Environmental Flow Assessment for Yamuna River from Hathnikund Barrage to Okhla Barrage

DRAFT FINAL REPORT

A view of Yamuna River downstream of Hathnikund Barrage

Sponsored by

NATIONAL MISSION FOR CLEAN GANGA (NMCG)

under Namami Gange Program

Submitted by

NATIONAL INSTITUTE OF HYDROLOGY

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April 2020

Confidential Report

Not for public circulation without prior approval of NMCG

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Acknowledgement

The study utilizes data from various Central and State Government agencies: Yamuna Basin Organization, Central Water Commission, New Delhi; Central Ground Water Board, New Delhi; Central Pollution Control Board, New Delhi; Delhi Jal Board, New Delhi; UP Irrigation Department (Okhla); UP Irrigation Department, Saharanpur; Irrigation & Water Resources Department, Panchkula, Haryana; Water Collection Division, Karnal, Haryana; State Pollution Control Board, Haryana. The support and cooperation of all the above agencies is thankfully acknowledged. Special thanks to Dr. J.A. Johnson, Scientist, Wildlife Institute of India, Dehradun, for joining the NIH team in field survey for identification of indicator fish species in the study reach of Yamuna river and for his contribution in Chapter 6 of the study. Sincere thanks to Director NIH for his support and encouragement in completing this study.

EXECUTIVE SUMMARY

River Yamuna during non-monsoon season carries very less flow in its stretch from Hathnikund to Okhla barrage, which adversely affects the quantity and quality of water in the river. The R&D Project titled 'Environmental Flow Assessment for Yamuna River from Hathnikund Barrage to Okhla Barrage' was awarded to National Institute of Hydrology, Roorkee, by National Mission for Clean Ganga under the Namami Gange Program. The work carried out to assess environmental flows (e-flows) in the study reach and recommendations emerging from the study are given below.

Assessment of e-flows for Yamuna river from Hathnikund barrage to Okhla barrage

Field investigations and data analyses: The assessment of e-flows for the study reach is based on integrated hydrodynamic and hydrological modelling using SWAT and HEC-RAS 1D. A variety of datasets are required as model inputs as well as to validate the model outputs. Besides the river water quality, the study also investigates the variation in groundwater levels over a period of more than four decades. All such necessary data were collected from concerned agencies. In addition, exhaustive field surveys were carried out for the following: (1) Identification of the indicator fish species and assessment of their habitat requirement based investigations in the river, and (2) river cross-section surveys for a total of 306 lines at closely spaced intervals.

The analysis of depth to groundwater levels for pre-monsoon and post-monsoon over a period of four decades from 1975 to 2018 has revealed maximum depletion in water levels ranging from 10 to 20 m in the Mawi-Baghpat reach. Receding groundwater levels have in turn affected the baseflow contribution to the flows in Yamuna. Maximum depletion in baseflows is in the reach between Mawi and Baghpat during the months of April and May. For the study reach, the ratio of baseflow to total river flow is found to be higher in the non-monsoon season than in the monsoon season. This pattern is representative of other gauges in the study reach and shows the importance of baseflows in sustaining river flows during non-monsoon period.

Water quality analysis have shown that between the Wazirabad and Okhla barrage, the river receives approx. 6140 kg/hr BOD load out of which around 70% load is contributed through Nazafgarh drain. The average non-monsoonal DO value in this river stretch is 0.4±0.12 mg/l as O_2. During the field survey by NIH team, the DO value in this stretch was non-detectable indicating the BOD load to the river higher than the assimilative capacity of the river. The water quality up to Wazirabad barrage is good for fish proliferation, however, the reduction in DO values downstream of Mawi is a cause for concern.

Ecology and habitat requirements of indicator fish species: Field surveys have revealed three major fish habitats types such as pools, riffles and runs at the sampling sites in Yamuna river. The identified indicator species, *Bangana dero* and *Raiamas bola* are thriving well in run habitat of channel with depth ranging from 60 to 90 cm and velocity in the range of 0.1 m/s. Hence, ensuring minimum water depth of 60 cm and flow of 0.1 m/s at riffle/run habitat in the river will safeguard the fish diversity in Yamuna river.

Integrated hydrological and hydrodynamic modelling: The integrated hydrologic and hydrodynamic modeling approach has been adopted to assess the e-flows between Hathnikund barrage and Okhla barrage and compute the releases required from Hathnikund barrage for maintaining these e-flows. For converting the habitat suitability depth values into the flow values, depth versus discharge curves have been developed at selected 13 locations covering the whole hydrologic regime using HEC-RAS simulations. Using the developed depth vs discharge curves for different sites, the minimum desirable flow values required for maintaining suitable physical habitat in terms of desirable flow have been estimated. The flows required to be released from Hathnikund barrage for maintaining the minimum desirable amount of flows at different sites during different seasons have been estimated using the flow series simulated by the calibrated hydrologic model SWAT. The release required from Hathnikund barrage during a specific month is computed by taking the maximum of the releases estimated from Hathnikund barrage for meeting the minimum depth requirement of 0.60 m at 13 identified locations corresponding to the specific month.

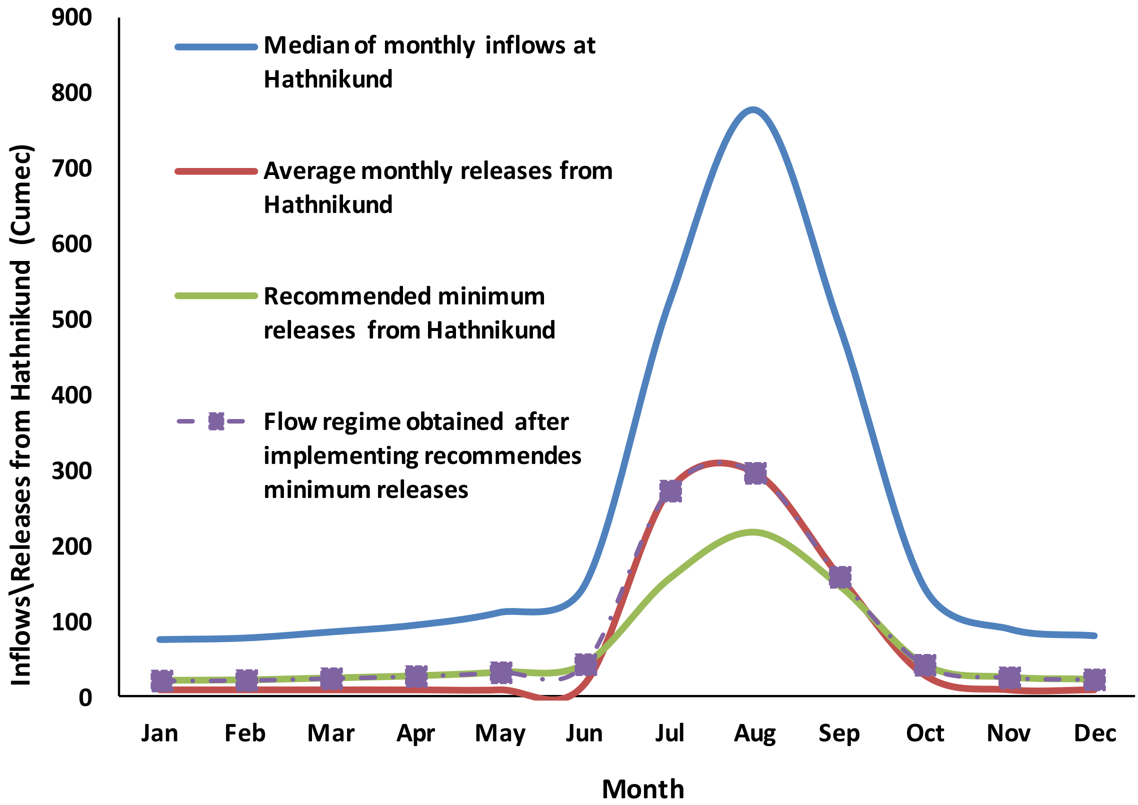
For carrying out various functions, the aquatic ecosystem needs natural flow variability within the year, for its sustenance. Incorporation of natural variability of flows has been carried out by taking the minimum depth of 60 cm for the month of May (being the driest month at all the G&D sites downstream of Hathnikund barrage) and modifying the releases as per the existing natural variability as observed in long-term historical data.

Recommendations

Final recommended releases from Hathnikund barrage for maintaining required habitat conditions between Hathnikund and Okhla barrage during different months of a year:

Month	Median of monthly inflows at Hathnikund barrage (cumec)	Average monthly releases from Hathnikund barrage (cumec)	Recommended minimum releases from Hathnikund barrage incorporating natural variability (cumec)	Flow regime obtained after implementing recommended minimum releases (cumec)	For inundating floodplains (cumec) *- once a month*
Jan	76	10	23	23	
Feb	78	10	23	23	
Mar	86	10	26	26	
Apr	95	10	29	29	
May	112	10	34	34	
Jun	148	18	44	44	
Jul	525	275	158	275	1400
Aug	780	298	220	298	1600
Sep	493	160	149	160	
Oct	145	30	44	44	
Nov	90	10	27	27	
Dec	81	10	24	24	

Recommended releases from Hathnikund Barrage for sustaining downstream ecosystem upto Okhla barrage are illustrated below.



It may be noted here that the e-flow assessment is based on water requirement of indicator fish species, however, the biodiversity, livelihood and spiritual groups can link their requirements to specific features of the river channel at the study sites.

Possible management strategies for maintaining e-flows in the study reach are recommended below:

- Reduction in diversions to WYC/EYC by increasing the irrigation efficiency in WYC and EYC commands, keeping in view the crop water requirement
- Regulate groundwater withdrawal in the basin especially in the Mawi-Baghpat stretch and augment groundwater recharge in order to sustain baseflows
- Augmentation of non-monsoon inflows at Hathnikund barrage by creating storage of monsoon runoff in the upstream reaches
- Treatment of effluent coming through various drains meeting river Yamuna

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Chapter 1

INTRODUCTION

1.1 About the Study

Ministry of Water Resources, River Development & Ganga Rejuvenation, vide its notification no. S.O. 3187 (E) dated 07.10.2016, empowers National Mission for Clean Ganga to determine the magnitude of ecological flows in the river Ganga and its tributaries, required to be maintained at different points in different areas at all times with the aim of ensuring water quality and environmentally sustainable rejuvenation, protection and management of river Ganga and its tributaries and notifying the same and take or direct all such measures necessary to maintain adequate ecological flows. River Yamuna during non-monsoon season carries very less flow in its stretch from Hathnikund to Okhla barrage, which adversely affects the quantity and quality of water in the river.

In the special meeting of the Expert Members of Principal Committee and Monitoring Committee of Hon'ble NGT held on 18.10.2018, the matter was discussed and it was informed that the environmental flow of 10 cumecs observed to be released at Hathnikund, was completely insufficient to maintain the uninterrupted flow of river Yamuna. In view of above, based on the recommendation of the Expert Committee (F. No. TE-16015/38/2018/ NMCG of Dec 2018), NMCG approached NIH Roorkee for comprehensive study "to analyze the minimum required environmental flows for river Yamuna in the stretch from downstream of Hathnikund to Okhla barrage". The study proposal describing the objectives, methodology, and data requirement was prepared and submitted to NMCG for approval. Work was initiated on the study by NIH after receiving study sanction letter from NMCG on March 25, 2019.

1.2 Study Objectives

The objectives of the study undertaken by NIH are as follows:

- To assess environmental flows for Yamuna river from Hathnikund barrage to Okhla barrage.
- To suggest management options for maintaining the recommended e-flows.

1.3 Environmental Flows

Rivers are the main source of freshwater globally. The importance of natural functions that rivers provide, and the value of the biodiversity that lives in or is dependent on them is increasingly being recognized worldwide. Flow is taken as the major driver of biodiversity in rivers. During recent decades, sufficient evidence has emerged that a river's flow regime, ranging from low flows to high flows, significantly affects the river ecosystem. River water is used for numerous services such as drinking water, irrigation and industrial water supply, fishing, boating, recreation and cultural activities. On account of the burgeoning human population, food and energy needs and changing life styles, pressure on rivers has intensified to meet the manifold increase in water demand.

To serve the various water demands, water is stored and diverted through various structures built on rivers that change the flow regime and reduce flow in the downstream reaches. These changes, in turn, lead to degradation in the services that the society gets from rivers. Data have shown that freshwater biodiversity is already suffering from over-abstraction of water, from pollution of rivers, and from poorly-planned water infrastructure. It, therefore, becomes imperative to decide the extent of changes we want in our rivers and how much of the natural regime we would like to maintain. The emerging science of environmental flows (e-flows) aims to ensure a balance between the use and the protection of natural water resources for people by analyzing data from hydrological, hydraulics, social, environmental, biological, and other relevant sectors.

There are many definitions of environmental flows. The International Union for Conservation of Nature (IUCN) (2003) defines "E-flows as 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". The IUCN makes a clear conceptual distinction between the water needed to maintain the ecosystem in near pristine condition, and that which is eventually allocated to it, following a process of a holistic assessment for e-flows. According to the widely quoted Brisbane Declaration (2007), "Environmental flows describe the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems" (Arthington, 2012).

Considering the above, following definition for e-flows is considered most appropriate and is adopted. The environmental flow requirement is the "acceptable flow regime required to maintain the river in reasonable condition or predetermined state". A trade off between water resources development and river maintenance in healthy or reasonable condition is, in general, an inevitable compulsion. National Water Policy (2012) stipulates that ecological needs of the river should be determined, through scientific study, duly accommodating development needs.

1.4 Organization of the Report

The study report is organized into eight chapters. Chapter 2 describes the study reach between Hathnikund and Okhla barrage, and, brings out the issues and challenges and the need for maintenance of e-flows. Methodology for assessment of e-flows is discussed in Chapter 3. Build-up of database for the study reach and data processing is dealt with in Chapter 4 which also provides details of field investigations undertaken during the course of this study. Chapter 5 deals with integrated hydrological and hydrodynamic modeling in the study reach and discusses results of hydrologic modeling using SWAT and hydrodynamic modeling using HEC-RAS. Chapter 6 on e-flows for sustaining indicator aquatic species discusses fish diversity in study reach, river habitat condition at sampling points, ecology and habitat requirements of indicator fish species, and suggested e-flow regime. Chapter 7 focuses on management options to maintain the recommended e-flows, while the conclusions and recommendations emerging from the study are provided in Chapter 8.

Chapter 2

STUDY REACH BETWEEN HATHNIKUND AND OKHLA BARRAGE

2.1 Yamuna River

The Yamuna River originates from the Yamunotri Glacier near Banderpoonch peaks in the Mussoorie range of the lower Himalayas at an elevation of about 6387 m above msl in Uttarkashi district in the state of Uttarakhand. The river traverses through Himachal Pradesh and Uttarakhand in the upper stretch of 200 km drawing water from several major streams. It enters the plains at DakPathar in Uttarakhand, where the river water is regulated through a weir and diverted into canal for power generation. It then reaches Hathnikund barrage in Yamuna Nagar district of Haryana state, where the river water is diverted into Western Yamuna Canal (WYC) and Eastern Yamuna Canal (EYC) for irrigation. Yamuna river enters Delhi near Palla village after traversing a route of about 224 km. The river runs parallel to Ganga before joining it at Allahabad. The tail end of WYC joins the river Yamuna near Palla and EYC also joins at Wazirabad reservoir. The river water is generally used for irrigation, drinking and industries as well as for mass bathing, laundry, cattle bathing, etc.

On the basis of hydrological and ecological conditions Yamuna has been classified into five segments that are Himalayan Segment, Upper Segment, Delhi Segment, Eutrophicated Segment and Diluted Segment. The river is diverted at 5 barrages during its course i.e. at Dak Patthar (about 160 km from origin in Uttarakhand); at Hathnikund (172 km from origin, just at foothills in Haryana); at Wazirabad (in NCT Delhi, 396 km from origin); at Okhla (in NCT – Delhi, 418 km from origin); and at Mathura (near Gokul village in U.P. about 570 km from origin). These barrages are the major water abstraction locations on the river. The water is contributed into the Yamuna River, not only through its tributaries but also by the irrigations canals and drains carrying waste water from various urban locations.

2.2 Issues and Challenges

The Yamuna river faces extremes of dry as well as flood conditions during a year. Due to high population density of the catchment, the river remains almost in dry state during January to June in many parts of its stretch and under flooded conditions during July-September. During the non-monsoon period (October to June), the river flow reduces significantly and some river stretches become totally dry, whereas, during monsoon period (July-September), the rivers receives significant amount of water, which is beyond its conveyance capacity resulting in floods (CPCB, 2006).

The construction of diversion structures at regular intervals (Hathnikund, Wazirabad, Okhla, Gokul etc.) for irrigation, domestic and industrial water supply, has largely modified the flow regime of the river. During the lean season, a river is kept alive not so much by directed surface runoff but by the base flows. Over the last three decades, drilling of a large number of bore wells – with pumps run by electricity – has led to overexploitation of both shallow and deep aquifers in adjacent districts of Uttar Pradesh and Haryana. Lack of regulation in the groundwater abstraction has depleted the water table resulting in changes in surface water dynamics during the lean season and dry river segments are commonly observed between Hathnikund and Wazirabad barrage in the non-monsoon period. Wastewater inflow in river Yamuna through various drains has aggravated the water quality problems and this has adversely affected biodiversity and aquatic ecosystem.

2.3 Need for Maintenance of E-flow

Yamuna, a major tributary of River Ganga, supports the livelihood of millions of people in its basin states. To fulfil the growing needs of drinking water, irrigation and industry, several structures have been built which store and divert large volumes of water from the river as it runs its course through the riparian states of Uttarakhand, Haryana, the National Capital Territory of Delhi and Uttar Pradesh. River Yamuna during lean season carries very less flow in its stretch from Hathnikund to Okhla barrage, which adversely affects the quantity and quality of river water. Large volumes of treated/untreated sewage and industrial effluent are discharged into the river from townships in Haryana and Uttar Pradesh and through several drains in Delhi segment. Encroachment and dumping of municipal and construction waste on the flood plains has impeded the flow and impaired its natural ability to rejuvenate itself. Overall, this not only affects the well-being of river, but also the health of citizens exposed to the hazards of polluted water in the river and possible seepages in groundwater.

Jain and Kumar (2013) have observed that there is a hierarchy of flows required for a river to perform its numerous natural functions. In the monsoon season, certain flows are required to transport sediments while in the non-monsoon season certain percentage of flow is needed to avoid algal choking, for which the requirements exceed those to meet other ecological elements.

Environmental flow is essential for Yamuna to regain the characteristics of a healthy living river system. Hon'ble NGT has given directions for the maintenance of requisite e-flow in River Yamuna downstream of the barrage at Hathnikund in Haryana and at Okhla in Delhi, so that there is enough fresh water flowing in the river till Agra for restoration of ecological functions of the river. Hon'ble Supreme Court has directed that a minimum flow of 10 cumec (353 cusec) must be allowed to flow through the river Yamuna. However, as per the report 'Action Plan of the Monitoring Committee for Rejuvenation of River Yamuna' (Chandra and Sajwan, 2018), the release of 10 cumecs of water in lean months is completely insufficient to sustain the flow in the river. This is because most of the 10 cumecs of water released from Hathnikund barrage evaporates or percolates into the ground as it flows downstream. As a result, most segments of Yamuna remain dry during lean season. The general BOD standard for discharge of effluent in inland surface water body is 30 mg/l. Here, it is assumed that there would be dilution with freshwater to achieve a desired BOD level of say 3 mg/l. With over 6140 Kg/h of total BOD load (refer Chapter 4) in the river in the Delhi segment, the Yamuna will require much more freshwater to achieve desired levels of BOD. It needs to be highlighted that the purpose of e-flow is not to improve the quality of river water by dilution.

2.4 Major Features of Study Reach Between Hathnikund and Okhla Barrage

Figure 2.1 shows the location of the entire Yamuna basin as a part of the Ganga basin. The study reach under investigation is the reach between Hathnikund and Okhla barrage.

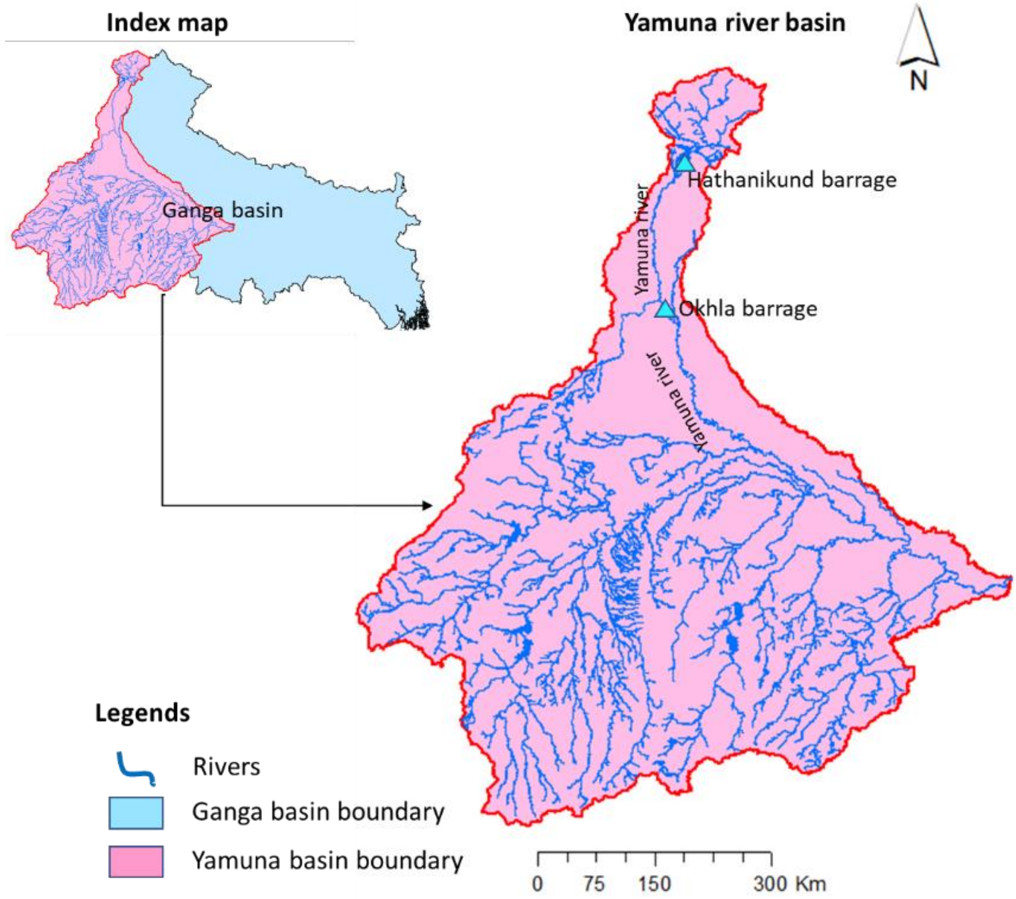


Fig. 2.1 Study area map showing the river stretch between Hathnikund and Okhla Barrage.

Figure 2.2 shows the annual rainfall in the reach under investigation. Between 1975 and 2016, the rainfall in the study reach varied greatly. In 1987, rainfall dropped to a low of 423 mm, however, the following year rainfall increased significantly to a peak of 1132 mm. During the period 1975-2016, highest rainfall of 1217 mm was recorded in the year 1978. During the decade 2007-2016, highest rainfall of 1083 mm was recorded in 2013, while lowest rainfall of 576 mm occurred in 2009. The average monthly rainfall and average monthly temperature are shown in Fig. 2.3.

Figure 2.4 shows the stream network of the Upper Yamuna basin upto Okhla barrage. It may be noted here that the basin of Sahibi river that merges with Najafgarh drain is not shown in the map (for water balance purposes, the inflow from Najafgarh drain would be utilized in the study). Figure 2.5 shows the Digital Elevation Model (DEM) of Upper Yamuna basin upto Okhla Barrrage. The DEM is prepared based on SRTM 30 m data set. From the source, the Yamuna river basin covers a number of slope classes as depicted in Fig. 2.6. It is seen from Fig. 2.6 that upto Hathnikund barrage the variation in slope is changing abruptly and the shape of the basin is circular which causes quick runoff. The shape of the basin from Hathnikund barrage to Okhla barrage is elongated and also exhibits less slope variation. Such morphology of the basin takes more time to produce runoff as compared to circular basin shape.

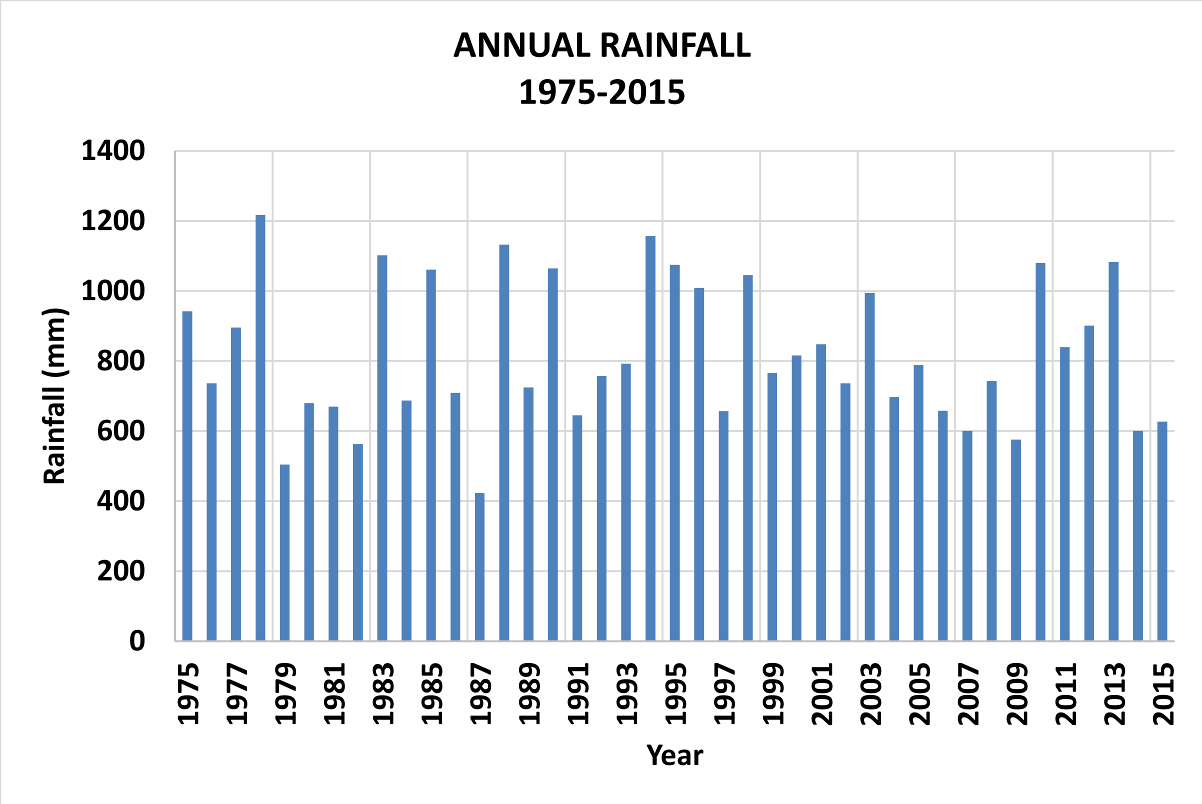


Fig. 2.2 Annual rainfall in study reach

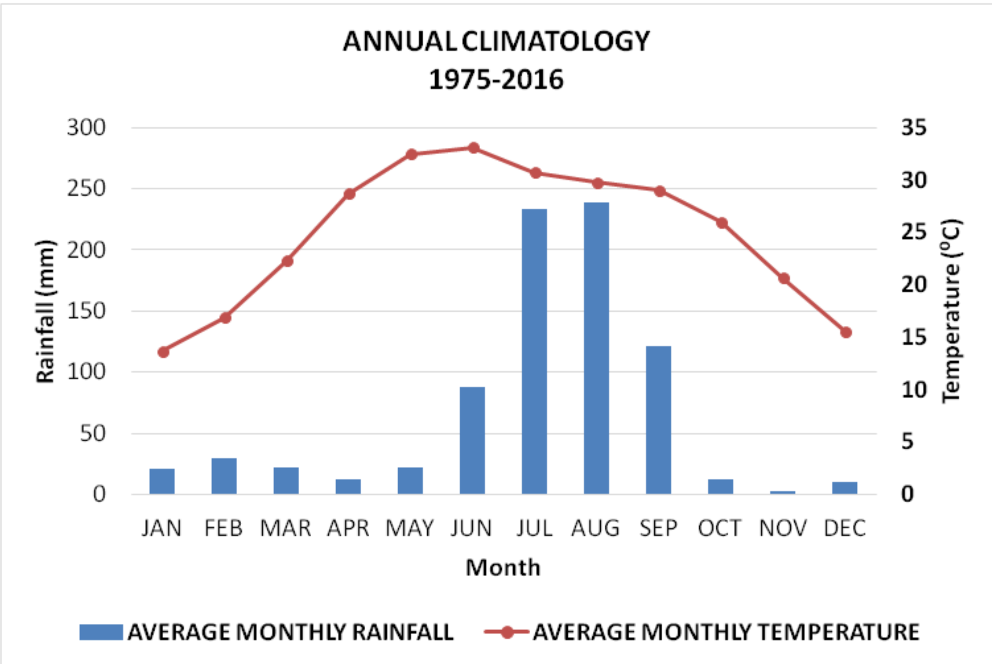


Fig. 2.3 Average monthly rainfall and average monthly temperature in study reach

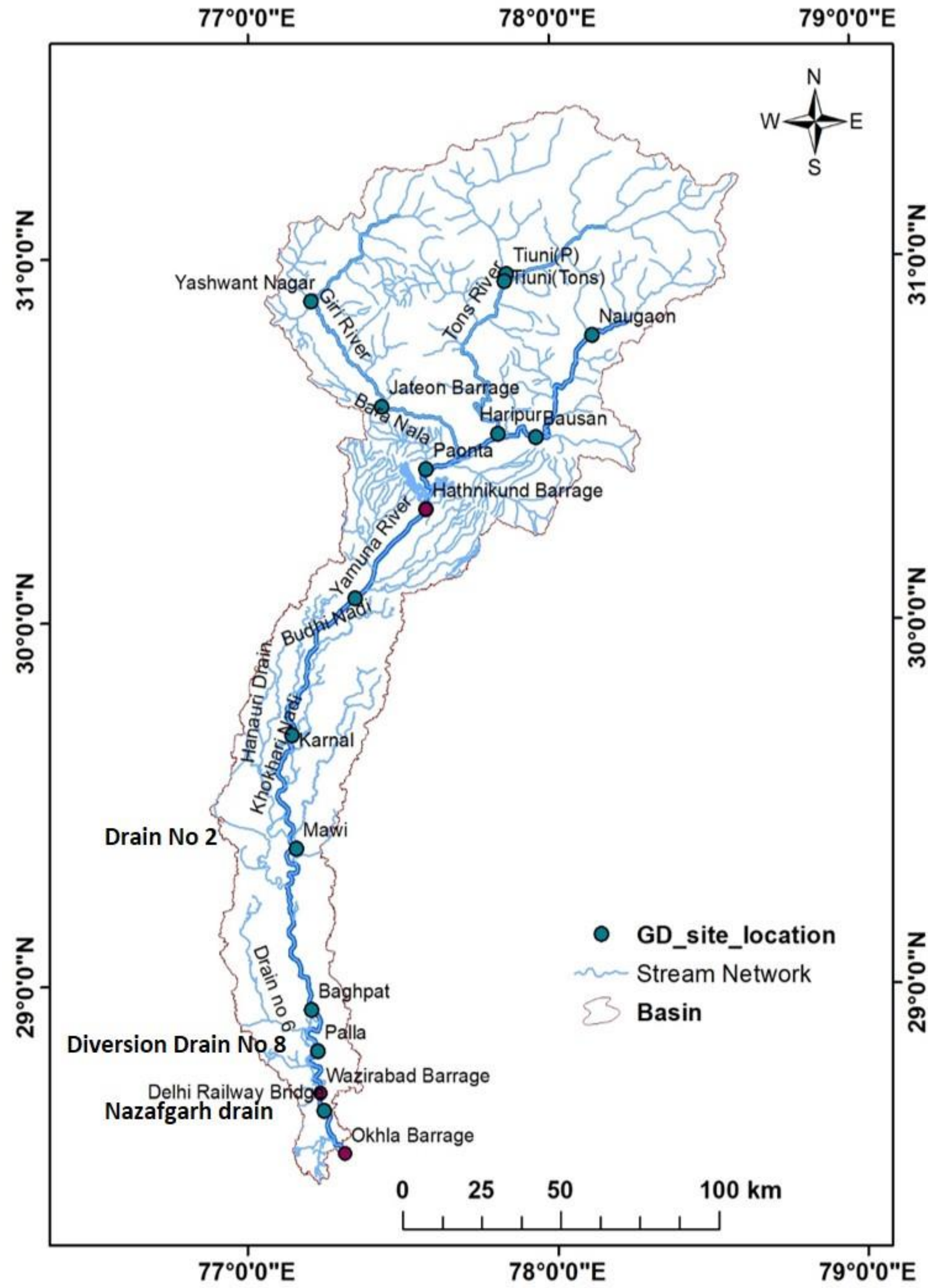


Fig. 2.4 Upper Yamuna stream network upto Okhla barrage

Hathnikund barrage was commissioned in 2002 to regulate the flow of Yamuna for irrigation in Haryana and Uttar Pradesh through two canals namely the Western Yamuna Canal and the Eastern Yamuna Canal, as well as the municipal water supply to Delhi. It replaced the Tajewala Barrage constructed in 1873 located about 3 km downstream of Hathnikund. In the Himalayan Segment of River Yamuna i.e. from Yamunotri Glacier to Hathnikund Barrage, the river water quality is good and it meets all the desired standards. To fulfill the water demand of the surrounding districts in the states of Haryana and Uttar Pradesh, little water (about 10 cumecs) of water is allowed to flow downstream of Hathnikund Barrage especially during summers and winters, on account of which the river remains dry in several stretches between Hathnikund and Delhi.

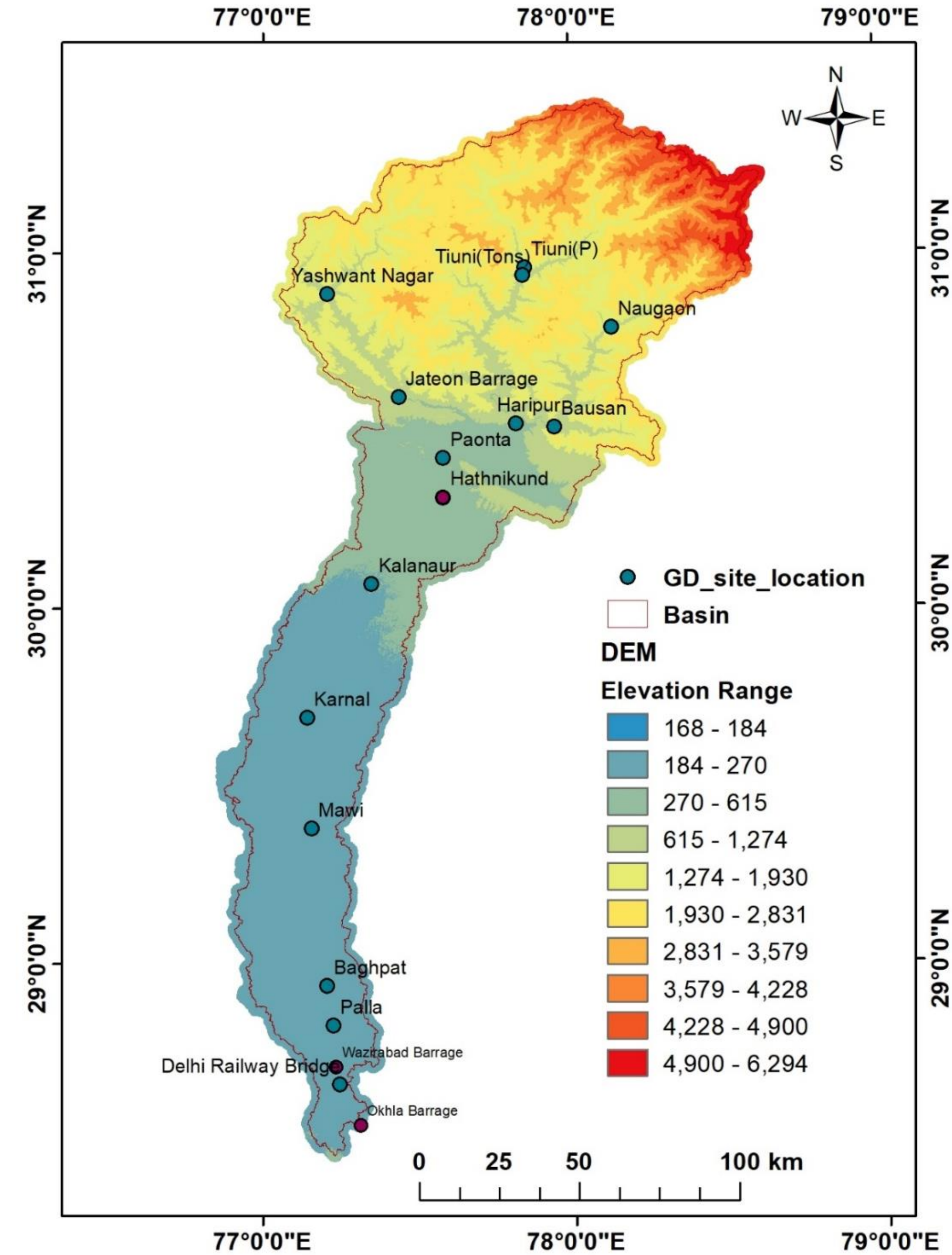


Fig. 2.5 Upper Yamuna Digital Elevation Model (DEM) upto Okhla barrage

In Delhi, the Yamuna water is again tapped by Wazirabad barrage for the domestic water supply to Delhi. Usually no water or extremely little water is allowed to flow downstream of this barrage during lean season. About 22 km downstream of Wazirabad barrage is the Okhla barrage. From this segment, Yamuna water is diverted into Agra canal for irrigation. River water is not allowed to flow downstream during summers; beyond the Okhla barrage, river water comprises the domestic and industrial wastewater generated from east Delhi, Noida and Sahibabad.

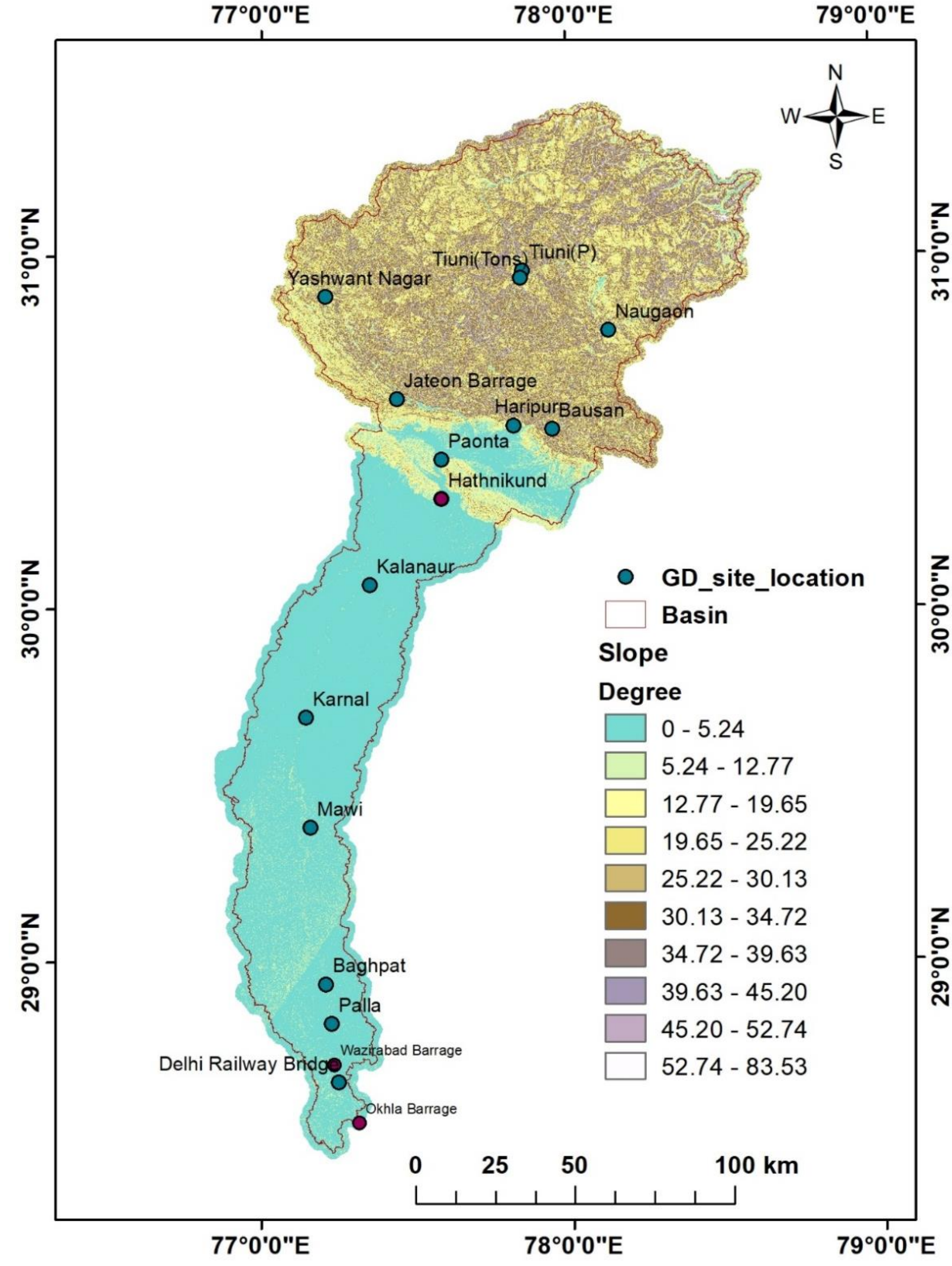


Fig. 2.6 Upper Yamuna Slope Map upto Okhla barrage

The river water is abstracted at different locations for varied uses. Substantial river water is abstracted at Hathnikund and Okhla. Figure 2.7 illustrates the points of major water abstractions and additions in Yamuna river in the study reach (CPCB, 2006). In the reach of river Yamuna between Hathnikund and Okhla barrage, discharge of river Yamuna is observed by CWC at Kalanaur, Karnal, Mawi, Baghpat, Palla and Delhi Railway Bridge G&D sites (refer Fig. 2.4). Delhi Railway Bridge is located between Wazirabad and Okhla barrage.

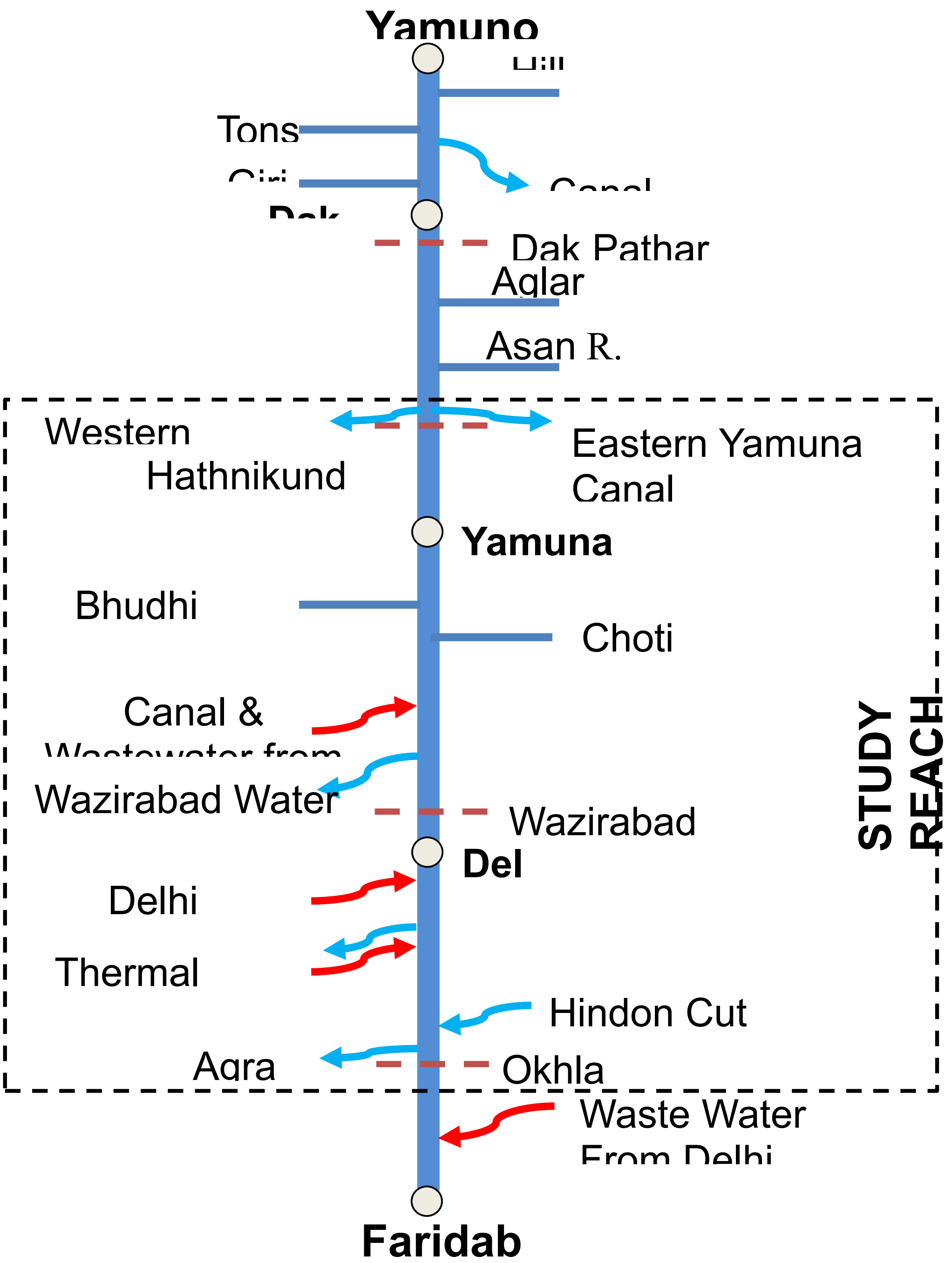


Fig. 2.7 Points of water abstraction and additions in Yamuna river (modified from CPCB, 2006).

Fig. 2.8 Nazafgarh drain joining Yamuna River near Signature Bridge, Delhi

Because of the low flows during lean season and huge quantity of waste it receives, the Yamuna river within the limits of Delhi has been given the dubious distinction of being one of the worst polluted rivers of the country by the Central Pollution Control Board (CPCB). For instance, at the location near Nazafgarh drain joining Yamuna River close to Signature Bridge in Delhi (Fig. 2.8) the DO value is not-detectable.

Chapter 3

METHODOLOGY FOR ASSESSMENT OF ENVIRONMENTAL FLOWS

3.1 General

Several methods/methodologies have been proposed in the literature for the assessment of e-flows. These methods/methodologies range from simplistic use of the hydrological record to establish minimum and flushing flows to sophisticated procedures linking changes in river discharge with hydraulic, geomorphological, ecological and socio-economic responses. Recent studies have combined a number of methods within a broader methodological framework designed to provide comprehensive recommendations on water allocations for ecosystem protection. The evolution and development of the science of e-flows and the methodology for estimation of e-flows adopted in the present study are discussed below.

3.2 Evolution of Science of E-Flows

The development of environmental flows assessment (EFA) methodologies began in USA in the late 1940s, mainly as a result of new environmental and freshwater legislation accompanying the peak of the dam-building era. Australia and South Africa are the other advanced countries that addressed the development and application of EFA methodologies (Tharme, 2003).

In several countries, the main objective of EFA has been to define a minimum acceptable flow based on predictions of instream habitat availability matched against the habitat preferences of one or a few species of fish (Jowett, 1997; Pusey, 1998). Since fish species such as trout and salmon are very sensitive to flow, it has been argued that if the flow is appropriate for these species, it will probably serve most other ecosystem needs. However, scientific literature reveals that this may not necessarily be so, and flow management is best addressed for the entire ecosystem. Recent EFA methodologies have increasingly taken a holistic approach (Brown and King, 2003; Instream Flow Council, 2002) due to existence of already over-allocated water resources projects in the absence of any e-flows regulations. EFA methodologies have been classified in several ways by different organizations as shown in Table 3.1.

Perspective and interactive approaches: Perspective EFAs recommend a single environmental flow. By using this perspective approach, however, insufficient information is supplied on the implications of not providing the recommended flow. Interactive EFAs focus on establishing the relationship between river flow and one or more attributes of the river system. This relationship may then be used to describe environmental/ecosystem implications (and resulting social/economic implication) of various flow scenarios. Interactive methodologies thus facilitate the exploration of trade-offs of several water allocation options.

Bottom-up and top-down approaches: The basis of most EFA methodologies is a bottom-up approach, which is the systematic construction of a modified flow regime from scratch on a month-by month (or more frequent) and element-by-element basis, where each element represents a well-defined feature of the flow regime intended to achieve specific objectives. In contrast, top-down approaches define the environmental flows requirement in terms of accepted departures from the natural (or other reference) flow regime. Thus, top-down approaches are less susceptible to omission of critical flow features than bottom-up approaches.

Methods and methodologies: Tharme (2003) distinguished the two levels of EFA as "methods" (procedures or techniques used to measure, describe or predict changes in important physical, chemical or biological variables of the stream environment) and "methodologies" (collection of several instream flow methods which are arranged into an organized iterative process which can be implemented to produce results). The critical review, development and evaluation of these assessment methodologies have been dealt in detail by several researchers (Tharme, 1996; Jowett, 1997; Dunbar et al., 1998; Tharme, 2003; Acreman and Dunbar, 2004; Jha et al., 2008, Arthington, 2012, Hatfield et al. 2013, Linnansaari et al., 2013).

Table 3.1 Overview of EFA methodologies

Organization	Category	Sub-category	Example
IUCN (Dyson et al. 2003)	Methods	Look-up Tables	Hydrological (e.g. Q95 index); Ecological (e.g. Tennant Method)
		Desktop Analysis	Hydrological (e.g. Richter Method); Hydraulic (e.g. Wetted Perimeter Method); Ecological
		Functional Analysis	Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Benchmarking Methodology
		Habitat Modelling	Physical Habitat Simulation Modelling (PHABSIM)
	Approaches		Expert Team Approach; Stakeholder Approach (expert and non-expert)
	Frameworks		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Ecological Limits of Hydrological Alteration (ELOHA)
World Bank (Brown and King, 2003)	Perspective Approaches	Hydrological Index Methods	Tennant Method, Desktop method

		Hydraulic Rating Methods	Wetted Perimeter Method
		Expert Panels	Expert Panel Assessment Method (EPAM); Scientific Panel Assessment Method (SPAM)
		Holistic Approaches	Building Block Methodology (BBM)
	Interactive Approaches		Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Ecological Limits of Hydrological Alteration (ELOHA)
IWMI (Tharme, 2003)	Hydrological Index Methods		Tennant Method, Desktop methods
	Hydraulic rating Method		Wetted Perimeter Method
	Habitat Simulation Methodologies		PHABSIM, MesoHabsim, Instream Flow Incremental Methodology (IFIM), System for Environmental Flow Assessment (SEFA)
	Holistic Methodologies		Holistic Approach; Instream Flow Incremental Methodology (IFIM); Downstream Response to Imposed Flow Transformation (DRIFT); Building Block Methodology (BBM); Expert Panel Assessment Method (EPAM); Scientific Panel Assessment Method (SPAM); Habitat Analysis Method; Ecological Limits of Hydrological Alteration (ELOHA)

3.3 Hydrological Methods

These are the simplest and most widespread EFA methods, also referred to as desk-top or look-up table methods. These methods rely primarily on historical flow records. Environmental flow is usually given as a percentage of average annual flow or as a percentile from the flow duration curve, on a seasonal or monthly basis.

Commonly, the Environmental Flow is represented as a proportion of flow (often termed the ‘minimum flow’, e.g. Q95 – the flow equalled or exceeded 95 percent of the time) intended to maintain river health. Most methods simply define the minimum flow requirement; however, in recognition of the ‘Natural Flow Paradigm’ more sophisticated methods have been developed that take several (up to 32) flow characteristics into account (such as low flow durations, rate of flood rise/fall etc).

Hydrological Index Methods provide a relatively rapid, non-resource intensive, but low resolution estimate of environmental flows. Therefore, the methods are most appropriate at the planning level of water resources development, or in low controversy situations where they may be used as preliminary estimates.

3.4 Hydraulic Rating Methods

As difficulties exist in relating changes in the flow regime directly to the response of species and communities; hence, approaches have been developed that use habitat for target species as an intermediate step. Within the total environmental niche required by an individual animal or plant living in a river, it is the physical aspects that are affected by changes in the flow regime.

The most obvious physical dimension that can be changed by altered flow regimes is the depth/wetted perimeter area of submerged river bed of the channel. Hydraulic rating methods provide simple indices of available habitat (e.g. depth/wetted perimeter) in a river at a given discharge. Graphs of discharge and wetted perimeter provide a basic tool for environmental flow evaluation. As a rule of thumb, shallow, wide rivers tend to show more sensitivity of their wetted perimeter to changes in flow than do narrow, deep rivers.

Gippel and Stewardson (1998) have highlighted the problems of trying to identify thresholds (critical discharges below which wetted perimeter declines rapidly) that can be used to define environmental flows.

Hydraulic rating methods are based on historical flow records (stage-discharge rating curve) and cross-section data. They model hydraulics as function of flow and assume links between hydraulics (wetted perimeter, depth, velocity) and habitat availability of target biota. In other words, they use hydraulics as a surrogate for the biota. Environmental flow is given either as a discharge that represents optimal minimum flow, below which habitat is rapidly lost, or as the flow producing a fixed percentage reduction in habitat availability. In recent years, hydraulic rating methods have been superseded by Habitat Simulation Methodologies or absorbed within Holistic Methodologies.

3.5 Habitat Simulation Methodologies

Habitat simulation methodologies are widely used and based on hydrological, hydraulic and biological response data. They model links between discharge, available habitat conditions (including hydraulics) and their suitability to target biota. Environmental flow is predicted from habitat-discharge curves or habitat time and exceedence series.

PHABSIM (Physical HABitat SIMulation model) (Bovee, 1986) is the most commonly applied habitat simulation methodology. Habitat simulation methodologies also make use of hydraulic habitat-discharge relationships, but provide more detailed, modelled analyses of both the quantity and suitability of the physical river habitat for the target biota. Thus, environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data. Flow-related changes in physical microhabitat are modelled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover; and more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within each representative river reach. Simulated information on available habitat is linked with seasonal information on the range of habitat conditions used by target fish or invertebrate species, commonly using habitat suitability index curves (Groshens and Orth, 1994). The resultant outputs, in the form of habitat-discharge curves for specific biota, or extended as habitat time and exceedence series, are used to derive optimum environmental flows. The habitat simulation-modelling package PHABSIM (Bovee, 1982; Bovee et al., 1998; Milhous *et al*. 1989; Stalnaker *et al*. 1994), housed within the Instream Flow Incremental Methodology (IFIM), is the pre-eminent modeling platform of this type. The relative strengths and limitations of such methodologies are described in King and Tharme (1994); Tharme (1996); Arthington and Zalucki (1998); Pusey (1998) and they are compared with other types of approaches in Tharme (2003).

As PHABSIM method is primarily meant for microhabitats, a number of efforts were made thereafter to develop methods for mesohabitats and macrohabitats. Parasiewicz (2001, 2007, 2008) came out with a mesohabitat scale (i.e. Channel units, like run, riffle, pool etc.) MesoHABSIM model. This model combined the system-scale assessment of ecological integrity with physical habitat distribution to simulate habitat changes at catchment scale. The same types of meso-scale models were later developed by Harby et al. (2007), Halleraker et al. (2007) and Paul and Locke (2009). Some other models in this category are River Hydraulic and HABitat Simulation Model (RHYHABSIM) developed by Jowett (1989) and Riverine HABitat SIMulation (RHABSIM) model (an extensive version of PHABSIM) by the U.S. Fish and Wildlife Service in association with Payne (1994). Recently, the developers of most of these models have together come up with the new model, System for Environmental Flow Analysis (SEFA).

3.6 Holistic Methodologies

Holistic Methodologies are actually frameworks that incorporate hydrological, hydraulic and habitat simulation models. They are the only EFA methodologies that explicitly adopt a holistic, ecosystem based approach to environmental flow determination. A wide range of holistic methodologies has been developed and applied, in Australia, South Africa and United Kingdom. Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals). Each of these components can be evaluated using a range of field and desktop techniques (Tharme, 1996; Arthington and Zalucki, 1998; Tharme, 2003) and their flow requirements are then incorporated into EFA recommendations, using various systematic approaches.

3.7 Proposed Methodology for E-Flows Assessment

A detailed literature review has revealed that the most sophisticated methodologies for e-flow assessment are the holistic methodologies which use all the elements of water availability and demand i.e. hydrology, hydraulics, ecology, socio-economics etc. Jain and Kumar (2014) have provided an account of various e-flow assessments carried out in Indian rivers.

Recently, the Hon'ble NGT formed a committee for assessment of environmental flows for Ganga river from Haridwar to Unnao and the committee recommended e-flows on the basis of hydraulic habitat requirement of indicator species using the HEC-RAS model (MOWR, 2018).

For the assessment of e-flows for Yamuna river from Hathnikund Barrage to Okhla barrage, the proposed methodology is formulated based on the following factors: data availability, time assigned for the study, and the previous such e-flow assessment for the Ganga basin (refer Fig. 3.1).

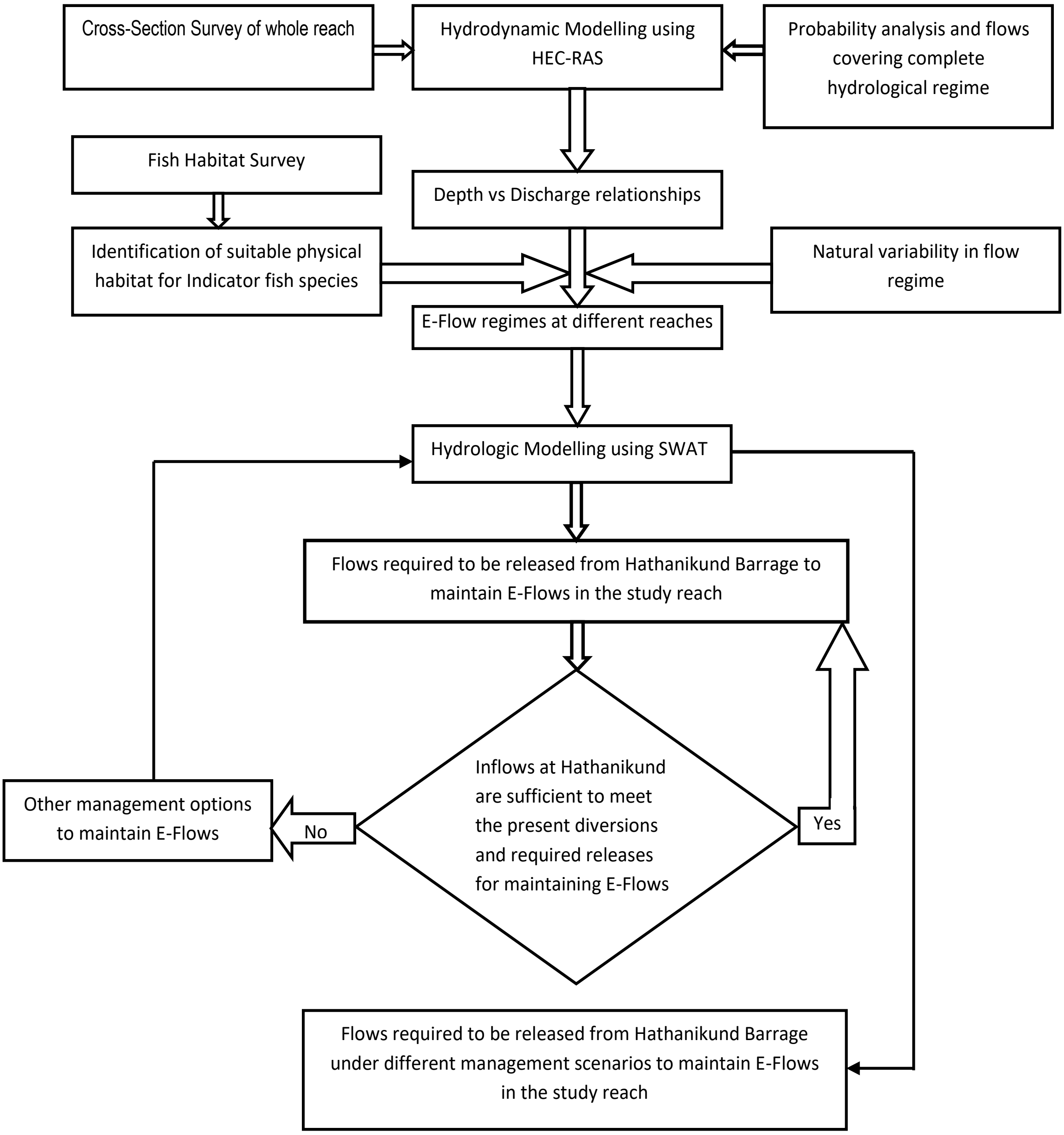


Fig. 3.1 Flowchart depicting the proposed methodology for e-flow assessment

In this proposed methodology, the physical habitat requirement of the indicator fish species will be converted into flow values using hydrodynamic modeling through HEC-RAS model as depicted in Fig. 3.2. Further, these flow values will be converted into flow regimes using the natural variability in river flow.

