

Ganga River Basin Management Plan - 2015

Mission 1: Aviral Dhara *January 2015*

by

Consortium of 7 “Indian Institute of Technology”s (IITs)



IIT
Bombay



IIT
Delhi



IIT
Guwahati



IIT
Kanpur



IIT
Kharagpur



IIT
Madras



IIT
Roorkee

In Collaboration with



IIT
BHU



IIT
Gandhinagar



CIFRI



NEERI



JNU



PU



NIT-K



DU



NIH
Roorkee



ISI
Kolkata

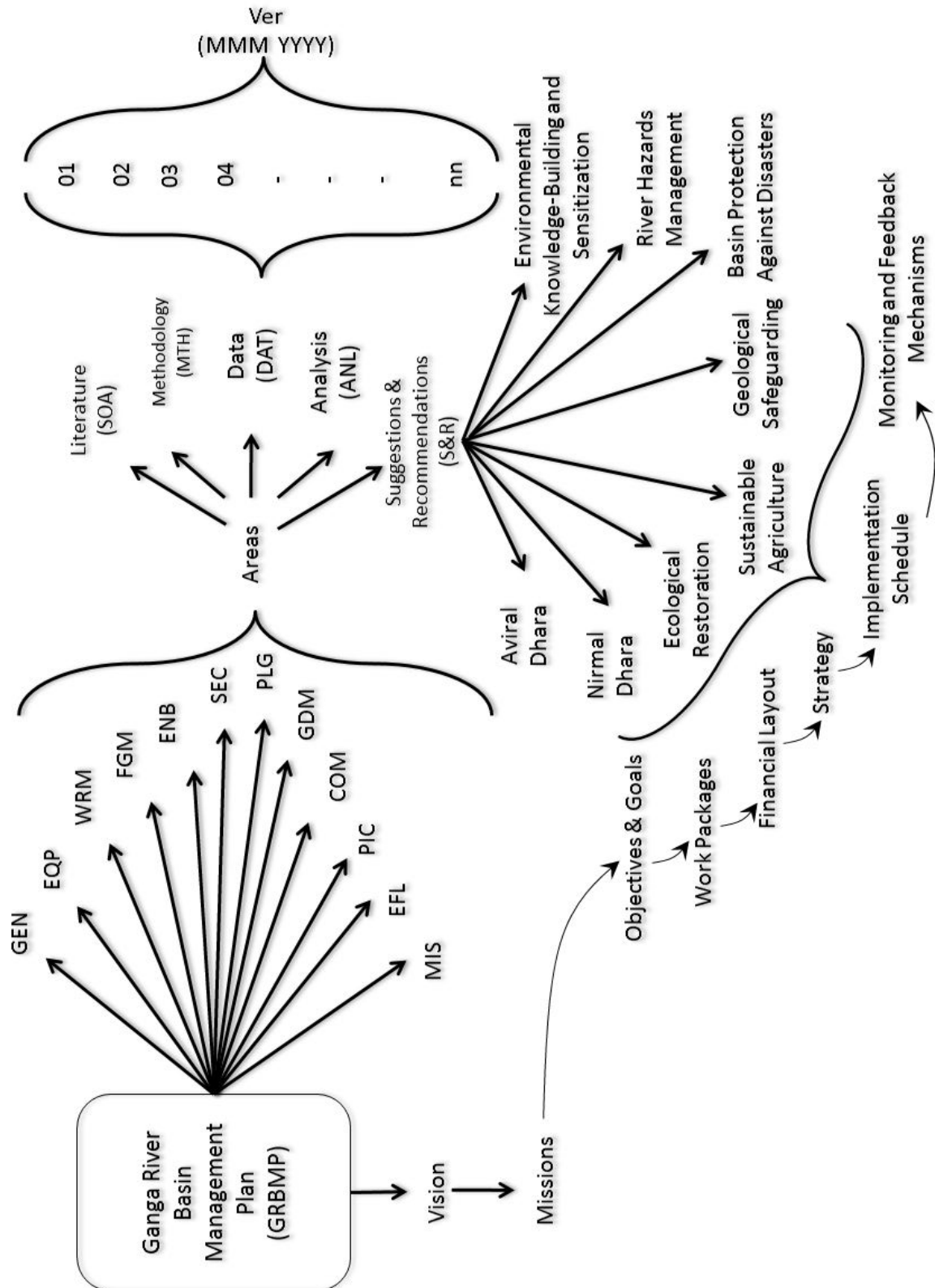


Allahabad
University



WWF
India

GRBMP Work Structure



Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government constituted the National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of River Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP). A Consortium of seven “Indian Institute of Technology”s (IITs) was given the responsibility of preparing the GRBMP by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. A Memorandum of Agreement (MoA) was therefore signed between the 7 IITs (IITs Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

The GRBMP is presented as a 3-tier set of documents. The three tiers comprise of: (i) Thematic Reports (TRs) providing inputs for different Missions, (ii) Mission Reports (MRs) documenting the requirements and actions for specific missions, and (iii) the Main Plan Document (MPD) synthesizing background information with the main conclusions and recommendations emanating from the Thematic and Mission Reports. It is hoped that this modular structure will make the Plan easier to comprehend and implement in a systematic manner.

