-cultural components.
2. Setting up objectives
  - a. Homogeneous zonation of River basin for identification of environmental flows sites
  - b. Determine the preferred environmental flows for River Gomti
  - c. Assess and make recommendations on the flow requirements for indicator species
  - d. Socio-cultural mapping and e-flows needs
3. Homogenous zones were identified, and further analysis was performed on the selected representative sites in the finally identified zones.
4. Water quality analysis: Long term water quality was analyzed from 2013 to 2017 for the selected sites.
5. Hydrological analysis
  - a. Hydrological indicators were analyzed, such as Mean Annual Flow (MAF), Baseflow Index (BFI), Hydrological Variability Index (HVI), number of high, low, and intermediate flow months.

- b. Hydrological data is used to develop long term hydrographs to understand the variability of flow river experiences.
  - c. The baseflow share in the MAF was also estimated, and the groundwater level scenarios in the basin were also evaluated.
  - d. The baseline hydrographs were compared with the historic hydrographs to understand the degree of hydrological alterations.
  - e. E-flows estimation was done based on hydrological methods, namely Tennant Method, Tessman Method, Variable Monthly Flow (VMF) Method, Smakhtin Method, Q90-Q50 method, and Global Environmental Flow Calculator (GEFC).
6. Hydraulic analysis
- a. The river cross-sections were analyzed, and using the available discharge and water level data, the stage-discharge curves, and wetted perimeter-discharge curves were prepared for each site.
  - b. E-flows estimation was done based on the depth requirements for spawning and migration of indicator species.
7. Ecological analysis
- a. The habitat preference of all the aquatic fauna, including birds, fishes, mammals and reptiles were studied based on secondary data in the form of literature present in the public domain such as Ali (1941), Gupta (2011), Menon (2014), Hanfee (1999), Kazmierczak (2000), Hanfee (1999) and Grimmett (1998).
  - b. Out of all the species reported in the basin, those listed in the IUCN red data list as near threatened, vulnerable, endangered and critically

endangered were considered to mark the ecological extents of the species present in the basin.

- c. Field surveys were conducted to assess the fish diversity present in the basin in the post-monsoon season of 2017 and 2018.
  - d. Based on the International, national, ecological, genetic resource, economic and fish sport values, the indicator species were identified.
  - e. The depth requirements for each indicator species were identified. The requirement of desired depth to sustain each indicator fish stock in the river was analyzed using the data collected during the field surveys further these results were enriched using the preexisting literature and expert guidance received from ICAR-NBFGR's scientist.
  - f. The manning 'n' equation was used to calculate the discharge and velocity required to maintain the corresponding depth.
8. Socio-cultural analysis
- a. Culturally significant, 14 temples were selected and surveyed.
  - b. The minimum water depth required to take baths during special days and perform sacred rituals was calculated.

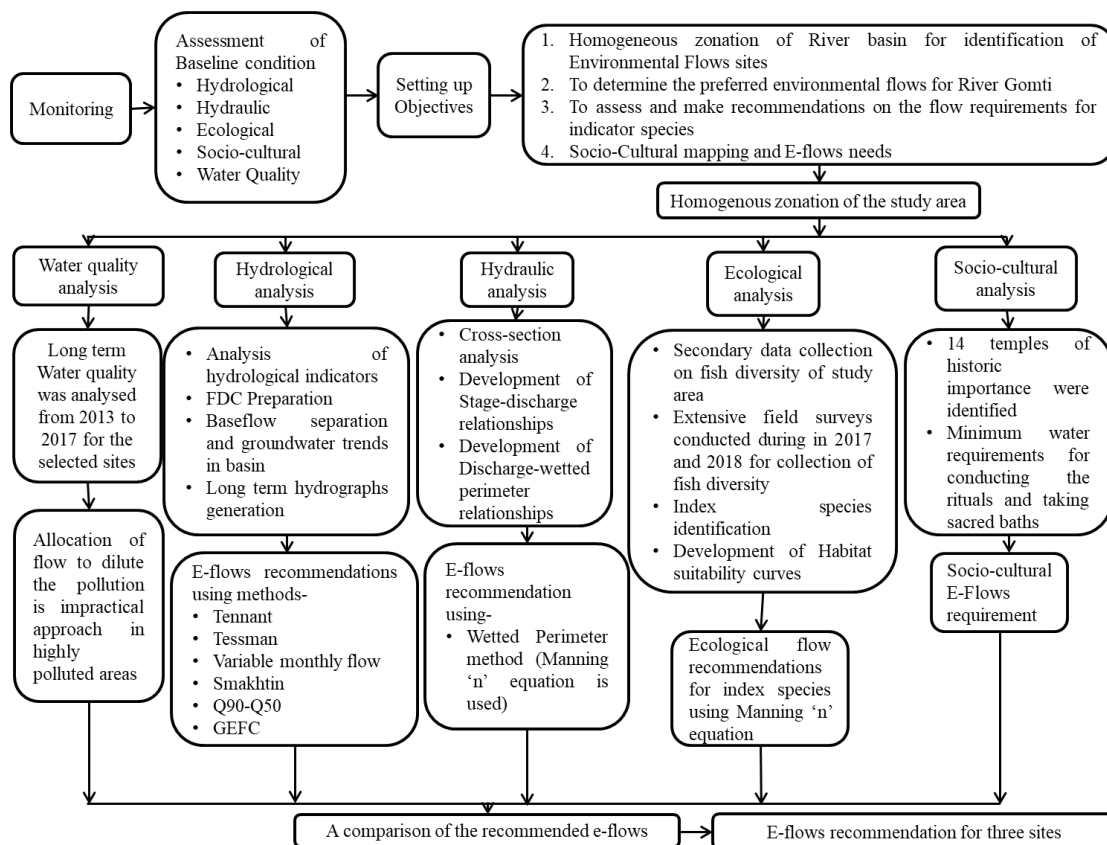
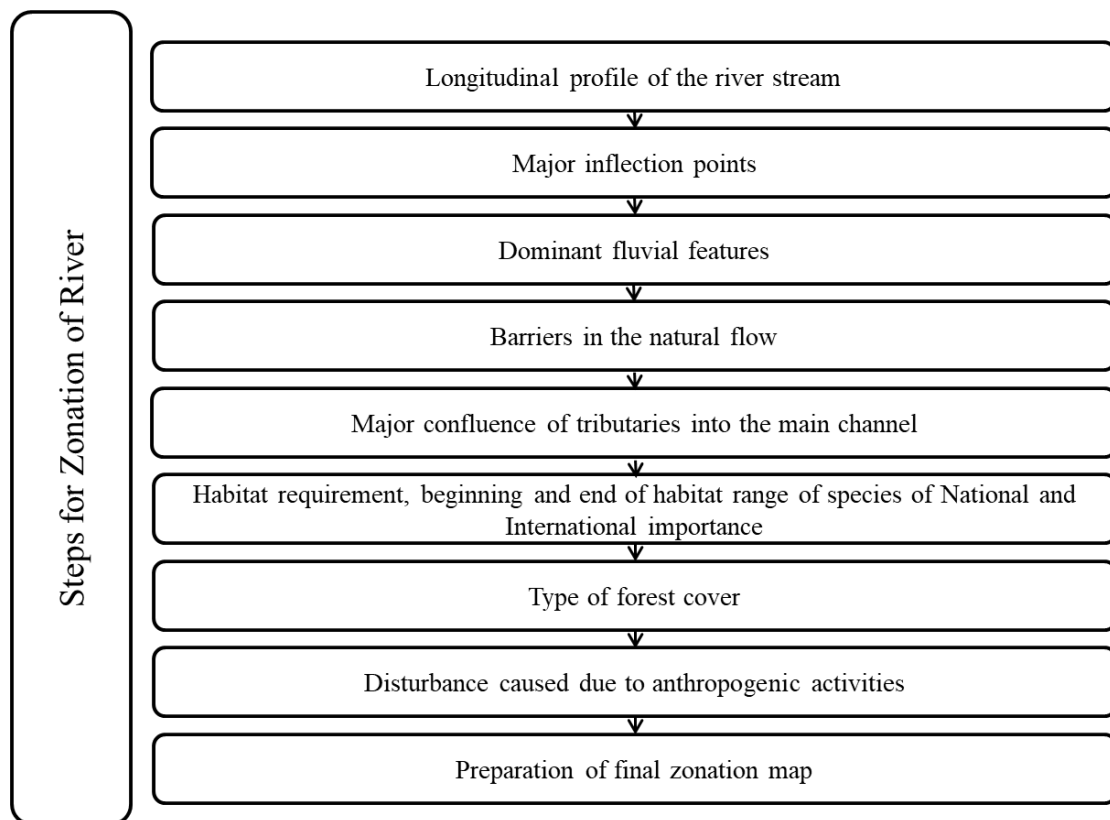


Figure 3.5: Flow chart of the methodology used for e-flows assessment in GRB

### 3.5 Homogeneous Zonation of the Gomti River

Zonation of a river is done to study the different characteristics of the river, and thus specific sampling sites were selected at each zone. The procedure for the zonation was adapted from WWF (2012) report on “Assessment of Environmental Flows for the Upper Ganga Basin” and the ‘Ganga River Basin Model and Information System, Report and Documentation’ by Vat (2018). These sites are representative of the overall character of their respective zones; thus, a detailed survey of channel morphology, flow characteristics and biodiversity was conducted on these sites. Zonation is done to identify almost homogenous conditions prevailing at different locations in the course of a river stream in terms of flow, gradient, size, sediment types, geomorphology and surrounding land use. In these identified zones, the ecological requirements and human usage of the river are more or less similar.

The methodology used for zonation includes a desk study followed by the field surveys. The steps involved in the process of zonation are as follows in Figure 3.6:



**Figure 3.6:** Steps for zonation of Gomti River

### 3.5.1 Longitudinal profiling of the river channel

For longitudinal profiling of the river channel, all the satellite images of the study area were acquired from Bhuwan (2015). A geospatial tool ArcGIS 10.1, has been used for digitizing the river channel and saved as a shapefile. Then the SRTM-90m Digital elevation database of the study area was used, and the shapefile of the river channel was masked over the Digital Elevation Model (DEM) layer. This final image is exported into AutoCAD software, and equidistant points were drawn throughout the river channel from its origin to the mouth. All the points were set 100 m apart from each other. This layer is saved in shapefile format and imported into ArcGIS tool to extract the elevation value associated with each point, creating the longitudinal profile of the river channel.

### **3.5.2 Checking for major inflection points**

The longitudinal profile of the river channel is checked for any extreme outlier value. These outliers were removed, and using the interpolation method, a smooth slope profile of the river channel is created. This slope profile is then looked upon to find any distinct inflection points. These inflection points were considered as the point of change in the river profile and slope of the river.

### **3.5.3 Identification of dominant geomorphological features**

The geospatial tool ArcGIS and Google Earth Pro was used to provide a versatile graphic and highly convenient information base that helped in checking the primary landforms present in the river channel and its riparian areas. Then, the ground-truthing of the final images and details obtained using the GIS tool. It gives information about the significant geomorphological features and the river morphology present in each area. This information is then used to do the zonation of the river channel into homogeneous geomorphological features.

### **3.5.4 Pointing out the significant barriers in the natural flow**

The barriers, whether natural or man-made, obstruct the natural flow of the river stream. They have been marked using ArcGIS and Google Earth Pro tool on the river channel. These points were taken as the point of change in the natural streamflow and river discharge and marked as zone boundary for the river channel.

### **3.5.5 Identification of significant confluence points**

ArcGIS and Google Earth Pro tools were used for digitizing the river channel and its tributaries. The significant drainages pattern appearing in the satellite images were also digitized. The significant tributaries whose length is more than 150Km were used to mark the significant confluence points on the river channel.

### **3.5.6 Identification of habitat of aquatic species of national and international importance**

All the species of fishes, amphibians, and turtles reported in the river Gomti were considered to conduct this analysis. Out of all the species reported in the river, species listed in the IUCN list as near threatened, threatened, or in the above categories were selected. The habitat extent maps for the selected species were obtained from the IUCN website and overlaid over one another in ArcGIS tool. The points where more than three beginning or ends of habitat extents were coinciding were marked as biodiversity zones on the river channel.

### **3.5.7 Types of the forest cover**

The types of forest cover present in the river basin and their extents were noted from past forest survey reports of Forest Survey of India (FSI) (1987) and Champion and Seth (2005). Significant types of forest cover were identified as tropical moist deciduous and tropical dry deciduous forest. The beginning and ending extents of these forests were marked as homogeneous forest zones using the ArcGIS tool.

### **3.5.8 Major anthropogenic influenced zones**

Identification of significant areas where anthropogenic activities are obstructing the natural flow by modifying the channel morphology was done. With the help of ArcGIS and Google Earth Pro, supported with the ground-truthing during the field surveys, the location of these zones was marked.

### **3.5.9 Preparation of the final zones**

All the points identified in the above eight steps were marked in separate shapefiles and overlaid in the ArcGIS tool to generate the final zones. The most repetitive points appearing in all the shapefiles were considered as the final points for defining the extents of the homogeneous zones on the river channel.

### **3.6 Baseflow Separation and Groundwater Trends in the Basin**

The base flow was separated using the BFI+ tool of hydro-office (Gregor, 2010a). The sliding interval method, a sub-type of *filtering separation method* was used to conduct baseflow separation. This baseflow separation method has been used by many researchers such as Rutledge *et al.* (1996), Cheng *et al.* (2014), Thomas *et al.* (2015), Jung *et al.* (2016). This method considers the day with the lowest discharge in half of the interval minus one day  $[0.5(2N^*-1)$  days] and then the day before and after this day assigned the selected value. The discharge at the point of intersection is assigned to the median day in the interval and then bar slides over next day value and the same process is repeated (Gregor, 2010a). These values are connected to give base flow hydrograph, the higher the base flow index, the more is the groundwater contribution in the river discharge.

The potential groundwater zones were also identified to understand the correlation between the surface flow and the groundwater availability in the basin. The groundwater depth data for pre- and post-monsoon seasons were obtained from the State Groundwater Department, Government of Uttar Pradesh, India, for years 2005 to 2015. A total of 764 sampling sites, including observatory wells and piezometers distributed throughout the basin, randomly were considered for years, 2005, 2010 and 2015. Shuttle Radar Topography Mission (SRTM)-90m Digital elevation database was acquired from the Consortium of International Agricultural Research Centers-Consortium for Spatial Information (CGIAR-CSI, 2017) for the year 2007 at 90m resolution to prepare the drainage map of the river basin. The geometric rectification and registering the images with the Survey of India toposheets on 1:50,000 scale was done using ERDAS Imagine software. The potential groundwater one maps were prepared using the groundwater depth data and the satellite images. Based on depth, groundwater levels were categorized into six sub-

categories ranging between 0-3mbgl (meter below ground level ) to 18-25mbgl from 2005 to 2015. ArcGIS 10.3 tool was used for the preparation of maps and data analysis. Geo-statistical interpolations were done using inverse distance weighted interpolation (IDW) (Xie *et al.*, 2011). The analyst model of ArcGIS 10.3 was used to obtain the distribution characteristics of groundwater level parameters. A cross-validation of the interpolation model was also done with the help of a statistical analysis method to verify the accuracy of the interpolation model (Dashtpargerdi *et al.*, 2013; Xiao *et al.*, 2016). The  $R^2$  of IDW interpolation was 0.97. The values of pre- and post-monsoon groundwater levels observation points for ten years were imposed on vector data of GRB to delineate the potential groundwater zones.

### **3.7 Environmental Flows Assessment Methodologies**

The environmental flows assessment (EFA) is done based on the mean monthly discharge data, and mean monthly water level data were obtained from the Central Water Commission (CWC), India, from 1978 to 2015. The river cross-sections for years 2005-2015 were also obtained from CWC. Based on the homogenous zones and availability of long term flow data, three sites were identified, namely Neemsar (upstream), Lucknow (midstream) and Maighat (downstream), for recommending e-flows for Gomti River. Based on the available data, baseline hydraulic conditions were calculated, such as Base Flow Index (BFI), Hydrological Variability Index (HVI), Mean annual flow (MAF), low flow and high flow range and several high, low and intermediate flow months for each site respectively. The baseline hydraulic conditions were analyzed using multiple tools. The base flow was separated using the BFI+ tool of hydro-office (Gregor, 2010a). Hydrological variability index (HVI) was calculated on the basis of the flow duration curve method, using  $HVI = [(Q_{25} - Q_{75}) / Q_{50}]$ , where  $Q_{25}$ ,  $Q_{75}$  and  $Q_{50}$  are the percentage of flow exceeded or equaled to 75%, 50%, 25% of the flow for the period of record

respectively. The higher the variability index, the greater are variable flow regimes. The flow duration curves were prepared by the FDC 2.1 tool of hydro-office (Gregor, 2010b). The methods used to recommend e-flows for Gomti River includes five hydrological methods, one hydraulic and one desktop method. The hydrological methods used were the Tennant method, Tesson method, Smakhtin method, Q90-Q50 method, and Variable monthly flow (VMF) method. The hydraulic method used was the wetted perimeter method using the Manning 'n' equation. The desktop tool used was the Global Environmental Flow Calculator (GEFC), developed by IWMI, to calculate the EFR.

### **3.7.1 Tennant Method**

The Tennant proposed the Tennant method in 1976, also called as Montana Method. This method recommends a portion of mean annual flow (MAF) as e-flows to maintain the biological integrity of a river ecosystem. This method is still among the most widely used method worldwide, often as the primary or basin-wide scoping level of a two-tier system of EFA (Reiser *et al.*, 1989; Tharme, 1996; Dunbar *et al.*, 1998; Sahoo *et al.*, 2016). This method links the average annual flow with different categories of environmental habitat conditions. The main component of the Tennant method is discharged statistics and historical flows based on which environmental flows (EF) estimation were made. In this method, a constant percentage of MAF is recommended as low and high flows for different seasons, respectively. This method also recommends a periodic flushing flow of 200% during the monsoon season. Table 3.6 shows the minimum flow recommendations given by Tennant to support the qualities of fish habitats based on his observations of flow to best mimic the natural hydrology of the river (Stalnakers *et al.*, 1996).

**Table 3.6:** Percentage of MAF based on Tennant method to maintain instream flow requirements

<b>Habitat quality</b>	<b>% of mean annual flow (MAF)</b>	
	<b>Low season flow (October-March)</b>	<b>High season flow (April- September)</b>
Flushing or maximum	200	200
Optimum	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	<10	<10

Source: Tennant, 1976

Tennant’s method recommends high flow from April to September, which is appropriate for temperate countries. In tropical countries, monsoon period is from June to September, and the non-monsoon period extends from October to May. Thus to suit the Indian monsoon cycle, the Tennant’s instream flow recommendations were modified and termed as Habitat Health Classes as shown in Table 3.7 below.

**Table 3.7:** HHC modified from Tennant’s instream flow regimes relating to the Indian monsoon cycle

<b>Habitat health classes</b>	<b>% of MAF</b>	
	<b>October –March (non-monsoon)</b>	<b>June-September (monsoon)</b>
Flushing or maximum	200	200
Optimum	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair	10	30
Poor	10	10
Severe degradation	<10	<10

Source: Modified from Tennant’s instream flow regimes (Tennant, 1976)

### **3.7.2 Tessman Method**

Tessman method is a modified form of Tennant method, which includes the monthly variations in recommending the e-flows (Tessman, 1980). Tennant method has been modified severally by various practitioners since Tennant first used it in 1976 in the USA. In this method, each month is assigned one of the three pre-defined categories of monthly flows in the ratio of Mean monthly flow (MMF) or Mean annual flow (MAF) (Table 3.10). Thus this method considers intra-annual variability while suggesting the EFRs depending on the individual flow seasons (high-, intermediate-, or low-flow months).

### **3.7.3 Smakhtin Method**

Smakhtin and Anupthas (2006) developed a method based on Flow duration curves methodology. This method is based upon the monthly flow data, which is used to develop the FDC, where the environmental Low flow requirements (LFR) were assumed to be equal to Q90 (the monthly flow, which is exceeded 90% of the time on average throughout a year). An FDC was constructed using FDC 2.1 tool developed by Hydro-office (Gregor, 2010b). The procedure of construction an FDC is by ranking all the flows recorded from higher to the lowest and assigning the probability or percentage of exceedance to each flow in the rank series.

This method follows a thumb rule to recommend the e-flows, as shown in Table 3.8. These rules are used in representing stepwise EFRs and are a substitute for the method suggested by Hughes and Münster (2000) and Hughes and Hannart (2003). The EFs recommendations are based upon four pre-defined conditions in terms of percentage of mean annual runoff (MAR) in this method.

**Table 3.8:** Percentage of MAR based on Smakhtin method to maintain monthly highest flow requirements

Low flow requirements (Q90)	Flow pattern	Recommended Highest flow requirements
If Q90 is more than 30% of mean annual flow (MAR)	stable flow	0
If Q90 falls between 20 to 30% of MAR	Intermediate flow	7% of MAR
If Q90 falls between 10 to 20% of MAR	Intermediate flow	15% of MAR
If Q90 is less than 10% of MAR	highly variable flow	20% MAR

### 3.7.4 Q90-Q50 Method

The Q90-Q50 method was developed by Paster et al. in 2014. It is based on the annual flow quantiles, which are used to recommend the minimum instream flow for high and low flow seasons. FDC 2.1 software (a tool by hydro-office) was used to draw Flow duration curves (Gregor, 2010b). Therefore, Q90 is the minimum flow threshold allocated for low flow seasons, and Q50 is the threshold allocated for the high flow season. The allocation of annual flow quantile Q50 as a high flow season is recommended by Allain and El-Jabi (2002).

### 3.7.5 Variable Monthly Flow Method

The variable monthly flow (VMF) is developed by Pastor *et al.* (2014). This method is a parametric method that recommends the EFs requirements based on average monthly flow (AMF). Along with low and high flow ecological flow requirements, this method also suggests the intermediate flow requirements to protect the freshwater ecosystems. This method addresses the natural variability of river discharge, similar to the Tessman and Hoekstra methods. The only difference is that

the VMF method adjusts the EFRs according to the flow season. This method was developed to conserve and protect the freshwater ecosystems by reserving 60% of the MMF in low-flow season and a minimum flow of 30% of MMF during the high-flow season. This method allows other water users to withdraw water up to 40% of the MMF during the low-flow season (Table 3.9).

**Table 3.9:** Description of all the hydrological e-flows methods used to recommend e-flows

<b>Hydrological Season</b>	<b>Tennant method</b>	<b>Tessman method</b>	<b>Smakhtin method*</b>	<b>Q90-Q50 method</b>	<b>VMF method</b>
Low-flow requirements (LFRs)	0.2 MAF	MMF	Q90	Q90	0.6 MMF
High-flow requirements (HFRs)	0.4 MAF	0.4 MMF	0-0.2 MAF	Q50	0.3 MMF
Intermediate-flow requirements (IFRs)	-	0.4 MAF	-	-	0.45MMF

### 3.7.6 Global Environmental Flow Calculator (GEFC)

Global Environmental Flow Calculator (GEFC) is a tool developed by International Water Management Institute (IWMI, 2006) estimates Environmental Management Classes (EMCs) by “reducing” the natural hydrologic regime in a comparative basis at specific thresholds that indicate specific degrees of ecological disruption which could be high, moderate or low. This tool recommends the EFs based on the Smakhtin and Anputhas (2006) method, which has four sub-steps to evaluate the EFRs of a river. The four steps are as follows: Simulate reference hydrological conditions, defining environmental management classes, establishing

environmental FDC from reference conditions and simulating continuous monthly time series of EFs.

### ***3.7.6.1 Simulate reference hydrological conditions***

The very first step in developing the reference hydrological conditions is to collect the monthly flow time series data. This data is used to build the flow duration curves (FDC) for each representative site. The environmental flow requirements were assessed based on the ‘natural’ flow variability. The observed data and long term data collected from CWC were used to simulate the FDC. In GEFC, the FDCs are calculated by entering the discharge data in the user-defined option. It is a better option than the pre-defined conditions as it delivers a more precise and site-specific desktop assessment of water supply availability. The FDC is represented in the form of table with 17 fixed percentage points corresponding to the flows are as follows: 0.01%, 0.1%, 1, 5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 95%, 99%, 99.9% and 99.99%. All these points ensure that the entire flow range is effectively covered and makes it easy to use in further analysis.

### ***3.7.6.2 Defining environmental management classes***

The step is aimed to identify the conditions required to maintain the ecosystem in a desired future state referred as ‘environmental management class’ (EMC), ‘ecological management category’ or ‘level of environmental protection’ (DWAF, 1997; Acreman and Dunbar, 2004; Smakhtin and Anputhas, 2006). The EMC developed in this method has six subclasses starting from A to F (Table 3.10). These six EMCs are categorized with matching levels of E-flows (DWAF, 1997). Each class specifies an environmental flow scenario from natural unregulated flow conditions. With the increase in the EMC, the water required to preserve the desired EMC will also increase.

**Table 3.10:** Environmental Management Classes (EMCs) for the estimation of environmental flows needed to maintain ecosystems

S.No.	EMC	River status	Most likely ecological condition
1	A	Natural	Minor modification in instream and riparian habitat of the natural river system
2	B	Slightly modified	Ecologically important rivers are slightly modified due to water resource development and basin modification. Even after modifications, these rivers have unharmed biodiversity and habitats
3	C	Moderately modified	The natural habitat and dynamics of the river biota are disturbed; however, the essential ecosystem functions are still intact. Sensitive species disappear or reduce in the modified extent and invasive alien species appears
4	D	Largely modified	Natural habitat, biota and basic ecological functioning of the river are highly disturbed. Species richness recorded lower than expected, intolerant species are negligible and invasive species flourish well
5	E	Seriously modified	The availability of habitat and its diversity declines; species richness is critically lower. Only robust species flourish
6	F	Critically modified	The extreme level of modifications by Anthropogenic actions in the ecosystem and its functions. Almost total loss of natural biota and habitat. In some worst cases, irreversible destruction occurs in ecosystem functions

Source: Environmental management classes (EMCs) adapted from Global Environmental Flow Calculator (GEFC) developed by the International Water Management Institute (DWAF, 1997; IWMI, 2006; Smakhtin and Anputhas, 2006)

### ***3.7.6.3 Establishing environmental FDC from reference conditions***

The original FDC is taken as the reference condition, and further lateral shifts towards left along the probability axis gives the summary of E-flows for each EMC (Smakhtin and Anputhas, 2006). The 17 percentage points, as mentioned in step-1, were used to conduct the shifting procedure. One step shift in the FDC means that a flow which was exceeded, 99.99% of the time in the original FDC will now be exceeded 99.9% of the time, and in further subsequent steps, the exceedance will shift to the next percentile that is 99.9%, 99%, 99% 95%, and further proceeds in a similar way. This lateral shift in curves is done using the linear extrapolation to define the 'new low flows' at the lower tail.

### ***3.7.6.4 Simulating continuous monthly time series of EFs***

The environmental FDC built for any EMC gives an indicative value of the acceptable EF regime to maintain this EMC. However, the curves prepared so far can be converted into actual environmental monthly flow time series, using a spatial interpolation procedure as described by Hughes and Smakhtin (1996). This method follows the principle that the flow concurring at the sites which are reasonably close corresponds to similar percentage points on their FDCs. With the help of available time series (this site is called source site), the streamflow time series is generated (this site is called destination site). That is how this method transfers the time series from one location for which data is available to the destination site with no available data. With the GEFC, the source site's FDC and time series represents the reference natural flow regimes, whereas the destination FDC represents the EF sequence to be generated. This method is not a spatial interpolation-based method, but it only uses a one-time series to generate another modified EF based on a transformation through

two sets of FDCs. The procedure to convert the modified EF to monthly flow time series is as follows:

- (i) Identifies the percentage point position of the natural streamflow on the natural flow's period-of-record FDC ('source site's' FDC), and
- (ii) Reads off the monthly flow value for the equivalent percentage point from the Environmental FDC ('destination site's' FDC).

The generation of monthly flow time series is the final output of this method. Therefore, the outputs can be presented in two forms: one is as environmental FDC and another as a corresponding environmental monthly flow time series.

### **3.7.7 Wetted Perimeter Method**

This method is an essential 'transect' based approach work on the wetted perimeter–discharge (WP-Q) relationship to evaluate environmental flows (Gordon *et al.*, 1992). In a channel cross-section, the wetted perimeter is the distance in contact with water along the bottom and sides of a channel cross-section. An increase in stream channel flow increases the wetted perimeter, but the rate of increase in the wetted perimeter is not the same throughout the entire range of flows (Figure 3.7). The channel cross-section surveys at several discharge levels were performed to derive the WP-Q relationship. Transects are placed near to the CWC gauge stations, where the fish passage was likely to be limited. Long term cross-section profiles and water levels were also obtained from CWC. Based upon the field surveyed data and CWC data the stage-discharge relationships were derived using logarithmic equations. The results of channel morphology surveys and other data collected were used to model the wetted perimeter–discharge relationship based on the Manning equation (Gordon *et al.*, 1992). Manning's equation is empirical finds its importance in

uniform flow open channel. The method also assumes the stream channel to be stable and unchanging over time (Annear *et al.*, 2004).

This equation is used to determine the flow required to ensure the desired water level, as well as an optimum value of section variables, i.e., channel velocity, flow area, Manning roughness coefficient, and channel slope, is calculated (Niazkar and Afzali, 2015; Yin, 2018). The Manning's equation is used to calculate the discharge required to maintain an adequate water level in the river channel at selected sites to facilitate the migration of fishes throughout the channel (Annear *et al.*, 2004). Manning's equation is as follows:

$$Q=A.V$$

$$V = \frac{K}{n} \frac{A}{P}^{\frac{2}{3}} S^{\frac{1}{2}}$$

Where:

K is a unit conversion factor

K=1.49 for (feet and seconds)

K=1.0 for SI units (meters and seconds)

A=Flow area of the channel

P=Wetted perimeter which is the portion of the circumference that is in contact with water

Q=Discharge (flow rate)

S=Downward (longitudinal) slope of the channel

V=Average velocity in the channel.

n=Manning roughness coefficient

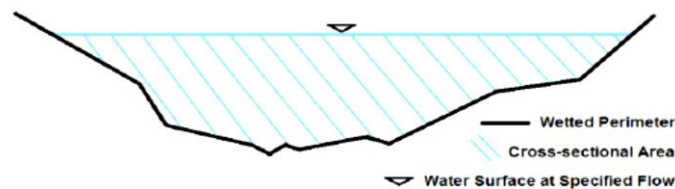
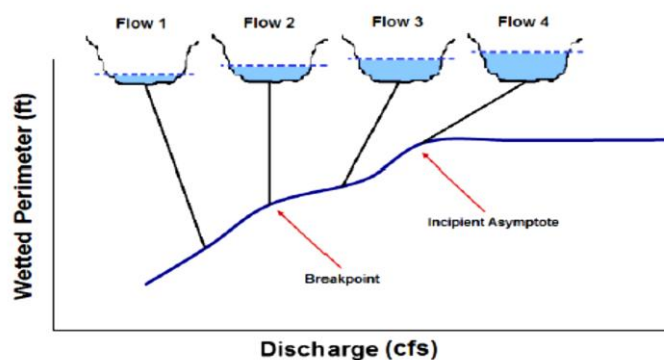


Figure 1. Visual representation of wetted perimeter



**Figure 3.7:** Wetted perimeter-discharge curve showing the breakpoint, incipient asymptote and a visual illustration of streambed cross-sections at different flow levels (Source: CDFW, 2013)

*Breakpoint:* It is the point that indicates the threshold below which aquatic habitat conditions for the critically significant food production decline rapidly. The breakpoint marked at the curve's point where there is maximum curvature (Niazkar and Afzali, 2015).

*Incipient asymptote:* It is the second inflection point, which is identified as the upper threshold for riffle food production. At this point, assumptions were made that flow is at or near optimum to produce food for riffle habitats (Leathe and Nelson, 1989). It is assumed to be the sufficient water level to maintain the existing fish population at a certain satisfactory level of persistent future production.

If the identifiable breakpoint and incipient asymptote were not present in WP-Q curves, this method would not be suitable for calculating the WP for the selected riffle site.

### **3.8 Stage Discharge Curves**

An empirical as well as theoretical, relationship exists between water level and the flow discharge in an open channel is known as ‘stage-discharge relation’ or ‘rating curve,’ or also the only rating. These are synonymous terms many times used interchangeably. The rating curve is important as well as extensively used tool in hydrology to estimate the discharge in natural or an artificial open stream channel. In this method, the stage levels are plotted against the corresponding discharge than by fitting these data with power or polynomial curve. It is a traditional and simple method to measure water levels with gauge and estimating the discharge using the stage-discharge relationship. This method allows the measurement of discharge in open channels in less time and also during the flooding seasons. It is a low cost and reliable method to estimate the flow of discharge in the river streams.

The stage-discharge relationship is essential in preparing the continuous records of discharge at the gauging stations. The discharge rating curve converts the continuous stage data to a continuous record of stream discharge, but it is also used to convert model forecasted flow hydrographs into stage hydrographs (Das and Chaudhary, 2014). These graphs are also useful in estimating the area getting inundated during the flooding events. These relations are typically established empirically from periodic measurements of stage and discharge (Das and Chaudhary, 2014). Generally, periodic measurements are required to validate the underlying stage-discharge relationship and to track changes or shifts in the rating curve (Braca, 2008). The ISO regulation 1100-2 (ISO, 2010) recommends at least 12-15 discharge measurements during the period of analysis. To estimate the stage and discharge relation in the study area, the river cross-sections, long term gauge discharge data, and water level data were acquired from CWC for three gauge stations, i.e., Neemsar,

Lucknow and Maighat respectively from 2005 to 2016. The field surveys were conducted to acquire the data on water levels in different periods of the year during the year 2015 and 2016. Thus the stage-discharge curves for the three CWC Gauging sites mentioned were prepared. The values of the stage and the corresponding calculated discharge levels were plotted in Microsoft Excel worksheet in an arithmetic plot. After plotting the stage versus discharge to the arithmetic scale, a smooth curve through the plotted points to get a rating curve equation in its standard form. It gives the required stage-discharge relationship that represents the combined effect of a wide range of channel and flow parameters.

### **3.9 Physico-Chemical Analysis of Water**

The Physico-chemical analysis of Gomti river water quality was performed at similar sites studied for e-flows assessment, i.e., Neemsar, Lucknow and Maighat. Sampling was done during May and June for pre-monsoon season and in September and October for the post-monsoon season. Sampling was done for consecutive two years, i.e., in the years 2016 and 2017. The secondary pre- and post-monsoon water quality data was obtained from the Central water commission (CWC) for the years 2013 to 2015. Analysis of all the physico-chemical parameters was done based on the standard methods, as described in APHA (1998). The water quality parameters evaluated were pH, electrical conductivity, total dissolved solids, temperature, turbidity, biological oxygen demand (BOD), chemical oxygen demand (COD) and dissolved oxygen (DO).

Based on the present water quality in the Gomti River, assessment of the river's health was done. The river's health was evaluated based upon the Central Pollution Control Board (CPCB) rivers water quality standards (Table 3.11).

**Table 3.11:** The best use of surface water classification given by CPCB

Quality class	Primary Water Quality Criteria	Designated best use
Class A	<ul style="list-style-type: none"> <li>• The Total Coliforms Organism MPN/100 ml should be 50 or less than 50</li> <li>• pH ranges between 6.5-8.5</li> <li>• Dissolved Oxygen 6 mg/l or more</li> <li>• Biochemical Oxygen Demand 5 days 20 °C 2 mg/l or less</li> </ul>	This water source can be used for drinking purposes without conventional treatment after disinfection
Class B	<ul style="list-style-type: none"> <li>• Total Coliforms Organism MPN/100 ml should be 500 or less</li> <li>• pH between 6.5-8.5</li> <li>• Dissolved Oxygen 5 mg/l or more</li> <li>• Biochemical Oxygen Demand 5 days 20 °C 3 mg/l or less</li> </ul>	This water source can be used for organized outdoor bathing
Class C	<ul style="list-style-type: none"> <li>• Total Coliforms Organism MPN/100 ml should be 5000 or less</li> <li>• pH between 6 and 9</li> <li>• Dissolved Oxygen 4 mg/l or more</li> <li>• Biochemical Oxygen Demand 5 days 20 °C 3 mg/l or less</li> </ul>	This water source can be used for public water supply after giving appropriate primary, secondary and tertiary water treatments
Class D	<ul style="list-style-type: none"> <li>• pH between 6.5 and 8.5</li> <li>• Dissolved Oxygen 4 mg/l or more</li> <li>• Free Ammonia (as N) 1.2 mg/l or less</li> </ul>	This water is suitable for propagation of wildlife and fisheries
Class E	<ul style="list-style-type: none"> <li>• pH between 6.0-8.5</li> <li>• EC at 25 °C <math>\mu\text{S}/\text{cm}</math> maximum 2250</li> <li>• Sodium absorption ratio (SAR) less than to 26</li> <li>• Boron maximum 2 mg/l</li> </ul>	The water source can be used for irrigation, industrial cooling and controlled waste disposal purposes

Source: CPCB, 1994

Dutta *et al.* (2017) have mentioned the optimum range of temperature, turbidity, electrical conductivity, and total dissolved solids between 22-23, 26.5-30.5, 300 to 350, and 250 to 300, respectively to maintain the healthy ecological conditions in the river (Dutta *et al.*, 2017).

### **3.10 Identification of Indicator Species**

The identification of indicator species was made to recommend the ecological flow requirements for the River stream suitable for their habitat. Setting up the indicator species criteria is an essential part of simulating the e-flows requirements (Jowett, 1997). In most of the cases, top carnivores of the ecological pyramid and long-lived organisms were selected as index species. In this way of selection of index species, some more sensitive and critical species in the interlinked food webs were missed out (Waddle, 2001). Thus it is imperative to take a well-structured method to identify the index species for the EFR determination.

In this study, the fish diversity of the Gomti River was considered to assess the indicator species. In Gomti River, before this study, only one attempt has been made to study the fish diversity of the complete river channel from its origin to its confluence point with river Ganges (Gupta, 2011). The identification of representative fish species of the study area, extensive field surveys were done. The data from both primary and secondary sources were considered for listing the species reported and currently present in the river's main channel. The identification of indicator species was made based upon the index value method, where all the species were given an index value based upon their protection levels (Shokoohi and Amini, 2014). In the index species selection method, the highest value (9) was assigned to international conservation, and the lowest value (1) was assigned to the fishing sport. Many species in this method are marked 'zero' for their ecological values (Table 3.12). This zero

does not mean that the species has no ecological importance, as every species is ecologically important. Many of these species are useful as they form the food source for other species. This representation indicates that these species have the minimum ecological significance in the habitat thus are not considered in the calculation of the index species.

**Table 3.12:** Index species selection criteria used in identifying the indicator species

Item no.	Definition	Value
1	The value corresponding to the international conservation: IUCN red list, endangered and facing a high risk of extinction	9
2	The value corresponding to the national conservation listed as protected or facing risk of extinction in the country	7
3	The value corresponding to the status of being a genetic resource of the country: the species that are monolocate and endemic	5
4	The value is corresponding to ecological importance: the species that play a specific role in the regional aquatic ecosystem. E.g., Algae eater that connect the top and bottom of the food pyramid	3
5	The value corresponding to economical importance: the species that are appropriate for economical use	2
6	The value corresponding to fishing sport: the species that are important for tourism and development of the region	1

Source: Shokoohi and Amini (2014)

**Index number** = [International conservation value (0 or 1) × 9] + [National conservation value (0 or 1) × 7] + [Genetic resource value (0 or 1) × 5] + [Ecological value (0 or 1) × 3] + [Economic value (0 or 1) × 2] + [Fish sport value (0 or 1) × 1]

The data collection for calculating index value for each species was done from multiple sources. The species International conservation values were obtained from the IUCN red data list. The National conservation values were obtained from the report by Molur and Walker (1998). Genetic resource values were obtained from the Aquatic Genetic Resource Information System of India (AqGRISI) website

(AqGRISI, 2018). Ecological values were obtained from multiple sources such as Sarkar *et al.* (2010), Sarkar *et al.* (2012). Economic values were quantified from multiple sources. Sport fishes value was obtained from the all Indian game fishing association (AIGFA) website (AIGFA, 2018).

### **3.10.1 Identification of life stages of fish**

The identification of life stages of fish is an essential aspect in recommending the flow requirements for each stage. Based on extensive field surveys, four main life stages were identified. These life stages were further studied to recommend the depth and flow velocity required in each life stage. A document published by Abdoli and Naderi (2008) was used to identify and define the life stages as:

*Spawning:* Nest building, egg and sperm release and fertilization

*Migration:* Mature adult migrates towards shallow water or spawning areas to lay eggs and Juvenile migrates to deep water pools

*Food:* Adult and juvenile moves through the vertical column of the river and also in the longitudinal river channel in search of food

*Resting:* Fish moving to the deep water in harsh environmental conditions in search of a place to hide and rest

### **3.10.2 Experimental Fishing**

Experimental fish samplings were performed in the upstream, midstream and downstream regions of the river Gomti during Aug-Jan in the year 2017 and 2018 according to Bain and Knight (1996). Professional fishers were hired to conduct the experimental fishing using cast nets of mesh size 2.2x2.2 cm. At each sampling site, representative specimens of fish species were fixed and stored in glass bottles filled with 10% formaldehyde for further identification. Identification was performed following the standard literature by Jayaram (1999) and Talwar and Jhingran (1991).