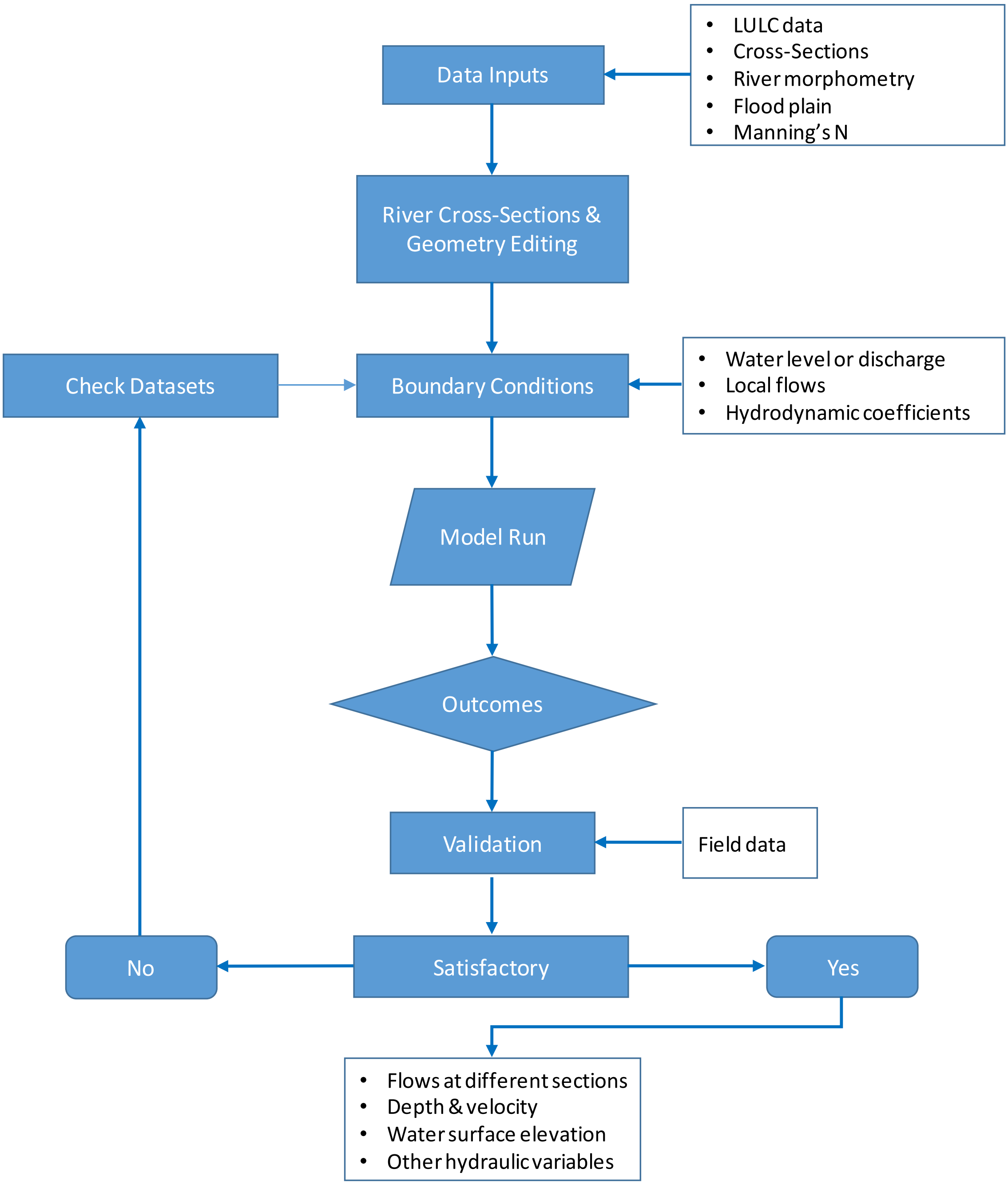


Fig. 3.2 Hydrodynamic Modeling using HEC-RAS 1D

To simulate the flow regime prior to and after the commencement of Hathnikund barrage, hydrological modeling using SWAT model has been proposed as shown in Fig. 3.3. The hydrological simulations will not only help to establish the virgin flow regime but also facilitate conversion of the flow values required to be maintained at various locations downstream of Hathnikund barrage to the flows required to be released from Hathnikund barrage. Moreover, the model simulations will also help in assessing the efficacy of the management options for maintaining the necessary flows.

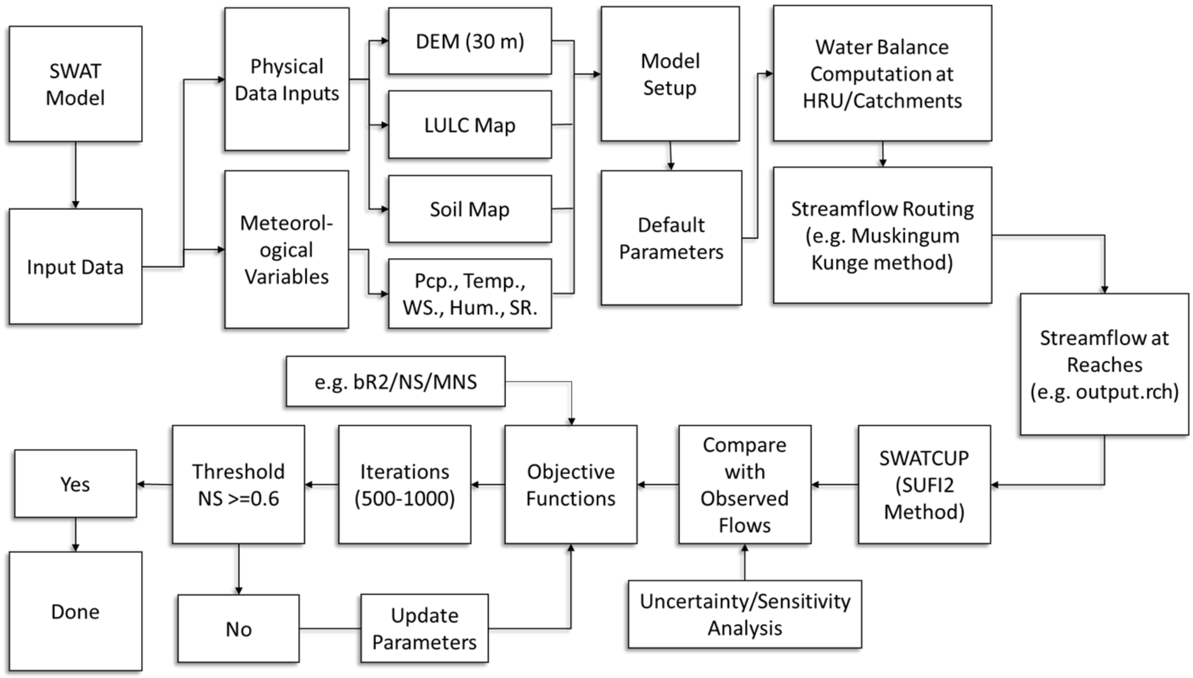


Fig. 3.3 Hydrologic Modeling using SWAT

To achieve the objectives, the whole methodology is segregated into three phases based on the availability of data/information as follows:

PHASE I (2 months)

- **Data collection and processing**
- **Hydrodynamic modeling using available coarse resolution dataset**
  - Setup HEC-RAS 1D hydraulic model with SRTM DEM (30 m) and default parameters.
  - Generation of discharge, water velocity and flood depth along the Yamuna river stretch from Hathnikund to Okhla barrage.

PHASE II (6 months)

- **Field surveys**
  - Generation of high resolution river cross-sections through field survey
  - Field survey for habitat requirement of indicator fish species
  - Collection of water quality samples to ensure the status of water quality of River Yamuna in present scenario. Parameters will be utilized in hydrological and hydrodynamic models for the assessment of the minimum requirement of environmental flows.

- **Hydrological and Hydrodynamic modeling**
  - Water balance analysis using SWAT (Soil and Water Assessment Tool) to generate local flows and outflows utilizing available dataset (e.g. SRTM 30 m DEM, LULC and SOIL map)
  - Generation of stage discharge relationships using HEC-RAS

PHASE III (4 months)

- **Integrated framework for Environmental Flows Assessment**
  - Development of SWAT model to simulate the flows both for present and virgin (before commissioning of Hathnikund/Tajewala barrage) flow conditions using DEM, LULC and soil data.
  - Generation of discharge, river depth, top width, velocity, flood area and water level along Yamuna river stretch from Hathnikund to Okhla barrage utilizing high resolution datasets
  - Determine the minimum required environmental flows for sustaining aquatic life, based on the results of hydrologic and hydrodynamic modelling and the secondary data on the habitat requirement of aquatic species
  - Estimation of releases from Hathnikund barrage to maintain the minimum required environmental flows at downstream reaches.

- **Qualitative Assessment of Yamuna river**
  - Pollutant load estimation at various locations in the concerned river reach using the primary and secondary water quality data of drains and canals joining Yamuna in the concerned river reach.

- **Management Options for Maintaining Recommended E-Flows**
  - Possibility of considering various future scenarios in terms of increasing irrigation efficiency, treatment of effluent coming through various drains meeting river Yamuna, creating storage in the upstream reaches etc. as management options for maintaining the recommended e-flows.

To achieve the study objectives, necessary data were collected from various agencies and processed. Details of the database generated are provided in Chapter 4.

Chapter 4

DATABASE FOR THE STUDY REACH AND DATA PROCESSING

4.1 Data Used in the Study

The key data requirements for environmental flow study are river flows, river geometry and habitat parameters. The present study deals with the assessment of environmental flows by using hydrodynamic and hydrological modelling approach, therefore, variety of datasets are required as input to the models as well as to validate the model outputs. The river inflow and outflow at different locations of the river at daily time interval, river cross sections, meteorological data like observed rainfall and temperature at daily time interval, recent land use land cover maps, soil maps with detailed information of soil parameters are utilized in the study. The analysis of variation in groundwater levels in the study reach between the years 1975 and 2018 have also been attempted. In addition, field surveys have been carried out for the following:

(i) ascertain the indicator fish species and their habitat requirement, and
(ii) river cross-section surveys at close spaced intervals

Table 4.1 lists the data collected from various agencies to achieve the study objectives.

Table 4.1 Data collected from various agencies for the study

SN	**Data collected**	**Agency**	**Data Length**	**Remark**
1	Daily gauge and discharge data at CWC gauging sites in study reach	YBO, CWC, New Delhi; UP Irrigation Dept. (Okhla)	1976-2018	Data breaks during 1991-1995
2	Daily Inflow, outflow, diversions at Hathnikund barrage	UP Irrigation Dept., Saharanpur	1976-2000	-
3	Releases from Wazirabad and Okhla barrage	UP Irrigation Dept. (Okhla); Delhi Jal Board	1995-2018	-
4	Daily discharge data of drains joining Yamuna from Haryana	Water Data Collection Division, Karnal, Haryana	1995 - 2018	Diversion drain No. 8 monthly data
5	Flow from Hindon Cut Canal	UP Irrigation Dept. (Okhla)	2005-2018	-
6	Groundwater level data in riparian states/ Delhi	CGWB, New Delhi	1971-2019	Pre-Post monsoon
7	River water quality data at G&D sites and Delhi segment	YBO, CWC, New Delhi	1995-2018	Monthly
8	River water quality & water quality of drains in Delhi Segment	CPCB, New Delhi	2014-2016	-

9	Flow drains joining Yamuna from Haryana	SPCB Haryana; Irrigation & Water Resources Dept. Haryana	1995-2018	Drain 2 daily data (1995-2018) Drain 8 Monthly data (2010-2018)
10	Groundwater level data and EC/TDS data for WYC	Irrigation & Water Resources Dept. Haryana	June 2019	Block wise
11	Cropping pattern, Land classification, Crop and Irrigation data	Irrigation & Water Resources Dept. Haryana	2015-2019	Block wise
12	Fish habitat suitability data through field visits to River Yamuna	NIH Roorkee and WII Deharadun	October 2019 & Feb 2020	-
13	River cross-section survey data at gauging sites at 10 km interval	YBO, CWC, New Delhi	2017	-
14	River cross-section survey undertaken by NIH at 306 locations	Geoscience Consultancy Services, Roorkee	-	309 locations

4.2 Analysis of Flow Data

4.2.1 Analysis of inflow and releases at Hathnikund barrage

Hathnikund barrage regulates the flow of Yamuna for irrigation in Haryana and Uttar Pradesh through the Western Yamuna Canal and the Eastern Yamuna Canal, as well as the municipal water supply to Delhi. A plot of eighteen years (2001-2018) average monthly inflows and releases from Hathnikund is shown in Fig. 4.1, while Fig. 4.2 shows the plot of average monthly inflows and releases from Hathnikund over the years 2001-2018.

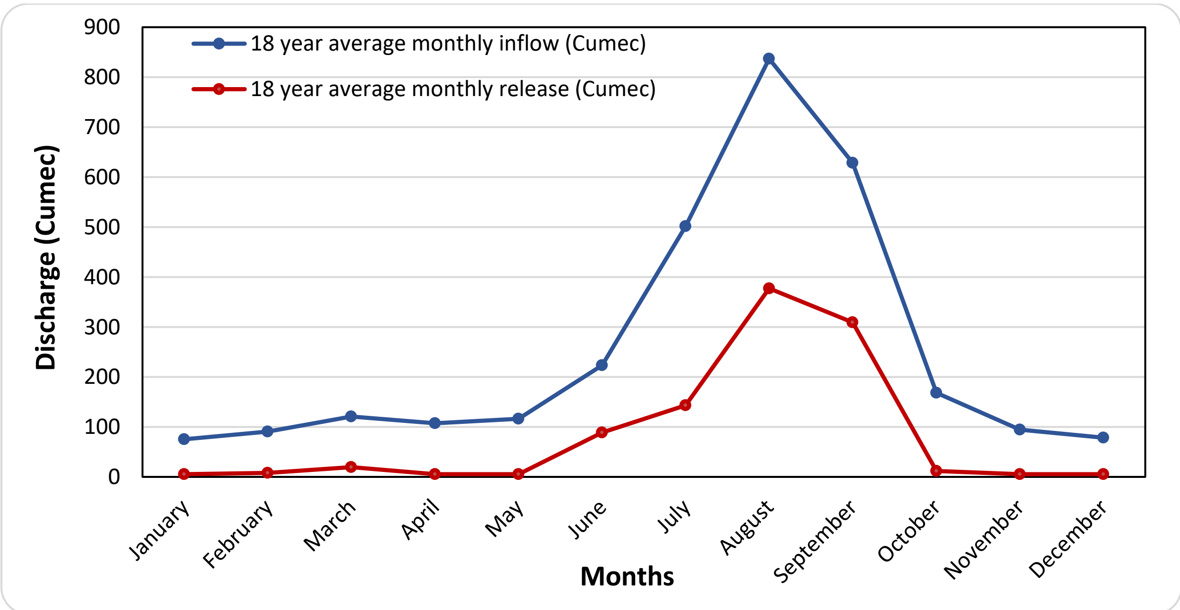


Fig. 4.1 Plot of eighteen years (2001-2018) average monthly inflows and releases from Hathnikund.

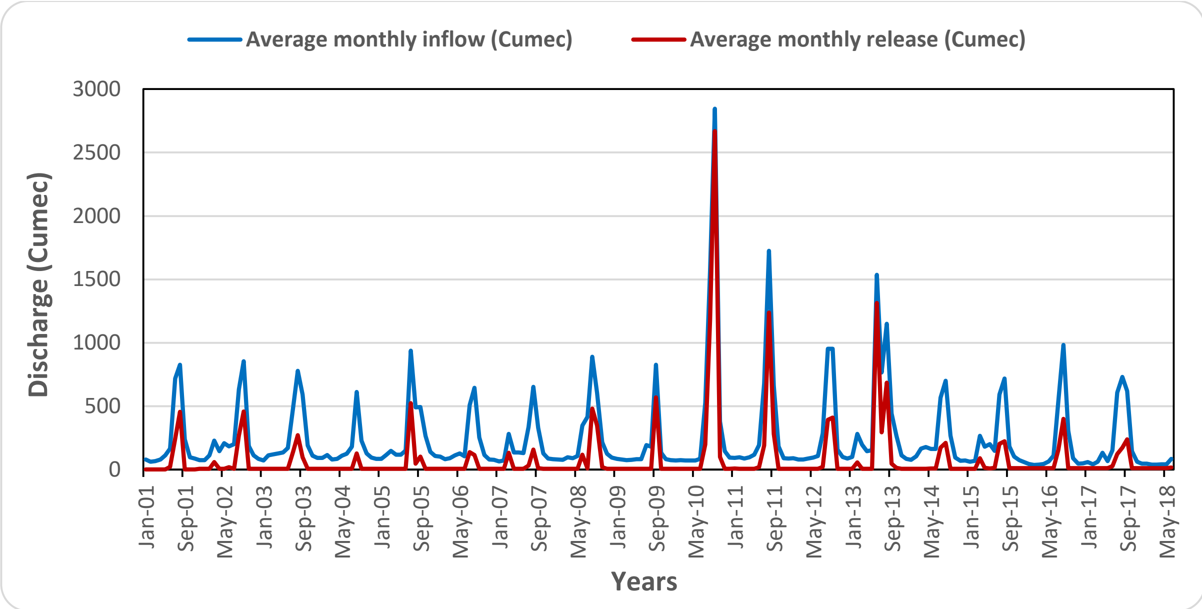


Fig. 4.2 Plot of average monthly inflows and releases from Hathnikund for the years 2001-2018.

4.2.2 Analysis of Monthly Releases from Hathnikund Barrage and Flows at Kalanaur, Karnal, Mawi, Baghpat, and Delhi Railway Bridge

Figure 4.3a illustrates the discharge observed at Kalanaur and downstream GD site Karnal for the years 1976-81. Figure 4.3b shows the discharge observed at Karnal and downstream GD site Mawi, Fig. 4.3c shows the discharge observed at Mawi and downstream GD site Baghpat, while Fig. 4.3d shows the discharge observed at Baghpat and downstream GD site Delhi Railway Bridge (DRB) for the years 1976-81.

Similarly, Fig. 4.4a illustrates the discharge observed at Kalanaur and downstream GD site Karnal for the years 2013-18. Fig. 4.4b shows the discharge observed at Karnal and downstream GD site Mawi, Fig. 4.4c shows the discharge observed at Mawi and downstream GD site Baghpat, while Fig. 4.4d shows the discharge observed at Baghpat and downstream GD site DRB for the years 2013-18.

In general, for most segments in the study reach during both time periods, the discharge observed at downstream site is more than the discharge at upstream site barring a few months, which reveals that certain amount of flow is getting added into the river from intermediate catchment, from drains, and irrigation return flow etc. However, for the Baghpat-DRB segment, the site at DRB is located downstream of Wazirabad barrage and the flow at this gauging site is largely influenced by the controlled releases from Wazirabad barrage and water contributed by various drains joining Yamuna between the barrage and DRB. The effect is largely visible for the period 2013-18.

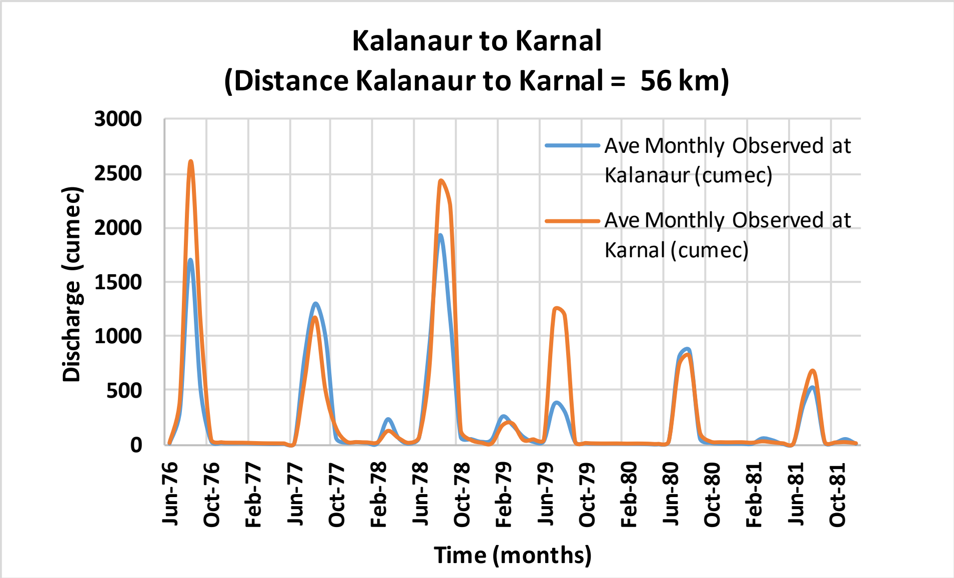


Fig. 4.3a Flow observed at Kalanaur and Karnal (1976-81)

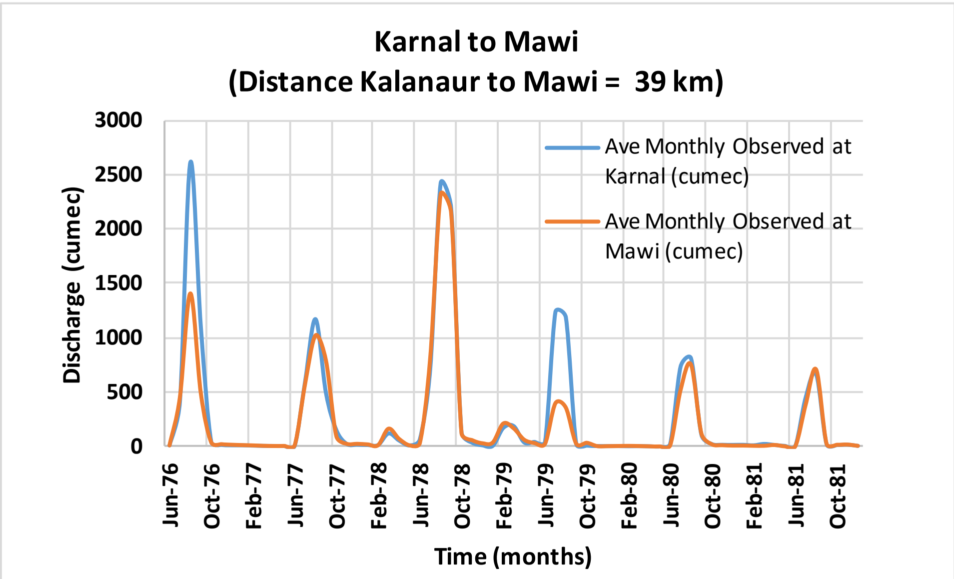


Fig. 4.3b Flow observed at Karnal and Mawi (1976-81)

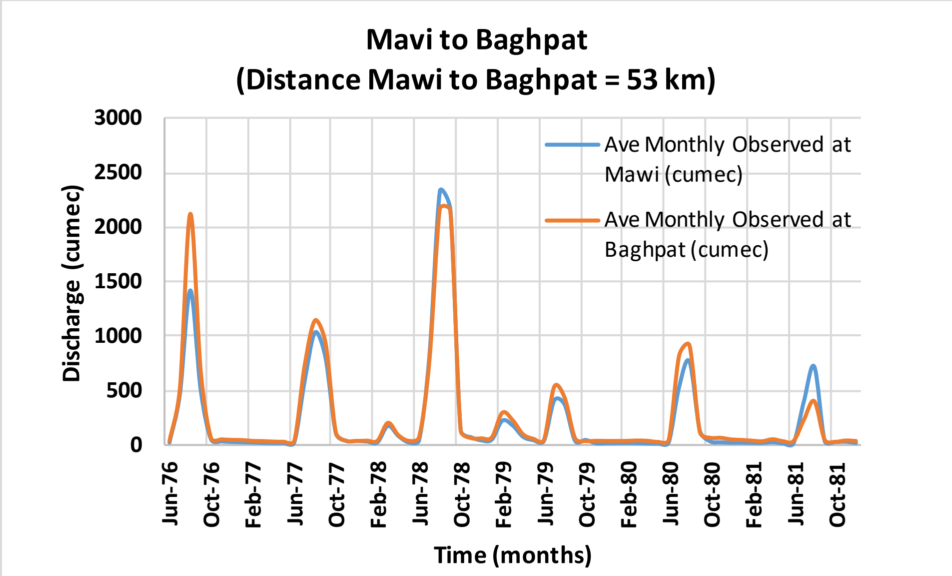


Fig. 4.3c Flow observed at Mawi and Baghpat (1976-81)

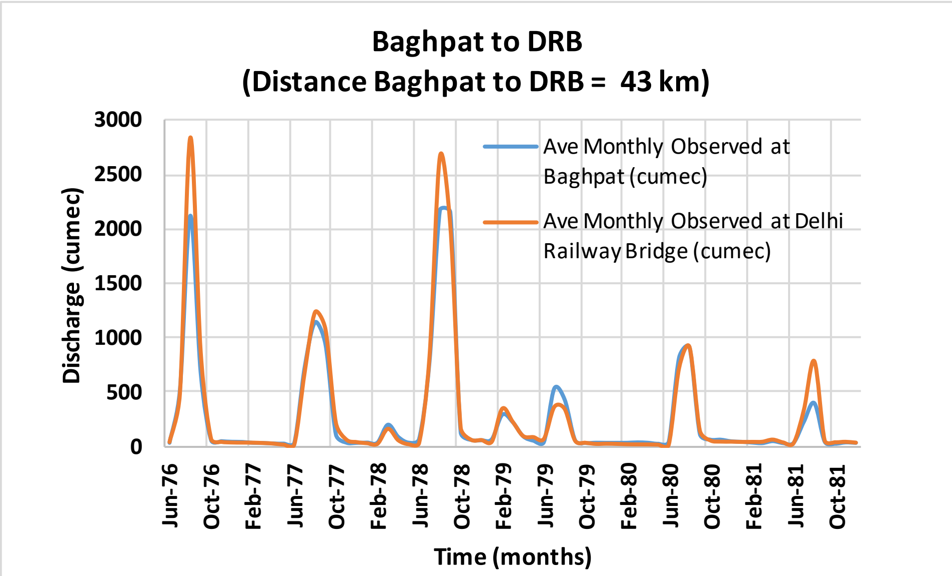


Fig. 4.3d Flow observed at Baghpat and Delhi Railway Bridge (1976-81)

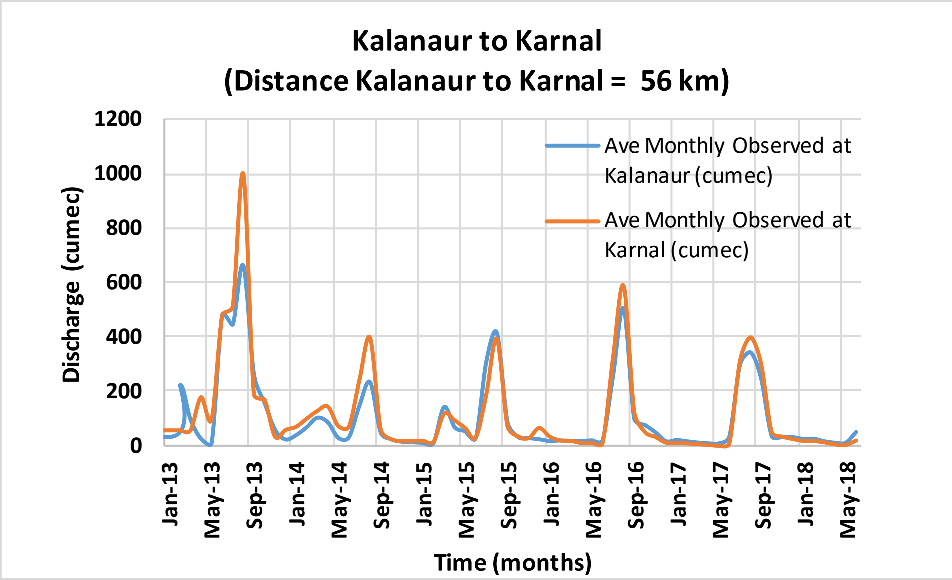


Fig. 4.4a Flow observed at Kalanaur and Karnal (2013-18)

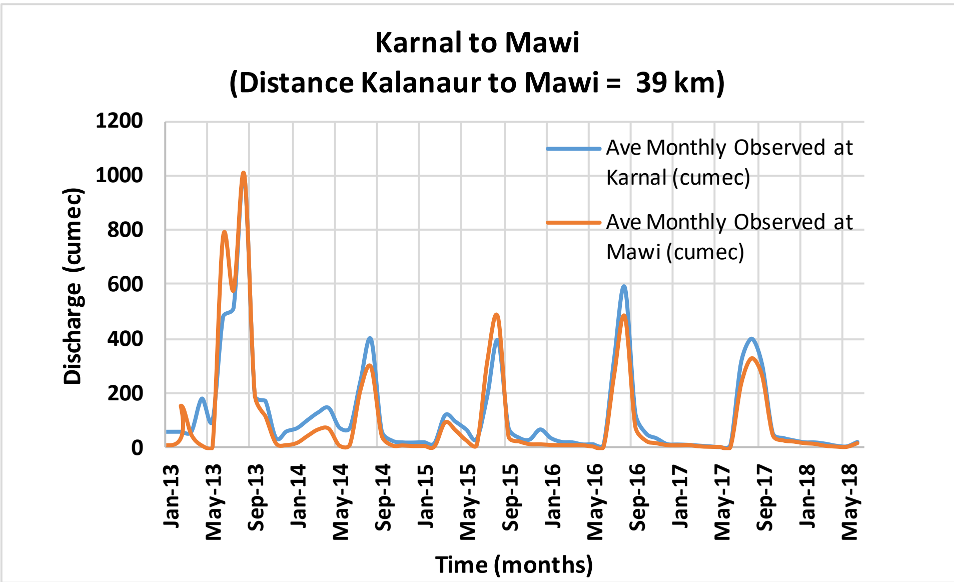


Fig. 4.4b Flow observed at Karnal and Mawi (2013-18)

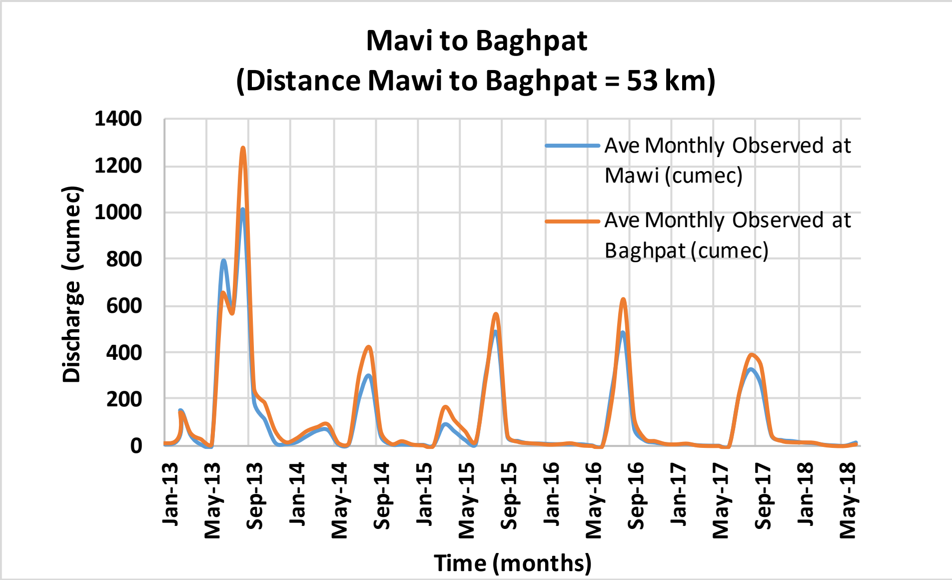


Fig. 4.4c Flow observed at Mawi and Baghpat (2013-18)

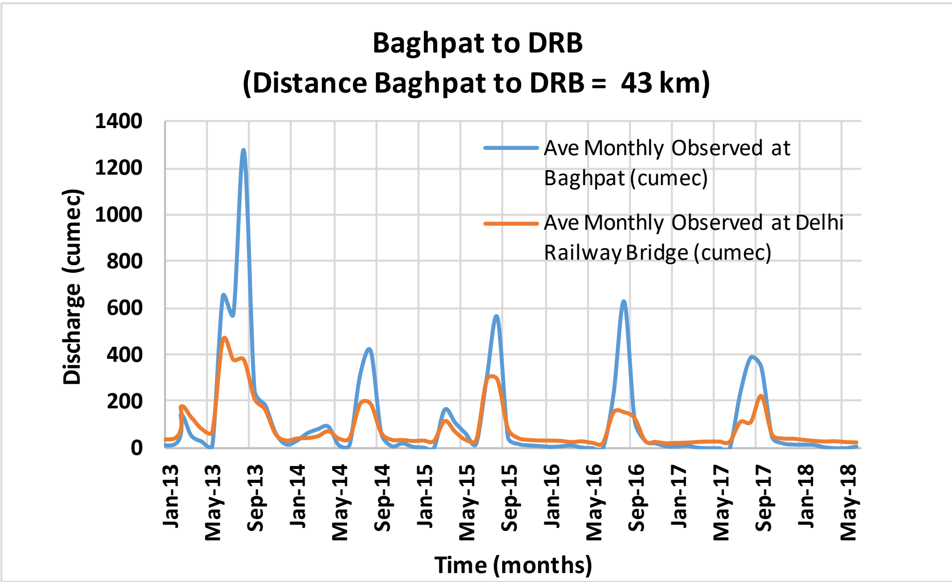


Fig. 4.4d Flow observed at Baghpat and Delhi Railway Bridge (2013-18)

4.3 Groundwater Depletion

In view of large withdrawals of groundwater in the riparian states of Haryana and Uttar Pradesh, groundwater levels have receded all along the river stretch from downstream of Kalanaur to Baghpat, which in turn has affected the baseflow contributon to the flows in Yamuna in this stretch during the non-monsoon period. The advent of diesel pumps and pumps run by electricity spurred the drilling of a large number of tube wells over the period of last three decades. To assess the deepening groundwater levels, since the period when groundwater overexploitation was not common, the depth to groundwater levels (DTWL) for pre-monsoon and post-monsoon are plotted for the years 1975 and 2018 in Figs. 4.5(a)-(d) for the locations available from CGWB. The plots clearly exhibit large depletion in groundwater levels over the period of four decades. Between Hathnikund and Okhla barrage, maximum depletion ranging from 10 to 20 m is recorded in the Mawi-Baghpat reach.

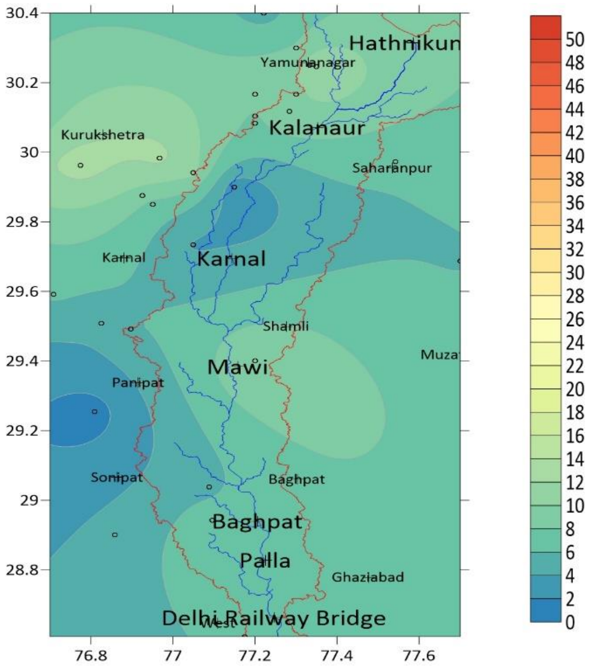


Fig. 4.5a DTWL (m) pre-monsoon 1975

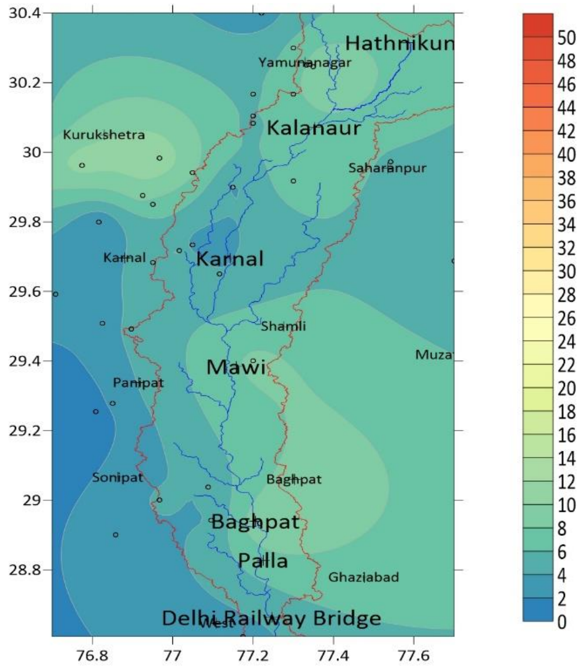


Fig. 4.5b DTWL (m) post-monsoon 1975

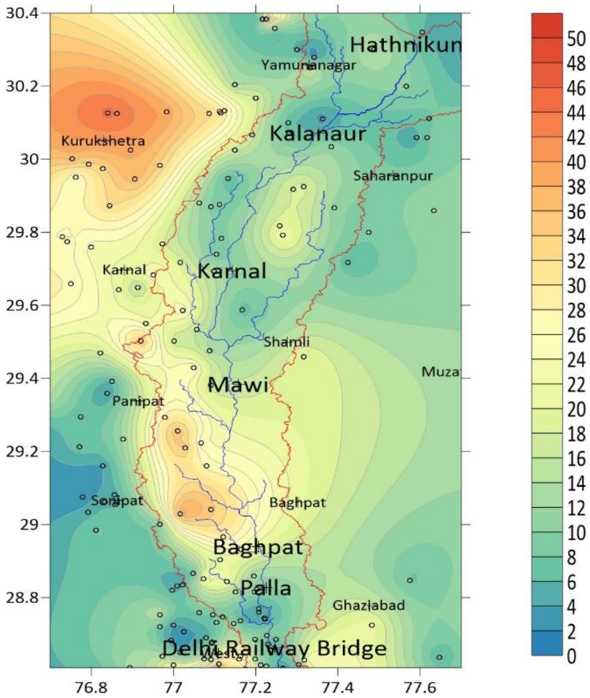


Fig. 4.5c DTWL (m) pre-monsoon 2018

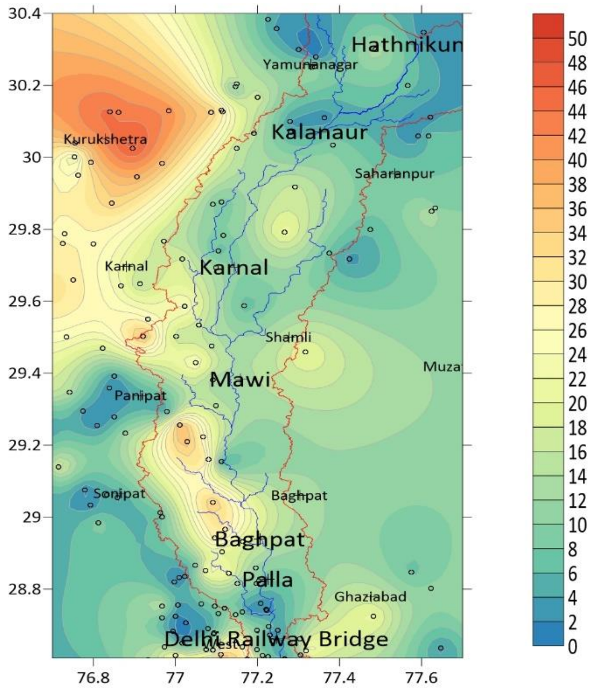


Fig. 4.5d DTWL (m) post-monsoon 2018

4.4 Field Survey for River Cross-Sections in Study Reach

For achieving accuracy in flow simulations using hydrodynamic modeling, the river cross-sections are needed at close intervals (this aspect is discussed in detail in Chapter 5). Since cross-sections at close intervals were not available, field surveys were carried out to determine the cross-sections along Yamuna river at 306 lines. The river cross-sections are taken every 1 km throughout the river from Hathnikund barrage to Okhla barrage, except for small stretches near locations marked in Fig. 4.6, where the cross-sections are taken at every 250 m. At each such location, 05 cross-sections were surveyed located 250 m apart within a reach of 1 km. Total locations where spacing interval was 250 m within a distance of 1 km are 14 in number, with the 14th location falling at Okhla barrage (refer Table 4.1a). Plots of a few surveyed river cross-sections are provided in Annexure 1.

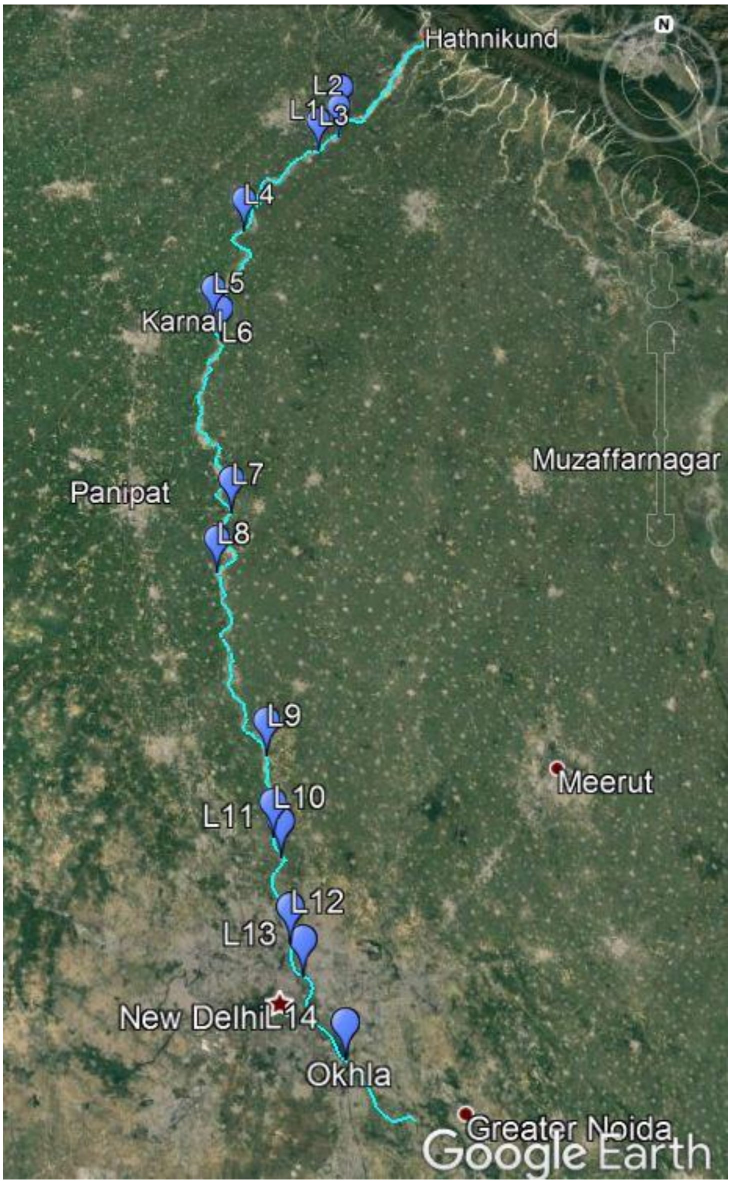


Fig. 4.6 The 14 identified locations on Yamuna river (where river cross-sections were surveyed 250 m apart inside a reach of 1 km; total 306 lines were surveyed at 1 km interval)

Table 4.1a Details of 14 locations where river cross-sections were surveyed at an interval of 250 m within a reach of 1 km. Such locations were identified either at gauging sites or at confluence of canal/ drains/ natural streams and main river.

Label	Latitude	Longitude	Type of Site (G&D site or confluence of streams/ drains with main river)	Distance from Hathnikund barrage (km)	Description of locations
Location 1	30° 8'27.10"N	77°24'16.60"E	Confluence site	31	Canal near Kanalsi
Location 2	30° 6'2.16"N	77°23'44.85"E	Confluence site	36	Drain near Birtapu
Location 3	30° 4'15.69"N	77°21'40.52"E	Confluence and G&D site	41	Gauging site near Kalanaur
Location 4	29°54'7.69"N	77°11'48.95"E	Confluence site	71	Drain near Ranipurbarasi must
Location 5	29°43'38.33"N	77° 7'52.35"E	Confluence site	97	Drain near Mohayuddinpur
Location 6	29°41'25"N	77° 8'44"E	G&D site	103	Gauging site near Karnal
Location 7	29°23'10.04"N	77° 9'29.39"E	G&D site	146	Gauging site near Mawi
Location 8	29°16'45.03"N	77° 7'26.85"E	Confluence site	163	Drain near Khojkipur
Location 9	28°59'14"N	77°12'7"E	G&D site	203	Gauging site near Bhagpat
Location 10	28°51'42.71"N	77°12'28.32"E	Confluence site	219	Drain near Palla
Location 11	28°50'2"N	77°13'13"E	G&D site	222	Gauging site near Palla
Location 12	28°42'27.40"N	77°13'49.33"E	Confluence site	243	Drain near Wazirabad
Location 13	28°39'42"N	77°14'57"E	G&D site	248	Gauging site near DRB
Location 14	28°32'54.58"N	77°18'49.13"E	G&D site	263	Okhla barrage

4.5 Field Survey for Habitat Requirement of Indicator Fish Species

To determine e-flows for maintaining ecological integrity and sustaining fisheries resources of river Yamuna, a rapid field survey was conducted in river Yamuna for identification of indicator fish species. A field team comprising of NIH members and river ecology expert from Wildlife Institute of India carried out field sampling between Hathnikund barrage and Panipat during the month of October 2019 and February 2020.

Fish and river habitat variables (flow and depth measurements) were carried out at various locations viz., Hathnikund, Yamuna Nagar and Panipat and above Delhi segment. Details of the field survey and findings are presented in Chapter 6.

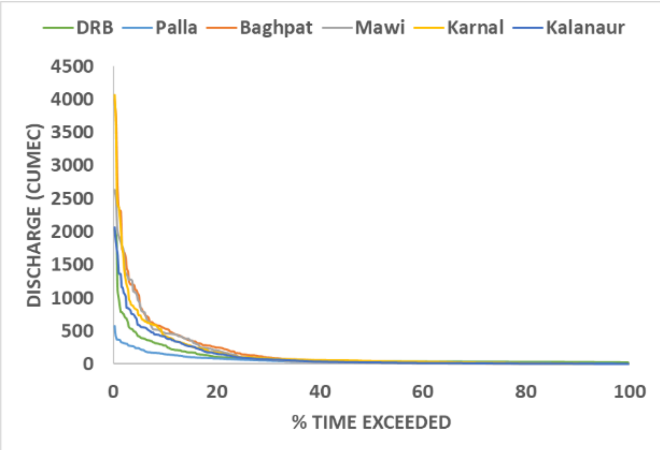
4.6 Flow Duration Curve

Flow Duration Curves (FDC) corresponding to different dependability years help understand the response of the basin in different hydrologic scenarios. FDC is constructed using long-term observed data (10 year return period) of a river at the desired locations. It is the graphical representation of discharge versus the exceedance probability.

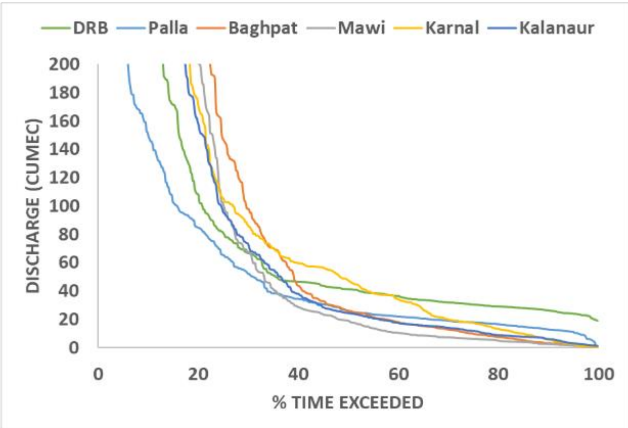
With the probability of exceedance corresponding to Q95, the FDC corresponding to 7-day mean discharge for the 10-year return period (7Q10) is defined as the appropriate e-flow during drought years/low-flow periods (Jain & Kumar, 2014). The 7Q10 flow for regulation purposes may useful for

- Water quality protection from waste water discharge.
- Habitat protection during drought condition.
- Chronic criteria for aquatic life.
- A local extinction flow.

The flow duration curves were constructed for Yamuna river at different gauging sites (Figs. 4.7a-b).



(a)



(b)

Fig. 4.7 Combined Flow Duration Curve for gauging sites at DRB, Baghpat, Mavi, Karnal and Kalanaur

The 7-day mean flows were obtained for a return period of 10 years (2009 – 2018) and the graphs (Figs. 4.7 and Fig. 4.8) has been plotted between percentile and discharge in cumec for different gauging sites at Delhi Railway Bridge (DRB), Baghpat, Mawi, Karnal and Kalanaur. The curve obtained in the graph represents the 7Q10 flow curve. In flow duration curve analysis, the high zone is centred at the 5th percentile and the low zone is centred at the 95th percentile. In the low zone flow is due to base flow or snow melt but in the high zone peak flow is due to the rain.

Flow duration curve analysis identifies intervals which can be used as a general indicator of hydrologic conditions (from wet to dry conditions) but it does not retain the temporal sequences of flows and so do not define the timing or duration of e-flows. Q90 and Q95 indicate 90% and 95% probability that such discharge will be available in the river, respectively. Table 4.2 shows the values of Q90 and Q95 as low flow indices for different gauging sites.

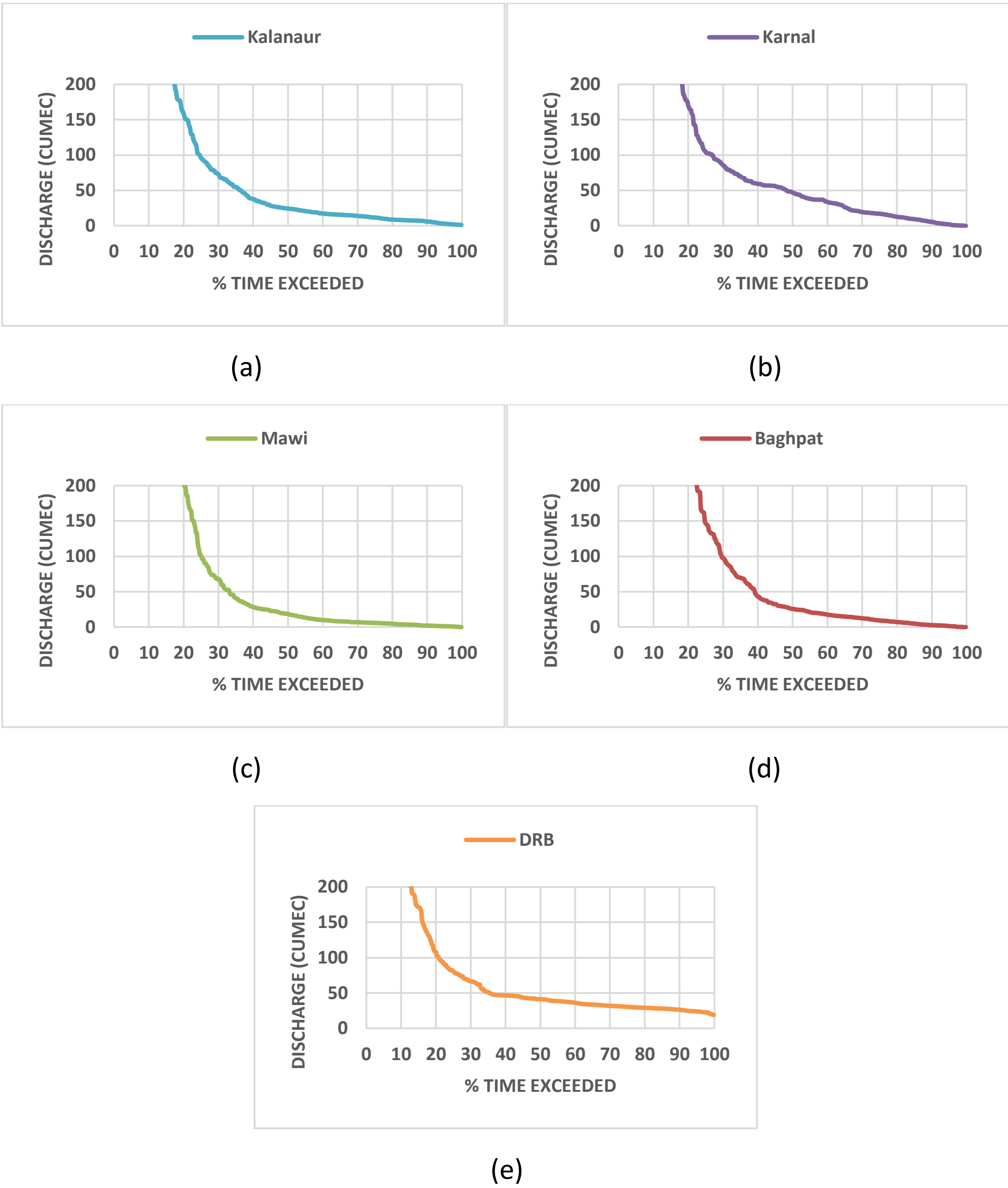


Fig. 4.8 Flow duration curve for gauging sites at (a) Kalanaur (b) Karnal (c) Mawi (d) Baghpat (e) DRB

Table 4.2 Percent of time exceeded 7-day average discharge of 10 year return period (7Q10) value corresponding to gauging sites

% Time exceeded	Gauging site				
	DRB	Baghpat	Mawi	Karnal	Kalanaur
Q90 of 7Q10	26.22	2.88	2.16	5.75	5.82
Q95 of 7Q10	23.74	1.44	1.38	2.19	2.82

However, the values of Q90 and Q95 in Table 4.2 do not meet the habitat requirement of the indicator fish species (refer Chapter 6) in the study reach and only indicate that such discharge will be available in the river at the different gauging sites.

4.7 Water Quality Status in Study Reach

The river water quality data monitored by CPCB (2015-2019) and CWC (2013-2018) was used to understand the spatial and temporal variation in the quality of the Yamuna River water. Few essential parameters like pH, Electrical Conductivity (EC), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Total Nitrogen (TN), and Total Phosphorous (TP) were studied. The pollutant load entering the river through various drains, monitored by CPCB during 2015-2019, was also analyzed to work out the mitigation measures to improvise the water quality for the healthy ecosystem.

pH: The mean pH of Yamuna river in the stretch under study varied in the range of 6.4 - 8.9 from 2015-2019. The pH exceeded the criteria of 8.5 prescribed for propagation of wild life and fisheries on few occasions (Figs. 4.9-4.14). However, the pH was mostly in the alkaline range. The observed pH at Paonta Sahib, Hathnikund, Yamunanagar, Sonipat, Wazirabad, Nizamuddin, and Okhla was 7.90±0.05, 7.52±0.05, 7.58±0.05, 7.65±0.05, 7.81±0.06, 7.50±0.04, and 7.48±0.03 respectively. It is observed that the pH of the river reduces from 7.90±0.05 to 7.52±0.05 as the river flows from Paonta Sahib to Hathnikund, however gradual increase in pH is observed till Sonipat and swift increase in pH is observed at Wazirabad (Figs. 4.15-4.16). The gradual increase in pH, in the stretch Hathnikund to Sonipat, may be due to groundwater and wastewater influx in the river. The sudden increase in pH at Wazirabad is due to the presence of phytoplankton in the river which consumes the CO_2 resulting in increased pH. Below Wazirabad barrage, the quick reduction in pH is due to influx of sewage and reducing condition of river. The reducing condition and excess carbon influx in the river results in generation of H_2S and CO_2, which on dissolution in water get converted to acids.