Data regarding threats faced by fish diversity were obtained from both primary and secondary sources. Primary sources include direct observations followed by interactions with local stakeholders and fishers. The secondary data sources include research articles, thesis and reports published by the reputed government organization, National Bureau of Fish Genetic Resources (NBFGR).

### **3.10.3 Fish catch and Diversity Analysis**

The stock size estimation was done using the catch per unit effort (CPUE) of the cast net for each sampling site following Biswas (1993). The CPUE is particularly beneficial if the relationship between catch and effort is linear through the origin (strict proportionality) (Lima *et al.*, 2000). Besides, the relative abundance (RA) or the percentage of the catch of fish and other fish diversity indices were also calculated. The Formula for RA of fishes is as follows:

$$RA = (\text{Number of samples of particular species} / \text{Total number of species}) \times 100$$

To calculate the species diversity Index PAleontological STatistics (PAST) software is used. The fish diversity index was calculated using the methods of Shannon and Wiener 1963.

$$H = \sum_{i=1}^n \left( \frac{n_i}{N} \right) \log_2 \left( \frac{n_i}{N} \right)$$

Where: H = Shannon–Wiener index of diversity,  $n_i$  = total numbers of individuals of species, N = total number of individuals of all species.

The formula for Simpson index is:

$$D = 1 - \sum_i \left( \frac{n_i}{n} \right)^2$$

Where, D= Simpson index,  $n_i$ = number of individuals of taxon i.

Berger-Parker dominance is simply the number of individuals in the dominant taxon relative to the total number of individuals. Buza's and Gibson's Evenness was calculated using the following formula:

$$\text{Buza's and Gibson's Evenness} = e^{H} s$$

Where, H = Shannon–Wiener index, S=Number of taxa.

### **3.11 Socio-Cultural Mapping and E-Flows Need**

The socio-cultural mapping is done to understand the aesthetic and social connections of the population living in the river basin with the river. Thus their requirements of flow in the river channel were assessed using the field surveys. To conduct this study, 14 temples near the stream channel were selected and surveyed. The survey included a detailed interview of the temple priests of all the selected temples. The outcome of these surveys was the desired level of water, which should be present near the temple to offer *pujas* and take sacred baths in the river.



*Chapter 4*  
*Homogeneous Zonation of the*  
*River Basin for Identification of*  
*Environmental Flows Sites*



## **4 Homogeneous Zonation of the River Basin for Identification of Environmental Flows Sites**

The identification of homogenous zones is the first step in environmental flows assessment for the Gomti River Basin (GRB). The river frequently changes during its course of travel from its origin to confluence point with sea or large rivers. Along with the natural factors, anthropogenic factors also affect the river channel and its habitat.

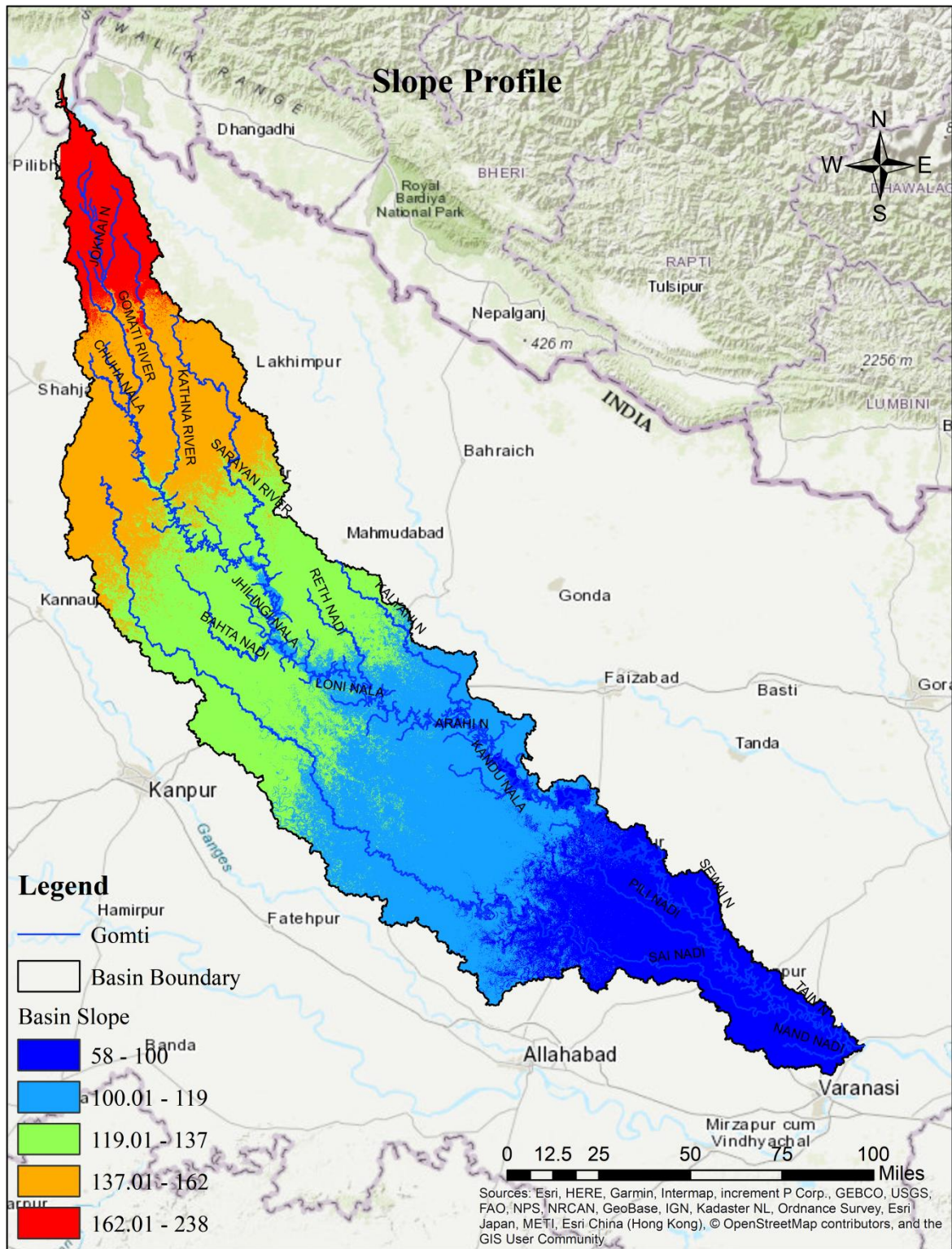
### **4.1 Steps for Homogenous Zonation**

In this study, the zonation was done following on nine steps, with each step identifying a particular set of characteristics in each zone. The steps used are briefly described as follows:

#### **4.1.1 Longitudinal Profiling of the River Stream**

In the longitudinal profile of Gomti River, a uniform gradient of 0.10 m per km is visible from its origin to its confluence point at Kathi, Varanasi, Uttar Pradesh (U.P.) (Figure 4.1). The elevation at the origin point of the river is about 188m above mean sea level (AMSL). The river travels 941Km towards its confluence point with the river Ganga in Kathi, Varanasi. The confluence point is located at about 67.80m above mean sea level (AMSL).

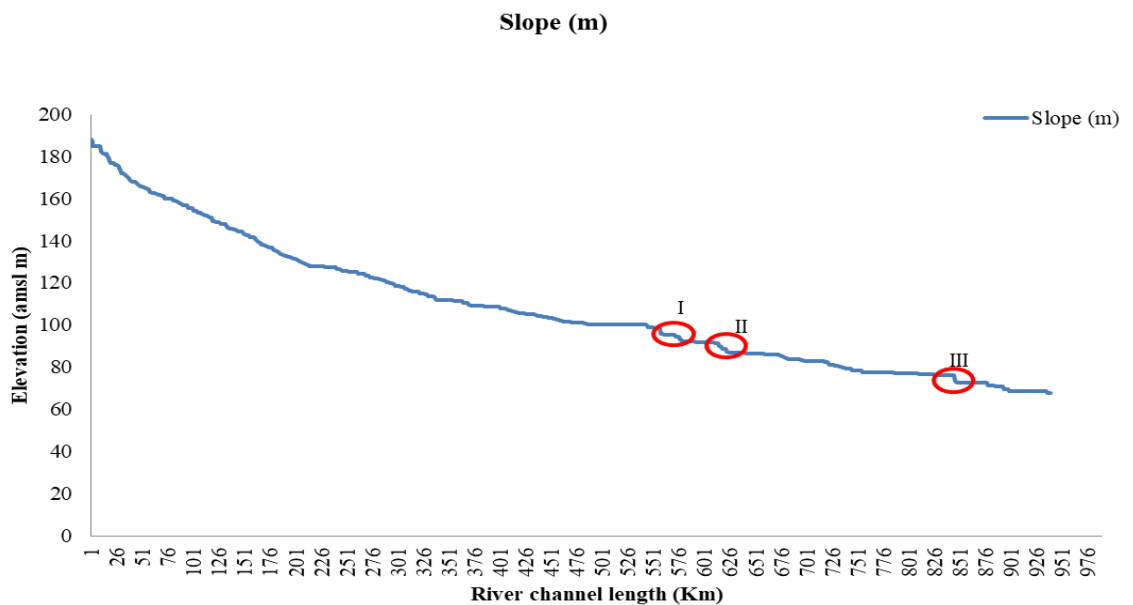
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**Figure 4.1:** Slope profile of Gomti River Basin

#### 4.1.2 Identification of Major Inflection Points

In the detailed study of the gradient profile of the river, no major inflection points were visible. However, three minor inflections were visible in the longitudinal profile of the river (Table 4.1, Figure 4.2 and 4.3). These inflections might be due to the construction of the state and national highways passing over the river. However, in the field survey no other distinct feature was observed, which could be a probable reason for it was observed during ground-truthing feature has evident. Thus, points were not considered in the preparation of the final zonation process.



**Figure 4.2:** The longitudinal profile of River Gomti, the circles indicates three minor inflection points

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**Table 4.1:** List of minor inflection points in the river profile

<b>Location</b>	<b>Latitude\Longitude</b>	<b>District</b>	<b>Dominant features</b>
State highway 13 (SH13) Major district road 3 (MDR3)	28°39'41.34" N 81°24'17.7" E	Barabanki	A State highway passes over the river channel where the inflection point is visible, no other feature which could be a probable reason for it was observed during ground-truthing
National Highway 330 (NH330)	26°29'28.99" N 81°44'46.05" E	Amethi	A National highway passes over the river channel where the inflection point is visible, no other feature which could be a probable reason for it was observed during ground-truthing
State highway 7 (SH7)	25°57'48.77" N 82°32'50.92" E	Jaunpur	State highway passes over the river channel where the inflection point is visible, no other feature which could be a probable reason for it was observed during ground-truthing

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**Figure 4.3:** Zonation based upon minor inflection points

### 4.1.3 Identification of Dominant Fluvial Features

On examining the river's width, type of floodplain, terraces, and other geomorphological features, six major zones were identified in Figure 4.5. The list of the significant geomorphological zones is given below (Table 4.2). Satellite pictures of major fluvial features visible in the GRB are shown in Figure 4.4.

**Table 4.2:** Zonation based on fluvial features

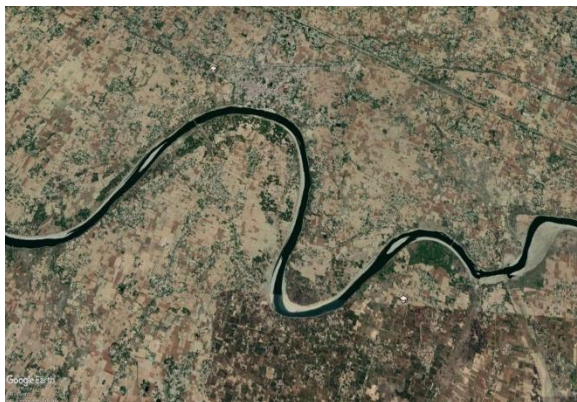
<b>Zone</b>	<b>Extent</b>	<b>Latitude\ Longitude</b>	<b>Approximate Channel-Width (m)</b>	<b>Dominant Features</b>
I	Pilibhit-Shahajahanpur	28°36'31.99" N 80°06'31.31" E- 28°08'28.55" N 80°12'07.20" E	Less than 30 except for initial 60 km where it has less than 10m width except at few places	The narrow and shallow channel, the river channel is dry throughout the zone except at few places, river channel has been encroached for agricultural practices at many places, the river is visible in the form of small pools in the channel, meandering, and oxbow lakes are visible
II	Shahajahanpur-Dadhna-mau	28°08'28.55" N 80°12'07.20" E- 27°28'25.87" N 80°23'18.68" E	20-40	Shifting river channel, visible paleochannels, alluvial deposits, oxbow lakes, meandering scars, dense riparian vegetation at some places, distinctly visible river channel
III	Dadhna-mau-Hydal power colony	27°28'25.87" N 80°23'18.68" E- 26°51'27.70" N 80°57'59.77" E	30-100	Shifting river channel, braiding river, visible paleochannels, alluvial deposits, oxbow lakes,

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Zone	Extent	Latitude\ Longitude	Approximate Channel-Width (m)	Dominant Features
				meandering scars, sparse riparian vegetation, small rural settlements settled in patches close to the river at some places
IV	Hydel power colony- Dilkusha colony	26°51'27.70" N 80°57'59.77" E- 26°49'57.96" N 80°57'58.60" E	100-200	The river is channelized, paved banks, river width controlled, a rubber dam is constructed, stagnant water, no vegetation on the Banks, urban settlements, deep channel
V	Dilkusha colony- Sultanpur	26°49'57.96" N 80°57'58.60" E- 26°16'14.20" N 82°04'27.28" E	60-130	Meandering, alluvial deposits, sand bar deposits in the channel, braiding, shifting channel, visible paleochannels, sparse vegetation, large patches of settlements near to the river channel, deep channel up to 2.5 m
VI	Sultanpur - Ganga river, Varanasi	26°16'14.20" N 82°04'27.28" E- 25°31'05.40" N 83°09'09.92" E	100-150	Multiple paleochannels, deep channel up to 3m, braiding, shifting channel, alternate sand point bars deposits in the channel, alluvial deposits,

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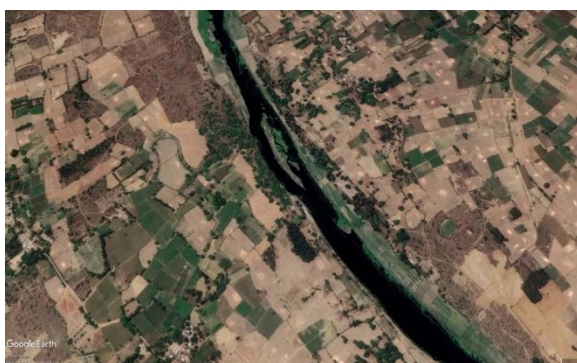
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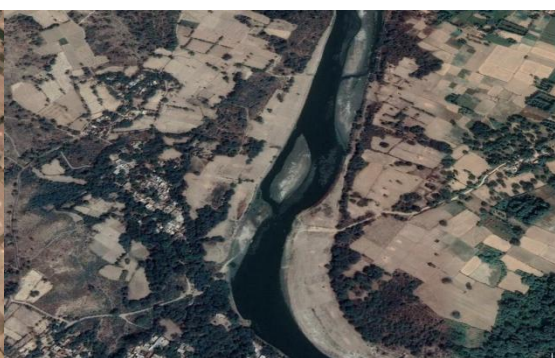
(a) Braiding river and alluvial deposits on alternate banks (Jaunpur district)



(b) Meandering river and paleochannels (Sultanpur district)



(c) Braiding river (Barabanki district)



(d) Braiding river (Sultanpur-Barabanki district boarder)



(e) Braiding river (Faizabad district)



(f) Alluvial deposits (Sultanpur district)



(g) Meandering river and intensive agricultural activities in the riparian zones (Shajahanpur district)

(h) Meandering river, paleochannels and oxbow lakes (Lakhimpurkheri district)



(i) Oxbow lakes (Lakhimpurkheri district)

(j) Meandering river, paleochannels and oxbow lakes (Lakhimpurkheri district)



(k) Channelized stretch of the middle section of the river (Lucknow district)

(l) Shifting channel and connected oxbow lake (Sultanpur district)

**Figure 4.4:** Major fluvial features visible in the satellite images from (a) to (l)

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**Figure 4.5:** Zonation based upon dominant fluvial features

#### 4.1.4 Barriers in the Natural Flow

The barriers, whether natural or artificial, obstruct the natural flow of the river. The natural barriers are mainly comprised of large heaps of unsorted landslide debris that appear to be obstructing the flow of the river to varying degrees. The Gomti River is a plain fed river of Ganga basin, and it does not have any major natural barriers in its course. Barriers in the river channel are mainly in the form of dams or barrages, and three such artificial barriers were identified in the river channel (Table 4.3, Figure 4.6).

**Table 4.3:** List of barriers present in the river channel

<b>Zone</b>	<b>Stretch within water flow barriers are present</b>	<b>Latitude/Longitude</b>	<b>Influencing Artificial flow Barrier(s), location</b>
I	Pilibhit- Kudia Ghat	28°36'31.99" N 80°06'31.31" E- 26°52'26.63" N 80°54'26.63" E	The earthen dam at Kudia Ghat, Lucknow
II	Kudia Ghat- Gomti Barrage	26°51'19.95" N 80°58'10.31" E	Gomti Barrage, Lucknow
III	Gomti barrage - La Martiniere College	26°51'19.95" N 80°58'10.31" E- 26°50'25.047" N 80°58'3.914" E	Rubber dam, Lucknow
IV	La Martiniere College- Ganga river, Varanasi	26°50'25.047" N 80°58'3.914" E - 25°31'05.40" N 83°09'09.92" E	The confluence point with Ganga, Varanasi

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**Figure 4.6:** Map of identified zones based on major flow barriers

#### 4.1.5 The Major Confluences of Tributaries into the Main Channel

There are 26 tributaries of Gomti, which are contributing a significant amount of flow into the river channel. Those tributaries, which are more than 150Km long, were considered as significant tributaries of River Gomti. The confluence points of four principal rivers, namely, Kathna (176 Km), Suruyan (274 Km), Kalyani (190 Km), and Sai (695 Km) rivers were considered for marking the major confluence zones in the river channel (Table 4.4, Figure 4.7).

**Table 4.4:** List of major confluences points in the river channel

Sr. No.	Zone	Extent (Major tributaries)	Latitude/Longitude	Predominant Tributary Type
1	I	Pilibhit- Dadhna Mau (Kathna River)	28°36'31.99" N 80°06'31.31" E- 27°28'24.48" N 80°23'30.57" E	Plain fed rivers of Ganga alluvial plain, channel width increase from less than 10m to average 40m
2	II	Dadhna Mau- Hindaaura (Sarayan River)	27°28'24.48" N 80°23'30.57" E- 27°11'58.072" N 80°47'24.541" E	Plain fed rivers of Ganga alluvial plain, channel width increases from 30-40m to 70-100m
3	III	Duwarika Pur (Kalyani River)	27°11'58.072" N 80°47'24.541" E- 26°41'34.40" N 81°35'47.99" E	Plain fed rivers of Ganga alluvial plain, channel width increases from 70-100 to 120-130m
4	IV	Hindaaura- Bijaipur (Sai River)	26°41'34.40" N 81°35'47.99" E- 25°39'05.07" N 82°48'07.53" E	Plain fed rivers of Ganga alluvial plain, channel width increases from 70-130m to 130-150m
5	V	Bijaipur- confluence point with the Ganges, Varanasi	25°39'05.07" N 82°48'07.53" E- 25°31'05.40" N 83°09'09.92" E	Channel width approximately 130-150m

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Before the confluence of river Kathina, the river channel width is less than 40m, after confluence width becomes 30-100m in the second zone. After the confluence of Sarayan River, the width of the channel further increases to 70-100m. The confluence of Kalyani and Sai River further increases the width and depth of the river channel to 130m to 150m and up to 3m, respectively. Sai River is a major tributary of GRB, which covers approximately 43% of the drainage area of the basin.



**Figure 4.7:** Identified major confluence points on the river Gomti

#### **4.1.6 The Habitat Requirement, Beginnings, and Ends of Habitat Ranges of Species of National and International Importance**

One hundred twenty-two species of higher fauna, including 63 species of fishes, 50 species of birds, six species of reptiles, and three species aquatic mammals were considered for marking the ecological regions. As per the conservation status in the IUCN Red List categories, 47 Near-threatened to endangered species were reported in the GRB (Table 4.5). Based on the beginnings and ends of their ranges, the river-channel has been categorized into 9 zones. Out of 47 species considered 22 species were found only in the limited extents other 25 species were present throughout the river-channel. A list of all the species considered to mark the environmental zones is as follows (Table 4.6, Figure 4.8).

**Table 4.5:** List of species of national and international importance considered to mark the Ecological regions out of total reported species

Type	Biological Name	Common Name	Conservation Status	Range/Location in the basin boundary
Birds	<i>Antigone antigone</i>	Sarus Crane	Vulnerable	Throughout the basin
	<i>Aquila nipalensis</i>	Steppe Eagle	Endangered	Throughout the basin
	<i>Ardeotis nigriceps</i>	Great Indian Bustard	Critically Endangered	Lakhimpurkheri, Hardoi, Shahjahanpur and some parts of Sitapur district
	<i>Aythya ferina</i>	Common Pochard	Vulnerable	Throughout the basin
	<i>Aythya nyroca</i>	Ferruginous Duck	Near Threatened	Pilibhit, Shajahanpur, Lakhimpurkheri, Hardoi, Sitapur and parts of Lucknow, Unnao and Barabanki district
	<i>Buceros bicornis</i>	Great Hornbill	Vulnerable	Found throughout the basin except for some parts of Barabanki, Pratapgarh, Jaunpur and Varanasi district
	<i>Chaetornis striata</i>	Bristled Grassbird	Vulnerable	Throughout the basin
	<i>Circus macrourus</i>	Pallid Harrier	Near Threatened	Throughout the basin
	<i>Clanga hastata</i>	Indian Spotted Eagle	Vulnerable	Throughout the basin
	<i>Ephippiorhynchus asiaticus</i>	Black-Necked Stork	Near Threatened	Throughout the basin
	<i>Esacus recurvirostris</i>	Great Thick-Knee	Near Threatened	Throughout the basin
	<i>Francolinus gularis</i>	Swamp Francolin	Vulnerable	Pilibhit, and in parts of Shajahanpur and Lakhimpurkheri

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Type	Biological Name	Common Name	Conservation Status	Range/Location in the basin boundary
				district
	<i>Gyps bengalensis</i>	White-rumped Vulture	Critically Endangered	Throughout the basin
	<i>Haliaeetus leucoryphus</i>	Pallas's Fish-Eagle	Endangered	Throughout the basin
	<i>Leptoptilos dubius</i>	Greater Adjutant	Endangered	Throughout the basin except Pilibhit, Shajahanpur, Lakhimpurkheri, and some parts of Hardoi and Sitapur district
	<i>Leptoptilos javanicus</i>	Lesser Adjutant	Vulnerable	Throughout the basin
	<i>Mareca falcata</i>	Falcated Duck	Near Threatened	Throughout the basin
	<i>Marmaronetta angustirostris</i>	Marbled Teal	Vulnerable	Pilibhit, Shajahanpur, Lakhimpurkheri, and in parts of Hardoi and Sitapur district
	<i>Mycteria leucocephala</i>	Painted Stork	Near Threatened	Throughout the basin
	<i>Numenius arquata</i>	Eurasian Curlew	Near Threatened	Throughout the basin
	<i>Oxyura leucocephala</i>	White-Headed Duck	Endangered	Pilibhit, Shajahanpur, and in some parts of Lakhimpurkheri district
	<i>Pelecanus crispus</i>	Dalmatian Pelican	Near Threatened	Unnao, Hardoi, Lucknow, Barabanki, and parts of

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Type	Biological Name	Common Name	Conservation Status	Range/Location in the basin boundary
				Sitapur, Lucknow, Raibareli, Sultanpur and Faizabad district
	<i>Pelecanus philippensis</i>	Spot-Billed Pelican	Near Threatened	Throughout the basin except some parts of Varanasi district
	<i>Psittacula eupatria</i>	Alexandrine Parakeet	Near Threatened	Pilibhit, and in parts of Shajahanpur and Lakhimpurkheri district
	<i>Rynchops albicollis</i>	Indian Skimmer	Vulnerable	Throughout the basin except some parts of Pilibhit district
	<i>Saxicola insignis</i>	White-Throated Bushchat	Vulnerable	Pilibhit, Shajahanpur and Lakhimpurkheri and some parts of Sitapur district
	<i>Sypheotides indicus</i>	Lesser Florican	Endangered	Throughout the basin
	<i>Threskiornis melanocephalus</i>	Black-Headed Ibis	Near Threatened	Pilibhit, Shajahanpur, Lakhimpurkheri, Hardoi and parts of Sitapur, Unnao and Lucknow district
	<i>Vanellus gregarius</i>	Sociable Lapwing	Critically Endangered	Hardoi, Sitapur, Lucknow, Barabanki, Unnao and some parts of Lakhimpur and Shajahanpur district
	<i>Vanellus vanellus</i>	Northern Lapwing	Near Threatened	Pilibhit, Shajahanpur, Lakhimpurkheri, and some parts of Sitapur
Reptiles	<i>Batagur dhongoka</i>	Three-Striped Roofed Turtle	Critically	Throughout the basin

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Type	Biological Name	Common Name	Conservation Status	Range/Location in the basin boundary
			Endangered	
	<i>Batagur kachuga</i>	Red-Crowned Roofed Turtle	Critically Endangered	Throughout the basin
	<i>Hardella thurjii</i>	Crowned River Turtle	Vulnerable	Throughout the basin
	<i>Gavialis gangeticus</i>	Gharial	Critically Endangered	Throughout the basin
	<i>Crocodylus palustris</i>	Mugger	Vulnerable	Throughout the basin
	<i>Chitra indica</i>	Indian Narrow-Headed Softshell Turtle	Endangered	Throughout the basin
Mammals	<i>Aonyx cinereus</i>	Asian Small-Clawed Otter	Vulnerable	Pilibhit, Shajahanpur, Lakhimpurkheri, Sitapur and parts of Hardoi and Barabanki district
	<i>Lutrogale perspicillata</i>	Smooth-Coated Otter	Vulnerable	Throughout the basin
	<i>Cuon alpinus</i>	Dhole	Endangered	Pilibhit, Shajahanpur and parts of Lakhimpurkheri district
Fishes	<i>Ailia coila</i>	Gangetic Ailia	Near Threatened	Throughout the basin
	<i>Bagarius bagarius</i>	Devil Catfish/Dwarf Goonch/Goonch	Near Threatened	In the downstream region of the river

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Type	Biological Name	Common Name	Conservation Status	Range/Location in the basin boundary
	<i>Chitala chitala</i>	Indian Featherback/Knifefish	Near Threatened	In the downstream region of the river
	<i>Cyprinus carpio</i>	Common Carp/ European Carp	Vulnerable	Throughout the basin
	<i>Hypophthalmichthys molitrix</i>	Silver Carp	Near Threatened	In the downstream region of the river
	<i>Ompok bimaculatus</i>	Butter Catfish	Near Threatened	Throughout the basin
	<i>Ompok pabda</i>	Pabdah Catfish	Near Threatened	In upstream region of the river
	<i>Wallago attu</i>	Helicopter Catfish	Near Threatened	Throughout the basin

\*Only those species are considered which are listed in IUCN Red data list as Endangered, Near Threatened, Vulnerable, and Critically Endangered

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**Table 4.6:** List of major ecological ranges identified on River Gomti

<b>Zone</b>	<b>Extent</b>	<b>Latitude\Longitude</b>	<b>Beginnings of Ranges (number of species)</b>	<b>Ends of Ranges (number of species)</b>	<b>Total Associated Changes in Range (number of species)</b>
I	Pilibhit- Aurangabad	28°36'31.99" N 80°06'31.31" E- 28°5'18.178" N 80°12'22.865" E	-	-	-
II	Aurangabad- Gulauli	28°5'18.178" N 80°12'22.865" E- 27°44'19.648" N 80°15'59.977" E	1	3	4
III	Gulauli-Atva	27°44'19.648" N 80°15'59.977" E- 27°21'4.263" N 80°27'34.026" E	1	3	4
IV	Atva – Hindaura	27°21'4.263" N 80°27'34.026" E- 80°47'24.541" E 27°11'58.072" N	2	1	3
V	Hindaura- Lucknow	80°47'24.541" E 27°11'58.072" N- 26° 53'16.50" N 80° 54.44.38" E	-	1	1
VI	Lucknow- Haidergarh	26° 53'16.50" N 80° 54.44.38" E- 26° 40'02.11" N 81° 27' 51.01" E	3	3	6
VII	Haidargarh- Sultanpur	26° 40'02.11" N 81° 27' 51.01" E- 26° 16'14.20" N 82° 04' 27.28" E	-	2	2
VIII	Sultanpur- Jaunpur	26° 16'14.20" N 82° 04' 27.28" E- 25° 44'54.03" N 82° 41' 08.00" E	-	6	6
IX	Jaunpur- Ganga river, Varanasi	25° 44'54.03" N 82° 41' 08.00" E- 25°31'05.40" N 83°09'09.92" E	-	-	Confluence point with the Ganges, Varanasi

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**Figure 4.8:** Areas identified with distinct ecological features on the river Gomti

#### **4.1.7 The Type of Forest Cover and Status of Riparian Vegetation**

The major forest types identified in the Gomti river basin were tropical moist deciduous and tropical dry deciduous types. Based on the presence of these forest-types, the river-channel has been divided into two major zones (Table 4.7, Figure 4.9).

**Table 4.7:** Major forest types zones identified

<b>Zone</b>	<b>Extent</b>	<b>Latitude\Longitude</b>	<b>Associated Forest Type(s)</b>
I	Pilibhit- Dadhna Mau	80°23'30.57"E 27°28'24.48"N	Tropical Moist Deciduous Forest
II	Dadhna Mau- (Ganga confluence)	Varanasi 80°10'11.42"E 25°30'27.94"N	Tropical Dry Deciduous Forest

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**Figure 4.9:** Identified zones based on major types of forest in the Gomti River Basin

#### 4.1.8 The Disturbances Caused Due to Anthropogenic Activities

At present anthropogenic interventions in the riverine systems is resulting in the alteration of the natural riverine systems and their associated ecological services. The anthropogenic activities such as channelizing, straightening of the river channel, construction of dams, and agriculture in the riparian areas and river channel are considered to mark the anthropogenically impacted zones on the river Gomti (Table 4.8, Figure 4.10).

**Table 4.8:** List of major zones identified based on anthropogenic impacts

Zone	Extent	Latitude\Longitude	Predominant Anthropogenic Impact(s)
I	Pilibhit-Shahajahanpur	28°36'31.99" N 80°06'31.31" E- 28°08'28.55" N 80°12'07.20" E	The river channel has been encroached for agricultural practices at many places, and river channel has gone dry in this region, visible at some places in the form of small ponds, the abstraction of groundwater intensive agriculture
II	Shahajahanpur - Kuriya Ghat	28°08'28.55" N 80°12'07.20" E- 26°52'29.55" N 80°54'47.45" E	Agricultural practices in the riparian corridors, rural and urban settlements close to the river channel in patches
III	Kuriya Ghat-La Martiniere College	26°52'29.55" N 80°54'47.45" E- 80°58'3.914" E 26°50'25.047" N	Urban settlements on the bank of the river, paved banks, channelized stretch, no riparian vegetation, obstruction of longitudinal flow, abstraction and pollution, obstruction of lateral flow, disturbance to catchment
IV	La Martiniere College - Ganga River, Varanasi	80°58'3.914" E 26°50'25.047" N- 80°10'11.42" E 25°30'27.94" N	The river receives several small sewage carrying drains, rural and urban settlement in patches, agricultural practices in the riparian zones



**Figure 4.10:** Major zones of significant anthropogenic impact identified in the GRB

#### **4.1.9 Preparation of Final Zonation Map**

All the zones were overlaid, and the areas appearing in more than two layers were considered to mark the final zones on the Gomti river channel (Table 4.9, Figure 4.11).

**Table 4.9:** List of final zones prepared by overlaying the eight homogeneous zones identified on river Gomti

<b>Final zones</b>	<b>Extent</b>	<b>Distance (Km)</b>
Zone I	Pilibhit to Shahajahanpur u/s	96.40
Zone II	Shahajahanpur d/s to Dadhna-mau (Sitapur) u/s	128.55
Zone III	Dadhna-mau (Sitapur) d/s to Lucknow u/s	179.16
Zone IV	Lucknow d/s to Sultanpur u/s	238.46
Zone V	Sultanpur d/s to Jaunpur u/s	218.04
Zone VI	Jaunpur d/s to Ganga river, Varanasi	80.66

u/s-Upstream, d/s- Downstream

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**Figure 4.11:** Final zonation map for river Gomti

#### **4.2 Identification of Sites for Recommending E-Flows**

The homogenous zones prepared help to identify the sampling sites in each zone. The zonation of the river helps recommend precise flow for each selected range of the river channel (WWF, 2012). Further, the field investigation and data collections were performed in the selected zones to identify the representative sites. The lack of long term data in all the zones identified and inaccessibility and lack of time makes it tough to consider the site in all the identified zones. However, this study would be beneficial in future works to assess and recommend e-flows. A baseline condition has been generated to develop a conservation and management work on river Gomti. In six identified zones three representative sites were selected. These sites were given the preference due to the following reasons:

1. CWC monitoring sites were located in these areas
2. Diversity of the habitat is visible
3. Easy to access
4. Suitable for accurate hydrological and hydraulic analysis

Sites selected are:

- Neemasar: Located between Zone I and II
- Lucknow: Located between Zone III and IV
- Maighat: Located between Zone IV and V

*Homogeneous Zonation of the River Basin for Identification of Environmental  
Flows Sites*

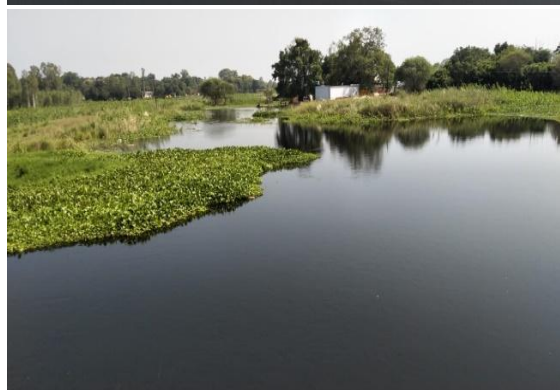
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Ravindar Nagar, Pilibhit



Ravindar Nagar, Pilibhit



Sunasir Ghat, Lakhimpurkheri



Sunasir Ghat, Lakhimpurkheri



Gutayia Bridge, Lakhimpurkheri



Gutayia Bridge, Lakhimpurkheri

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Imliya Ghat, Lakhimpurkheri



Banjarghat, Lakhimpurkheri



Upstream Amrighat, Lakhimpurkheri



Downstream Amrighat,  
Lakhimpurkheri



Gola Marg, Lakhimpurkheri



Gola Marg, Lakhimpurkheri



Uchva Ghat, Lakhimpurkheri



Uchva Ghat, Lakhimpurkheri

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Fatuabad Ghat, Lakhimpurkheri



Fatuabad Ghat, Lakhimpurkheri



Kakar Ghat, Lakhimpurkheri



Ghatiya Ghat, Lakhimpurkheri



Ghatiya ghat, Lakhimpurkheri



Ghatiya ghat, Lakhimpurkheri

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Shambhu Ghat, Sitapur



Shambhu Ghat, Sitapur



Ghaila Pul, Lucknow



Ghaila Pul, Lucknow



Gaughat, Lucknow



Gaughat, Lucknow

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Gulala Ghat, Lucknow



Pakka Pul, Lucknow



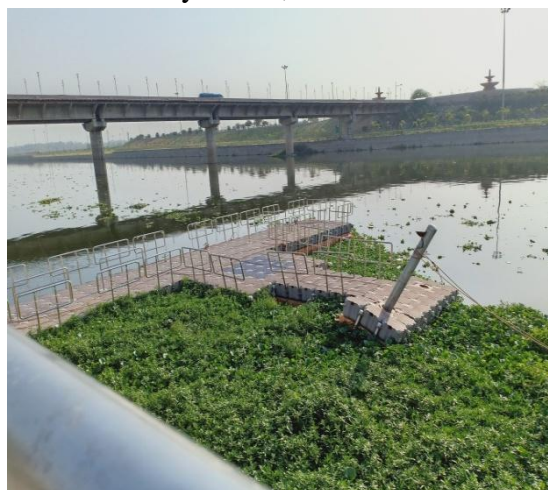
Pakka Pul, Lucknow



Kudiya Ghat, Lucknow



Kudiya Ghat, Lucknow



Riverfront, Lucknow

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Downstream to rubber dam, Lucknow



Downstream to rubber dam, Lucknow



Piperaghat, Lucknow



Piperaghat, Lucknow



Piperaghat, Lucknow



Sultanpur



Jaunpur



Gomti Sai Confluence

**Figure 4.12** : Major sites of Gomti River



*Chapter 5*  
*To Determine the*  
*Environmental flows for River*  
*Gomti*



## **5 To Determine the Environmental Flows for River Gomti**

The e-flows assessment is done for three sites on the Gomti River stream. The e-flows assessment included the hydrological and hydraulic study of the selected sites. The initial analysis included the baseflow separation, Flow Duration Curve (FDC) analysis, cross-section analysis, water quality analysis, and analysis of other hydrological indicators such as Mean Annual Flow (MAF), Baseflow Index (BFI), Hydrological Variability Index (HVI), number of high flow, low flow and intermediate flow months. To assess the e-flows requirements, the results of five hydrological methods and a desktop method were compared with the long term hydrographs. It indicates the variation in the e-flows recommended by each method.

### **5.1 Analysis of Hydrological Indices**

Hydrological indicators are essential in understanding the riverine hydrological conditions. The long term flow data were used to analyze the Base Flow Index (BFI), Mean Annual Flow (MAF), Hydrological Variability Index (HVI), the number of high flow (HF) and low flow (LF) months for each site respectively (Table 5.1). Hydrological indicators are a key indicator for the identification of the natural flow regimes. The native biodiversity and the integrity of the riverine system depend on the natural flow regimes. To understand the natural variability of flow in the stream, hydrological variability is calculated as emphasized by Richter *et al.* 1996, Gao *et al.* 2009, Pastor *et al.* 2014, Yu *et al.* 2017. Higher the variability index more variable, the flow in the stream will be, as in this case, HVI is 0.89, 1.20, and 1.46 for Neemsar, Lucknow and Maighat, respectively.

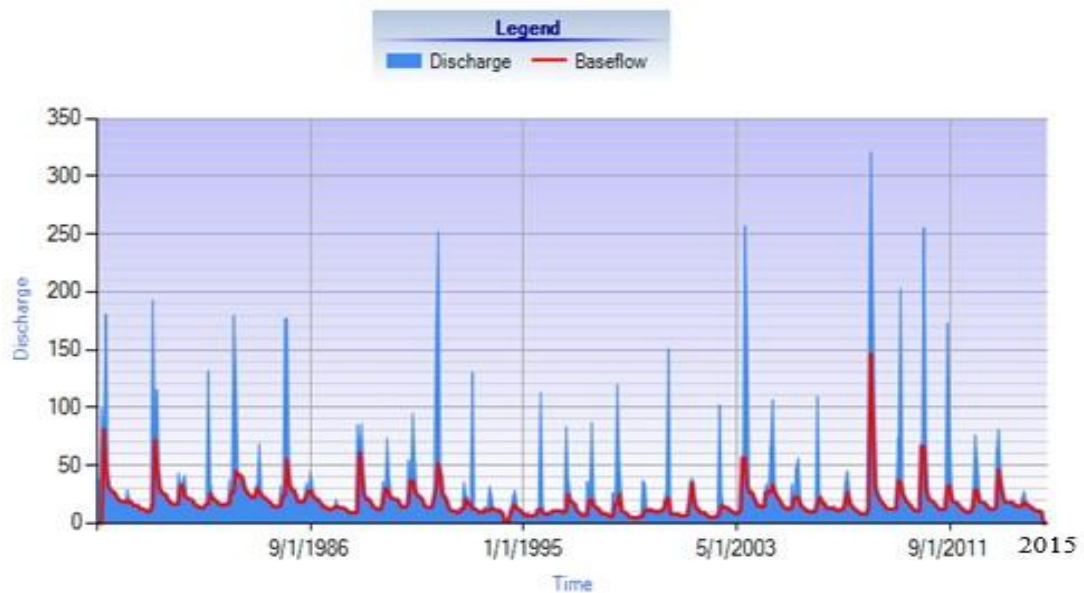
**Table 5.1:** Hydrological indicators of selected study sites in Gomti River Basin

Study Sites	Geographical Location (CWC gauge station)	MAF (m <sup>3</sup> /sec)	Low Flow-High Flow Range (m <sup>3</sup> /sec)	BFI (Hydro-office Computed) Sliding interval method	HVI [(Q25-Q75)/Q50]	No. of LF Months i.e. MMF<0.4 MAF	No. of HF Months i.e. MMF>0.8 MAF	Number of Intermediate Flow Months
Neemsar	27°20'46"/ 80°28'40"	30.787	1.73-320.57	0.78	0.89	1(May)	4 (July, Aug, Sep, Oct)	6 (Nov, Dec, Jan, Feb, Mar, Apr, Jun)
Lucknow	26°50'00"/ 80°57'00"	67.46	3.85-916.96	0.76	1.20	2 (Apr, May)	4 (July, Aug, Sep, Oct)	6 (Nov, Dec, Jan, Feb, Mar, Jun)
Maighat	25°38'17"/ 82°51'47"	234.71	20.83-3545.73	0.69	1.46	4 (Mar, Apr, May, Jun)	5 (July, Aug, Sep, Oct, Nov)	3 (Dec, Jan, Feb)

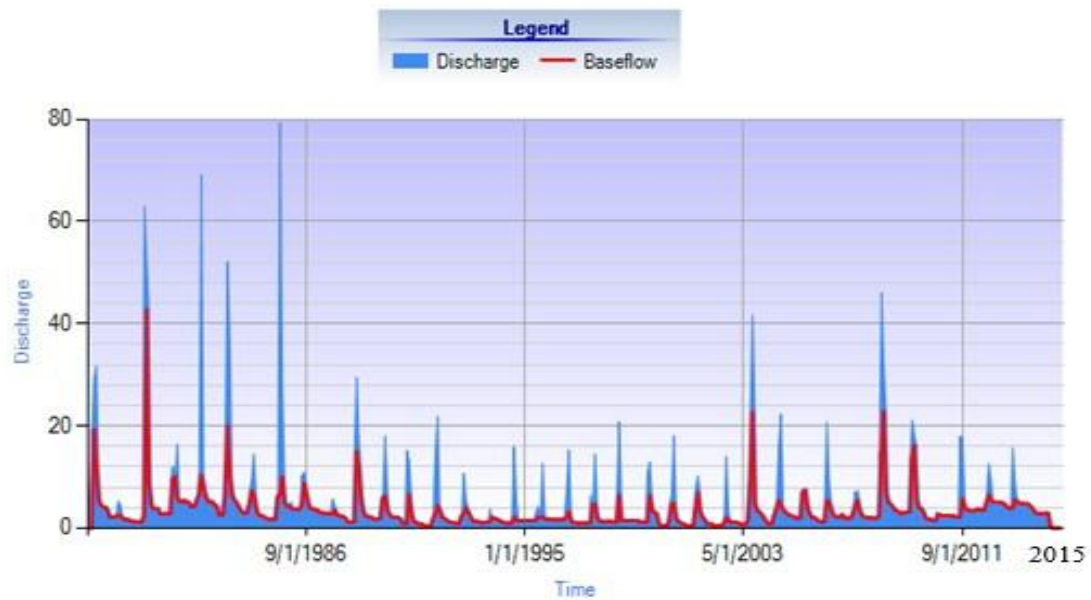
**Source:** Based on long term flow data (1978-2015) obtained from CWC

## 5.2 Baseflow Separation and Groundwater Trends in Gomti River Basin

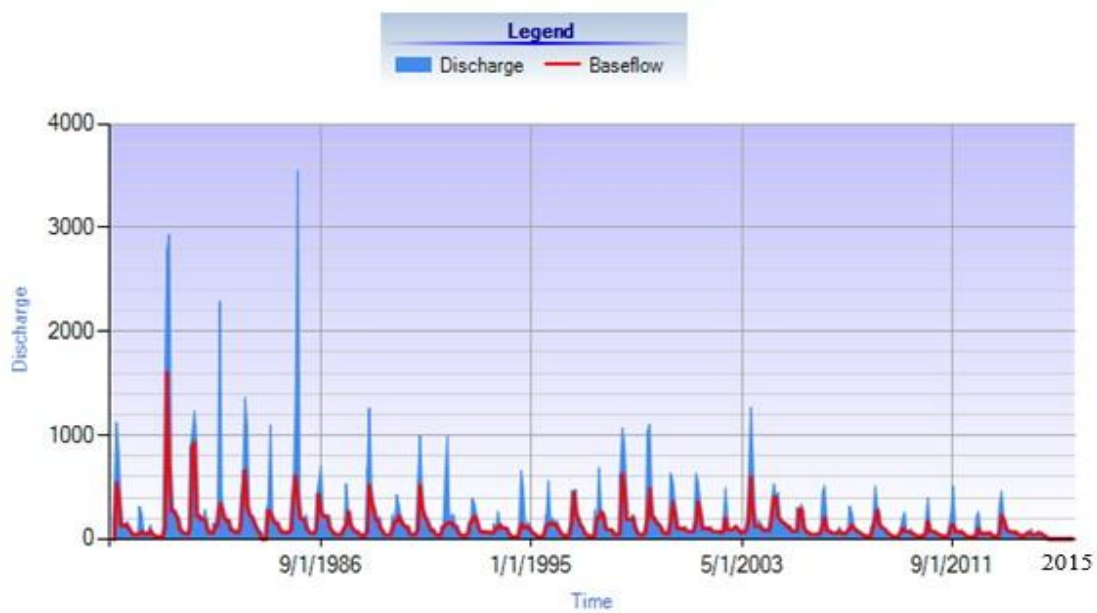
Gomti, being a groundwater-fed river, has a large proportion of groundwater component in its overall flow and baseflow or the groundwater discharged to the stream constitutes a major source of streamflow during the dry periods. The contribution from groundwater was evaluated by separating the baseflow from the river's total discharge. During the lean flow periods, the groundwater usage is highest, and baseflow reduces due to which river is not able to meet the minimum flows requirements. Baseflow separation graphs are shown in Figure 5.1 (a, b, c) for three different sites from upstream to downstream. The analysis showed that the river has a baseflow index at each site, i.e. Neemsar, Lucknow, and Maighat of 0.78, 0.76, and 0.69, respectively. The baseflow contribution evaluated is highest for the upstream stretch as compared to the midstream and downstream stretch of the river.



(a) Neemsar



(b) Lucknow



(c) Maighat

**Figure 5.1:** Graphs showing the baseflow contribution at (a) Neemsar, (b) Lucknow and (c) Maighat, respectively

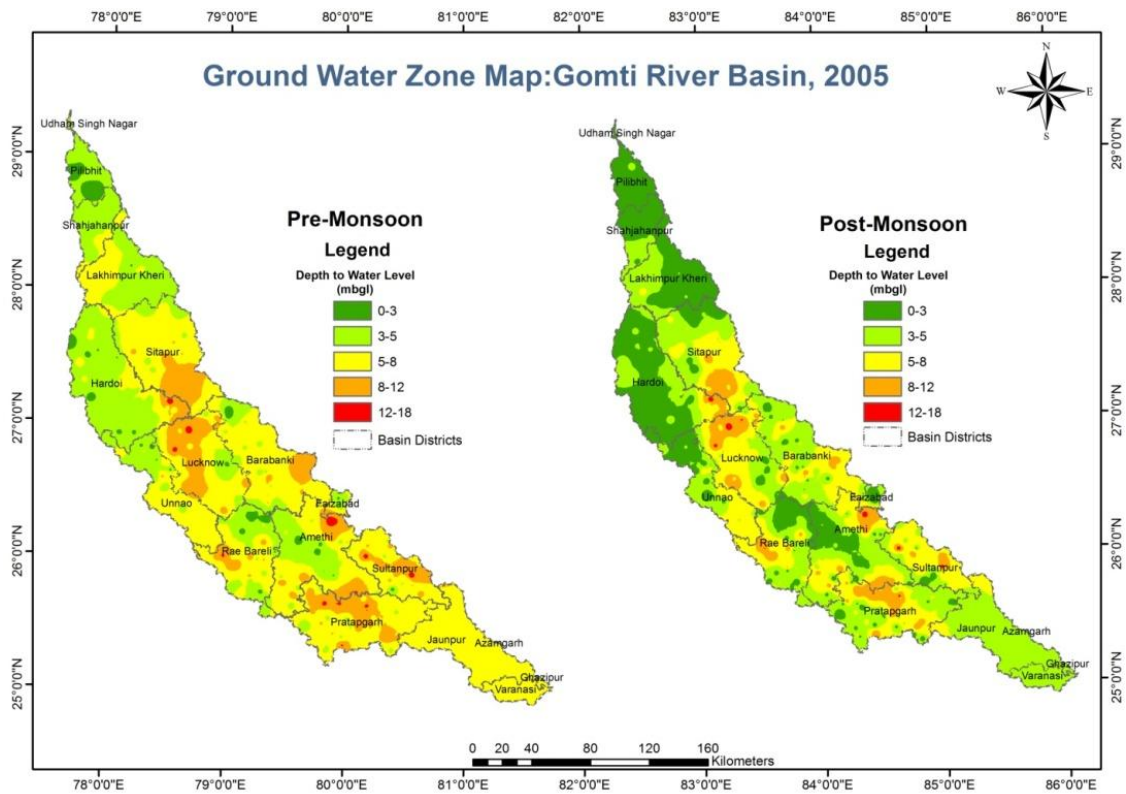


Figure 5.2: Groundwater Zone map of GRB in pre- and post-monsoon, 2005

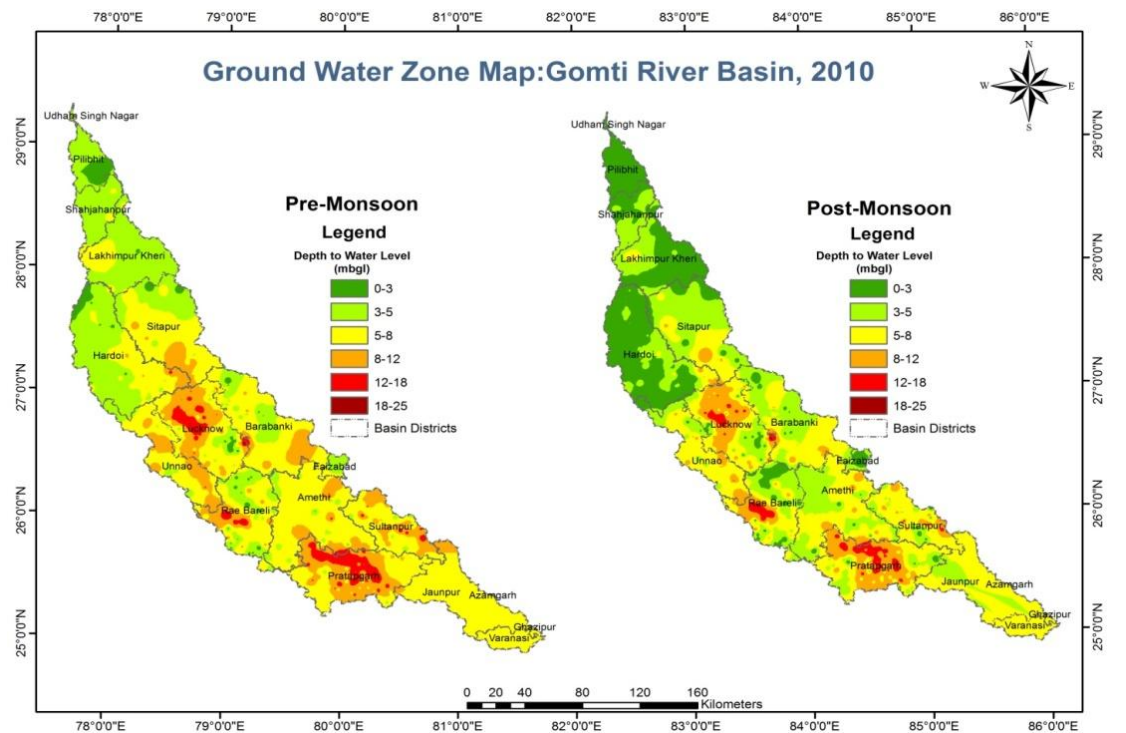


Figure 5.3: Groundwater Zone map of GRB in pre- and post-monsoon, 2010

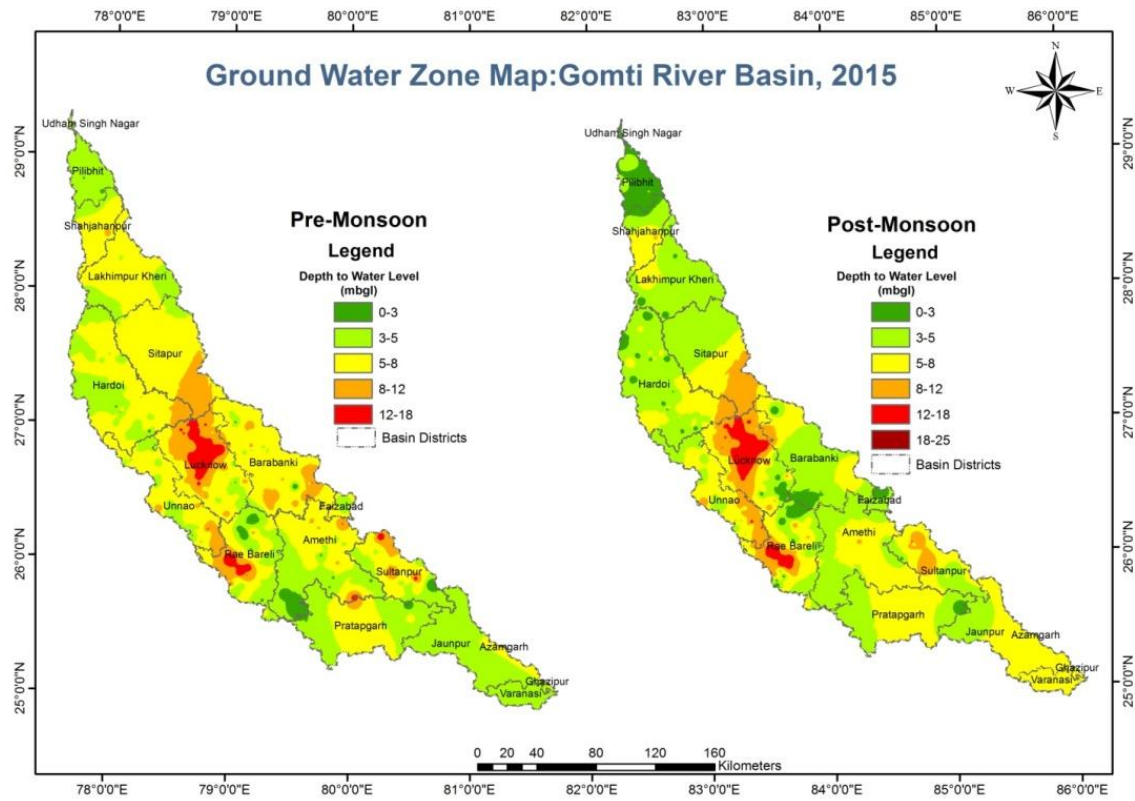








Figure 5.4: Groundwater Zone map of GRB in pre- and post-monsoon, 2015

**Table 5.2:** Trend of groundwater depths in the Gomti River Basin and its coverage in the pre- and post-monsoon of the year 2005, 2010 and 2015

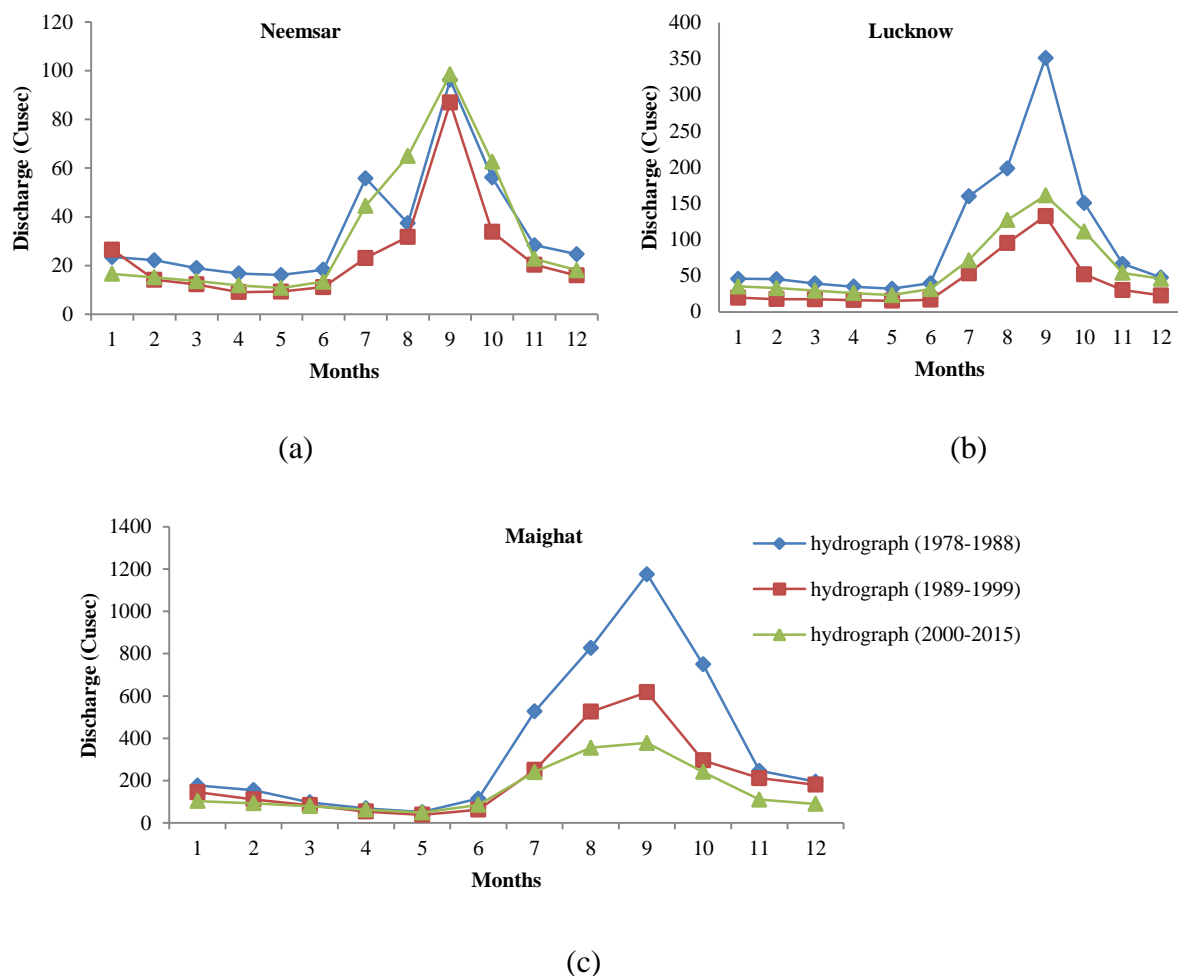
Colour code	Mbgl	Pre-Monsoon 2005		Post-Monsoon 2005		Pre-Monsoon 2010		Post-Monsoon 2010		Pre-Monsoon 2015		Post-Monsoon 2015	
		Area (km <sup>2</sup> )	%	Area (km <sup>2</sup> )	%	Area (km <sup>2</sup> )	%	Area (km <sup>2</sup> )	%	Area (km <sup>2</sup> )	%	Area (km <sup>2</sup> )	%
	< 3	605.78	1.96	8017.12	26.05	627.46	2.03	6330.807	20.57	475.26	1.54	1690.01	5.49
	3-5	9407.39	30.57	12515.55	40.67	8445.29	27.44	9361.741	30.42	10695.88	34.76	13900.15	45.17
	5-8	16528.15	53.72	8040.31	26.13	15559.51	50.57	11303.24	36.73	16005.67	52.02	11663.98	37.91
	8-12	4107.41	13.35	2137.243	6.94	5180.92	16.83	3195.65	10.38	2962.27	9.62	2765.53	8.98
	12-18	118.00	0.38	56.52	0.18	946.67	3.07	571.42	1.85	627.65	2.04	742.90	2.41
	18-25	-	-	-	-	6.87	0.02	3.87	0.01	-	-	4.15	0.01
	Total	30766.74		30766.74		30766.74		30766.74		30766.74		30766.74	

\*mbgl (Meter Below Ground Level)

The seasonal variations were visible in the groundwater zone maps prepared (Figure 5.2, 5.3, 5.4 and Table 5.2). The pre-monsoon data of the year 2010 showed an increase in the basin is having groundwater depth between 0-3mbgl to 2.03% from 1.96% as observed in 2005, whereas in 2015, the area cover declines to 1.54%. In post-monsoon season, a constant decline is observed from 2005 to 2015, i.e., from 26.05% in 2005 to 20.57% in 2010 and finally to 5.49% in 2015. It indicates the loss of shallow groundwater during this period from 2005 to 2015. In 2005 pre-monsoon, 30.57% of the basin area was recorded with groundwater between 3-5mbgl, which declined to 27.44% in 2010, and further, it increased to 34.76% in 2015. Comparable trends were observed in post-monsoon of 2010. A decrease was observed from 2005 groundwater levels, and an increase in 2015 was observed from 40.67% to 30.42%, in 2010 and further to 45.17% in 2015 of the basin area, respectively. In the basin area with groundwater depth, up to 5mbgl has declined by 16% between the post-monsoon of 2005 and 2015. Further, moving towards deeper aquifers, a marginal decrease of 1.70% coverage area is observed in 5-8mbgl category between pre-monsoon of 2005 and 2015, and an increase in area by 11.78% is observed during the post-monsoon season between 2005 and 2015. A declining tendency in the basin area having groundwater depth of 8-12mbgl is observed in pre-monsoon, from 13.35% in 2005 to 8.98% in 2015. The post-monsoon trend in this period shows a marginal gain in the coverage area by 2.04%. Further, 0.38% of the area had groundwater depth in the range of 12-18mbgl in pre-monsoon of 2005, which increased to 2.04% in 2015 indicated a declining tendency. The post-monsoon trend also exhibits a declining tendency in this range between 2005 and 2015. In 2005, no area was found to have groundwater table more than 18mbgl both in pre-and post-monsoon seasons;

however, in post-monsoon of 2015, around 4.15 km<sup>2</sup> of the area came under this category, indicating lowering of the groundwater table.

River Gomti with a higher component of groundwater in its discharge is vulnerable to effects due to a decrease in the groundwater levels. The over-abstraction of groundwater in the basin is resulting in the decrease of the flow in the stream in the past 15 years (Figure 5.5), similar trends were observed by Owen *et al.* (1991) in the River Colne, Chilterns (UK). In 2018, out of 26 tributaries, around 23 tributaries had gone dry in the lean flow season, as the river is flowing in the discontinuous losing phase. Similar effects of over-abstraction and decrease in the groundwater on the surface flow are presented by Acreman *et al.* (2000) in a study done on rivers and wetlands of the UK and by Hunt (1999) and Kirk and Herbert (2002). A continuous decrease in the groundwater table is a result of higher rates of evapotranspiration and more dependency on groundwater storage for fulfilling the agriculture water demands. In the downstream regions, the Gomti River is facing droughts like conditions (Abeysingha *et al.*, 2016). Gomti River has a baseflow component of 78%, 76%, and 69% in river discharge at Neemsar, Lucknow, and Maighat, respectively. The high baseflow component is an indicator of the porous and permeable geological structure of the basin (Mohammadlou and Zeinivand, 2018). Many aquatic species have a low tolerance to drying habitats, not well-adapted to dry conditions. If the drying of the channel becomes regular and the frequency of intermittency increases, many species may be eliminated from newly intermittent rivers. The habitat fragmentation due to the drying channel may limit the recolonization possibilities within the fluvial systems.



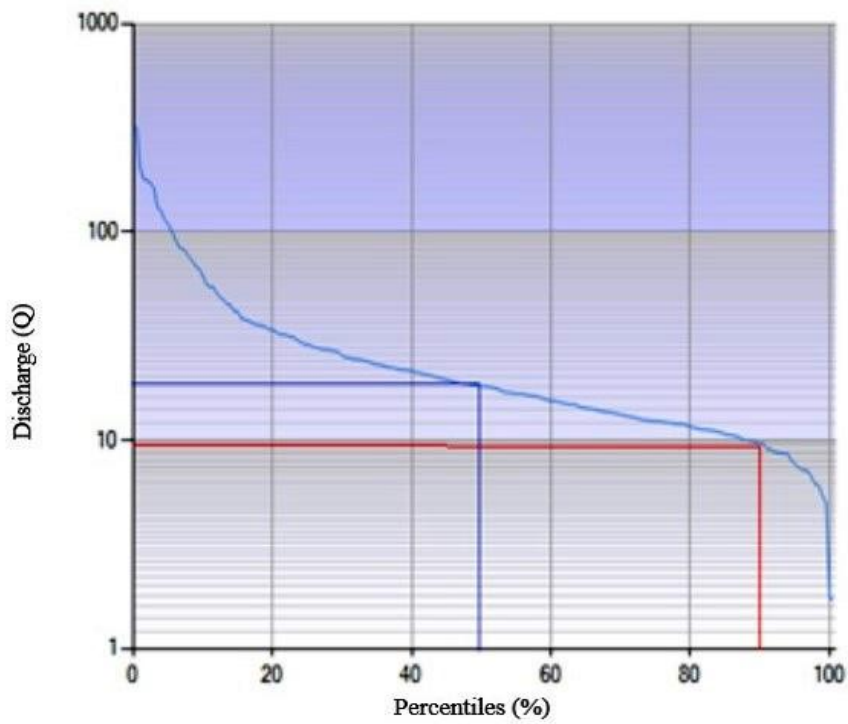
**Figure 5.5:** Hydrograph showing flow trend at the gauged sites, (a) Neemsar, (b) Lucknow and (c) Maighat

### 5.3 Preparation of Flow Duration Curve (FDC) for Three Sites

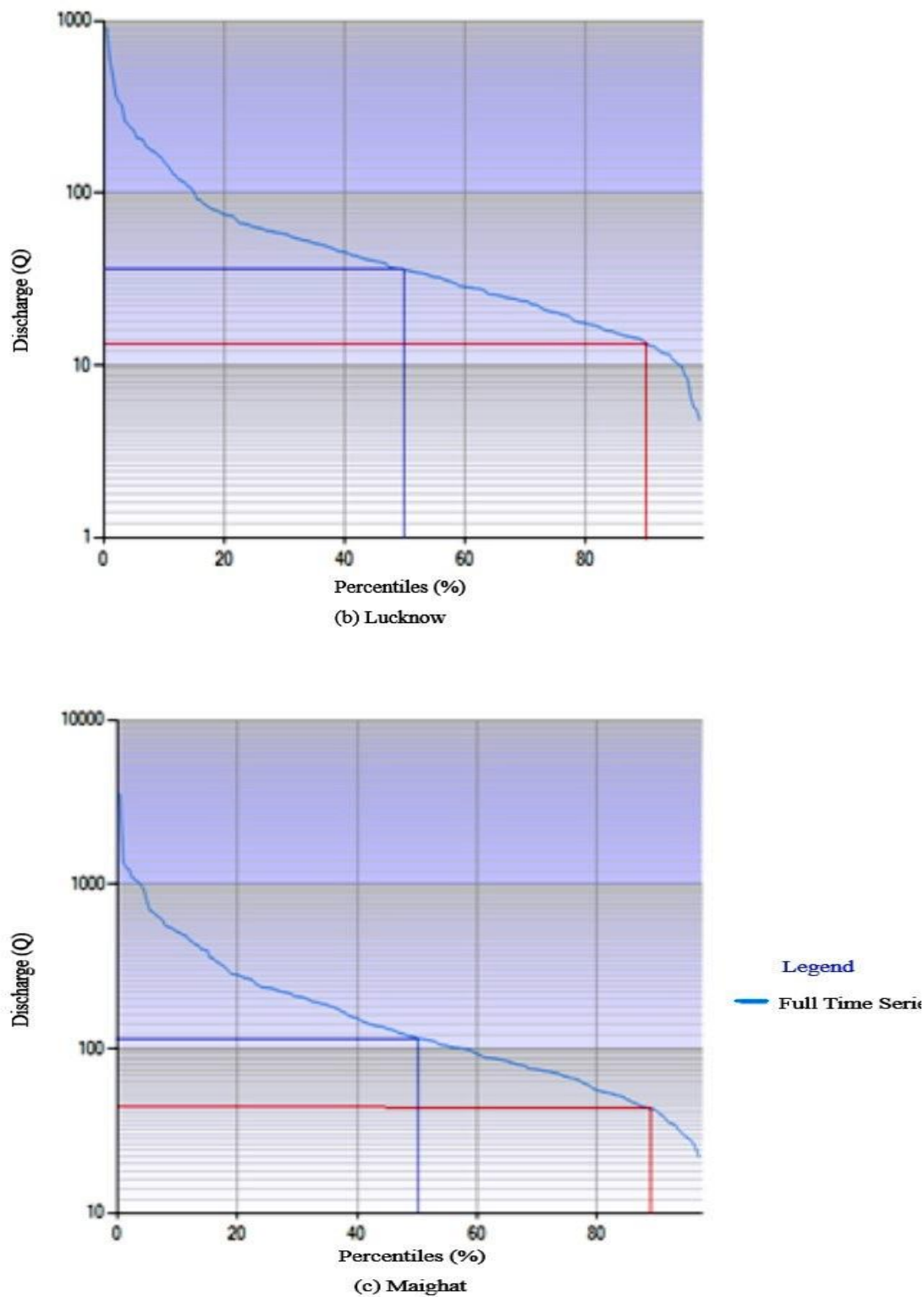
Flow duration curves are semi-logarithmic plots. The shape of the plot is an indicator of the type of flow in the river channel. If the curve has a steep slope, it indicates the catchment has a critically large amount of direct runoff whereas, if the slope is relatively flat, it indicates substantial storage of water within the catchment either in the form of surface or groundwater (Gore *et al.*, 1996). The FDC prepared for three study sites are presented in Figure 5.6. The value for Q50, Q75, and Q90 calculated for the study sites are as follows (Table 5.3):

**Table 5.3:** The results of discharge present at Q50, Q75 and Q90 percentage of exceedance

Sites	Q50	Q75	Q90
Neemsar	18.13	12.33	9.61
Lucknow	35.67	20.19	13.08
Maighat	115.115	66.146	39.89



(a) Neemsar



**Figure 5.6:** Flow Duration Curves (FDC) for three sites (a) Neemsar (b) Lucknow and (c) Maighat where red and blue line indicates Q90 and Q50 (Q90 and Q50 are the flow exceeding 90% and 50% respectively during the period of record 1978 – 2015)

### 5.4 Analysis of Cross-Sections

The analysis of cross-sections is an important part of the overall hydraulic analysis. Cross-section analysis is the initial step in analyzing the wetted perimeter-discharge and stage-discharge relationships. The cross-section analysis data for the selected sites for pre- and post-monsoon season of year 2015 is presented in Figure 5.7 (a1, a2); 5.8 (b1, b2); 5.9 (c1, c2). The cross-section analysis of Neemsar shows a comparatively shallow and narrow channel with distinct right and left banks.

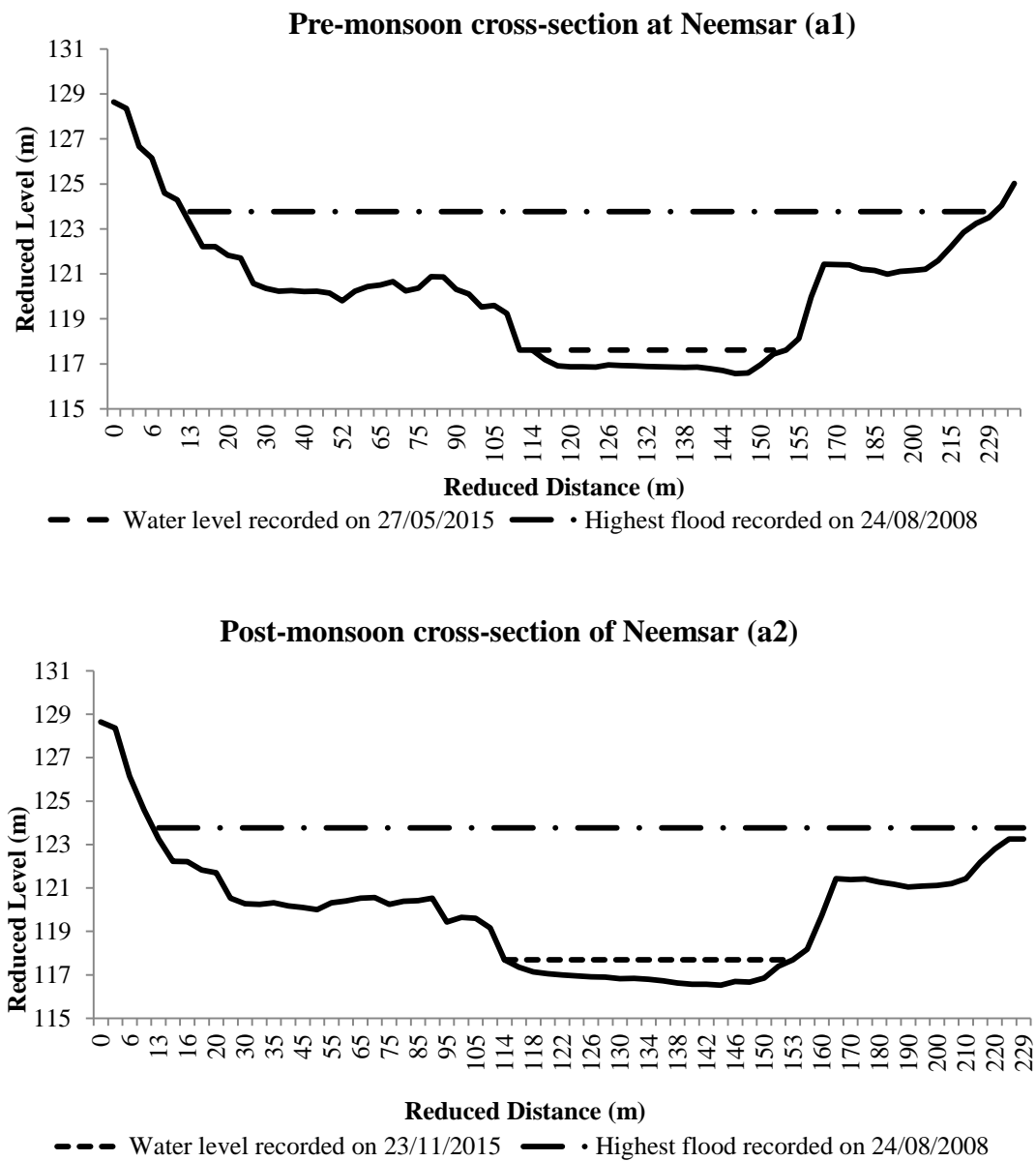
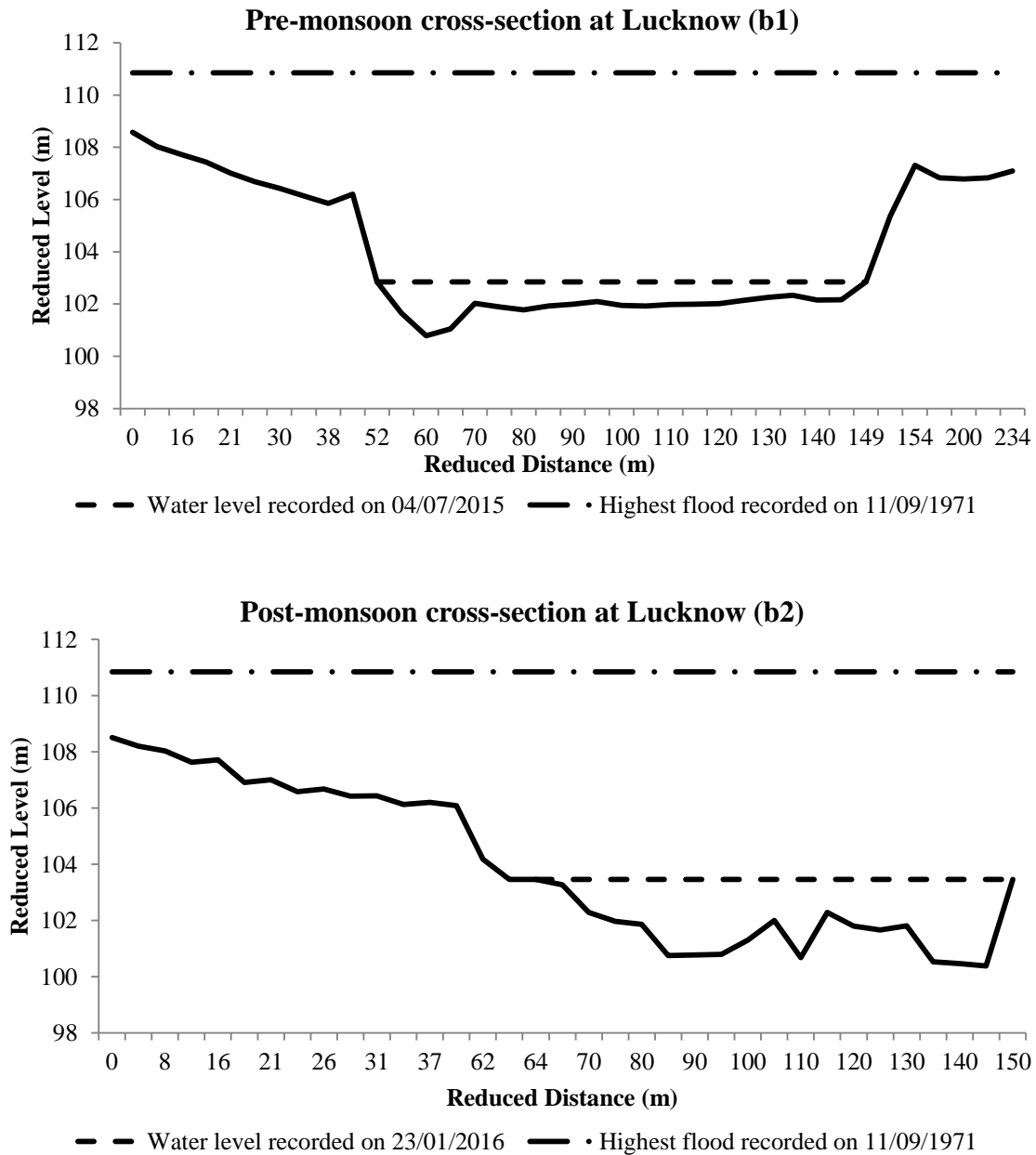
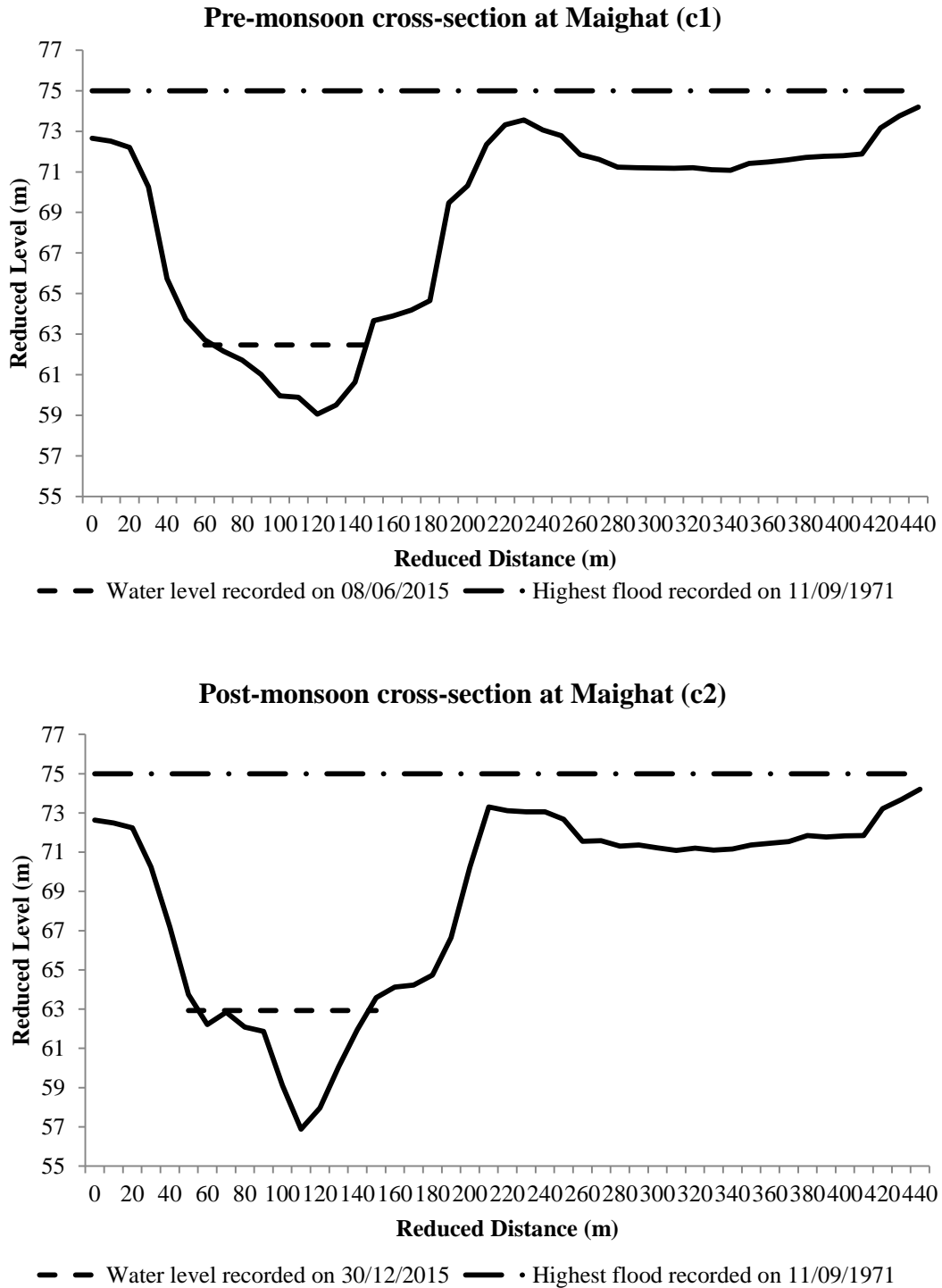


Figure 5.7: Pre-monsoon (a1) and post-monsoon (a2) cross-section of Neemsar



**Figure 5.8:** Pre-monsoon (b1) and post-monsoon (b2) cross-section of Lucknow

The cross-section analysis of Lucknow indicates the channel has increased in depth and width in comparison to the Neemsar site. However, the impact of the channelization work undertaken in this stretch is visible on the right bank of the river. In the pre-monsoon sampling, distinguishable left and right banks were visible. In the post-monsoon sampling conducted in Jan 2016, the right bank was paved for developmental works. As a result, the channel width at this site got confined.