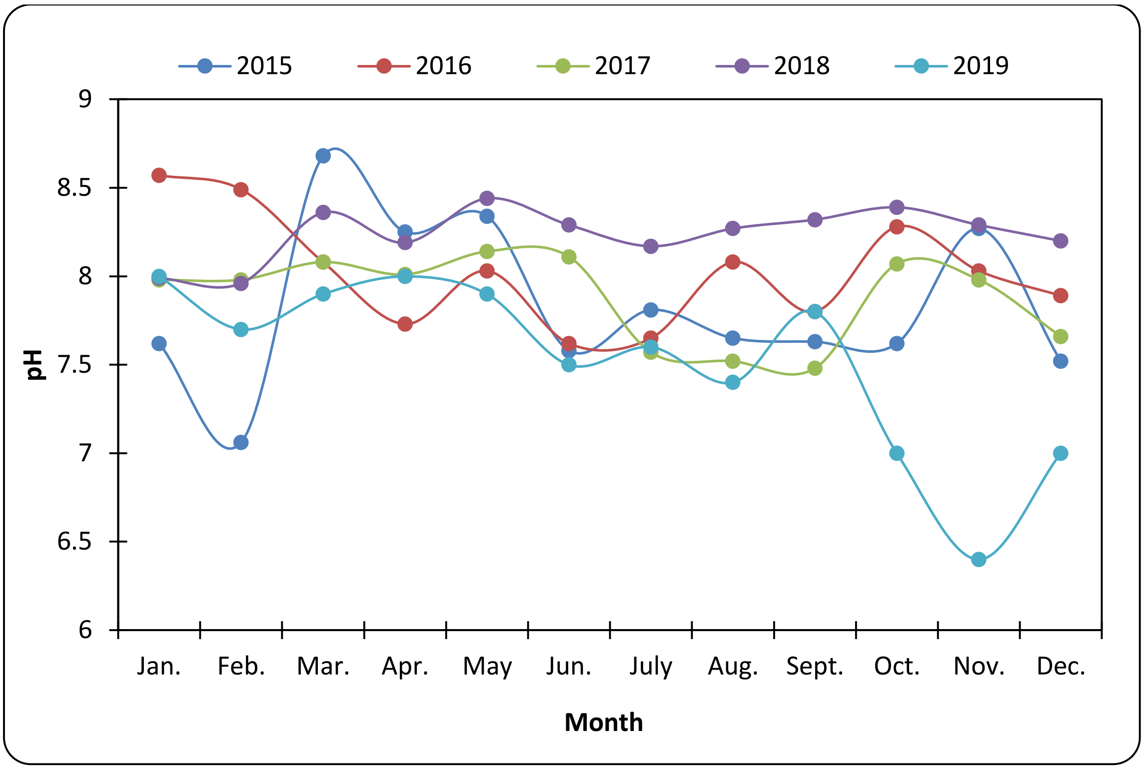


Fig. 4.9 pH variation at Paonta Sahib

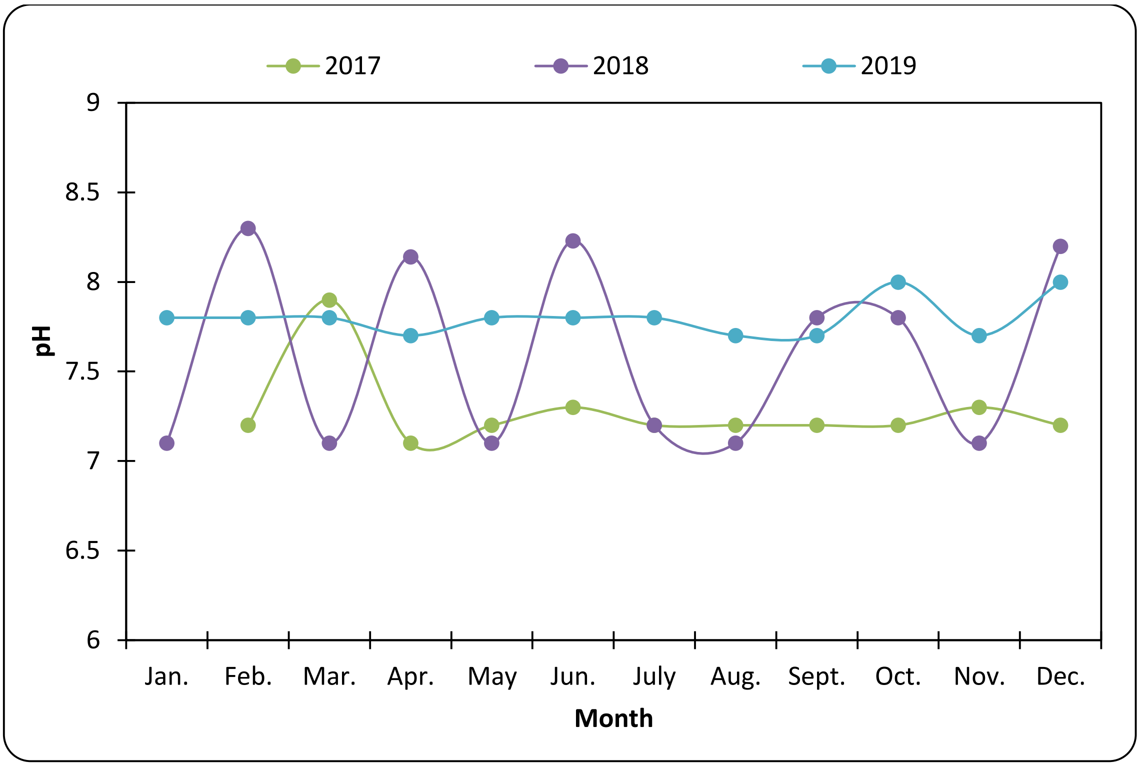


Fig. 4.10 pH variation at Hathinikund

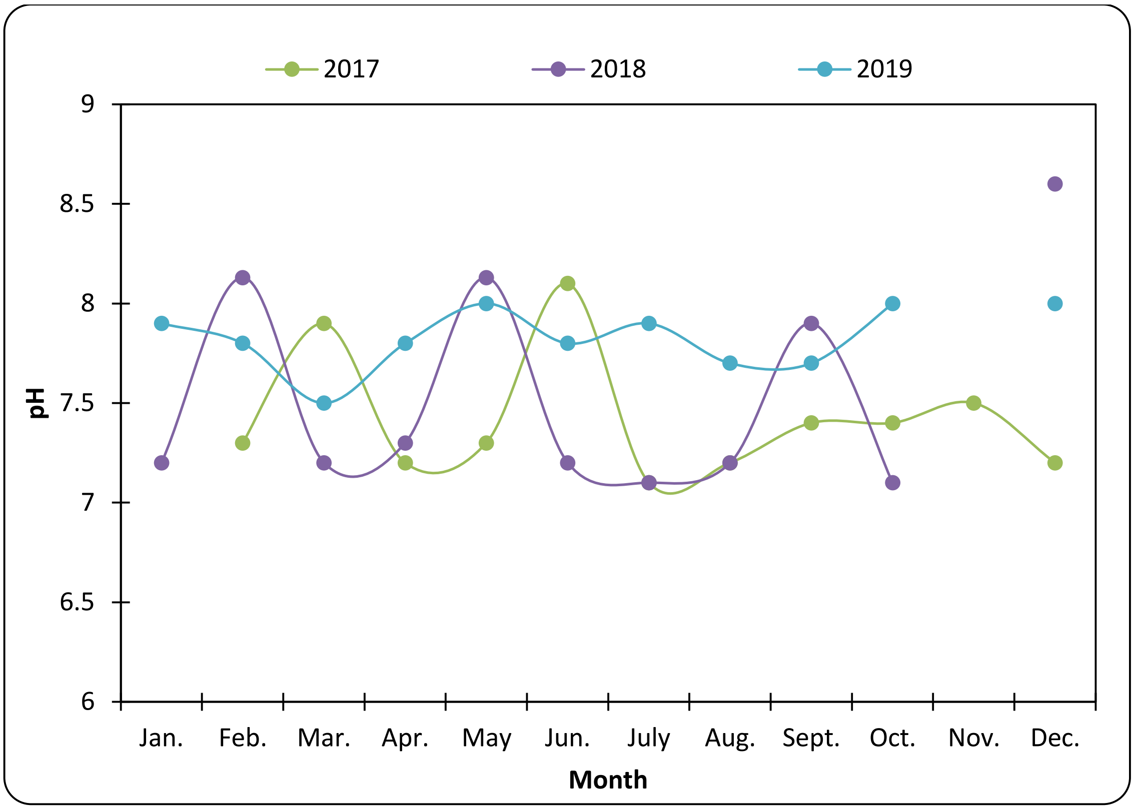


Fig. 4.11 pH variation at Yamunanagar/ Kalanaur

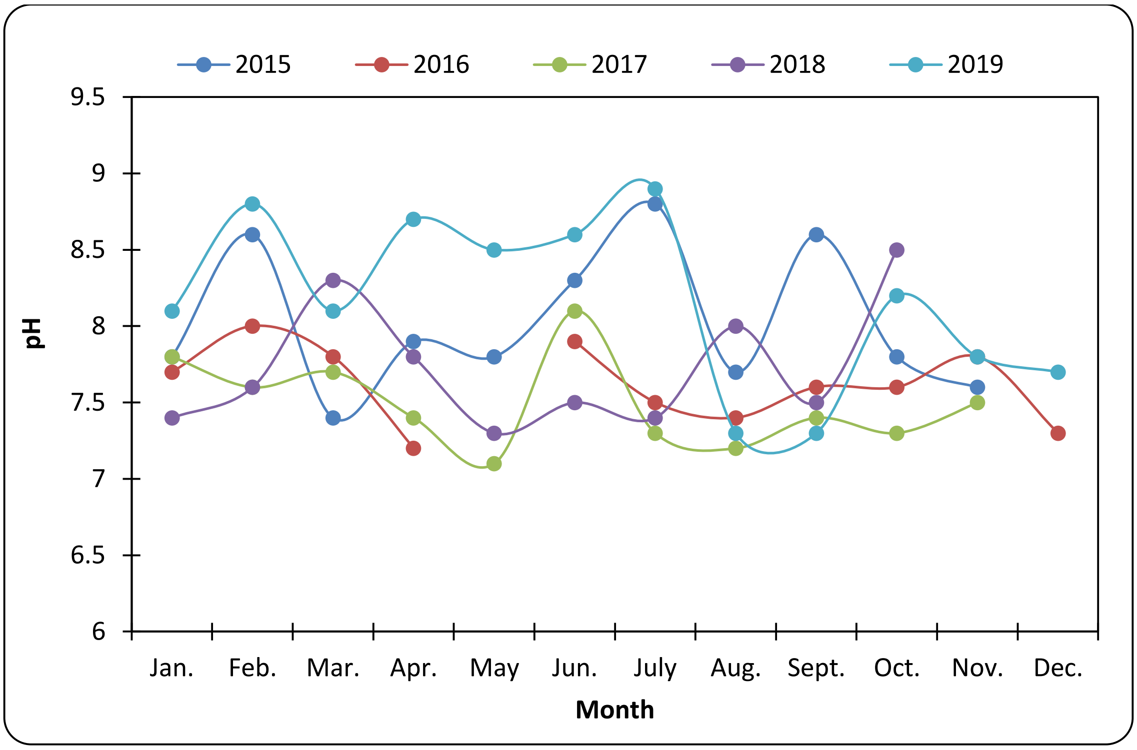


Fig. 4.12 pH variation at Wazirabad

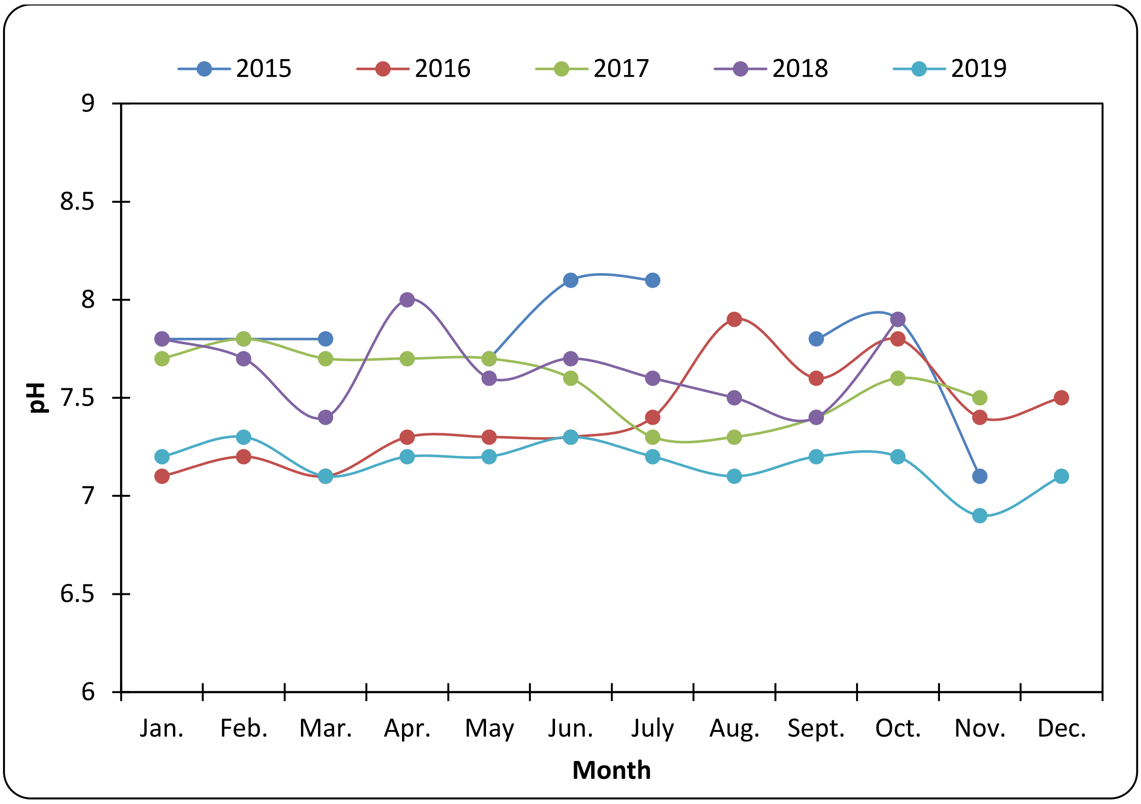


Fig. 4.13 pH variation at Delhi Railway Bridge

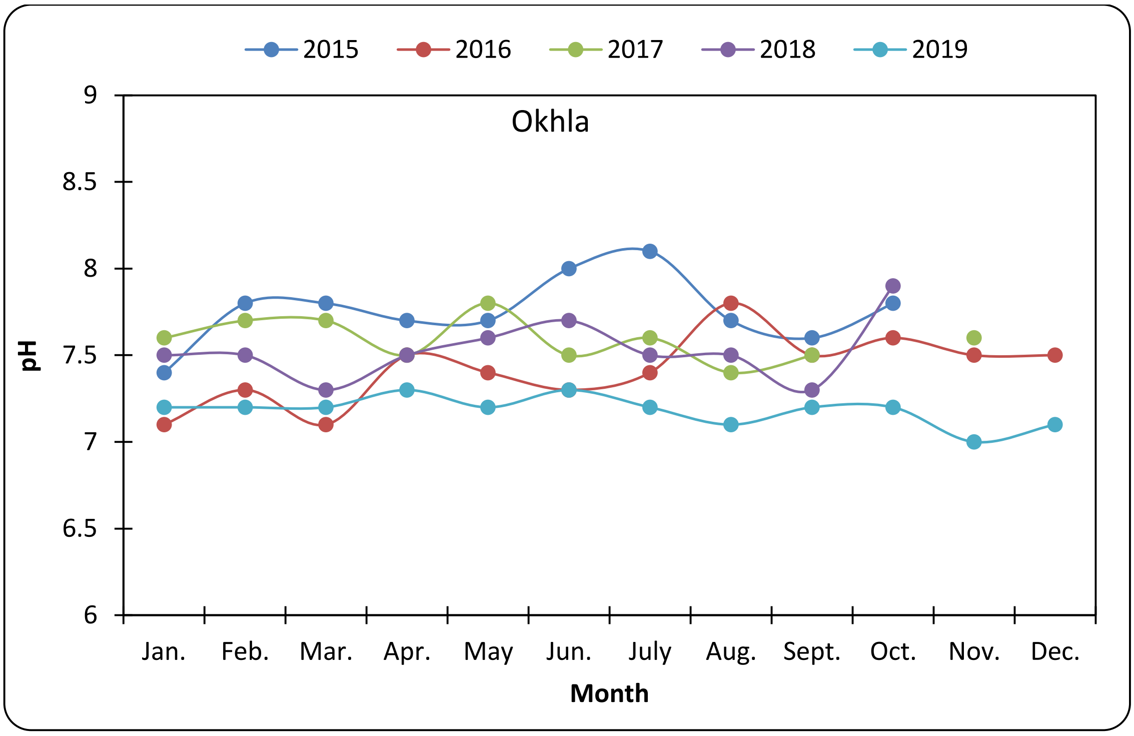


Fig. 4.14 pH variation at Okhla

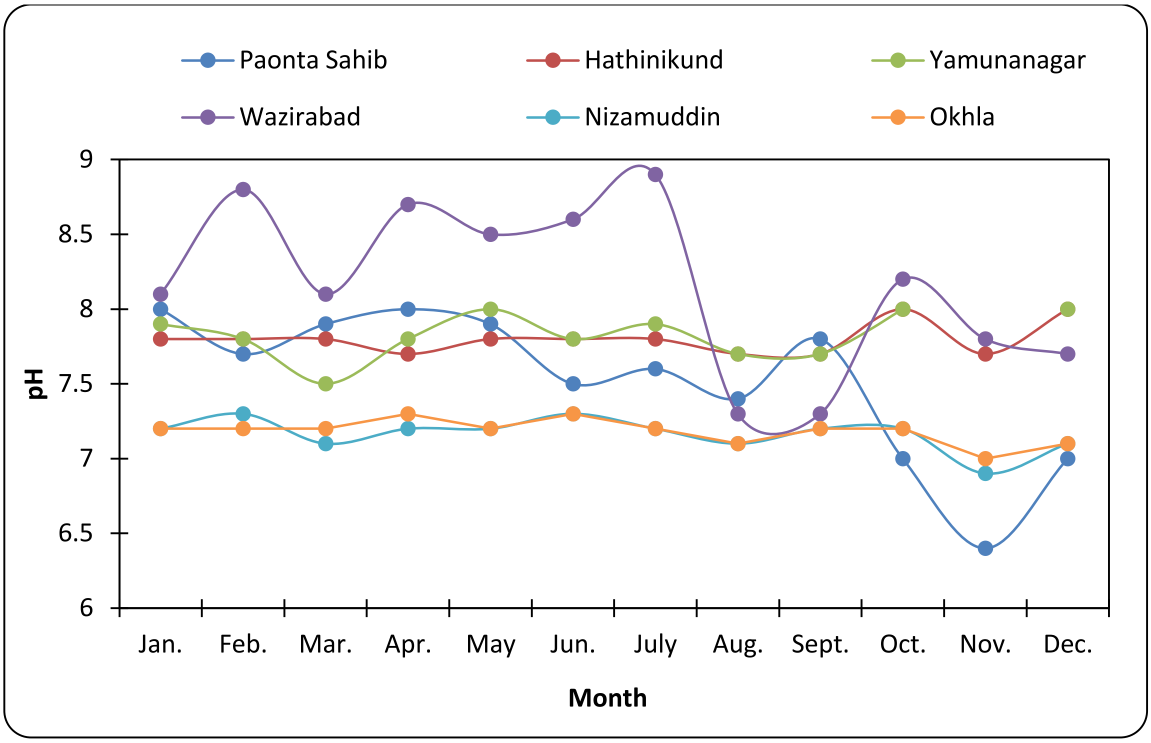


Fig. 4.15 pH variation at different locations during 2019

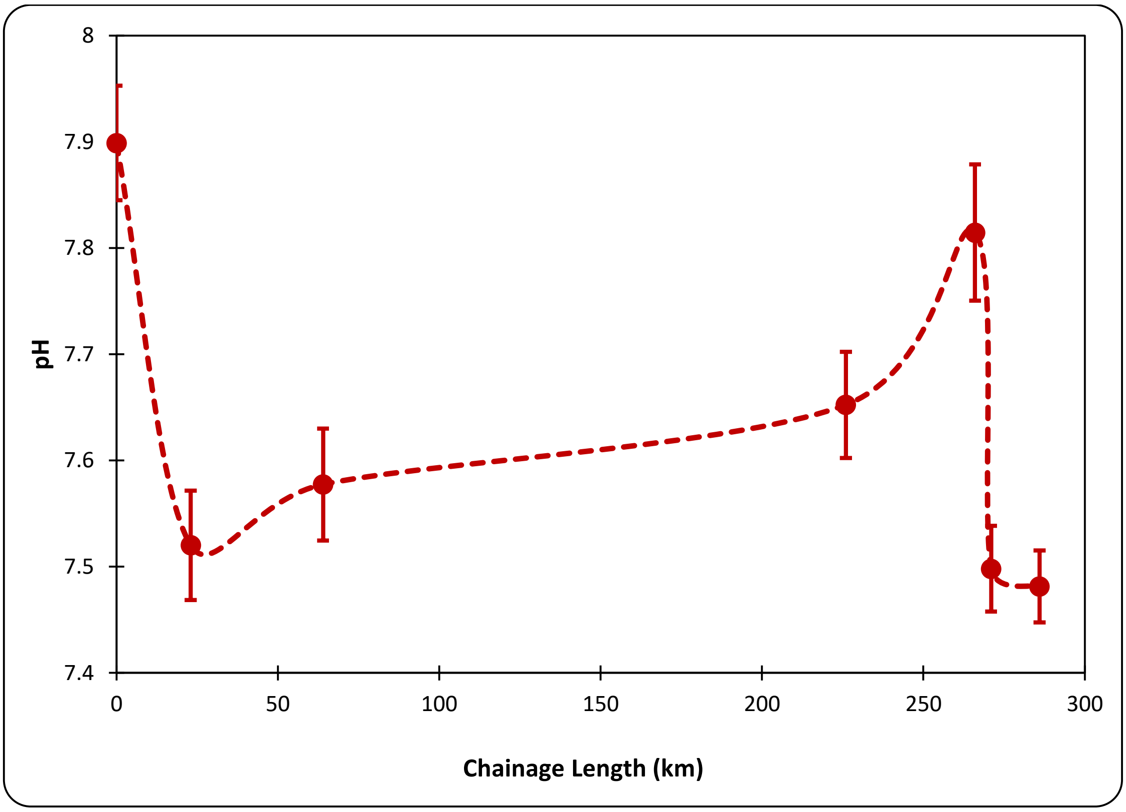


Fig. 4.16 Average annual pH variation at different locations – Paonta Sahib (0 km), Hathinikund (23 km), Yamunanagar (64 km), Sonipat (226 km), Wazirabad (266 km), Nizamuddin (271 km), Okhla (286 km) (2015-2019)

Electrical Conductivity: The EC values indirectly denotes the dissolved solids in the water and indicates the change in the water quality. The EC value of Yamuna River was in the range of 128-3860 µS/cm in the stretch from Paonta Sahib to Okhla during 2015-2019. The EC values were higher in the post monsoon stretch for all the location, however, a sudden change in conductivity to the tune of 2 times and 4 times is observed at Sonipat and Nizamuddin respectively (Figs. 4.17 -4.24).

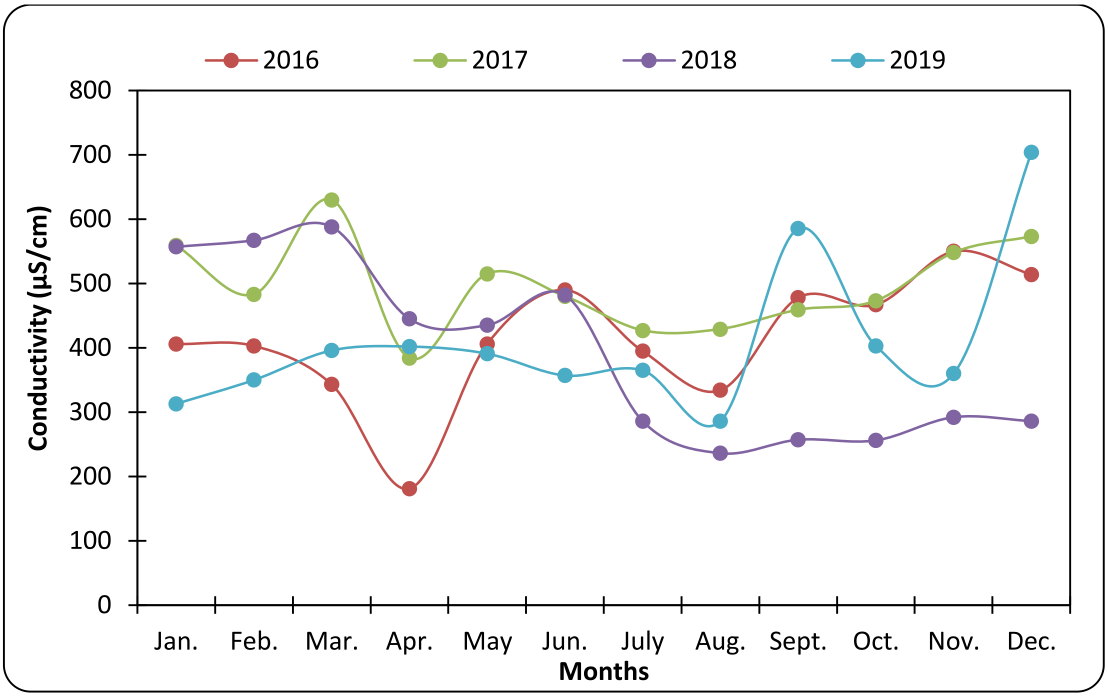


Fig. 4.17 EC variation at Paonta Sahib

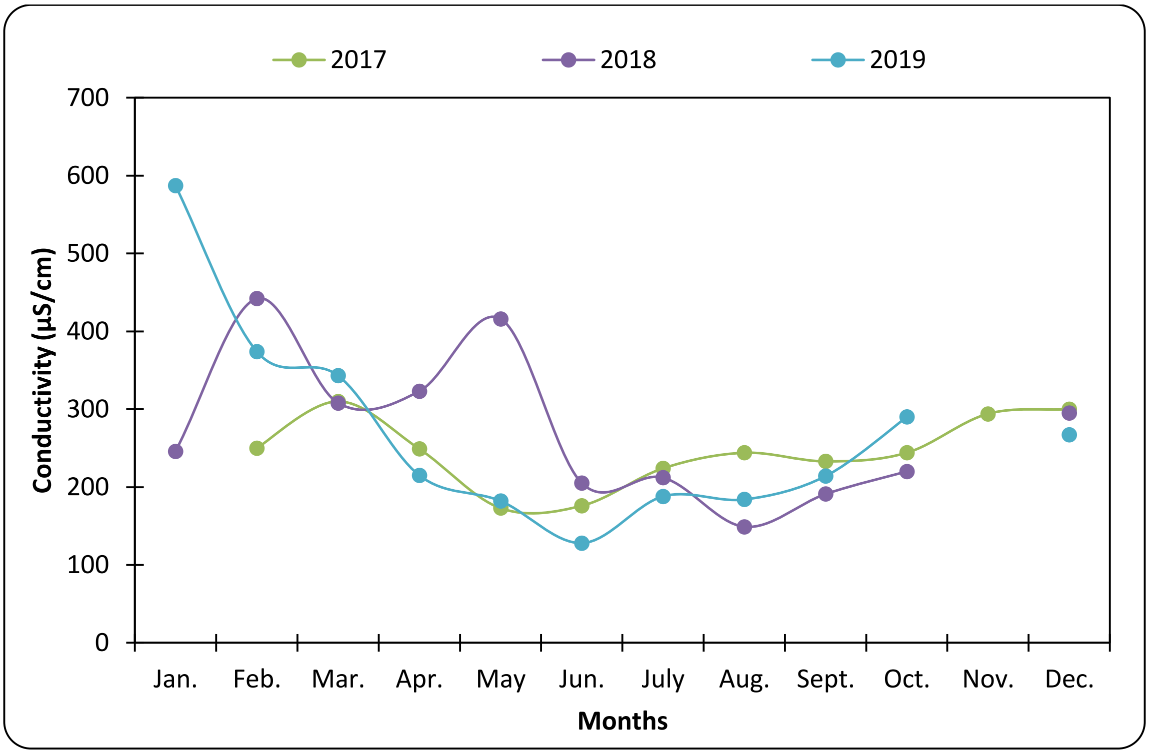


Fig. 4.18 EC variations at Hathinikund

The observed conductivity at Paonta Sahib, Hathinikund, Yamunanagar, Sonipat, Wazirabad, Nizamuddin, and Okhla was 413.5±16.78 µS/cm, 263.5±13.78 µS/cm, 311.5±17.66 µS/cm, 599.7±50.75 µS/cm, 620.7±78.02 µS/cm, 1370.5±76.04 µS/cm, and 1043.5±47.24 µS/cm respectively. The drastic increase in conductivity at Sonipat and Nizamuddin indicates influx of high TDS effluent in the river.

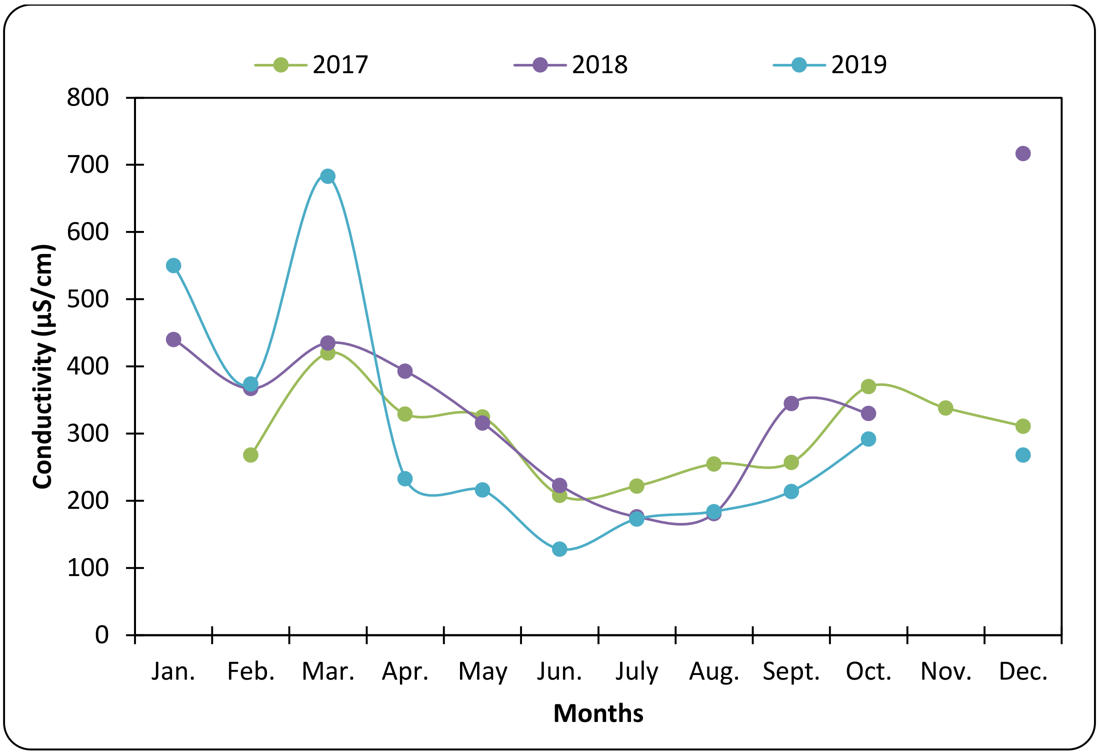


Fig. 4.19 EC variation at Yamunanagar/ Kalanaur

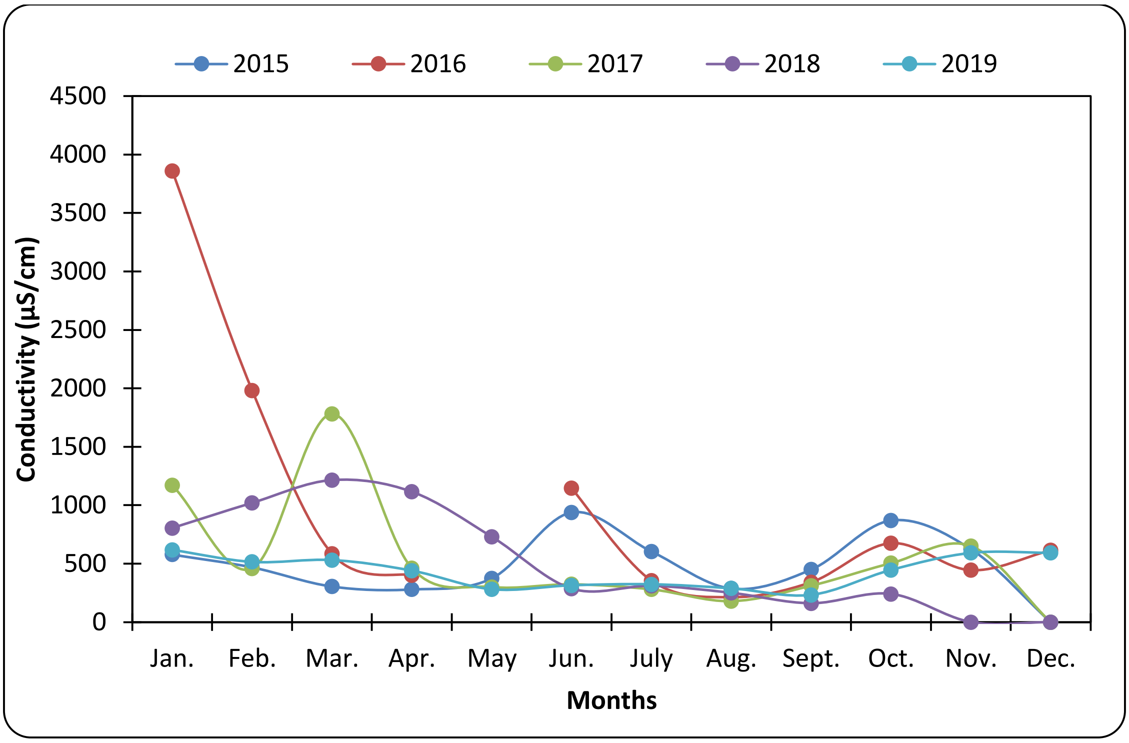


Fig. 4.20 EC variation at Wazirabad

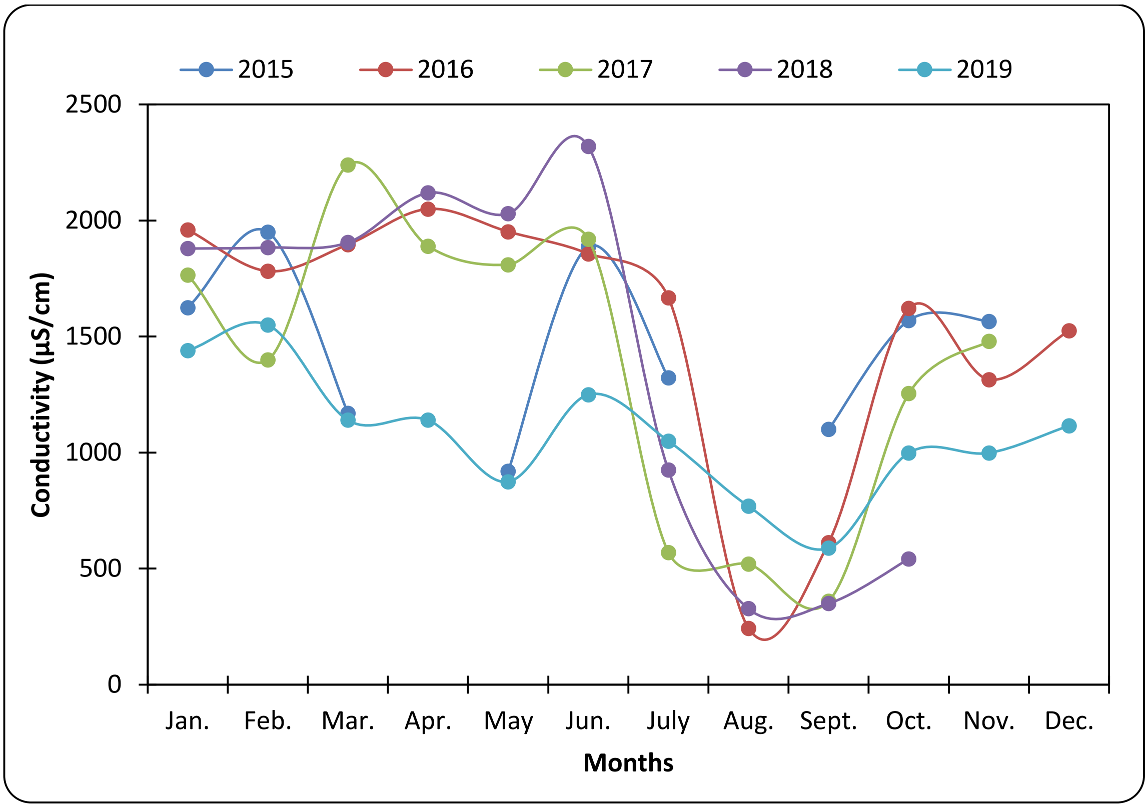


Fig. 4.21 EC variation at Delhi Railway Bridge

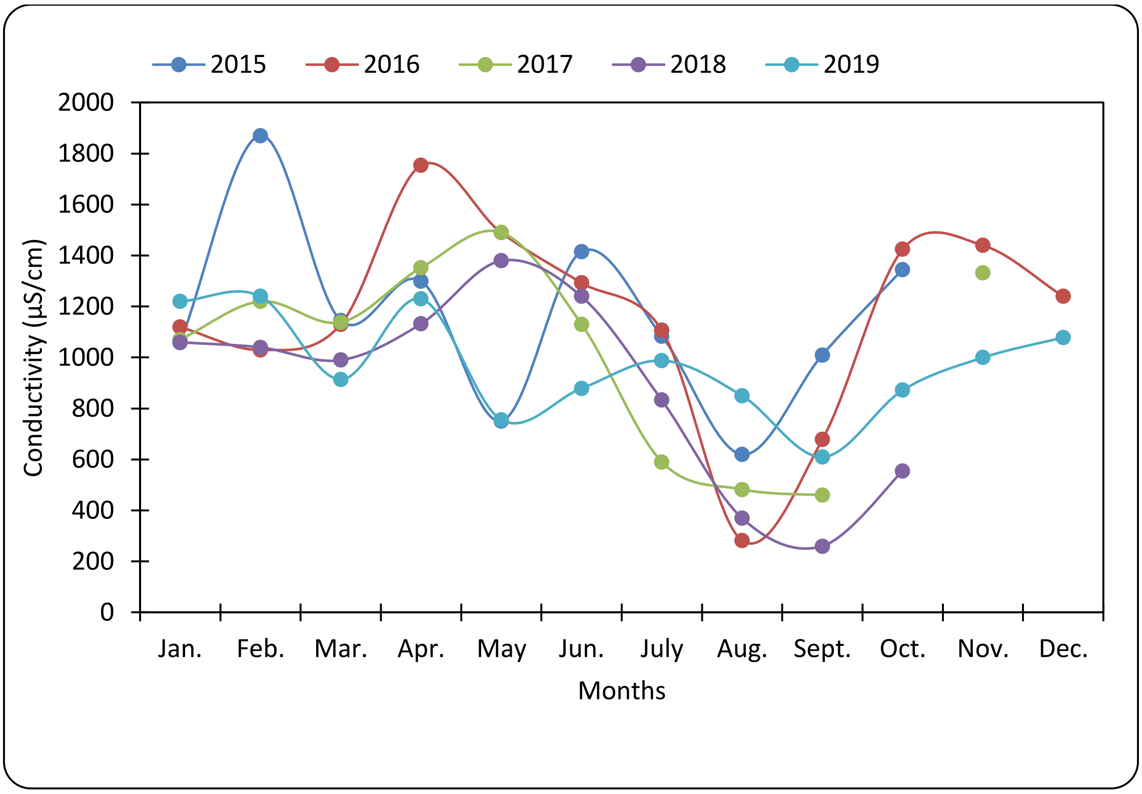


Fig. 4.22 EC variation at Okhla

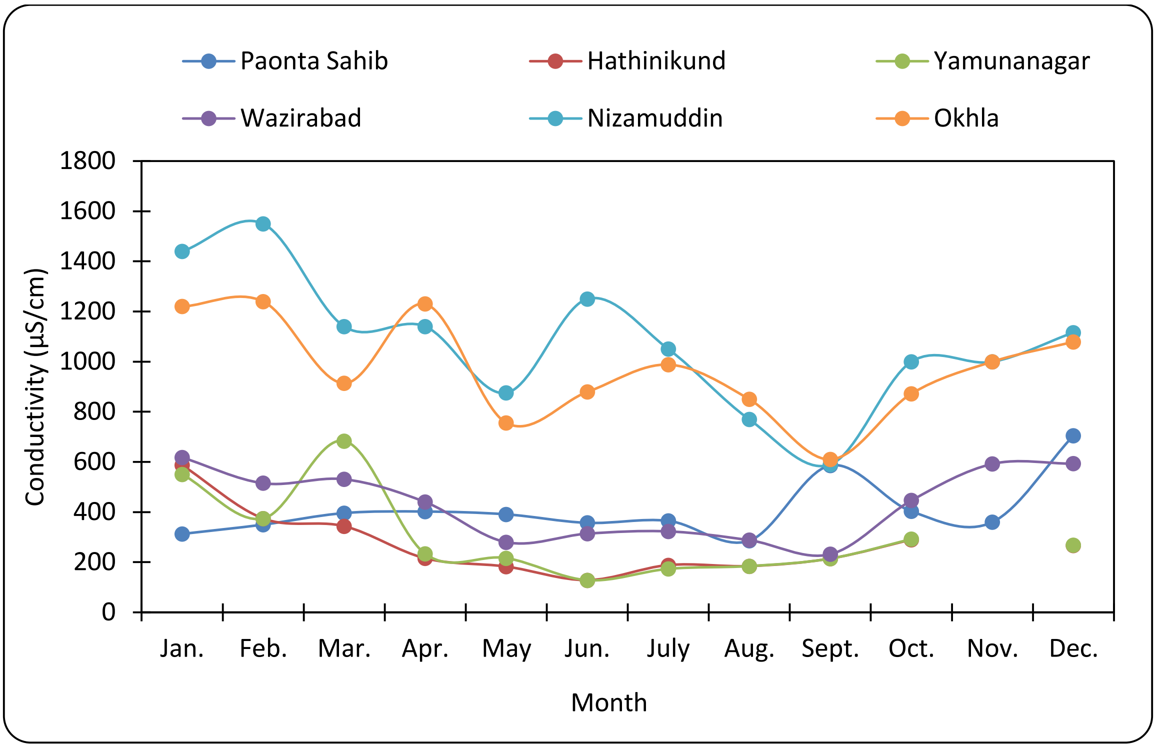


Fig. 4.23 EC variation at different locations during 2019

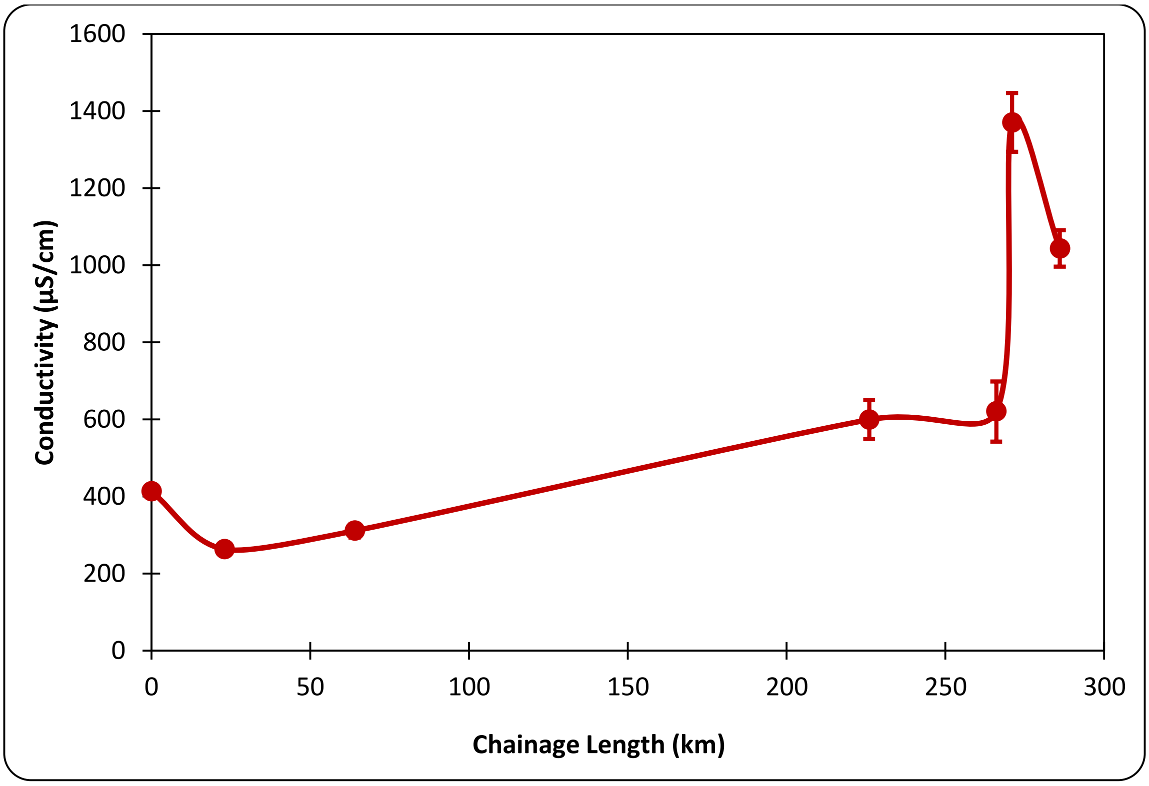


Fig. 4.24 Average annual EC variation at different locations – Paonta Sahib (0 km), Hathinikund (23 km), Yamunanagar (64 km), Sonipat (226 km), Wazirabad (266 km), Nizamuddin (271 km), Okhla (286 km) (2015-2019)

Dissolved Oxygen: DO concentration in the Yamuna River varied in the range of non-detectable (ND) - 15.5 mg/l in the stretch from Paonta Sahib to Delhi (**Fig.** 4.25-4.32). The required DO value for propagation of wildlife and fisheries is more than 4 mg/l, however, some fish species can survive at DO concentration as low as 1.4 mg/l.

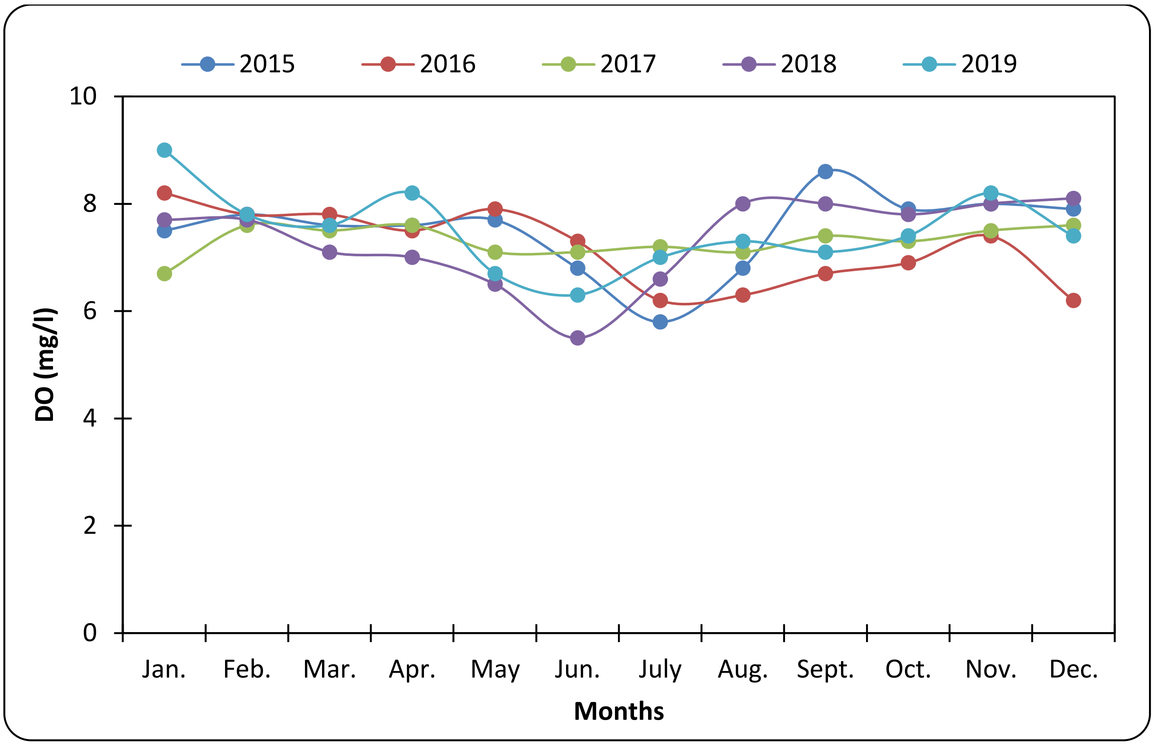


Fig. 4.25 DO variations at Paonta Sahib

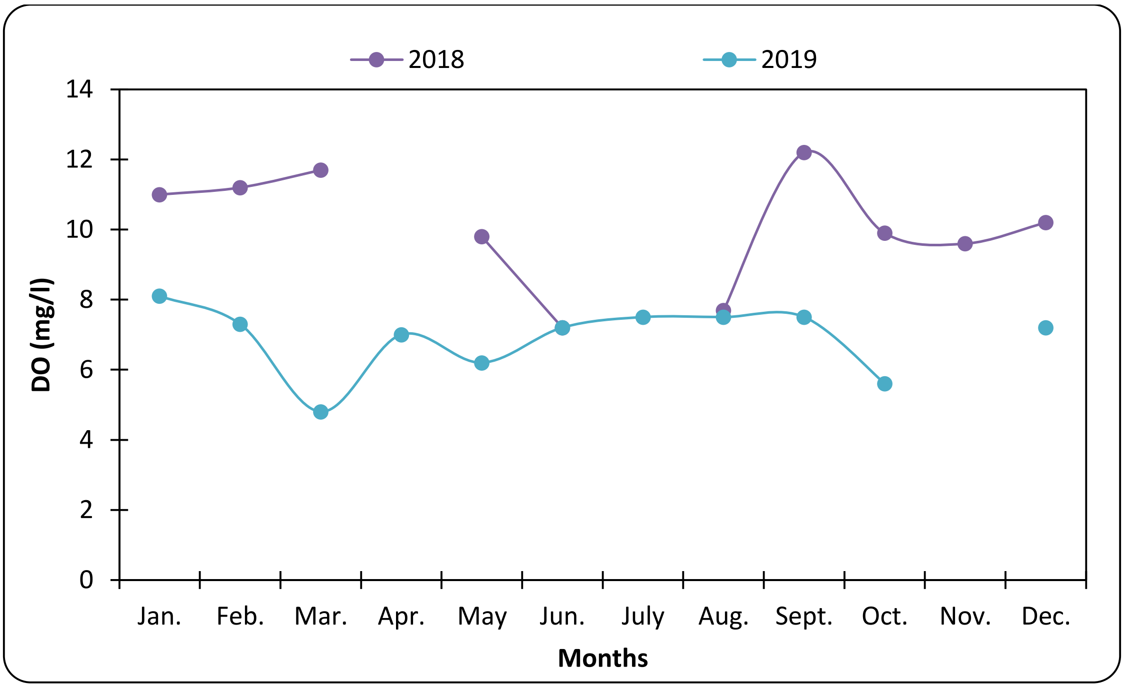


Fig. 4.26 DO variations at Hathinikund

The DO levels were satisfactory in the stretch between Paonta Sahib and Sonipat. The DO levels in Yamuna River at Wazirabad exceeded the saturation level at several occasions during October to March, may be due to presence of phytoplankton and macrophytes in the water. The DO level in Yamuna River at Nizamuddin and Okhla has remained below 2 mg/l during most part of the year and cannot sustain fishery. This dip in DO levels is due to dumping of untreated effluents in the river and the situation can be improved by proper treatment of wastewater entering the river.

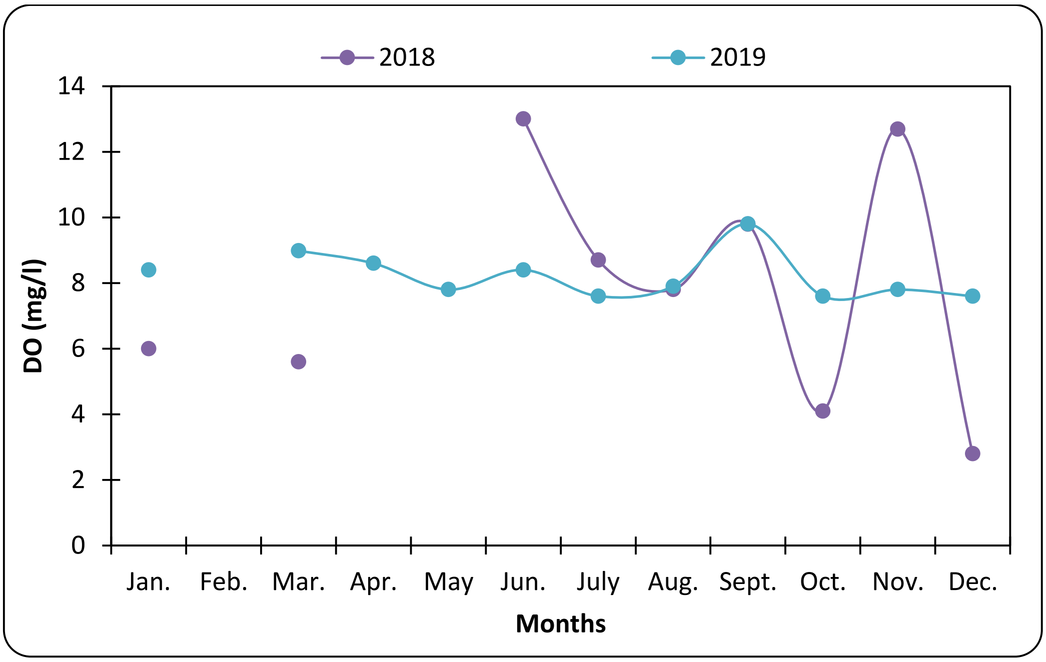


Fig. 4.27 DO variation at Yamunanagar/ Kalanaur

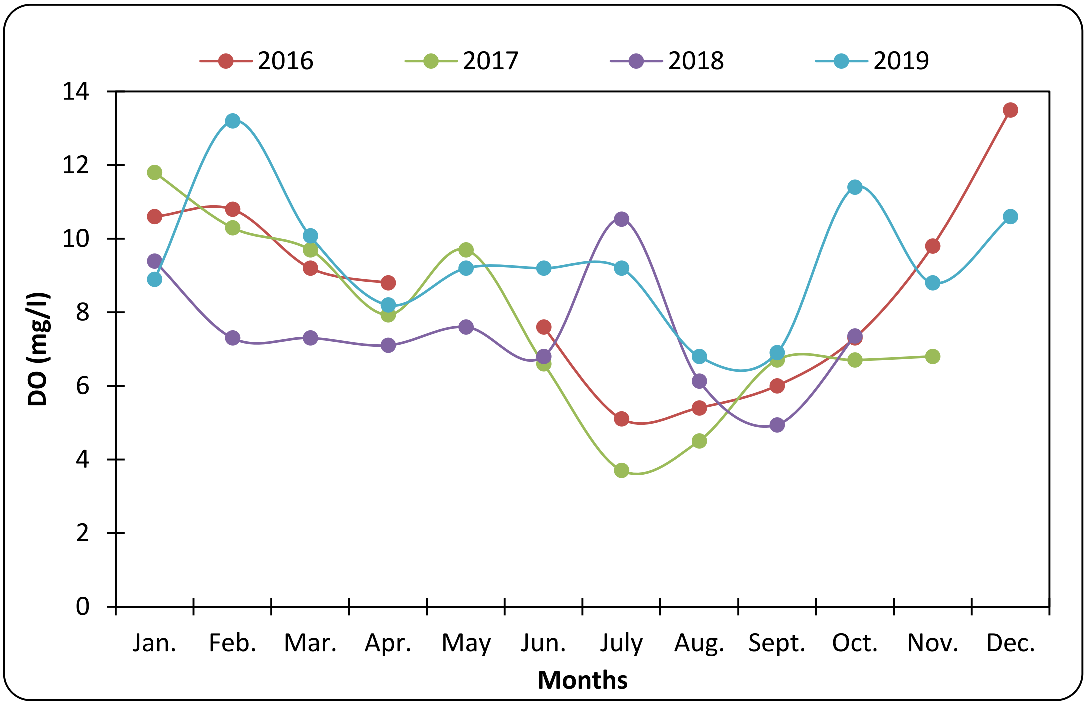


Fig. 4.28 DO variation at Wazirabad

The average annual DO at Paonta Sahib, Hathnikund, Yamunanagar, Sonipat, Wazirabad, Nizamuddin, and Okhla was 7.4±0.09 mg/l, 8.6±0.36 mg/l, 7.8±0.40 mg/l, 7.8±0.40 mg/l, 8.5±0.36 mg/l, 1.4±0.19 mg/l, and 1.4±0.16 mg/l respectively. Sudden dip in DO levels at Nizamuddin indicates influx of high load of carbon in the river surpassing its natural carrying capacity.

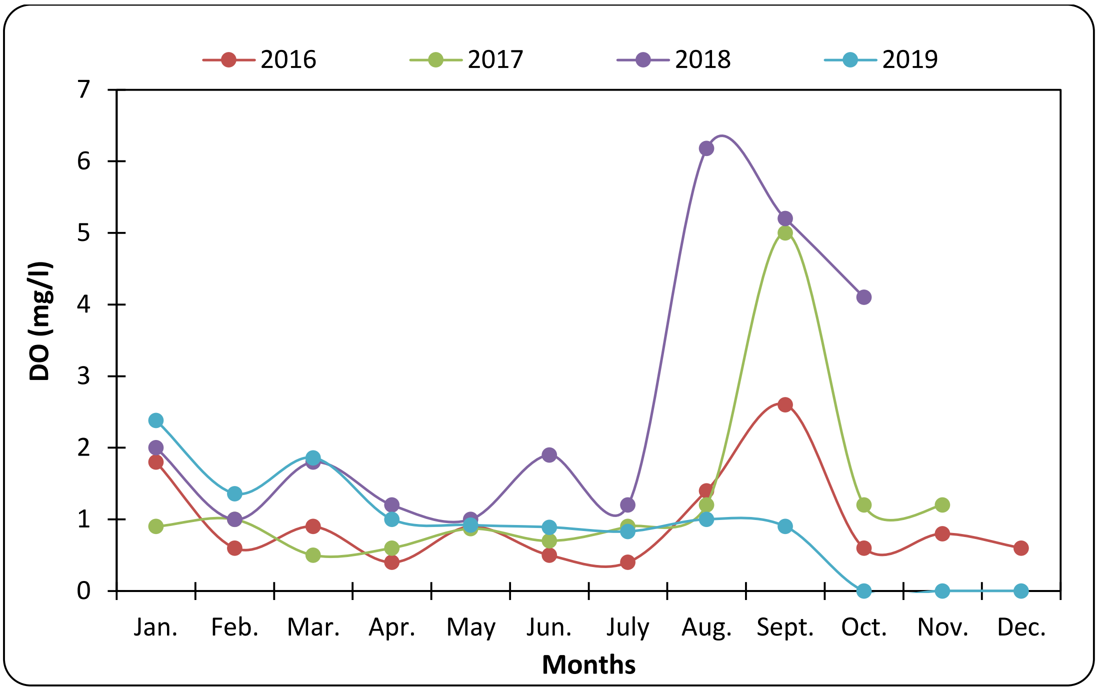


Fig. 4.29 DO variation at Delhi Railway Bridge

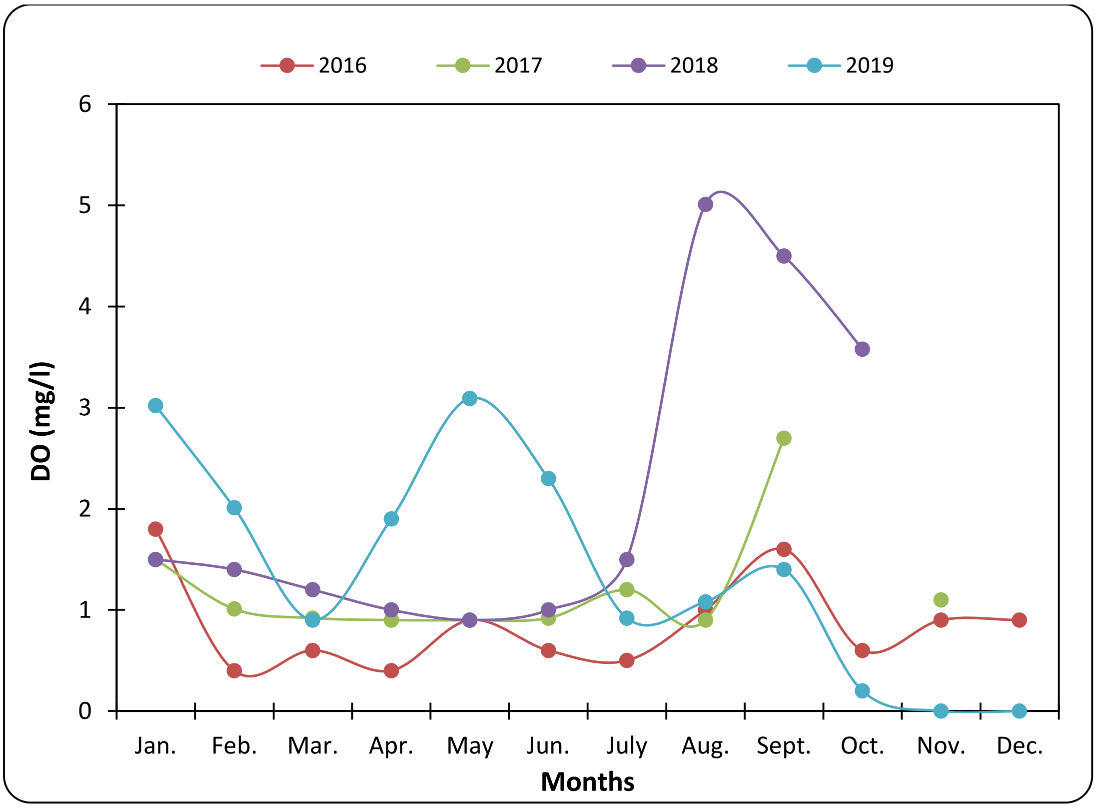


Fig. 4.30 DO variation at Okhla

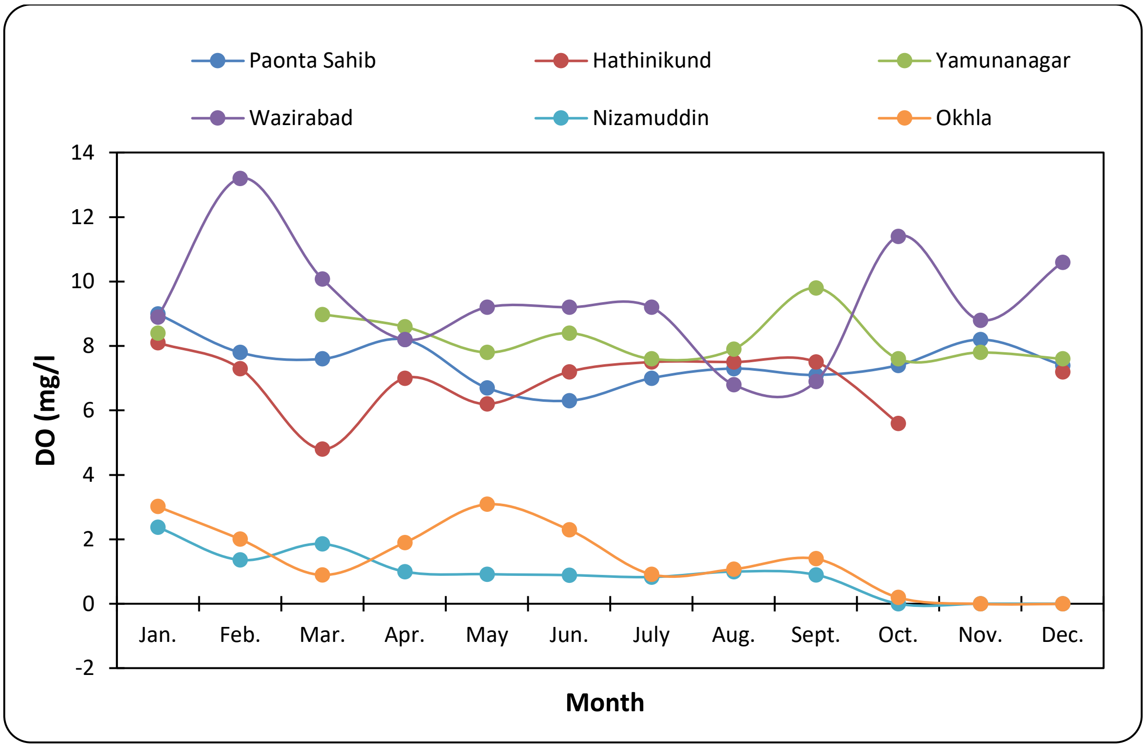


Fig. 4.31 DO variation at different locations during 2019

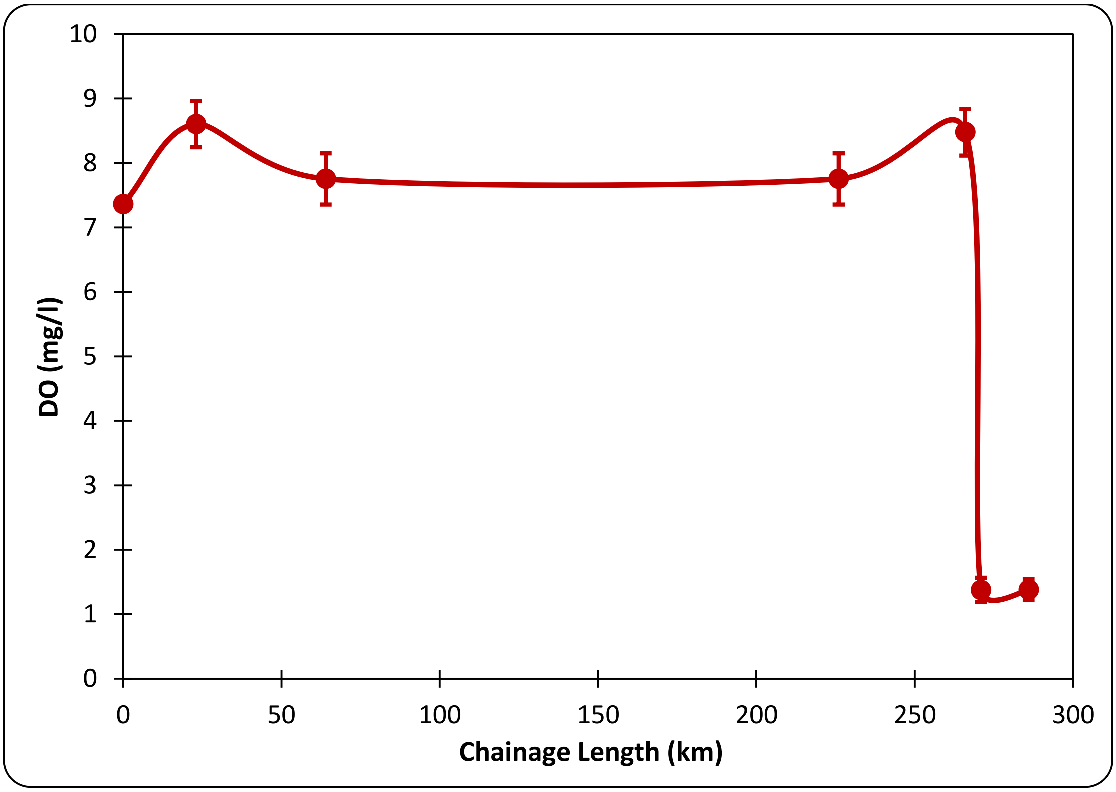


Fig. 4.32 Average annual DO variation at different locations – Paonta Sahib (0 km), Hathinikund (23 km), Yamunanagar (64 km), Sonipat (226 km), Wazirabad (266 km), Nizamuddin (271 km), Okhla (286 km) (2015-2019)

The DO values were measured during the field survey conducted during June 07-08, 2019 (Table 4.3). The DO in the river at Dahesara village and Sonia Vihar Sports Club was observed to be 10.3 mg/l at around 18:00 HR and 11.0 mg/l at around 13:00 HR respectively. Few people were catching fish in Sonia Vihar and the size of fish were around 10 cm indicating the environment conduciveness for few species of fish. The team also interacted with fishermen catching fish from the river near Dahesara village and was informed that the river contains fish of size 15-20 cm; however, during monsoon the fishermen can get catch of bigger size. It was also informed that the discharge in the drain/canal meeting Yamuna River is contaminated during certain periods of the year.

Table 4.3 DO values of Yamuna River & incoming drains (June 07-08, 2019)

S N	**Location**	**Latitude**	**Longitude**	**On site DO value (mg/l)**
Yamuna River				
1	Near Dahesra Village	28.863° N	77.207° E	10.3
2	Sonia Vihar Water Sports Club, Wazirabad road, Delhi	28.713° N	77.236° E	11.0
3	Yudhister Setu	28.671° N	77.236° E	ND
4	Okhla head Park	28.568° N	77.296° E	ND
5	Okhla Barrage	28.545° N	77.311° E	ND
Drains				
6	Drain Near Dhobi Ghat, Batla house, Okhla	28.572° N	77.290° E	ND
7	Drain near Shakti Enclave, friends colony, New Delhi	28.574° N	77.273° E	ND
8	Drain near Power Grid, Maharani Bagh, Ganga Bihar, Sarai Kale Khan	28.568° N	77.274° E	ND
9	Drain near Railway road bridge, Pragati Maidan, New Delhi	28.611° N	77.251° E	1.2
10	Nazafgarh drain Joining to Yamuna River Near Signature Bridge	28.709° N	77.228° E	ND
11	Wazirabad road, Usmanpur, Shahadra, Delhi, Near Signature Bridge	28.708° N	77.235° E	ND
12	Western Yamuna Canal near Dahesara	28.864° N	77.192° E	12.68

The DO concentration in the river water in the upstream of Wazirabad barrage upto Dahesara was higher than the saturation value due to presence of algae and the photosynthesis taking place, but this condition is also of concern as the DO values may reduce to lower levels during night time as a result of respiration. In fact, the fishermen informed that during few occasion in the recent past they observed fish kill. The diurnal variation in DO values will reflect the condition of river in the upstream of barrage for the propagation of fish. The DO values were non-detectable in the river stretch below Wazirabad barrage upto Okhla barrage.

Biochemical Oxygen Demand: The BOD of pristine rivers is generally below 1 mg/L, for moderately polluted rivers 2 – 8 mg/l, and for severely polluted rivers more than 8 mg/L (WWAP, 2016). The BOD value in the river stretch from Paonta Sahib to Delhi were in the range of ND to 45 mg/l during 2015-2019 (**Fig.** 4.33-4.40). BOD values were minimum at Yamunanagar (ND) and highest at Okhla (45 mg/L). Based on the BOD vales, the stretch of Yamuna river upto Yamunanager can be considered as moderately polluted. The stretch between Yamunanagar to Wazirabad is in the category of moderately polluted for most part of the year except few occasions, when the BOD exceeds 8 mg/l.

Yamuna River in Delhi from Wazirabad to Okhla is severely polluted. The average annual DO at Paonta Sahib, Hathinikund, Yamunanagar, Sonipat, Wazirabad, Nizamuddin, and Okhla was 0.84±0.07 mg/l, 1.55±0.13 mg/l, 1.65±0.0.16 mg/l, 5.19±0.66 mg/l, 3.28±0.29 mg/l, 21.8±1.55 mg/l, and 16.92±1.19 mg/l respectively (**Fig.** 4.39-4.40). The appreciable increase in BOD at Sonipat is due to pollutant input through Drain 8 in the upstream of sampling station. Reduction in BOD was observed at Wazirabad due to self-cleansing capacity of the river, however, the chainage length between Sonipat and Wazirabad (5 km) and extent of reaeration is not sufficient enough to bring down the BOD to less than 2 mg/l. In the downstream of Wazirabad, sudden increase in BOD of river water is due to reduction in the freshwater flow from Wazirabad barrage and influx of excessive amount of almost untreated sewage, at several locations, into the river.

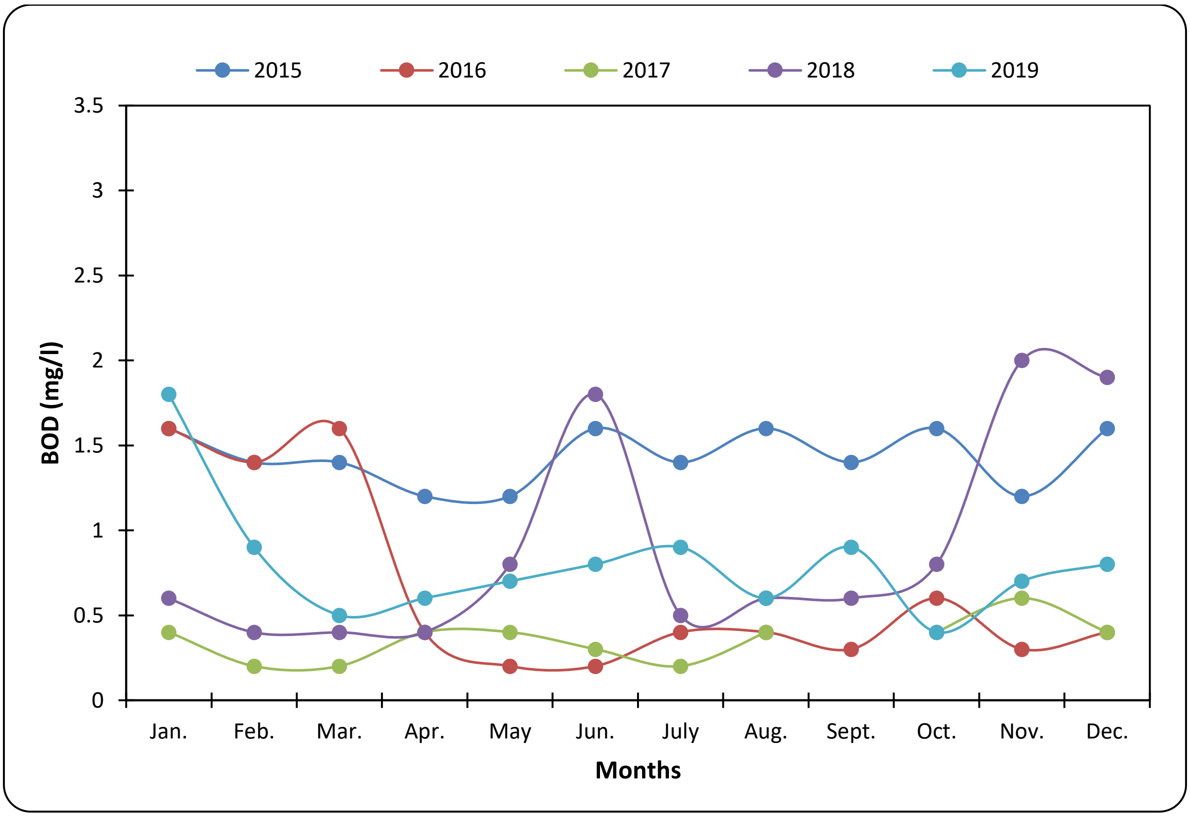


Fig. 4.33 BOD variations at Paonta Sahib

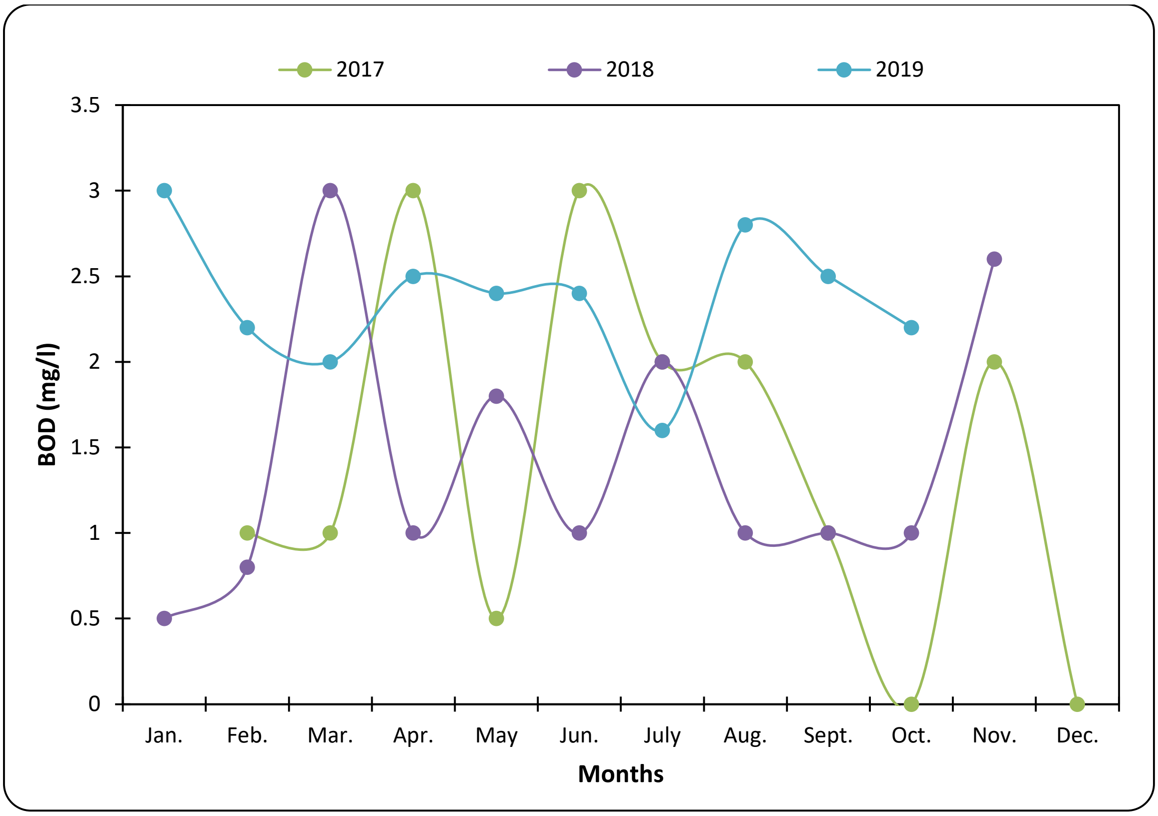


Fig. 4.34 BOD variations at Hathinikund

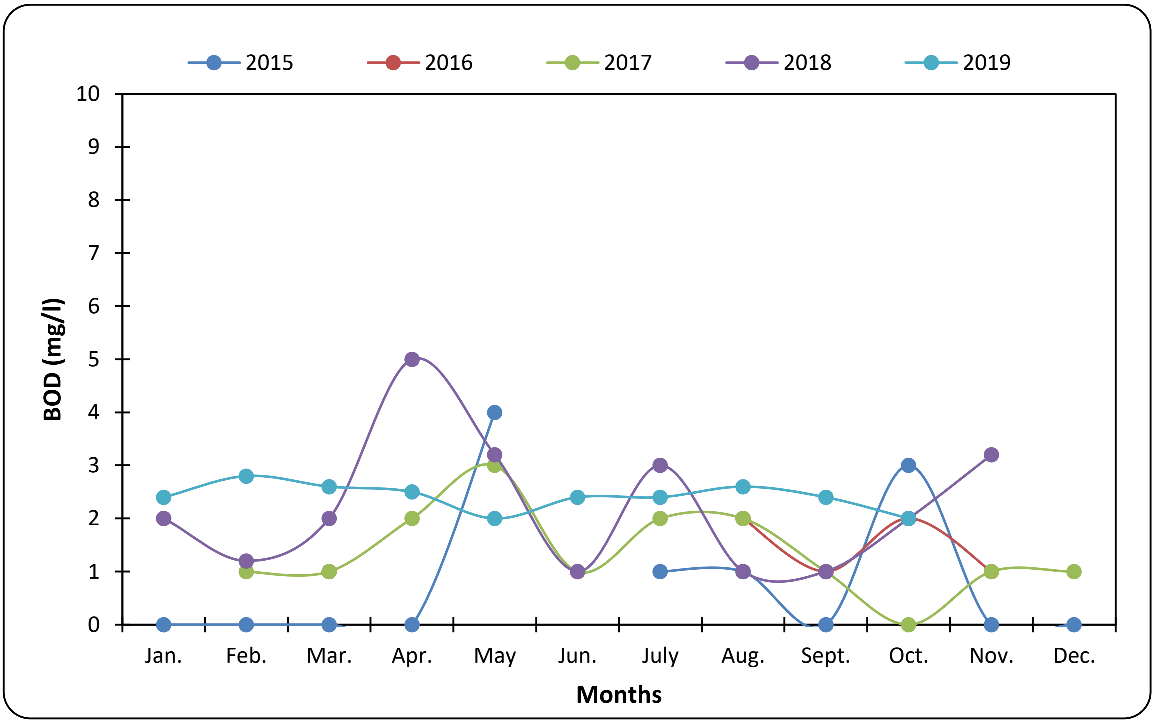


Fig. 4.35 BOD variation at Yamunanagar/ Kalanaur

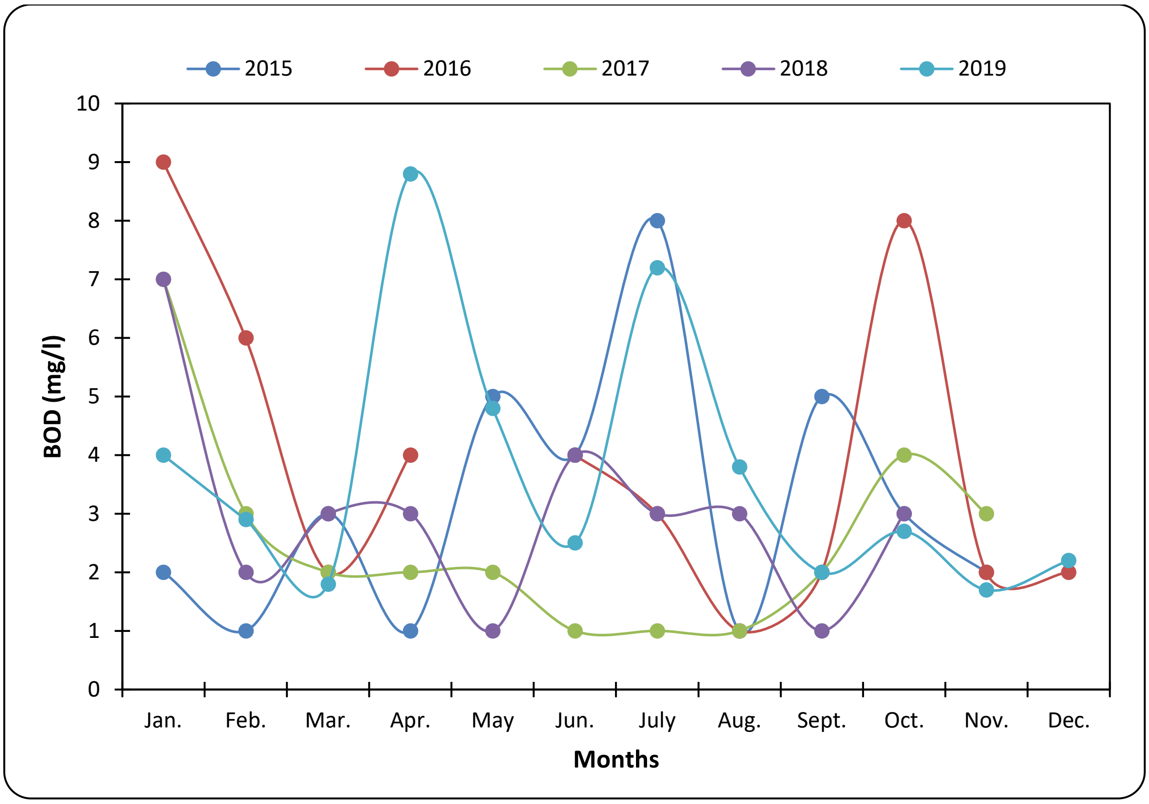


Fig. 4.36 BOD variation at Wazirabad

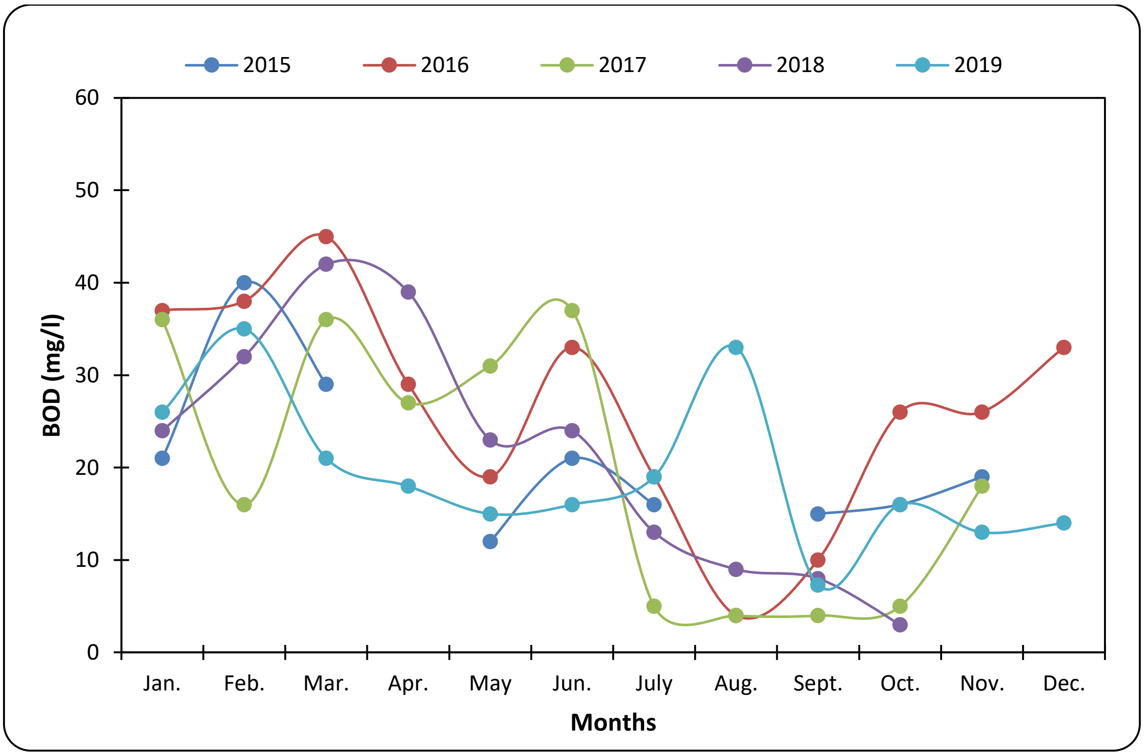


Fig. 4.37 BOD variation at Delhi Railway Bridge

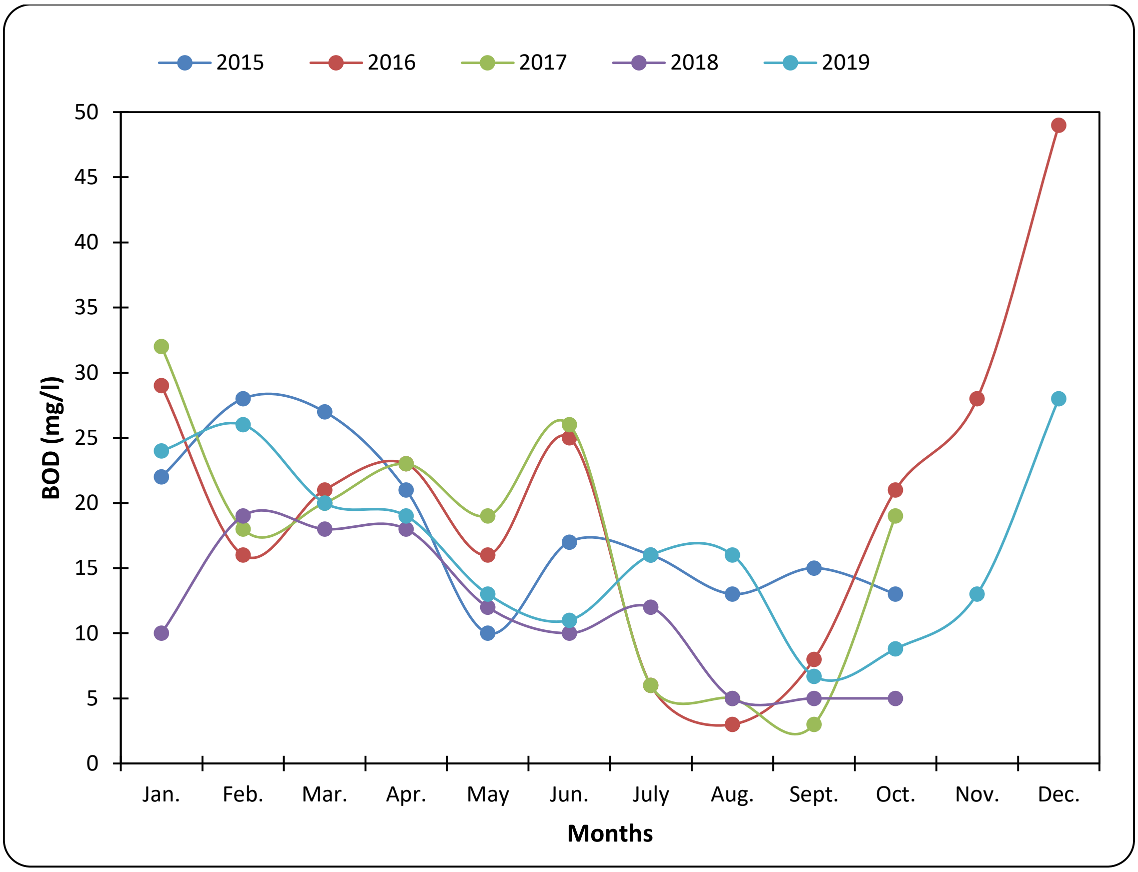


Fig. 4.38 BOD variation at Okhla

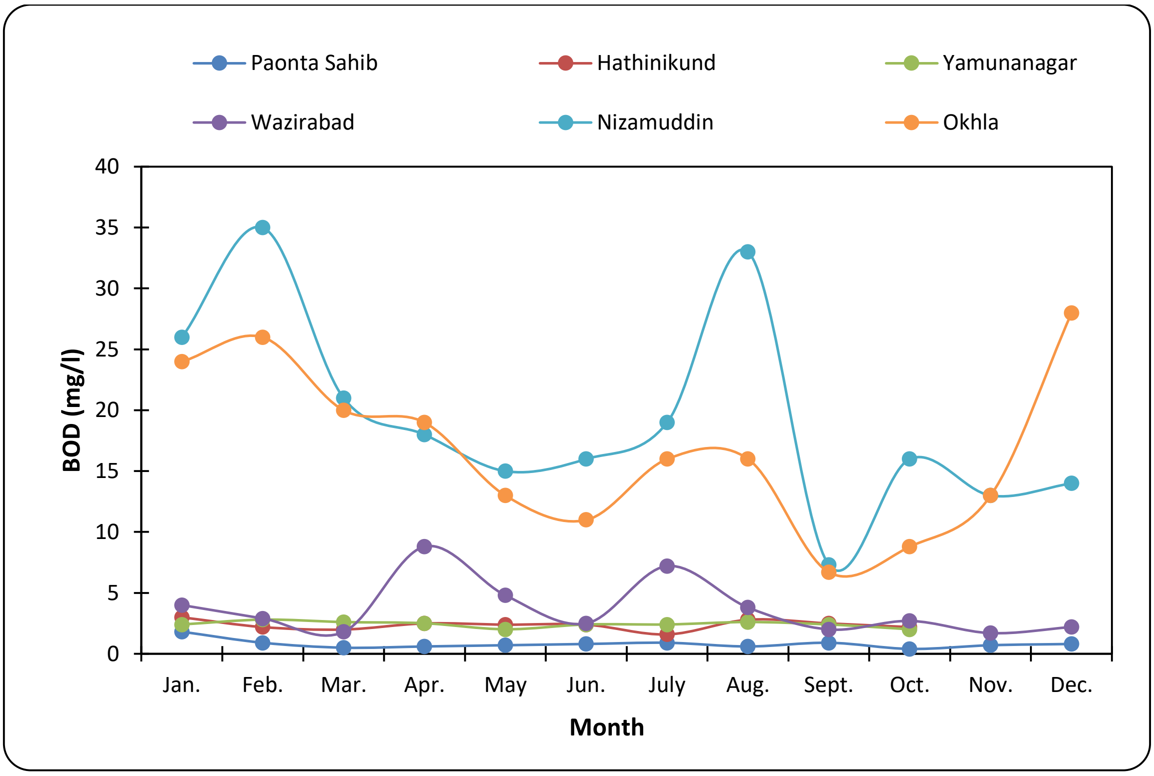


Fig. 4.39 BOD variation at different locations during 2019

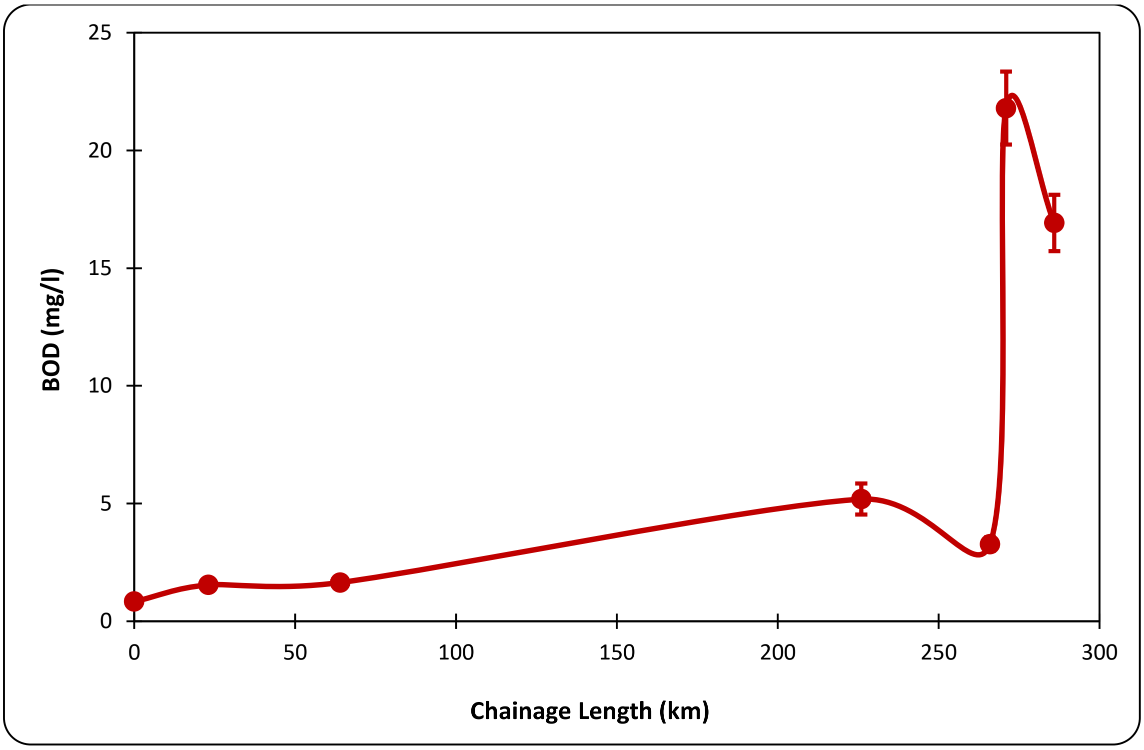


Fig. 4.40 Average annual BOD variation at different locations – Paonta Sahib (0 km), Hathinikund (23 km), Yamunanagar (64 km), Sonipat (226 km), Wazirabad (266 km), Nizamuddin (271 km), Okhla (286 km) (2015-2019)

Total Nitrogen: Excess nitrate is not toxic to aquatic life, but increased nitrogen may result in overgrowth of algae, which can decrease the dissolved oxygen content of the water, thereby harming or killing fish and other aquatic species. Total nitrogen concentration of less than 0.7 mg/l denotes good water quality, 0.7-1.5 denotes fair water quality, and greater than that represents poor water quality and eutrophic state. Total Nitrogen values in the Yamuna River was in the range of 0.001 – 119 mg/L (Fig. 4.41-4.45). The nitrogen concentration in the river water is on the higher side i.e. more than 1.5 mg/l from Paonta Sahib itself and in Delhi the concentration is almost 20 times higher during most of the time.

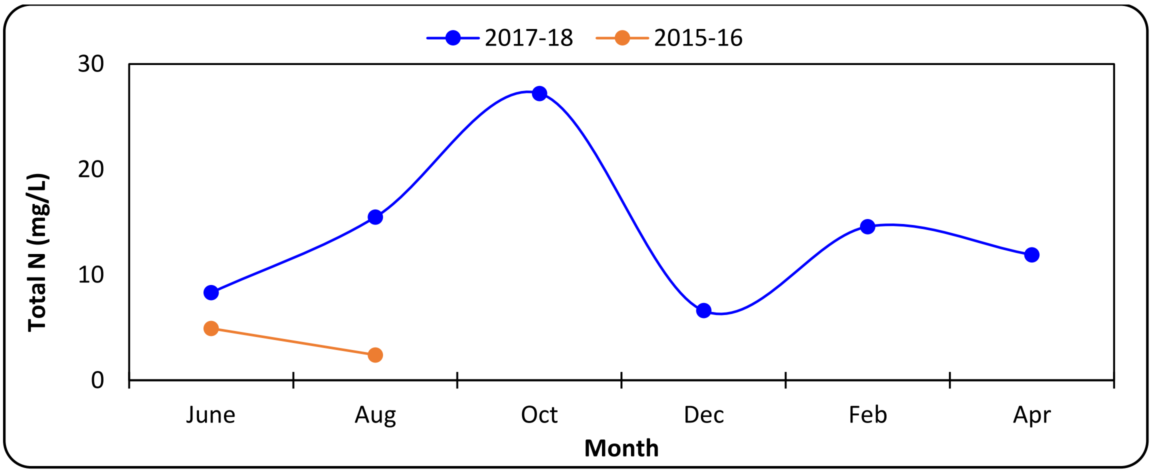


Fig. 4.41 TN variations at Paonta Sahib

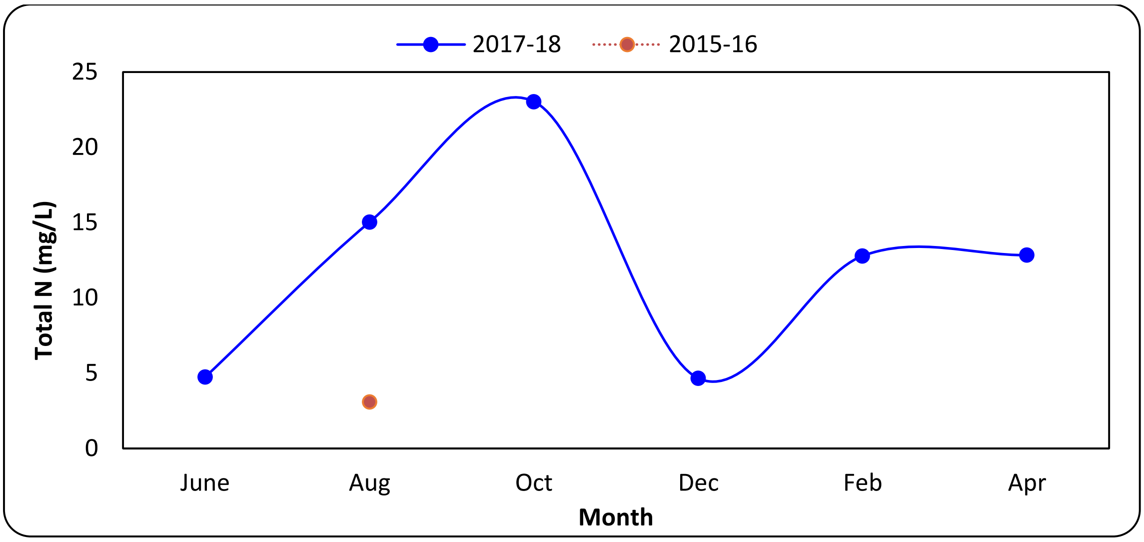


Fig. 4.42 TN variations at Yamunanagar/ Kalanaur

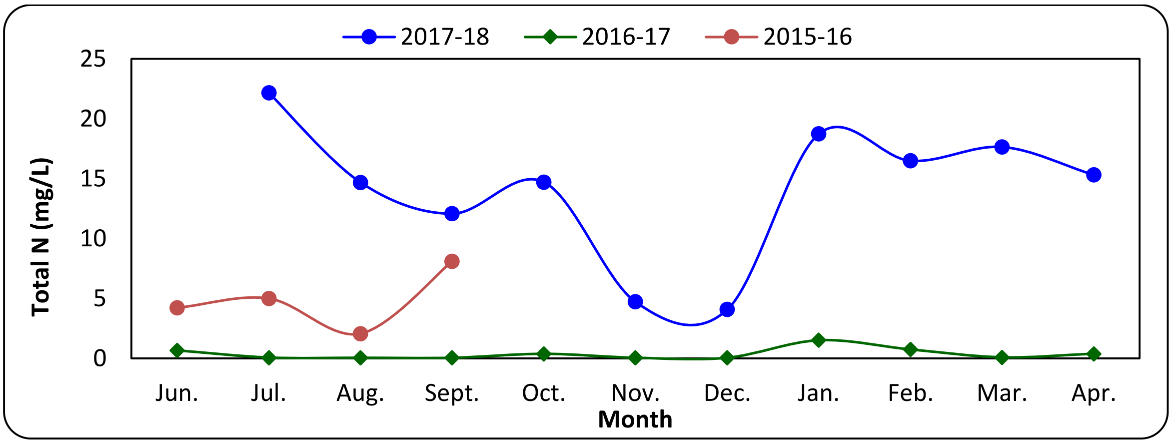


Fig. 4.43 TN variations at Panipat / Mawi

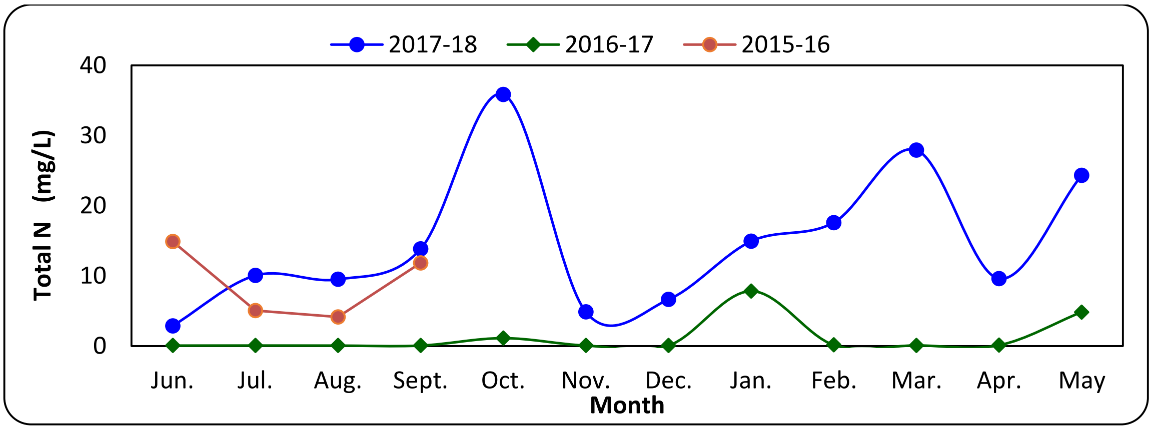


Fig. 4.44 TN variations at Sonipat / Palla

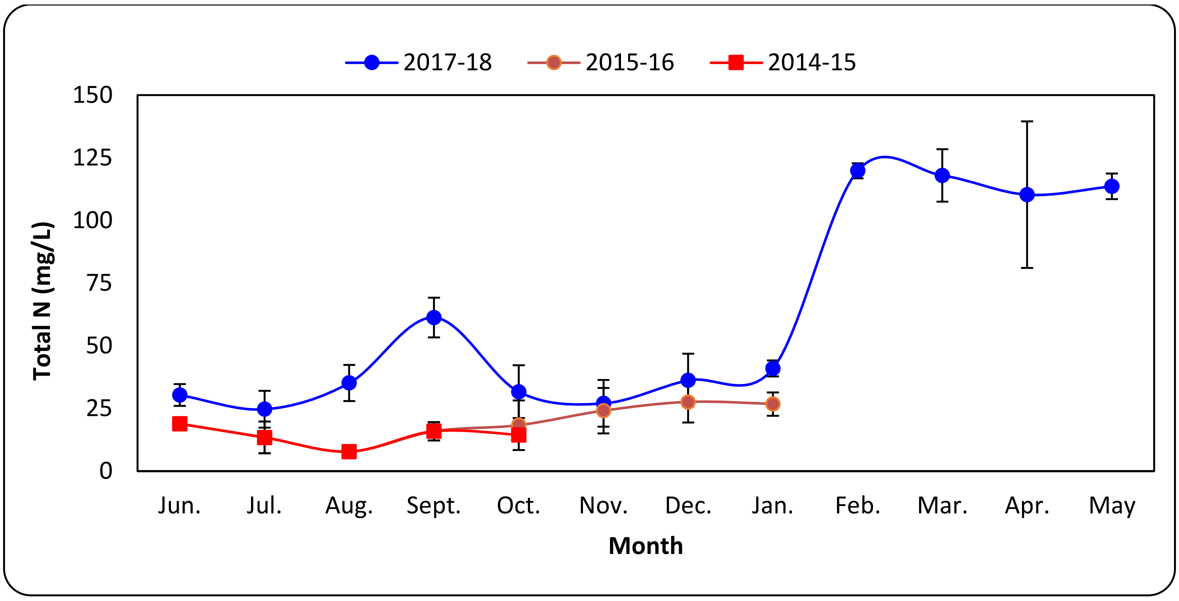


Fig. 4.45 TN variations at Delhi Railway Bridge

Total Phosphorus: TP is an essential nutrient for all life forms, but at high concentrations the most biologically active form of phosphorus (orthophosphate) can cause water quality problems by overstimulating the growth of algae. TP concentration of less than 0.025 mg/l denotes good water quality, 0.025-0.075 mg/l denotes fair water quality, and greater than 0.075 mg/l represents poor water quality and eutrophic state. The TP concentration in the river varied from 0.001 mg/l to 13.4 mg/l. Maximum concentration was observed at Delhi (**Fig.** 4.46-4.50).

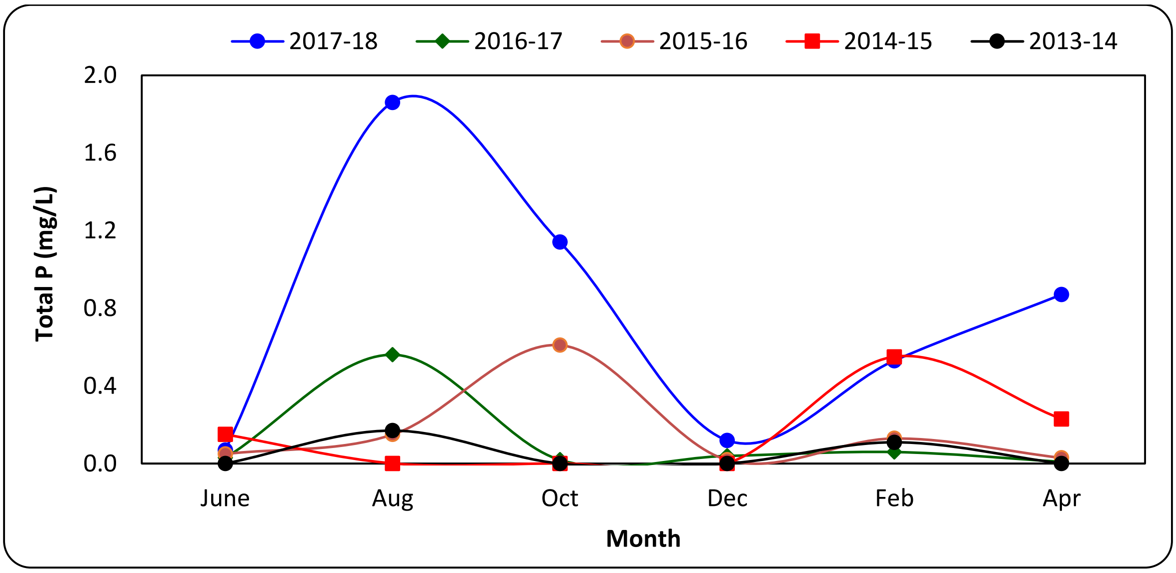


Fig. 4.46 TP variations at Paonta Sahib

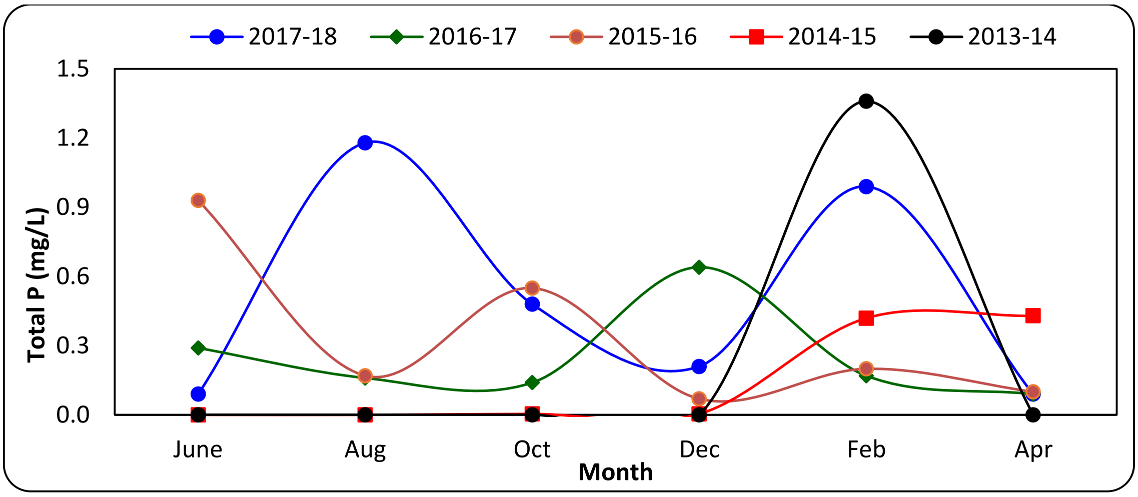


Fig. 4.47 TP variations at Yamunanagar/ Kalanaur

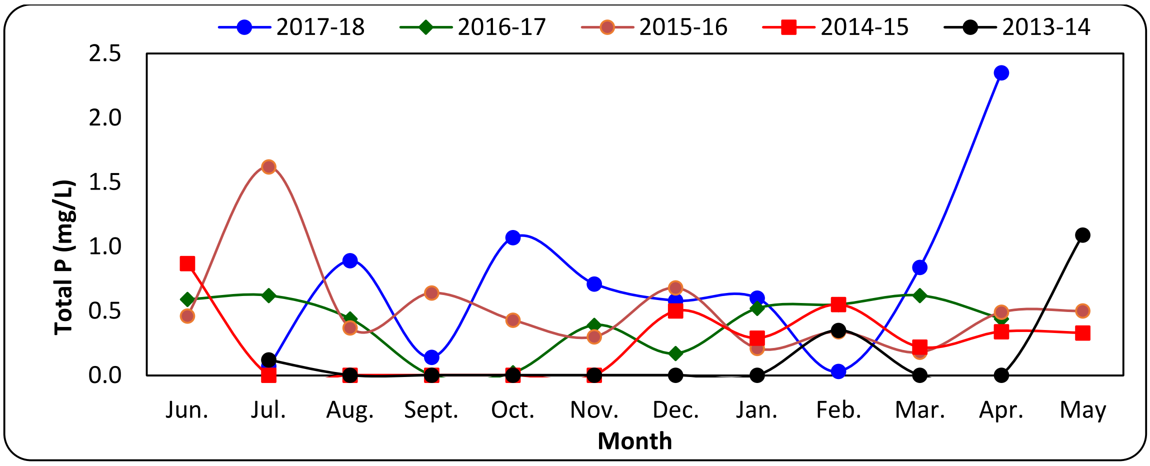


Fig. 4.48 TP variations at Panipat / Mawi

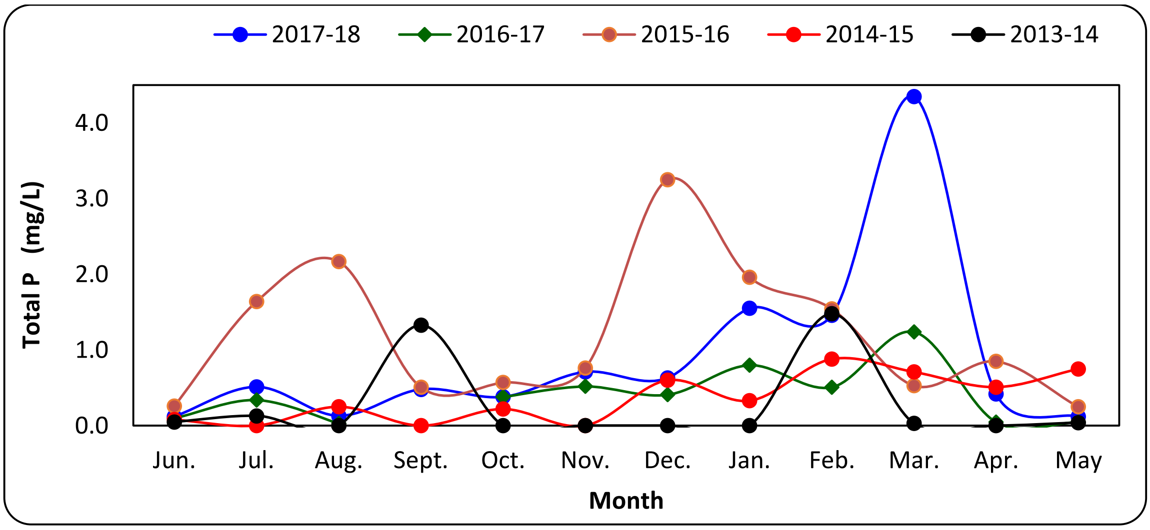


Fig. 4.49 TP variations at Sonipat / Palla

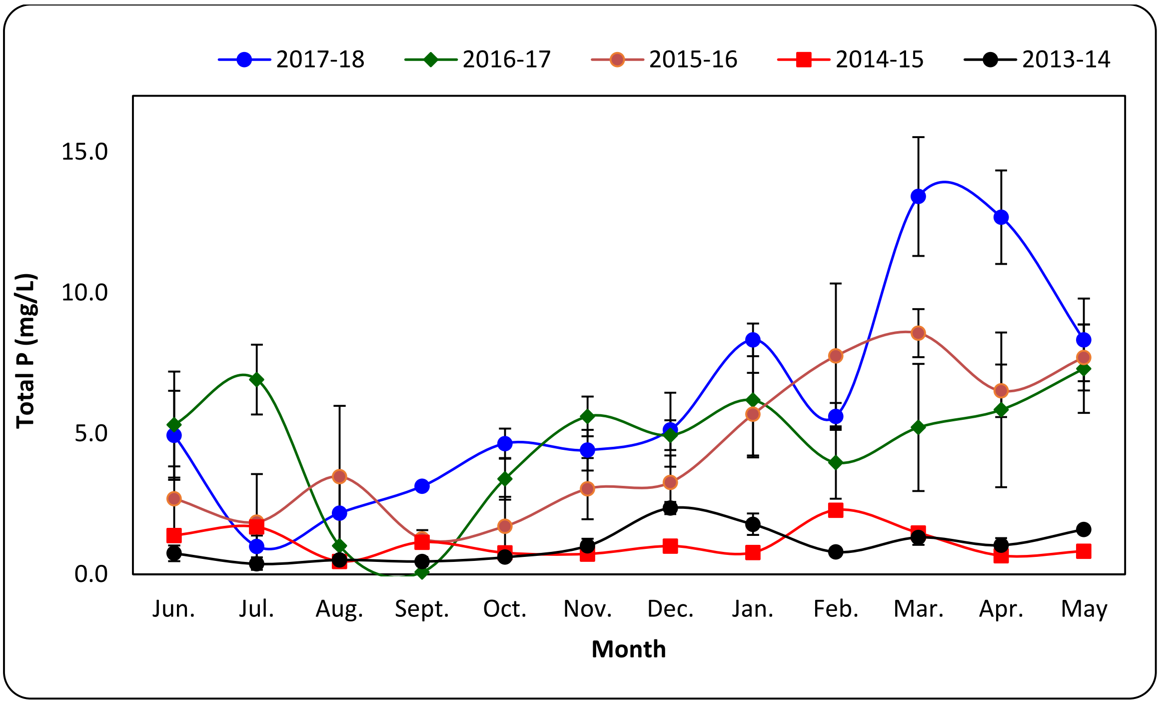


Fig. 4.50 TP variations at Delhi Railway Bridge

4.7.1 Pollutant load influx and river water quality

As discussed in the preceding sections, the water quality of Yamuna river starts deteriorating downstream of Yamunanagar / Kalanaur. Accordingly, flow and BOD concentrations of drains meeting River Yamuna were collected from CPCB, New Delhi, and Water Data Collection Division, Karnal, Haryana. The drain flow and BOD data were analysed for the pollutant load influx and impact on the river water quality. The average BOD load and flow for the non-monsoon season is provided in Fig. 4.51.

The average non-monsoonal BOD concentration in river water upto Kalanaur is less than 4 mg/l which is desired and indicates the healthy state of the river. In addition, the DO values were more than 6 mg/l indicating the conducive environment for the fishes to proliferate. It also indicates the high assimilative capacity of the river in this stretch. However, the influence of Drain 2 and Diversion drain 8 dumping significant amount of organic load in the river is clearly visible with the increase in BOD level and decrease in DO levels. For healthy fish environment, the DO levels in the river should not reduce below 50% of saturation value for significant periods. DO values less than 30% of saturation value are lethal to the coarse fish and results in fish deaths. Although, the BOD value of the river water increased, the DO levels in the river water were sufficient enough for the sustenance of aquatic life.

Below Wazirabad barrage upto Okhla barrage, the river receives approx. 6140 kg/hr BOD load out of which around 70% load is contributed through Nazafgarh drain. The average non-monsoonal DO value in the river stretch is 1.1±0.14 mg/l as O_2. However, during the field survey by NIH team, the DO value in this stretch was non-detectable indicating the BOD load to the river higher than the assimilative capacity of the river.

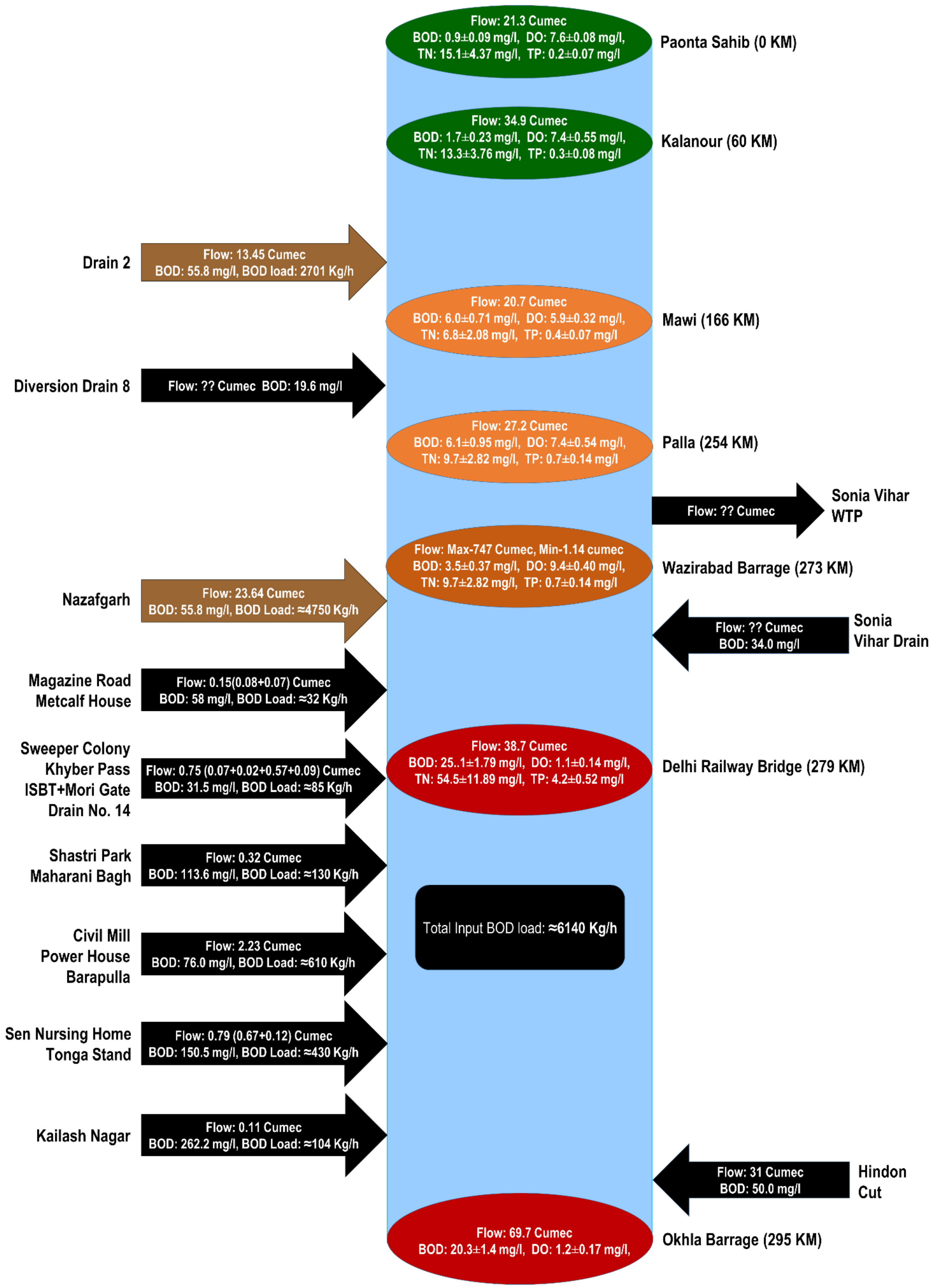


Fig. 4.51 Pollutant load influx and river water quality

When organic matter is discharged into a watercourse it serves as a food source for the bacteria present there, which sooner or later commence the breakdown of this matter to less complex organic substances and ultimately to simple compounds such as carbon dioxide and water. If previously unpolluted, the receiving water will be saturated with dissolved oxygen (DO), or nearly so, and the bacteria present in the water will be aerobic types. Thus the bacterial breakdown of the organic matter added will be an aerobic process - the bacteria will multiply, degrading the waste and utilising the DO as they do so. This is happening in River Yamuna upto Wazirabad Barrage.

If the quantity of organic waste present is sufficiently large, the rate of bacterial uptake of oxygen will outstrip that at which the DO is replenished from the atmosphere and from photosynthesis. Subsequently, the anaerobic bacteria become active and utilize the oxygen in sulphate (SO_4^{2-}) present in water and generate hydrogen sulphide resulting in obnoxious odour. This is the case with the river stretch below Wazirabad barrage.

From the above, it can be concluded that Delhi is the most critical stretch of Yamuna, however, the contamination starts from Paonta Sahib as is evident from the nutrients concentration in the river. In terms of organic contamination, the stretch downstream of Mawi is contaminated and needs immediate attention. The DO values also indicate the same. Although, the water quality upto Wazirabad barrage is good for fish proliferation, the reduction in DO values is a concern. The river is almost dead below Wazirabad barrage.

4.7.2 Impact of e-flow release on river water quality

The proposed e-flow for maintaining 0.60 m depth will require release of approx. 22.81-43.66 cumec flow from Hathnikund barrage during non-monsoon period, resulting in approx. 9.49-64.14 cumec of flow becoming available at Wazirabad. If this flow will be discharged in the river, it will result in dilution and reduction in BOD concentration of river from 25 mg/l to approx. 12-21 mg/l, with highest concentration in May. This dilution will not lead to elimination of emanating bad odour and sustenance of aquatic life. For achieving BOD concentration of around 5 mg/l, 10 time dilution will be required, requiring an addition flow of approx. 390 cumec which is not a sustainable solution. Instead, treatment of the incoming drains carrying sewage / wastewater is recommended as more viable solution.

Way Forward: The diurnal variation in the river water quality for pH, temperature, conductivity, dissolved solids, DO, BOD, nutrients (N & P), phytoplanktons, alkalinity, and microbes is required to be monitored for the non-monsoon period for computing the assimilative capacity of the river and better understanding of river quality.

Chapter 5

INTEGRATED HYDROLOGICAL AND HYDRODYNAMIC MODELING

5.1 Integrated Modeling Approach

The integrated hydrologic and hydrodynamic modeling approach has been adopted to assess e-flows between Hathnikund barrage and Okhla barrage on Yamuna river and compute the releases required from Hathnikund barrage for maintaining these e-flows. The hydrological model SWAT has been used to simulate streamflow (discharge), overland flow, groundwater recharge, evapotranspiration (ET) and total water yield in the study reach of Yamuna. For model calibration and validation, observed discharge available for the years 1977-1981 and 2001-2016 at five gauging sites (i.e. Kalanaur, Karnal, Mawi, Baghpat and Delhi Railway Bridge) have been compared with simulated flow conditions. After calibration and validation, the virgin flows (considering no structure between Paonta Sahib and DRB) have been computed and compared with regulated flows (considering Hathnikund barrage downstream of Paonta Sahib). For the hydrodynamic analysis of streamflows in the study reach of Yamuna river, the one dimensional (1D) hydrodynamic model HEC-RAS has been employed and the hydrodynamic variables such as maximum water depth, hydraulic depth, wetted perimeter, top width and water velocity for the range of discharges as available at Hathnikund barrage have been computed at different sections of the river. HEC-RAS has been used to derive depth vs discharge curves at different river sections. These curves have been further utilized to estimate the minimum flows, based on SWAT modeling, that are required to be released from Hathnikund barrage for maintaining suitable physical habitat for indicator fish species for the whole river reach from Hathnikund to Okhla barrage.

5.2 Hydrologic Modeling using SWAT

The key points of employing SWAT in the present study are given below:

- **SWAT Model:** Hydrological model setup to generate regulated (controlled) and unregulated (virgin) discharge scenarios at different gauging sites between Hathnikund and Okhla Barrage.
- **Data Inputs:** Model data inputs comprise different physical/topographical data layers such as SRTM 30 meter DEM, Landuse/Landcover (LULC) map, soil map with multiple parameters, and observed meteorological variables such as daily minimum-maximum temperature, precipitation, solar radiation, wind speed and humidity.
- **SWAT Simulation:** Simulation runs at daily time step.
- **Model Calibration:** Multi-site calibration performed in SWATCUP by applying SUFI2 method utilizing daily observed discharge available at different sections of the river.
- **Computation of Unregulated (virgin) Discharge:** To estimate the availability of flows at different gauging sites during lean/ non-monsoon season.

5.2.1 Generation of database for hydrologic modelling

The watershed characteristics of Yamuna river (from Hathnikund to Okhla barrage) are shown in Fig. 5.1. The map also illustrates the gauging sites (discharge), various inlets (water sources meeting Yamuna river) and outlets (sources diverting water from the Yamuna river) for which the respective data was available. The LULC and soil maps of the region are also shown in Fig. 5.1 which are required for hydrologic modeling using SWAT (refer Chapter 3). Necessary meteorological parameters such as rainfall etc. were also processed.

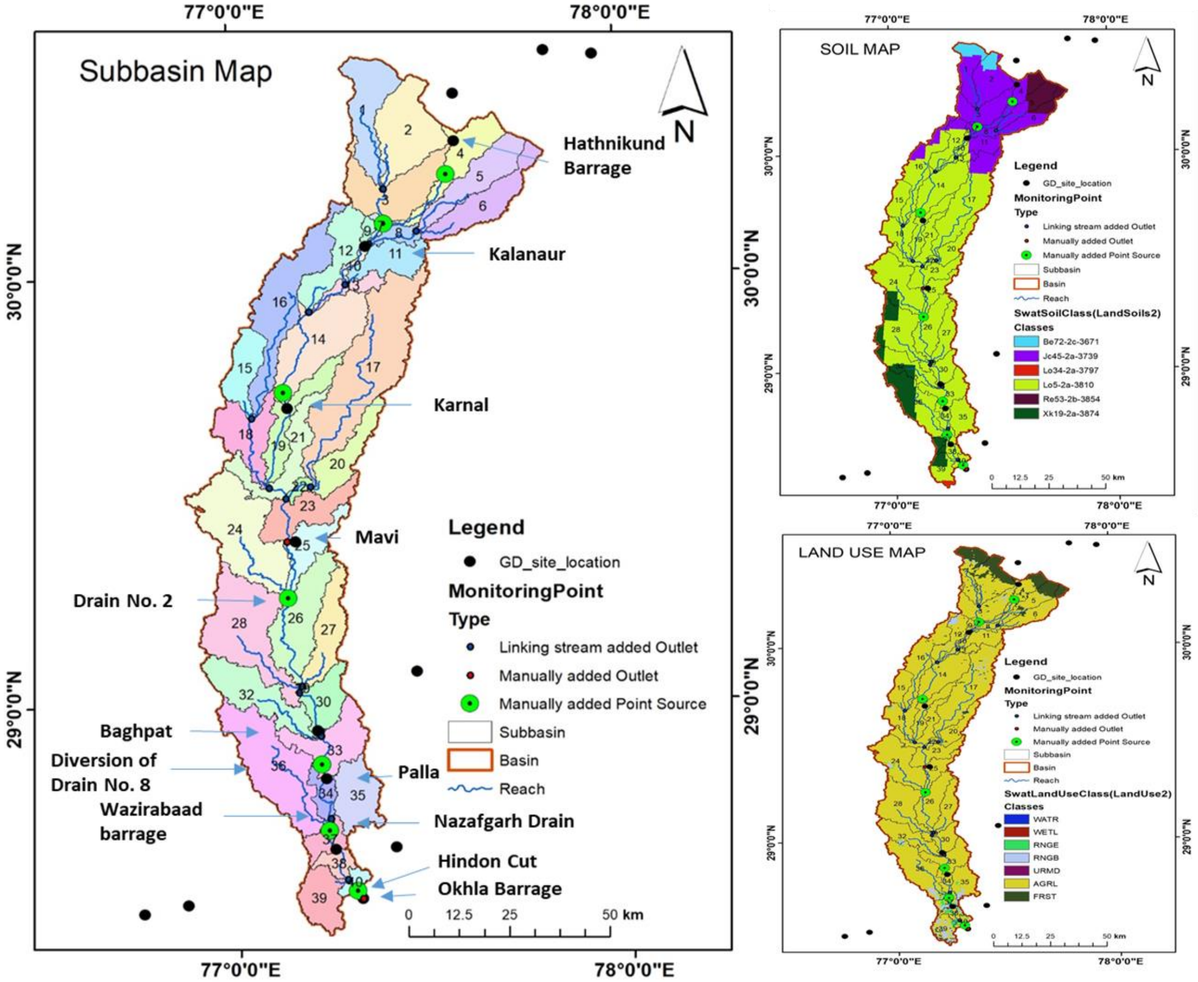


Fig. 5.1 Sub-basin wise watershed characteristics of Yamuna river (from Hathnikund to Okhla barrage) along with LULC and soil maps.