**Figure 5.9:** Pre-monsoon (c1) and post-monsoon (c2) cross-section of Maighat

In the lower stretch, the river channel deepens in general, a similar pattern is observed in the case of Maighat. In the post-monsoon season, a visible change in the channel cross-sections was observed. The depth of the river channel has increased, but the width remains approximately the same as it was in pre-monsoon season.

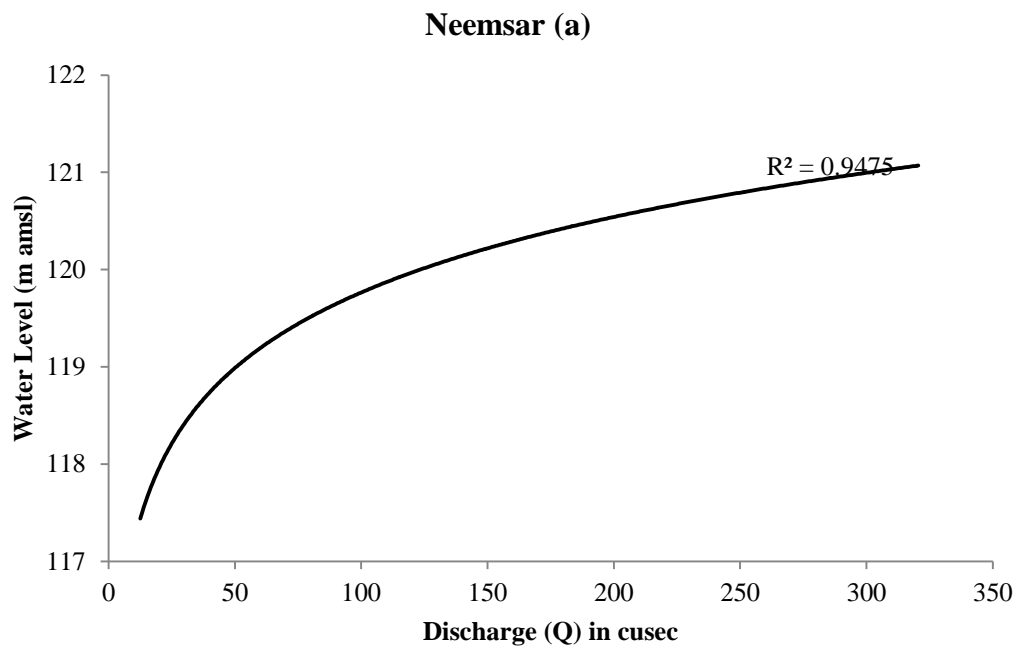
The stream channel analysis is done to understand the stream channel and the water discharge that shapes the channel. The analysis of the size or cross-section of the channel is indicative of how much water the channel contains (WRC, 2000). The channel slope is measured to determine how fast the water will flow in the channel. The slope of the stream bed is primarily affected by the form of the river channel as it turns and twists and its shallow and deep pools (WRC, 2000). The river was divided into three regions, from its origin to its confluence with the river Ganges. In the first 314km of the river stream length slope calculated based upon the DEM data is 0.22m/km, in the next segment from 314 km to 626 km the calculated slope is 0.09m/km, the final segment from 626 to the confluence point the slope of the river channel is 0.06m/km. The cross-section profile and slope are used to predict the flow velocity, discharge, and stream power with a level of flow. The information gathered in the stream channel analysis found useful in conducting the channel restorations works.

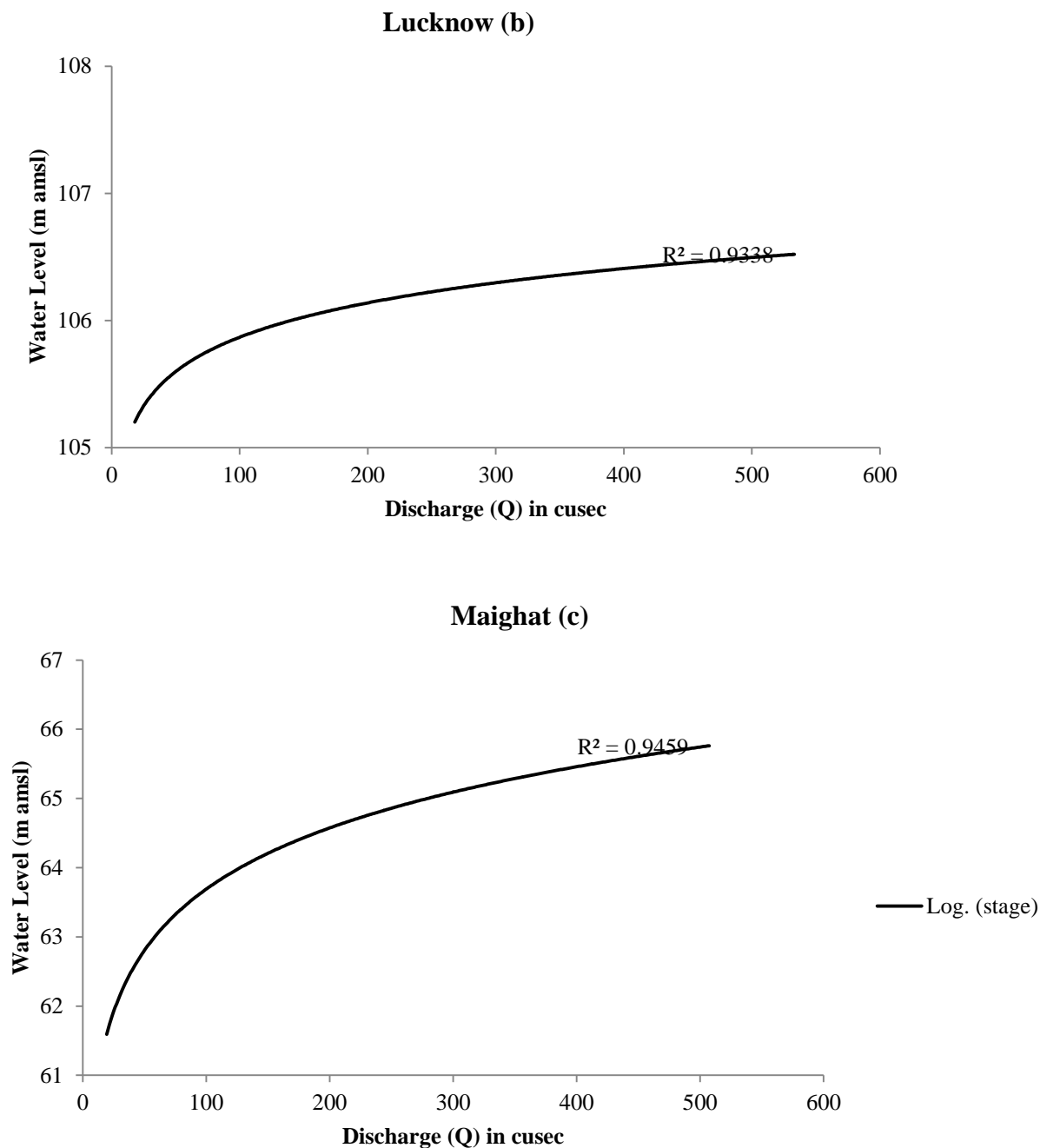
The water depth in the upper river section is usually the lowest and highest in the downstream region (Niazkar and Afzali, 2015). The upstream region of river Gomti at Neemsar is comparatively shallow in comparison to the downstream regions at Maighat. The flow recommended at the Neemsar was to sustain healthy spawning grounds, and in the midstream and downstream regions, flow is recommended to sustain the healthy fish population.

### **5.5 Stage-Discharge Relationship**

Stage and discharge relationship is important in transforming continuous stage data to a continuous record of stream discharge. This relationship is useful in transforming the forecasted flow hydrographs into stage hydrographs. The stage hydrographs are then useful in estimating the inundated area during floods and lean

flow seasons. The satisfactory stage-discharge curves at gauging stations are essential in deriving reliable discharge data values. The stage-discharge curves for the three gauging sites were prepared in Microsoft Excel worksheet against the corresponding estimated flow discharge in an arithmetic plot with the stage as ordinate and discharge as abscissa. A linear trend line equation between ‘log Q’ (on Y-axis) and ‘log (h – ho)’ (on X-axis) was plotted to get a smooth stage-discharge curve plot (Braca, 2008). The coefficient of determination ( $R^2$ ) for the logarithmic plot was observed to be 0.95, 0.93 and 0.95 for Neemsar, Lucknow, and Maighat respectively (Figure 5.10).





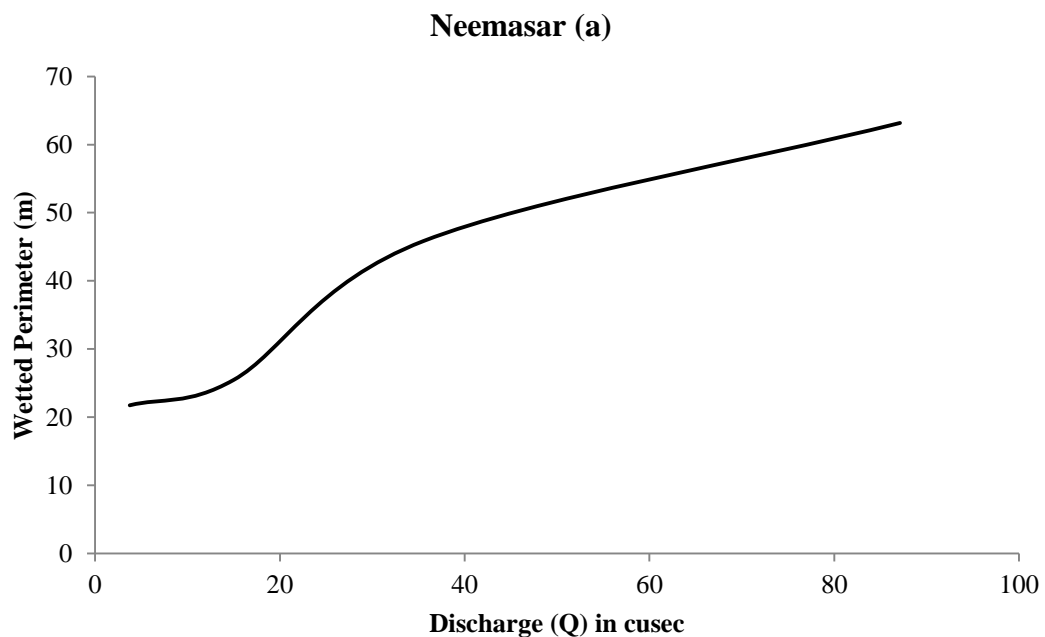
**Figure 5.10:** Stage-discharge relationship graphs for the three gauging sites Neemsar (a), Lucknow (b) and Maighat (c)

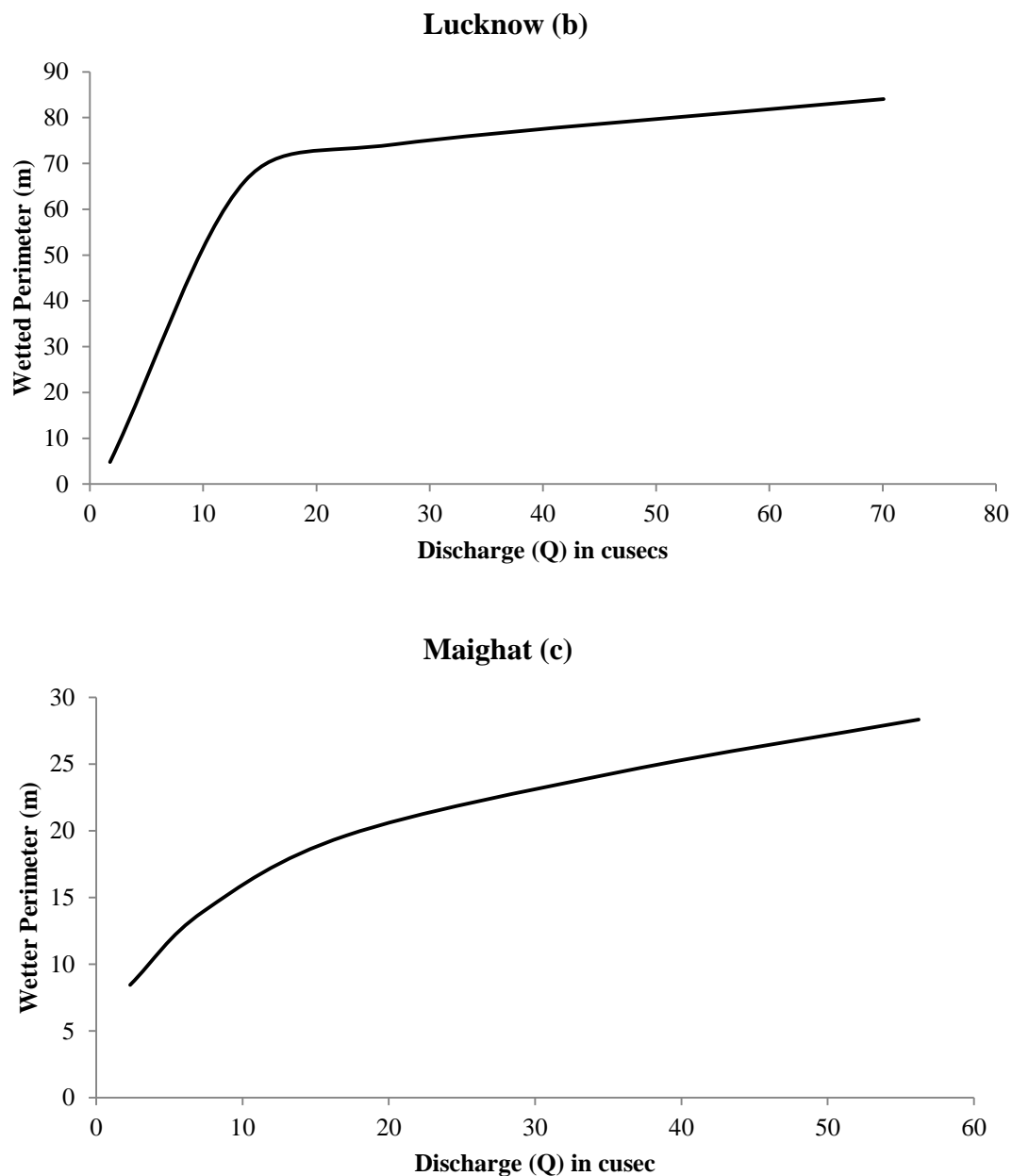
The relation between stage-discharge is dependent on multiple factors that would result in a change in the change of stage-discharge curve shape, position or in its loops. The critical factor that can modify the rating curve is change in the channel cross-section (Herschy, 2009). The use of logarithmic scale to plot the rating curves

has an advantage over arithmetic scales, therefore mostly stage-discharge relations are usually analyzed graphically using logarithmic plotting (Braca, 2008).

### **5.6 Wetted Perimeter-Discharge Relationship**

In several studies, the estimation of the wetted perimeter–discharge relationships are used to define the minimum flow requirements for fish rearing (Efstratiadis, 2014). In the absence of hydrometric data, the stage-discharge relationship is derived from the manning equation. In recommending the flow using the wetted-discharge relations, it is assumed that if the critical hydraulic areas were protected and maintained well, then the whole aquatic ecosystem will be in a satisfactory state. The shape of the stage-discharge relation graph is highly dependent on the stream bed profile. The graphical representation of the Neemasar and Maighat site indicates an approximately parabolic to trapezoidal shape of the stream cross-sections as shown in Figure 5.11(a), 5.11(c). However, the graphical representation of the wetted perimeter and discharge relation for Lucknow indicates a nearly rectangular cross-section profile as shown in Figure 5.11(b).





**Figure 5.11:** Wetted perimeter-discharge relationship graphs for the three gauging sites Neemsar (a), Lucknow (b) and Maighat (c)

### 5.7 Hydraulic Analysis

This River has undergone a sudden change in the mid-stream region due to anthropogenic activities, which have resulted in the severe degradation of hydraulic as well as ecological conditions of the river. Changes in the hydraulic parameters pre and post channelization are visible in Table 5.4 and 5.5. Sites denoted as S1, S2 and S3 are Neemsar, Lucknow and Maighat sites, respectively.

**Table 5.4:** Hydraulic analysis of river for Pre-Channelization conditions (2008)

Hydraulic parameters	Formula used	Pre-monsoon			Post-monsoon		
		S1	S2	S3	S1	S2	S3
Wetted perimeter (P) (m)	(Average depth x 2) + wetted width	35.85	134.86	91.52	38.95	124.41	134.26
Cross-section area (A) (m <sup>2</sup> )	Average depth x wetted width	31.62	379.20	68.31	53.1	378.19	276.9
Hydraulic radius (R) (m)	Cross-section area/ Wetted perimeter	0.88	2.81	0.75	1.36	3.04	2.06
Width/depth ratio	Wetted width/average depth	78.13	43.87	118.58	24.41	52.23	61.03

**Table 5.5:** Hydraulic analysis of river for Post-Channelization conditions (2016)

Hydraulic parameters	Formula used	Pre-monsoon			Post-monsoon		
		S1	S2	S3	S1	S2	S3
Wetted perimeter (P) (m)	(Average depth x 2) + wetted width	42.44	108.17	74.04	45.06	110.18	84.56
Cross-section area (A) (m <sup>2</sup> )	Average depth x wetted width	39.29	208.08	141.4	44.20	195.96	182.4
Hydraulic radius (R) (m)	Cross-section area/ Wetted perimeter	0.92	1.92	1.91	0.98	1.78	2.157
Width/depth ratio	Wetted width/average depth	41.75	36.82	34.65	41.83	57.88	35.09

The hydraulic analysis of the Gomti River done for the pre- and post-channelization scenarios indicated a change in the channel characteristics. It is clear that in Lucknow, wetted perimeter, cross-section area, and hydraulic radius have

reduced in 2016 after the channelization project. There is marginal decrease in width/depth ratio. The higher the hydraulic radius, the lower the amount of water in contact with the bed and banks, which means that the river bed is comparatively smooth with less friction, and water can move at a higher velocity. With this analysis, it is clear that the hydraulic radius of the river has got hampered. The channelization of the Gomti River at Lucknow has changed the hydraulics of the river throughout the channel beyond this point.

### **5.8 Physico-Chemical Analysis of Gomti River Water**

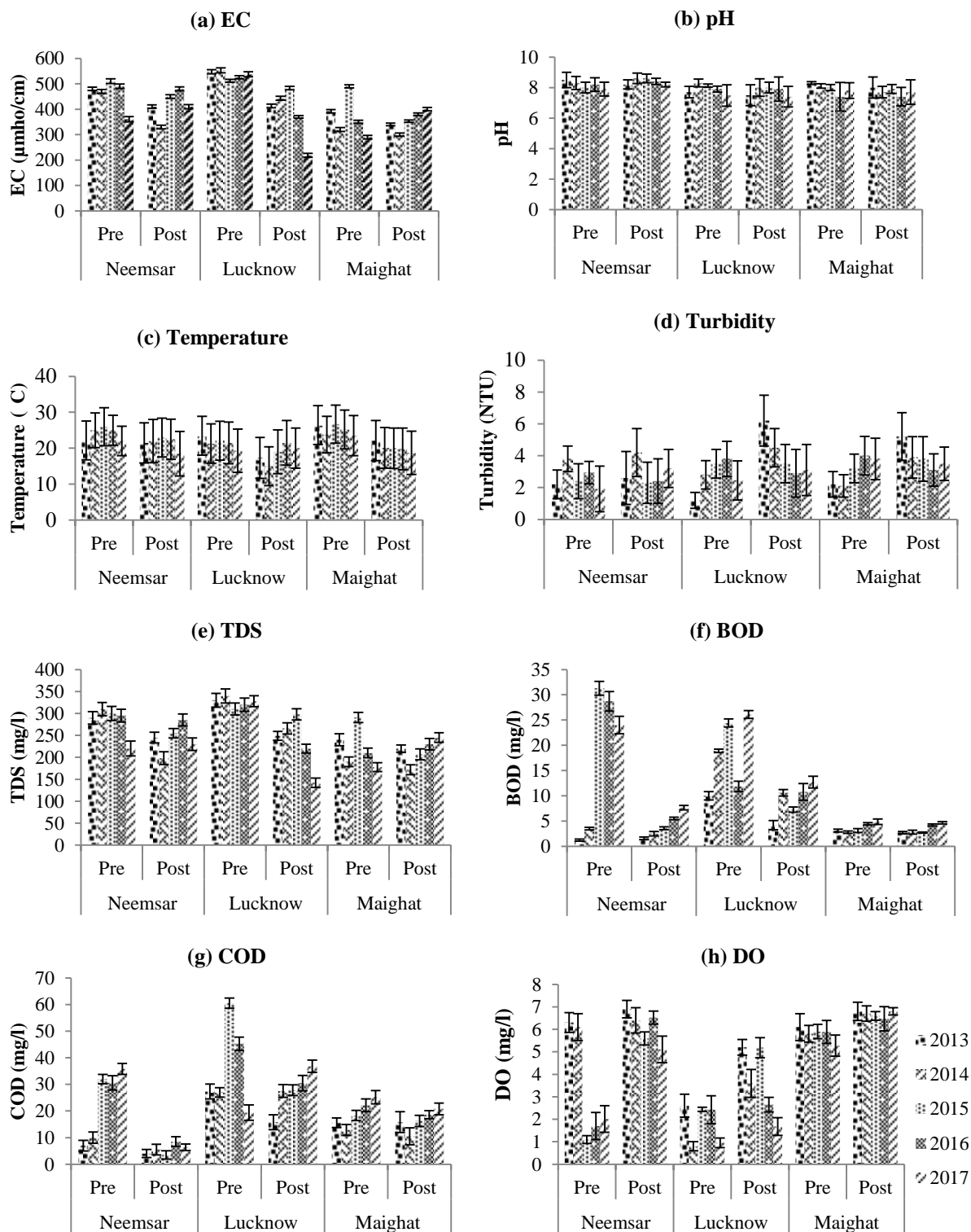
The water quality is an essential component in maintaining the healthy ecological conditions in any lotic aquatic system. The analysis of the river's water quality indicates that the river is falling in class 'D or below at all the monitored sites. In the pre-monsoon season (May- June) at Neemsar (upstream), water quality is found to be falling between 'D' and 'E' class. DO is recorded in the range of 'A' and 'B' class, but BOD demand is recorded high for this region. The total coliform count was recorded between 1100 to 2084 MPN, and the pH is in the range of 7.9 to 8.5. The river water was found unfit for direct drinking and outdoor bathing but could be used for public supply after proper treatment. Moving downwards to the Lucknow (midstream) region, water quality has further deteriorated to the 'E' class as per the recorded concentrations of both DO and BOD. The pH was recorded between 7.48-8.30, and the total coliform count was in range of 113500 to 159966.67 MPN in past five years. It can be concluded that the water in the middle stretch is highly polluted and is not fit for any purpose. In Maighat (lower) stretch, the water quality improves as DO improves to class 'A', but BOD is still higher falling between classes 'D' and 'E'. The total coliform count was in the range of 12626 to 44500 MPN, and the river water can be used for the propagation of wildlife and fisheries, irrigation, and industrial cooling purposes. In the post-monsoon season (Sep-Oct) in the Neemsar

region, water quality has improved with pH recorded between 8.2 to 8.6, DO between 5.1 to 6.9 mg/l, and BOD between 1.6 to 7.65 mg/l and total coliform count in the range of 850-1400 MPN. The river water quality approximately lies between ‘C’ and ‘D’ class. Whereas in midstream region pH was 7.4 to 8.0, DO was 1.68 to 5.20 mg/l, BOD was 4.2 to 12.70, and total coliform count was 83250 to 130000 MPN. The water quality in the middle stretch is between ‘D’ and ‘E’ class. In the downstream region, The pH was recorded between 7.7 to 8.0, DO was between 6.5 to 6.8 mg/l, BOD was 2.7 to 4.65, and total coliform count was between 6476.67 to 34000 MPN. The river water quality is approximately in between ‘D’ or ‘E’ class. The water quality parameters checked for the suitability of water for ecological needs in pre- and post-monsoon season as integration of water quality its e-flows been shown in Figure 5.12 (a, b, c, d, e, f, g, h), 5.13.

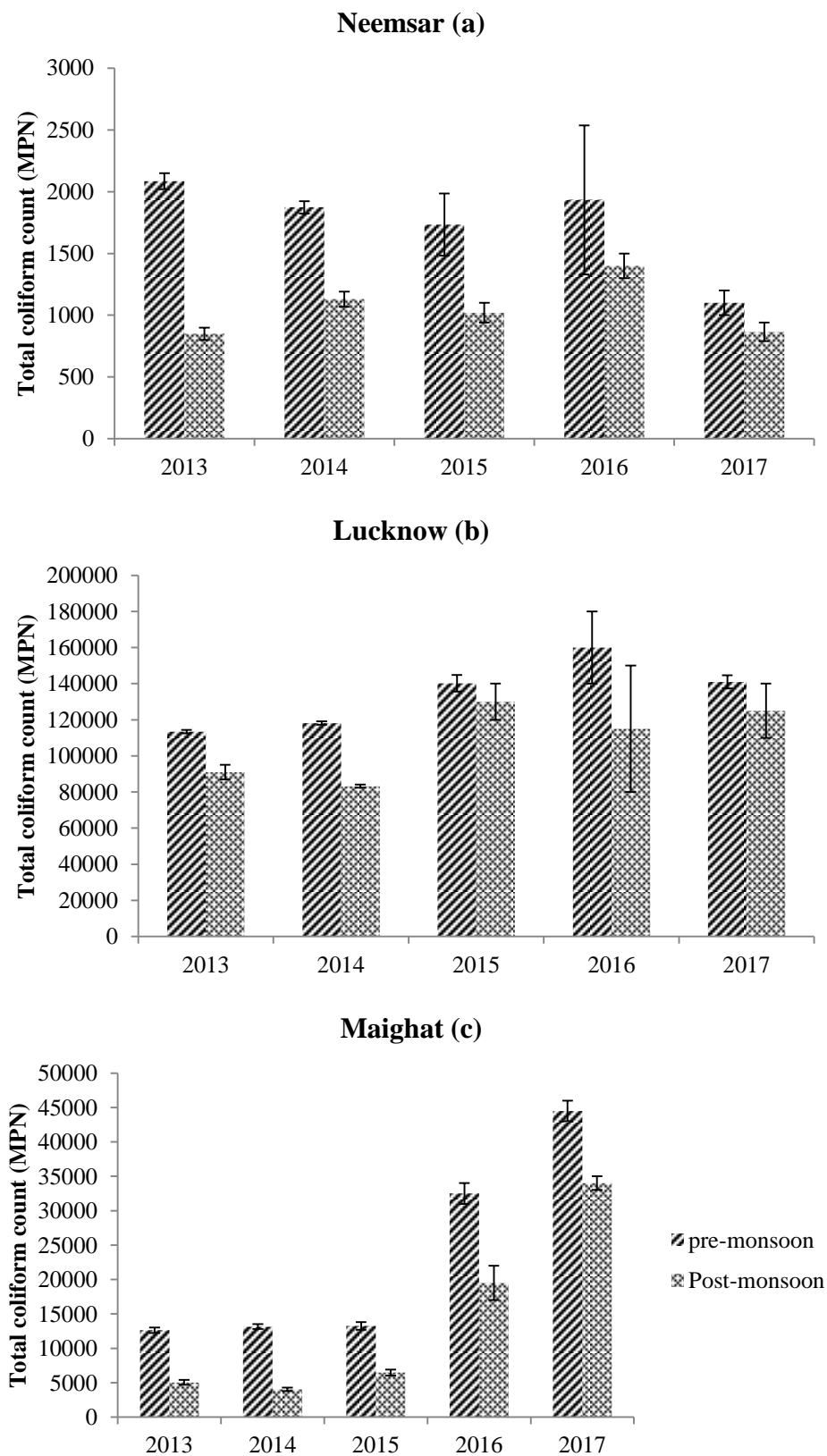
**Table 5.6:** Status of water quality in GRB at three studied sites in pre- and post-monsoon season and e-flows requirements

Zones	Classes		E-Flows Requirements
	Pre- monsoon	Post- monsoon	
Neemsar (Pilibhit to Dadhna-mau, Sitapur u/s)	Between ‘D’ and ‘E’	Between ‘C’ and ‘D’	The river water quality is in the hapless state, mainly falling below ‘D’ class throughout the year. The flow allocation to dilute the pollution load in the river will be
Lucknow (Dadhna-mau, Sitapur u/s to Sultanpur u/s)	‘E’ or below	Between ‘D’ and ‘E’	unfeasible option. As the allocated flow might surpass the total available natural flow in the river. Rather the dumping of the untreated drains directly into the river
Maighat (Sultanpur u/s to Ganga river, Varanasi)	Between ‘D’ and ‘E’	Between ‘D’ and ‘E’	should be prevented. This will resolve half of the problem related to poor water quality of the river water.

Water quality is included as an essential component of environmental flows in all the definitions given so far. However, environmental flows assessment methods mainly focus on the quantity of water required to maintain ecosystem integrity, whereas very few studies have focused on considering the water quality assessment as a part of e-flows assessment procedure (Scherman *et al.*, 2003; Chen, 2013; Chaudhary, 2019). The only approach used to control water quality comprises protecting the quality according to water quality guidelines to recommend a level of resource protection, but it has never been linked to environmental flows (Palmer, 2007). The drawback of using the water quality based e-flows assessment methodologies is that these methods assume the initial river water quality conditions to be constant and do not do consider the actual water quality conditions. The actual water quality conditions would change sharply due to anthropogenic interference. The water quality based flow recommendations will help dilute the pollution loaded in the river. However, in the cases where pollution load is very high similar to the river Gomti, water quality-based e-flow estimates would surpass the natural flow available in the river (Chaudhary, 2019). As in this case, the water quality is poor in the midstream region in comparison to the upstream and downstream regions (Table 5.6). The urbanization and major morphometric changes in this stretch have resulted in the degradation of the water quality in past years. The improvement in the water quality in the downstream region indicates the ability of water to replenish itself as it moves away from the pollution sources (McColl, 1974). The water quality plays an important role in defining the habitat suitability as well as the environmental categories to recommend the e-flows for endangered and keystone species.



**Figure 5.12 (a, b, c, d, e, f, g, h):** Physico-chemical analysis of river water for three sites Neemsar, Lucknow and Maighat respectively during pre- and post-monsoon seasons for the year 2013 to 2017



**Figure 5.13:** Total coliform count of river water for three sites Neemsar (a), Lucknow (b) and Maighat (c) respectively during pre- and post-monsoon seasons for the year 2013 to 2017

### 5.9 Environmental Flows Assessment

An environmental flows assessment is done using five hydrological and one desktop method. The hydrological methods used were Tennant Method, Q90-Q50 Method, Smakhtin Method, Tessman, and Variable Monthly Flow. Due to the unavailability of the long term river discharge data for all the six homogeneous zones, the e-flows were recommended for three sites where CWC gauge stations were located, namely Neemsar, Lucknow, and Maighat. The results of recommended e-flows by five hydrological methods showed the potential e-flows for River Gomti at three sites (Table 5.7). Site wise estimation is done to take into account the fluvial variability into consideration. These methods recommend a portion of the discharge as the e-flows requirements of the river.

**Table 5.7:** Estimation of the e-flows requirements for Gomti River using five hydrological methods

<b>Neemsar</b>		<b>e-flows in cusec</b>			
<b>Month</b>	<b>Tennant Method</b>	<b>Q90-Q50 Method</b>	<b>Smakhtin Method</b>	<b>Tessman</b>	<b>Variable Monthly Flow</b>
<b>Jan</b>	6.15	9.61	9.61	12.37	9.63
<b>Feb</b>	6.15	9.61	9.61	12.37	7.53
<b>Mar</b>	6.15	9.61	9.61	12.37	6.60
<b>Apr</b>	6.15	9.61	9.61	12.35	7.41
<b>May</b>	6.15	9.61	9.61	11.78	7.07
<b>June</b>	6.15	9.61	9.61	12.37	6.38
<b>Jul</b>	12.31	18.13	0*	16.60	12.45
<b>Aug</b>	12.31	18.13	0*	18.75	14.06
<b>Sep</b>	12.31	18.13	0*	37.76	28.32
<b>Oct</b>	12.31	18.13	0*	20.84	15.63
<b>Nov</b>	6.15	9.61	9.61	12.37	10.66
<b>Dec</b>	6.15	9.61	9.61	12.37	8.72

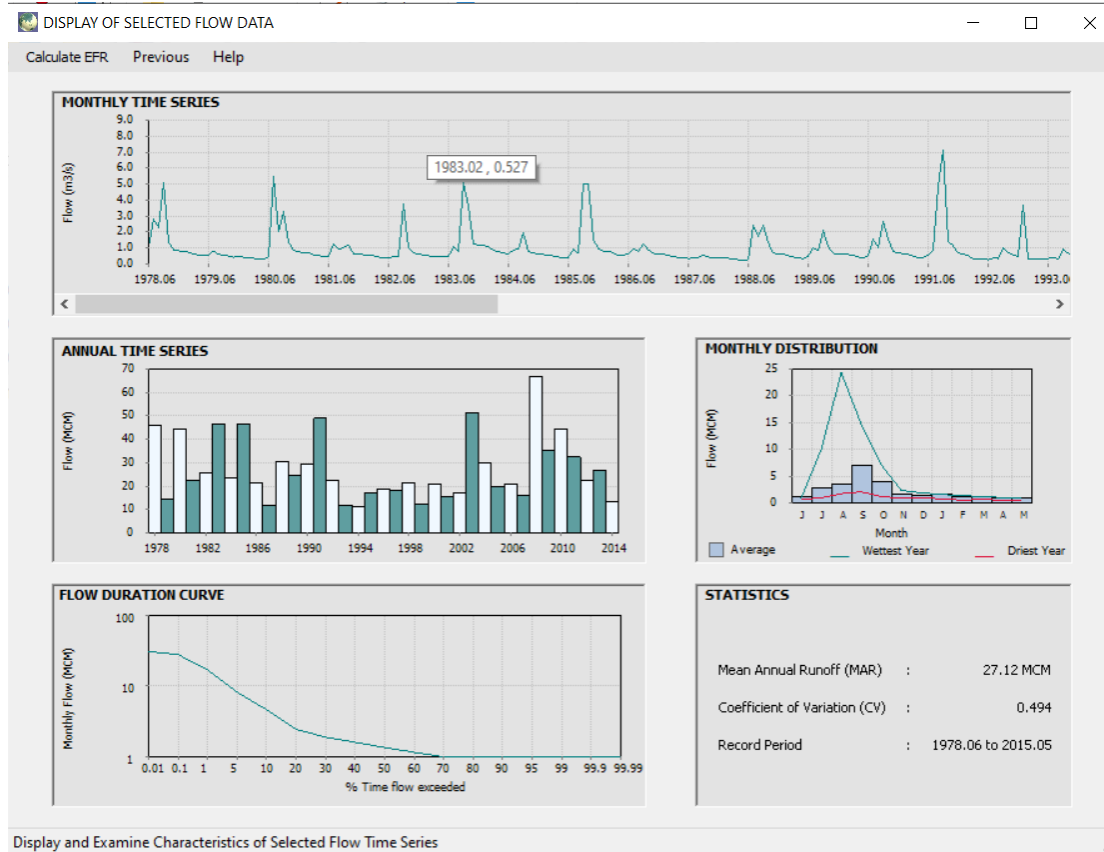
*To Determine the Environmental Flows for River Gomti*

<b>Lucknow</b>					
<b>e-flows in cusec</b>					
<b>Month</b>	<b>Tennant Method</b>	<b>Q90-Q50 Method</b>	<b>Smakhtin Method</b>	<b>Tessman</b>	<b>Variable monthly flow</b>
<b>Jan</b>	13.49	13.08	13.08	26.88	15.02
<b>Feb</b>	13.49	13.08	13.08	26.88	13.99
<b>Mar</b>	13.49	13.08	13.08	26.88	12.54
<b>Apr</b>	13.49	13.08	13.08	24.96	14.98
<b>May</b>	13.49	13.08	13.08	22.81	13.69
<b>June</b>	13.49	13.08	13.08	26.63	13.33
<b>Jul</b>	26.88	35.67	10.12	36.40	27.58
<b>Aug</b>	26.88	35.67	10.12	55.40	41.61
<b>Sep</b>	26.88	35.67	10.12	83.20	62.61
<b>Oct</b>	26.88	35.67	10.12	41.97	31.48
<b>Nov</b>	13.49	13.08	13.08	26.88	22.80
<b>Dec</b>	13.49	13.08	13.08	26.88	17.96
<b>Maighat</b>					
<b>e-flows in cusec</b>					
<b>Month</b>	<b>Tennant Method</b>	<b>Q90-Q50 Method</b>	<b>Smakhtin Method</b>	<b>Tessman</b>	<b>Variable monthly flow</b>
<b>Jan</b>	46.7	39.89	39.89	94.37	61.20
<b>Feb</b>	46.7	39.89	39.89	94.37	51.75
<b>Mar</b>	46.7	39.89	39.89	86.00	51.60
<b>Apr</b>	46.7	39.89	39.89	62.00	37.20
<b>May</b>	46.7	39.89	39.89	47.00	28.20
<b>June</b>	46.7	39.89	39.89	87.00	52.20
<b>Jul</b>	93.82	115.12	35.39	131.60	98.70
<b>Aug</b>	93.82	115.12	35.39	218.40	163.80
<b>Sep</b>	93.82	115.12	35.39	274.40	205.80
<b>Oct</b>	93.82	115.12	35.39	163.60	122.70
<b>Nov</b>	46.7	39.89	39.89	94.370	81.45
<b>Dec</b>	46.7	39.89	39.89	94.370	66.60

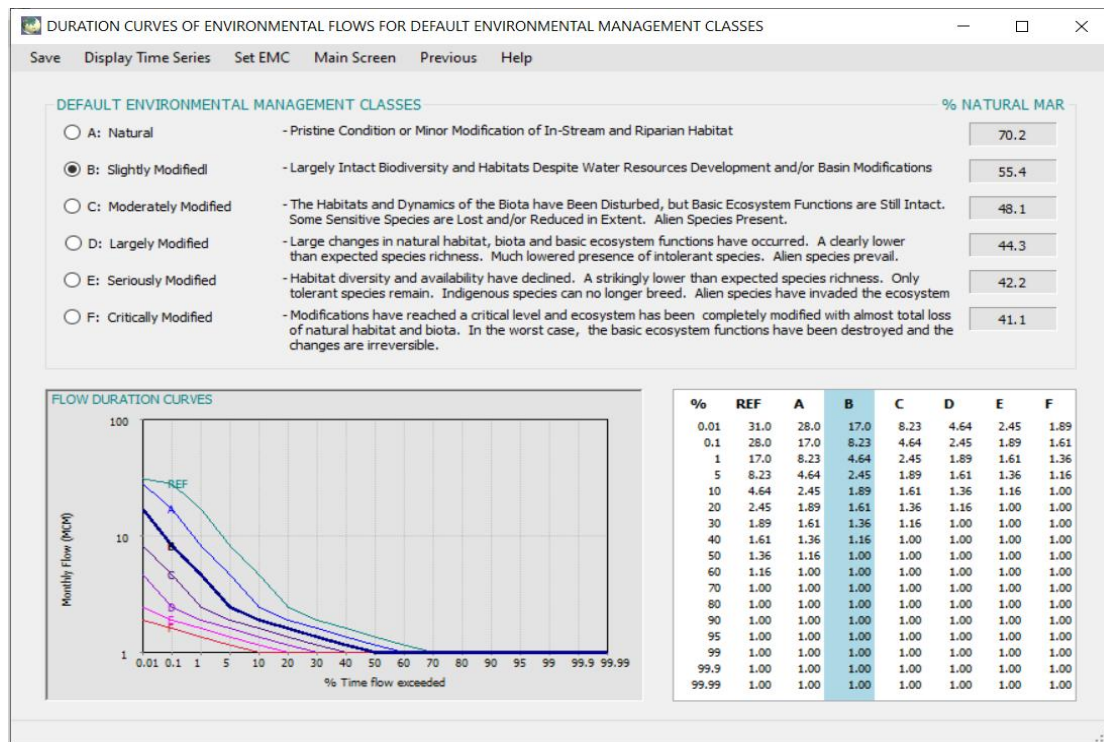
\*At Neemsar site, the Q90 for the month of Jul-Oct is greater than 30% of MAF; therefore, according to Smakhtin method, the recommended HFR is zero for that area

The results of the GEFM method used to assess the e-flows requirements for Neemsar, Lucknow and Maighat are indicated in Figure 5.14 (a, b, c), 5.15 (a, b, c), and 5.16 (a, b, c), respectively. This tool recommends e-flows by ‘reducing’ the natural hydrologic regime on a proportional basis at specific thresholds that indicate specific degrees of ecological disturbance. This method computes the monthly time series, annual time series, Flow duration curves, monthly distribution of discharge for driest and wettest years. This method categorizes the river discharge into six EMCs ranging from natural to critically modified classes based upon available long term flow data. The Mean Annual Runoff (MAR) for the three sites from Jun 1978 to May 2015 was estimated at 27.12 MCM, 60.07 MCM and, 207.3 MCM for Neemsar, Lucknow and Maighat, respectively. The computed MAR is taken as the reference condition for each site and discharge was recommended in the form of time series, as shown in the graph of natural reference flow and environmental flow graphs for all the sites.