5.2.2 Model calibration and simulation of flows

The SWAT model was setup for the entire study reach from Hathnikund to Okhla barrage. For model calibration and validation, data pertaining to the periods 1977-1981 and 2001-2016 was utilized. The data corresponding to the period 1977-1981 was specifically employed to evaluate baseflows prior to the commencement of large groundwater withdrawals in the region and have been assumed to simulate the scenario similar to pre-regulated conditions. The optimization algorithm, SWAT Calibration and Uncertainty Program (CUP) based Sequential Uncertainty Parameter Fitting Approach 2 (SUFI2), was applied for the model calibration, validation, and parameterization. For calibration, a multi-site calibration scheme has been implemented and the parameters were optimized. In SUFI2, modified Nash-Sutcliffe (MNS) and coefficient of determination R^2 equations have been used as an objective function. The results of calibration and validation, for both time periods, are illustrated on a monthly time scale in Fig. 5.2 through the regression plots. The calibration and validation results for all gauging stations are found to be satisfactory with $R^2 \geq 70\%$ (maximum $R^2 = 0.99$).

Period: 1978-81 **Period: 2003-2016**

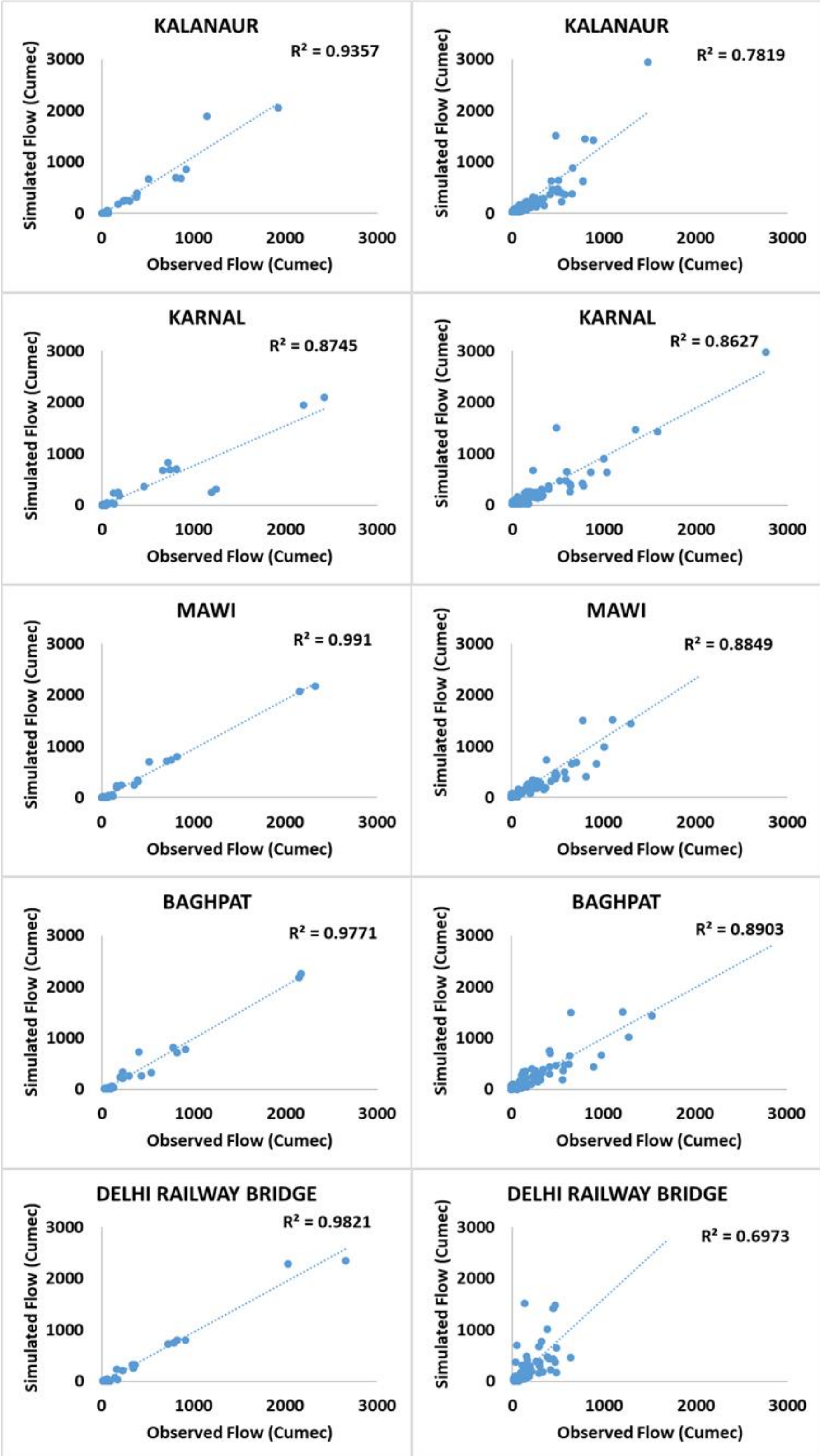


Fig. 5.2 Results of calibration and validation from SUFI2 at five gauging locations during 1978-1981 and 2003-2016.

5.2.2.1 Unregulated versus regulated flows

(a) Period 1977-1981

To compare the virgin flows (considering no structure at Hathnikund) versus regulated flows (considering the presence of barrage at Hathnikund), the SWAT model was calibrated against the observed flows monitored during 1977-1981 at the five gauging sites. Subsequently, the optimized parameter values such as curve number, groundwater delayed flow, baseflow etc. were incorporated in SWAT to simulate the virgin flows downstream of Yamuna river (from Hathnikund to Okhla).

Since major groundwater withdrawals commenced in the 1980s, it has been presumed that the model calibration parameters pertaining to the period 1977-81 can be employed in SWAT to simulate the unregulated flow conditions and assess the groundwater contribution to the non-monsoon flows in the Yamuna river. The calibrated parameter values during this time period have been implemented in SWAT for the period 2001-2016. The simulated regulated and non-regulated flows for the years 1977-1981 are shown in Fig. 5.3

As mentioned in Chapter 4, a total of 14 unique locations (including the 05 gauging sites) have been identified in study reach between Hathnikund and Okhla barrages to illustrate the simulated flows. Time series plots for each of these locations shown in Fig. 5.3, compare the availability of flow at the given location during both regulated and unregulated conditions. These time series plots highlight the flow variability during monsoon and non-monsoon time periods, and help in assessing the changes in river flow from upstream end to downstream end of the study reach.

(b) Period 2001-2016

The calibrated model was used to generate the regulated and non-regulated flows for the existing conditions during the period 2001-2016 which correspond to the period of heavy groundwater withdrawals and lowering of the water table compared to the period 1977-81. The regulated flows have been compared with unregulated flows at the 14 identified locations (refer Fig. 5.4) to highlight variations (availability and losses) in discharge from the upstream end to the downstream end of the study reach. These plots aided in identifying significant losses and availability of minimum flows in the study reach.

5.2.2.2 Baseflows in the study reach

Figure 5.5 shows the long term monthly water balance components for the period 1978-81. Simulation runs corresponding to the period 1978-81 and 2003-2016 have shown that the baseflows have on an average decreased by upto 37% during the months of March, April and May. Hydrograph analyses using the baseflow filter program which is based on the digital filtering method have shown that maximum depletion is in the reach between Mawi and Baghpat during the months of April and May. Base flow index (BFI) is an important baseflow characteristic and indicates the contribution of baseflow to the river flow. A BFI close to 0.0 means a river has a low proportion of baseflow, while a BFI close to 1.0 shows a

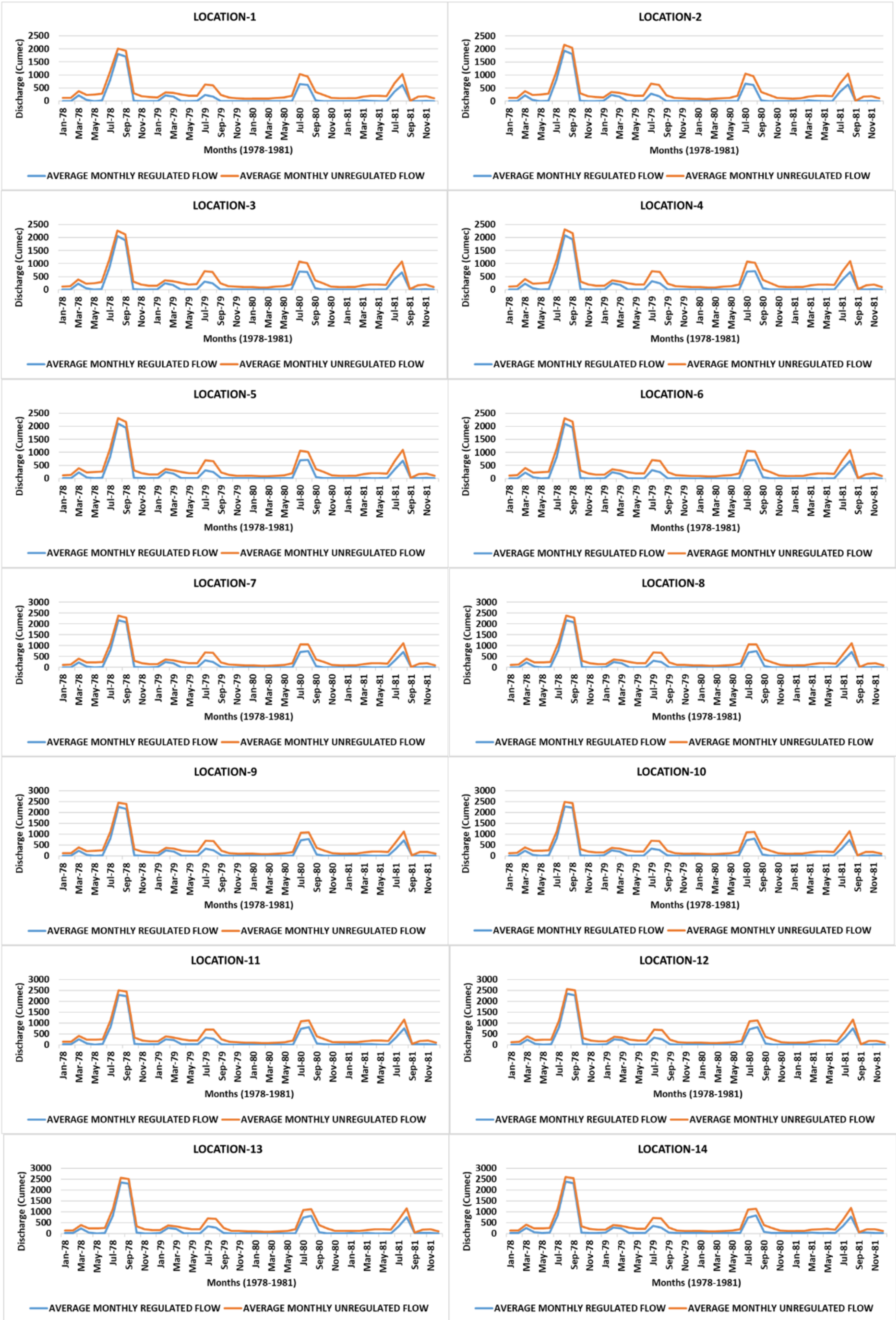


Fig. 5.3 Regulated vs unregulated flows during 1978-1981 at selected 14 locations in between Hathnikund to Okhla barrage.

Fig. 5.4 Regulated vs unregulated flows during 2003-2016 at selected 14 locations in between Hathnikund to Okhla barrage.

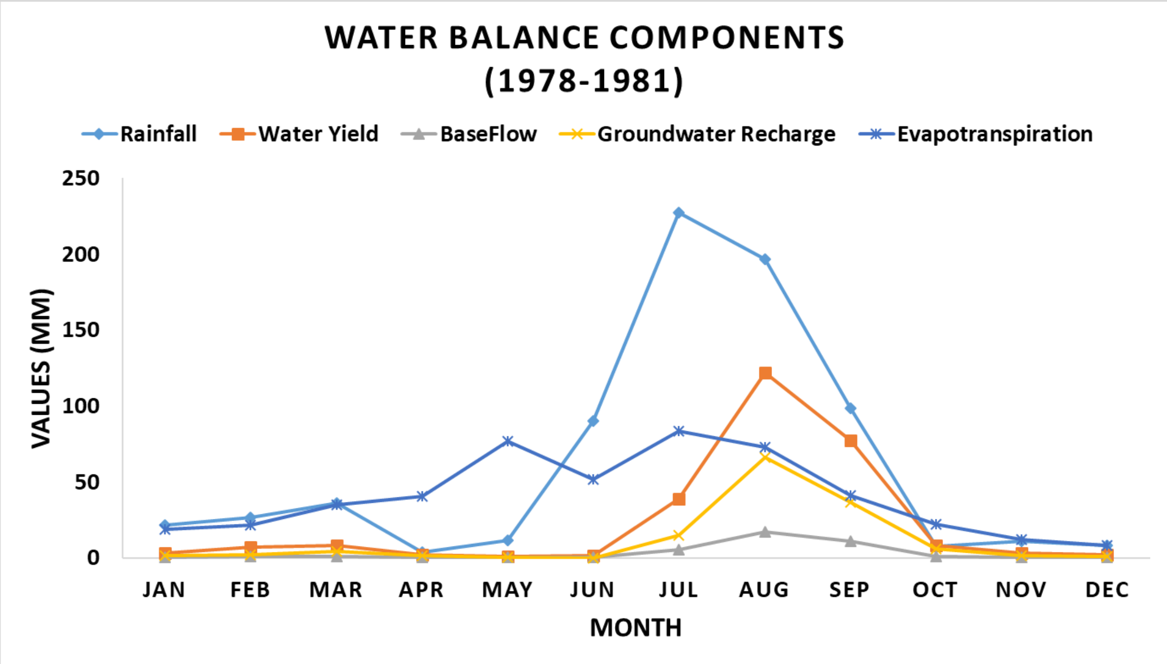


Fig. 5.5 Long term monthly water balance components (period 1978-81) for the study reach between Hathnikund and Okhla barrage

high proportion of baseflow. For the study reach, the ratio of baseflow to total river flow is found to be higher in the non-monsoon season than in the monsoon season, thus resulting in a higher BFI. This pattern is representative of other gauges in the study reach. A decreasing trend in BFI for all the seasons was found for Baghpat, and for non-monsoon and lean seasons for Mawi. Decreases in BFI are linked to prolonged over-abstraction of groundwater, which is evident from Figs. 4.5(a)-(d), that reveal declining groundwater levels in the Mawi-Baghpat reach. Figure 5.6 illustrates the declining trend of mean monthly baseflows for the month of May for Baghpat.

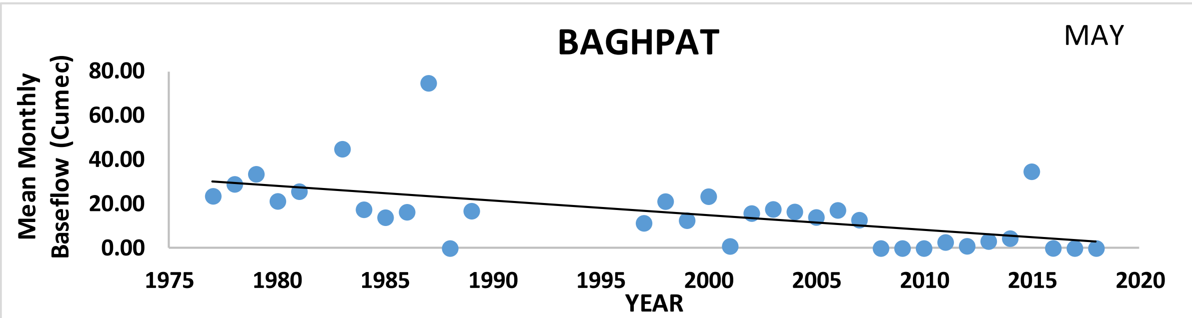


Fig. 5.6 Variation in mean monthly baseflows for the month of May for Baghpat

5.2.3 Conclusions from SWAT based analysis

The calibration and validation results show a good match between observed and simulated flows compared at the five gauge locations during the time periods 1978-1981 and 2003-2016. The calibrated model has been employed to simulate unregulated discharge (i.e. virgin flows) at 14 locations (including the gauging sites) considering no structure at Hathnikund. Virgin flows at all gauging sites have been compared with the regulated flow conditions to estimate the actual flow availability as compared to regulated conditions downstream of Hathnikund barrage in River Yamuna for the time periods 1977-1981 and 2001-2016.

Simulations using the calibrated SWAT model for unregulated and regulated flows show that during the time period 1978-1981, significant amount of flow is available even during non-monsoon season for unregulated flow conditions (i.e. virgin flows) compared to the regulated conditions. In case of the non-monsoon scenario of time period 2003-2016, the average monthly regulated flow is further reduced during January and February at all the gauging sites compared to the non-monsoon scenario of time period 1978-81. Therefore, the simulated discharge scenarios from SWAT, generated at different locations between Hathnikund and Okhla barrage, are found helpful in the assessment of flow availability during both non-monsoon and monsoon seasons

5.3 Hydrodynamic Modeling using HEC-RAS

The key points of employing HEC-RAS in the present study are given below:

- **HEC-RAS 1D Model:** Hydrodynamic model setup to compute depth vs. discharge curves, water surface elevation, and velocity at different cross sections. These parameters are found necessary to compute the e-flows. Boundary conditions along with several hydrodynamic variables are necessary to setup HEC-RAS 1D for steady state analysis. For establishing the depth vs. discharge curves, several model runs were taken corresponding to boundary conditions at the upstream and downstream end of the study reach.

- **Boundary Conditions:** The upstream boundary condition comprise of steady flow values at Hathnikund barrage. These values were derived from probability analysis of observed inflows and releases at Hathnikund Barrage for dry, wet and normal years for different seasons (refer Section 5.4). Downstream boundary condition corresponds to normal depth computed from downstream slope value. Standard and measured hydrodynamic variables have been utilized to construct the HEC-RAS model.

- **Setup Cross-Sections:** Surveyed river cross-sections (total 306 sections; refer Chapter 4) at very close intervals were incorporated in the model to account for variations in discharge, flow depth and velocity.

- **Depth vs Discharge curves:** Depth vs discharge curves have been derived at different river sections (total 13 identified locations; 14th identified location corresponds to Okhla barrage) utilizing discharge for non-monsoon and monsoon seasons for the computation of e-flows.

5.3.1 Generation of Database for Hydrodynamic Modeling

HEC-RAS requires river cross-sections at various locations to compute the stage-discharge relationship at different sites in the river. Based on initial simulation studies performed using HEC-RAS, it was concluded that the HEC-RAS 1D model needs to be setup with river cross-sections spaced at very close intervals to maintain high accuracy in the simulated values, especially for studies pertaining to assessment of e-flows. Further observations are noted below.

- As per the initial HEC-RAS simulation using high resolution DEM, it was observed that river cross-sections generated from DEM do not provide smooth profile and vertical accuracy, therefore, computational uncertainty (or error) in the results is enhanced.
- Surveyed river cross-sections from CWC were not spaced at sufficiently close intervals and could not account for significant variability of flows and depths in the study reach.
- Several surveyed river cross-sections obtained from CWC did not cover the whole flood plain of Yamuna. An attempt was made to extrapolate these values from DEM, which gave lot of computational errors (in terms of abnormal depths and velocities in many sections).

In the first stakeholder committee meeting, experts suggested that for generation of accurate e-flows, high precision and cross-sections at close intervals are needed; DEM generated cross-sections should not be relied upon. Therefore, necessary field surveys were carried out to determine river cross-sections at every at 1 km (with an interval of 250 m near gauging or confluence sites) in the study reach.

Total locations where spacing interval was 250 m within a distance of 1 km are 14 in number, with the 14^{th} location falling at Okhla barrage (refer Table 4.3). At each such location, 05 cross-sections were surveyed located 250 m apart within a reach of 1 km. The details of field survey undertaken to obtain river cross-sections at close intervals are provided in Chapter 4.

All these surveyed cross-sections were incorporated in HEC-RAS to generate the hydrodynamics variables such as depth etc. As an illustration, cross sections at 13 locations in HEC-RAS are shown in Fig. 5.7. The Manning's roughness coefficients for the study reach were obtained from CWC.

5.3.2 Simulation of Flows using HEC-RAS

For the computation of flows, water depth, and velocities, the HEC-RAS model has been setup and simulations were performed in the selected reach of Yamuna river from Hathnikund to Okhla barrage. The HEC-RAS setup and cross section details are presented in Fig. 5.8. The HEC-RAS based outputs (in form of maps) have been shown in Fig. 5.9, which illustrate the hydrodynamic characteristics of the selected portion of Yamuna river.

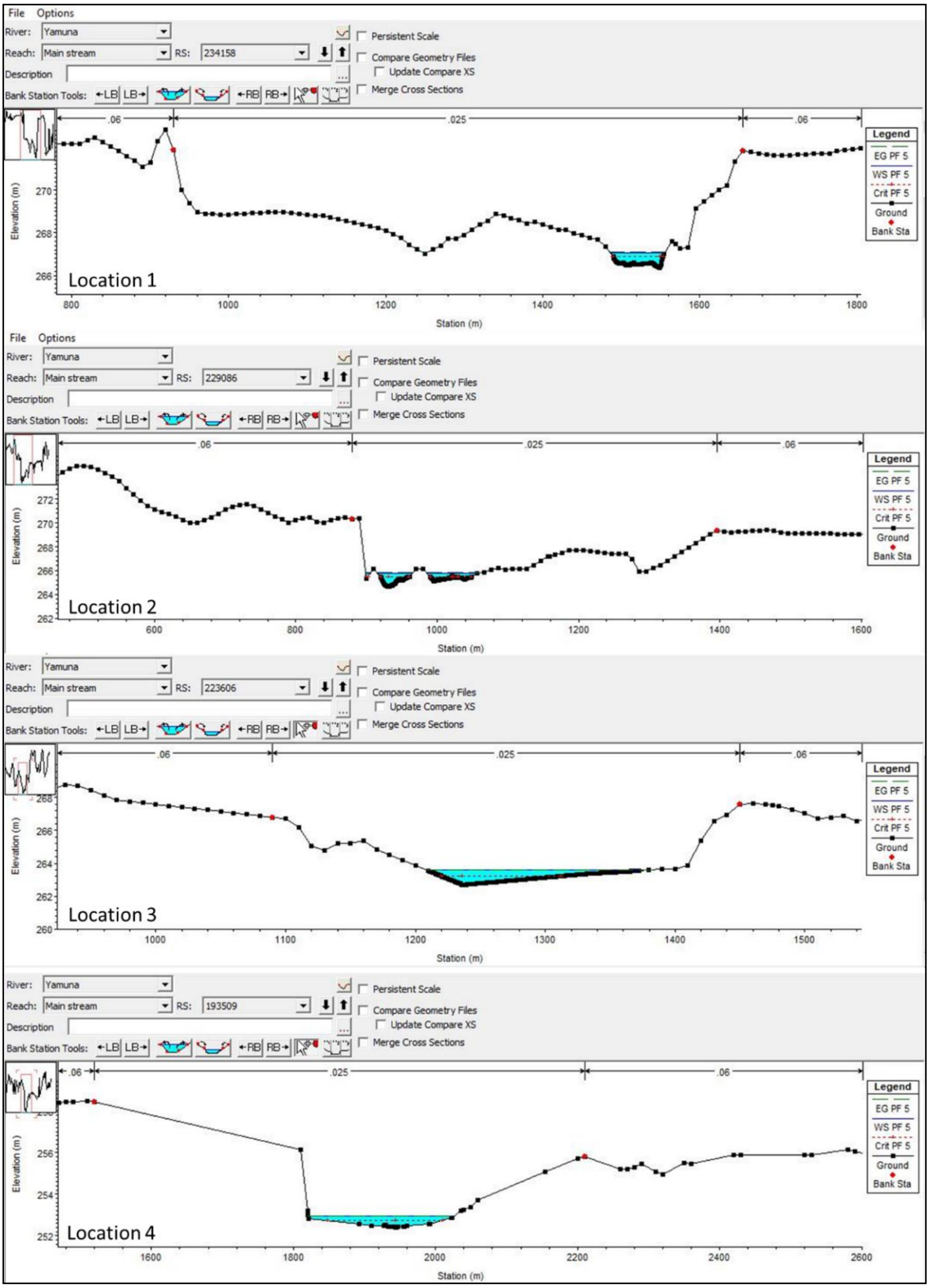


Fig. 5.7 Cross sections showing water level plotted at 13 locations from Hathnikund to Okhla (contd...)

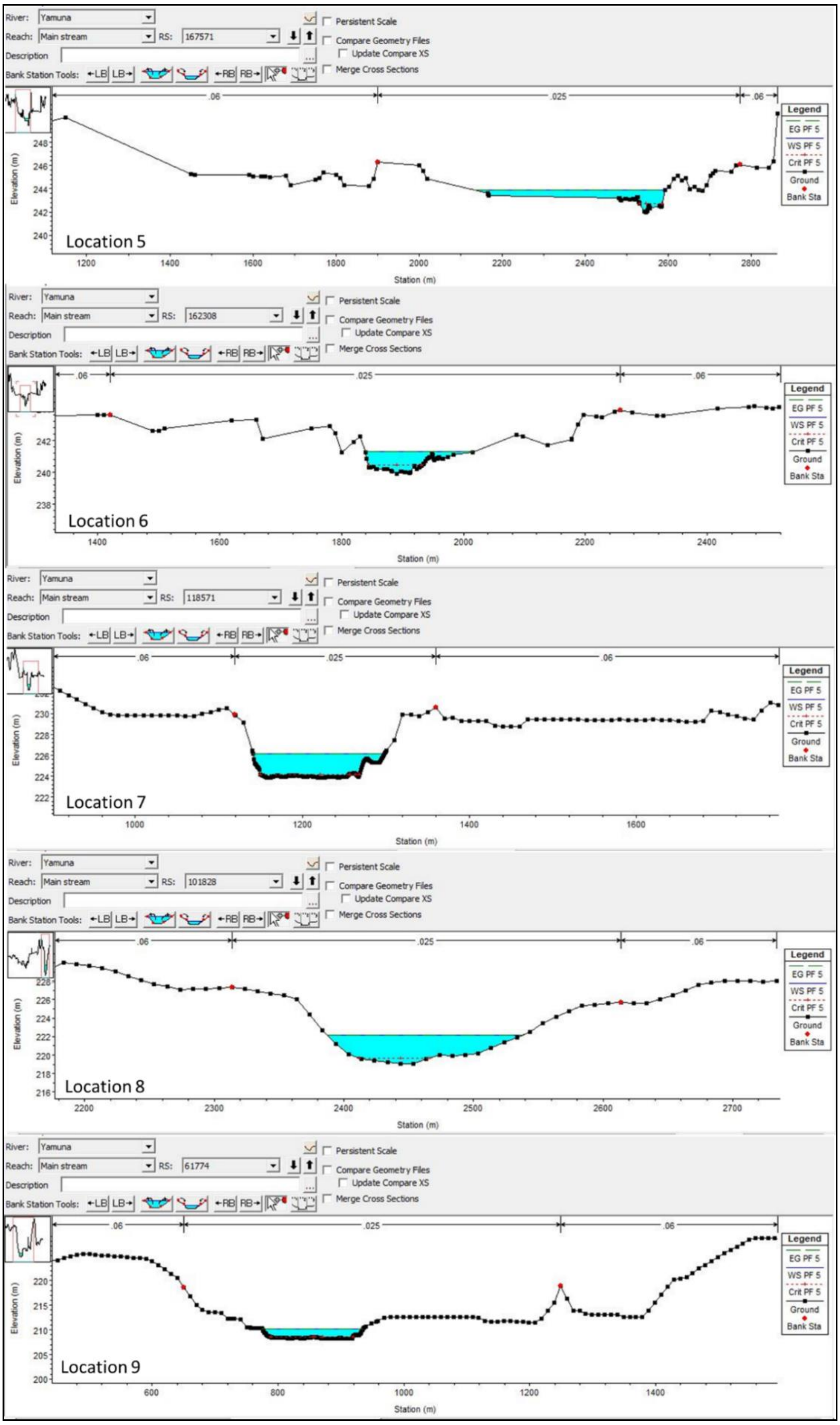


Fig. 5.7 Cross sections showing water level plotted at 13 locations from Hathnikund to Okhla (contd...)

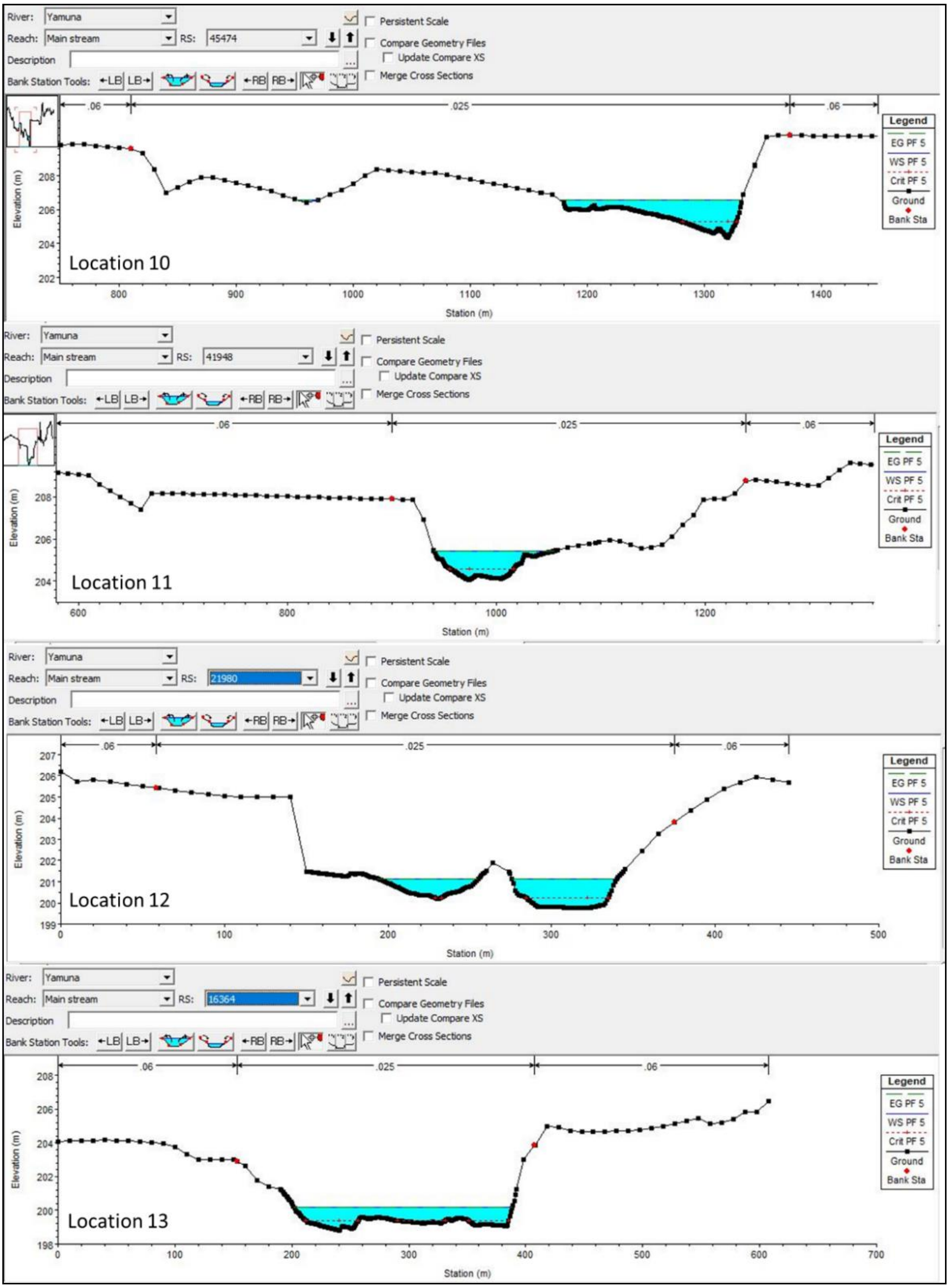


Fig. 5.7: Cross sections showing water level plotted at 13 locations from Hathnikund to Okhla.

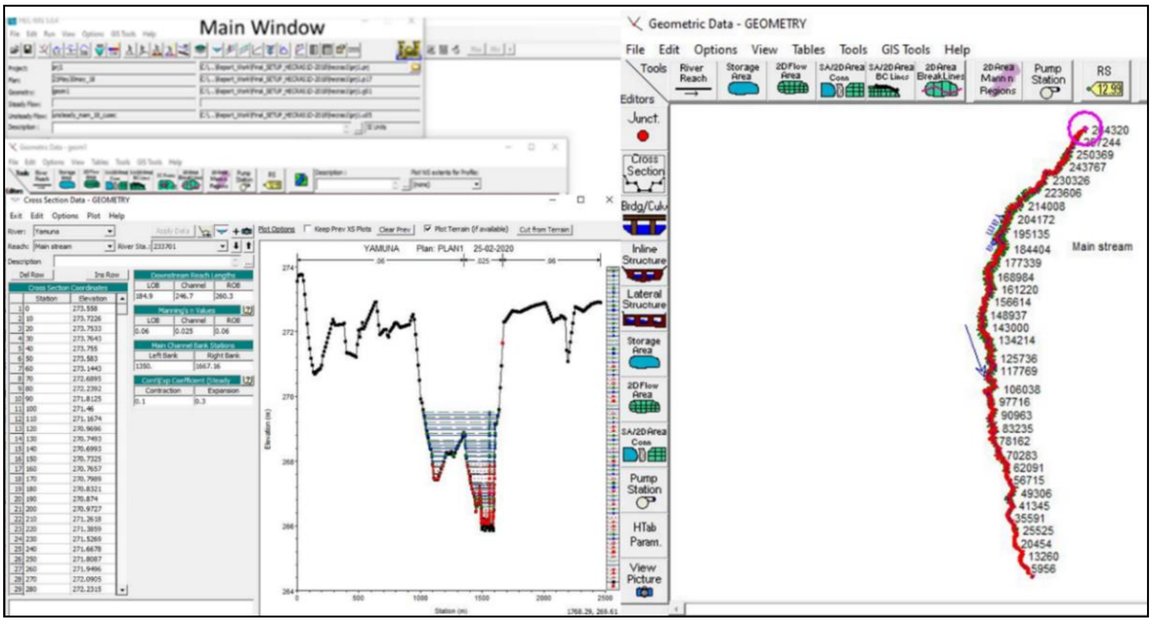


Fig. 5.8: HEC-RAS model setup with river cross sections geometry.

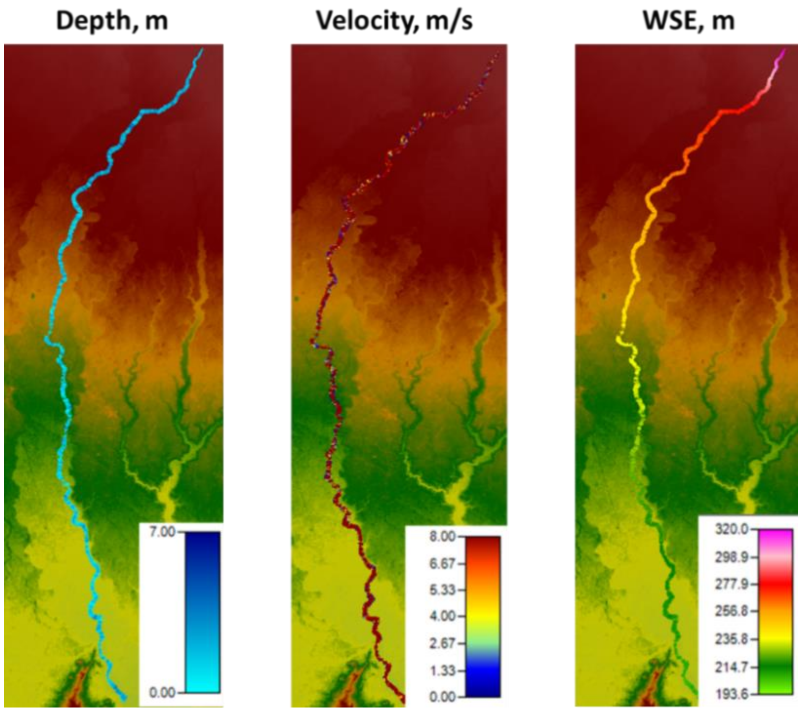


Fig. 5.9 HEC-RAS output in terms of depth, velocity and water surface elevation

5.4 Depth vs Discharge Relationships using HEC-RAS

To obtain the flow values corresponding to habitat suitability depth values for indicator fish species (refer Chapter 6), depth versus discharge curves are required to be developed covering the whole hydrologic regime. For this purpose, probability analysis of observed inflows and releases at Hathnikund Barrage was carried out, and, average flows for dry, wet and normal years for different seasons (monsoon, lean, non-monsoon) have been identified as summarized in Table 5.1.

Considering the minimum and maximum flow values for different seasons, 20 flow values have been chosen for HEC-RAS simulations as listed in Table 5.2, that vary from 5 to 1000 cumec. These 20 flow values constitute the upstream boundary condition for different simulations performed using HEC-RAS 1D model populated with surveyed river cross-sections. To formulate the depth vs discharge relationships for the 13 identified locations, the model output corresponding to the 13 locations, at every 250 m interval, was extracted. The maximum depth of water level was computed by detecting minimum channel elevation from water surface elevation. To achieve better accuracy, the output corresponding to first and last 250 m cross-section (falling within the 1 km reach of every identified location) was neglected and the depth and discharge of three middle cross-sections were averaged to arrive at the depth and discharge of the respective identified location. Such depth and discharge data were generated corresponding to different flow values listed in Table 5.2 for each of the 13 locations.

The simulated depth values have been plotted against the corresponding flow values to arrive at the depth vs discharge curves. The depth vs discharge curves derived from HEC-RAS simulations are shown in Fig. 5.10 for 13 locations (including the gauging sites at Kalanaur, Karnal, Mawi, Baghpat and Delhi Railway Bridge) in the study reach.

Using the developed depth vs discharge curves for different sites, the minimum flows required to be released from Hathnikund barrage for maintaining suitable physical habitat for indicator fish species in terms of flow depth have been estimated, as described in Chapter 6.

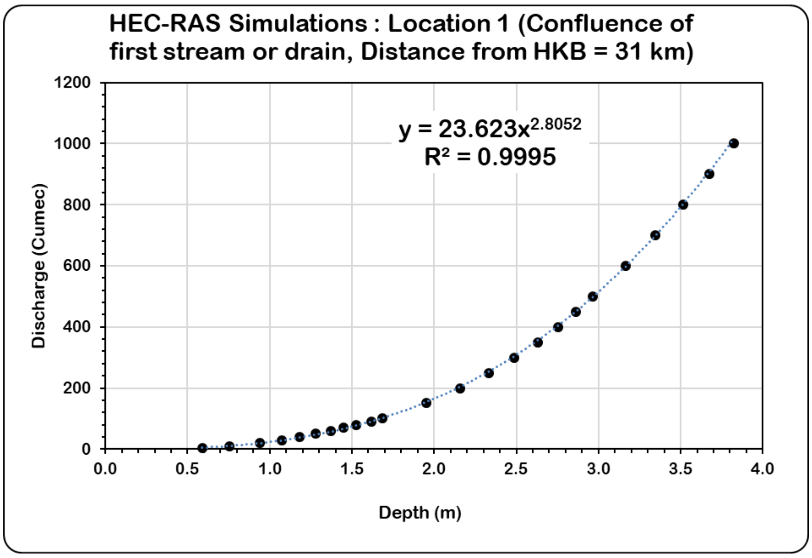
Table 5.1 Summary of average seasonal flow statistics for inflows and releases from Hathnikund Barrage

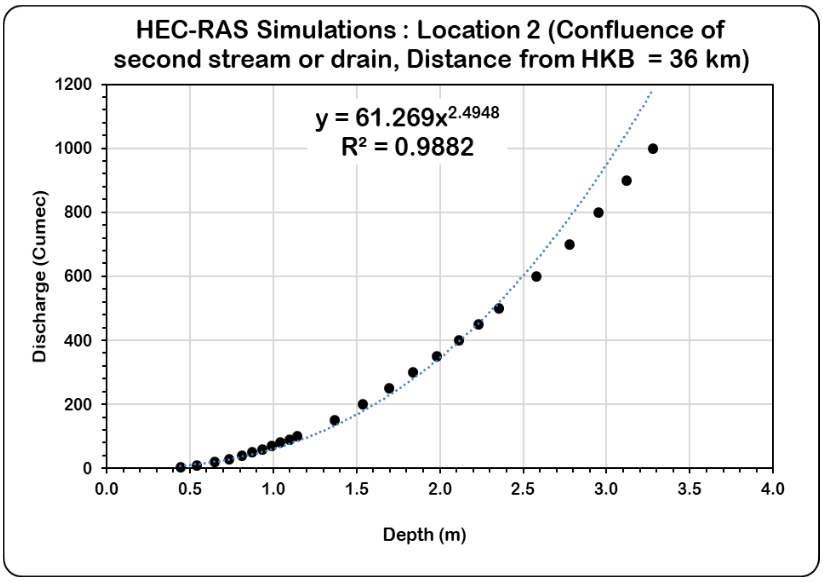
Average seasonal inflow at Hathnikund (cumec)				
S N	**Season**	**Dry Year (2004-05)**	**Normal Year (2014-15)**	**Wet Year (2013-14)**
I	Monsoon (June, July, Aug, Sep)	286	424	973
II	Lean (Dec, Jan, Feb, Mar)	107	117	107
III	Non-Monsoon/Non Lean (Apr, May, Oct, Nov)	113	135	180
Average seasonal outflow at Hathnikund (cumec)				
S N	**Season**	**Dry Year (2007-08)**	**Normal Year (2009-10)**	**Wet Year (2013-14)**
I	Monsoon (June, July, Aug, Sep)*	50	145	99
II	Lean (Dec, Jan, Feb, Mar)	5	5	25
III	Non-Monsoon/Non Lean (Apr, May, Oct, Nov)	5	8	8

* In normal year 2009-10, the Sept 2019 outflow is very high

Table 5.2 Flow values selected for HEC-RAS simulations

Season	Min	Max	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
Monsoon (June, July, Aug, Sep)	140	973											100	200	300	400	500	600	700	800	900	1000
Lean (Dec, Jan, Feb, Mar)	5	164	5	10	20	30	40	50	60	70	80	90	100	200								
Non-Monsoon (Apr, May, Oct, Nov)	18	678		10	20	30	40	50	60	70	80	90	100	200	300	400	500	600	700			





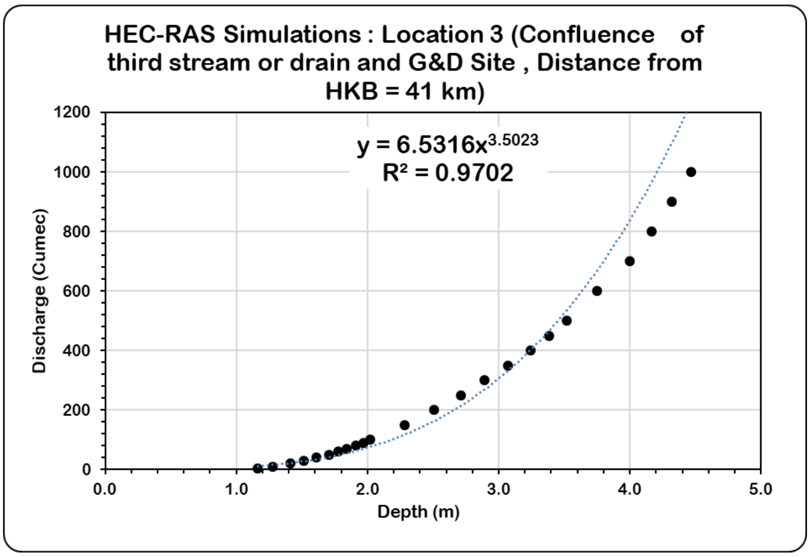
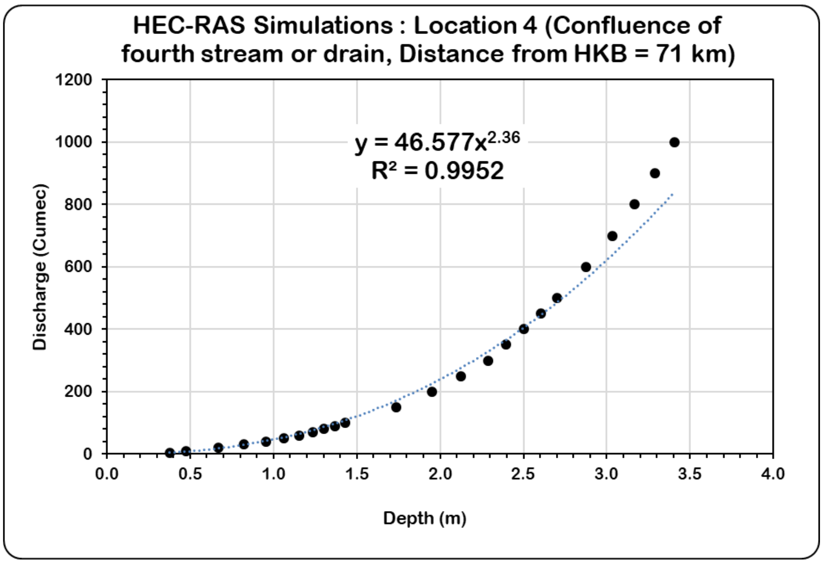
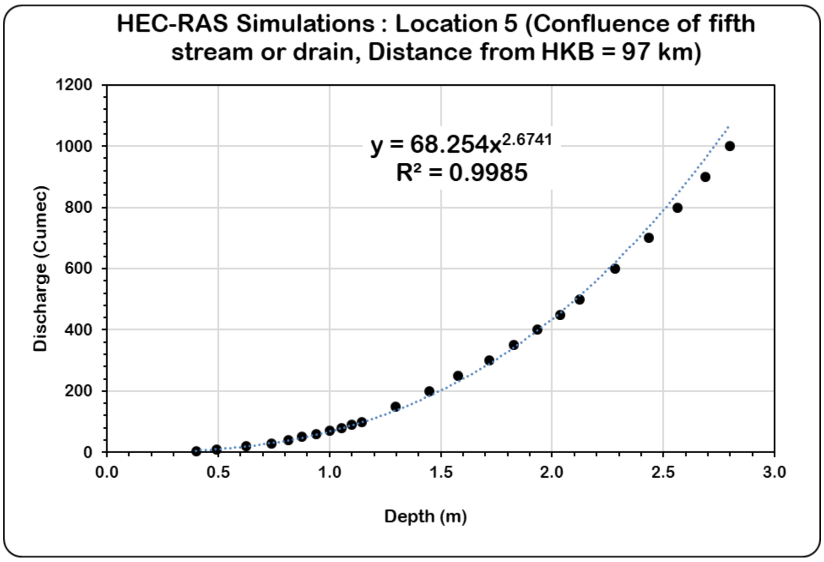


Fig. 5.10 Depth vs discharge curves corresponding to 13 locations between Hathnikund Barrage (HKB) to Okhla barrage (contd..)





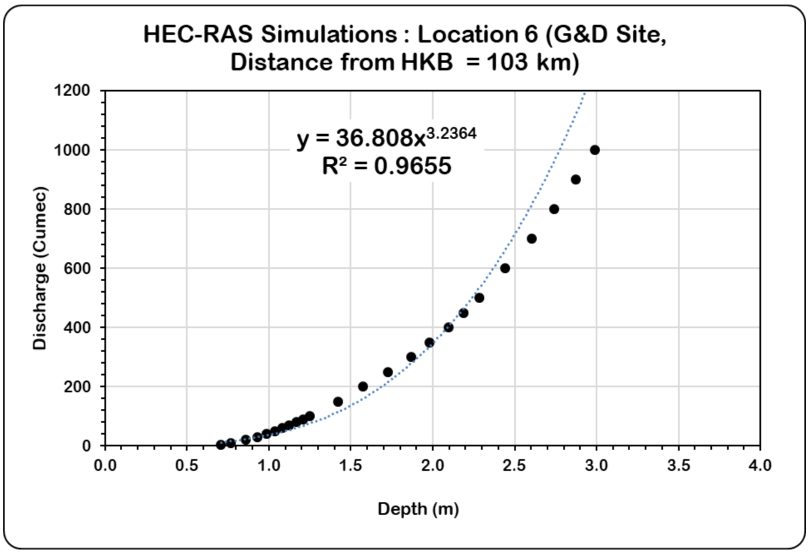
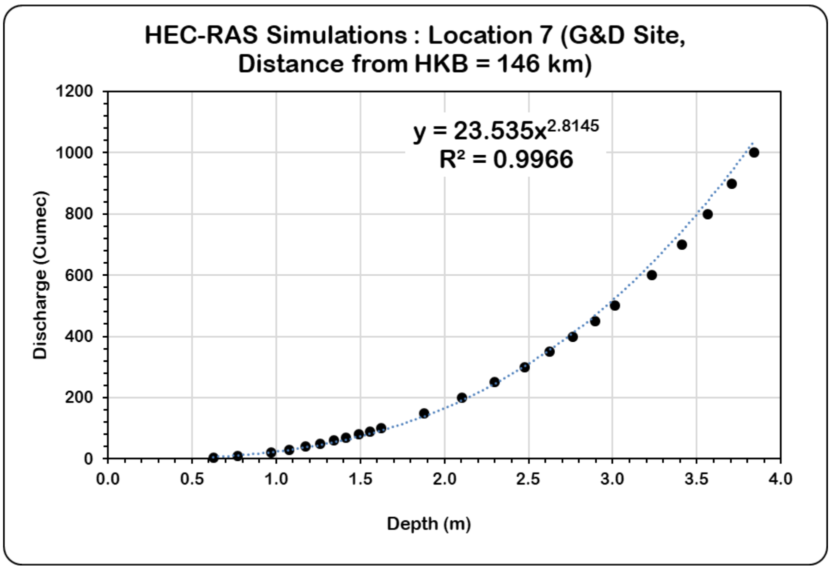
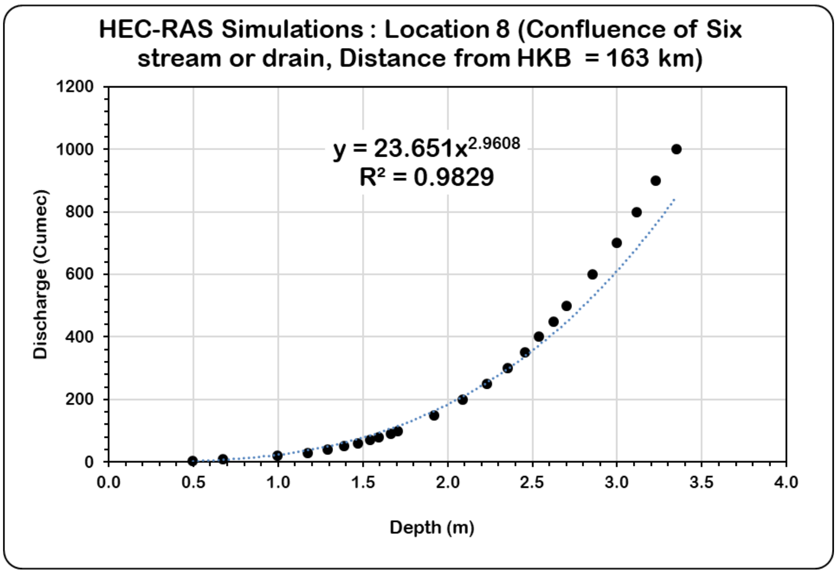


Fig. 5.10 Depth vs discharge curves corresponding to 13 locations between Hathnikund Barrage (HKB) to Okhla barrage (contd..)





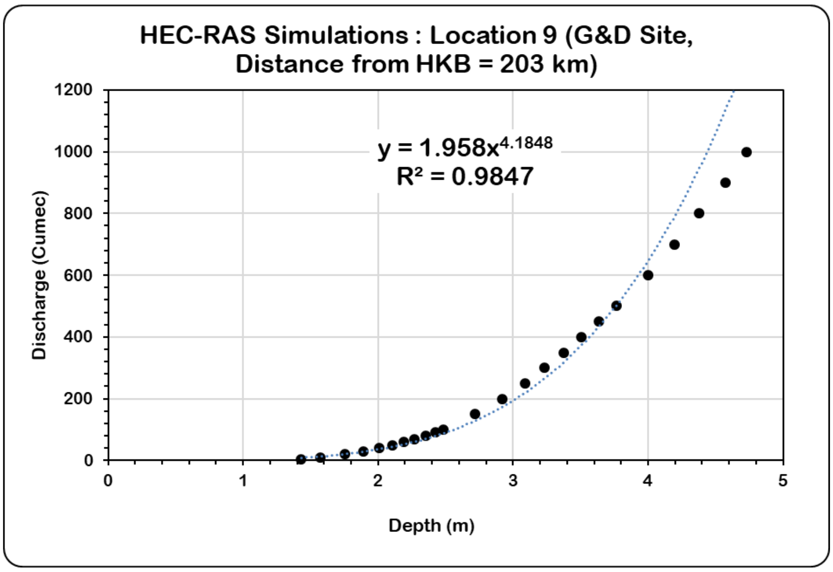
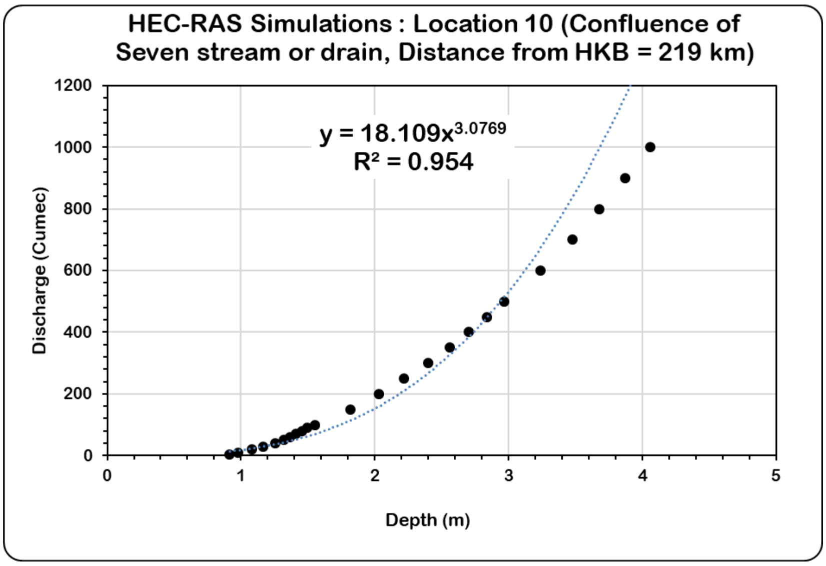
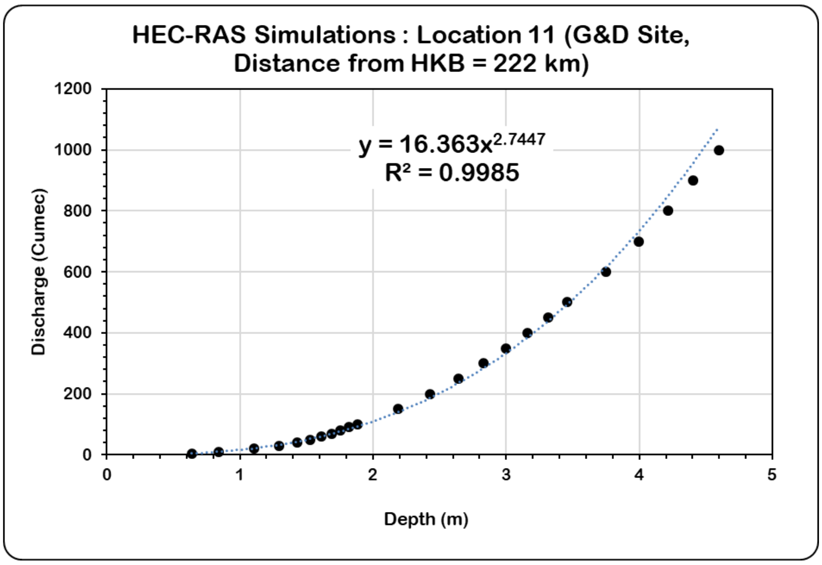


Fig. 5.10 Depth vs discharge curves corresponding to 13 locations between Hathnikund Barrage (HKB) to Okhla barrage (contd..)





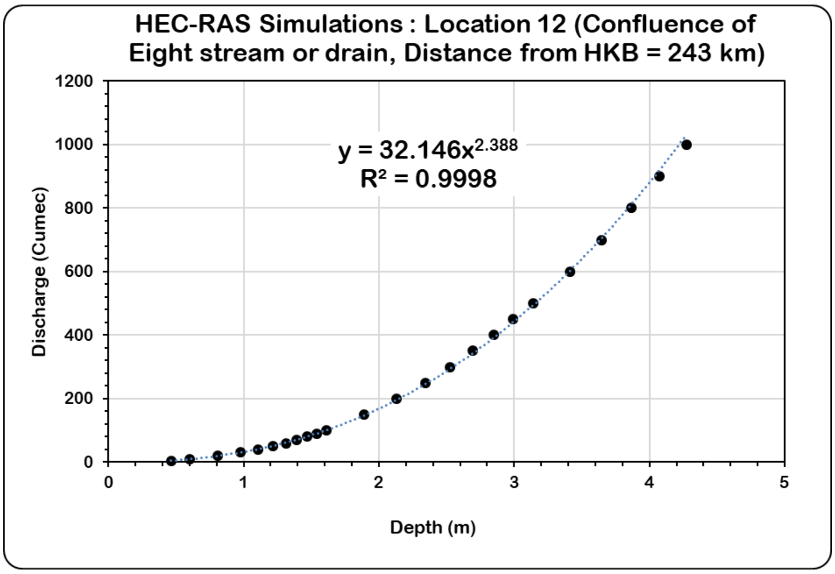


Fig. 5.10 Depth vs discharge curves corresponding to 13 locations between Hathnikund Barrage (HKB) to Okhla barrage (contd..)

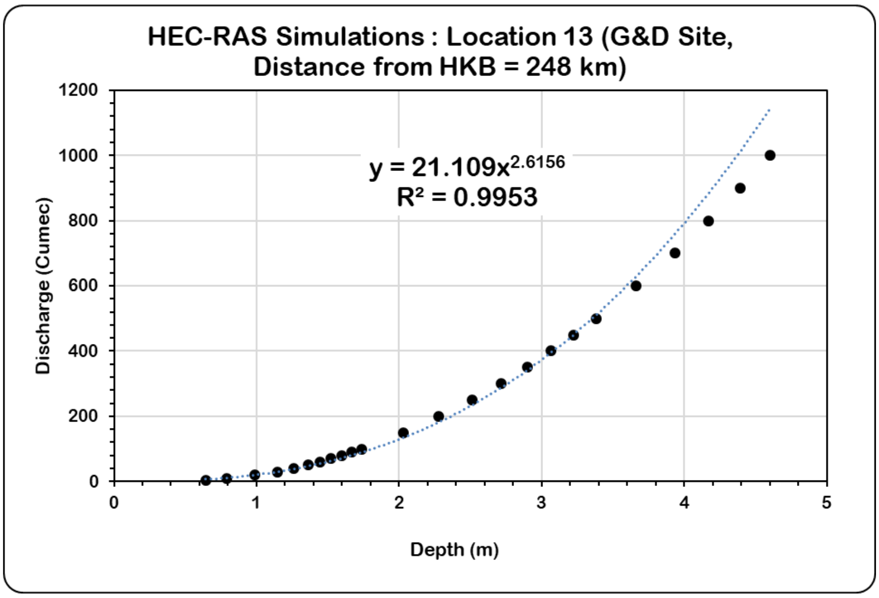


Fig. 5.10 Depth vs discharge curves corresponding to 13 locations between Hathnikund Barrage (HKB) to Okhla barrage

Chapter 6

E-FLOWS FOR SUSTAINING INDICATOR AQUATIC SPECIES

6.1 Indicator Fish Species in Yamuna River

River Yamuna is one of the major tributaries of river Ganga, and it is home to many fish species reported in river Ganga. More than 140 species of fish have been reported to inhabit river Yamuna, however, during last few decades, the fish catch composition has reduced due to extreme pollution of river water. As per the comprehensive survey conducted by the Central Inland Fisheries Research Institute (CIFRI) from headwaters of river Yamuna upto Delhi, 93 fish species belonging to 23 families occur in river Yamuna (Sharma et al., 2014, 2017). The important iconic fishes of river Yamuna are: Golden Mahseer (*Tor putitora*), Snow trout (*Schizothrorax richardsonii*), Kalaban (*Bangana dero*), Indian trout (*Raiamas bola*), Chagunius carp (*Chagunius chagunio*) and Calbasu carp (*Labeo calbasu*). As per the existing information, the river segment between Hathnikund Barrage and Panipat is considered as a more important river habitat in terms of fish diversity and this section of the river inhabits many important iconic fish species of river Yamuna (except snow trout). Further, it is observed that the important reophilic species such as *Bangana dero* and *Raiamas bola* are reported to occur between Hathnikund barrage and Panipat. The river receives heavy loads of domestic and industrial wastes along its course through Haryana, Delhi and Uttar Pradesh. This results in change in the fish species composition, change in trophic structure and abundance of invasive species in the lower reaches of the river (Kazmi and Hansen, 1997; Mishra and Moza, 1997; Moza and Mishra, 2003; Mishra et al., 2007; Vass et al., 2010).

Given this background, a rapid field survey was conducted in the study reach of river Yamuna for identification of indicator fish species and for determining the e-flow requirement for maintaining ecological integrity and sustaining fisheries resources of river Yamuna. A field team comprising of NIH scientists, and, river and fish ecology expert from Wildlife Institute of India carried out field sampling between Hathnikund barrage and Panipat during the month of October 2019. Another visit was undertaken in the month of February 2020. Fish and river habitat variables such as flow and depth measurements were carried out at four locations, Hathnikund, Yamuna Nagar, Panipat and above Delhi segment~~-~~. Fish sampling was performed using monofilamentous cast net (size 10 mm) and gillnets of different mesh size (12 mm; 16 mm & 24 mm). In addition, on site fish catch from different fishermen were recorded. At each sampling location availability of flow and depth at every 1 m interval were recorded across the river channel at multiple locations (Fig. 6.1). The site downstream of Hathnikund barrage was relatively shallow, hence the measurements taken here were made manually, whereas at Yamuna Nagar and near Panipat, boats of local fishermen were used for measuring depth and flow. Similarly, flow and depth use by target flow indicator fishes were recorded at each catch location at the time of fish sampling. Flow measurement was recorded using flow probe hand-held meter (Global waters, USA) and depth was recorded using graduated measuring rod and depth finder (Model: DT1-H-B, Hawkeye, USA). Based on the habitat feature recorded in different segments of Yamuna river and use by the indicator fish species, the habitat suitability curves were generated as per Johnson et al. (2017).

Fig. 6.1 Measurement of fish habitat variables at Yamuna Nagar in river Yamuna

6.2 Fish Diversity in Study Reach of Yamuna River

During the present survey, 40 species of fishes were recorded in the river sector from Hathnikund to above the Delhi segment during the sampling period. The list of fish species recorded during the sampling period is listed Table 6.1. Members of cyprindae family are dominant members in the fish assemblage structure. The common cyprinid fishes recorded during survey are: *Bangana (Labeo) dero*, *Raiamas bola*, *Chagunius chagunio, Cirrhinus reba, Labeo calbasu, Labeo rohita, Garra gotyla* and *Systomus sarana* (Fig. 6.2). Surprisingly, the most charismatic and conservation significant species, Golden Mahseer (*Tor putitora*) was not recorded in Yamuna river below Hathnikund barrage. Historically, this species was reported to be present in the downstream reaches of river Yamuna and few individuals of Golden Mahseer were reported in recent study by Central Inland Fisheries Research Institute (Sharma et al., 2014). It is a well known fact that depletion of Golden Mahseer in downstream reaches of river Yamuna is mainly attributed to modifications in the river habitat (changes in substrate composition), volume of water, over fishing and pollution. However, the presence of good population of reophilic species such as *Bangana dero* and *Raiamas bola* between Hathnikund and Panipat indicate that the habitat condition and quality of water is still conducive for such species. The record of reophilic species such as *Bangana dero* and *Raiamas bola* in this river sector is in accordance with earlier report on fishes of river Yamuna in these sectors (Sharma et al., 2014). These species contribute considerably in local fish catch in Yamuna River between Hathnikund and Panipat and play a major role in local economics (Fig. 6.2). Other than economically important fish species, many small fish species such as *Aspirodia morar, Barilius bendalisis, Barilius vagra, Pethia chonconius, Puntius chola and Puntius sophore* (Fig. 6.3) are commonly present in the river sector between Hathnikund and below Panipat. However, the condition of Yamuna river below Panipat deteriorates further because of large-scale modification in river bed and input of more pollution into the river channel. As a result, it exhibits more abundance of non-native invasive and pollution tolerant species such as *Cyprinus carpio* and *Tilapia nilotica*, which constitute over 90% of fish catch in this section (Fig. 6.4).

Table 6.1 List of fish species recorded at Hathnikund, Yamuna Nagar, Panipat and below Panipat

S. No.	Species	Hathnikund	Yamuna Nagar	Panipat	Below Panipat
1.	*Amblypharyngodon mola*		√	√	√
2.	*Aspirodia morar*			√	√
3.	*Bangana dero*	√	√	√	
4.	*Barilius bendelisis*	√	√		
5.	*Barilius vagra*	√	√		
6.	*Chagunius chagunio*		√		
7.	*Chela laubuca*			√	
8.	*Cirrhinus mirgala*		√	√	
9.	*Cirrhinus reba*		√	√	
10.	*Cyprinus carpio*			√	√
11.	*Cyprinus specularies*				√
12.	*Devario devario*	√	√		
13.	*Garra gotyla*	√			
14.	*Glossogobius giuris*		√		
15.	*Labeo bata*		√		
16.	*Labeo pangusia*	√			
17.	*Laboe calbasu*		√		
18.	*Labeo rohita*		√	√	
19.	*Lepidocephalus guntea*		√	√	
20.	*Mastacembelus armatus*		√	√	
21.	*Mystus cavasius*		√	√	
22.	*Mystus vittatus*		√	√	
23.	*Osteobrama cotia*		√	√	
24.	*Pethia conchonius*		√	√	
25.	*Pethio ticto*		√		
26.	*Puntius chola*		√	√	
27.	*Puntius sophore*		√	√	
28.	*Pseudoambasis ranga*		√		
29.	*Raiamas bola*	√	√	√	
30.	*Rasbora danicorinus*		√		
31.	*Salmostoma bacalia*		√	√	
32.	*Securicula gora*			√	√
33.	*Sperota aor*		√		
34.	*Sperota seenghala*			√	
35.	*Systomus sarana*			√	√
36.	*Tarquilabeo latius*	√			
37.	*Tilapia nilotica*				√
38.	*Trichogaster fasciata*		√		
39.	*Wallago attu*		√	√	√
40.	*Xanotodon cancila*		√	√	

Labeo calbasu

Labeo rohita

Chagunius chagunio

Bangana dero

Raiamas bola

Systomus sarana

Cirrhinus reba

Garra gotyla

Fig. 6.2 Common cyprinid fishes recorded in Yamuna River between Hathnikund and Panipat

Aspirodia morar

Barilius bendalisis

Devario devario

Barilius vagra

Rasbora daniconius

Puntius chola

Pethia conchonius

Puntius sophore

Fig. 6.3 Common minnows and barbs recorded in Yamuna River between Hathnikund and Panipat

Cyprinus carpio

Tilapia niloitica

Fig. 6.4 Dominant exotic fish species recorded downstream of Panipat in Yamuna River

6.3 River Habitat Condition at Sampling Points in Yamuna River

Three major fish habitats types such as Pools, Riffles and Runs were observed at all the sampling points in River Yamuna. Pools are deeper section of the channel unit, where water velocity is very less or almost nil (Fig. 6.5a). Deeper pools with rocky and boundary bed materials are predominant in river segment between Hathnikund and Yamuna Nagar, whereas very wide and shallow pools with sandy bed materials were observed in river channel below Panipat. Riffles are swift flowing section of the channel unit, where water velocity is at the maximum and bed materials often consist of large and small boulders (Fig. 6.5b). This type of habitat was observed only in the river sector just below Hathnikund barrage. Runs are transitional zones between pool and riffle habitat, where velocity is low and substratum is mostly homogenous, usually gravel or sand bed (Fig. 6.5c). This type of habitat is more common in river sector between Yamuna Nagar and Panipat.

(a) Pool

(b) Riffle

(c) Run

Fig. 6.5 Different types of fish habitats in Yamuna river

6.4 Ecology and Habitat Requirement of Indicator Fish Species for E-Flow Estimation

Based on the present study and historical information, three conservation significant species are selected and their ecological requirements (flow and depth preference) are considered for estimating e-flow requirement in Yamuna river segment stretching from Hathnikund to above the Delhi segment. Here, we have proposed two options for estimation of e-flow, as described below.

6.4.1 Option 1: Restoring the river habitat to historical condition

For restoring the river habitat to the historical condition, the conservation significant species Golden Mahseer may be selected as indicator species (Fig. 6.6). Though this species is not available downstream of Hathnikund barrage, the habitat suitability curve for Golden Mahseer generated from upstream reaches of Yamuna River and other tributaries of River Ganga has been used for estimating e-flow downstream of Hathnikund barrage. Here, it is assumed that the estimated flow based on Golden Mahseer may improve the habitat condition suitable for repopulating the Golden Mahseer in the downstream reaches of the Yamuna river. It may be noted here that the estimated flow will provide more suitable habitat in terms of volume, but does not guarantee in bringing back the river habitat features such as substrate heterogeneity suitable for Golden Mahseer.

Fig. 6.6 The Golden Mahseer, *Tor putitora*

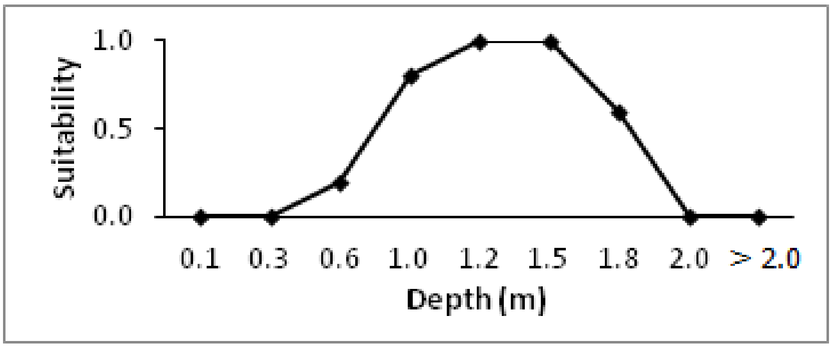
Ecology of the Golden Mahseer (Tor putitora)

The Golden Mahseer is one of the endangered, mighty game fish of India. It is a migratory species which attains a maximum weight of upto 54 kg (Talwar and Jhingran, 1991). This species is well known for its utility in angling sports (Fig. 6.6). It inhabits the montane and sub-montane regions, in streams and rivers. This species is native to Himalayan river system and distributed at altitudes ranging from 300 m to 1000 m. It occurs in rapid streams with rocky bottom, riverine pools. The fish is a column feeder in freshwater found in subtropical conditions with temperatures 12°C - 30°C. It is omnivorous in food habits during adult stage and feed on periphytic algae and diatoms in juvenile stage (IUCN, 2011). It migrates from the

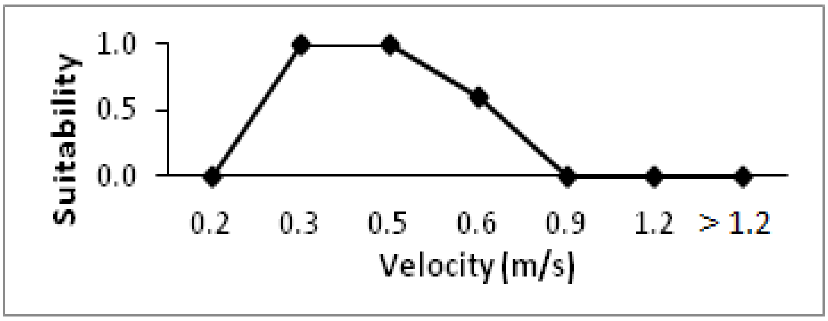
foot hills to upper reaches of the river and tributaries for spawning and finds suitable habitat such as clean, stable, well-oxygenated, gravel habitats for spawning (Sharma, 1984).
However, the feeding and breeding habitats are almost lost throughout their distributional range. Their population is fast depleting and at present are chiefly localised to certain major river systems and is fast approaching extinction in the streams of northern India. Large fishes are only found in some of the perennial pools. This species is declining from its natural habitat due to reduction in volume of water, river habitat modifications, over fishing and pollution (IUCN, 2011). The summary of species biology is given Table 6.2. The adult Golden Mahseer prefers depth > 1 m and velocity > 0.1 m/sec at pool habitat. Based on the field observations in Alaknanda and Bhagirathi rivers, the habitat suitability curve generated for Golden Mahseer is presented in Fig. 6.7.

Table 6.2 Summary of the biology and flow-related ecological requirements of Golden Mahseer (*Tor putitora*) in Alaknanda and Bhagirathi river basin

Observed Requirements	Adults	Juveniles	Spawning	Incubation and Larval development
Depth	Deep (>1.5 m)	Shallow (<0.75-1.5 m)	Shallow to high (0.5 - 2.0 m)	Shallow to high
Velocity	Medium to high (0.5-1.5 m/s)	Low to medium (0.1-1.5 m/s)	Low to medium (0.1-1.0 m/s)	Low to medium (0.1-0.5 m/s)
Habitat	Riffles, pools, glides	Pools, backwater pools closer to the banks and run habitats	riffles, backwater pools	Backwater Pools and secondary channels
Substratum	Bed rock, Boulders, Cobbles, gravel to sandy bottom	Cobbles, gravel to sandy bottom	Bedrock undercut, Boulder undercut, Gravel bed	Cobbles, gravel to sandy bottom Leaf litter
Temperature	12-30 °C	12-20 °C	<12 °C	10-15°C
Dissolved O_2	8-12 mg/l	8-12 mg/l	8-12 mg/l	8-12 mg/l
Food	Omnivorous: small fishes, benthic invertebrate's larvae, mollusc, crab, fronts and seeds etc.	Benthic invertebrates larvae, worms etc.,	Not applicable	Periphytic algae and diatoms
Breeding Period	March – April; October to December			
Passage Requirement	Moves long distance to streams associated with main river, nearby side channels, shallow water and pools to breed			



a) Depth suitability curve



b) Velocity suitability curve

Fig. 6.7 Habitat suitability curves for Golden Mahseer (*Tor putitora*)

6.4.2 Option 2: Based on the current fish community assemblage

For making an e-flow assessment based on the current fish community assemblage occurring in the Yamuna river between Hathnikund and Okhla barrage, the results of present survey revealed that the river sector between Hathnikund and Panipat has good population of reophilic species such as *Bangana (Labeo) dero* and *Raiamas bola*. These two species are relatively flow sensitive, which also indicate better quality river habitat in terms of water quality. These two reophilic species live in riffle/run habitat with moderately flowing channel unit.

Ecology of the Kalaban (Bangana (Labeo) dero)

Bangana (Labeo) dero is one of the Indian native carps and constitutes a large percentage of fish catch in river Yamuna in the segment between Hathnikund barrage and Panipat. This species can be easily distinguished from other Indian minor carps by a narrow, round body and presence of the characteristic groove on the head tip (Fig. 6.8). *Bangana dero* lives in riffle and run habitats with moderate velocity. It is a bottom dwelling fish, feeds on diatoms, algae and detritus matters. Field observations made in Yamuna river at Hathnikund, Yamuna Nagar and Panipat show that it prefers the depth range from 60 to 90 cm and velocity in the range of 0.1 to 0.2 m/sec at riffle/ run habitat. Based on field observations in Yamuna river, the habitat suitability curve generated for *Bangana dero* is presented in Fig. 6.10.

Fig. 6.8 The Kalaban, *Bangana dero*

Table 6.3 Summary of the biology and flow-related ecological requirements of Kalaban (*Bangana dero*) in Yamuna river basin

Observed Requirements	Adults	Juveniles	Spawning	Incubation and Larval development
Depth	Prefers 60-90 cm in Run/ Riffle habitat	Shallow (<30– 40 cm)	No information	No information
Velocity	Medium to high (0.1-0.2m/s)	Low to medium (>0.1 m/s)	-	-
Habitat	Riffle, run and pools edges	Pools, backwater pools closer to the banks and run habitats	-	-
Substratum	Boulders & Cobbles	Cobbles, gravel to sandy bottom	-	-
Temperature	20-30 °C	20-25 °C	-	-
Dissolved O_2	6-8 mg/l	6-8 mg/l	-	-
Food	Diatoms and algal feeder	Algae	-	-
Breeding Period	September to November			
Passage Requirement	Moves to upstream and side channels & streams associated with main river			

Ecology of the Indian trout - Raiamas bola

Raiamas bola is one of the elegant and popular game fish of India. It occurs in streams and rivers of foot-hills of Himalaya and it is also found in upper reaches of river Ganga and

Yamuna. It is one of the minor carps and forms a major portion of the local fish catch. This species can be easily distinguished from other Indian minor carps by a streamlined body with many blue colour spots on the lateral side of the body (Fig. 6.9). It thrives in riffle and run habitat with moderate velocity. Mostly it is found in surface layer of river channel, where they largely forage on drifting aquatic insects, terrestrial insects and small fishes. During the field survey, this species was recorded in Yamuna river at Yamuna Nagar and Panipat, it shares the habitat with *Bangana dero* and prefers depth ranges similar to *Bangana dero i.e*. from 60 to 90 cm and velocity in the range of 0.1 to 0.2 m/s at run habitat. The habitat suitability curve generated for *Raiamas bola* is presented in Fig. 6.10.

Fig. 6.9 Indian trout, *Raiamas bola*

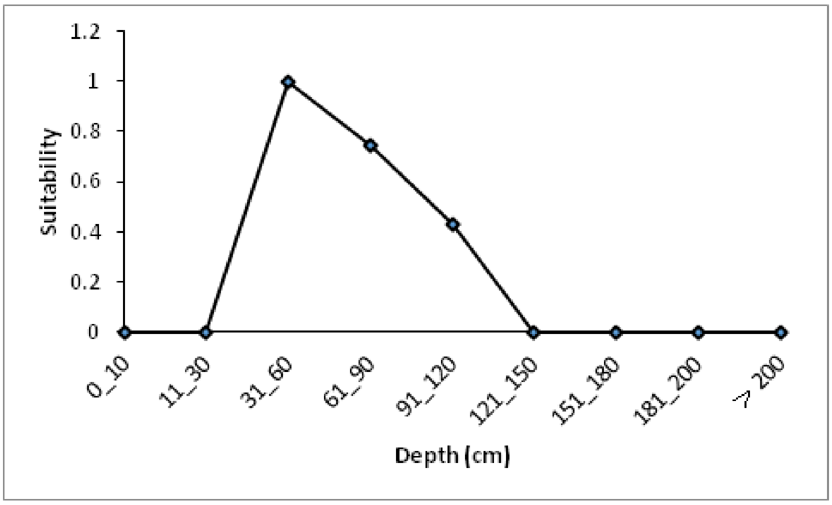
Table 6.4 Summary of the biology and flow-related ecological requirements of Indian trout (*Raiamas bola*) in Yamuna river basin

Observed Requirements	Adults	Juveniles	Spawning	Incubation and Larval development
Depth	Prefers 60-90 cm in Run/ Riffle habitat	Shallow run habitat (<30-40 cm)	No information	No information
Velocity	Medium to high (0.1-0.2m/s)	Low to medium (>0.1 m/s)	-	-
Habitat	Riffle & run habitat	Run habitat	-	-
Substratum	Lives in upper layer of river channel (Surface guild)	Sandy and grass bed	-	-
Temperature	20-30 °C	20-20 °C	-	-
Dissolved O_2	6-8mg/l	6-8 mg/l	-	-
Food	Mostly drifted terrestrial and aquatic insects	Insects and other animal matters	-	-
Breeding Period	September to November			
Passage Requirement	Moves to upstream and side channels & streams associated with main river			

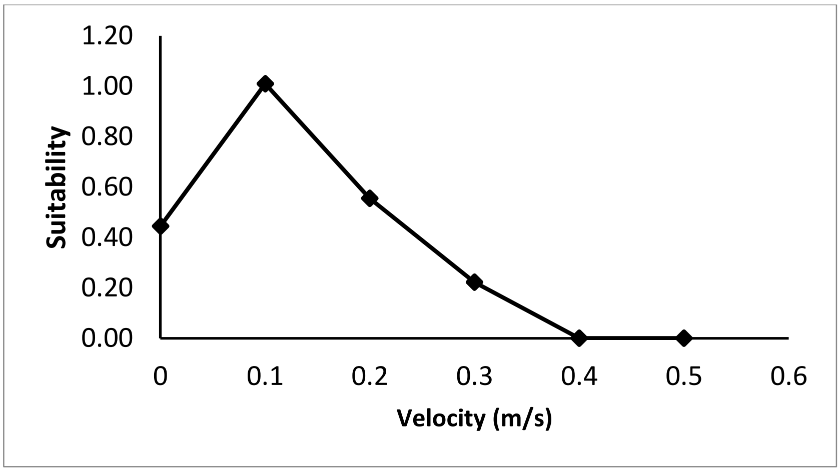
6.5 Habitat Suitability for Indicator Fishes of Yamuna river

The selected indicator species, *Bangana dero* and *Raiamas bola* are thriving well in run habitat of channel with depth ranging from 60 to 90 cm and with velocity of 0.1 m/s (Fig. 6.10). Further, it is observed that wherever these species are present, the other economically important species besides other small barbs and minnows also thrive well. *Hence, ensuring minimum water depth of 60 cm and flow of 0.1 m/s at riffle/run habitat of river Yamuna will safeguard the fish diversity in Yamuna river.*

If it is desired to restore the Golden Mahseer population in the downstream sector of the Yamuna River below Hathnikund barrage, then the habitat suitability of Golden Mahseer can be selected for estimating e-flows i.e., depth > 1 m and with velocity > 0.1 m/s.



a) Depth suitability curve



b) Velocity suitability curve

Fig. 6.10 Habitat suitability curves of *Bangana dero* and *Raiamas bola*

6.6 Suggested E-Flow Regime

The flow regime of a river has direct influence on the aquatic ecosystem. Although, there are a number of components of flow regime and related hydraulic and geomorphologic changes in the river, yet, water depth is considered as the most important criteria for e-flow assessment in the present case due to two reasons: (i) for e-flow implementation purposes, other hydraulic variables have more complex relationships with respect to the change in flows; (ii) provision of proper water depth according to different seasons will also ensure lateral and longitudinal connectivity required for various river functions and for survival and growth of fish species.

For converting the habitat suitability depth values into the flow values, depth versus discharge curves were developed covering the whole hydrologic regime using HEC-RAS simulations, as described in detail in Chapter 5. Using the developed depth vs discharge curves for different sites, the minimum desirable flow values required for maintaining suitable physical habitat in terms of desirable flow depths (i.e., 0.60 m, 0.75 m, 0.90 m, and for inundating the floodplains) at 13 identified locations (refer Section 5.3.1) have been estimated.

Further, the flows required to be released from Hathnikund barrage for maintaining the minimum desirable amount of flows at different sites during different seasons have been estimated using the flow series simulated by the calibrated hydrologic model SWAT. The regression plots along with the equations developed for the flows at each of the 13 identified locations are given in Annexure 2.

It needs to mentioned here, that the linear regression equations between releases from Hathnikund barrage and simulated flows at these 13 locations have very good coefficient of determination (R^2>0.6) for most of the months, but, as we go farther from Hathnikund barrage, R^2 value decreases due to more uncertainty arising due to rainfall events occurring in the catchment downstream of Hathnikund barrage. If we exclude these points, more than 50% of the points are falling within 20% error band. Moreover, for the estimation of final recommended releases, we are using the releases required for the month of May and subsequently building the recommended releases series using the natural variability. R^2 values for May is most significant and coefficient of determination R^2 values for May for all these 13 locations are more than 0.6.

The different magnitudes of flows required to be released from Hathnikund barrage for maintaining desirable depth at these 13 locations during different months are presented in the Tables A3.1 - A3.13 provided in Annexure 3.

The release required from Hathnikund barrage during a specific month (say May) is computed by taking the maximum of the releases estimated from Hathnikund barrage for meeting the minimum depth requirement of 0.60 m at the 13 different locations corresponding to the specific month. Table 6.5 shows the releases required from Hathnikund barrage for maintaining required habitat conditions at all the 13 locations between Hathnikund to Okhla barrage during the different months of a year.

For carrying out various functions, the aquatic ecosystem needs natural flow variability, within the year, for its sustenance. Incorporation of natural variability of flows may be carried either through taking different optimum depths for different seasons (viz., 0.60 m for lean season, 0.75 m for non-monsoon & non-lean and 0.90 m for monsoon season) or taking minimum depth (0.60 m) for lean season and modifying the releases as per the existing natural variability as observed in long-term historical data. Although, the analysis has been carried out for both the cases, it is recommended to choose the latter option as it better represents the natural variability.

Accordingly, we have estimated the releases required from Hathnikund Barrage for the month of May (being the driest month at all the G&D sites downstream of Hathnikund barrage) and subsequently, built upon the releases required during different months by using the ratio of average flows of the consecutive months keeping in mind that these computed values for different months are not less than the releases required for maintaining 0.60 m at all the 13 identified locations.

The final recommended releases from Hathnikund barrage for maintaining required habitat conditions between Hathnikund and Okhla barrage during the different months of a year are given in Table 6.6 and also illustrated in Fig. 6.11.

As evident from Table 6.5, these recommended releases from Hathnikund barrage are approximately 30% of the inflows at Hathnikund barrage which is comparable to the e-flow recommendations in the MOWR, RD & GR Notification dated 9th Oct 2018 for Upper Ganga basin upto Haridwar that suggests 20%, 25% and 30% of inflows as environmental flows during lean season, non-monsoon & non-lean season, and monsoon season, respectively.

As evident from Fig. 6.11, the recommended minimum releases for non-monsoon season are slightly higher than the current average monthly releases from Hathnikund barrage, however, for the monsoon months of July and August, the current average monthly releases are much higher than the recommended releases. Since during the monsoon months of July and August, inflows at Hathnikund are significantly higher than the diversion capacity of barrage, the flow regime during these monsoon months will be the same as the current releases. Therefore, after implementation of recommended minimum releases from Hathnikund barrage, the flow regime downstream of Hathnikund barrage will comprise of recommended minimum releases during non-monsoon season and current releases during monsoon season.

It may be noted here that this analysis is based on water requirement of indicator fish species, however, the biodiversity, livelihood and spiritual groups can link their requirements to specific features of the river channel at the study sites.

Table 6.7 provides the expected flows at Wazirabad barrage for recommended values of flows released from Hathnikund barrage in a year with average rain for the present scenario, after meeting out all the current demands of water upstream of Wazirabad barrage.

Table 6.5 Releases required from Hathnikund barrage for maintaining suitable habitat at all the downstream locations

Month	Inflows at Hathnikund (cumec)			Releases (cumec) from Hathnikund required for maintaining E-Flows																
				For maintaining 0.60 m depth					For maintaining 0.75 m depth					For maintaining 0.90 m depth					For inundating floodplains
	Median Max.	Median	Median Min.	Min. required releases	Releases incorporating natural variability (starting from May)	% of Median Max.	% of Median	% of Median Min.	Min. required releases	Releases incorporating natural variability (starting from May)	% of Median Max.	% of Median	% of Media n Min.	Min. required releases	Releases incorporating natural variability (starting from May)	% of Median Max.	% of Median	% of Median Min.	Min. required releases (once in a month)
Jan	108.28	75.71	55.99	20.73	22.81	21.07	30.13	40.74	24.63	30.06	27.76	39.70	53.69	30.23	46.37	42.82	61.25	82.82	
Feb	143.68	77.60	57.43	20.54	23.38	16.27	30.13	40.71	27.55	30.81	21.44	39.70	53.65	37.11	47.53	33.08	61.25	82.76	
Mar	163.22	85.92	61.09	20.39	25.89	15.86	30.13	42.38	31.95	34.11	20.90	39.70	55.84	48.63	52.62	32.24	61.25	86.14	
Apr	170.04	95.23	71.40	27.54	28.69	16.87	30.13	40.19	39.71	39.71	23.35	41.70	55.62	57.97	58.33	34.30	61.25	81.69	
May	187.34	111.96	70.29	33.73	33.73	18.01	30.13	47.99	44.45	44.45	23.73	39.70	63.24	68.57	68.57	36.60	61.25	97.56	
Jun	307.78	147.53	73.62	30.72	44.45	14.44	30.13	60.38	35.84	58.57	19.03	39.70	79.56	48.74	90.36	29.36	61.25	122.74	
Jul	1,472.82	524.95	147.80	37.96	158.16	10.74	30.13	107.01	41.37	208.41	14.15	39.70	141.01	45.87	321.52	21.83	61.25	217.54	1398.18
Aug	1,873.81	729.60	357.98	3.06	219.82	11.73	30.13	61.41	7.31	289.66	15.46	39.70	80.91	12.91	446.86	23.85	61.25	124.83	1631.01
Sep	1,003.18	493.28	197.97	-9.46	148.62	14.81	30.13	75.07	-1.29	195.84	19.52	39.70	98.92	16.39	302.12	30.12	61.25	152.61	
Oct	288.24	144.92	96.69	16.26	43.66	15.15	30.13	45.16	26.80	57.54	19.96	39.70	59.51	44.72	88.76	30.79	61.25	91.80	
Nov	131.87	89.66	63.20	16.19	27.01	20.48	30.13	42.74	29.78	35.59	26.99	39.70	56.32	48.12	54.91	41.64	61.25	86.89	
Dec	115.42	80.71	59.66	18.23	24.32	21.07	30.13	40.76	28.84	32.04	27.76	39.70	53.71	43.17	49.43	42.83	61.25	82.86	

Table 6.6 Final recommended releases required from Hathnikund barrage for maintaining suitable habitat at all downstream locations between Hathnikund and Okhla barrage

Month	Median of monthly inflows at Hathnikund barrage (cumec)	Average monthly releases from Hathnikund barrage (cumec)	Recommended minimum releases from Hathnikund barrage incorporating natural variability (cumec)	Flow regime obtained after implementing recommended minimum releases (cumec)	For inundating floodplains (cumec) *- once a month*
Jan	76	10	23	23	
Feb	78	10	23	23	
Mar	86	10	26	26	
Apr	95	10	29	29	
May	112	10	34	34	
Jun	148	18	44	44	
Jul	525	275	158	275	1400
Aug	780	298	220	298	1600
Sep	493	160	149	160	
Oct	145	30	44	44	
Nov	90	10	27	27	
Dec	81	10	24	24	

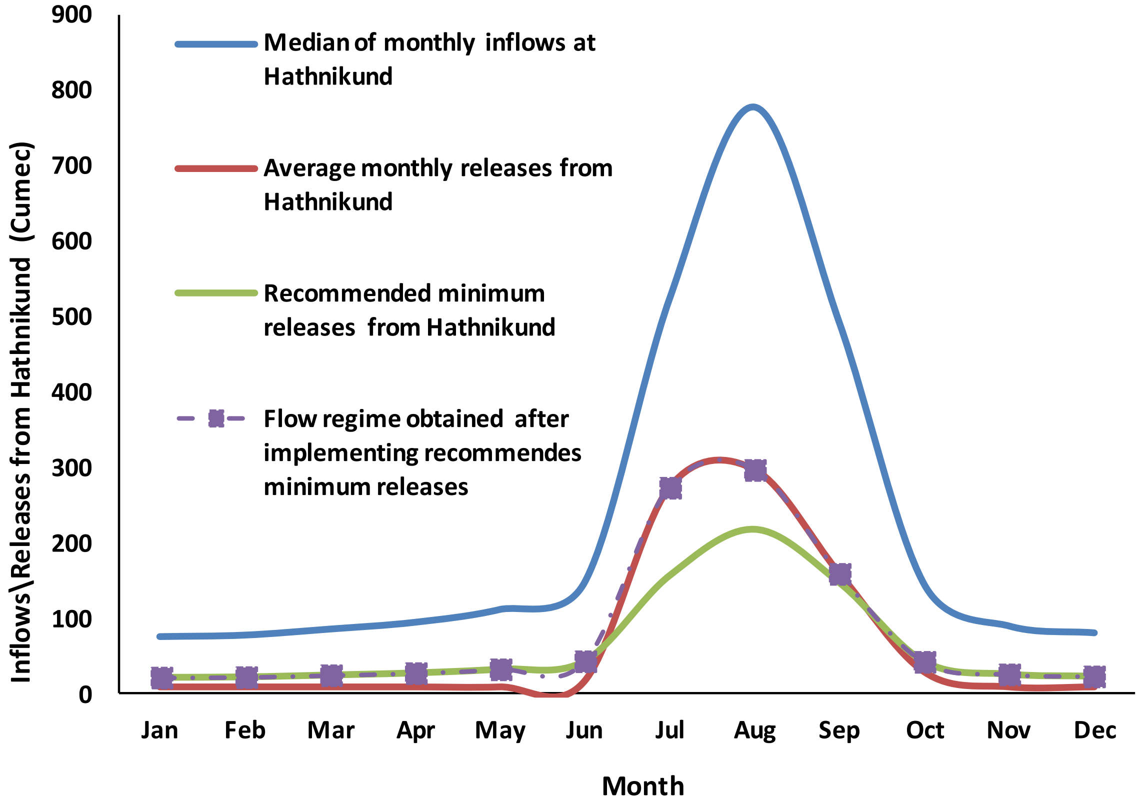


Fig. 6.11 Recommended releases from Hathnikund Barrage for sustaining downstream ecosystem upto Okhla barrage

Table 6.7 Expected flows at Wazirabad barrage for recommended values of flows released from Hathnikund barrage

MONTH	Recommended releases from Hathnikund barrage (cumec)	Expected flows at Wazirabad barrage under average conditions (cumec)
Oct	44	64
Nov	27	40
Dec	24	33
Jan	23	34
Feb	23	27
Mar	26	19
Apr	29	12
May	34	9
Jun	44	28

Chapter 7

MANAGEMENT OPTIONS TO MAINTAIN RECOMMENDED E-FLOWS

7.1 Available Water at Hathnikund Barrage

In the present scenario, approximately 47.5% and 9.8% of inflows at Hathnikund barrage are diverted to Western Yamuna Canal (WYC) command and Eastern Yamuna Canal (EYC) command, respectively, during monsoon season, while 78.5% and 13.0% of inflows at Hathnikund barrage are diverted to WYC and EYC commands, respectively, during non-monsoon season (Table 7.1). Thus, only 42.7% and a meagre 8.5% of inflows at Hathnikund barrage are released into the river during monsoon and non-monsoon seasons, respectively. Figures 7.1 and 7.2 show the observed time series of inflows, diversions and releases at Hathnikund barrage.

Table 7.1 Diversion and releases from Hathnikund barrage

Season	Observed Conditions		
	% of flows diverted to WYC command	% of flows diverted to EYC command	% of flows released from Hathnikund barrage
Monsoon	47.5	9.8	42.7
Non-monsoon	78.5	13.0	8.5

7.2 Management Options

It is apparent from Table 7.1 and Figs. 7.1-7.2 that during the monsoon season sufficient flows are being released downstream from the Hathnikund barrage; however, releases during non-monsoon season are significantly low and do not meet the e-flow requirement in the downstream reaches of Yamuna river. In such case, possible management options for maintaining e-flows are listed below.

- Reduction in diversions to WYC/EYC by increasing the irrigation efficiency in WYC and EYC commands, keeping in view the crop water requirement
- Regulate groundwater withdrawal in the basin especially in the Mawi-Baghpat stretch and augment groundwater recharge in order to sustain baseflows
- Augmentation of non-monsoon inflows at Hathnikund barrage by creating storage of monsoon runoff in the upstream reaches
- Treatment of effluent coming through various drains meeting river Yamuna

The management options are discussed in detail in subsequent sections.

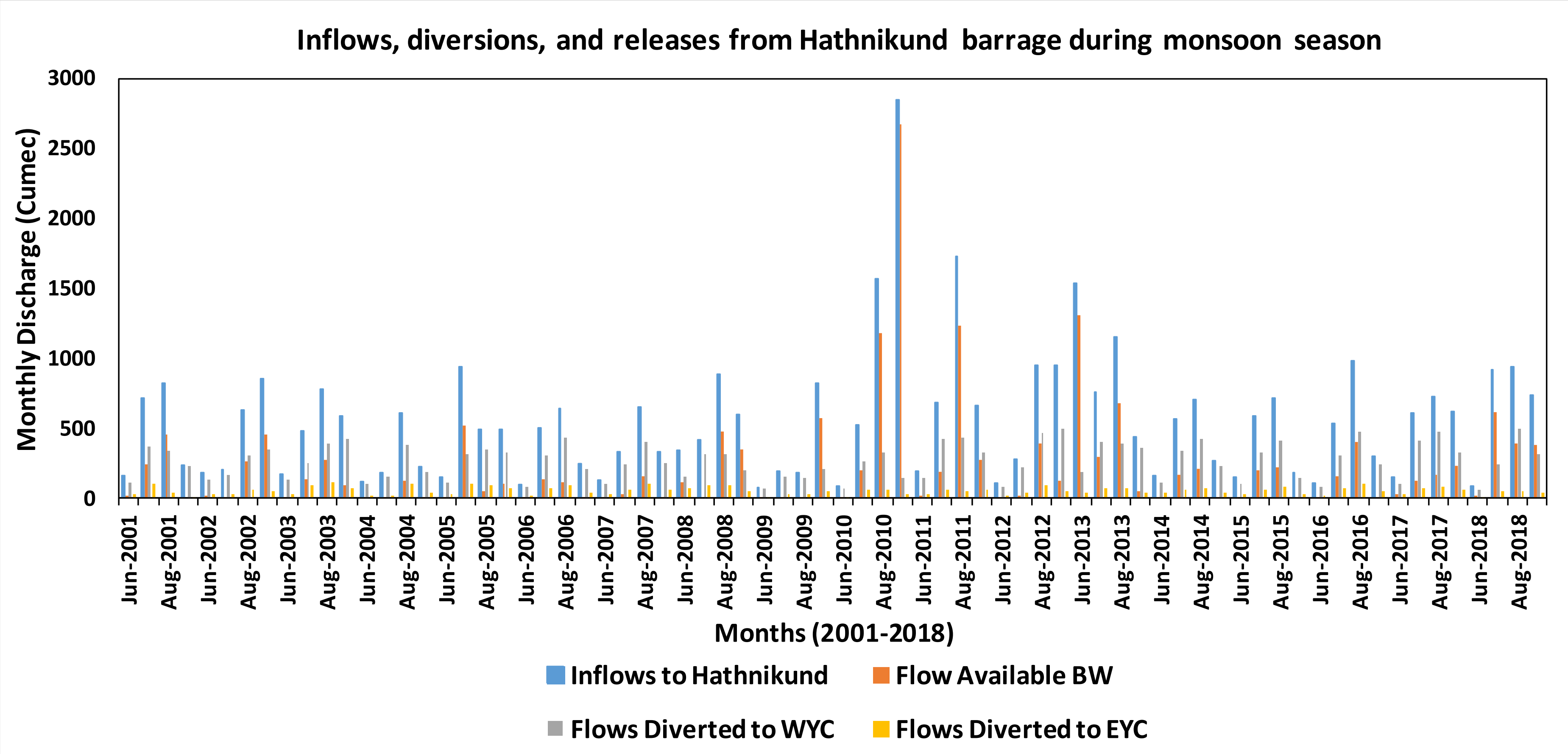


Fig. 7.1 Observed time series of inflows, diversions and releases from Hathnikund Barrage during monsoon season.

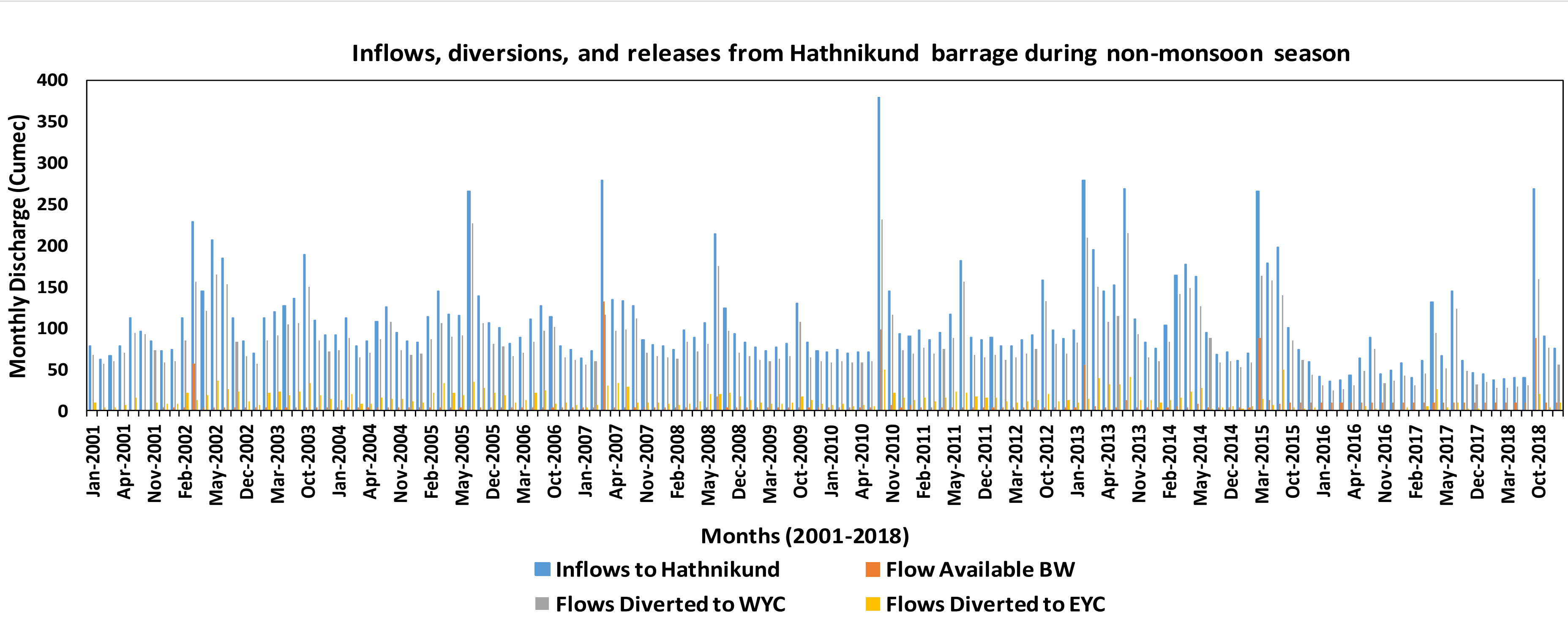


Fig. 7.2 Observed time series of inflows, diversions and releases from Hathnikund Barrage during non-monsoon season.

7.2.1 Increase in irrigation efficiency and reduction in diversions to WYC/EYC

The increase in releases recommended from Hathnikund Barrage for maintaining e-flows would lead to reduction in diversions to WYC/EYC during the lean and non-monsoon season. Table 7.2 presents the average diversions from Hathnikund Barrage under existing scenario and average available diversions at Hathnikund Barrage under recommended scenario of minimum e-flows along with desirable percent increase in irrigation efficiency for different months of the year. The percent decrease in available diversions at Hathnikund Barrage for recommended minimum releases is equivalent to the desirable percent increase in irrigation efficiency.

The percent increase (except for monsoon months) in irrigation efficiency varies from 7% to 26% for different months. As per CWC (2014) guidelines for 'Improving Water Use Efficiency in Irrigation, Domestic & Industrial Sectors', the scope for increasing efficiency using surface water is 30% while in respect of groundwater it is 20%. The desirable increase in irrigation efficiency in WYC / EYC falls very well within the scope of above guidelines.

Policy Measures for improving Efficiencies: Besides charging of irrigation water on volumetric basis and linking it to reliability, timeliness, and adequacy of irrigation water supplies; the incentives & disincentives listed below may also be considered (CWC, 2014):

- Institution of awards at minor/major distributary level for implementing scientific water management procedures
- Providing incentives to Water Users Associations, in the form of reduced bulk rates for water, subsidized inputs etc.
- Creating disincentives for growing water intensive crops in soils and climate that are not conducive for such crops.

Adoption of scientific water management practices such as proper assessment of command area size, proper fixing of outlet sizes to match the crop water requirements, scientific estimation of crop water demands, scheduling of irrigation based on soil-water-plant interactions, minimising evaporation losses from irrigated fields through use of mulches, conjunctive use of surface water and groundwater, blending of water for irrigation application in salinity-affected areas, and technological up-gradation by adoption of sprinkler/micro-sprinkler/drip irrigation systems can help in achieving the desirable level of irrigation efficiency.

7.2.2 Regulate groundwater withdrawal in the basin and augment groundwater recharge to sustain baseflows

The major water intensive crops grown in large parts of WYC and EYC are paddy, sugarcane and wheat. Water guzzler crops like paddy and sugarcane have almost 100 percent assured irrigation in Haryana and UP canal commands and these areas totally depend on surface and groundwater resources. Provision of subsidised electricity to farmers has led to indiscriminate groundwater exploitation and excessive water use in agriculture. High consumption of water for irrigation mainly supported through groundwater is causing hydrological and economic distress manifested through depleting water tables and mounting energy subsidies for groundwater pumping. In short, with respect to the rate of

Table 7.2 Desirable increase in irrigation efficiency for maintaining e-flows downstream of Hathnikund Barrage

Month	Present Scenario					Recommended Scenario		
	Average Inflows to Hathnikund Barrage (cumec)	Average releases from Hathanikund Barrage (cumec)	Average diversions from Hathnikund Barrage (cumec)	% Diversion to WYC	% Diversion to EYC	Recommended minimum releases from Hathnikund Barrage for maintaining e-flows (cumec)	Average availability for diversions at Hathnikund Barrage (cumec)	Desirable % increase in irrigation efficiency
	I	II	III	IV	V	VI	VII	VIII
			(II-I)				(I-VI)	((III-VII)/III*100)
Jan	73.67	5.66	68.02	88.52	11.48	23.00	50.67	**26**
Feb	87.34	8.15	79.19	89.14	10.86	23.00	64.34	**19**
Mar	116.02	19.31	96.71	87.57	12.43	26.00	90.02	**07**
Apr	104.83	5.92	98.91	84.77	15.23	29.00	75.83	**23**
May	112.43	5.90	106.53	83.65	16.35	34.00	78.43	**27**
Jun	216.48	83.96	132.52	79.75	20.25	44.00	172.48	**NA**
Jul	524.32	170.16	354.16	81.74	18.26	158.00	366.32	**NA**
Aug	842.58	378.71	463.88	83.20	16.80	220.00	622.58	**NA**
Sep	664.06	310.93	353.12	84.75	15.25	149.00	515.06	**NA**
Oct	174.20	16.26	157.94	88.31	11.69	44.00	130.20	**18**
Nov	94.24	5.67	88.57	86.46	13.54	27.00	67.24	**24**
Dec	78.57	5.74	72.83	85.51	14.49	24.00	54.57	**25**

irrigation water applied, Haryana and Western UP do not display a sustainable economic water productivity scenario. The non-judicious irrigation water application in these regions is unsustainable in the medium to long term (Sharma et al., 2018).

There is a need to focus on bringing efficiency in irrigating water guzzler crops like rice and sugarcane, especially in regions where their irrigation water productivity is low despite high land productivity. In case of paddy, the states can consider diversifying the existing rice based cropping pattern towards other less water consuming crops like maize with assured processing technology support and dairy farming and/or can invest in water saving technologies like precision irrigation or SRI (System of Rice Intensification) practices for improving water use efficiency. Considering low water requirement, SRI practice is particularly very useful during non-monsoon cultivation of paddy.

Although paddy is the crop of Kharif (monsoon) season and there is not much problem of water availability during this season, yet, due to more assured water supply through canal systems, farmers have shifted from traditional Rabi crops (wheat) to paddy/sugarcane cultivation during Rabi season for better monetary returns. This needs to be discouraged through policy interventions. In Haryana, cotton crop is also grown by farmers. As an option, farmers in Haryana may also consider increasing area under cotton crop by replacing water guzzling paddy crop and employing efficient water use practices, thereby considerably reducing groundwater pumpage.

Unlike rice, wheat crop responds favourably to optimal irrigation and cannot withstand excessive water application. However, if the water stress prevails during the crop's critical growth stage, it may result in negative impact on the crop yield. If water management technologies like sprinkler irrigation is implemented in the commands, there is further scope of conserving the available water resources and thereby sustainably improving the productivity as well as profitability.

Sugarcane is one of the most water intensive crops grown in the canal commands. Micro/ drip irrigation may be adopted by farmers to economize on water application and achieve higher productivity and water- and fertilizer-use efficiency. Drip tapes are especially useful for sugarcane as these are laid sub-surface causing no hindrance in agricultural activities even during using implements and their life is three years which coincides well with life of sugarcane.

As discussed in Chapter 4 and 5, as a consequence of large withdrawals of groundwater in the riparian states of Haryana and Uttar Pradesh, groundwater levels have receded all along the river stretch from downstream of Kalanaur to Baghpat, which in turn has affected the baseflow contributon to the flows in Yamuna in this stretch during the non-monsoon period. Between Hathnikund and Okhla barrage, maximum depletion ranging from 10 to 20 m is recorded in the Mawi-Baghpat reach.

There is an urgent need to regulate groundwater draft in Haryana and Western Uttar Pradesh. Adoption of measures discussed above would not only arrest the alarming decline of groundwater levels but would also sustain necessary baseflows to Yamuna river during the non-monsoon season in the long run.

7.2.3 Augmentation of non-monsoon inflows at Hathnikund barrage by creating storage of monsoon runoff in the upstream reaches

Non-monsoon inflows at Hathnikund barrage may be augmented by creating storage structures in the upstream reaches and conserve a portion of monsoon flows. In this regard, three multi-purpose storage projects — Lakhwar, Kishau and Renuka — in the Upper Yamuna Basin are already under consideration by Department of Water Resources, River Development and Ganga Rejuvenation.

These three projects are expected to augment the seasonal water availability in the downstream sections of the river. As per preliminary analysis by Uttarakhand Jal Vidyut Nigam Limited (UJVNL), Dehradun, it is estimated that the water availability corresponding to 90% dependability in the non-monsoon season from November to June will increase by approximately 168%. In this regard, a study at NIH Roorkee sponsored by UJVNL is under progress with the aim to assess the impact of different combinations of these three storage projects on the water availability at Hathnikund barrage in the monsoon period as well as the non-monsoon period.

It is envisaged that these storage structures shall provide the total benefits in terms of additional irrigation potential, water availability for various uses, and increased power generation capacity for the basin states.

7.2.4 Treatment of effluent coming through various drains meeting river Yamuna

The water quality of Yamuna River in Delhi stretch is very poor to sustain the river ecology, however, the deterioration in river water quality starts from Mawi. All the drains/streams meeting river Yamuna do not meet the criteria recommended by NGT vide its order dated 30.04.2019 w.r.t. application no. 1069/2018 in terms of pollutant load. NGT has recommended that treated sewage to be discharged in water bodies should have less than 10 mg/l BOD, however, the non-monsoon average BOD of the drains discharging in the river ranges from 19.6 mg/l to 262.2 mg/l. The high BOD in the drains indicates inadequate treatment of effluents being discharged in them. If the effluents joining river Yamuna through these drains are treated at source in line with NGT order, the river will become healthy to sustain biodiversity, else around 390 cumec flow will be required to be discharged from Wazirabad barrage, which is not a viable solution. Therefore, it is suggested to identify the industries/municipalities not treating the effluents to the desired levels and force them to treat the effluents before discharging in the drains meeting river Yamuna.

7.3 Concluding Remarks

To conserve the surface water and groundwater resources and improve the water availability in the WYC and EYC commands as well as sustain e-flows (both in terms of quantity and quality) in Yamuna river, a multi-dimensional approach is required that is based on different management possibilities and suitable technology as discussed in preceding sections.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Inferences Drawn from the Study

The work documented in this report, envisaging to assess environmental flows for Yamuna river from Hathnikund barrage to Okhla barrage, essentially comprises of the following:

- Description of the study reach between Hathnikund and Okhla barrage
- Methodology adopted for assessment of environmental flows
- Build-up of database (collection of data from various sources and generating data from field investigations) and data analysis
- Integrated hydrological and hydrodynamic modeling based on SWAT and HEC-RAS 1D
- E-flows for sustaining indicator aquatic species
- Management options to maintain recommended e-flows

Major activities undertaken during the course of the study, and, inferences drawn from (1) field investigations and data analyses, (2) ecology and habitat requirements of indicator fish species, (3) integrated hydrological and hydrodynamic modeling, are summarized below. Recommendations emerging from the analysis are provided in Section 8.2.

8.1.1 Field investigations and data analyses

The assessment of environmental flows for the study reach is based on integrated hydrodynamic and hydrological modelling approach using SWAT and HEC-RAS 1D. A variety of datasets are required as model inputs as well as to validate the model outputs, such as observed river flows, inflows and releases from barrages, river cross sections, DEM, observed rainfall and temperature, land use land cover maps, soil maps etc. Besides the river water quality, the study also investigates the variation in groundwater levels over a period of more than four decades. All such necessary data were collected from respective agencies. In addition, exhaustive field surveys were carried out for the following:

- Identification of the indicator fish species and assessment of their habitat requirement based investigations in the river, and
- river cross-section surveys for total 306 lines at closely spaced intervals; the river cross-sections were taken at every 1 km for the whole reach, and for 14 selected stretches (at gauging sites or at confluence of canal/ drains/ natural streams and main river) 5 cross-sections were taken at every 250 m.

All the data were processed to analyse the river flows and water quality in different reaches.

Analysis of monthly flows has shown that in general, for most segments in the study reach, the discharge observed at downstream site is more than the discharge at upstream site barring a few months, which reveals that certain amount of flow is getting added into the river from intermediate catchment, from drains, and irrigation return flow etc. However, for the Baghpat-DRB segment, the site at DRB is located downstream of Wazirabad barrage and the flow at this gauging site is largely influenced by the controlled releases from Wazirabad barrage and water contributed by various drains joining Yamuna between the barrage and DRB.

In view of large withdrawals of groundwater in the riparian states of Haryana and Uttar Pradesh, groundwater levels have receded all along the river stretch from downstream of Kalanaur upto Baghpat. The analysis of depth to groundwater levels for pre-monsoon and post-monsoon periods over a period of four decades from 1975 to 2018 has revealed maximum depletion ranging from 10 to 20 m in the Mawi-Baghpat reach.

Receding groundwater levels have in turn affected the baseflow contribution to the flows in Yamuna. Hydrograph analyses based on digital filtering method have shown that maximum depletion in baseflows is in the reach between Mawi and Baghpat during the months of April and May. Base flow index (BFI) is an important baseflow characteristic and indicates the contribution of baseflow to the river flow. For the study reach, the ratio of baseflow to total river flow is found to be higher in the non-monsoon season than in the monsoon season, thus resulting in a higher BFI for non-monsoon season. This pattern is representative of other gauges in the study reach and shows the importance of baseflows in sustaining river flows during non-monsoon period. A decreasing trend in BFI for all the seasons was found for Baghpat, and for non-monsoon season for Mawi. Decreases in BFI are linked to prolonged over-abstraction of groundwater, which is evident from declining groundwater levels in the Mawi-Baghpat reach.

Water quality analysis have shown that between the Wazirabad and Okhla barrage, the river receives approximately 6140 kg/hr BOD load out of which around 70% load is contributed through Nazafgarh drain. The average non-monsoonal DO value in the river stretch is 1.1±0.14 mg/l as O_2. However, during the field survey by NIH team, the DO value in this stretch was non-detectable indicating the BOD load to the river higher than the assimilative capacity of the river. Thus, Delhi is the most critical stretch of Yamuna, however, the contamination starts from Paonta Sahib as is evident from the nutrients concentration in the river. In terms of organic contamination, the stretch downstream of Mawi is contaminated and needs immediate attention. The DO values also indicate the same. Although, the water quality upto Wazirabad barrage is good for fish proliferation, the reduction in DO values is a cause for concern.

8.1.2 Fish diversity in study reach and habitat requirement of indicator fish species

Two rapid field surveys were conducted in the study reach of river Yamuna for identification of indicator fish species and for determining the e-flow requirement for maintaining ecological integrity and sustaining fisheries resources of river Yamuna. During the survey, 40 species of fishes were recorded in the river sector from Hathnikund to above the Delhi segment. The Golden Mahseer (*Tor putitora*), the most charismatic and conservation significant species, was not recorded in Yamuna river below Hathnikund barrage. Historically, this species was reported to be present in the downstream reaches of river Yamuna. It is a well known fact that depletion of Golden Mahseer in downstream reaches of river Yamuna is mainly attributed to modifications in the river habitat (changes in substrate composition), volume of water, over fishing and pollution.

The presence of good population of reophilic species such as *Bangana dero* and *Raiamas bola* between Hathnikund and Panipat indicates that the habitat condition and quality of water is still conducive for such species. The condition of Yamuna river below Panipat deteriorates further because of large-scale modifications in river bed and increasing pollutant loads. As a result, it exhibits more abundance of non-native invasive and pollution tolerant species such as *Cyprinus carpio* and *Tilapia nilotica*, which constitute over 90% of fish catch in this stretch.

Field surveys have revealed three major fish habitat types such as pools, riffles and runs at the sampling sites in Yamuna river. Based on the present surveys and historical information, two options exist for estimation of e-flow.

- Option 1: For restoring the river habitat to historical condition, the conservation significant species Golden Mahseer may be selected as indicator species, although this species is not available downstream of Hathnikund barrage. The adult Golden Mahseer prefers depth > 1 m and velocity > 0.1 m/sec at pool habitat.

- Option 2: Based on the current fish community assemblage, the river sector between Hathnikund and Panipat has good population of reophilic species such as *Bangana (Labeo) dero* and *Raiamas bola*. These two reophilic species live in riffle/run habitat with moderately flowing channel unit.

The option of considering Golden Mahseer has not been explored further in the study since assessment of e-flow based on its habitat requirement will provide more suitable habitat in terms of volume, but does not guarantee in bringing back the river habitat features such as substrate heterogeneity suitable for Golden Mahseer.

The identified indicator species, *Bangana dero* and *Raiamas bola* are thriving well in run habitat of channel with depth ranging from 60 to 90 cm and velocity in the range of 0.1 m/s. The habitat suitability curves of these two species have been generated based on data recorded during field visits. It has been observed that wherever these species are present, the other economically important species, and, other small barbs and minnows also thrive well. *Hence, ensuring minimum water depth of 60 cm and flow of 0.1 m/s at riffle/run habitat in the river will safeguard the fish diversity in Yamuna river.*

8.1.3 Integrated modeling and development of e-flow regime

The integrated hydrologic and hydrodynamic modeling approach has been adopted to assess e-flows between Hathnikund barrage and Okhla barrage and compute the releases required from Hathnikund barrage for maintaining these e-flows. The hydrological model SWAT has been used to simulate streamflow (discharge), overland flow, groundwater recharge, evapotranspiration and total water yield in the study reach of Yamuna. For the hydrodynamic analysis of streamflows in Yamuna river, the HEC-RAS 1D model has been employed and the hydrodynamic variables such as maximum water depth, hydraulic depth, wetted perimeter, top width and water velocity for the range of discharges as available at Hathnikund barrage have been computed at different sections of the river.

Simulations using the calibrated SWAT model for unregulated and regulated flows show that significant amount of flow is available even during non-monsoon season for unregulated flow conditions (i.e. virgin flows) compared to the regulated conditions. The simulated discharge scenarios from SWAT, generated at different locations between Hathnikund and Okhla barrage, are found helpful in the assessment of flow availability during both non-monsoon and monsoon seasons

For converting the habitat suitability depth values into the flow values, depth versus discharge curves have been developed covering the whole hydrologic regime using HEC-RAS 1D simulations. Using the developed depth vs discharge curves for different sites, the minimum desirable flow values required for maintaining suitable physical habitat in terms of desirable flow depth of 60 cm, and, for inundating the floodplains at 13 identified locations, have been estimated. Further, the flows required to be released from Hathnikund barrage for maintaining the minimum desirable amount of flows at different sites during different seasons have been estimated using the flow series simulated by the calibrated hydrologic model SWAT. The release required from Hathnikund barrage during a specific month is computed by taking the maximum of the releases estimated from Hathnikund barrage for meeting the minimum depth requirement of 0.60 m at 13 identified locations corresponding to the specific month.

For carrying out various functions, the aquatic ecosystem needs natural flow variability, within the year, for its sustenance. Incorporation of natural variability of flows has been implemented by taking minimum depth (60 cm) for the month of May (this being the driest month at all the G&D sites downstream of Hathnikund barrage) and modifying the releases as per the existing natural variability observed in long-term historical data, with the condition that these computed values for different months are not less than the releases required for maintaining 60 cm at all the 13 identified locations.

8.2 Recommendations

8.2.1 Suggested e-flow regime

The final recommended releases from Hathnikund barrage for maintaining required habitat conditions between Hathnikund and Okhla barrage during the different months of a year are given in Table 8.1 and also illustrated in Fig. 8.1.

The recommended releases from Hathnikund barrage are approximately 30% of the inflows at Hathnikund barrage which is comparable to the e-flow recommendations in the MOWR, RD & GR Notification dated 9th Oct 2018 for Upper Ganga basin upto Haridwar that suggests 20%, 25% and 30% of inflows as environmental flows during lean season, non-monsoon & non-lean season, and monsoon season, respectively.