# To Determine the Environmental Flows for River Gomti

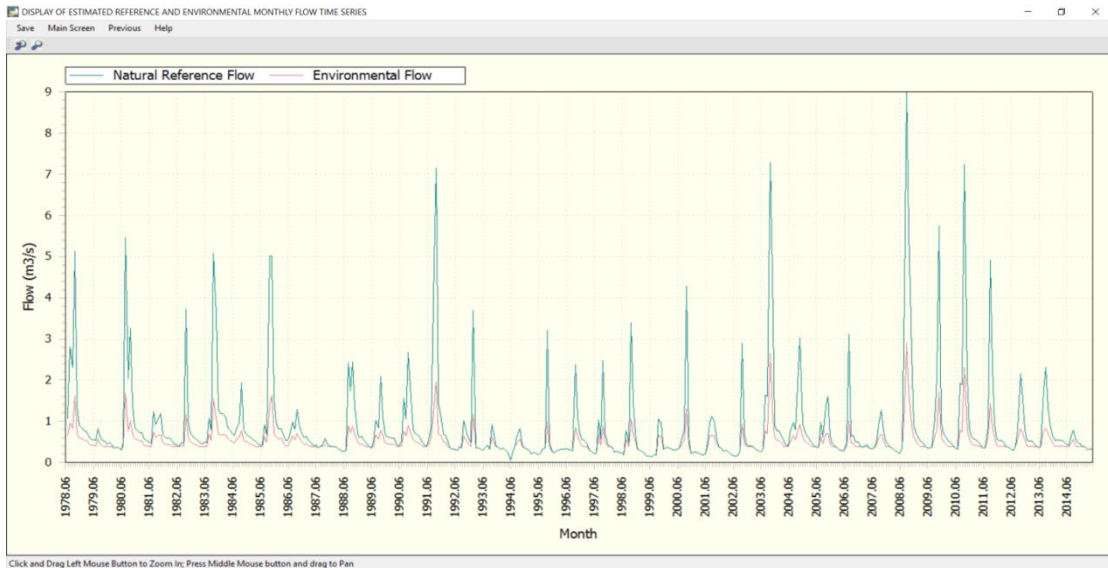


(a)



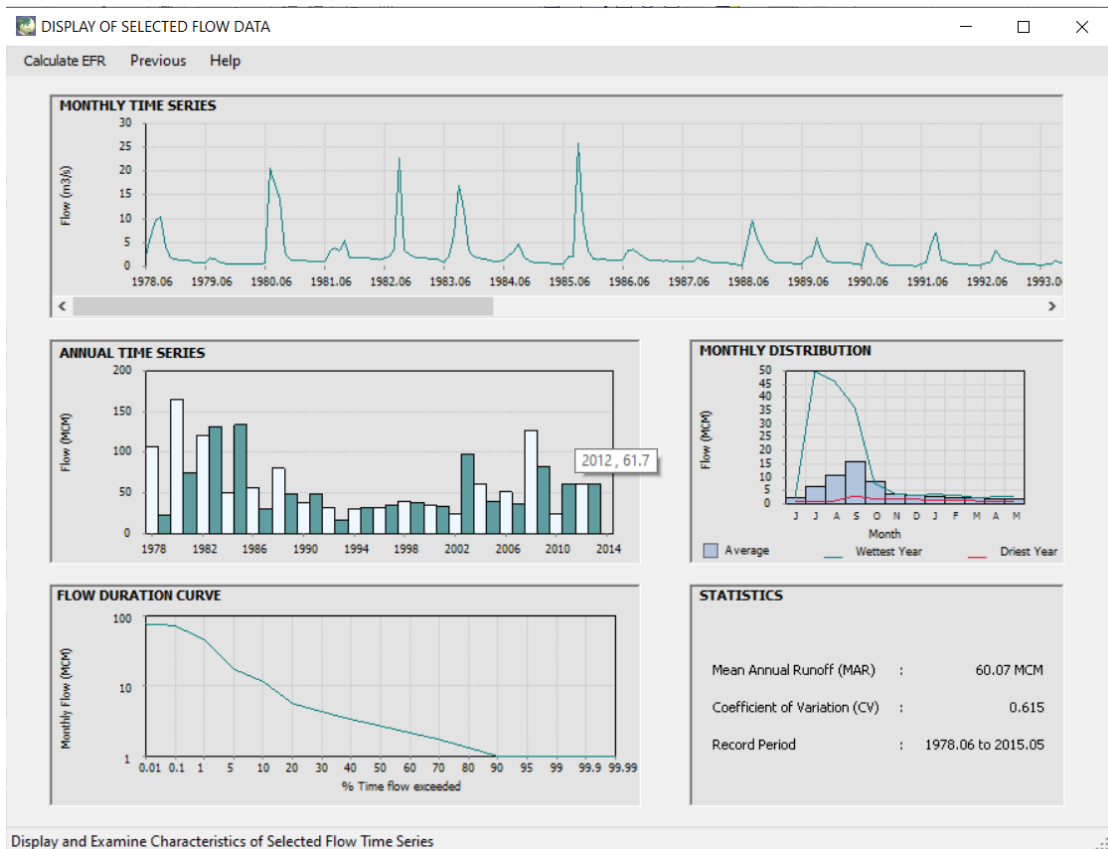
(b)

## To Determine the Environmental Flows for River Gomti



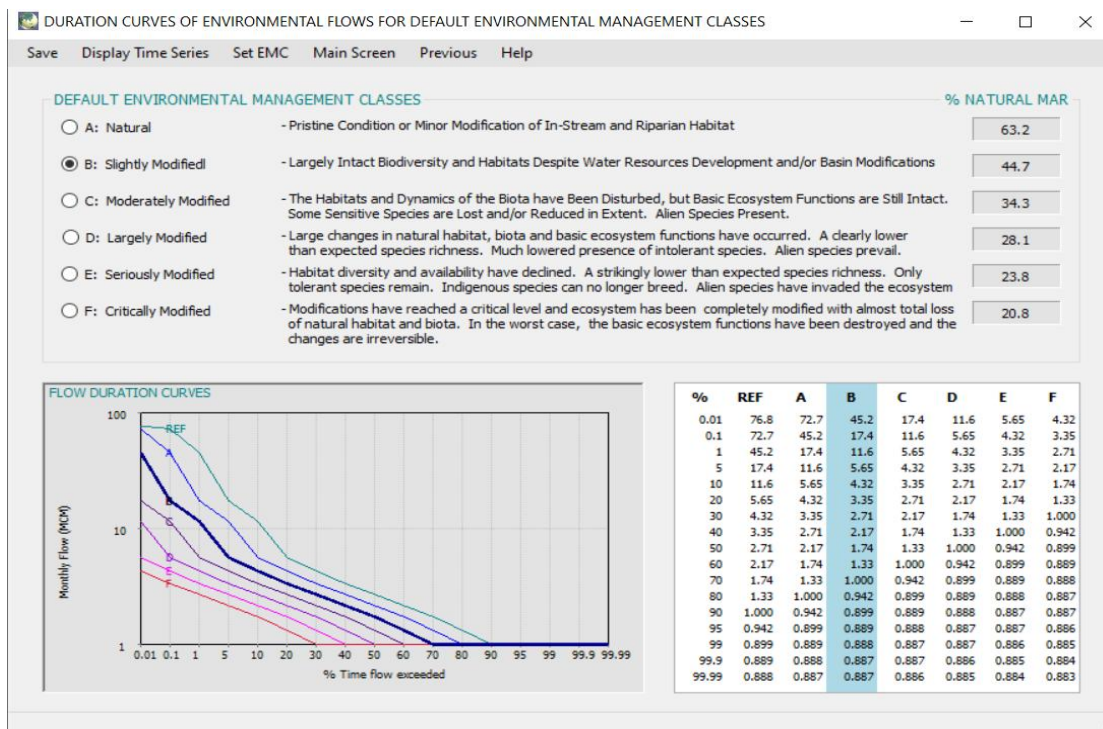
(c)

Figure 5.14 (a, b, c): E-flows calculation using user-defined data in GEFC at Neemsar

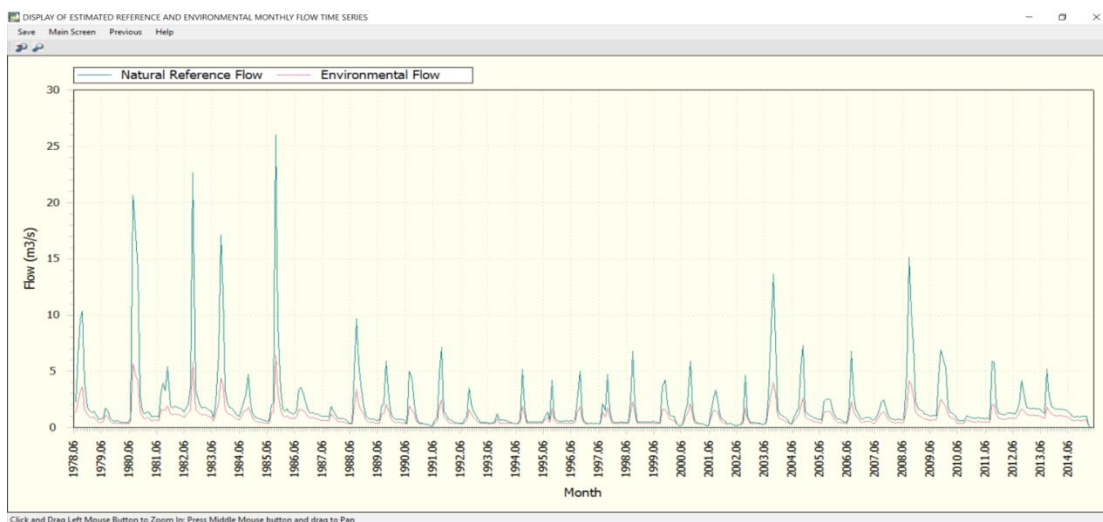


(a)

# To Determine the Environmental Flows for River Gomti



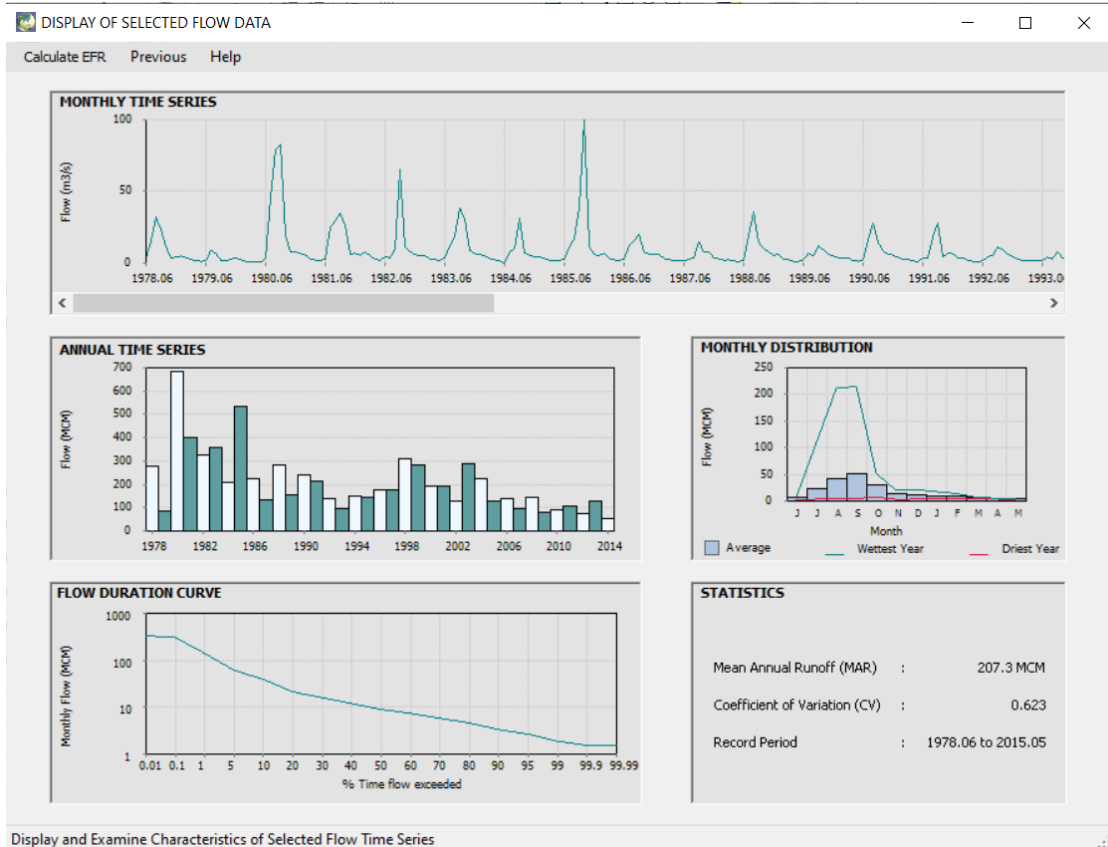
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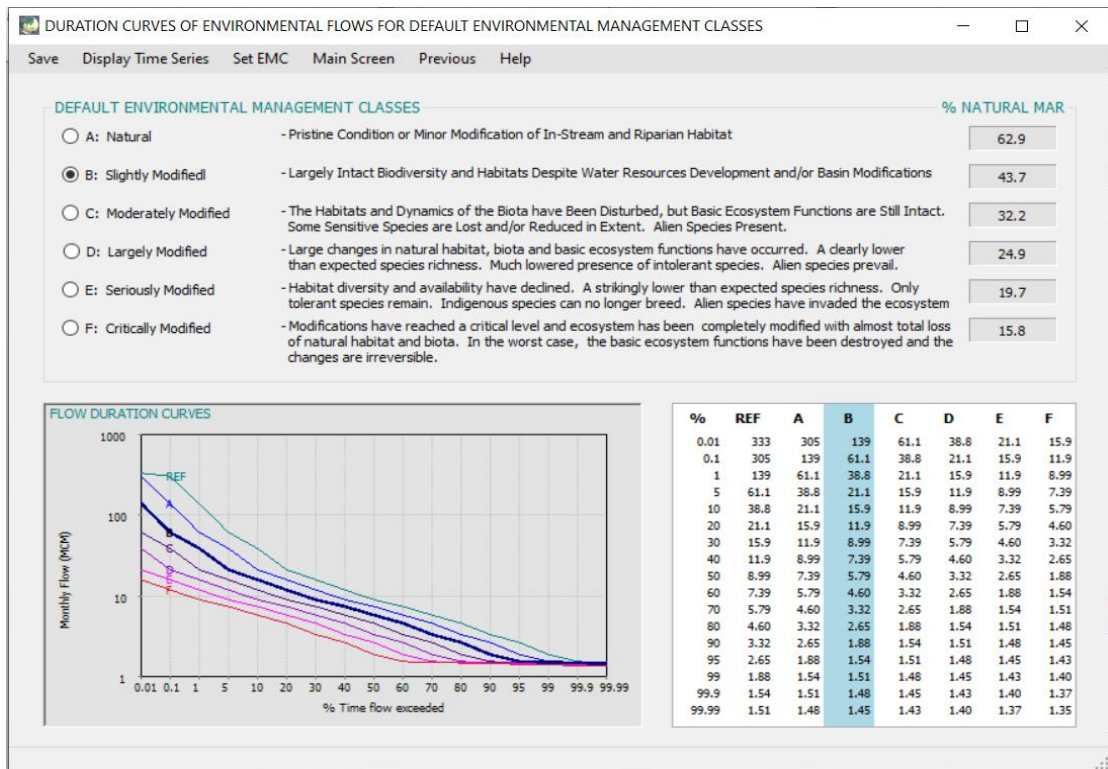
(c)

**Figure 5.15 (a, b, c):** E-flows calculation using user-defined data in GEFC at Lucknow

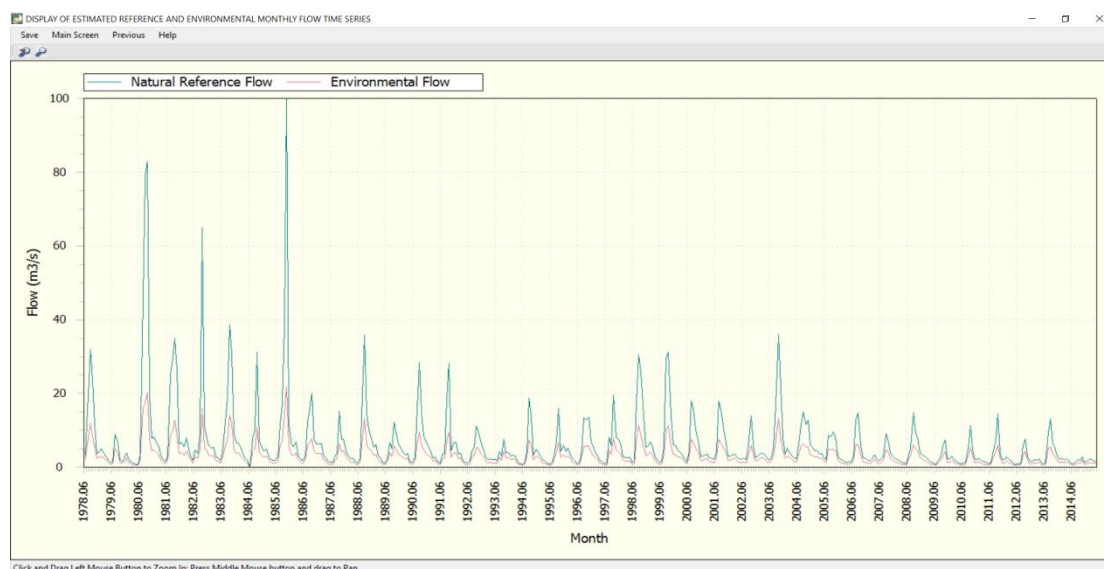
# To Determine the Environmental Flows for River Gomti



(a)



(b)



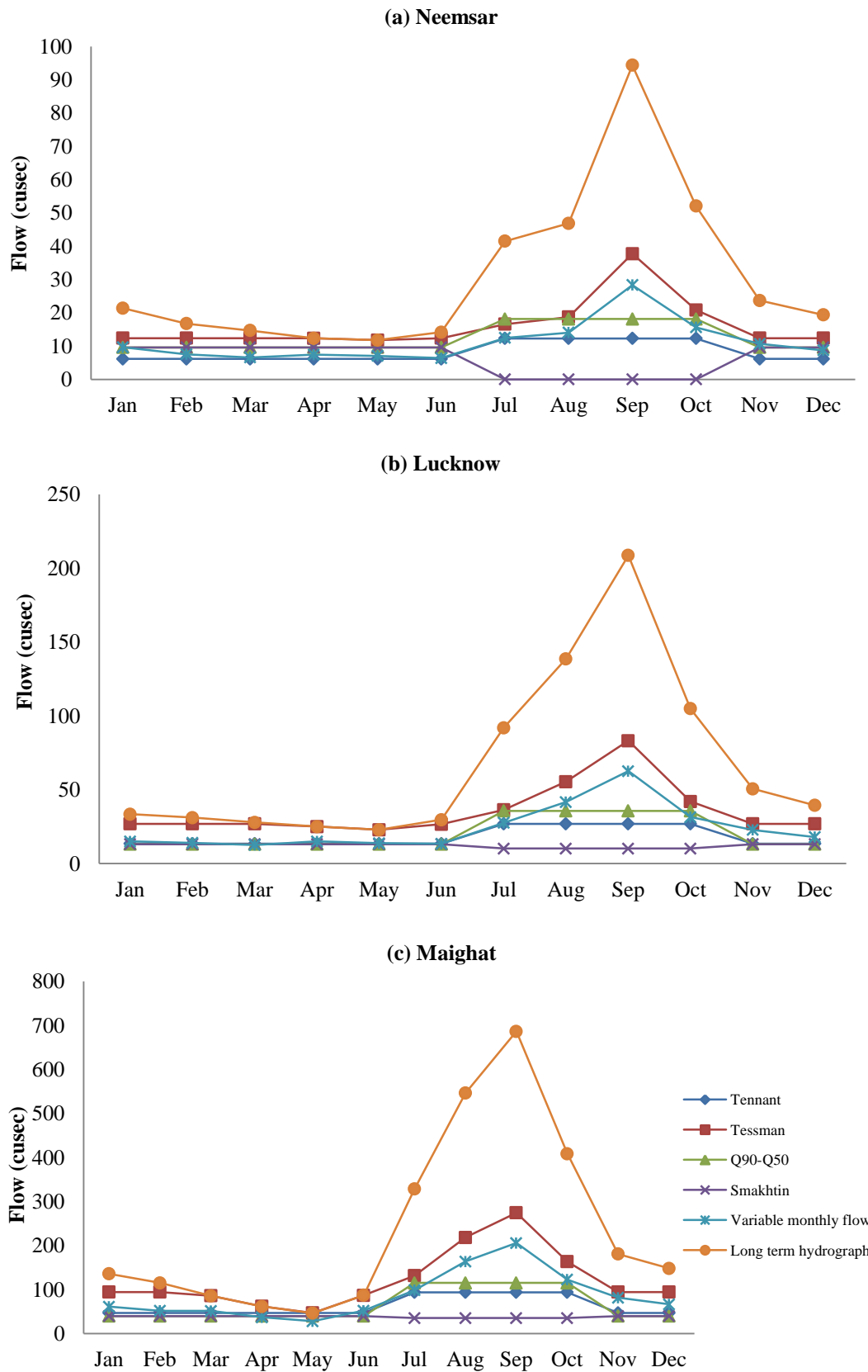
(c)

**Figure 5.16 (a, b, c):** E-flows calculation using user-defined data in GEFC at Maighat

### 5.10 Recommended E-flows for Gomti River

The e-flows assessment done using the hydrological and desktop methods indicates a spectrum of e-flows requirements for each site. Each method is recommending a unique e-flows value for each studied site. The comparison of the natural flow and the long term hydrographs to the hydrological flows recommended by each method indicates the Tessman method is giving the highest e-flows recommendations followed by Variable monthly flow, Q90-Q50, Tennant, and Smakhtin method respectively for all the sites in Figure 5.16 (a, b, c). The comparison clearly shows that the hydrological methods are recommending deficient flow during the monsoon season. The Tessman method is allocating 100% of MMF during the lean period of flow as e-flows. On ground implementation of this method would be an unfeasible situation. As there will be no water to fulfill other requirements such as domestic, agricultural and industrial needs (Paster *et al.*, 2014). From an ecological point of view leaving 100% of MMF during the lean period will be beneficial in maintaining the suitable riverine habitat for the aquatic and riparian biodiversity. This

method is recommending comparatively low flow in the high flow season, which might create a situation of risk of invasion, and proper distribution of the nutrients, sediments, and channel maintenance will not be possible in the absence of flushing flows (O’Keeffe, 2009). VMF is recommending between 30% to 60% of MMF, which recommending fair for low flow season, but still, the flushing flow needs of intermittent Indian River systems will not be meet (Bond *et al.*, 2008). During the high flow season, VMF method allocates 30% of MMF, and the Tessmann method allocates 40% of MMF. Thus the allocation for high flow does not differ significantly between VMF and Tessmann methods (Paster *et al.*, 2014). Therefore, both the hydrological methodologies are lacking in recommending the flushing flow requirements of the Indian River in the monsoon season. The variability of Indian rivers plays a vital role in maintaining the aquatic ecosystem integrity and shaping the natural flow paradigm (Kale, 2002). Remaining three methods, i.e. Q90-Q50, Tennant, and Smakhtin methods are recommending flow for two periods, only constant high flow of 4 months (June to September) and constant low flow of 8 months (October to May). These methods lack in addressing the seasonal flood pulse and lean flow of tropical rivers. This variability influence the ecology of the river, as the movement of water, sediment, nutrient and organisms from the channel towards the floodplains during the flooding season and visa-versa in low flow or base flow periods is directly dependent on it (Wohl, 2018). Variable flow is a master variable in maintaining the aquatic habitat, river morphology, biotic life, river connectivity and water quality (Karr, 1991; Bunn and Arthington, 2002; Jain, 2015; Joshi, 2017). In this comparison, Smakhtin method is giving the lowest flows for the monsoon period, which is impractical and not suitable for Indian rivers.



**Figure 5.17 (a, b, c):** The comparison of results of five hydrological e-flows methods along with long term hydrograph for three sites (a) Neemsar, (b) Lucknow and (c) Maighat

The flow recommended using the hydrological method were compared with the Habitat Health Classes, which indicates even after modifications in the Tennant's instream flow recommendations according to the Indian monsoon cycle (Table 5.8). The e-flows recommendations made using the Smakhtin, Tennant, and Q90 and Q50 methods is between 'Poor' to 'Good' categories. However, Tessman and VMF are recommending in between 'Good' and 'Excellent categories of HHCs.

**Table 5.8:** Comparison of e-flows assessment methods with respect to categories of Habitat Health Classes (HHC)

<b>Methods</b>	<b>Neemsar</b>	<b>Lucknow</b>	<b>Maighat</b>
Tennant method	Good	Good	Good
Q90-Q50 method	Excellent	Good	Between fair and good
Smakhtin method	Poor	Poor	Poor
Tessman method	Between good and excellent	Between good and excellent	Between good and excellent
VMF method	Between good and excellent	Between good and excellent	Between fair and good

The GEFC recommends the flow in terms of percentage of MAR to maintain the river's environmental conditions in predefined six EMC classes (Table 5.9). To maintain the river in class 'B' at all the three sites 55.4% of MAR is required to maintain at Neemsar site i.e. 15.02 MCM, 44.7% of MAR is required at Lucknow site i.e. 26.85 MCM and 43.7% of MAF is required at Maighat site i.e. 90.59 MCM. Studies have presented that e-flow volume in the range of 60-70% of the natural mean annual runoff has the probability of having healthy rivers (Jones, 2002; Smakhtin and Eriyagama, 2008).

**Table 5.9:** Estimated percentage for each EMC at all the three studied sites

<b>Environmental Management Classes</b>	<b>e-flows (% of MAR)</b>		
	<b>Neemsar</b>	<b>Lucknow</b>	<b>Maighat</b>
A	70.2	63.2	62.3
B	55.4	44.7	43.7
C	48.1	34.3	32.2
D	44.3	28.1	24.9
E	42.2	23.8	19.7
F	41.1	20.8	15.8

The e-flows recommendations using the GEFC based upon user defined data are comparably high in comparison to the hydrological methods. The major issue in this method is the justification of the e-flow recommendation made based upon the lateral FDC shifts per EMC. As the FDC shifts are not based upon the site-specific knowledge of the relation between the ecological characteristics and the flow modifications in the river with changed hydrological regimes. The class ‘A’ and ‘B’ results are recommending unrealistically high flow in the river which needs further attention, similar results were observed in the case of river Ganga and Brahmaputra (Smakhtin and Eriyagama, 2008). The developers of GEFC have accepted that this method presents low-confidence estimates of e-flows. Also, the evaluation of the results and checking the suitability of the recommended flow is a problem in the absence of ecological data.



*Chapter 6*  
*Flow Requirements for*  
*Indicator Fish Species*



## **6. Flow Requirements for Indicator Fish Species**

The results of the hydrological methods need to be validated in light of the ecological needs of the river Gomti. The quantification of the ecological flow needs was done using the fishes as model organisms. The index value for each species collected during the experimental fishing or reported earlier in the published studies was calculated. The highest scorers were further studied to assess the required depth for maintaining the fish stock. The required depth was estimated for different life stages such as spawning, migration, food and resting. Based upon the required depth the corresponding cross-section area, wetted perimeter, and average depth were calculated. The manning 'n' equation was used to calculate the discharge and velocity at the various depths.

### **6.1 Fish Fauna of River Gomti**

In the experimental fishing done during post-monsoon and winter seasons in 2017 and 2018, a total of 55 species belonging to 38 genera, 17 families and 6 orders were recorded from the upstream, midstream and downstream sampling sites of the river Gomti (Figure 6.1, 6.2 and Table 6.1). Cyprinidae was recorded as the most abundant family contributing 79.18% (21 species) of fish fauna followed by Bagridae (7 species) and Schilbeidae (6 species). The total number of individuals, relative abundance and conservation status as per IUCN Red List Criteria of each species are presented in Table 6.2. The relative abundance (RA) analysis of the fish species revealed *Puntius sophore* (22.05%) as the most dominant species followed by *Puntius chola* (17.57%), *Amblypharyngodon mola* (12.97%), *Puntius ticto* (10.60%), *Osteobrama cotio* (3.92%), *Rasbora daniconius* (2.98%), *Notopterus notopterus* (2.40%) and *Clupisoma garua* (1.88%). The RA of the two Indian major carps *Catla catla* (0.06%) and *Labeo rohita* (0.55%) was recorded, which is very poor compared to other species. On the contrary, the RA of *Cirrhinus mrigala* was found moderately higher (1.62%) compared to *Catla catla* and *Labeo rohita*. The relative abundance of

the medium carp *Labeo calbasu* was also found relatively lower as compared to *Cirrhinus mrigala*, but this species showed a wide distribution across different segments of the river. *Labeo* was recorded as the most abundant genus, followed by *Puntius*, *Mystus* and *Channa*. Some of the species of the conservation importance, which were recorded during sampling and analysis of data are *Ompok bimaculatus*, *Notepterus notepterus*, *Clupisoma garua*, *Cirrhinus reba*, *Sperata seenghala* and *Rita rita*. The species with lowest RA were *Chela laubuca* (0.03%), *Catla catla* (0.06%), *Labeo daro* (0.06%), *Glyptothorax telchitta* (0.06%), *Chagunius chagunio* (0.10%), *Sperata aor* (0.10%) and *Mastacembelus armatus* (0.10%). An invasive species *Cyprinus carpio* was also recorded with RA of 1.56%. The distribution pattern of the fish species in the river Gomti among the three sites varies, and only four species were found distributed throughout the river, and these are *Labeo calbasu*, *Chanda nama*, *Glossogobius guiri* and *Colisa fasciatus*.

**Table 6.1:** List of fish sampling locations in upstream (Sitapur), midstream (Lucknow) and downstream (Jaunpur)

Sampling Sites	Sampling location	Latitude/ Longitude
Sitapur	Rasoolpur	27°39'44.265" N 80°18'26.285" E
	Ramshala	27°26'32.278" N 80°24'29.079" E
	Raghunthpur	27°16'54.743" N 80°34'38.3" E
	Khale Korwa	27°14'7.405" N 80°43'4.843" E
Lucknow	Ghailapul	26°54'9.198" N 80°52'21.618" E
	Pakkapul	26°52'28.463" N 80°54'50.501" E
	Rubber Dam	26°50'22.51" N 80°57'57.887" E
	Pipra Ghat	26°49'50.443" N 80°58'36.391" E
Jaunpur	Baruaa Uttari	26°9'17.53" N 82°19'58.713" E
	Jagdishpur	26°0'24.946" N 82°26'0.652" E
	Dariyawganj	25°50'54.73" N 82°35'9.977" E
	Bijaipur	25°39'16.503" N 82°48'2.627" E



**Figure 6.1:** Map of sampling location in upstream (Sitapur), midstream (Lucknow) and downstream (Jaunpur) regions, respectively

**Table 6.2:** List of fish species with threatened status, number of individuals and relative abundance

<b>Genus Species</b>	<b>Upstream (Sitapur)</b>	<b>Midstream (Lucknow)</b>	<b>Downstream (Jaunpur)</b>	<b>IUCN Threat status</b>	<b>Total no.</b>	<b>Relative abundance (RA)</b>
<b>Notopteridae</b>						
<i>Notopterus notopterus</i>	Yes	Yes	No	Least concern	74	2.40
<b>Clupeidae</b>						
<i>Gudusia chapra</i>	No	No	Yes	Least concern	20	0.65
<b>Cyprinidae</b>						
<i>Amblypharyngodon mola</i>	Yes	Yes	No	Least concern	400	12.97
<i>Catla catla</i>	Yes	No	No	Least concern	2	0.06
<i>Aspidoparia morar</i>	Yes	No	No	Least concern	4	0.13
<i>Chagunius chagunio</i>	No	No	Yes	Least concern	3	0.10
<i>Chela laubuca</i>	No	No	Yes	Least concern	1	0.03
<i>Cirrhinus mrigala</i>	Yes	No	Yes	Least concern	50	1.62
<i>Cirrhinus reba</i>	No	No	Yes	Least concern	8	0.26
<i>Cyprinus carpio*</i>	Yes	No	Yes	Vulnerable	48	1.56
<i>Devario devario</i>	Yes	No	No	Least concern	10	0.32
<i>Labeo bata</i>	Yes	No	Yes	Least concern	29	0.94
<i>Labeo calbasu</i>	Yes	Yes	Yes	Least concern	38	1.23
<i>Labeo dero</i>	Yes	No	No	Least concern	2	0.06

<b>Genus Species</b>	<b>Upstream (Sitapur)</b>	<b>Midstream (Lucknow)</b>	<b>Downstream (Jaunpur)</b>	<b>IUCN Threat status</b>	<b>Total no.</b>	<b>Relative abundance (RA)</b>
<i>Labeo gonius</i>	Yes	No	No	Least concern	12	0.39
<i>Labeo rohita</i>	Yes	No	No	Least concern	17	0.55
<i>Osteobrama cotio</i>	Yes	Yes	No	Least concern	121	3.92
<i>Puntius sarana sarana</i>	Yes	No	No	Least concern	15	0.49
<i>Puntius sophore</i>	Yes	Yes	No	Least concern	680	22.05
<i>Puntius chola</i>	No	Yes	No	Least concern	542	17.57
<i>Puntius ticto</i>	Yes	Yes	No	Least concern	327	10.60
<i>Rasbora daniconius</i>	Yes	Yes	No	Least concern	92	2.98
<i>Salmostoma bacaila</i>	Yes	No	No	Least concern	41	1.33
<b>Cobitidae</b>						
<i>Lepidocephalus guntea</i>	Yes	No	No	Least concern	4	0.13
<b>Bagridae</b>						
<i>Sperata aor</i>	No	Yes	Yes	Least concern	3	0.10
<i>Sperata seenghala</i>	Yes	No	No	Least concern	22	0.71
<i>Mystus cavasius</i>	Yes	No	Yes	Least concern	44	1.43
<i>Mystus tengara</i>	Yes	No	No	Least concern	28	0.91
<i>Mystus vittatus</i>	Yes	Yes	No	Least concern	48	1.56
<i>Mystus bleekeri</i>	No	Yes	No	Least concern	7	0.23
<i>Rita rita</i>	No	Yes	No	Least concern	5	0.16

Genus Species	Upstream (Sitapur)	Midstream (Lucknow)	Downstream (Jaunpur)	IUCN Threat status	Total no.	Relative abundance (RA)
<b>Siluridae</b>						
<i>Ompok bimaculatus</i>	Yes	No	No	Near threatened	18	0.58
<i>Ompok pabda</i>	Yes	No	No	Near threatened	9	0.29
<i>Wallago attu</i>	Yes	No	No	Near threatened	6	0.19
<b>Schilbeidae</b>						
<i>Ailia coila</i>	No	No	Yes	Near threatened	19	0.62
<i>Eutropiichthys vacha</i>	Yes	No	Yes	Least concern	34	1.10
<i>Clupisoma garua</i>	Yes	No	Yes	Least concern	58	1.88
<i>Glyptothorax telchitta</i>	Yes	No	No	Least concern	2	0.06
<i>Bagarius bagarius</i>	No	No	Yes	Near threatened	5	0.16
<i>Gagata cenia</i>	Yes	No	Yes	Least concern	6	0.19
<b>Claridae</b>						
<i>Clarias batrachus</i>	No	Yes	No	Least concern	5	0.16
<b>Heteropneustidae</b>						
<i>Heteropneustes fossilis</i>	Yes	Yes	No	Least concern	12	0.39
<b>Belonidae</b>						
<i>Xenentodon cancila</i>	Yes	No	No	Least concern	8	0.26
<b>Ambassidae</b>						
<i>Parambassis ranga</i>	No	Yes	No	Least concern	5	0.16

<b>Genus Species</b>	<b>Upstream (Sitapur)</b>	<b>Midstream (Lucknow)</b>	<b>Downstream (Jaunpur)</b>	<b>IUCN Threat status</b>	<b>Total no.</b>	<b>Relative abundance (RA)</b>
<i>Chanda nama</i>	Yes	Yes	Yes	Least concern	18	0.58
<b>Gobiidae</b>						
<i>Glossogobius guiris</i>	Yes	Yes	Yes	Least concern	12	0.39
<b>Nandidae</b>						
<i>Nandus nandus</i>	Yes	Yes	No	Least concern	6	0.19
<b>Anabantidae</b>						
<i>Anabas testudineus</i>	No	Yes	No	Data deficient	8	0.26
<b>Belontiidae</b>						
<i>Colisa fasciatus</i>	Yes	Yes	Yes	Least concern	30	0.97
<b>Channidae</b>						
<i>Channa marulius</i>	Yes	No	Yes	Least concern	26	0.84
<i>Channa punctata</i>	Yes	No	Yes	Least concern	39	1.26
<i>Channa striatus</i>	Yes	Yes	No	Least concern	11	0.36
<b>Mastacembelidae</b>						
<i>Macrogathus pancalus</i>	Yes	Yes	No	Least concern	42	1.36
<i>Mastacembelus armatus</i>	Yes	No	No	Least concern	3	0.10
<b>Cichlidae</b>						
<i>Oreochromis niloticus</i>	No	Yes	No	Near threatened	5	0.16

\*Exotic species

## **6.2 Fish Biodiversity Analysis**

To get insight into the fish biodiversity of the river Gomti, different fisheries measurements viz. Species Richness, Shannon Index, Simpson Index, Berger Parker Dominance Index, and Evenness were calculated for each sampling site. Table 6.3 presents the site-wise details on these measurements.

### **6.2.1 Species Richness**

The species richness represents a number of different species in an ecological community. It was measured in all three sampling sites, which showed considerable variation among the sites. The highest richness was recorded in the upstream followed by the downstream of the river Gomti. The maximum species richness was recorded at Sitapur (41 species), followed by Jaunpur (24). At Lucknow (midstream), the lowest species richness with 23 species was recorded.



*Mastacembelus armatus*



*Rasbora daniconius*



*Cirrhinus mrigala*



*Puntius chola*



*Sperata seenghala*



*Sperata aor*



*Ailia coila*



*Mystus Vitatus*



*Rita rita*



*Chela laubuca*



*Puntius sarana sarana*



*Chanda nama*



*Mystus cavasius*



*Catla catla*



*Xenentodon cancila*



*Salmostoma bacaila*



*Cyprinus carpio*



*Clarias batrachus*



*Wallago attu*



*Gegata cenia*



*Eutropiichthys vacha*

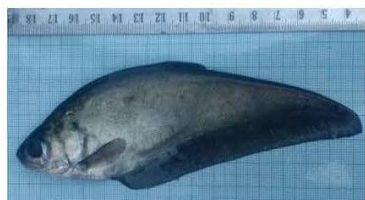


*Clupisoma garua*



*Labeo bata*

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*Notopterus notopterus*



*Oreochromis biloticus*



*Amblypharyngodon mola*



*Colisa fasciatus*



*Osteobrama cotio*



*Labeo calbasu*



*Anabas testudineus*



*Puntius sophore*



*Glossogobius giuris*



*Heteropneustes fossilis*



*Channa striatus*



*Parambassis ranga*



*Gudusia chapra*



*Bagarius bagarius*



*Mystus bleekeri*



*Macrognathus pancalus*



*Nandus nandus*



*Channa marulius*



*Channa punctata*



**Figure 6.2:** List of fish species collected during experimental fishing

### **6.2.2 Shannon Index**

To characterize the species diversity in the river Gomti, the Shannon fish diversity index was calculated for all the stretches, which ranged from 1.85 to 3.07. Shannon's index accounts for both abundance and evenness of the species present. The maximum diversity index was recorded in the upstream at Sitapur (3.07). In the midstream at Lucknow and downstream at Jaunpur, the fish diversity index was calculated 1.85 and 2.91, respectively. The low diversity index at Lucknow is due to the abundant occurrence of few species and relatively less abundance of other species. At Jaunpur, the fish diversity index is nearly equal to the fish diversity index at Sitapur, which shows that both Sitapur and Jaunpur contributes more in representing the diversity of the river.

### **6.2.3 Species Dominance Index (Berger-Parker Dominance Index)**

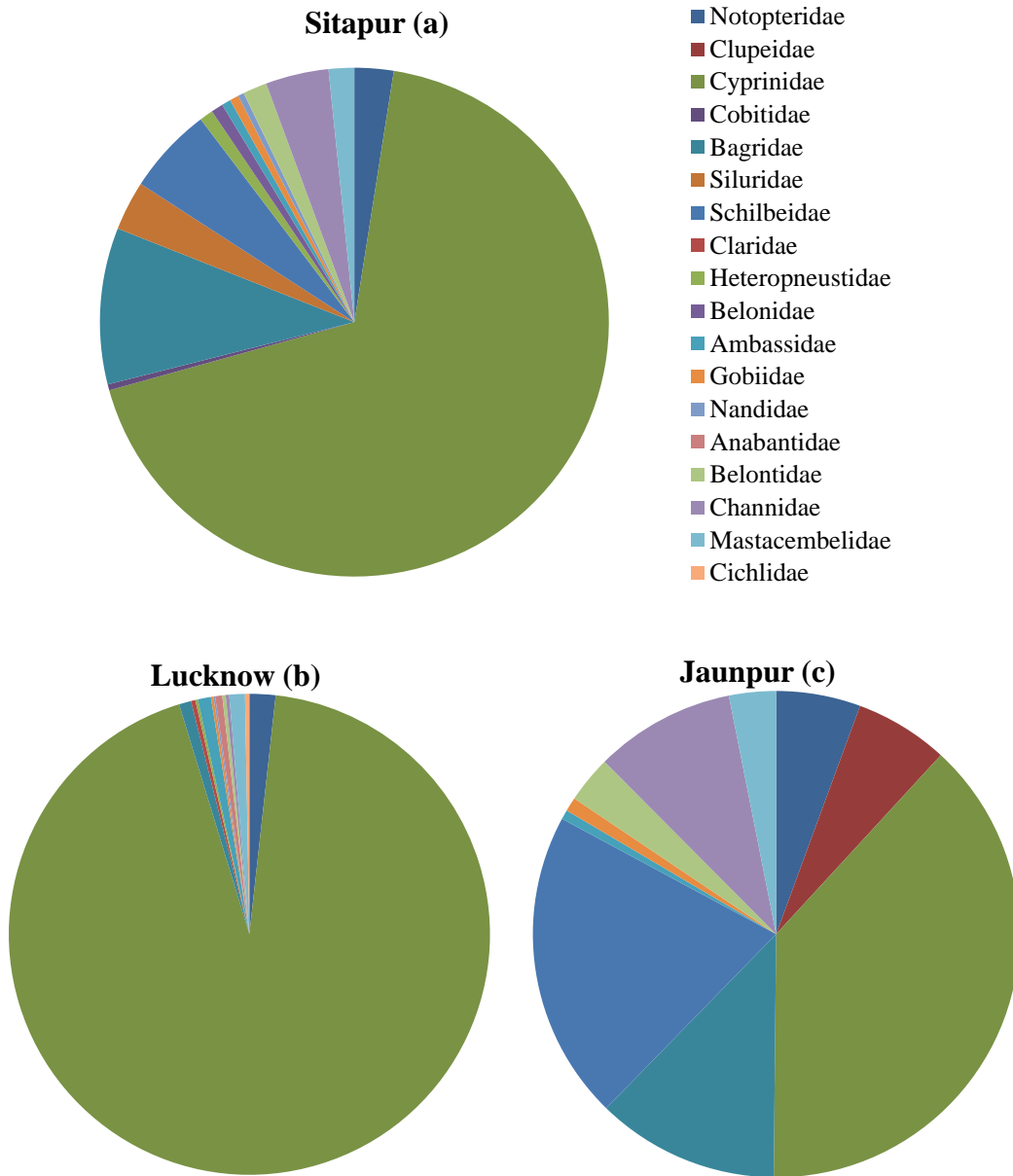
The species dominance in the river Gomti ranged from 0.12 to 0.32. The highest dominance was reported in the midstream at Lucknow (0.32). In the upstream at Sitapur and the downstream at Jaunpur, the species dominance was found 0.21 and 0.12, respectively. The highest value of dominance index at Lucknow indicates that only a few species at this site represent the biomass though they are less in population with the lowest diversity.

**Table 6.3:** The diversity index Species richness, Shannon index, Simpson index, Berger parker dominance index, evenness and catch per unit effort in the sites of the river Gomti

Location	Site type	Species richness (S)	Simpson index (D)	Shannon (H)	Berger Parker Dominance Index	Evenness ( $e^H/S$ )	Catch per unit effort (CPUE)
Sitapur	Up stream	41	0.92	3.07	0.21	0.52	0.67
Lucknow	Mid-stream	23	0.79	1.85	0.32	0.21	0.19
Jaunpur	Down stream	24	0.94	2.91	0.12	0.76	1.35

### 6.3 Fish Distribution Pattern

The results of experimental fishing indicate that out of six indicator species none of the species is present throughout the river stream *Wallago attu*, *Ompok bimaculatus*, *Ompok pabda* are found in the upstream region, *Ailia coila* and *Bagarius bagarius* were found in downstream region only, and no specimens of *Chitala chitala* was collected during the sampling.



**Figure 6.3:** Family wise representation of fish specimens recorded from Sitapur, Lucknow and Jaunpur sites of the river Gomti

### 6.3.1 Upper Stretch

At Sitapur, a total of 41 species were reported belonging to 13 families, of which Cyprinidae dominates with 17 species (Figure 6.3). In earlier studies, *C. reba* was reported from this stretch but in the present study, no specimen of *C. reba* was recorded. Further, specimens of *Heteropneustes fossilis* were recorded with a relative abundance of 0.86, which were not reported from this stretch in earlier studies. The

relative abundance of major carps and other species such as *Catla catla* (0.19%), *Labeo dero* (0.19%), *Glyptothorax telchitta* (0.19%), *Gagata cenia* (0.19%), *Mastacembelus armatus* (0.29%) was found relatively low in this stretch. In this stretch, the population of young individuals is more than old ones. The large proportion of young individuals is a good sign of the establishment of the population in their niche. The higher abundance percentage of small and miscellaneous species relative to other major species such as *Puntius sophore* (20.82%), *Amblypharyngodon mola* (10.98%), *Puntius ticto* (9.07%) and *Osteobrama cotio* (6.21%) was recorded. This could be due to a decrease in the abundance of large carnivores fishes such as *Wallago attu* (0.57%) and *Nandus nandus* (0.38%). The number of species reported in the present and the study done by Gupta (2011) is the same but a decline was noticed in the CPUE and diversity index both.

### **6.3.2 Middle Stretch**

At Lucknow, a total of 23 species belonging to 13 families were recorded, of which Cyprinidae dominates with 7 species recorded in this stretch. The reported species richness was 12 from the earlier studies by Gupta (2011), which have now been increased to 23. This site is recorded with the highest Berger parker Dominance Index, which indicates an abundance of few dominant species in the total number of the individuals recorded from the sampling site. Studies have suggested that the disturbed and naturally stressed communities have poor-species evenness, it is clearly evident from Simpson and Shannon diversity indices i.e., 1.85 and 0.79, which is least among the three studied sites (Caruso *et al.*, 2007). Also, the Evenness index is recorded least for this site i.e., 0.21. From this stretch, exotic fish was also reported in the experimental fishing namely *Oreochromis niloticus*. Identification of which has

been done based upon the number of gill rakers present in pairs of two adding to a total of 34 in number.

### **6.3.3 Lower Stretch**

At Jaunpur, the species richness was found decreased from 37 as reported by Gupta (2011) to 24 belonging to 10 families, out of which Cyprinidae dominates with 8 species followed by Schilbeidae with 5 species. The CPUE was found decreased in this stretch from 1.55 to 1.35. In comparison to earlier studies, the present study reports no specimen of *C. catla*, *C. chitala*, *L. gonius*, *L. rohita*, *O. cotio*, *P. sophore*, *R. daniconius*, *S. bacaila*, *S. seenghala*, *M. vittatus*, *R. rita*, *O. bimaculatus*, *W. attu*, *X. cancila*, and *M. armatus*. However, *M. cavasius* which was not reported from this stretch in the earlier studies was recorded with a relative abundance of 4.98%. This stretch was found to be dominated by older ones could be the result of degradation in the natural spawning habitats, connectivity loss, and modification in the middle stretch.

### **6.4 New Distribution and Biological Changes**

In the present study, a number of fish species, which were predominantly present in the upstream and downstream of the river Gomti (Gupta, 2011) and never reported earlier from Lucknow, were recorded from this region during sampling. The species, which were reported earlier from Lucknow include *Gudusia chapra*, *Labeo boggut*, *Botia lohachata*, *Pterygoplichthys disjunctivus*, *Nangra nangra*, *Clarias batrachus*, *Clarias gareipinus*, *Heteropneustes fossilis*, *Rhinomugil corsula*, *Nandus nandus*, *Anabas testudineus*, *Tetrodon culcutia*, of which no specimen of *Gudusia chapra*, *Pterygoplichthys disjunctivus*, *Labeo boggut*, *Clarias gareipinus*, *Botia lohachata*, *Tetrodon culcutia*, *Rhinomugil corsula* and *Nangra nangra*, was recorded. Only *Clarias batrachus*, *Heteropneustes fossilis*, *Nandus nandus*, *Anabas testudineus*

were recorded from this stretch. Along with few specimens of the never reported species were also collected namely, *Mystus bleekeri*, *Parambassis ranga* and *Oreochromis niloticus*.

### **6.4.1 Exotics**

The alteration in the watercourse makes it vulnerable to the invasion (Copp *et al.*, 2009). The introduction of exotic fishes may lead to a decrease in the native fish species diversity (Gozlan, 2009; Strayer, 2010; Trumpickas *et al.*, 2011). A total of 2 exotic species *C. carpio* and *Oreochromis niloticus* were recorded from the river Gomti river, out of which *C. carpio* was reported from both upper stretch and lower stretch with a relative abundance of 1.56%. On the other hand, *Oreochromis niloticus* was reported for the first time in the river Gomti from the middle stretch with a relative abundance of 0.16%. These species are a threat to the native species, which are already under stress (*Chagunius chagunio* and *Chitala chitala*) and migratory species (*Bagarius bagarius*, *Ompok pabda*, and *Walago attu*) as well as to the threatened species with smaller size groups (Light and Marchetti, 2007; Hermoso and Clavero, 2011; Sarkar *et al.*, 2011; Sarkar *et al.*, 2015).

### **6.5 Habitat Disruption**

The illegal fishing, nutrient enrichment and harvesting of the juvenile fish are the other causes for decrease of the fish population in the Gomti River (Figure 6.4a). In this specific case, the development of riverfront has resulted in the loss of the diverse habitats of river Gomti. Also, the continuity of river flow has got disturbed due to the construction of barrages and dams. During the construction of the riverfront project, the flow of river Gomti was obstructed using an earthen dam and sandbags at Kudia Ghat which are still obstructing the continuity of flow (Figure 6.4b). The loss of the physical habitat structure of a river due to developmental activities plays an

important role in determining the distribution and abundance of fishes (Shelford, 1911; Kang *et al.*, 2009). The longitudinal connectivity of a river is an essential element in maintaining the continuous migration and movement of water, sediments and biota (Graf, 2006; Reyjol *et al.*, 2014; Pelicice *et al.*, 2015; Fuller *et al.*, 2015). Due to obstruction in the flow, the river is getting eutrophic resulting in lavish growth of water hyacinth and *Azolla* and at some places; these have covered the full channel of the river. It results in de-oxidation of the water column underneath the accumulation and thus makes the area unsuitable for the aquatic organisms. Thus, fishes migrate in search of new suitable habitats due to change in the present habitat. The barriers in the river continuity not only impact the current ecology but also restrict the migration of future species (Radinger *et al.*, 2016; Radinger *et al.*, 2017; Gibson-Reinemer *et al.*, 2017; Radinger *et al.*, 2018) as each habitat supports a significant population structure.

Further, natural streams have more variability in terms of channel depth, channel width, flow velocity, bedforms, substrate composition and ecological habitats (Poole, 2002). In the process of channelization, the naturally sinuous streams are converted in more straight channels with homogenized channel morphometry, hydrology and sediment structures (Kairo *et al.*, 2017). In channelized streams, habitat degradation and variability loss become a major threat to the running water biodiversity (Johansson, 2013; Hartson *et al.*, 2014). The absence of areas of deep, slow water alternating with areas of shallow, swift water in channelized rivers makes it less habitable for most of the aquatic organisms except a few who prefers fast-flowing waters (Hartson *et al.*, 2014). Less number of chutes and sloughs in the river channel make the channelized streams less suitable for spawning and nursing and as a result, fishes migrate. These changes in the riverine morphology and habitats are

## Flow Requirements for Indicator Fish Species

posing high stress on the migratory and less tolerant on the stress species due to which the relative abundance of the most common native species such as *C. catla*, *A. morar*, *C. chagunio*, *C. laubuca*, *L. daro*, *P. sarana*, *L. guntea*, *S. aor*, *R. rita*, *W. attu*, *G. telchitta*, *B. bagarius*, *G. cenia*, *C. batrachus*, *N. nandus*, *M. armatus* has decreased below 0.20 in the river Gomti.



**Figure 6.4:** (a) River surface covered with water hyacinth, *Azolla* and illegal fishing using mosquito nets was spotted at Ghaila Pul Lucknow, (b) Earthen dam at kudiya ghat, profligate water hyacinth growth downstream to the earthen dam at kudiya ghat and in channelized stretch at Lucknow

### 6.6 Indicator Species Assessment

Apart from fishing experiments, several secondary sources were employed to get the data on the species reported in the Gomti River during previous years. The total number of fish species reported earlier, and those which are collected in the field

surveys were included in the index species selection process. The indicator species were selected based on the index species selection method as provided by Shokoohi and Amini (2014). The results of the analysis are presented in Table 6.4.

**Table 6.4:** Index value given to each species based on their international, national, genetic resource, ecological and economic value

Species	International conservation value	National conservation value	Genetic resource value	Ecological value	Economic value	Fish sport value	Grand total
<i>Pterygoplichthys</i>							
<i>disjunctivus</i>	0	0	0	0	0	0	0
<i>Labeo boggut</i>	0	0	0	0	0	0	0
<i>Ctenopharyngodaon</i>							
<i>idellus</i>	0	0	0	3	2	1	6
<i>Gagata cenia</i>	0	0	0	0	0	0	0
<i>Macrognaathus</i>							
<i>pancalus</i>	0	0	0	0	0	0	0
<i>Clarias gareipinus</i>	0	0	0	0	0	0	0
<i>Rasbora daniconius</i>	0	0	0	0	2	0	2
<i>Lepidocephalus guntea</i>	0	0	0	0	2	0	2
<i>Chela laubuca</i>	0	0	0	0	0	0	0
<i>Mystus tengara</i>	0	0	0	0	0	0	0
<i>Mastacembelus</i>							
<i>armatus</i>	0	0	0	0	0	0	0
<i>Gudusia chapra</i>	0	0	0	0	2	0	2
<i>Amblypharyngodon</i>							
<i>mola</i>	0	0	0	0	2	0	2
<i>Esomus danricus</i>	0	0	0	0	2	0	2
<i>Botia lohachata</i>	0	7	0	0	0	0	7
<i>Oreochromis niloticus</i>	9	0	0	0	2	0	11
<i>Notopterus notopterus</i>	0	7	0	0	0	0	7
<i>Aspidoparia morar</i>	0	7	0	0	0	0	7
<i>Devario devario</i>	0	7	0	0	0	0	7
<i>Labeo gonius</i>	0	7	0	0	0	0	7
<i>Puntius ticto</i>	0	7	0	0	0	0	7
<i>Salmostoma bacaila</i>	0	7	0	0	0	0	7
<i>Mystus bleekeri</i>	0	0	0	0	2	1	3
<i>Mystus cavasius</i>	0	7	0	0	0	0	7
<i>Xenentodon cancila</i>	0	7	0	0	0	0	7

## *Flow Requirements for Indicator Fish Species*

Species	International conservation value	National conservation	Genetic resource value	Ecolo gical value	Econo mic value	Fish sport value	Grand total
<i>Glossogobius guiris</i>	0	7	0	0	0	0	7
<i>Anabas testudineus</i>	0	7	0	0	2	0	9
<i>Hypophthalmichthys molitrix</i>	9	0	0	0	2	1	12
<i>Tetrodon culcutia</i>	0	7	0	0	0	0	7
<i>Channa punctata</i>	0	7	0	0	0	1	8
<i>Labeo bata</i>	0	7	0	0	2	0	9
<i>Osteobrama cotio</i>	0	7	0	0	2	0	9
<i>Puntius sophore</i>	0	7	0	0	2	0	9
<i>Nandus nandus</i>	0	7	0	0	2	0	9
<i>Labeo calbasu</i>	0	7	0	0	2	1	10
<i>Sperata seenghala</i>	0	7	0	0	2	1	10
<i>Channa striatus</i>	0	7	0	0	2	1	10
<i>Chanda nama</i>	0	0	0	3	2	0	5
<i>Parambassis ranga</i>	0	0	0	3	2	0	5
<i>Cirrhinus mrigala</i>	0	7	0	0	2	1	10
<i>Labeo rohita</i>	0	7	0	0	2	1	10
<i>Labeo dero</i>	0	7	0	0	0	0	7
<i>Puntius chola</i>	0	7	0	0	0	0	7
<i>Mystus vittatus</i>	0	7	0	0	0	0	7
<i>Eutropiichthys vacha</i>	0	7	0	0	0	0	7
<i>Clupisoma garua</i>	0	7	0	0	0	0	7
<i>Glyptothorax telchitta</i>	0	7	0	0	0	0	7
<i>Rhinomugil corsula</i>	0	7	0	0	0	0	7
<i>Sperata aor</i>	0	7	0	0	0	1	8
<i>Cirrhinus reba</i>	0	7	0	0	2	0	9
<i>Cyprinus carpio</i>	9	0	0	0	2	1	12
<i>Puntius sarana sarana</i>	0	7	0	0	2	0	9
<i>Rita rita</i>	0	7	0	3	0	0	10
<i>Clarias batrachus</i>	0	7	0	0	2	0	9
<i>Heteropneustes fossilis</i>	0	7	0	0	2	0	9
<i>Colisa fasciatus</i>	0	7	0	0	2	0	9
<i>Channa marulius</i>	0	7	0	0	2	1	10
<i>Catla catla</i>	0	7	0	0	2	1	10
<i>Wallago attu</i>	9	7	0	0	2	1	19
<i>Chagunius chagunio</i>	0	7	0	0	0	0	7
<i>Nangra nangra</i>	0	7	0	0	0	0	7
<i>Ailia coila</i>	9	7	0	0	0	0	16
<i>Bagarius bagarius</i>	9	7	0	0	0	1	17

Species	International conservation value	National conservation	Genetic resource value	Ecological value	Economic value	Fish sport value	Grand total
<i>Ompok bimaculatus</i>	9	7	0	0	0	0	16
<i>Chitala chitala</i>	9	7	0	0	0	0	16
<i>Ompok pabda</i>	9	7	0	0	2	0	18

\* '0' does not indicate 'no importance', however, it indicates minimum importance was allocated while calculating the index as each species has its ecological importance and plays an important role in the food webs in a river system.

The total values thus obtained for each species are used to distinguish the index species. A threshold limit is defined by adding 90% of the observed median to itself, i.e., the median of index number for the fishes is 7, and then the lower limit of index number will be

$$= \text{median} + (0.9 \times \text{median}) = 7 + (0.9 \times 7) = 13.3$$

The top scorers are identified as the indicator species for the Gomti River (Table 6.5).

**Table 6.5:** The selected indicator species

S.No.	Index Species	Index Value Score
1	<i>Wallago attu</i>	19
2	<i>Ompok pabda</i>	18
3	<i>Bagarius bagarius</i>	17
4	<i>Ailia coila</i>	16
5	<i>Ompok bimaculatus</i>	16
6	<i>Chitala chitala</i>	16

Based on the different life stages identified, i.e., spawning, migration, food, and resting, the water depth requirements for each life stage are identified. The water level depth required to maintain each life stage (Figure 6.5 and Table 6.6). The fishes in harsh and unfavorable conditions move into the deep pools. Thus the availability of the deep pools is important in providing the space for hiding as well as resting for fishes (Abdoli and Naderi, 2008; Shivaji, *et al.*, 2014).

**Table 6.6:** Average depth requirements for different life stages of index species

<b>Indicator Species</b>	<b>Average depth for Spawning</b>	<b>Average depth for Migration</b>	<b>Average depth for Food</b>	<b>Average depth for Resting</b>
<i>Wallago attu</i>	1.5±0.71	2.5±0.71	4.5±2.45	7±2.16
<i>Ompok pabda</i>	1.5±0.71	3±1.00	6±1.58	7±2.16
<i>Bagarius bagarius</i>	1.5±0.71	3±1.00	7±2.16	9±1.00
<i>Ailia coila</i>	1.5±0.71	2.5±0.71	3±1.41	3.5±0.71
<i>Ompok bimaculatus</i>	0.3±0.28	1±0.71	0.75±0.35	1.5±0.71
<i>Chitala chitala</i>	1.5±0.71	3±1.00	5.5±1.87	7±2.16

\*based upon expert suggestion from NBFGR and published studies

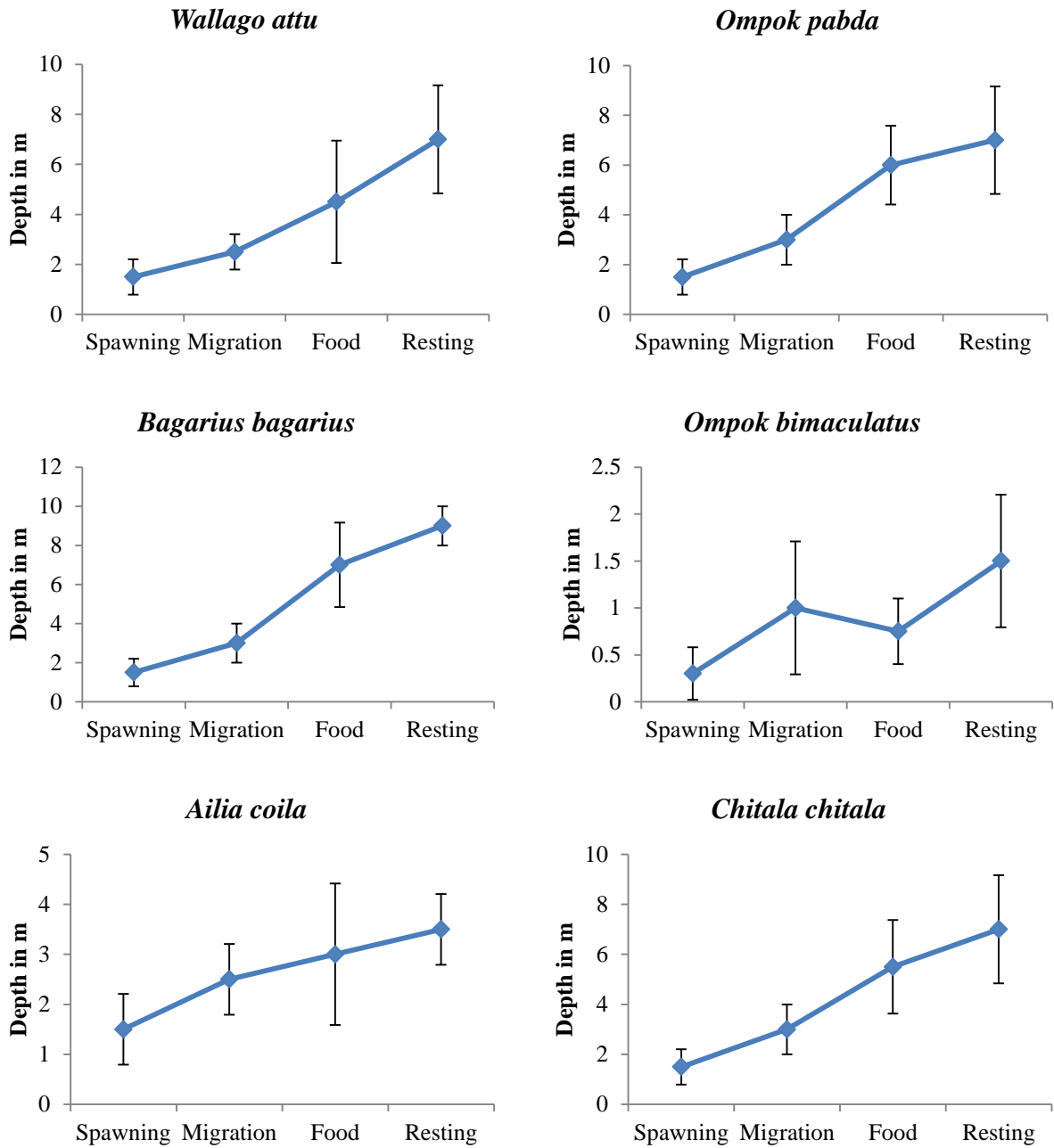


Figure 6.5: Water depth requirements of the selected index species

### 6.7 Flow Recommendation for Indicator Species

The flow recommendations for the indicator species were made based on stage-discharge curves and wetted perimeter-discharge relationships. The depth requirements for each species based on their life cycle were made. The manning ‘n’ equation was used to calculate the discharge required to maintain the desired water level at each site. The probable duration of breeding is from June-September and the

time of maximum spawning is from July-August. Fishes of any river migrate in search of spawning, feeding and resting grounds. Thus it is essential to maintain flow in between a range in the river so that the indicator species could migrate freely within their spawning, feeding, and resting grounds. Out of all the selected indicator species *Ompok pabda*, *Bagarius bagarius*, and *Chitala chitala* require between 2m to 4m deep water to migrate.

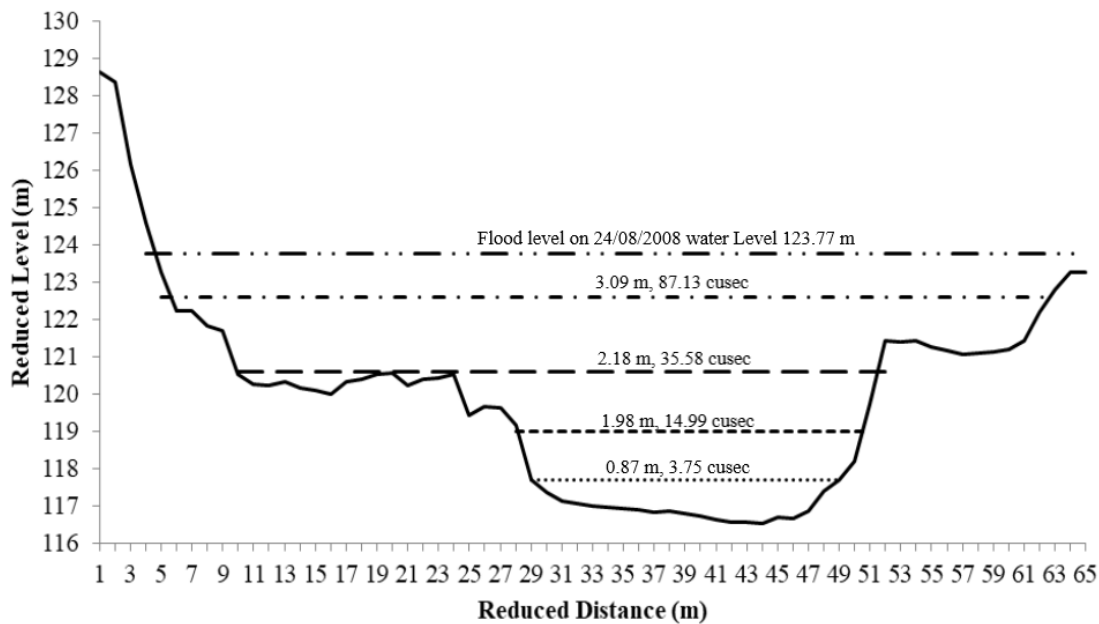
### **6.8 E-flows Recommendation to Sustain Good Fish Diversity**

It is not possible to have a uniform volume of water level at each point in the river. The geomorphology of the river shows that at the Neemsar site, the river is shallow with associated right and left banks. This region is suitable for the spawning of the fishes. The ideal depth for healthy spawning of the indicator species of 2m of water depth will be suitable. The further river is deep at the Maighat site. Thus this site is suitable for supporting different life forms. However, proper connectivity should be maintained between the two sites. In the past years, the central part of the river has been channelized thus is a matter of concern for smooth and frequent migration of fishes. Thus an escape channel with an average depth of 2 m should be provided for the undisturbed movement of fishes and other aquatic animals.

The water level and the corresponding discharge are represented in the cross-section diagrams of the Gomti River at the three studied sites in Figure 6.6 (a, b, c). To maintain healthy fish diversity and to focus on sustaining aquatic biodiversity in its best, it is important to maintain a variable flow regime. It is very well evident from the studies that a specific value of flow would never be suitable to fulfill the ecological needs (Arthington *et al.*, 2018). This study recommends maintaining a range of flow in the river, which could suitably fulfill the ecological needs. At, Neemsar an average depth of 1.98m to 2.18m should be maintained to facilitate the

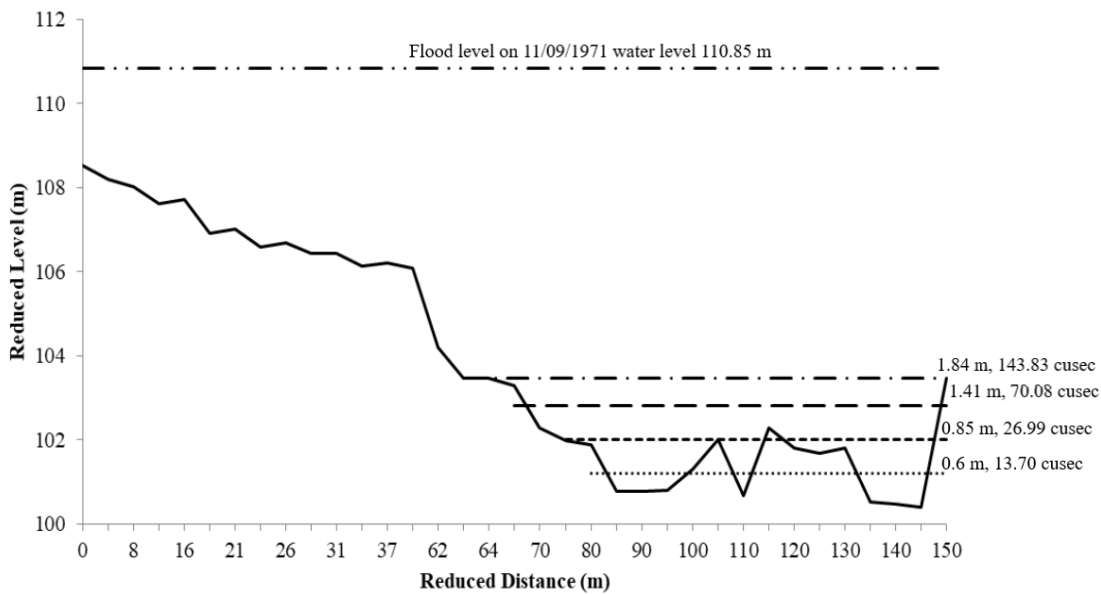
spawning and migration. The fishes will be able to find the resting grounds in deep pools present in the channel in the upstream region. At Lucknow site, 1.41m to 1.84m depth, as well as proper well-functioning escape channels, should be present to support the mobility from upstream to the downstream regions. In the midstream region, sudden modifications should be monitored to understand the pattern of change in the biodiversity and their future needs. At Maighat site, the river is comparatively deep could be suitable for sustaining the large and healthy fish stock with suitable deep pools and average column height of 3.08m to 6.04m deep would be suitable for the uninterrupted movement of the fishes (Table 6.7). There is also a need for small floods each year in the upstream and downstream region, an average depth of 3.09m and 7.57m is recommended as the flushing flow depth each year. In the midstream region, the small flushing flows were not recommended due to the channelization of the stream in the Lucknow city. At the Maighat site, a broad range of the flow level is recommended to sustain the fish diversity during low flow months identified as of March to June, a minimum of 3.08m average depth should be maintained. In the intermediate flow months identified as from December to January, a minimum of 4.72m average depth (Discharge (Q): 35.97 cusecs, Velocity: 0.51m/s, Cross Section Area (CSA): 70.80 m<sup>2</sup>, Wetted Perimeter: 24.44m) should be maintained and in the high flow months identified as of July to November, a minimum average depth of 6.04m should be maintained with small annual flushing flows depth of 7.57m.

**River cross-section, average water depth and discharge at Neemsar**

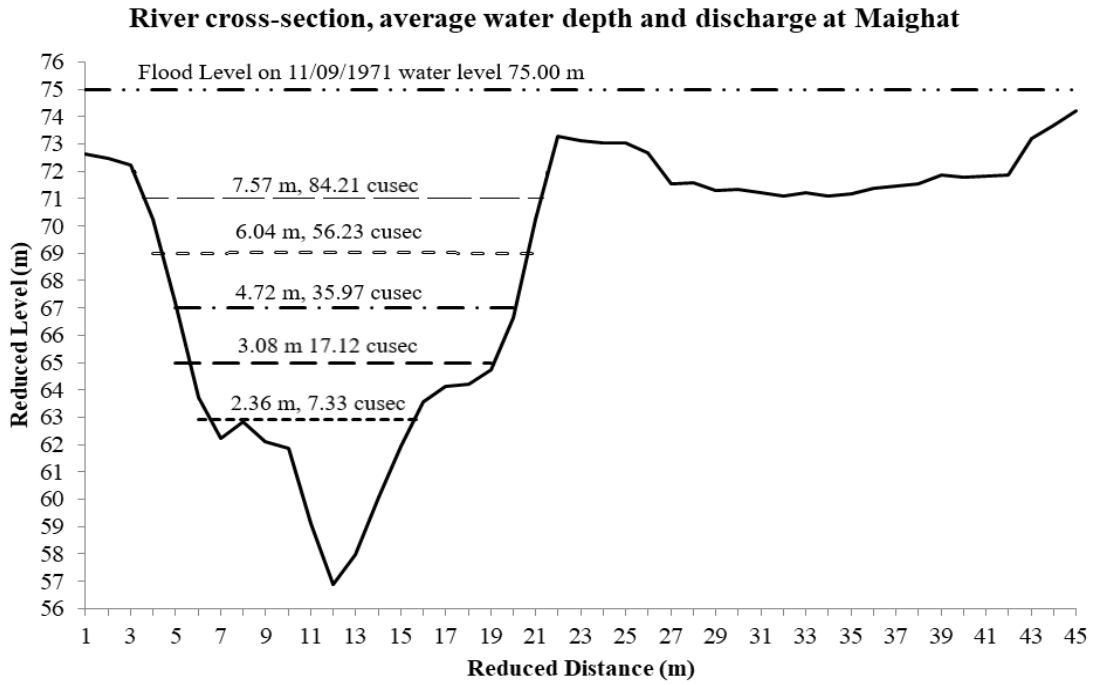


(a)

**River cross-section, average water depth and discharge at Lucknow**



(b)



(c)

**Figure 6.6 (a, b, c):** River cross-section, average depth and discharge at Neemsar, Lucknow and Maighat

**Table 6.7:** E-flows requirements of index species and recommended flushing flows

<b>Location</b>	<b>Range of flow levels that should be maintained at studied sites for sustaining fish diversity</b>		<b>Recommendations for small flushing floods each year</b>
Neemsar	Average depth: 1.98 m Discharge (Q): 14.99 cusec Velocity: 0.35 m/s Cross Section Area (CSA): 42.57 m <sup>2</sup> Wetted Perimeter: 25.46 m	Average depth: 2.18 m Discharge (Q): 35.58 cusec Velocity: 0.39 m/s Cross Section Area (CSA): 90.47 m <sup>2</sup> Wetted Perimeter: 45.86 m	Average depth: 3.09 m Discharge (Q): 87.128 cusec Velocity: 0.50 m/s Cross Section Area (CSA): 176.02 m <sup>2</sup> Wetted Perimeter: 63.18 m
Lucknow	Average depth: 0.85 m Discharge (Q): 26.98 cusec Velocity: 0.44 m/s Cross Section Area (CSA): 61.30 m <sup>2</sup> Wetted Perimeter: 74.19 m	Average depth: 1.84 m Discharge (Q): 143.83 cusec Velocity: 0.73 m/s Cross Section Area (CSA): 195.96 m <sup>2</sup> Wetted Perimeter: 110.18 m	Due to channelization, the river capacity is limited and flushing flows cannot be recommended for this stretch of the river
Maighat	Average depth: 3.08 m Discharge (Q): 17.12 cusec Velocity: 0.41m/s Cross Section Area (CSA): 41.56 m <sup>2</sup> Wetted Perimeter: 19.66 m	Average depth: 6.04 m Discharge (Q): 56.23 cusec Velocity: 0.57m/s Cross Section Area (CSA): 98.19m <sup>2</sup> Wetted Perimeter: 28.33m	Average depth: 7.57m Discharge (Q): 84.21 cusec Velocity: 0.64 m/s Cross Section Area (CSA): 132.41 m <sup>2</sup> Wetted Perimeter: 32.63 m

\*The average water depth, which can be 1.84m in 2016 in bank full condition above this level right bank will overflow

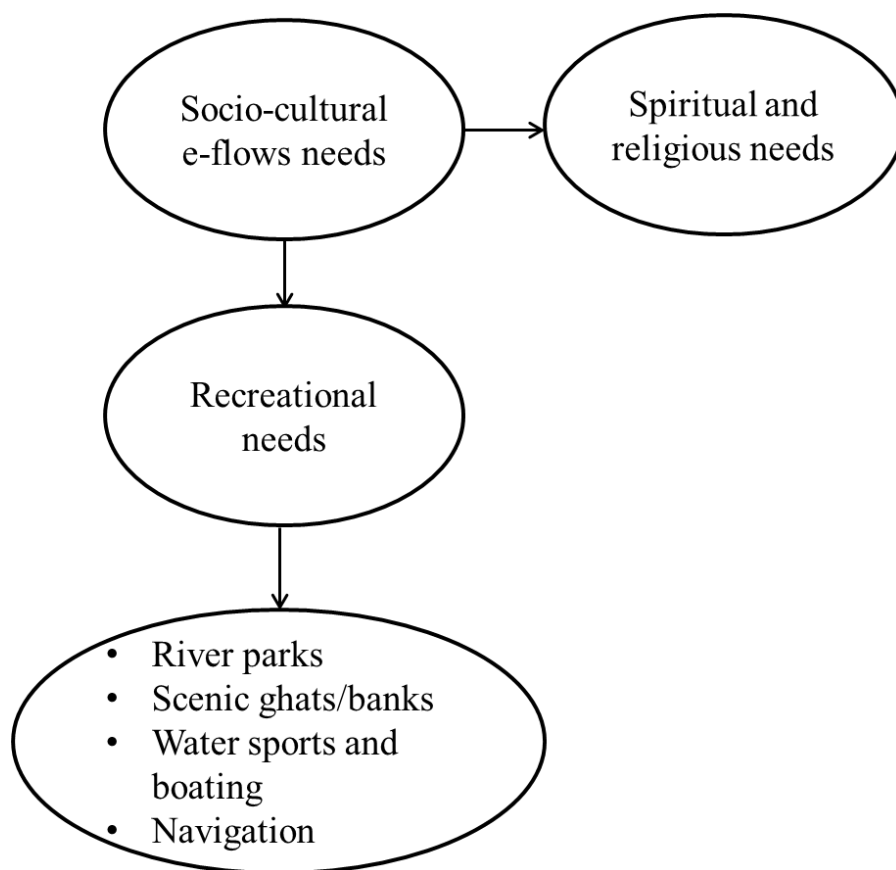


*Chapter 7*  
*E-Flow Requirements for Socio-  
Cultural Needs*



## **7 E-Flow Requirements for Socio-Cultural Needs**

Rivers in India are considered sacred and valued by locals due to their cultural and societal significance. Gomti is also named as Adi-Ganga. This river finds its mention in *Ramayana*, *Ramcharitramanas*, *Mahabharat*, and *Vishnupuran*. Gomti has a great cultural, spiritual, economic and ecological significance for the people in its catchments (Figure 7.1). Many Hindu temples and ashrams are present on the banks of the River Gomti and within the basin. On important days of the Hindu calendar, thousands of people converge on the river to pray and take sacred baths. Major 14 sites of spiritual importance were identified where people attach spiritual and religious importance namely, Ekottar Nath temple, Sunasir Nath temple, Jangali Nath temple, Dhaumya Rishi ashram, Naimisharyna Chakra Teerth, Rudravart Mahadev temple, Chandrika Devi temple, Kudia Ghat, Mankameshwar temple, Hanuman Setu temple, Sita Kund temple, Dhopap temple, Jamagadani Ashram and Markeandey Rishi Ashram (Figure 7.2). The socio-cultural needs also include the need for recreational purposes such as river parks, scenic ghats, water sports, and navigation there is a need to identify the possibilities of all the activities mentioned above in the river Gomti. The present possibilities of recreational activities in the identified 6 homogenous zones are evaluated (Table 7.1).