As evident from Fig. 8.1, the recommended minimum releases for non-monsoon season are slightly higher than the current average monthly releases from Hathnikund barrage, however, for the monsoon months of July and August, the current average monthly releases are much higher than the recommended releases. Since during the monsoon months of July and August, inflows at Hathnikund are significantly higher than the diversion capacity of

Table 8.1 Final recommended releases required from Hathnikund barrage for maintaining suitable habitat at all downstream locations between Hathnikund and Okhla barrage

Month	Median of monthly inflows at Hathnikund barrage (cumec)	Average monthly releases from Hathnikund barrage (cumec)	Recommended minimum releases from Hathnikund barrage incorporating natural variability (cumec)	Flow regime obtained after implementing recommended minimum releases (cumec)	For inundating floodplains (cumec) *- once a month*
Jan	76	10	23	23	
Feb	78	10	23	23	
Mar	86	10	26	26	
Apr	95	10	29	29	
May	112	10	34	34	
Jun	148	18	44	44	
Jul	525	275	158	275	1400
Aug	780	298	220	298	1600
Sep	493	160	149	160	
Oct	145	30	44	44	
Nov	90	10	27	27	
Dec	81	10	24	24	

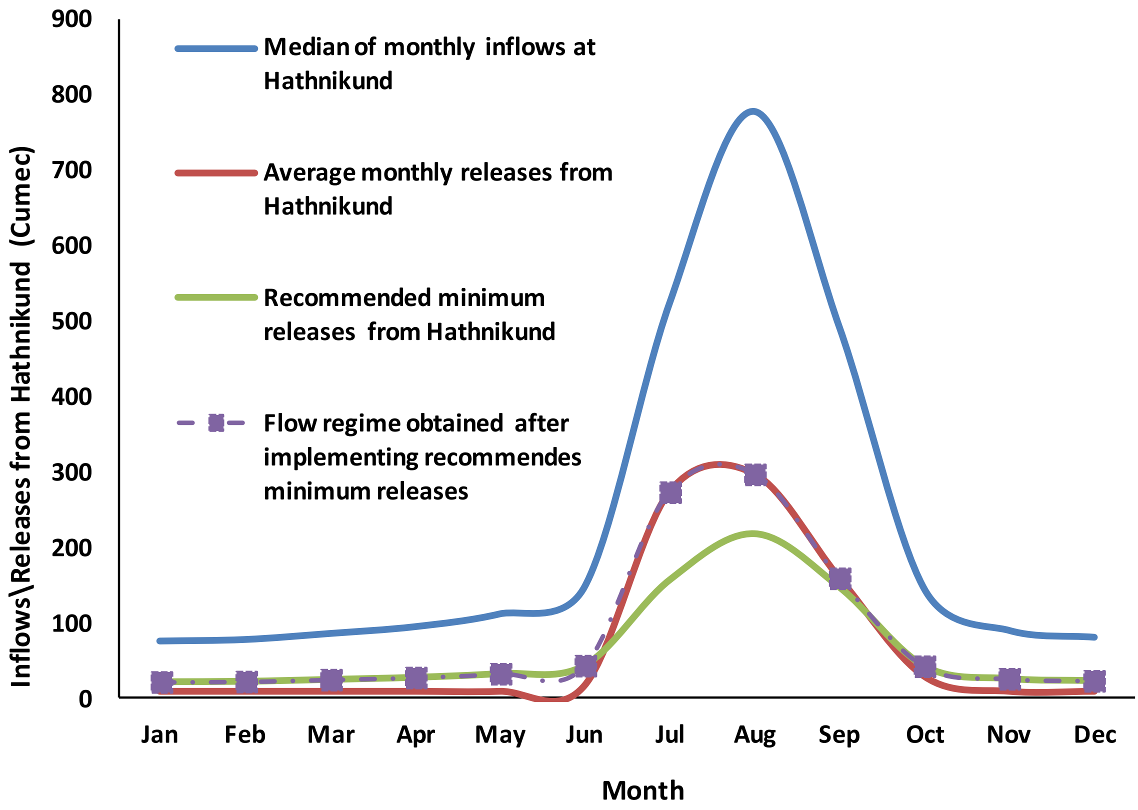


Fig. 8.1 Recommended releases from Hathnikund Barrage for sustaining downstream ecosystem upto Okhla barrage

barrage, the flow regime during these monsoon months will be the same as the current releases. Therefore, after implementation of recommended minimum releases from Hathnikund barrage, the flow regime downstream of Hathnikund barrage will comprise of recommended minimum releases during non-monsoon season and current releases during monsoon season.

It may be noted here that this analysis is based on water requirement of indicator fish species, however, the biodiversity, livelihood and spiritual groups can link their requirements to specific features of the river channel at the study sites.

Table 8.2 provides the expected flows at Wazirabad barrage for recommended values of flows released from Hathnikund barrage in a year with average rain for the present scenario after meeting out all the current demands of water, upstream of Wazirabad barrage.

Table 8.2 Expected flows at Wazirabad barrage for recommended values of flows released from Hathnikund barrage

MONTH	Recommended releases from Hathnikund barrage (cumec)	Expected flows at Wazirabad barrage under average conditions (cumec)
Oct	44	64
Nov	27	40
Dec	24	33
Jan	23	34
Feb	23	27
Mar	26	19
Apr	29	12
May	34	9
Jun	44	28

8.2.2 Management options to maintain recommended e-flows

In the present scenario, approximately 47.5% and 9.8% of inflows at Hathnikund barrage are diverted to WYC and EYC commands, respectively, during monsoon season, while 78.5% and 13.0% of inflows at Hathnikund barrage are diverted to WYC and EYC commands, respectively, during non-monsoon season. Thus, only 42.7% and a meagre 8.5% of inflows at Hathnikund barrage are released into the river during monsoon and non-monsoon seasons, respectively. The releases during non-monsoon season are significantly low and do not meet the e-flow requirement in the downstream reaches of Yamuna river. Possible management strategies for maintaining e-flows are recommended below.

- Reduction in diversions to WYC/EYC by increasing the irrigation efficiency in WYC and EYC commands, keeping in view the crop water requirement
- Regulate groundwater withdrawal in the basin especially in the Mawi-Baghpat stretch and augment groundwater recharge in order to sustain baseflows
- Augmentation of non-monsoon inflows at Hathnikund barrage by creating storage of monsoon runoff in the upstream reaches
- Treatment of effluent coming through various drains meeting river Yamuna

It is observed that all the drains/streams meeting river Yamuna do not meet the criteria recommended by NGT vide its order dated 30.04.2019 w.r.t. application no. 1069/2018 in terms of pollutant load. NGT has recommended that treated sewage to be discharged in water bodies should have less than 10 mg/l BOD, however, the non-monsoon average BOD of the drains discharging in the river ranges from 19.6 mg/l to 262.2 mg/l. The high BOD in the drains indicates inadequate treatment of effluents being discharged in them. If the effluents joining river Yamuna through these drains are treated at source in line with NGT order, the river will become healthy to sustain biodiversity, else around 390 cumec flow will be required to be discharged from Wazirabad barrage, which is not a viable solution as such quantum of flows were not available during non-monsoon season even in pristine conditions.

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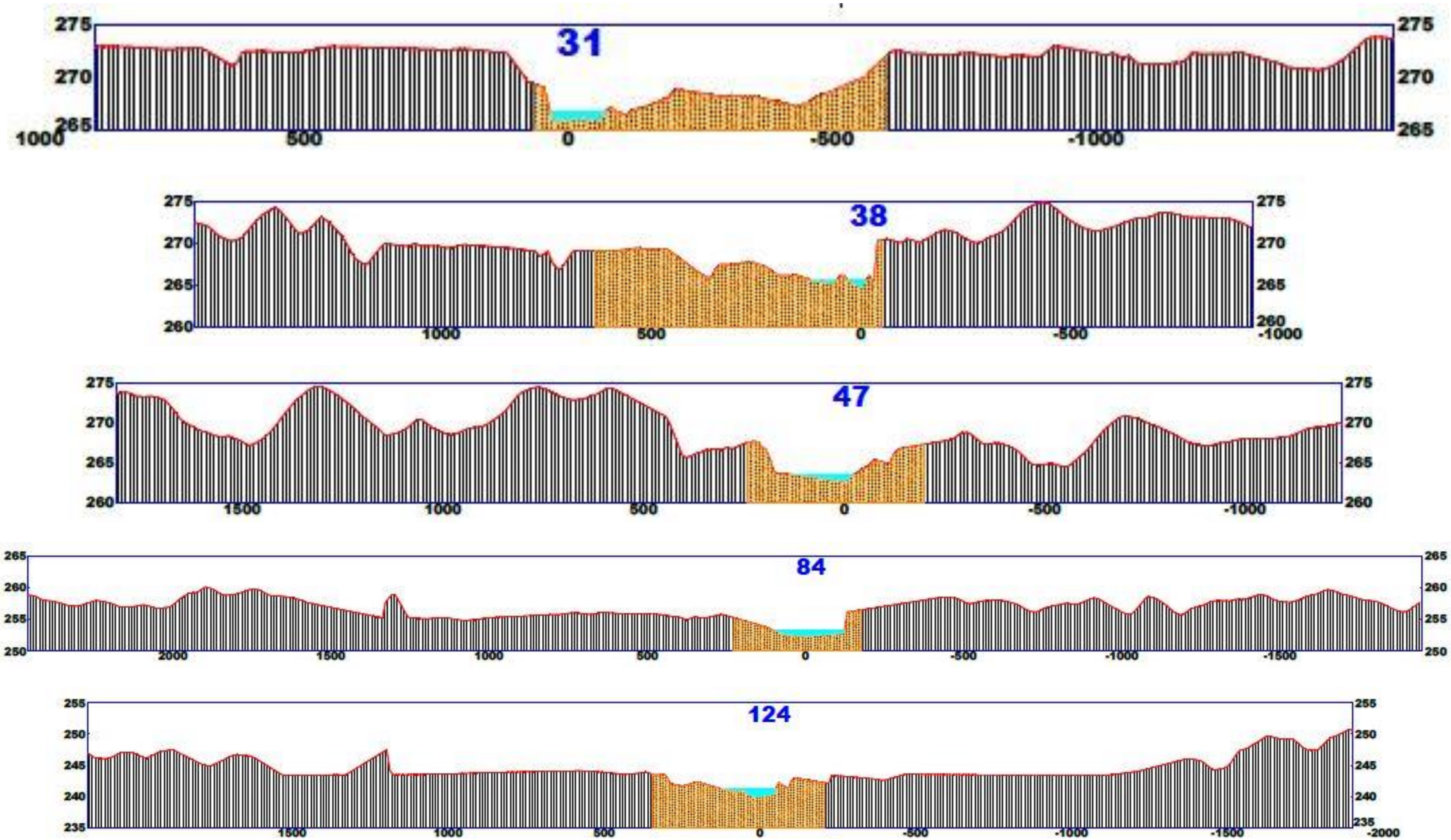
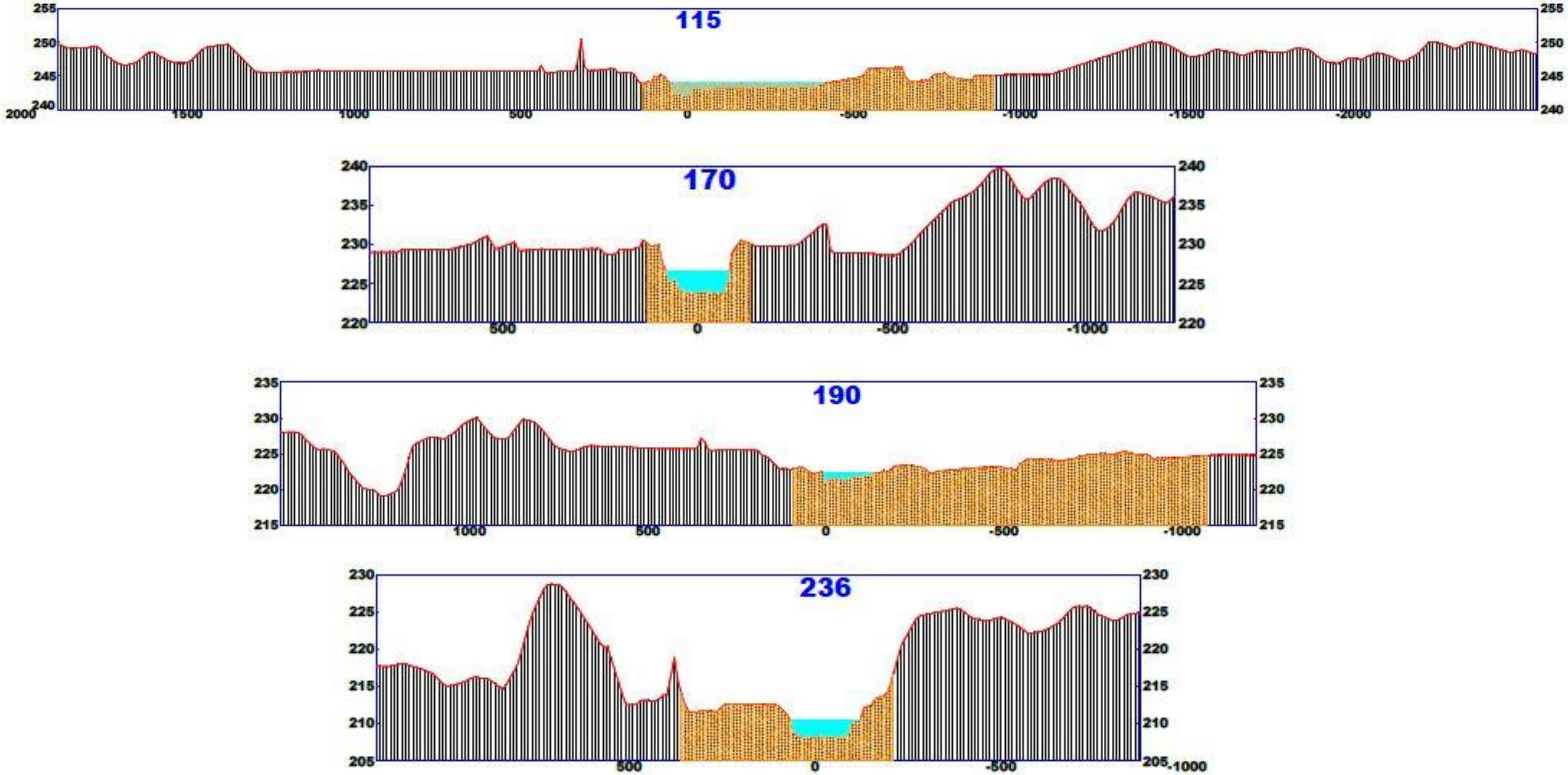
Annexure 1

River cross-sections along Yamuna river

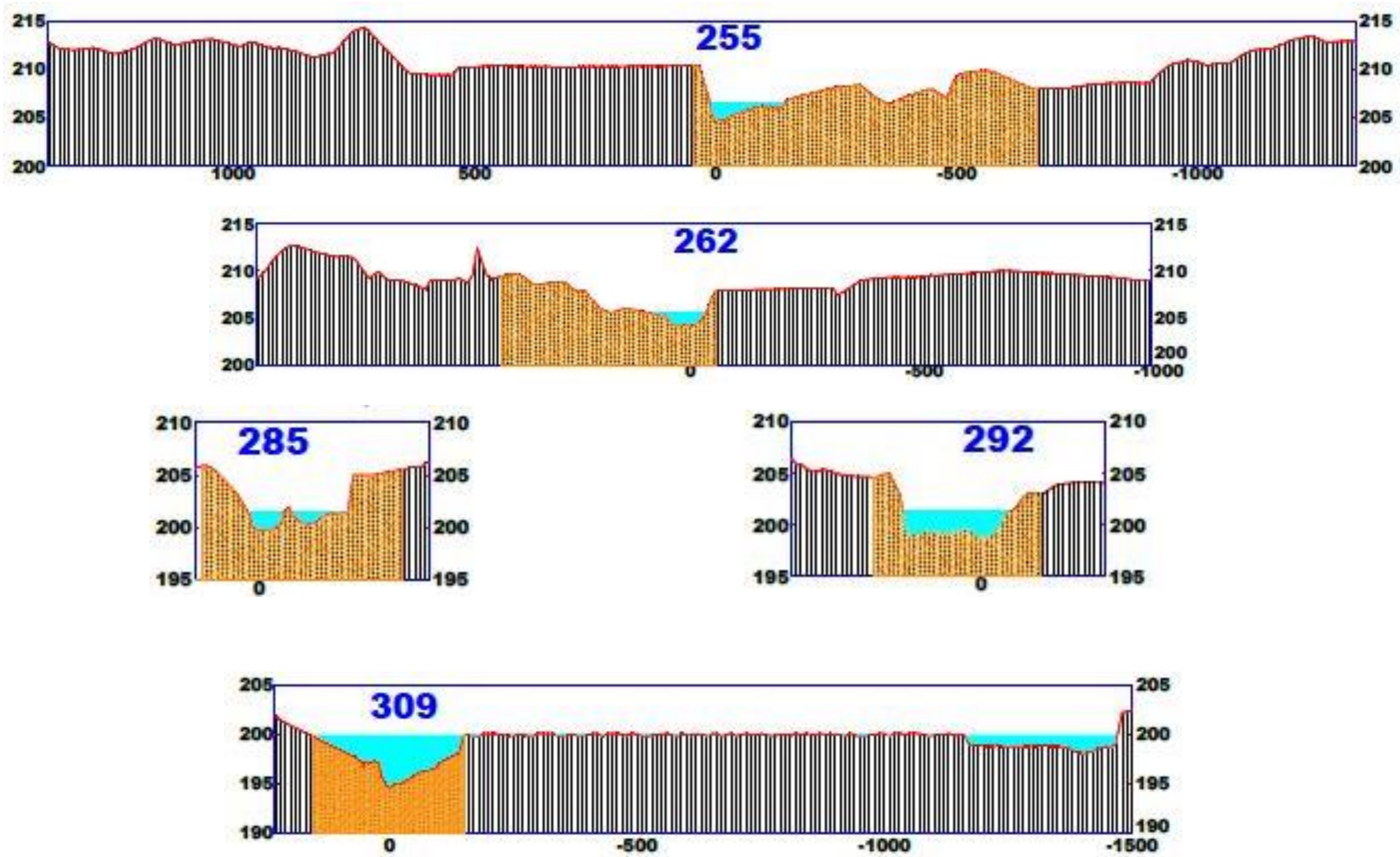
ANNEXURE 1



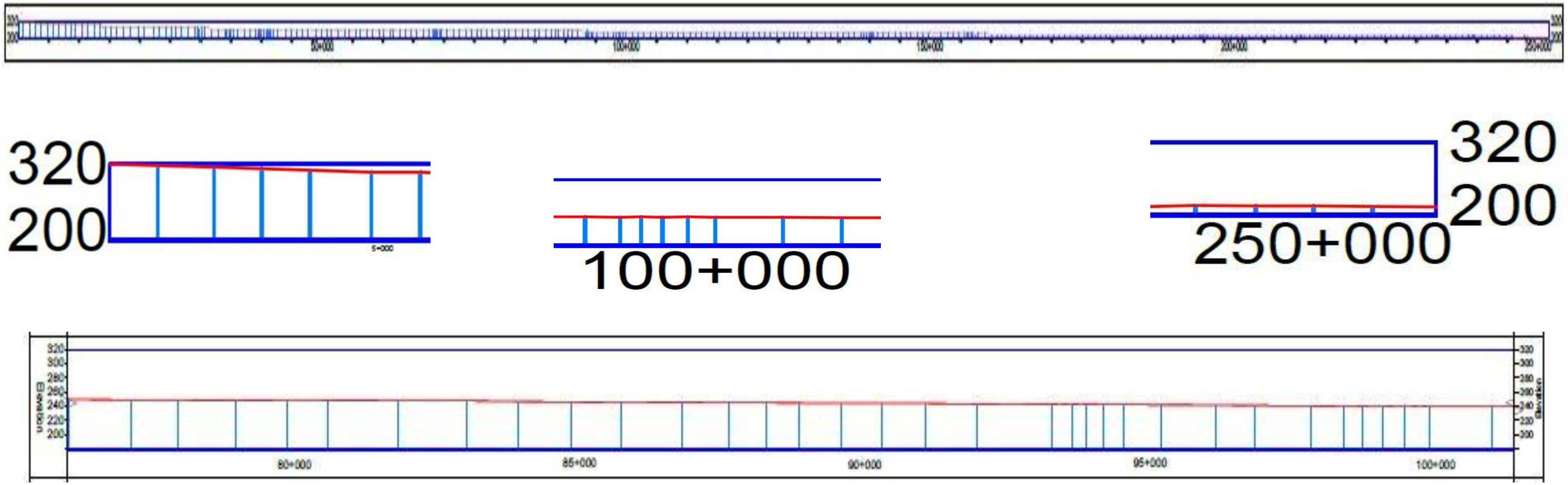
Few surveyed river cross-sections along Yamuna river



Few surveyed river cross-sections along Yamuna river



Few surveyed river cross-sections along Yamuna river



Longitudinal profile and selected sections

Annexure 2

Hathnikund Releases vs Simulated Discharge at Selected Sites for Different Months

ANNEXURE 2

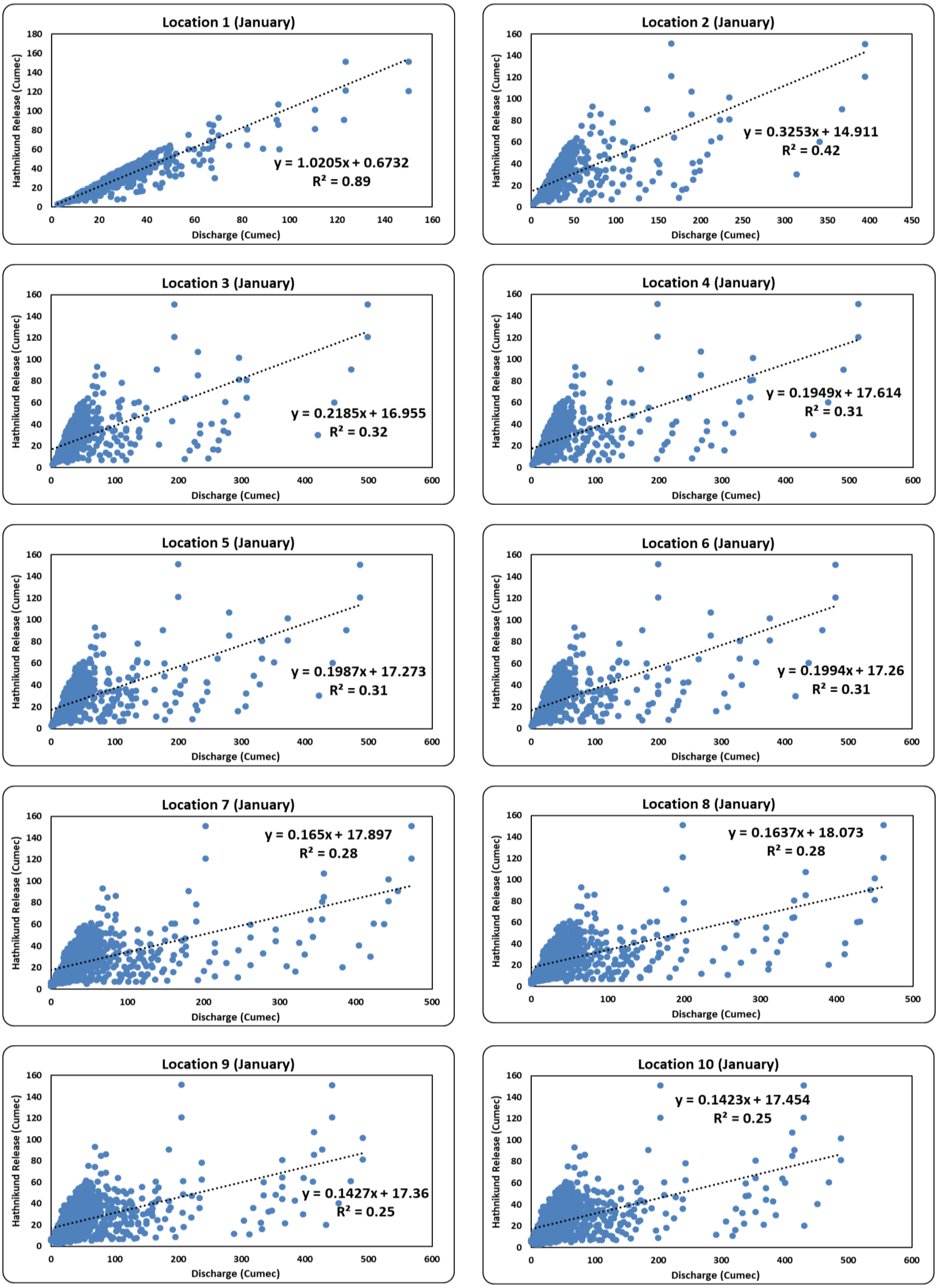
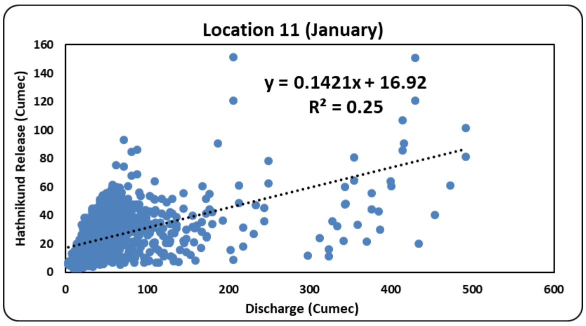
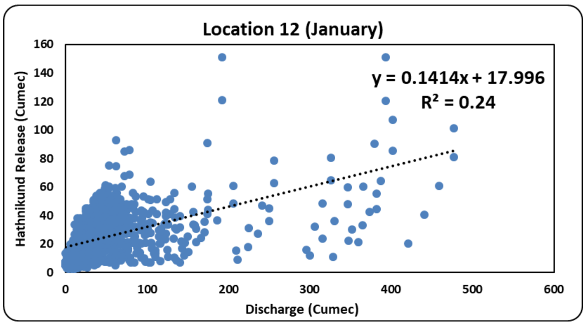


Fig. A2.1 Hathnikund releases vs simulated discharge on selected sites for month of January (contd...)





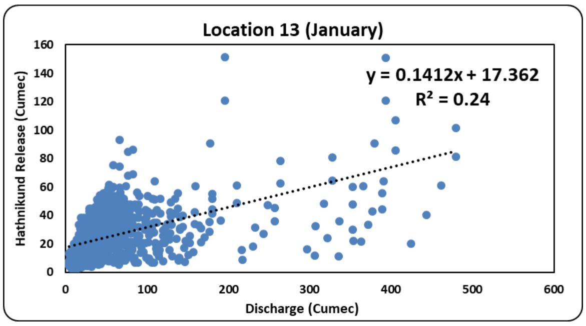


Fig. A2.1 Hathnikund releases vs simulated discharge on selected sites for month of January

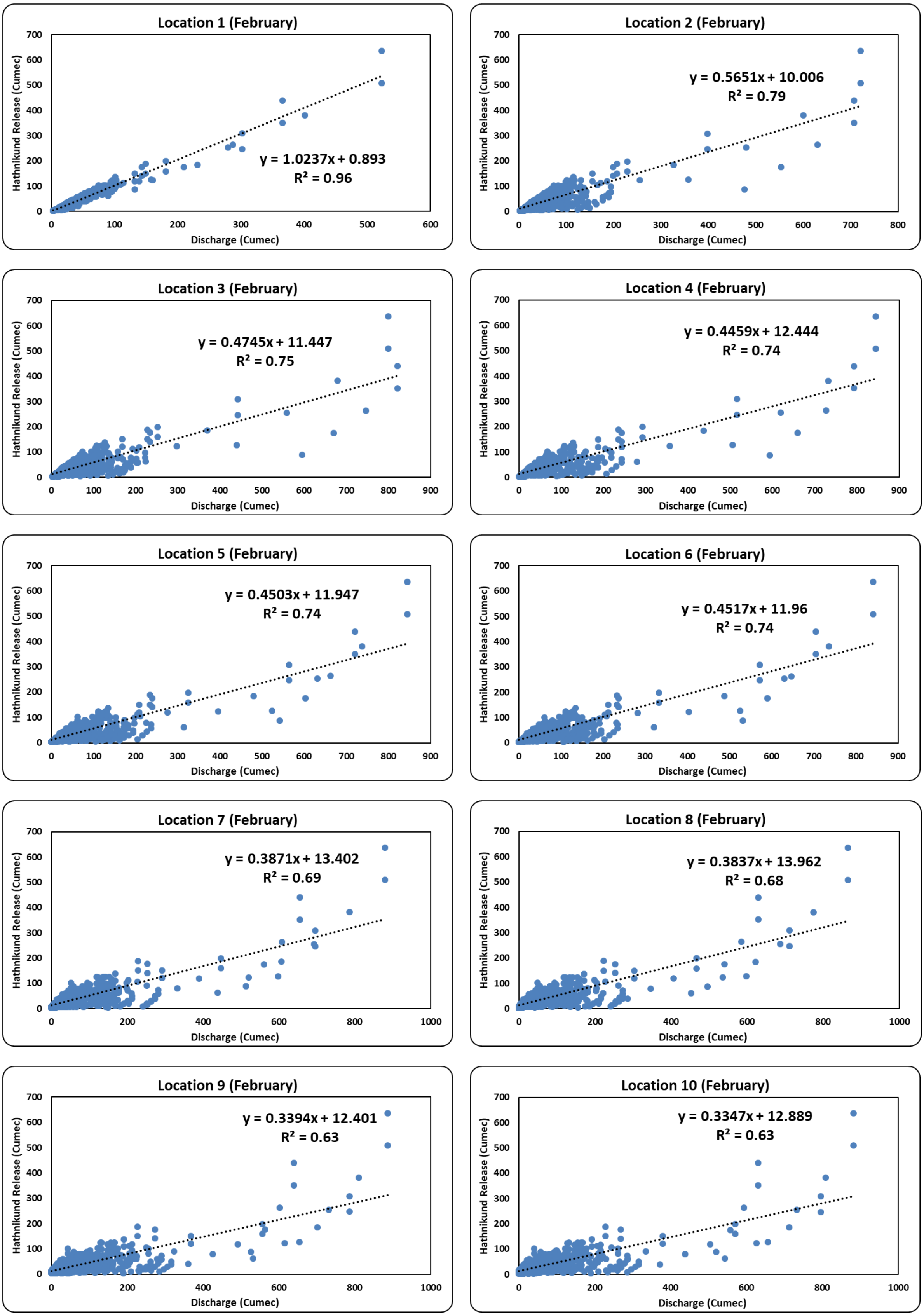
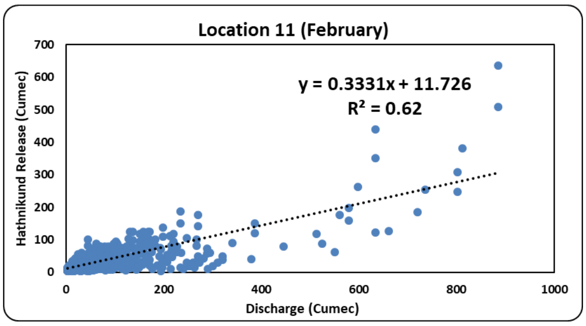
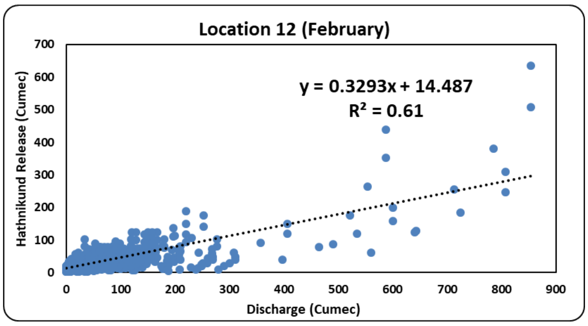


Fig. A2.2 Hathnikund release vs simulated discharge on selected sites for month of February (contd...)





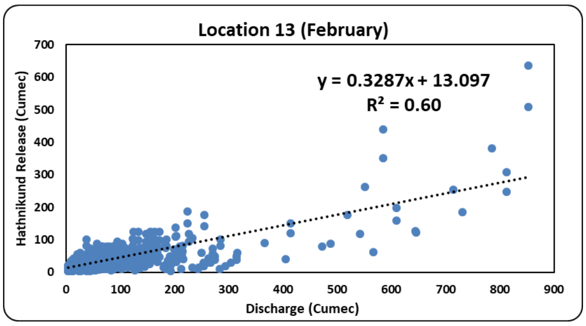


Fig. A2.2 Hathnikund release vs simulated discharge on selected sites for month of February

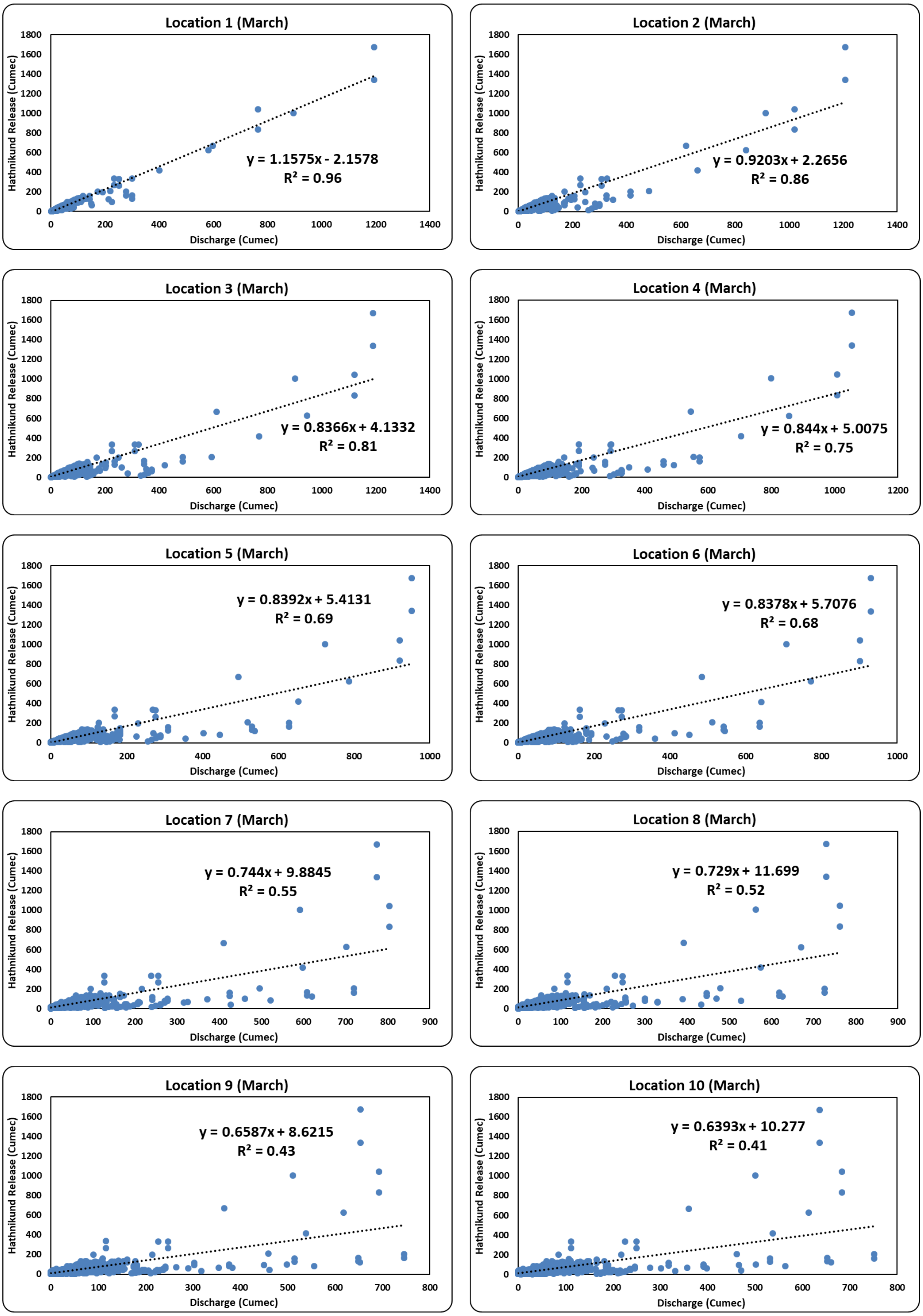


Fig. A2.3 Hathnikund release vs simulated discharge on selected sites for month of March (contd...)

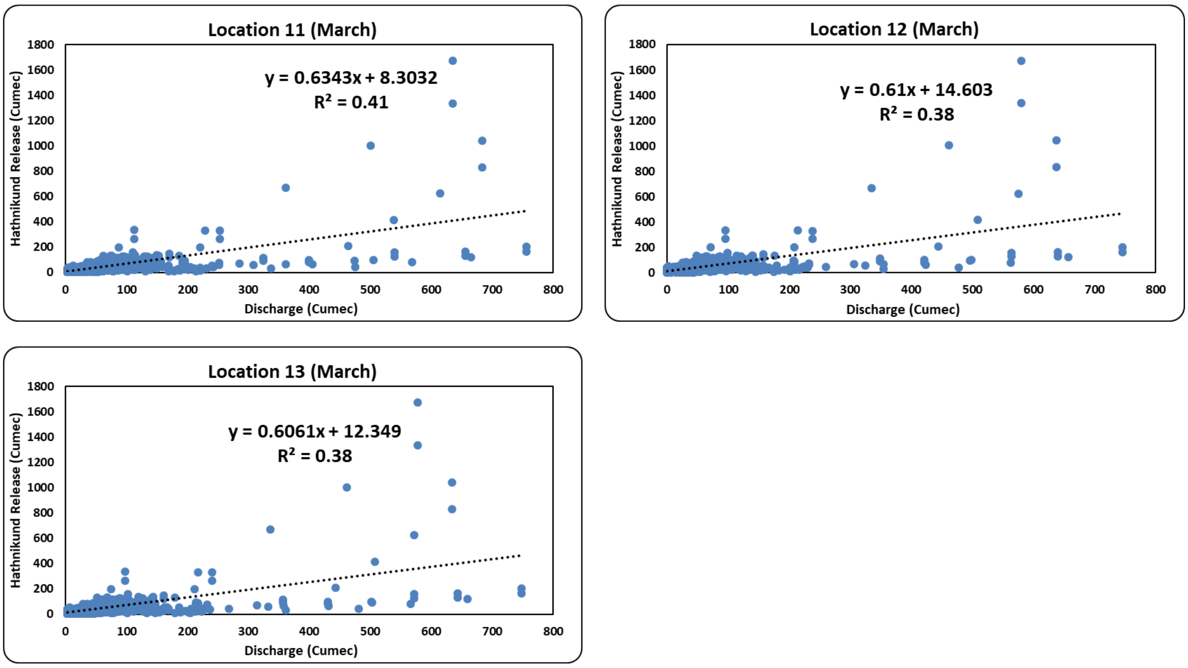


Fig. A2.3 Hathnikund release vs simulated discharge on selected sites for month of March

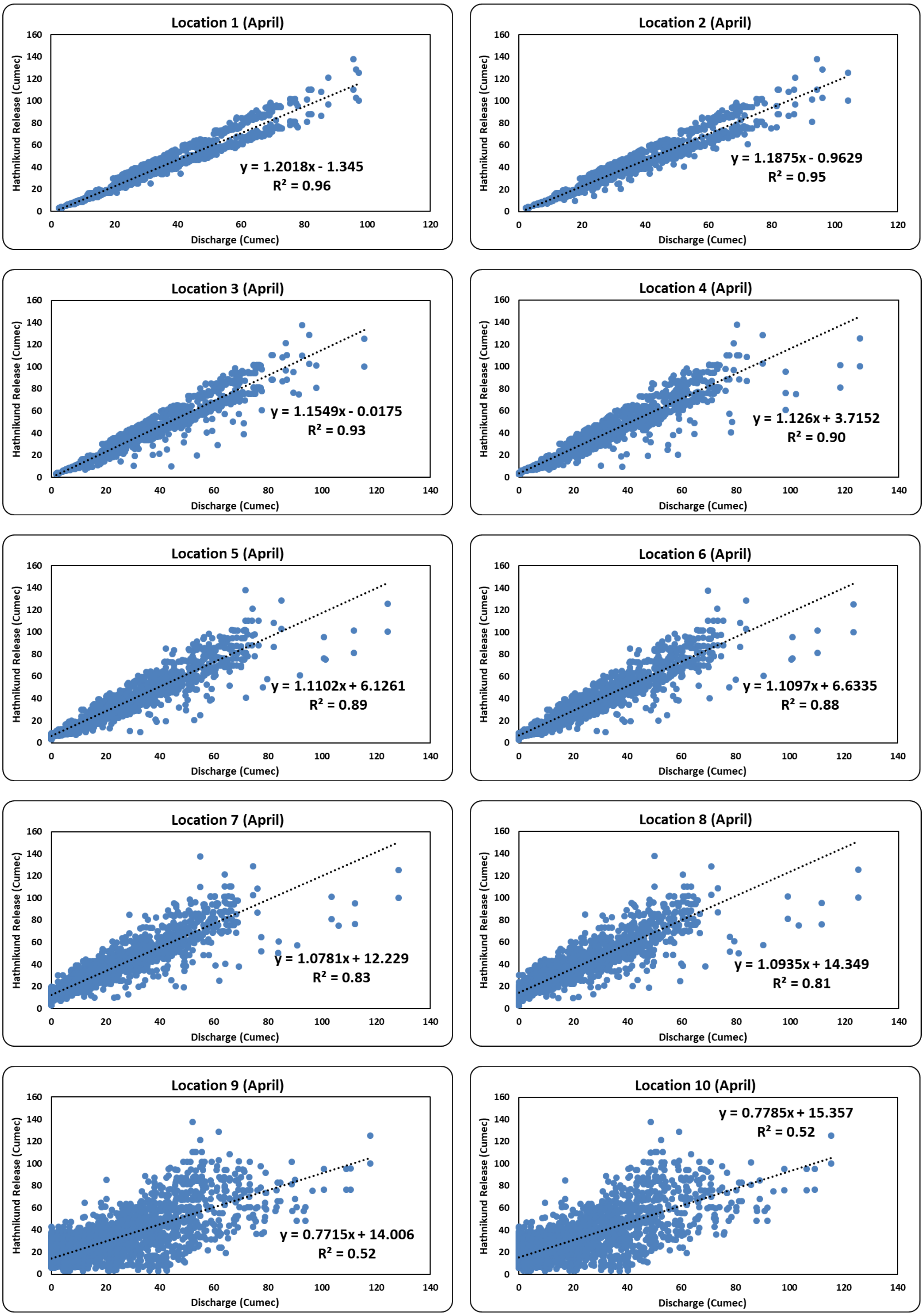


Fig. A2.4 Hathnikund release vs simulated discharge on selected sites for month of April (contd...)

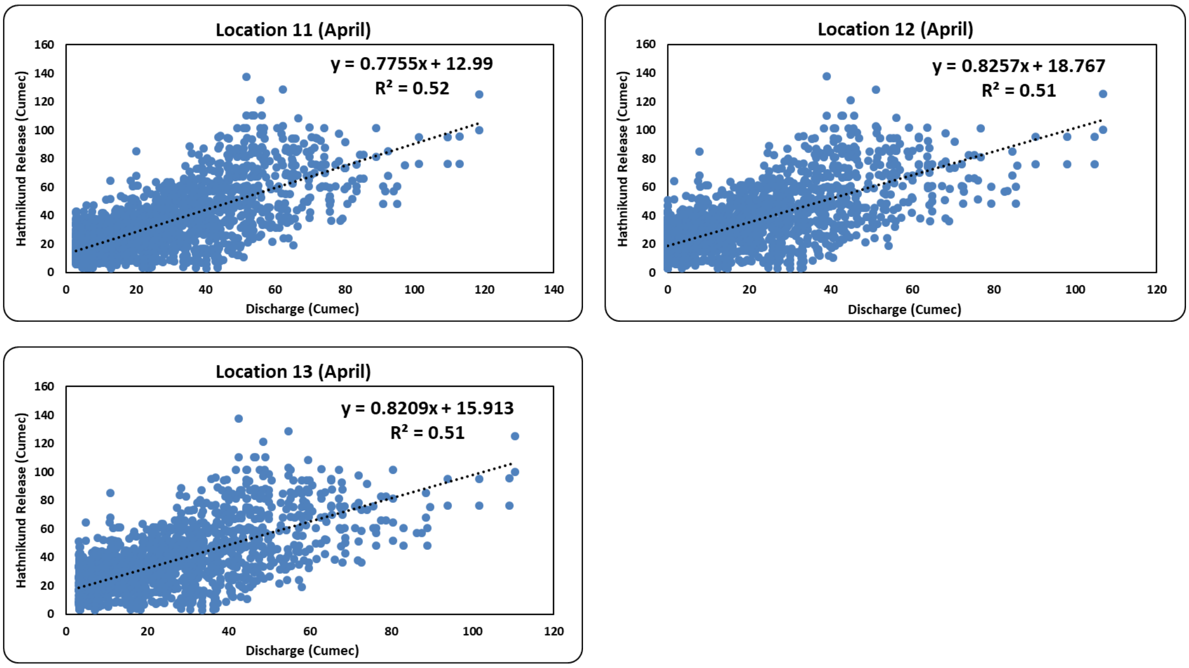


Fig. A2.4 Hathnikund release vs simulated discharge on selected sites for month of April

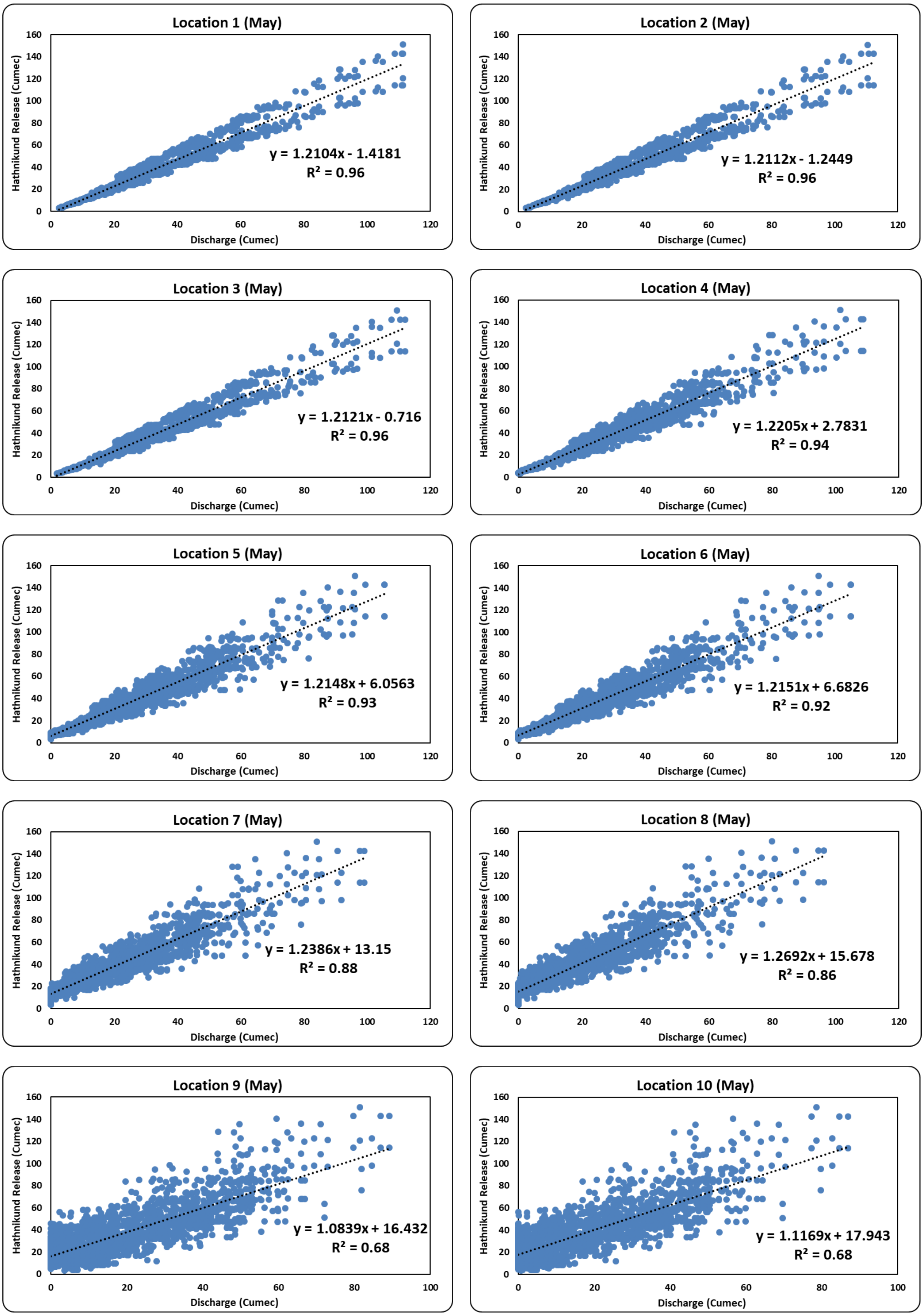


Fig. A2.5 Hathnikund release vs simulated discharge on selected sites for month of May (contd...)

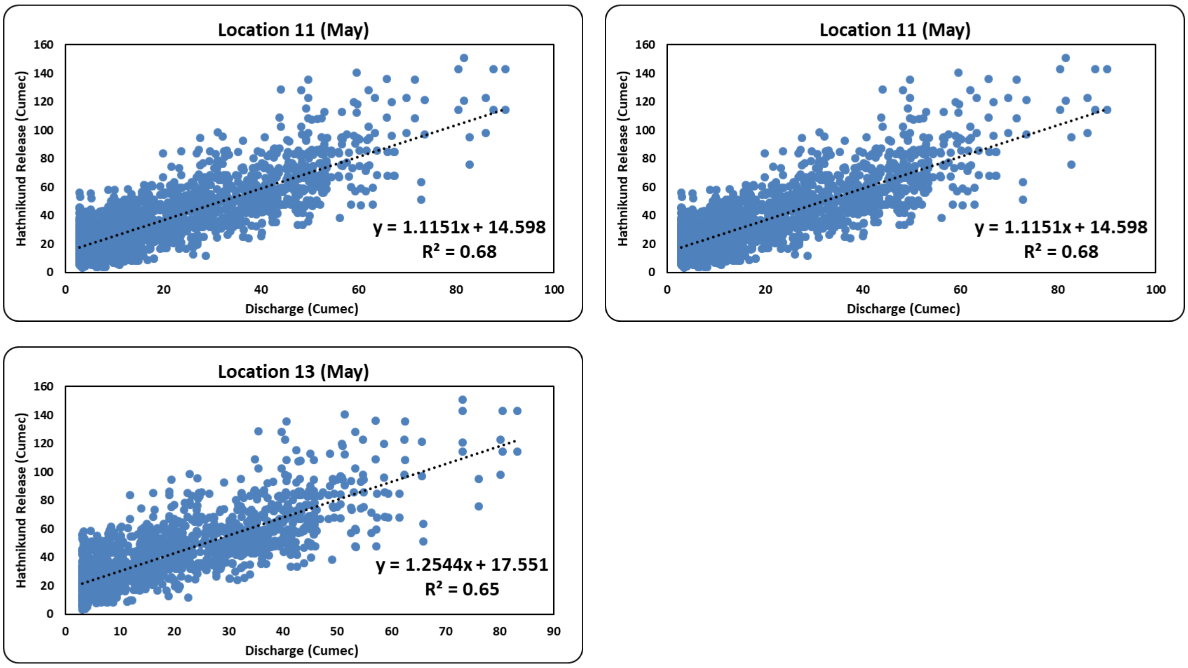


Fig. A2.5 Hathnikund release vs simulated discharge on selected sites for month of May

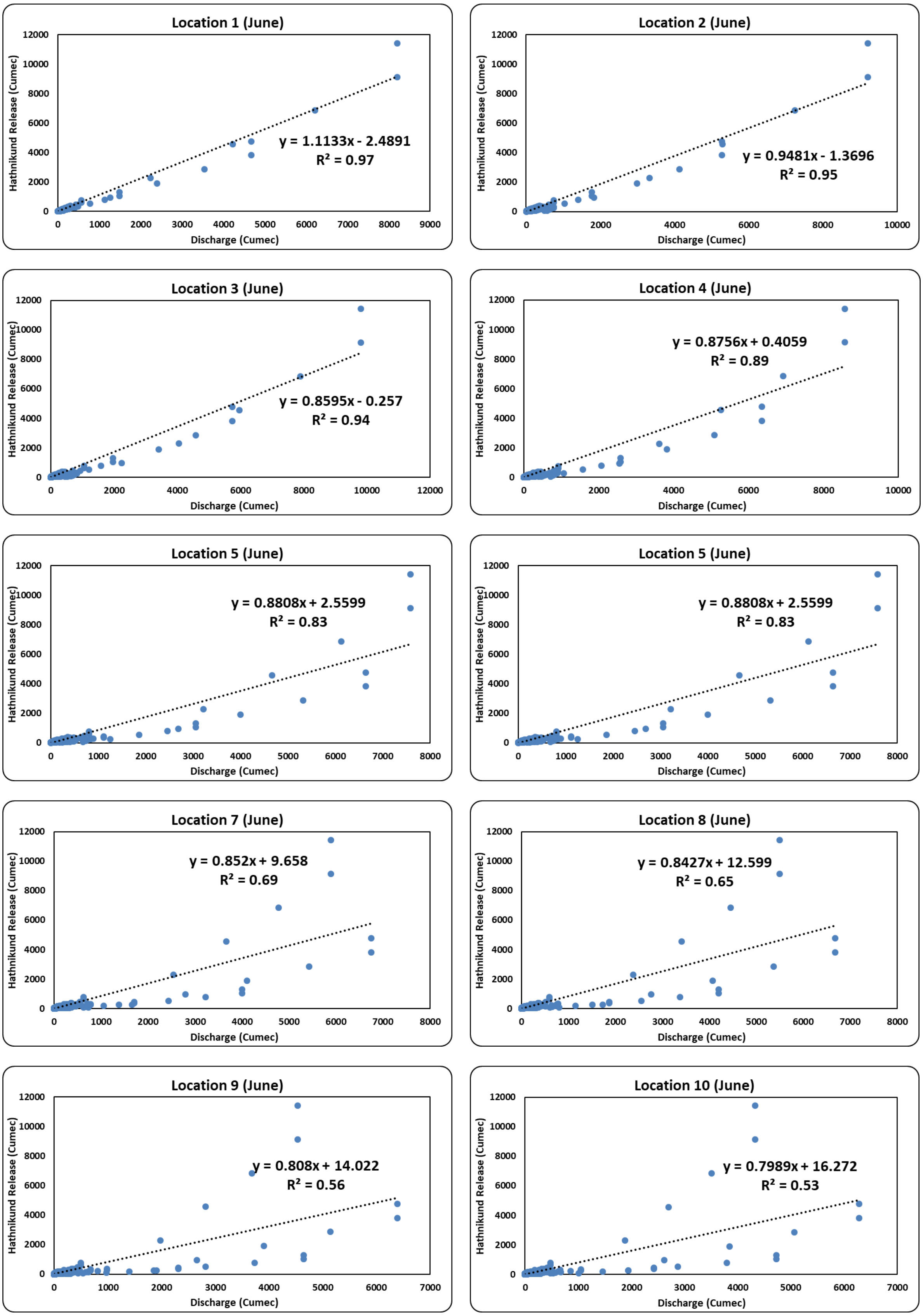


Fig. A2.6 Hathnikund release vs simulated discharge on selected sites for month of June (contd...)

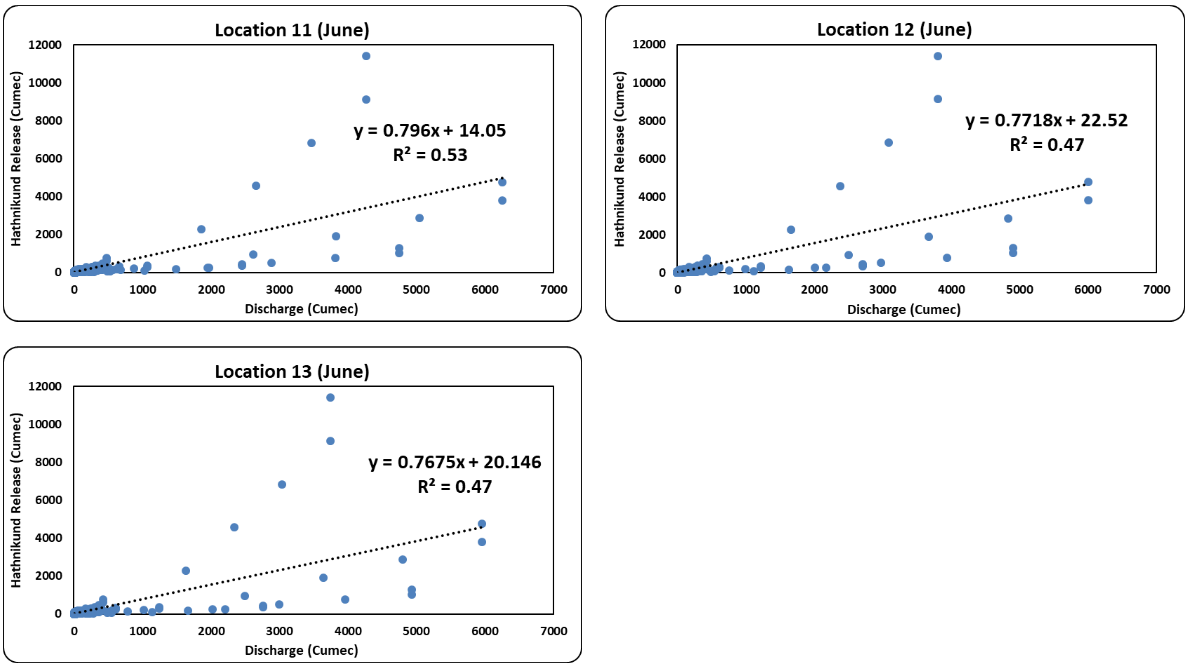


Fig. A2.6 Hathnikund release vs simulated discharge on selected sites for month of June

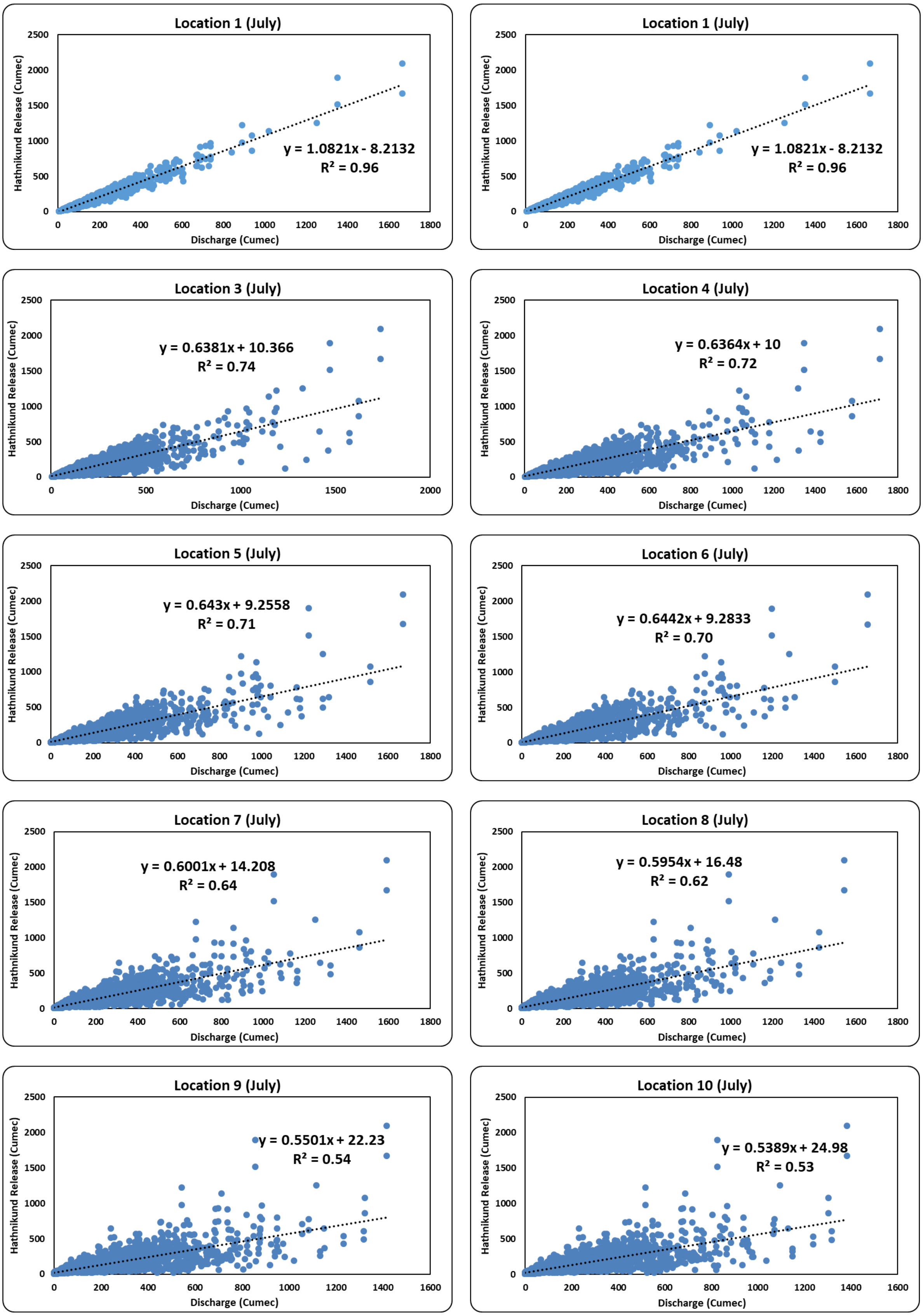


Fig. A2.7 Hathnikund release vs simulated discharge on selected sites for month of July (contd...)