**Figure 7.1:** Identified socio-cultural aspects to evaluate e-flow needs and future possibilities

**Table 7.1:** Identified sites for the different recreational needs in River Gomti

Recreational needs	Pilibhit to Shahajahanpur u/s	Shahajahanpur d/s to Dadhna-mau (Sitapur) u/s	Dadhna-mau (Sitapur) d/s to Lucknow u/s	Lucknow d/s to Sultanpur u/s	Sultanpur d/s to Jaunpur u/s	Jaunpur d/s to Ganga river, Varanasi
Spiritual and religious sites	✓	✓	✓		✓	✓
River Parks		✓	✓			
Scenic Ghats	✓	✓	✓	✓	✓	✓
Water sports		✓	✓			
Boating		✓	✓	✓	✓	✓
Navigation			✓		✓	✓



**Figure 7.2:** List of major temples located along the river

Ekottar Nath temple is situated in Pilibhit bordering Shajhanpur district. According to local people, the Shiva lingam present in this temple was believed to be established by Lord Indra to get rid of the curse of Gautam rishi. Sunasir Nath temple in Shsjahanpur is also famous as the Choti Kashi of Vishvanath temple, and Jangali Nath temple in Lakhimpur Kheri is dedicated to Lord Shiva. Dhaumya Rishi Ashram in Hardoi and Naimisharyna Chakra Teerth in Sitapur has reference in Mahabharata (Book 12: Santi Parva), Vishnupuran (Section 13) and Ramcharitramanas (Pg 165: Shlok 142, chaupayi 1-4). Rudravart Mahadev temple is also a famous Lord Shiva temple situated in Sitapur. In Lucknow, Chandrika Devi temple, Kudiya ghat, Mankameshwar temple and Hanuman Setu temples are the main Hindu temples. Mankameshwar temple finds its mention in Ramayana (The Ramayan, Chapter 6: Sita). Sita Kund is situated in Sultanpur, which finds its mention in Ramcharitra Manas (Pg 536, shlok 187 chaupai 1-4). Dhopap temple of Lord Shiva is situated in Sultanpur. This temple is mentioned in the texts of Vishnupuran (Section 14). According to the folklore, Jamagadani Ashram was the place where Maharshi Jamagadani used to stay. This ashram is also believed to be the birthplace of Parshuram, who is considered as the sixth avatar of Lord Vishnu. Markeandey Rishi ashram is situated in Kathi, Varanasi, at the confluence of Gomti and Ganga, which is famous for Lord Shiva temple (The Mahabharata, Book 3: Vana Parva: Markandeya-Samasya Parva). All these places are of immense religious and spiritual value to both local residents as well as people from other parts of the country. A list of sacred bathing days when people visit rivers and perform sacred rituals and take a holy dip (Table 7.2).

**Table 7.2:** List of sacred bathing days as per the Hindu calendar for consideration of minimum bathing depth

<b>Sacred bathing days</b>	<b>No. of days in a year</b>	<b>Minimum depth required</b>
Purnima (full moon)	One each month (12)	In the field surveys, the average depth between 0.76m to 0.91m was found to be the minimum depth required to perform religious pujas and taking sacred baths in the river. The condition is that water should be preferably odorless and colorless
Amavasya (No moon)	One each month	
Mondays in the month of Sawan	4-5	
Thrayodashi in the month of Sawan and Falgun of Lunar fortnight or waxing moon as per Hindu calendar	2	
Ekadashi (11 <sup>th</sup> day of the lunar cycle) of every month (2 in each month)	24	
Makarsankranti	1	
Dusshera	1	
Navami of Navratri (in March and October)	2	
Chatt Puja	3-4	
Kumbh (once 12 years)	5 Major days excluding Mahashivratri	
Mahashivratri	1	

### **7.1 Socio-Cultural E-Flow Needs of River Gomti**

During the field surveys, it was observed that on special bathing days, people visit these places and take Holy dip in the River Gomti. In both monsoon and non-monsoon months, minimum flow and depth are required to enable rituals and bathing at these places. The minimum depth required to satisfy the cultural needs at the studied sites for special bathing days was calculated to be 0.87m depth during the non-monsoon period and 1.98m of water depth during the monsoon periods at

### *E-Flow Requirements for Socio-Cultural Needs*

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Neemsar. At Lucknow, the calculated average water depth required for the non-monsoon period is 0.85m, and for the monsoon period, it is 1.41m, whereas for Maighat the non-monsoon depth required is estimated to be 2.1m and for monsoon period required depth is 3.08m (Table 7.3).

**Table 7.3:** The minimum and maximum e-flows needs for socio-cultural needs

	Minimum flow requirements			Maximum flow requirements		
	Average Depth (m)	Discharge (Q) (cusec)	Velocity (V) (m/s)	Average Depth (m)	Discharge (Q) (cusec)	Velocity (V) (m/s)
Neemsar	0.87 m	3.74	0.22	1.98 m	14.99	0.35
Lucknow	0.85m	26.98	0.44	1.41 m	70.08	0.6
Maighat	2.1 m	2.31	0.25	3.08 m	17.11	0.41



*Chapter 8*  
*Summary and Conclusion*



## **8 Summary and Conclusion**

Various structural controls and ever-increasing freshwater demands are resulting in altered river functions compromising the resilience of the riverine ecosystems. Assessment of the Gomti River Basin was done to recommend e-flows requirements to sustain the riverine ecosystems and associated ecological services at its best. Gomti River was selected for accessing the e-flows requirements as it is a sub-basin of the larger Ganga River Basin. Gomti River, being a groundwater-fed river can become a nurturing ground for various aquatic organisms during the lean flow seasons if the requisite flow is maintained. Thus this river can play a crucial part in the conservation and management of aquatic fauna of Ganges.

### **8.1 Homogeneous Zonation of River Basin for Identification of E-Flows Sites**

A constant flow in the river cannot sustain the riverine ecosystems. Thus, it is essential to maintain a variable flow regime in the river stream. To recommend variable flows for the river stream, initially, it is vital to find the homogenous stretches in the river stream based upon various parameters. In the homogenous zonation process, six distinct zones identified are Pilibhit to Shahajahanpur, Shahajahanpur to Dadhna-mau (Sitapur), Dadhna-mau (Sitapur) to Lucknow, Lucknow to Sultanpur, Sultanpur to Jaunpur and Jaunpur to Ganga River, Varanasi. These six zones are distinct from one another and would require a distinct flow to maintain its channel morphology and associated ecosystems. The e-flows recommendation for each site was not possible during this study due to the unavailability of long term and real-time data for all the sites. Thus, three sites, namely Neemsar (located between Zone-I and II), Lucknow (located between Zone III and IV) and Maighat (located between Zone-IV and V) were selected to recommend e-flows for Gomti river. For these three sites, stream geomorphology, baseflow

component, number of high and low flow months, type of fish diversity supported and other studied parameters are different; thus, a variable, site-specific flow is desired.

### **8.2 Environmental Flows for River Gomti**

This objective was aimed to recommend e-flows for River Gomti. Hydrological, desktop and hydraulic methods were used as well as the assessment of suitable water depth for the identified indicator species was done to recommend the e-flows requirements. The baseline data were collected on fish diversity, river cross-sections, water quality and habitat diversity. The baseline data and the secondary data collected was used to calculate the hydrological indicators, separating the baseflow, flow duration curves, calculation of stage-discharge relation curves, wetted perimeter-discharge relation curves, hydraulic analysis and water quality analysis. These analyses are fundamental preliminary analysis in the e-flows assessment. The five hydrological methods used for recommending e-flows are Tennant, Tessman, Q90-Q50, Smakhtin and Variable Monthly Flow. The instream flow recommendations made by Tennant method were modified according to the Indian monsoon cycle and termed as Habitat Health Classes (HHC). The Tennant, Q90-Q50 and Smakhtin methods are recommending flows for two periods only, i.e. for high flow and low flow seasons. Thus, these methods are not able to address the variability of flow in the Gomti river stream. The Tessman and Variable monthly flow methods are better hydrological methods in comparison to the above three methods used. The Tessman method is recommending the highest e-flow in comparison to other hydrological methods. The E-flows recommendations were made based upon the user-defined data in Global Environmental Flow Calculator (GEFC). The GEFC is recommending the flow following the natural reference flow. The flow recommended by GEFC is in the form of shifting FDCs based upon pre-defined EMCs. This method lacks the

establishing the relation between the ecological characteristics and the flow modifications in the river with changed hydrological regimes. The class 'A' and 'B' results are recommending unrealistically high flow in the river which needs further attention. This method provides low-confidence estimates of e-flows as the recommendation based on EMC is not very well justified in this method. The recommendation by the hydrological and desktop methods indicates a few percentages of MAF or MMF as e-flows. All the methods are recommending different values of flow. At this stage, it is hard to conclude which method is well suited for the Gomti River as the actual implementation of these estimates is not done yet. These methods individually will not be able to provide the flow in correspondence to maintain the critical riverine ecosystems and ecology. Thus a combination of eco-hydrological methods should be tried. As in this case, a combination of Tesson and ecological estimates can be used as a part of a holistic approach. This combination, when implemented in practice with a continuous monitoring and feedback system, would ensure suitable environmental protection for the aquatic ecosystem.

Water quality plays a vital role in maintaining the overall integrity of the riverine ecosystem. However, the e-flows assessment methods principally focused on the quantity of water required. The flow allocation for the dilution of pollution at highly polluted sites will not be a feasible situation as the allocated flow might surpass the total available natural flow in the river. The water quality analysis of the Gomti river indicated that the river is falling between 'D' and 'E' class, as per CPCB standards based on DO and BOD concentrations. The best practice to improve the water quality of the river is to prevent the discharge of untreated water into the river.

### **8.3 Flow Requirements for Indicator Species**

The variability in climatic conditions, high variability in flow regimes and high ecological diversity suggest that the hydrological methods alone are not adequate to recommend the adequate environmental flows to address the needs of GRB. Thus there is a need to add extra steps to make them suitable for tropical rivers. One of the steps is e-flows requirements for indicator fish species. Six indicator species were identified based on their international, national, genetic, ecological, economical and sport fishing values. The water depth requirements to sustain each life form of fishes, i.e., spawning, migration, food and resting were identified. Spawning and migration being the two most crucial life stages to sustain the fish population were considered to recommend the e-flows. The information gathered during surveys and taking the expert opinions, a 2m depth profile is considered suitable for the spawning, and 4m depth is considered suitable for migration purposes for juveniles and adults. The channel morphology does not remain the same throughout the stream. To access the corresponding flow for maintaining the desired depth in the stream, stage-discharge relation curves and wetted perimeter-discharge relationship curves were used. The stage-discharge relation curves were prepared using the logarithmic equations. The wetted perimeter-discharge relationship curves were prepared using the manning 'n' equation. The channel is shallow in its beginning and deepens as it flows down towards the confluence with Ganga. Thus a range of flow is recommended as e-flows for maintaining the fish diversity based upon the desired depth. An average depth of 1.98 m to 2.18 m is recommended in the upper stretch i.e. at the Neemsar site of the river stream, the corresponding discharge is between 14.99 cusecs to 35.58 cusecs, respectively. The upstream site being shallow with parabola shape stream morphology and a high baseflow component will be suitable for spawning of fishes. However,

over-abstraction of the groundwater and steadily decreasing groundwater level had resulted in the drying of the upper parts of the river and its associated tributaries. At the Lucknow (midstream) site depth of 0.85 m to 1.84 m is recommended with corresponding discharge between 26.98 cusecs to 143.83 cusecs. The midstream region should also facilitate the active movement in the stream from upstream to downstream. The change in the habitats and the hydraulic parameters of the river due to channelization could have resulted in an increased abundance of exotic species such as *C. carpio* and *O. niloticus*. These non-native species are a threat to the native fish species. In the downstream region at Maighat the average depth range should be between 3.08 m to 6.04 m, with the corresponding discharge of 17.12 cusec to 56.23 cusecs, respectively. As the depth of the river channel increases, the downstream stretch will be highly suitable for maintaining the rich stock of fishes. There is also a need for small floods each year in the upstream and downstream region, an average depth of 3.09m and 7.57m is recommended as the small flushing flow depth each year. In the midstream region, the small flushing flows were not recommended due to the channelization of the stream in the Lucknow city. At the Maighat site, a broad range of the flow level is recommended to sustain the fish diversity during low flow months identified as of March to June, a minimum of 3.08m average depth should be maintained. In the intermediate flow months identified as from December to January, a minimum of 4.72m average depth (Discharge (Q): 35.97 cusecs, Velocity: 0.51m/s, Cross Section Area (CSA): 70.80 m<sup>2</sup>, Wetted Perimeter: 24.44m) should be maintained and in the high flow months identified as of July to November, a minimum average depth of 6.04m should be maintained with small annual flushing flows depth of 7.57m. This study points out that the planning and implementation of any developmental project in the river corridors should be carried out in small phases.

After completion of each phase, the interlinking of the functional responses of fish communities to habitat disruption should be analyzed.

### **8.4 Socio-Cultural Mapping and E-flows Need**

The e-flows requirements for fulfilling the socio-cultural needs indicate that, at Neemsar site an average depth of 0.87 m in lean flow season and 1.98 m in high flow season is suitable. To maintain the desired depth, a discharge of 3.74cusec and a velocity of 0.22 m/s in lean flow seasons and a discharge of 14.99 cusecs and a velocity of 0.35 m/s in high flow seasons are required. At Lucknow, to maintain an average depth of 0.85m in lean flow season, a discharge of 26.98cusec and velocity of 0.44 m/s is required. In high flow seasons at Lucknow, to maintain average depth of 1.41m, a discharge of 70.08 cusecs and velocity of 0.6 m/s is required. At Maighat site, the channel is deep and parabola shape, to maintain an average depth of 2.1m, a discharge of 2.31cusec and velocity of 0.25 m/s is required in lean flow seasons. In high flow seasons, an average depth of 3.08 m can be attained with a discharge of 17.11cusec, and velocity of 0.41m/s is required. One has to realize that practically it is difficult to maintain the required depth of water and flow velocity. Therefore as a thumb rule, efforts should be made to at least maintain the depth-flow-velocity conditions significant enough to not fall below the recommended values with minimum deviations in the flow.

### **8.5 Maintaining the Baseflow Contributions to E-Flows**

In this study, it was observed that the baseflow contribution is high in the Gomti River. The contribution observed at the three sites is about 78, 76 and 69% at Neemsar, Lucknow and Maighat, respectively. This study highlights the importance of surface water and groundwater interactions for planning a holistic management approach for the river systems. Baseflow contributions are crucial for maintaining the variable flow regimes in perennial rivers. To maintain the 'aviral' (un-fragmented) flow in the groundwater-fed rivers, the groundwater resources should be adequately

enough. The groundwater and surface water interactions continue to provide groundwater recharge in high flow periods and regain the riverine flow in lean flow periods through baseflow. This study further stresses on the need of restoring sufficient groundwater recharge possibilities in the form of natural inland water bodies such as ponds and lakes. In place of larger water storage systems, small check dams on lower order streams would be beneficial in controlling the quick flow of the water towards downstream regions.

### **8.6 E-Flows Assessment Approach for Indian River Systems**

The results of the study indicate the e-flows requirements for the index species is exceeding the flows as per MAF calculated for each site. The e-flows recommendations made by hydrological methods and the desktop method are in a percentage of MAF and MMF. The ecological flow requirements are much higher than what hydrological methods are recommending. Every river has unique flow requirements. To maintain the healthy riverine ecosystems, only thumb rule can be applied to keep the flow near to the natural flow regime as much as possible. The over-abstraction of water is not only dehydrating the ecosystems but also dehydrating the national economy. Water resource management should not focus on short term economic goals. Instead, it should focus on the long term ecological sustainability of the freshwater ecosystems. The e-flows assessment used in this study has some limitations and has room for further modifications. Some of the limitations are as follows:

1. The hydrological methods do not address the variability and duration of flow required.
2. Tennant, Smakhtin and Q90-Q50 methods recommend flow for two periods only i.e., high and low flow periods.

3. The industrial, domestic and agricultural demand-side management was not considered in this study.
4. The assessment of the actual riparian corridor width was not done in this study.

This study also puts forward to take a bottom-up approach where tributaries can be managed first, and subsequently, the main channel will be approached. In any e-flows assessment studies, it is hard to predict whether the selected method will deliver results which will improve the overall ecology of the study area. Thus, this study suggests that initially, the assessment and implementations of the e-flows should be done on a smaller tributary of a larger river system. The River Gomti is a major tributary of river Ganga, and by restoring its flow, and many other tributaries of Ganga River a better River Basin Management outcome can be achieved.

### **8.7 Restoration of River-Corridors and Connected Water Bodies**

The strong connections of the riparian population with the river will ensure healthy riparian corridors and river water quality. Well informed and aware society will not pollute their water bodies and prevent them from further degradation. Any developmental plans on the bank of the river and in its corridors should incorporate a thorough environmental impact assessment (EIA) study. In these EIA studies, a public hearing should be mandated irrespective of the extent of the development project. Assessment of the riparian width for each river should be done and this area should be protected and left in the name of the river from the origin of the river to its mouth. Healthy riparian corridors will facilitate uninterrupted ecological services.



*Chapter9*  
*Recommendation*



## **9 Recommendations**

The e-flows assessment is not just about the amount of water to be left in the river channel. It should include a holistic approach involving the groundwater recharge possibilities in the basin, maintaining healthy riparian corridors and preventing wastewater from entering into the river. Based on the understanding developed during this study, we made the following recommendations:

**1. *Capping on groundwater abstraction and increasing groundwater recharge:***

The groundwater plays a vital role in maintaining the flow in the river stream in the lean flow seasons. The inland water bodies are an essential part of any river basin as they are critical in recharging the aquifers. Gomti River Basin is densely populated and has a large area under agriculture. Over-abstraction of groundwater and illegal lift pumps installed near the river stream are putting extra stress on the riverine system. The surface-groundwater interactions and precise baseflow predictions would be beneficial in quantifying the total inland water storage required in the GRB. To increase the groundwater recharge, suitable rainwater harvesting sites should be identified. To reduce the water flow velocity, multiple small check dams as first and second-order streams can be made in place of single large storage structures. All these measures will ensure flow in the river channel during the lean flow seasons.

**2. *Riparian corridor encroachment and maintenance of healthy riparian***

***corridors:*** Healthy riparian corridors are an asset to a healthy riverine ecosystem. Few essential services provided by riparian corridors are slowing floodwater velocity, act as stream bank stabilizers, filter overland flows, provide fish spawning habitats, maintain stream temperature, and maintain the nearby terrestrial biodiversity. Thus healthy riparian corridors should be

maintained along the river stream. In India, there is no rule and regulations to prevent riparian corridors. There is a need to assess the natural riparian corridor width of all the rivers. After a successful estimation of river corridor width, the land falling in the river corridors should be legally registered in the name of the river. Further, any encroachments in the river's land should be liable to punishments and penalties. The recommended minimum riparian width could be as follows:

**Table 9.1:** Recommended riparian corridor width

<b>Stream order</b>	<b>Minimum vegetated riparian zone along the bank</b>	<b>Minimum riparian corridors width</b>
I Order	10m	20m +channel width
II Order	20m	40m +channel width
III Order	30m	60m +channel width
IV Order	40m	80m +channel width
V Order and greater	50m	100m +channel width

**3. The bottom-up approach in river basin management:** In Tropical countries like India, the e-flows assessment methods being used are mainly developed in temperate countries. The climatic conditions and monsoon cycles are very different in tropics from temperate countries. The researchers are still learning based on hit and trial processes. The methods which are successful in other river basins, may not be suitable for another river system. Thus, it is recommended to take a bottom-up approach for e-flows assessment. The bottom-up approach would include the management and conservation of a small tributary of a larger river basin in the initial phase i.e., the conservation process starts from the first-order streams and gradually moving towards the higher-order streams. If the used method gives satisfactory results, then this method can be taken ahead to the higher-order stream. The incorporation of a

regular monitoring and feedback system in this approach would be beneficial in ensuring the protection of a suitable environment for the aquatic ecosystem. Thus, larger river systems can be prevented from any damage while selecting suitable e-flows assessment methods.

- 4. *Aquatic diversity and habitat suitability:*** The conservation of native diversity of flora and fauna should be the prime focus while recommending the e-flows. Future studies should not only focus on the dominant predators while recommending the e-flows. The interlinking species of multiple food chains should also be taken into consideration as the disturbances due to missing interlinks can completely alter the composition of the native biodiversity. The habitat suitability assessment should include a thorough study of both aquatic and terrestrial native flora and fauna. Thus, while e-flows assessment and its on-ground implementation, the native biodiversity can be maintained close to natural biodiversity.



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# *Publications*



**Publications**

1. **Sharma, U.**, Adeeba, Dutta, V. (2020). Impact of Declining Groundwater Levels on River Flows in the Ganga Alluvial Plain – A Case Study of Gomti River, India. *Indian J Ecology* 47(1):2020.
2. **Sharma, U.**, Pathak, A. K., and Dutta, V. (2019). Impact Assessment of Channelization on River Corridors of a Major Tributary of Ganges, India Using Geospatial Techniques. *Ecology, Environment and Conservation journal, Eco. Env. & Cons.* 25 (July Suppl. Issue): 2019; pp. (S18-S25).
3. **Sharma, U.** (2019). Effective framework for Environmental-flows estimation for data deficient Indian rivers, *Journal of Applied and Natural Science*, 11(2): 545 – 555 (2019) ISSN: 0974-9411 (Print), 2231-5209 (Online).
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5. Dutta, V., **Sharma, U.**, Iqbal, K., Adeeba, Kumar, R., Pathak, A.K. (2018). Impact of river channelization and riverfront development on fluvial habitat: evidence from Gomti River, a tributary of Ganges, India, *Environmental Sustainability*, <https://doi.org/10.1007/s42398-018-0016-0>.
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# Impact assessment of channelization on river corridors of a major tributary of Ganges, India using geospatial techniques

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## ABSTRACT

This study presents spatial and temporal changes in the river corridors of the river Gomti, a major tributary of Ganges, before and after a major channelization project carried out in the urban stretch of Lucknow city in Uttar Pradesh, India. Landsat 8 satellite images of May 2014 and May 2017 were used to derive the information on changes of the different landscape features in the river corridors that got modified because of channelization after 2016. The results showed that the area of the active channel of river Gomti in the urban stretch got reduced by 6.54 Km<sup>2</sup> which is 35.49% of the channel due to changes in the river structure and morphology. The area of dense vegetation increased by 3.88%, subsequently, the area of sparse vegetation reduced by 8.96%, growth in the built-up area was noticed by 6.32% and open land by 2.5%, whereas no significant change in the wasteland area was noticed. Further, vegetative health index was calculated using the normalized difference vegetation index (NDVI). The results showed an increase in bare land with some sparse vegetation and a decrease in both moderate and dense vegetation as a result of channelization. The decrease in both moderate as well as dense vegetation shows an overall decrease in the forested area in the river corridors because of the construction of riverfront and increase in the urban sprawl on both banks of the river.

**Key words** : River Corridors, Channelization, Land use/cover changes, NDVI analysis, Remote Sensing, GIS

## Introduction

River corridor that accommodates dimensions, plan forms, slope, and a buffer of a naturally stable channel is necessary for natural maintenance and natural restoration of dynamic equilibrium condition (Jones *et al.*, 2010). They are very diverse zones where anthropogenic interventions such as channelization, constructions of dams and barrages are considered as drivers for change in the natural hydrologic cycle, vegetation and land use/ land cover (Behren *et al.*, 2013; Cooper *et al.*, 2013). Urban expansion

near the river channel results in expansion of impermeable surfaces, degradation of the riparian zones and disturbance in ecological services (Rodríguez and Ramírez, 2014). Such changes have direct interactions with climate, ecosystem processes, biogeochemical cycles, biodiversity, and, even more, important human activities in that area. Globally, fast-growing cities are at higher risk of losing their natural ecosystems due to anthropogenic activities. Therefore, there is an urgent need to assess and monitor LULC change in the river corridors because of developmental works globally (Li, *et al.*, 2018).

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For LULC and urban change studies, remote sensing in combination with geographical information systems (GIS) and global positioning systems (GPS) is much useful in mapping, modeling and analyzing the change (Abdand Alnajjar, 2013).

To give the international look to the river Gomti in Lucknow, Uttar Pradesh an ambitious project of riverfront development was undertaken that included many works like de-silting of the river and channelization of the river up to 8.1 km (construction of diaphragm wall and trunk drain), landscaping on both banks (beautification and development of green belt on both banks of the river) and illumination of all the structures including barrage, bridges on both banks of the river were proposed in the project costing to INR 967 crore (IWRS website). Thus, to evaluate and determine the change in the landscape diversity in the corridors of the river Gomti where this project was implemented, Landsat 8 data of the years 2014 and 2017 were downloaded and analyzed to (i) understand the changes in LULC types (ii) determine and analyze the drivers causing changes in river corridors.

### Study area

The river Gomti is a major tributary of the Ganga river system originating from a natural lake (elevation of about 200 m; north latitude 28° 34'0 and east longitude 80° 07'0) near Pilibhit town in Uttar

Pradesh. The river flowing through the central and eastern part of Uttar Pradesh traverses a total distance of about 941 Km and contributes 7.39 million cum of water per year to the main river Ganga near Varanasi. The river drains a catchments area of about 31009 km<sup>2</sup>. The river meanders for another 12 km through the middle of Lucknow city. Lucknow is the largest urban settlement in the basin and its increasing population is posing high stress on the riverine ecosystem which has got further aggravated by the construction of riverfront. This project has modified the riparian corridors, floodplains and nearby LULC pattern of the river in a very short period of time. The present study was conducted to evaluate and determine the changes in LULC types and analyze the drivers causing changes in different landscape features of the river corridor. A buffer of 2km from the midstream on both sides was considered in the study, which includes riparian corridors, floodplain, and settlements.

### Materials and Methods

#### Data acquisition

Landsat 8 satellite images of 2014 and 2017 were downloaded from the earth explorer of United States Geological Survey (USGS) website. Among

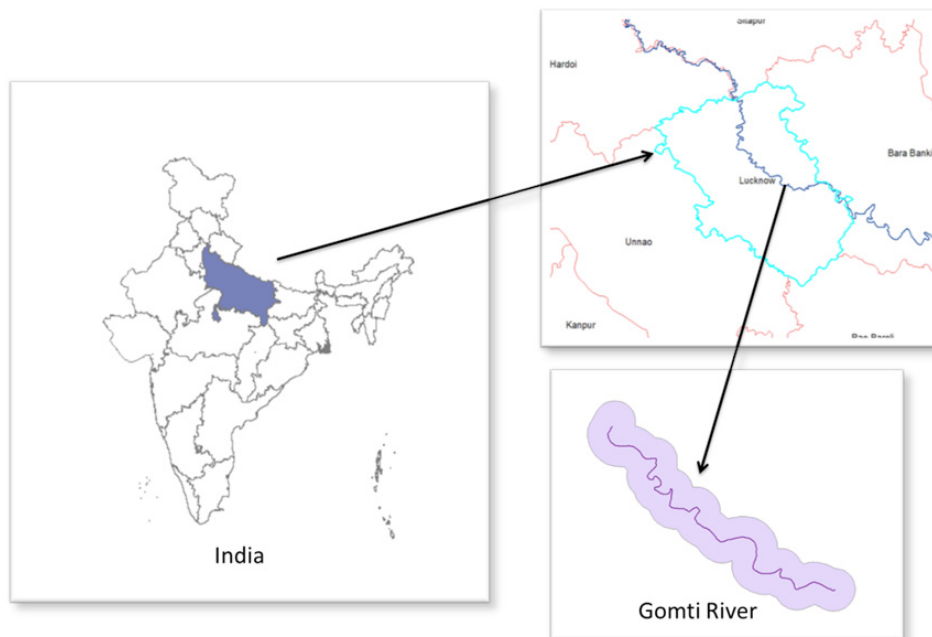


Fig. 1: Map of the study area

the downloaded satellite images, the cloud-free and better reflectance satellite images of recording dated 18/05/2014 and 26/05/2017 were selected for the study of LULC types. The diagrammatic sketch of the methodology used in completing the work is depicted in Figure 2.

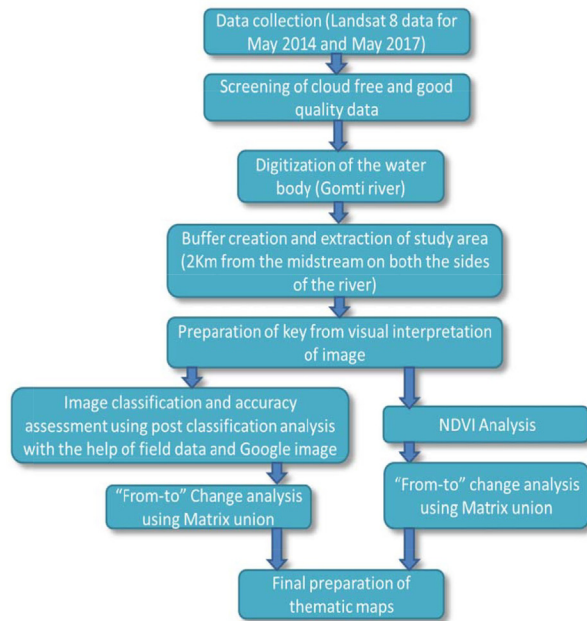


Fig. 2. Flow diagram depicting the study methodology

### Processing of satellite images

Out of all the reflective bands in the selected images, only the reflective bands 2, 3, 4 and 5 were used in the image classification. During the years 2014 and 2017, surveys were done to collect field data on different landscape features in the river corridor of the study area using the GPS. The selected images of May 2014 and May 2017 were geometrically corrected to Universal Transverse Mercator map projection system. To conduct this study, a buffer region of 2 km from the midstream on both sides was considered, which included riparian corridors, floodplain, and settlements. The river channel along with the buffer region was extracted from both May 2014 and May 2017 images. The area of the buffer including the river is 159.398 km<sup>2</sup>. The GPS data of the different landscape features in combination with the Google images of May 2014 and May 2017 and toposheet acquired from Survey of India were used for image interpretation, classification and evaluating the classification accuracy of the classified maps derived from remote sensing images. During the

field surveys, the hard copies of the false color composite of Landsat 8 images were used with GPS to correlate the different LULC features on the ground with the features on the map.

### Land use and land cover classification

To classify images the selected images, interpretation keys were prepared from the digital satellite images of both the years and unsupervised classification technique was applied. ERDAS Imagine 16 and ArcGIS 10.3 were used for LULC classification, change analysis studies and preparation of the thematic maps from the digital satellite data. Based on the LULC properties of the study area, a classification system of six classes was designed. These classes are water body, dense vegetation, sparse vegetation, built-up, open land, and wasteland. We created two sets of ground truth samples for images of May 2014 and May 2017 out of which, one was used as a training data set and other as testing data set for accuracy assessment. However, out of 6 classes, there were other classes which were misclassified during the classification process of LULC types with the certain built-up area having similar spectral characteristics as of wasteland.

### Post classification refinement and accuracy assessment

The post classification refinement of the classified images was done using the Google images of May 2014 and May 2017 and the field data collected using GPS. This was done to improve the accuracy of the classification because of the simplicity and effectiveness of the unsupervised classification technique.

### Land use and land cover change detection analysis

This study employs change detection analysis after post classification refinement of the classified images of May 2014 and May 2017. To do the change analysis firstly, a comparison between the classified thematic images covering 6 classes was done by comparing their histograms. Thereafter, the matrix union technique was applied on the classified thematic images that provided a new thematic layer of changed classes containing different combinations of "from-to" for all the 6 classes.

### Vegetation health analysis

To study the vegetation health in the river corridor, the normalized difference vegetation index (NDVI)

was applied to the raw images of May 2014 and May 2017. There are many indices for highlighting vegetation areas on a remote sensing scene. NDVI is the most commonly and widely used vegetation index. Studies have shown that NDVI is better in demonstrating the vegetation change detection (Bhandari *et al.*, 2012). Comparison of NDVI with other techniques such as PCA, unsupervised and supervised classification for detecting vegetation responses to climatic factors and vegetation regrowth patterns was found to be much accurate (Jeevalakshmi *et al.*, 2016). The calculation for NDVI is based upon the ratio difference between measured canopy reflectance in the red and near-infrared bands respectively (Gandhi *et al.*, 2015).

$$\text{NDVI} = \text{NIR-red} / \text{NIR+red}$$

NDVI was calculated for all scenes. To assess the change in the vegetative health in the corridor of the river Gomti, a comparative analysis between the NDVI images of May 2014 and May 2017 was done using the matrix union method as described above. Table 1 shows the groups and classes used for modeling the NDVI and detecting changes in the different classes of vegetation.

**Table 1.** Groups and classes of Digital Number values used for vegetation change detection

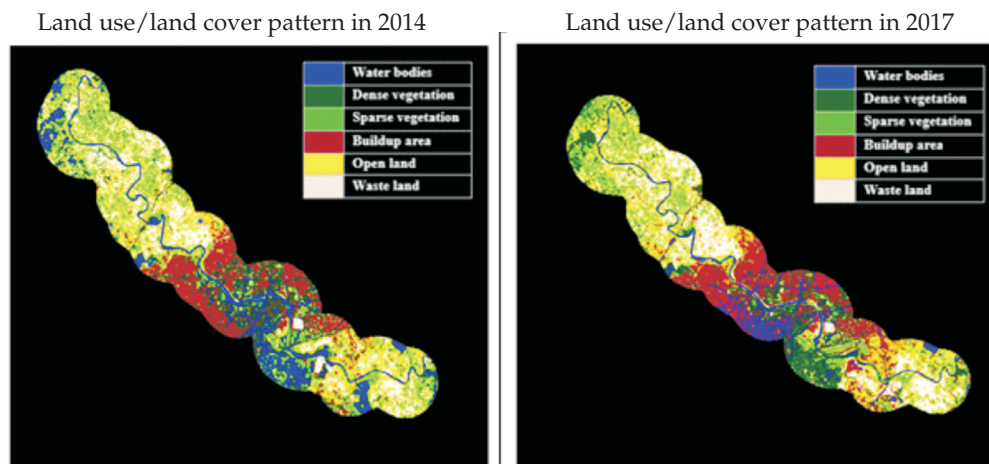
S. No.	Groups	Classes
1	Below 0.1	No vegetation
2	0.1 to below 0.2	Bare soil with some vegetation
3	0.2 to below 0.3	Moderate vegetation
4	0.3 and Above	Dense vegetation

This classification of NDVI classes was done based on the digital number value (DN) of the pixels.

## Results

The post-classification refinement analysis of the classified images of May 2014 and May 2017 provided the précised classified LULC maps featuring six classes. Figure 3 shows LULC maps featuring six classes and Table 2 presents the area covered by the six classes in May 2014 and May 2017. From this table, it is evident that there is a change in the area of each class from 2014 to 2017. The data in Table 2 shows a decrease in the area of water, sparse vegetation and wasteland. On the contrary, it shows an increase in the area of dense vegetation, built-up and open land.

From LULC maps depicted in Figure 3, the inland water bodies show a decrease in area from 18.43 Km<sup>2</sup> in 2014 to 11.89 Km<sup>2</sup> in 2017. This decrease in area covered by the river Gomti is a clear indication in the change of river channel width, deepening of the river channel covering most of the water in less area. Further, construction of the rubber dam might have resulted in ponding of the maximum rainwater in the city from Gomti barrage to the rubber dam. There is a possibility that the river might have also lost its connection with the groundwater due to the construction of deep diaphragm walls on both sides on the bank of the river channel. A fluctuation of 35.49% was recorded in the area of water bodies in the study area. An increase in the area of the dense vegetation cover was recorded from 22.88 Km<sup>2</sup> in 2014 to 26.76 Km<sup>2</sup> in



**Fig. 3.** Change in Land use/land cover in river corridors between 2014 and 2017

**Table 2.** Land use/land cover pattern in the corridors of the river Gomti at Lucknowcity with a change in the area of each class

Land use and land cover classes	Area in 2014 (km <sup>2</sup> )	Area in 2017 (km <sup>2</sup> )	Area change from 2014 to 2017 (km <sup>2</sup> )	% change in the area of classes from 2014 to 2017
Water	18.43	11.89	-6.54	-35.49
Dense vegetation	22.88	26.76	3.88	16.95
Sparse vegetation	27.45	19.25	-8.96	-29.86
Built-up area	26.29	32.61	6.32	24.05
open land	38.62	41.12	2.50	6.47
Waste land	27.04	26.87	-0.17	-0.61

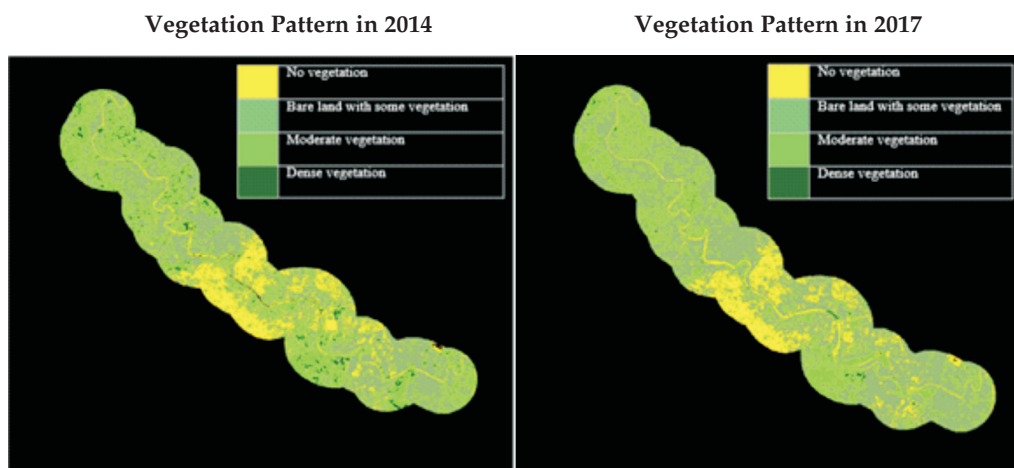
2017. The area under the sparse vegetation was found decreased from 27.45 Km<sup>2</sup> in 2014 to 19.25 Km<sup>2</sup> in 2017. An increase in the built-up area was noticed in 2017 (32.61 Km<sup>2</sup>) from 2014 (26.28 Km<sup>2</sup>). Moreover, over the past four years, the area of open land was found increased to 41.11 Km<sup>2</sup> from 38.62 Km<sup>2</sup>. This increase in the area of open land is majorly due to the clearing of land for construction of riverfront as well as for other human requirements. In wasteland, no significant change in area (-0.61%) was noticed.

NDVI analysis of the satellite images of May 2014 and May 2017 is depicted in Figure 4. The area covered by the different classes of vegetation and per-

centage change in each vegetation class is presented in Table 3. From this table, it is evident that a decrease in the vegetative coverage was found in all the three classes except bare land with some vegetation class. This increase in the area of bare land with some vegetation is a result of recent land cleaning and plantations done in the past years. However, the decrease in both moderate and dense vegetation of -9.36 Km<sup>2</sup> and -5.0 Km<sup>2</sup> respectively is a clear indicator of cleaning of the high rise grasslands, cutting of trees and conversion of lands into paved walkways near the riverfront and other developmental works on the cleaned land areas. Further, the recent construction activities and an increase in the

**Table 3.** Change in area under different vegetation classes in the corridors of the river Gomti River at Lucknow city

Categories of NDVI	Area in 2014 (km <sup>2</sup> )	Area in 2017 (km <sup>2</sup> )	Area change 2014 to 2017 (km <sup>2</sup> )	% change in area
No vegetation	21.15	19.28	-1.87	-8.84
Bare land with some vegetation	90.97	107.14	16.17	17.78
Moderate vegetation	40.77	31.42	-9.36	-22.95
Dense vegetation	6.51	1.51	-5.01	-76.88

**Fig. 4.** NDVI images of 2014 and 2017 in the corridors of the river Gomti at Lucknow

urban sprawl have also resulted in the cleaning of the densely vegetative areas in the city.

## Discussion

This study highlights comparative evaluation of the landscape features in the corridors of the river Gomti using the pre and post channelization effect. This channelization of the river Gomti in the Lucknow city is a result of a riverfront development project, which has changed the variety of landscape elements present in the river corridors in a short span of time. Such pace of developmental activities in the corridors of the river Gomti has disturbed the surface waters quality, the fluvial stygoscape, riparian systems, and geomorphic features of the river (Dutta *et al.*, 2018). The naturally present vegetation categorized as moderate and dense, which were noticed decreased over years are the results of long landscape evolution and these are predominantly responsible for sustaining a high level of landscape diversity in the river corridors (Lees and Peres, 2008). An increase in the built-up area in the corridors of the river Gomti could be a threat to the species pool of both terrestrial and aquatic communities dwelling in the lentic, lotic, riparian and associated habitats. Since the riparian zones are heavily affected by the adjacent conditions (Pascacio *et al.*, 2018), such influences in the riparian zone of the river Gomti are inevitable. Further, the riparian areas adjacent to the grasslands, crops and human settlements were found from bad to moderate condition (Rodríguez and Ramírez, 2014). Additionally, the human settlements are moving close to the river Gomti because of an increase in urbanization and channelization of the river corridors. It is well evident that reaches close to the human settlements are heavily impacted and studies have shown that urbanization is the biggest land use factor severely affecting the riparian corridors (Pascacio *et al.*, 2018). The elevation of banks, construction of levees, pavements and walls increases the proportion of impervious surface in the river corridors which could be an outcome of the land use change in the urban areas ultimately intensifying the degradation of fluvial ecosystems (Walsh *et al.*, 2005). Further, it is obvious that paving and compaction of the riverine corridors alter the riverine ecosystem services by altering the flood capacity, flow pattern (Rodríguez and Ramírez, 2014), habitat availability (Tánago and Jalón, 2006) and water quality of stream (Pascacio *et*

*al.*, 2018) Undoubtedly, the proportion of impervious surface in the corridors of the river Gomti after implementation of the riverfront development project has considerably decreased the overall water width and depth in the river Gomti in the Lucknow region due to channelization. The average pre channelization width and depth at the Lucknow region was 128.98 m and 2.94 m respectively in 2008, which has been decreased to 104.25 m and 1.996 m in 2016 (data source: CWC). The studies have shown that the natural streams have more variability in terms of channel depth, channel width, flow velocity, bedforms, substrate composition and ecological habitats. In the process of channelization, the naturally sinuous streams get converted in more straight channels with homogenized channel morphometry, hydrology and sediments structures (Kairo *et al.*, 2017). Because of these, the habitat degradation and variability loss have become the major threat to the running water biodiversity of the river Gomti. The absence of deep pools, slow water alternating with shallow areas, swift water in the channelized part of the river Gomti were noticed in the present study, which makes the stream less habitable for most of the aquatic organisms except which prefer fast flowing waters (Hartson *et al.*, 2014). Further, less number of chutes and sloughs in the river channel were noticed in the study area that make the channelized river less suitable for spawning and nursing site, as a result, fishes migrate. During low flows, it was found that natural sinuous streams have more water storage than a channelized stream what presently the river Gomti suffers. It is well evident that in a channelized stream, the total drift of invertebrates becomes comparatively low (decrease in the standing crop) (Kairo *et al.*, 2017) because of which the amount of food availability decreases resulting into competition for the available food among fishes. A site located just below the channelized reach also experiences a huge disturbance in the types of sediment deposition and overall in-stream dynamics. Thus, the complete downstream reaches get affected in an unpredictable manner. In addition, channelizing a river/ stream isolates it from the surrounding riparian areas (Kennedy and Turner, 2011).

Finally, this is to be said that the improvements in the Gomti river basin at Lucknow city could have been better if the development program would have been implemented with community participation and rigorous environmental impact assessment pro-

cess. The community participation in such activities acts as a catalyst in the final success of riverfront development and recreation of the riverfronts. This project aimed to repair and enhance the environment by connecting the neighborhood to the river and its riparian corridors. Further, the benefits of the wider riparian buffer of the river corridors in the urban landscape planning should be recognized and considered. The development done so far on the river Gomti at Lucknow city lacks adequate open space and buffer zones for providing the better and enhanced ecosystem services to the biological communities in their niche, ecological restoration for improving ecological services, increased habitat corridor potential for different biological communities and finally the conservation and improvement of overall biodiversity. However, the success of this project bridged the gaps between society and the river and society started valuing the river and its corridors.

## Conclusion

This study used geospatial techniques to derive the information on different landscape features in the corridors of the river Gomti and analyze the drivers causing changes in the different landscape features. The use of temporal satellite data for the study area has provided ample information on changes that occurred in the corridors of the river over a short period of time. In the study, efforts were made to map and document the information on different landscape features like river boundary, water extent boundary, land use/land cover types, built-ups/settlements and vegetation type, which could be useful for planning, monitoring, and management of the landscape resources. The combination of moderate and high-resolution data (Landsat 8 and Google earth Images) provided detailed land use/land cover maps at good classification accuracy ( $\geq 90\%$ ) for implementing future restoration and regulatory measures in the corridors of the river. The study done so far supports that restoration works may improve the overall ecological condition in the channelized stretch of the river. The implementation of the riverfront development work on the banks of the river Gomti and rapid expansion on both banks brought out the significant changes in the landscape attributes in the riparian cover. Overall, the study showed a change in the different landscape features and decline in the river structure,

geomorphology and vegetation quality, and type. The expansion in urban settlements, construction of impermeable surfaces on the banks of the river and increase in the urban sprawl in the corridors of the river Gomti were evaluated as prime drivers for the deterioration of fluvial ecosystem functions, which can make the restoration work difficult in future. To rejuvenate the river, the river restoration projects should be of longer duration so that the environmental impacts of the projects could be studied at each level of implication and improved before moving to the next phase.

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## Effective framework for Environmental-flows estimation for data deficient Indian rivers

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### Abstract

Data deficiency is a major problem in recommending appropriate environmental flows (e-flows) requirements for rivers in many parts of the world. Several studies have been done using a variety of e-flows assessment methodologies. Large dams and hydropower projects are major manipulators of the flow regimes resulting in degraded ecosystems ubiquitously. In India attempts have been made to develop e-flows requirements of rivers to maintain a good riverine ecosystem. Most of the studies are based on hydrological methods, which do not take all the variables affecting flow-regimes into consideration. This paper highlights the problems in assessment of e-flows and their on-ground implications in India. In this study, probable solutions to these problems are suggested a conceptual framework for data deficient areas is proposed. This framework is based upon extensive baseline surveys of fluvial morphology, ecology and of indigenous population. Framework has six steps namely: monitoring the baseline conditions, setting up objectives, hydrological analysis, ecological analysis, climatic anomalies incorporation and recommendations. Finally, e-flows recommendations are made based on hydrological studies, habitat suitability curves and area of inland water body which should be maintained in the river basin. All these recommendations are compared and suitable e-flows recommendations are made based on studied variables. The review also suggests for bottom-up approach for e-flows assessment i.e. e-flows assessment and application should be done on small tributaries of rivers in initial phase of projects and those methods which deliver satisfactory results should only be applied to larger rivers.

**Keywords:** Environmental flows, River basin management, Data deficiency, Indian rivers, Framework design

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### INTRODUCTION

India has a large network of rivers over which people depend for socio-economic and cultural needs. Physiologically all these river systems are characterized by large seasonal variation in their discharge due to seasonal rainfall and prolonged dry periods. The mainland has 19 major (Amarasinghe *et al.*, 2005), 45 medium and 120 minor rivers which are grouped on the basis of origin into Himalayan and peninsular rivers and east flowing or west flowing on the basis of direction of flow (Rao, 1975). With changing land use pattern, inefficient agricultural practices, growing urban and industrial water demand and high demand of energy, the river system is getting highly disturbed due to which several rivers are under stress conditions (Richter and Thomas, 2007). As per the National Water Policy-2002 water allocation for ecosystem is 4th priority, and there is no mention in water allocation and demand assessment about water required for maintaining river ecosystems (NWP, 2002, 2012). Least preference

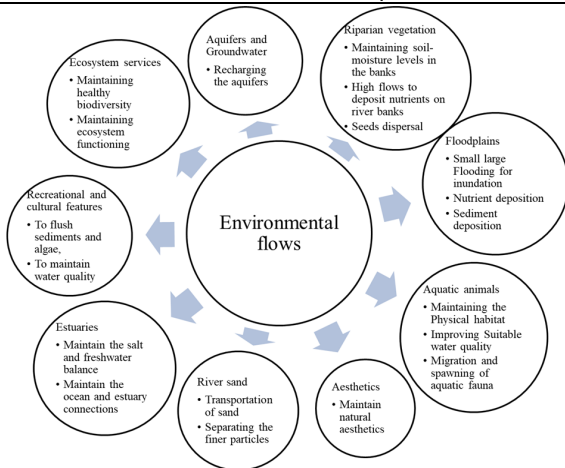
for water allocation has been given to maintain river health and its ecosystem in all the developmental processes (Smakhtin, and Anputhas, 2006). In India overall water demand is growing at a very high rate of 62.95% i.e from about 656 Km<sup>3</sup> in 2010 to 1069 Km<sup>3</sup> in 2050 (Thatte, 2009).

In India, a few attempts have been made to evaluate the environmental flows (e-flows) requirements of River systems in past few years. However, the integrated river basin management plans are still lacking in incorporating the e-flows assessment in the planning processes. Being ecologically and culturally diverse, the requirements and availability of river water is not same at all the places in India (CISMHE, 2007). The concept of maintaining the minimum flow in Indian rivers is considered as e-flows for the river (Durbude, 2014) but it cannot work for all water bodies as each water body has an individual natural flow regime (Acreman and Ferguson, 2010).

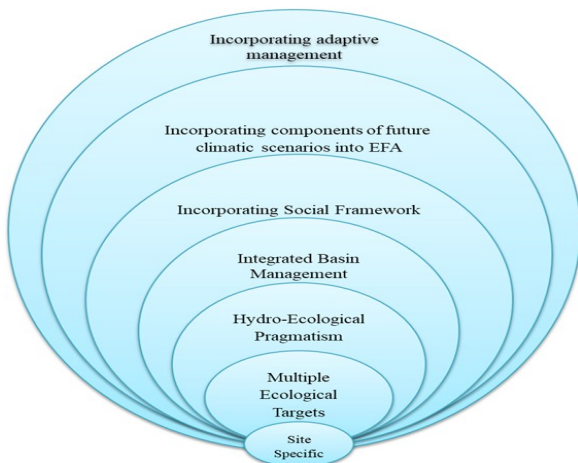
**Environmental flows: Overview, need and evolution:** Rivers are lotic water systems which drain landscape, include the biotic interactions among

**Table 1.** E-flows definition given by different institutions.

Organization	Definition of e-flows	Reference
World Bank	The quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems which provide goods and services to people	Richard and Hirji, 2003
IUCN	The water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated	IUCN, 2011
Conservation Gateway	The quantity and timing of water flows required to maintain the components, functions, processes and resilience of aquatic ecosystems and the goods and services they provide to people	Conservation Gateway, 2010
International Rivers organization	Quantity, timing, and quality of water flows below a dam, with the goal of sustaining freshwater and estuarine ecosystems and the human livelihoods that depend on them	International Rivers organization, 2014

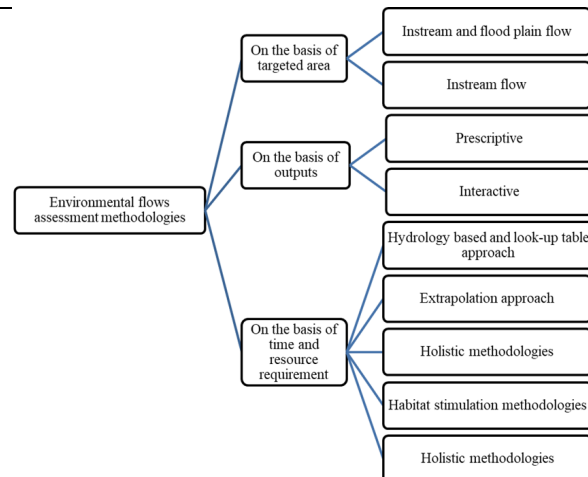


**Fig.1.** Ecological and social components of river and their associated functions needed to be addressed while recommending e-flows (Source: Author's own elaboration).

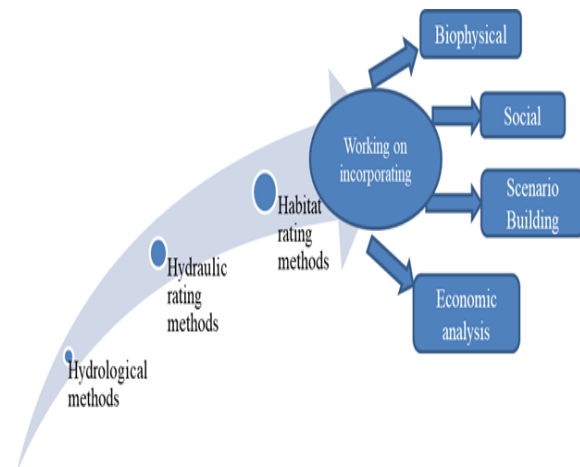


**Fig. 2.** The evolution of e-flows methodologies from simple and site specific to more robust methodologies incorporating multiple indicators (Source: Sharma et al., 2016).

flora, fauna and micro-organisms, along with facilitating abiotic physical and chemical interactions. These lotic systems need water to stay flowing and deliver variety of ecosystem services (Finn and Jackson, 2011, Wantzen et al., 2016). The



**Fig. 3.** Classification of e-flow assessment methodologies based on their targets, output and requirements (Source: Author's own elaboration).



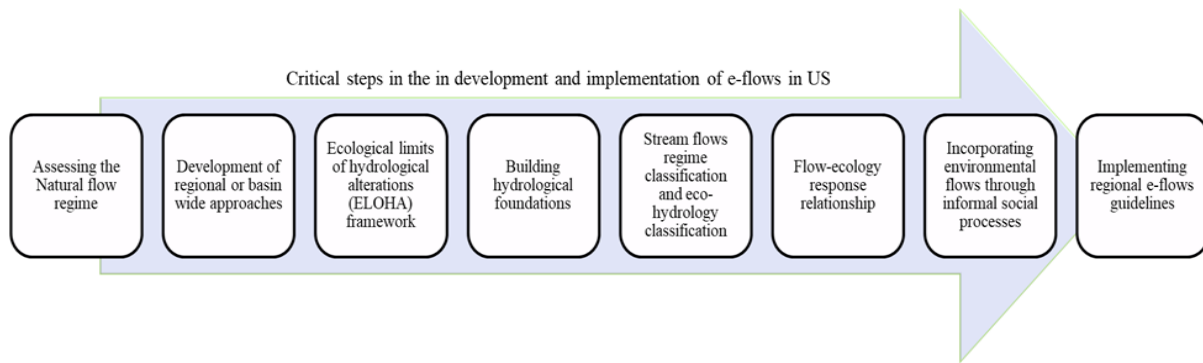
**Fig. 4.** Evolution of e-flows methods in South Africa and future desired inputs (Source: Author's own elaboration).

construction of dams and over water abstraction has resulted in disturbing riverine ecosystems (Poff et al., 2017). Pollution loading from point and non-point sources is another big problem and reason for degradation of riverine ecosystems. To

**Table 2.** Showing the studies done different on Indian Rivers, methodology used and recommendations of the study.

S.N.	Location	Methodology used	Recommended e-flows	Recommendations	Reference
1	Cauvery River	hydrological index methods, look up tables, EMC-FDC approach, Tennant and modified Tennant method	Name of the Site Belus Hadige Akkihebal Kollega Maintenance flow (cumec day) 5.32 20.79 12.24 91.22	Maintain the minimum flow in the river to maintain the river ecosystem. Look up table may not be appropriate for Indian condition.	Durbude (2014)
2	Upper Ganga Basin	Building Block Methodology	Name of the Site Maintenance flows as % of MAR Drought year flows as % of MAR Kaudiyala Kachla Bithoor 72% 45% 47% 44% 18% 14%	Site specific e-flows Can be applied to other rivers	WWF-India (2012)
3	Mahanadi River	the Tennant method and RVA (Range of Variability Analysis) uses IHA (Indicators of hydrologic Alterations)	Tennant method: minimum (low) flow should be higher than that of 7-day minimum predicted by the RVA analysis For excellent habitat: MAF for the month of October-March (4.93-161.91 cumec) and April-September (62-1186.5 cumec) for the years 1978-2010.	Low flow: Defined as 10% of the total flow (Montana method), whereas for the 7-day minimum flow (RVA analysis), low flow is less than 10% of the total annual flow. As per the results Tennant method isn't applicable for this basin	Bhattacharjee and Jha (2014)
4	Alaknanda and Bhagirathi	Hydrological Index method: Look up table and Q90, Q95 method	Maximum and minimum e-flows recommendation 2% to 15% of MAR	No seasonal recommendations were made to address river variability, Study does not address the cumulative impacts of current power projects.	AHEC (2011)
5	Alaknanda and Bhagirathi	Building Methodology (BBM) and Habitat Method	e-flows were recommended to maintain 'C' Environment Management Class, based on flow requirements for two species mahseer and snow trout: the mahseer and snow trout zone no fish zone only for the lean season other dry zones 21.8% of Mean Seasonal Flow 14.5% of the Mean Seasonal Flow 20% of monthly average flow from November to March 25% of monthly average flow in October and April 30% of monthly average flow from May to September	EMC approach is based on two species only the Golden mahseer and snow trout. In conducting a holistic study they missed on socio-economic and cultural impacts, and hence the objective setting is not very clear	Wildlife Institute of India (2012)
6	Brahmani and Baitarani River	Flow Duration Curve approach	FDC were computed for 1-day, 7-day and 30-day mean, the results suggested the 7Q10 FDC was recommended for drought years/low flow periods and 7Q100 FDC was found appropriate for normal precipitation years.	The 7Q10 of FDC yearly mean is beneficial in: protection or regulation of water quality from wastewater discharges or waste load allocations, habitat protection during drought conditions, chronic criteria for aquatic life, and A local extinction flow. 7Q100 is not a common practice	Jha <i>et al.</i> (2008)
7	Sone River (Maikalsut)	Global Environmental Flow Calculator (GEFC), desktop software by International Water Management Institute (IWMI) based on Flow Duration Curve (FDC) approach	Name of the Site flows as % of MAR Indrapuri Barrage 5.16% and 2-5 % wetted perimeter	As per the analysis: 18.9 % of MAR is required to restore the stretch from Critically modified (F) to Moderately modified Class (C), and to Slightly modified Class (B), 34.2 % of MAR will be required.	Jha <i>et al.</i> (2014)
8	Kumbh mela (At sangam) in Allahabad	Building Block Methodology	Kumbh mela water depth: 1.2 m for Entire Duration and a stage of 73.53±0.11 m Flow: 225 cumecs (7,950 cusecs) surface width: 175 m Special Snan Days: depth of 1.5 m, a stage of 73.83±0.11 m Flow: 310 cumecs (10,950 cusecs).		WWF-India, (2013)
9	Bhadra River	Tennant method (Tennant law (TMC) analysis)	8,855 TMC 26,565 TMC 53,129 TMC poor flow at 10%, moderate flow at 30% excellent flow	Downstream to the Bhadra reservoir 10 times the flow was above the excellent flow conditions. 12 times flow was meeting the poor conditions 10 times flow was above Moderate flow conditions	Babu and Kumara (2009)

(Source: Adopted from Dutta *et al.*, 2019 and modified from various sources)



**Fig. 5.** Critical steps in expansion and implementation of e-flows assessment in United States (Source: Adopted from Dutta *et al.*, 2019)

compensate for changes of flow for the regulated rivers, water may be released from dams and in case of unregulated rivers the over abstraction of water from the river should be protected. For the very first time the e-flows were defined during Brisbane Declaration held in 2007 which stated e-flows as 'the quality, quantity, and timing of water flows required to sustain freshwater, estuarine ecosystem and the human livelihoods' well-being that depend on these ecosystems' (Brisbane Declaration, 2007). This definition was further modified in 2018 and the importance of social and cultural dimensions in e-flow management was also addressed (Arthington *et al.*, 2018). The revised e-flows definition states "environmental flows describe the quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being". Other attempts were also made to define the e-flows as per their understanding and requirements of water flow (table 1).

Rivers naturally experience periods of very low or no flow or it could be flooding that occurs every year or occasional large floods that spread out onto floodplains (Richard and Hirji, 2003). This variability of flows is very important in maintaining the functionality and resilience of the river ecosystem and it is very important for the recommended environmental flows to mimic this variability. The river in its undisturbed naturally flowing state is called as the pristine. To fulfill the growing water demands, the natural form of the rivers gets distorted and thus the need to restore the pristine or near pristine flows in the river system came into picture. However, the environmental flow regimes allow for some degree of hydrologic alteration unlike the natural flow regime.

Variable flow is the master variable should be maintained in the river stream to maintain and protect river features such as aquatic animals, riparian vegetation, river sand, estuaries, aquifers and ground water, aesthetic value, recreation and cultural features, ecosystem services as well as overall functioning of environment (Bunn and

Arthington, 2002, Lytle and Poff, 2004, Acreman *et al.*, 2014a, Brisbane Declaration, 2007, Poff *et al.*, 2010). A peculiar flow pattern of every river determines the shape of its stream channel, its stream habitats and its biotic components. Both low and high flows are equally important in maintaining diverse flora and fauna (Arthington *et al.*, 2006, Yarnell *et al.*, 2015). Low flows are important for organisms which require low flow velocity whereas small floods are important for fish spawning, flushing away pollutants, cleaning up the river beds, sorting the river stones thus giving a new habitat for seed germination and migration of fishes in river (Yarnell *et al.*, 2015). Large floods are important for maintaining the river channel, cleaning up cobbles and boulder on the river bed, transportation of silt, deposition of silt, eggs and seeds, recharging of soil moisture level in river banks. Large floods occurring once 8 to 10 years are mandatory to clean the connection between estuaries and sea, inundating the back water and promoting growth of new species in the floodplains. These variable flows are also important for creating geological barriers for speciation. Thus any alteration in the flow pattern can lead to depletion in water quality, establishment of invasive species and loss of biodiversity. The ecological and social components of river and their associated functions need to be addressed while recommending the e-flows (Fig.1).

In other parts of the world, the e-flows assessment studies have started with simple hydrological studies which in due course of time have evolved to more robust and suitable for their rivers (Acreman *et al.*, 2014b, Arthington, 2015, Poff and Matthews, 2013, Poff *et al.*, 2017). These studies have also been adapted to other places to manage their rivers to their near natural or pristine forms. Fig. 2, illustrates the evolution of e-flows methodologies from simple and site specific to more robust methodologies incorporating multiple indicators. India is a developing nation, which is in a state of rapid development Thus, it is a crucial to have a robust and well-studied water management plans and infrastructure. Developed nations

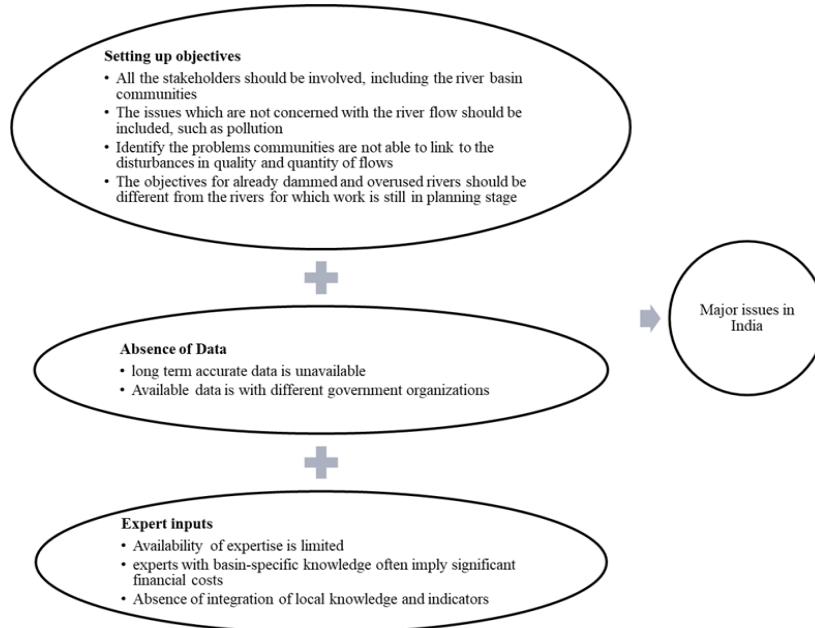


Fig. 6. Major issues identified in e-flows assessment in India (Source: Author's own elaboration).

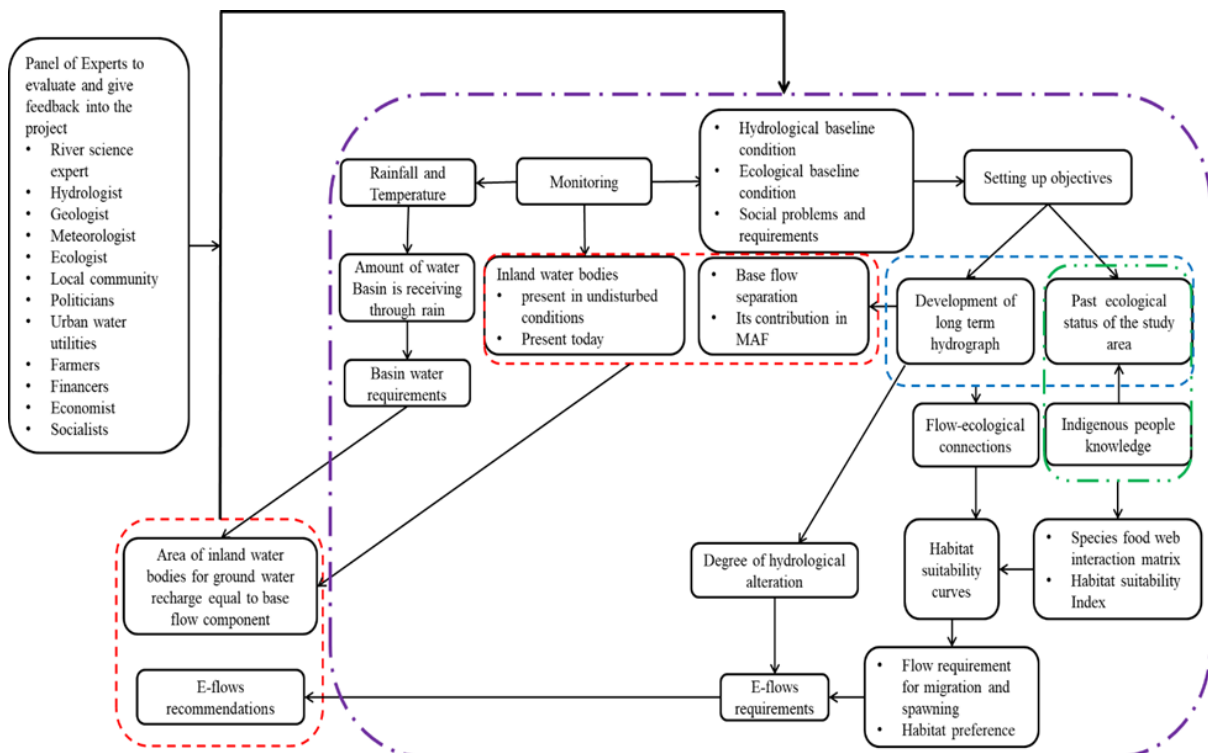


Fig. 7. Framework for determining environmental flows requirements for data deficient Indian rivers (Source: Author's own elaboration).

have gone through this stage years back where they have regulated their water bodies to a major extent to store water and harness hydro-energy. However, it took them many years to Figure out the adverse effects those ambitious programs had on the local biodiversity and river ecosystems. Even today large sections of the rivers are getting modified due to damming, channelization and water diversion projects such as Mekong Basin

Southeast Asia has more than 80 dams in process (Verma *et al.*, 2009), Himalayas in India has over 300 (Grumbine and Pandit, 2013) and Andes has more than 150 (Finer and Jenkins, 2012) dams which are resulting in drought conditions in the lower basin areas of the rivers (Poff and Matthews, 2013). River Gomti had got channelized as a result it has lost its natural flow and biodiversity (Dutta *et al.*, 2018). E-flows assessment method-

ologies have been categorized into broad categories based their targeted areas, output requirements and resource and time requirements (Fig. 3).

In United States and South Africa, multiple methods have been developed for e-flows assessment and are still working on improving the existing methodologies. South African scientists have used Hydrological, hydraulic rating and Habitat rating methods, yet they are not able to deliver the satisfactory results to manage their rivers (King and Brown, 2006, King and Brown 2018). Further studies are under process to incorporate the biophysical, social, scenario based and economical analysis. In US, work is in process to suggest and implement the e-flows through strict guidelines on regional basis (Poff *et al.*, 2007, Poff *et al.*, 2010, The Nature Conservancy, 2012, Poff and Matthews, 2013, Poff *et al.*, 2017).

**Effect of hydrological alteration and e-flows study in India:** India is home for variety of rivers, each behaving in a very distinct way in terms of its flow, channel forms and biodiversity supported. Half of rivers are perennial and half are seasonal. Most of the perennial rivers originate from Himalayas and most of the seasonal rivers originate from peninsular ranges. Himalayan rivers get their flow from snow melt and monsoon water both and keep flowing round the year. Peninsular rivers receive water from monsoon rains due to which they have alternate wet and dry period of flow. We are constantly developing structures to tap or store the water at its place or far from its natural pathways. This has left desiccated rivers, life less with distorted ecosystem and loss of livelihoods. Anthropogenic articulation to prevent every single drop of water from going into sea; thus disturbs the whole water cycle which changes the ecological processes downstream to the dams and sets in motion a complex chain of reactions that completely transform the floodplain vegetation dynamics (Wieringa and Morton, 1996, Pandit and Grumbine, 2012). Very few studies have been reported in India to study the effect of hydrological alterations on the terrestrial and downstream riparian ecosystems (Dudgeon, 2000, Grumbine and Pandit, 2013). Study done in Himalayan region pointed the adverse impacts on terrestrial biodiversity in the Indian Himalaya as well as the trends of land-use changes from 292 dams proposed by Government of India (Pandit and Grumbine, 2012, GOI, 2008). The ambitious projects to harness maximum hydropower are showing continental-scale effect favoring spread of cosmopolitan, non-native species on the expense of native biota (Poff *et al.*, 2007). Maximum hydropower projects in India are proposed in species-rich subtropical and temperate zones in the Indian Himalaya (Pandit, 2007). Not just the damming will alter the flow regimes it will also lead to

submergence of a large area resulting in direct elimination of species and land use change. Other negative impacts will be fragmentation, loss of forest, sudden species loss and loss of livelihoods of the local inhabitants of that area (Terborgh, 1974, Terborgh *et al.*, 2001, Pandit, 2013, Grumbine, and Pandit, 2013). Study done on Bhadra River at Lakkavalli, Shimoga District of Karnataka State (India) focused on the adverse ecological impacts downstream of Bhadra Dam (Kumara *et al.*, 2010). Downstream to the dam the river bed is gradually shrinking as a result a massive loss of riparian, aquatic habitat and water quality is visible. The disturbance in the natural ecosystem of Bhadra River has not only effected the riverine vegetation, birds, reptiles and various aquatic life forms but also more than 60% of the downstream dwellers have changed their livelihood occupations. Another study was done to study the effects of Sardar Sarovar Dam in Kutch, western India, showed that the extensive canal networks of large dams in Rajasthan have made the deserts bloom same as happened in Arizona (Mehta, 2001, McCully, 1996). Attempts to understand the ecological dynamics and people interactions with the environment have been done with both local and scientific perspective (Dahlberg and Blaikie, 1999). In India the existing pattern of inter-state virtual water trade as another big issue which further exacerbates scarcity in already water scarce areas (Verma *et al.*, 2009).

In India, the e-flows assessment and environmental water demands has gained popularity in recent years. India is witnessing rapid urbanization, industrialization and intensification of agriculture, all of which is greatly affecting the rivers in different ways. This is resulting in degradation of the rivers and associated ecosystems. All this is not only limited to the environment, we humans are also suffering the consequences of all these developmental activities. In India very limited studies have been done to assess the environmental flows in river systems. The first National Workshop on Environmental Flows, held at New Delhi, in March 2005, brought together over 60 participants from national agencies and research institutions. The workshop generated a significant interest to the concept of environmental flows in the country and it also revealed the existing confusion in this field. One of the major problems with developing environmental flow work in our country is that despite existing significant knowledge on some aquatic ecosystem components (e.g., fish), its contribution in environmental flow assessments is still limited. There are few studies for e-flows assessment has been done in India.

This review highlights that studies done so far based on hydrological methodologies alone are unable to recommend suitable e-flows. The studies based on Holistic method Building Block Meth-

odology (BBM) lack in considering the holistic ecological conditions. As their e-flows recommendation are based on Environment Management Classes (EMC) which are not developed specifically for the studied area. The ecological requirements were based upon only two species thus effects on the overall food web and community interactions are not taken into consideration (Wildlife Institute of India, 2012). Thus there is a need for a framework suitable for rivers where suitable real time data is not available.

**Problem identification and effective framework for e-flows estimation:**

In India first National water policy was drafted in 1987 for planning, development and management of water resource. India's water policy was later amended in 2002 and 2012. In the first issue of National water policy (1987) the focus was on environmental protection and rehabilitation of project affected peoples and livestock, public health consequences of water impoundment and dam safety. With time new issues came into picture and further in 2002, 2012 National water policy (NWP, 2002, 2012) improvements were made to address the issues like water resource planning and watershed management strategies which emphasis on hydrological perspectives for management studies, soil conservation, catchment area treatment, preservation of forest, increase in forest cover and construction of check dams. However the effect of water storage behind dams, diversion and river basin encroachment were not paid much attention. Indian water policies have the following objectives:

- On priority water is allocated for different uses;
- Priorities are set among different uses of water;
- Conservation of water resources;
- Water is Implemented as the fundamental human right;
- Satisfactory water quality should be maintained for various uses;
- Safeguard water for human survival and poverty eradication;
- Water in India falls in Concurrent list thus power is considered by both the central and state government. When it comes to having a state water policy out of 29 states and 7 union territories only 14 states have their own water policies to manage the state water resources. Out of all the state policies only Assam state has a mention of water allocation for river life, flood management, wetland and water body restoration, watershed area management and environmental water allocation strategies. A Goa State policy has put special attention on the ecological sustainability of Western Ghats. The main loopholes in both National and state water policies is that they have not incorporated the ecological and environmental water requirements. In the planning process worldwide major issue is that human being is kept at the center of all the planning and management works.

Other problems include on-ground implementation of environmental laws incorporating the environment impact assessment. India's National environmental impact assessment (EIA) law enacted in 1994 with special concern for threatened and endangered species, protected areas, and other biodiversity concerns. But on ground application and strict implementation of these laws is still lacking. On paper their implication remains uncertain (Dudgeon, 2000), but slight attention had been paid to ecological evaluation and proper implementation of EIA processes in large-scale development projects in India (Pandit and Grumbine, 2012, Bandyopadhyay and Gyawali, 1994, Agrawal, 2010, Singh, 2006).

The other problems in assessment and recommendation of e-flows in India are setting relevant objectives, as there is no correct method for e-flows assessment its completely depends on the people, social, and political desires from a river (Anantha *et al.*, 2017, O'Keeffe and Le Quesne, 2009). Absence of real time, accurate data is another big issue and the data available is headed by different departments. The most crucial part is to have an expert of all the fields such as hydrology, hydraulics, geology, ecology, economics, and quality control. In the paucity of availability of such experts, getting the expert advice would incur significant financial costs (Anantha *et al.*, 2017). Major issues in conducting e-flows assessment in India are listed in the flow diagram (Fig. 6)

**E-Flows estimations framework:** Tropical rivers are very dynamic with a variety of flows and physical properties. In a developing nation, there is still time to learn from other's mistakes and plan for better future. In this study we have studied the e-flows assessment works done in India and the methodologies adopted to conduct these studies. In the light of the problems identified in this study we suggest solutions to the identified problems.

A single data repository should be constructed where data from all the government departments should be radially available.

A committee of 2-3 members of each field should be made having scientists from all parts of India. These scientists will not only bring their scientific knowledge but will also bring the indigenous knowledge in the assessment processes.

The process of objective setting should be done from river's perspective and not from human perspective.

The extra water available in river should only be eligible for abstraction. The urban water utilities should not only act as water suppliers or service providers rather they should focus on proper management of the available water resources in both demand and supply perspective.

Feedback mechanism and constant adaptation at in all the development projects around rivers.

This framework is designed to recommend e-flows requirements for data deficit areas. This method is a multi-steps process including extensive biological sampling and social surveys. This framework is based upon extensive fluvial morphology, ecological and social surveys. The steps of the designed framework are as follows:

**Monitoring the baseline conditions:** This step includes the survey of the fluvial morphology and ecology of the study area.

Further the social surveys were conducted to understand their association with the river. These surveys also helpful in understanding the riverine condition prior to the disturbances occurred in recent years.

Thus these surveys will help in understanding the extent of damages River and its ecosystem had gone.

**Setting up objectives:** Objectives were set from the river's perspective i.e River should be able to sustain its ecological services.

The problems and requirements of indigenous peoples directly dependent on river for their socio-economical requirements should also be considered.

**Hydrological analysis:** Hydrological data is used to develop long term hydrographs, to understand the variability of flow river experiences.

The base flow share in the mean annual flow was also estimated.

The baseline hydrographs were compared with the historic hydrographs to understand the degree of hydrological alterations.

E-flows estimation was done based on hydrological and hydraulic methods.

**Ecological analysis:** The food and habitat preference of all the aquatic fauna were studied.

The indigenous people knowledge about the changes they have noticed in the aquatic biodiversity was recorded. The secondary data available in public domain as well as with government organizations were also incorporated in the study.

The species food web interaction matrix and habitat suitability index were prepared. Based on the habitat suitability matrix for most dominant and species acting as interlinks between the food chains, e-flows requirements for migration and spawning was recommended.

**Climatic anomalies incorporation:** Rainfall and temperature data was used to estimate the net amount of water river basin is receiving. This will be helpful in estimating the area of inland storage required to store this water was estimated.

**Recommendations:** The environmental flows requirements based on the method.

The area of inland water bodies should be present in the basin to sustain the base flow requirements. In this method, focus is to have decentralized water storage systems in the basin rather stressing the river to meet all the water requirements. Fur-

ther we propose that water left after meeting the river's requirements should only be abstracted from the river. This amount of water abstracted should be managed in the best by the water utilities. Here the role of water utilities should not only be of a water supplier but they should act as an integrated part of water resource management. The water utilities view their role as:

**Water supplier:** Their role should be to evaluate water availability, consumer demand, and treatment capacities required.

**Service provider:** As a service provider the role should be to provide quality services and built efficient treated water supply and wastewater collection system.

**Integrated water resource management:** Return water back to nature of quality harmless to natural water bodies.

Feedback is an important component for success of any project. The feedback system should be composed of experts from all the fields associated thus they can bring their knowledge into the next stage of the work. This will be helpful in addressing issues from all the associated spheres and would increase the chances of getting a success multiple folds.

## DISCUSSION

In data deficient areas such as India, it is a tricky job to conduct e-flows assessment studies. The studies reported so far are based on hydrological methodologies (Jha *et al.*, 2008, Babu and Kumara, 2009, AHEC, 2011, Durbude, 2014, Bhattacharjee and Jha, 2014) and only a few studies have used holistic methods (Rajvanshi, 2012, WWF, 2012, 2013.). There is no study done reporting the implementation of recommended e-flows and its outcome. Lack of strong legislature remains a loophole in on-ground implication of e-flows assessment exercise for all river basins of India as well as to implement it on ground. We are still in the developing stage so we have an advantage of learning from others mistake and success stories in developing our own e-flows assessment frameworks. In place of top down approach in river management plans i.e. we are currently focusing on managing large rivers first and no focus is on small tributaries. It could be dangerous as we are still in phase of hit and trial process of using e-flows assessment methodologies. Rather we should adopt bottom-up approach i.e. we first start managing small tributaries and those methods which deliver satisfactory results should be taken further for managing larger rivers. In this study a conceptual framework is developed for recommending e-flows in data deficient rivers. This study is mainly based on base line conditions present and the conditions present in long past at the study area. This framework has six steps to recommend e-flows, as well as the area of inland

water bodies required for adequate ground water recharge to be maintained the base flow component in the river basin. The feedback system of this framework is an important step to fulfill the knowledge gaps in this framework (Wohl, 2015) as all these experts will bring knowledge from their allied field. This step will help in improving this framework at each stage of its commencement. Thus, this method will be able to reach long term goals of river basin management for data deficient rivers with its flexibility and adaptability.

## Conclusion

Data deficiency is a major issue in recommending the appropriate e-flows requirements. India being a developing nation lacks in accurate real time data collection for majority of river basins. The availability of data is not just the only problem. There are other problems as highlighted in this study that is also posing problems in e-flows assessment studies and their on-ground implementation. With this study we have also tried to suggest probable solutions to the Figured problems. Finally, a conceptual framework is also proposed for the assessment of e-flows in data deficit areas. This method is in its initial stage of development and there is a whole room for its further improvement. This method is less data intensive but is based on extensive field survey. But in future the availability of data and expert knowledge will be helpful in further refine and development of robust holistic method. This study also suggests using bottom-up approach for e-flows assessment. Taking small steps in river management will give ample of time to the river to adapt to the changing conditions. The e-flows assessment studies should be made compulsory before taking up any hydropower or river beautification project. A strong legislature framework and strict implementation is also needed for future success of the river basin management plans.

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Subject: MS 2069-19 entitled “Impact of Declining Groundwater Levels on River Flows in the Ganga Alluvial Plain – A Case Study of Gomti River, India ”

MS No- 2069-19

Dear Dr Dutta

The manuscript “Impact of Declining Groundwater Levels on River Flows in the Ganga Alluvial Plain – A Case Study of Gomti River, India ” by Urvashi Sharma, Adeeba and Venkatesh Dutta is accepted for publication in special issue of **Indian J Ecology 47(1):2020**

Thank for your interest in the Journal and the Society

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