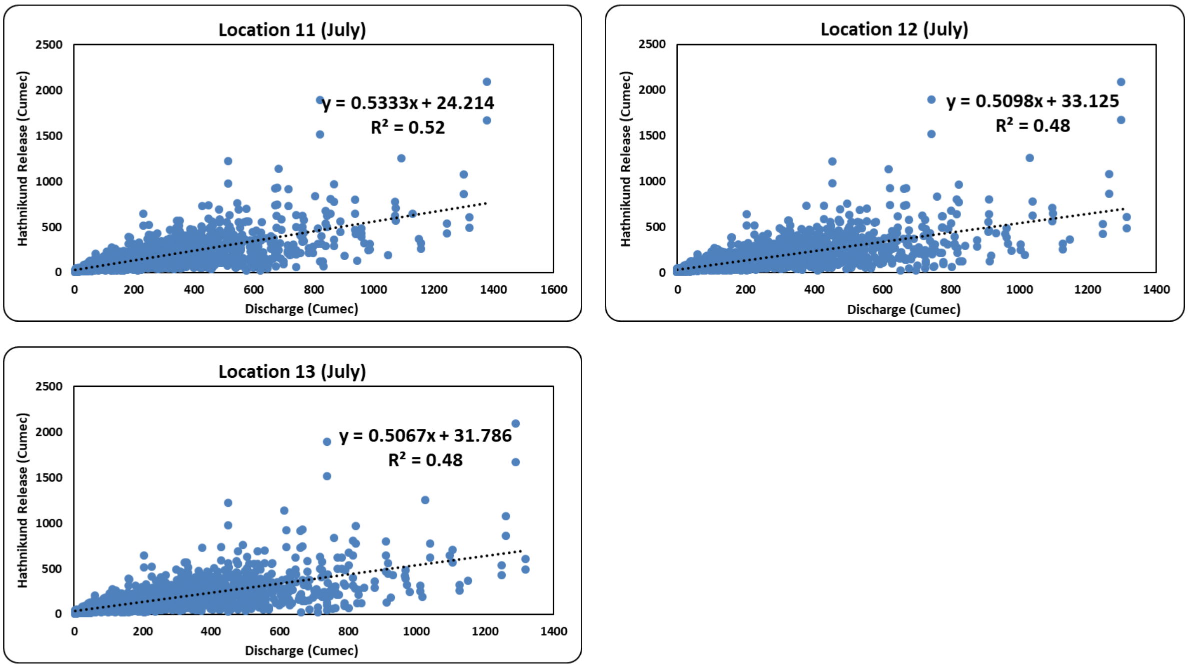


Fig. A2.7 Hathnikund release vs simulated discharge on selected sites for month of July

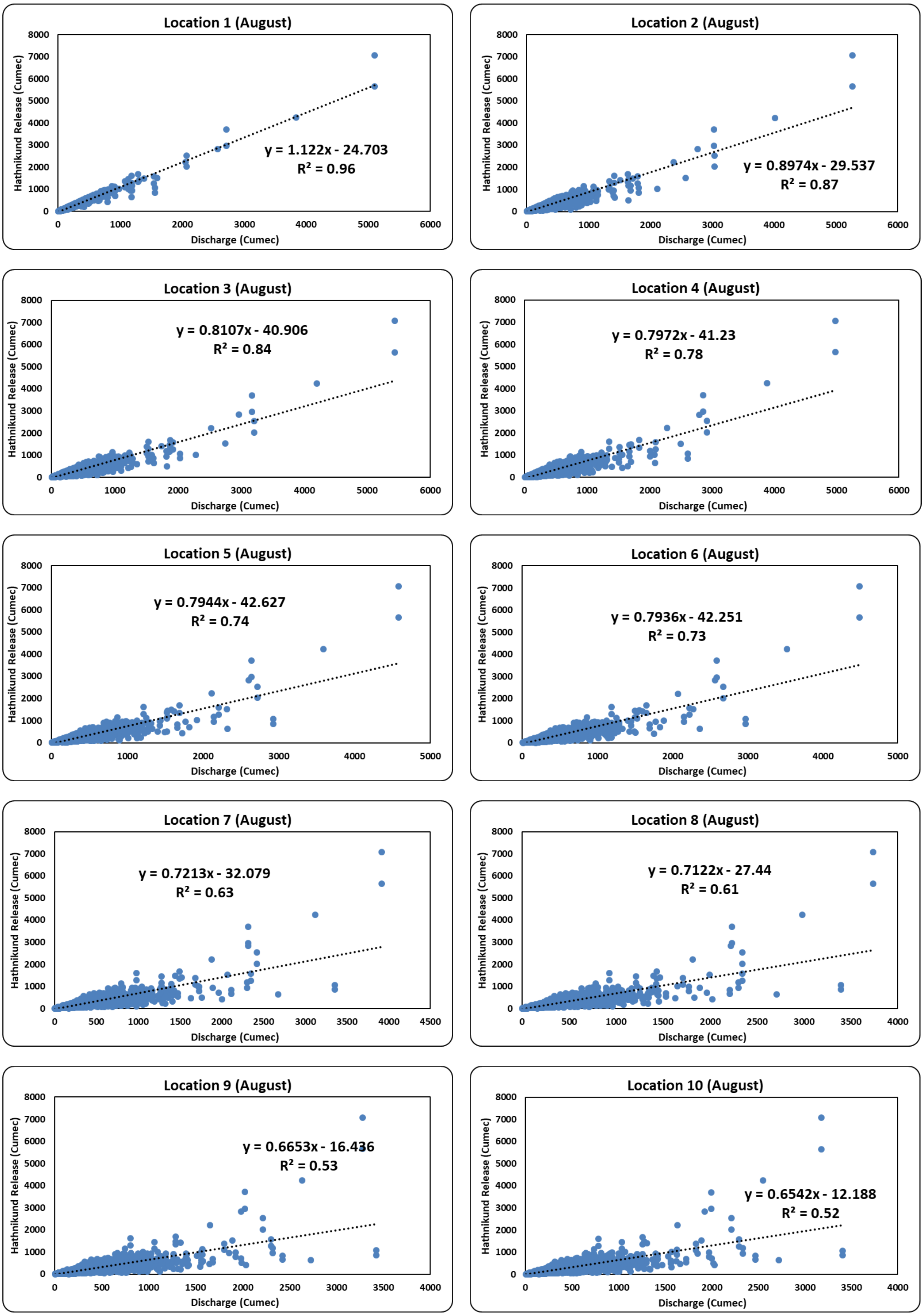


Fig. A2.8 Hathnikund release vs simulated discharge on selected sites for month of August (contd...)

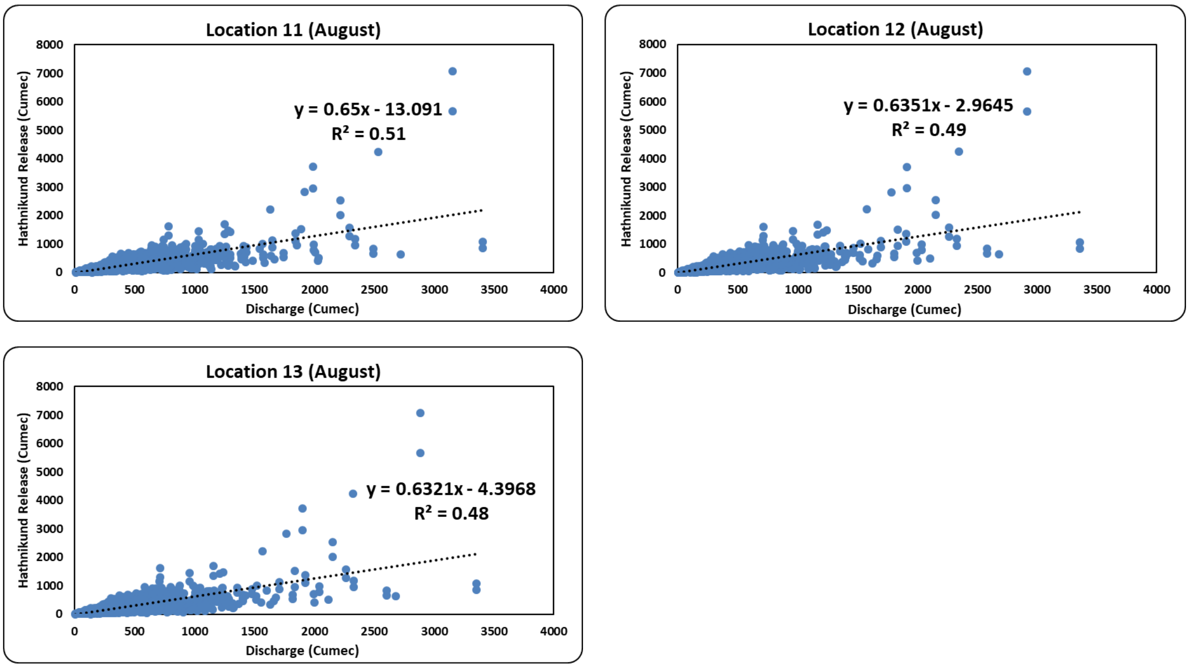


Fig. A2.8 Hathnikund release vs simulated discharge on selected sites for month of August

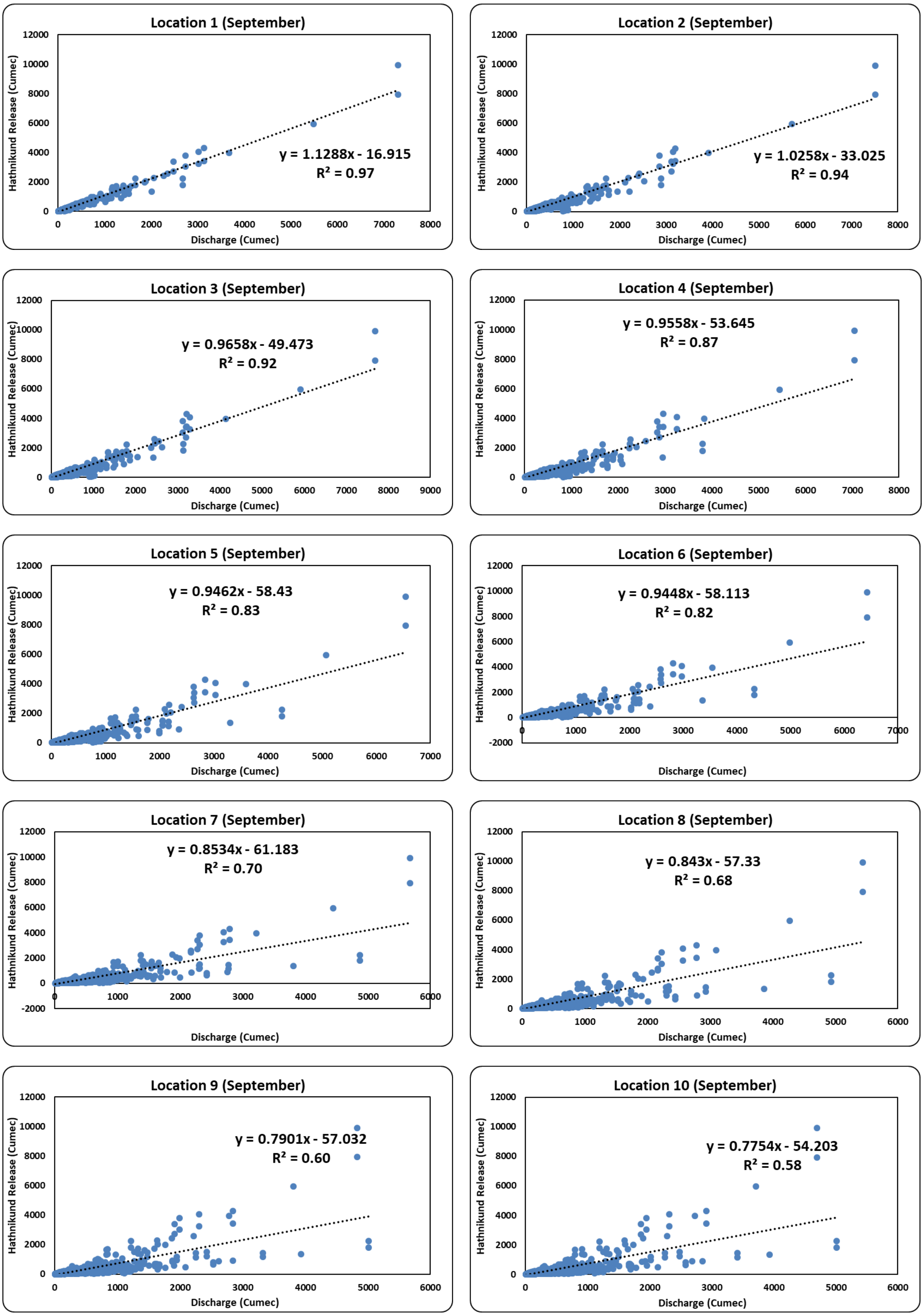
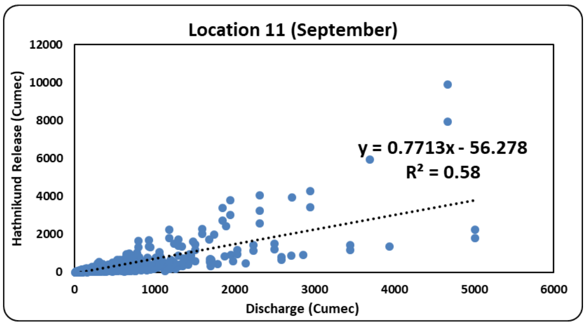
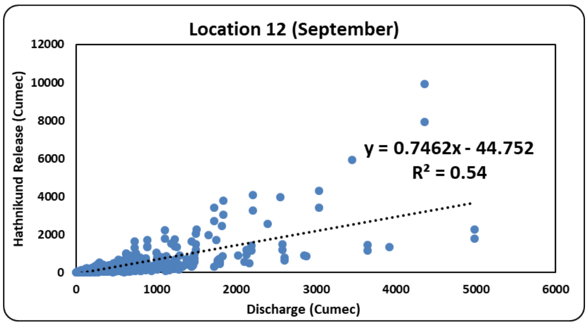


Fig. A2.9 Hathnikund release vs simulated discharge on selected sites for month of September (contd...)





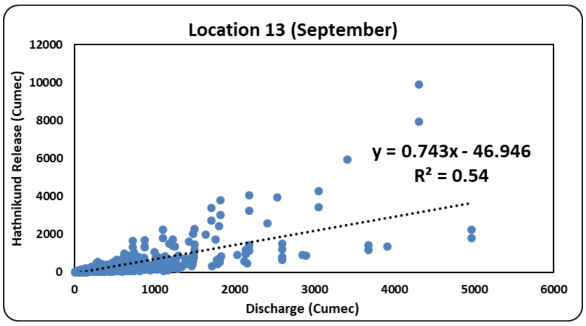


Fig. A2.9 Hathnikund release vs simulated discharge on selected sites for month of September

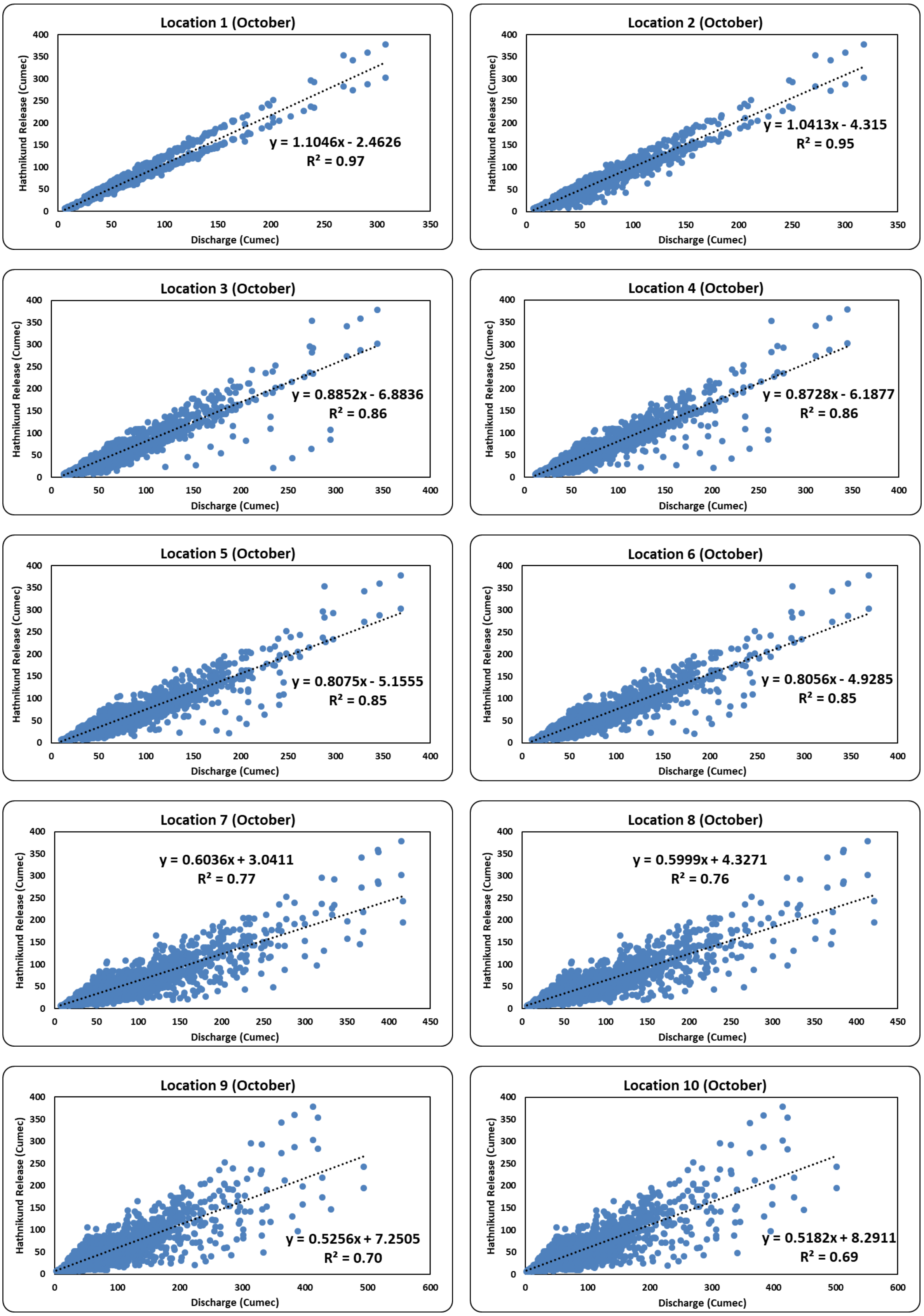


Fig. A2.10 Hathnikund release vs simulated discharge on selected sites for month of October (contd...)

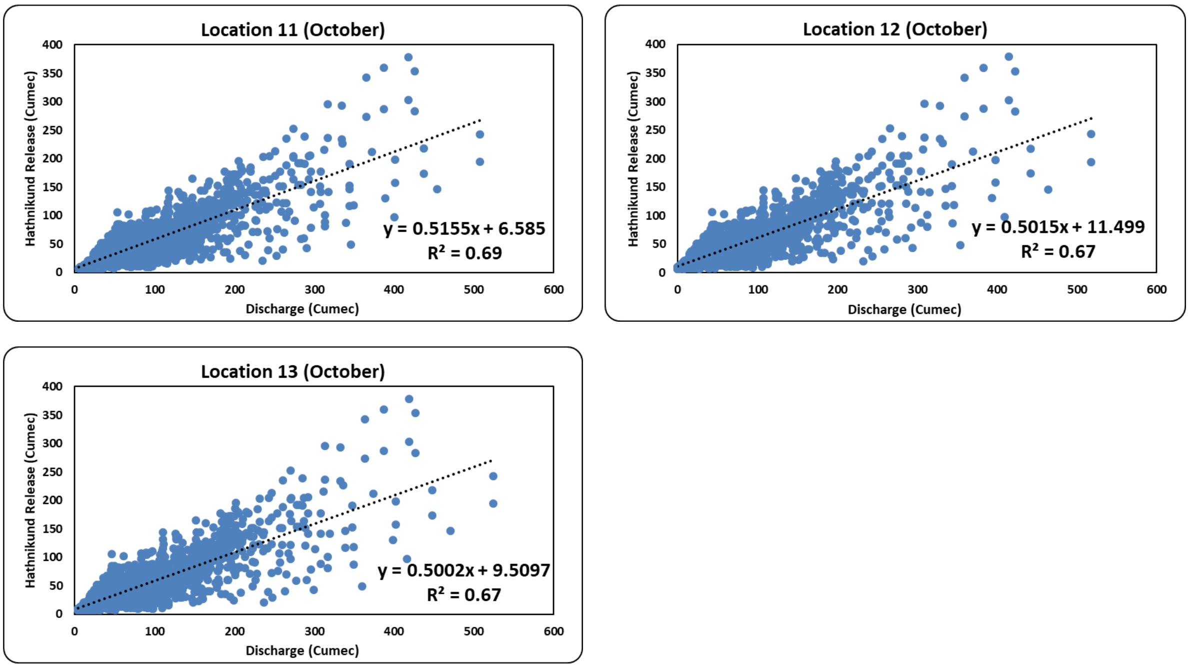


Fig. A2.10 Hathnikund releases vs simulated discharge on selected sites for month of October

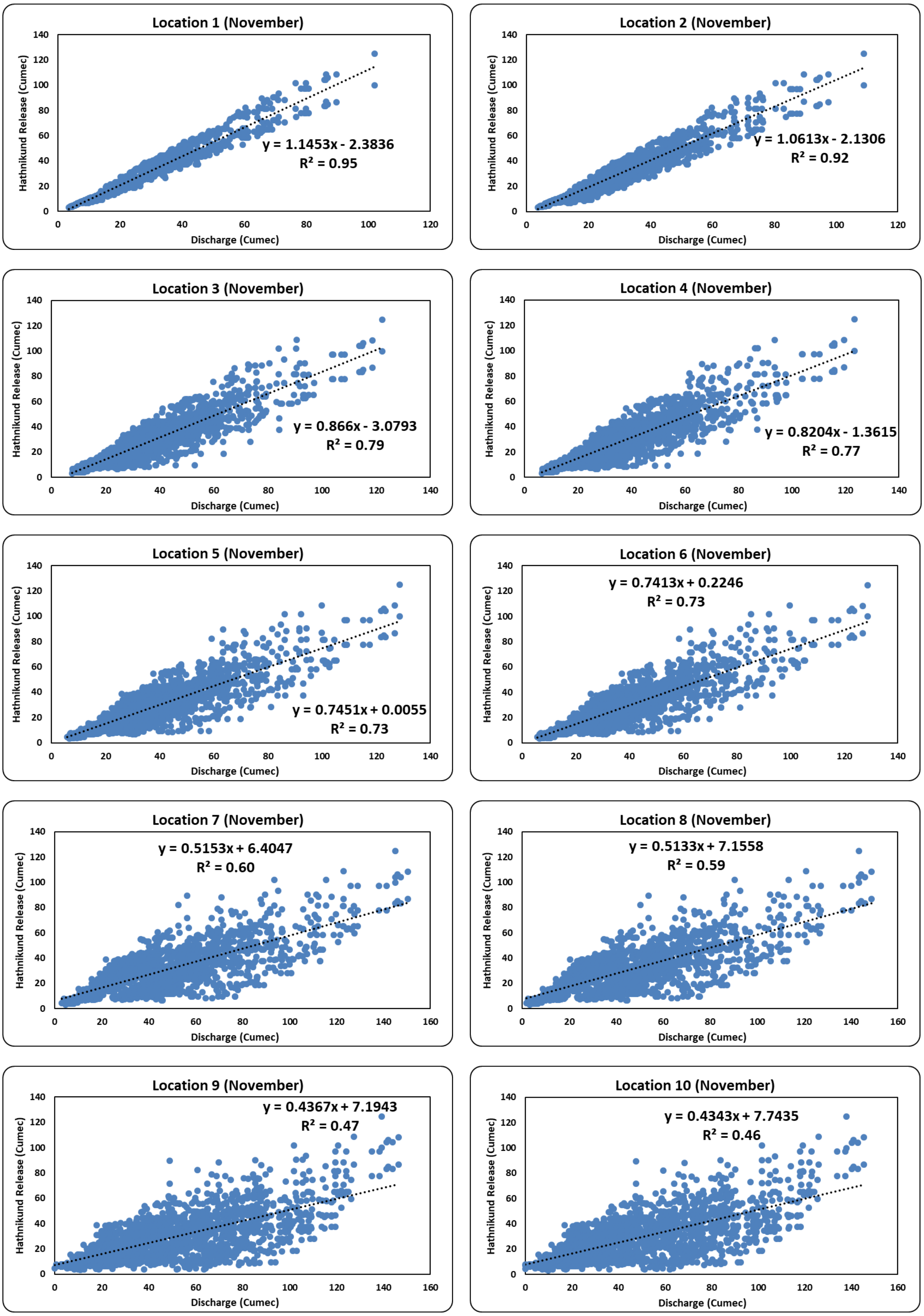


Fig. A2.11 Hathnikund releases vs simulated discharge on selected sites for month of November (contd...)

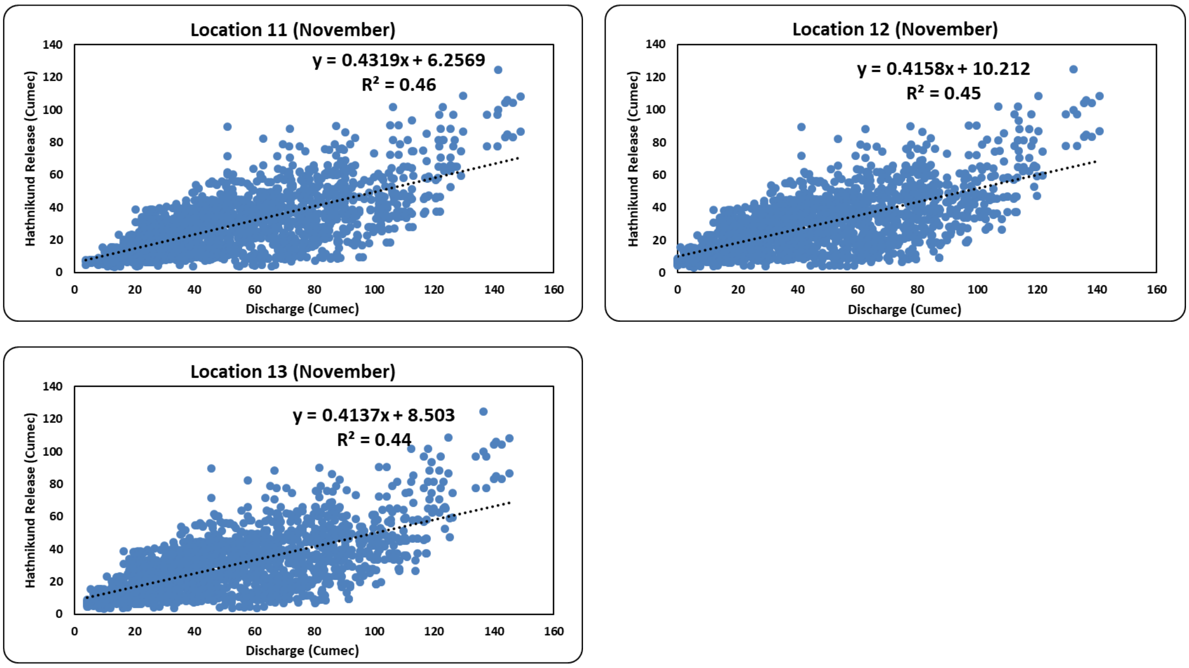


Fig. A2.11 Hathnikund releases vs simulated discharge on selected sites for month of November

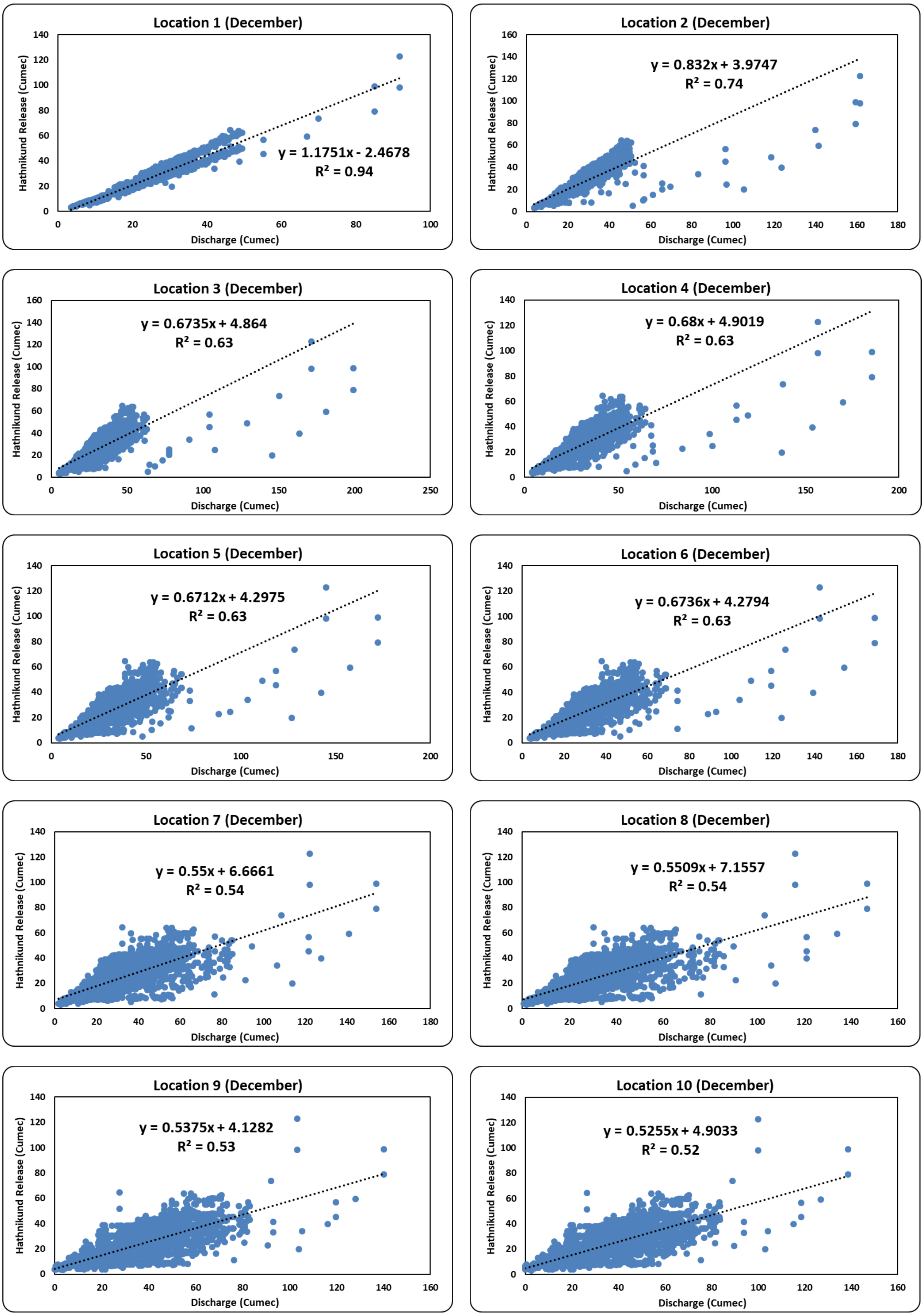


Fig. A2.12 Hathnikund releases vs simulated discharge on selected sites for month of December (contd...)

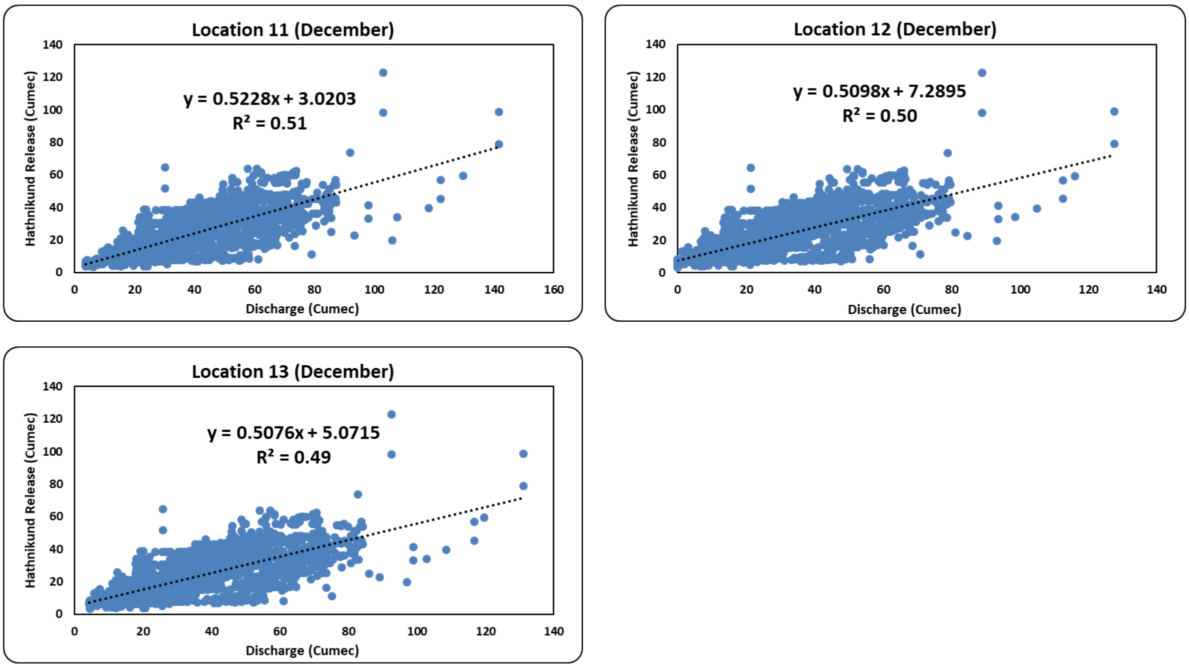


Fig. A2.12 Hathnikund releases vs simulated discharge on selected sites for month of December

Annexure 3

Releases Required from Hathnikund Barrage for Maintaining Suitable Habitat at 13 Identified Locations

ANNEXURE 3

Table A3.1 Releases required from Hathnikund barrage for maintaining suitable habitat at location 1

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	For Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 1	31	Confluence of Stream or Drain	Q (EF) = 23.623X (Depth) ^ (2.8052)	3.65	5.64	10.54	17.58	892.65	Qr = 1.0205X Q1 (EF) + 0.6732	Jan	6.43	11.43	18.61	911.62
									Qr = 1.0237X Q1 (EF) + 0.893	Feb	6.66	11.68	18.89	914.69
									Qr = 1.1575 X Q1 (EF) + 2.1578	Mar	8.68	14.36	22.50	1035.39
									Qr = 1.2018 X Q1 (EF) - 1.345	Apr	5.43	11.32	19.78	1071.44
									Qr = 1.210 X Q1 (EF) + 1.418	May	8.24	14.17	22.69	1081.52
									Qr = 1.1133X Q1 (EF) - 2.4891	Jun	3.79	9.25	17.08	991.29
									Qr = 1.082X Q1 (EF) - 8.213	Jul	14.31	3.19	10.81	957.63
									Qr = 1.122X Q1 (EF) - 24.70	Aug	31.02	-12.87	-4.98	976.85
									Qr = 1.1288X Q1 (EF) - 16.915	Sep	-10.55	-5.02	2.93	990.70
									Qr = 1.104X Q1 (EF) - 2.642	Oct	3.58	8.99	16.76	982.84
									Qr = 1.1453X Q1 (EF) - 2.3836	Nov	4.07	14.46	17.75	1019.96
									Qr = 1.175X Q1 (EF) - 2.467	Dec	4.16	14.85	18.19	1046.39

Table A3.2 Releases required from Hathnikund barrage for maintaining suitable habitat at location 2

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	For Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 2	36	Confluence of Stream or Drain	Q (EF) = 61.269 X (Depth) ^ (2.4948)	4.37	17.13	29.89	47.11	1479.15	Qr = 0.3253 X Q2 (EF) + 14.911	Jan	20.48	24.63	30.23	496.08
									Qr = 0.5651 X Q2 (EF) + 10.006	Feb	19.69	26.90	36.63	845.88
									Qr = 0.9203X Q2 (EF) + 2.2656	Mar	18.03	29.77	45.62	1363.53
									Qr = 1.1875 X Q2 (EF) - 0.9629	Apr	19.38	34.53	54.98	1755.53
									Qr = 1.211X Q2 (EF) + 1.244	May	21.99	37.44	58.29	1792.50
									Qr = 0.9481 X Q2 (EF) - 1.3696	Jun	14.87	26.97	43.29	1401.02
									Qr = 0.743X Q2 (EF) + 5.995	Jul	18.72	28.20	41.00	1105.01
									Qr = 0.897X Q2 (EF) - 29.53	Aug	-14.16	-2.72	12.72	1297.27
									Qr = 1.0258X Q2 (EF) - 33.025	Sep	-15.45	-2.36	15.30	1484.29
									Qr = 1.041X Q2 (EF) - 4.315	Oct	13.52	26.80	44.72	1535.48
									Qr = 1.0613X Q2 (EF) - 2.1306	Nov	16.05	29.59	47.86	1567.70
									Qr = 0.832X Q2 (EF) + 3.974	Dec	18.23	28.84	43.17	1234.63

Table A3.3 Releases required from Hathnikund barrage for maintaining suitable habitat at location 3

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 3	41	Confluence of Stream or Drain and G&D Site	Q (EF) = 6.5316 X (Depth) ^ (3.5023)	3.81	1.09	2.38	4.52	1006.81	Qr = 0.2185 X Q3 (EF) + 16.955	Jan	17.19	17.48	17.94	236.94
									Qr = 0.4745 X Q3 (EF) + 11.447	Feb	11.96	12.58	13.59	489.18
									Qr = 0.8366 X Q3 (EF) + 4.1332	Mar	5.05	6.13	7.91	846.43
									Qr = 1.1549 X Q3 (EF) -0.0175	Apr	1.24	2.74	5.20	1162.74
									Qr = 1.212X Q3 (EF) + 0.716	May	2.04	3.61	6.19	1220.96
									Qr = 0.8595X Q3 (EF) - 0.257	Jun	0.68	1.79	3.62	865.09
									Qr = 0.638X Q3 (EF) + 10.36	Jul	11.06	11.88	13.24	652.70
									Qr = 0.810X Q3 (EF) - 40.90	Aug	-40.02	-38.97	-37.24	774.61
									Qr = 0.9658X Q3 (EF) - 49.473	Sep	-48.42	-47.17	-45.11	922.90
									Qr = 0.885X Q3 (EF) - 6.883	Oct	-5.92	-4.77	-2.89	884.14
									Qr = 0.866X Q3 (EF) - 3.0793	Nov	-2.13	-1.01	0.83	868.81
									Qr = 0.673X Q3 (EF) + 4.864	Dec	5.60	6.47	7.90	682.44

Table A3.4 Releases required from Hathnikund barrage for maintaining suitable habitat at location 4

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 4	71	Confluence of Stream or Drain	Q (EF) = 46.577 X (Depth) ^ (2.36)	3.8	13.95	23.62	36.32	999.41	Qr = 0.1949 X Q4 (EF) + 17.614	Jan	20.33	22.22	24.69	212.40
									Qr = 0.4459 X Q4 (EF) + 12.444	Feb	18.66	22.98	28.64	458.08
									Qr = 0.844 X Q4 (EF) + 5.0075	Mar	16.78	24.94	35.66	848.51
									Qr = 1.126X Q4 (EF) +3.7152	Apr	19.42	30.31	44.62	1129.05
									Qr = 1.220X Q4 (EF) + 2.783	May	19.80	31.60	47.10	1222.06
									Qr = 0.8756X Q4 (EF) + 0.4059	Jun	12.62	21.09	32.21	875.49
									Qr = 0.636X Q4 (EF) + 10	Jul	18.87	25.02	33.10	645.63
									Qr = 0.794X Q4 (EF) - 42.62	Aug	-31.54	-23.86	-13.78	750.91
									Qr = 0.9558X Q4 (EF) - 53.645	Sep	-40.31	-31.07	-18.93	901.59
									Qr = 0.872X Q4 (EF) - 6.187	Oct	5.98	14.41	25.49	865.30
									Qr = 0.8204X Q4 (EF) - 1.3615	Nov	10.08	18.02	28.44	821.28
									Qr = 0.68X Q4 (EF) + 4.901	Dec	14.39	20.96	29.60	684.50

Table A3.5 Releases required from Hathnikund barrage for maintaining suitable habitat at location 5

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 5	97	Confluence of Stream or Drain	Q (EF) = 68.254 X (Depth) ^ (2.6741)	3.01	17.41	31.62	51.50	519.77	Qr = 0.1987 X Q5 (EF) + 17.273	Jan	20.73	23.56	27.51	120.55
									Qr = 0.4503 X Q5 (EF) + 11.947	Feb	19.79	26.19	35.14	246.00
									Qr = 0.8392 X Q5 (EF) + 5.4131	Mar	20.03	31.95	48.63	441.60
									Qr = 1.1102X Q5 (EF) + 6.1261	Apr	25.46	41.24	63.30	583.17
									Qr = 1.214X Q5 (EF) + 6.056	May	27.20	44.45	68.57	637.05
									Qr = 0.8808X Q5 (EF) + 2.5599	Jun	17.90	30.42	47.92	460.37
									Qr = 0.643X Q5 (EF) + 9.255	Jul	20.45	29.59	42.37	343.47
									Qr = 0.794X Q5 (EF) - 42.62	Aug	-28.79	-17.51	-1.73	370.08
									Qr = 0.9462X Q5 (EF) - 58.43	Sep	-41.95	-28.51	-9.71	433.37
									Qr = 0.807X Q5 (EF) - 5.155	Oct	8.90	20.37	36.40	414.30
									Qr = 0.7451X Q5 (EF) + 0.0055	Nov	12.98	23.57	38.37	387.28
									Qr = 0.671X Q5 (EF) + 4.297	Dec	15.98	25.52	38.85	353.06

Table A3.6 Releases required from Hathnikund barrage for maintaining suitable habitat at location 6

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 6	103	G&D Site	Q (EF) = 36.808 X (Depth) ^ (3.2364)	4.1	7.05	14.51	26.17	1236.85	Qr = 0.1994 X Q6 (EF) + 17.26	Jan	18.66	20.15	22.48	263.89
									Qr = 0.4517 X Q6 (EF) + 11.96	Feb	15.14	18.51	23.78	570.64
									Qr = 0.8378 X Q6 (EF) + 5.7076	Mar	11.61	17.86	27.64	1041.94
									Qr = 1.1097X Q6 (EF) + 6.6335	Apr	14.45	22.73	35.68	1379.16
									Qr = 1.215X Q6 (EF) + 6.682	May	15.24	24.31	38.48	1509.45
									Qr = 0.881X Q6 (EF) + 3.0475	Jun	9.26	15.83	26.11	1092.71
									Qr = 0.644X Q6 (EF) + 9.283	Jul	13.82	18.63	26.14	805.81
									Qr =0.793 X Q6 (EF) - 42.25	Aug	-36.66	-30.75	-21.49	938.57
									Qr = 0.9448X Q6 (EF) - 58.113	Sep	-51.46	-44.41	-33.38	1110.46
									Qr = 0.805X Q6 (EF) - 4.928	Oct	0.74	6.75	16.14	990.73
									Qr = 0.7413X Q6 (EF) + 0.2246	Nov	5.45	10.98	19.63	917.10
									Qr = 0.673X Q6 (EF) + 4.279	Dec	9.02	14.04	21.89	836.68

Table A3.7 Releases required from Hathnikund barrage for maintaining suitable habitat at location 7

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 7	146	G&D Site	Q (EF) = 23.535 X (Depth) ^ (2.8145)	5.12	5.59	10.47	17.50	2306.64	Qr = 0.165 X Q7 (EF) + 17.897	Jan	18.82	19.63	20.78	398.49
									Qr = 0.3871 X Q7 (EF) + 13.402	Feb	15.57	17.46	20.17	906.30
									Qr = 0.744 X Q7 (EF) + 9.8845	Mar	14.04	17.68	22.90	1726.02
									Qr = 1.0781 X Q7 (EF) + 12.229	Apr	18.25	23.52	31.09	2499.01
									Qr = 1.238X Q7 (EF) +13.15	May	20.07	26.12	34.81	2868.77
									Qr = 0.852X Q7 (EF) + 9.658	Jun	14.42	18.58	24.56	1974.91
									Qr = 0.600X Q7 (EF) + 14.20	Jul	17.55	20.48	24.70	1398.18
									Qr = 0.721X Q7 (EF) - 32.07	Aug	-28.04	-24.52	-19.46	1631.01
									Qr = 0.8534X Q7 (EF) - 51.183	Sep	-46.41	-42.25	-36.25	1917.30
									Qr = 0.603X Q7 (EF) + 3.341	Oct	6.71	9.66	13.89	1394.24
									Qr = 0.5153X Q7 (EF) + 6.4047	Nov	9.28	11.80	15.42	1195.01
									Qr = 0.55X Q7 (EF) + 6.666	Dec	9.74	12.43	16.29	1275.32

Table A3.8 Releases required from Hathnikund barrage for maintaining suitable habitat at location 8

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 8	163	Confluence of Stream or Drain	Q (EF) = 23.651 X (Depth) ^ (2.9608)	3.95	5.21	10.09	17.31	1114.06	Qr = 0.1637 X Q8 (EF) + 18.073	Jan	18.93	19.72	20.91	200.44
									Qr = 0.3837 X Q8 (EF) + 13.962	Feb	15.96	17.83	20.60	441.43
									Qr = 0.729 X Q8 (EF) + 11.699	Mar	15.50	19.06	24.32	823.85
									Qr = 1.0935X Q8 (EF) + 14.349	Apr	20.05	25.38	33.28	1232.58
									Qr = 1.269X Q8 (EF) + 15.67	May	22.28	28.48	37.64	1429.41
									Qr = 0.8427X Q8 (EF) + 12.599	Jun	16.99	21.10	27.19	951.42
									Qr = 0.595X Q8 (EF) + 16.48	Jul	19.58	22.48	26.78	679.35
									Qr = 0.712X Q8 (EF) - 27.44	Aug	-23.73	-20.26	-15.11	765.77
									Qr = 0.843X Q8 (EF) - 57.33	Sep	-52.94	-48.82	-42.74	881.82
									Qr = 0.599X Q8 (EF) + 4.327	Oct	7.45	10.37	14.70	671.65
									Qr = 0.5133X Q8 (EF) + 7.1558	Nov	9.83	12.34	16.04	579.00
									Qr = 0.550X Q8 (EF) + 7.155	Dec	10.02	12.71	16.68	619.89

Table A3.9 Releases required from Hathnikund barrage for maintaining suitable habitat at location 9

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 9	203	G&D Site	Q (EF) = 36.808 X (Depth) ^ (3.2364)	4.37	5.64	10.54	17.58	1479.15	Qr = 0.1423 X Q9 (EF) + 17.454	Jan	18.26	18.95	19.96	227.94
									Qr = 0.3394 X Q9 (EF) + 12.401	Feb	14.31	15.98	18.37	514.43
									Qr = 0.6587 X Q9 (EF) + 8.6215	Mar	12.33	15.56	20.20	982.94
									Qr = 0.7715X Q9 (EF) + 14.006	Apr	18.35	22.14	27.57	1155.17
									Qr = 1.083X Q9 (EF) + 16.43	May	22.53	27.85	35.47	1618.35
									Qr = 0.808X Q9 (EF) + 14.022	Jun	18.58	22.54	28.23	1209.18
									Qr = 0.550X Q9 (EF) + 22.23	Jul	25.33	28.03	31.90	835.77
									Qr = 0.665X Q9 (EF) - 16.43	Aug	-12.68	-9.42	-4.74	967.21
									Qr = 0.7901X Q9 (EF) - 57.032	Sep	-52.58	-48.70	-43.14	1111.65
									Qr = 0.525X Q9 (EF) + 7.250	Oct	10.21	12.78	16.48	783.81
									Qr = 0.4367X Q9 (EF) + 7.1943	Nov	9.66	11.80	14.87	653.14
									Qr = 0.537X Q9 (EF) + 4.128	Dec	7.15	9.79	13.57	798.43

Table A3.10 Releases required from Hathnikund barrage for maintaining suitable habitat at location 10

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 10	219	Confluence of Stream or Drain	Q (EF) = 18.109 X (Depth) ^ (3.0769)	4.15	3.76	7.47	13.09	1279.63	Qr = 0.1423 X Q10 (EF) + 17.454	Jan	17.99	18.52	19.32	199.54
									Qr = 0.3347 X Q10 (EF) + 12.889	Feb	14.15	15.39	17.27	441.18
									Qr = 0.6373 X Q10 (EF) + 10.277	Mar	12.67	15.04	18.62	825.78
									Qr = 0.7785X Q10 (EF) + 15.357	Apr	18.28	21.17	25.55	1011.55
									Qr = 1.116X Q10 (EF) + 17.94	May	22.14	26.28	32.55	1446.00
									Qr = 0.7989X Q10 (EF) + 16.272	Jun	19.28	22.24	26.73	1038.57
									Qr = 0.538X Q10 (EF) +24.98	Jul	27.00	29.00	32.03	713.42
									Qr = 0.654X Q10 (EF) - 12.18	Aug	-9.72	-7.29	-3.62	824.70
									Qr = 0.7754X Q10 (EF) - 54.203	Sep	-51.29	-48.41	-44.05	938.02
									Qr = 0.518X Q10 (EF) + 8.291	Oct	10.24	12.16	15.07	671.14
									Qr = 0.4343X Q10 (EF) + 7.7435	Nov	9.38	10.99	13.43	563.49
									Qr = 0.525X Q10 (EF) + 4.903	Dec	6.88	8.83	11.78	676.71

Table A3.11 Releases required from Hathnikund barrage for maintaining suitable habitat at location 11

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows 0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains	Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Month	Releases from Hathnikund required for maintaining E-Flows 0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 11	222	G&D Site	Q (EF) = 16.363 X (Depth) ^ (2.7447)	3.95	4.03	7.43	12.25	1114.06	Qr = 0.1421 X Q11 (EF) + 16.92	Jan	17.49	17.98	18.66	175.23
									Qr = 0.3331 X Q11 (EF) + 11.726	Feb	13.07	14.20	15.81	382.82
									Qr = 0.6343 X Q11 (EF) + 8.3032	Mar	10.86	13.02	16.08	714.95
									Qr = 0.7755 X Q11 (EF) + 12.99	Apr	16.11	18.75	22.49	876.94
									Qr = 1.1151 X Q11 (EF) + 14.598	May	19.09	22.88	28.26	1256.89
									Qr = 0.796X Q11 (EF) + 14.05	Jun	17.26	19.96	23.80	900.84
									Qr = 0.5333 X Q11 (EF) + 24.214	Jul	26.36	28.18	30.75	618.34
									Qr = 0.65 X Q11 (EF) - 13.091	Aug	-10.47	-8.26	-5.13	711.05
									Qr = 0.7713 X Q11 (EF) - 56.278	Sep	-53.17	-50.55	-46.83	803.00
									Qr = 0.5155 X Q11 (EF) + 6.585	Oct	8.66	10.41	12.90	580.88
									Qr = 0.4319 X Q11 (EF) + 6.2569	Nov	8.00	9.47	11.55	487.42
									Qr = 0.5228 X Q11 (EF) + 3.0203	Dec	5.13	6.90	9.43	585.45

Table A3.12: Releases required from Hathnikund barrage for maintaining suitable habitat at location 12

Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows 0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains	Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Month	Releases from Hathnikund required for maintaining E-Flows 0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 12	243	Confluence of Stream or Drain	Q (EF) = 32.146 X (Depth) ^ (2.388)	5.25	9.49	16.17	25.00	2474.72	Qr = 0.1414 X Q12 (EF) + 17.996	Jan	19.34	20.28	21.53	367.92
									Qr = 0.3293 X Q12 (EF) + 14.487	Feb	17.61	19.81	22.72	829.41
									Qr = 0.61 X Q12 (EF) + 14.603	Mar	20.39	24.47	29.85	1524.18
									Qr = 0.8257 X Q12 (EF) + 18.767	Apr	26.60	32.12	39.41	2062.14
									Qr = 1.2579 X Q12 (EF) + 21.792	May	33.73	42.14	53.23	3134.74
									Qr = 0.7718 X Q12 (EF) + 22.52	Jun	29.85	35.00	41.81	1932.51
									Qr = 0.5098 X Q12 (EF) + 33.125	Jul	37.96	41.37	45.87	1294.74
									Qr = 0.6351 X Q12 (EF) -2.9645	Aug	3.06	7.31	12.91	1568.73
									Qr = 0.7462 X Q12 (EF) -44.752	Sep	-37.67	-32.68	-26.10	1801.88
									Qr = 0.5015 X Q12 (EF) + 11.499	Oct	16.26	19.61	24.03	1252.57
									Qr = 0.4158 X Q12 (EF) + 10.212	Nov	14.16	16.94	20.61	1039.20
									Qr = 0.5098 X Q12 (EF) + 7.2895	Dec	12.13	15.53	20.03	1268.90

Table A3.13 Releases required from Hathnikund barrage for maintaining suitable habitat at location 13

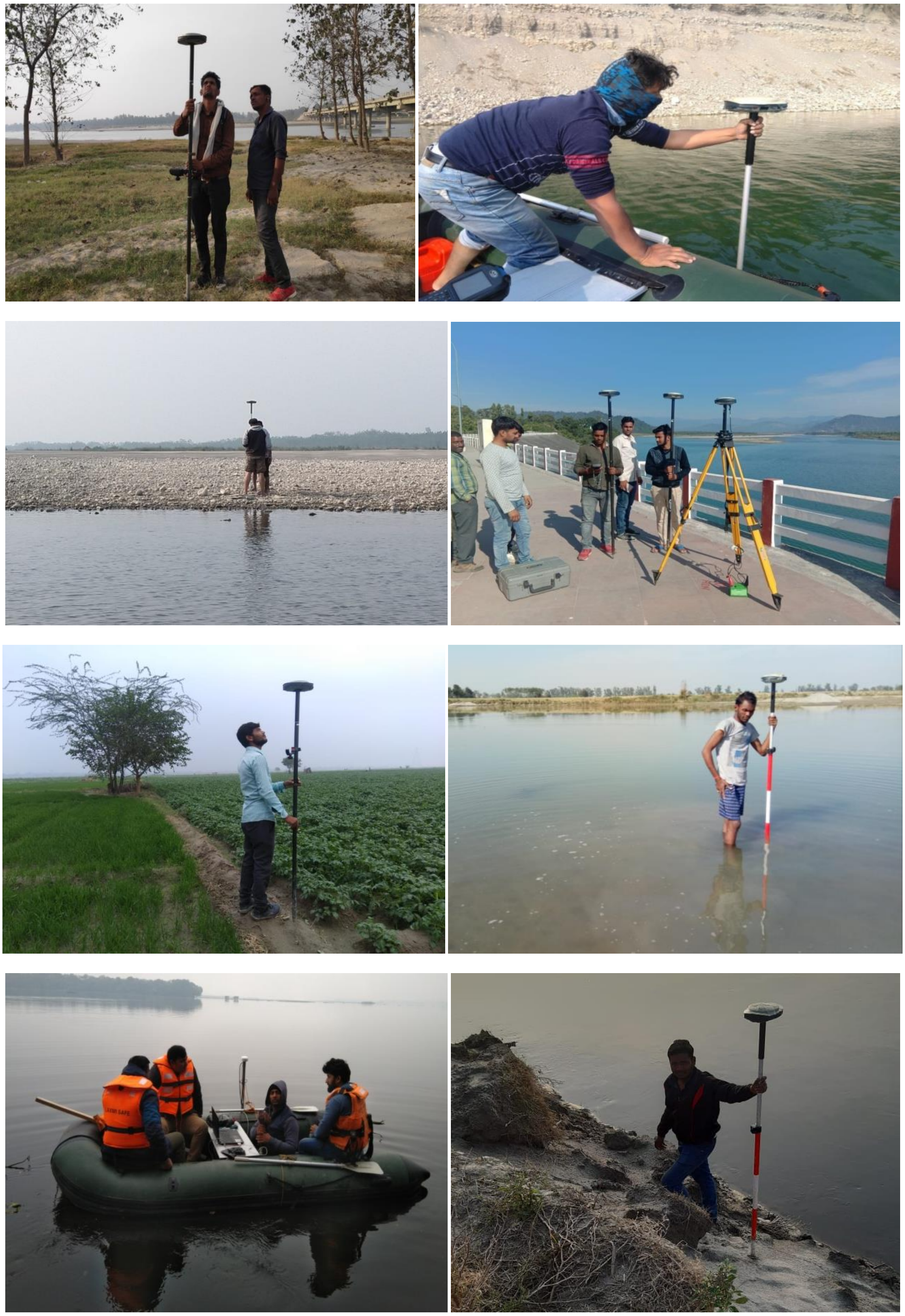
Location No.	Distance from Hathnikund Barrage (km)	Type of Site (G&D Site / Meandering / confluence of Streams or drains	Relationship between Depth (X) and Discharge (Y)	Depth for Inundating Floodplains (m)	Discharge at different sites required for maintaining E-Flows				Relationship between Simulated Discharge (X) and Hathnikund Releases (Y)	Releases from Hathnikund required for maintaining E-Flows				
					0.60 m	0.75 m	0.90 m	Depth for Inundating Floodplains		Month	0.60 m	0.75 m	0.90 m	For Inundating Floodplains
Location 13	248	G&D Site	Q (EF) = 21.109 X (Depth) ^ (2.6156)	4.98	5.55	9.95	16.02	2134.04	Qr = 0.1412 X Q13 (EF) + 17.362	Jan	18.15	18.77	19.62	318.69
									Qr = 0.3287 X Q13 (EF) + 13.097	Feb	14.92	16.37	18.36	714.56
									Qr = 0.6061 X Q13 (EF) + 12.349	Mar	15.71	18.38	22.06	1305.79
									Qr = 0.8209X Q13 (EF) + 15.913	Apr	20.47	24.08	29.07	1767.75
									Qr = 1.2544 X Q13 (EF) + 17.551	May	24.51	30.03	37.65	2694.49
									Qr = 0.7675 X Q13 (EF) + 20.146	Jun	24.40	27.78	32.44	1658.02
									Qr = 0.5067 X Q13 (EF) + 31.786	Jul	34.60	36.83	39.91	1113.10
									Qr = 0.6321 X Q13 (EF) -4.3968	Aug	-0.89	1.89	5.73	1344.53
									Qr = 0.743 X Q13 (EF) -46.946	Sep	-42.82	-39.56	-35.04	1538.65
									Qr = 0.5002 X Q13 (EF) + 9.5097	Oct	12.29	14.49	17.53	1076.96
									Qr = 0.4137 X Q13 (EF) +8.503	Nov	10.80	12.62	15.13	891.36
									Qr = 0.5076 X Q13 (EF) + 5.0715	Dec	7.89	10.12	13.21	1088.31

Annexure 4

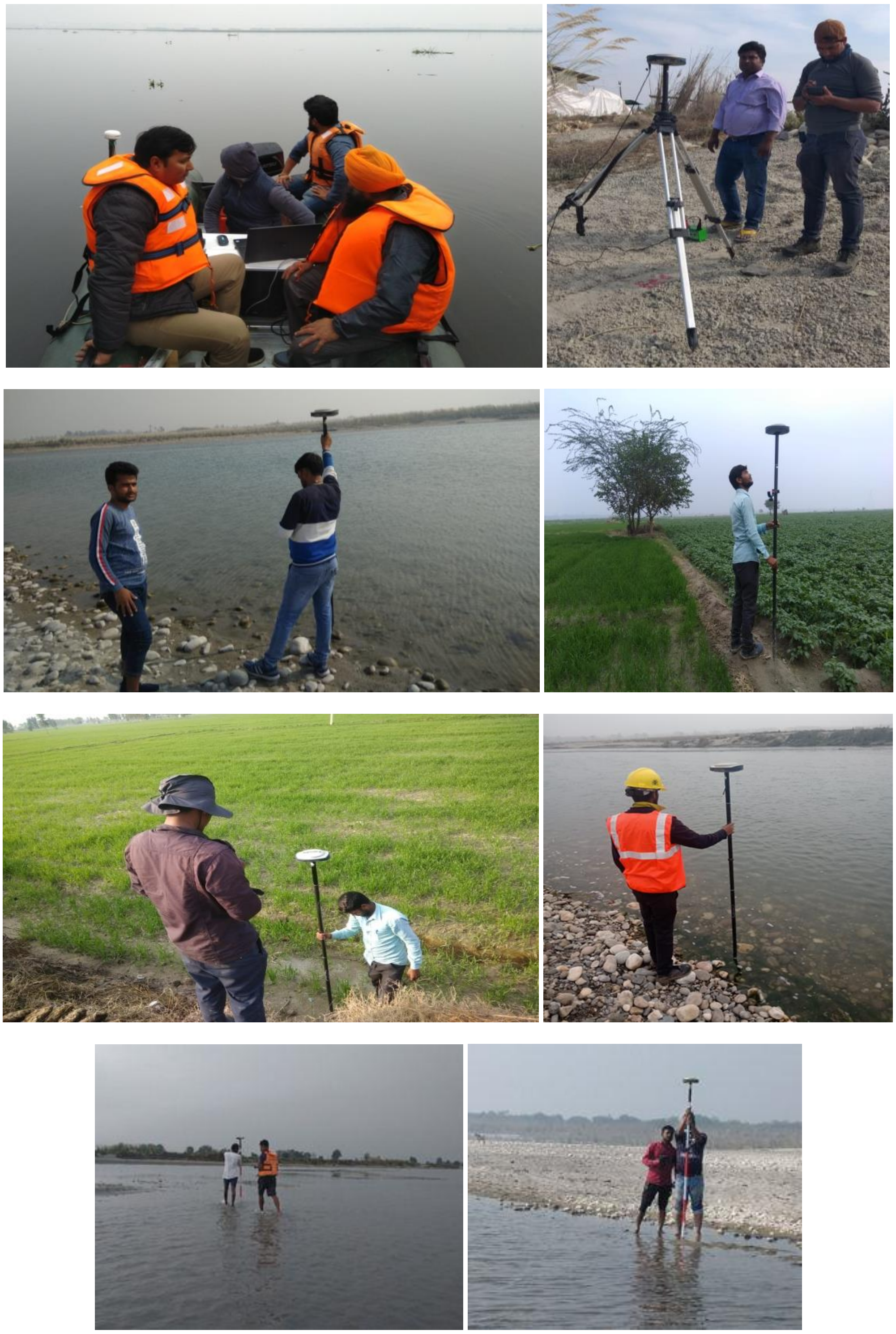
Field Investigations in Yamuna River

(a) Survey for identification of indicator fish species and for determining the e-flow requirement for maintaining ecological integrity

(b) Water quality survey



(a) River Cross-Section Survey (contd...)



(b) River Cross-Section Survey

Environmental Flow Assessment for Yamuna River from Hathnikund Barrage to Okhla Barrage




Research Study Report

National Institute of Hydrology, Roorkee