There are two aspects to the development of GRBMP that deserve special mention. Firstly, the GRBMP is based mostly on secondary information obtained from governmental and other sources rather than on primary data collected by IIT Consortium. Likewise, most ideas and concepts used are not original but based on literature and other sources. Thus, on the whole, the GRBMP and its reports are an attempt to dig into the world’s collective wisdom and distil relevant truths about the complex problem of Ganga River Basin Management and solutions thereof.

Secondly, many dedicated people spent hours discussing major concerns, issues and solutions to the problems addressed in GRBMP. Their dedication led to the preparation of a comprehensive GRBMP that hopes to articulate the

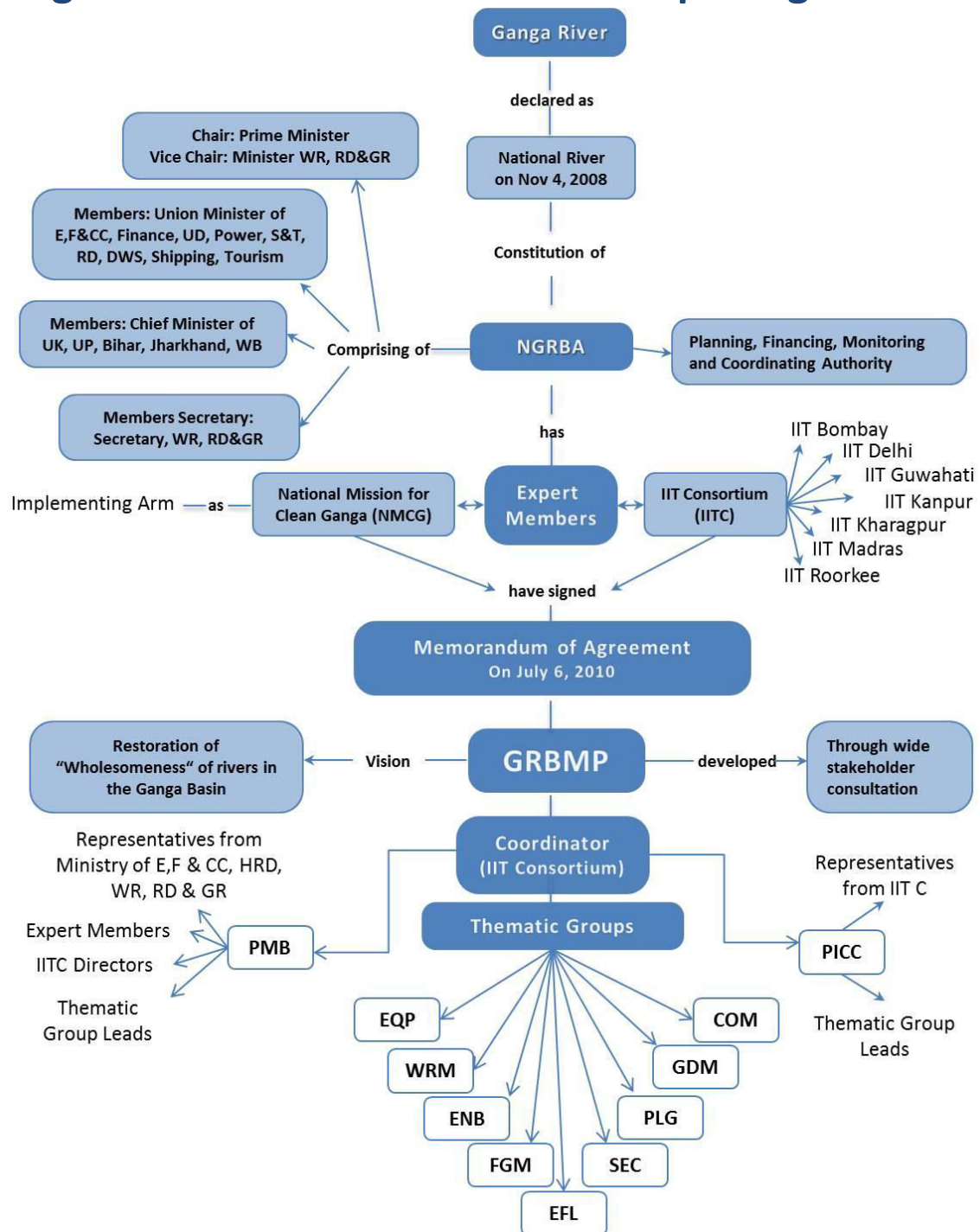
outcome of the dialog in a meaningful way. Thus, directly or indirectly, many people contributed significantly to the preparation of GRBMP. The GRBMP therefore truly is an outcome of collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team and of the associate organizations as well as many government departments and individuals.

Dr Vinod Tare
Professor and Coordinator
Development of GRBMP
IIT Kanpur

Authors

Vinod Tare (vinod@iitk.ac.in) and Gautam Roy (gautamwho@gmail.com)

Organizational Structure for Preparing GRBMP



NGRBA: National Ganga River Basin Authority
NMCG: National Mission for Clean Ganga
MoEF: Ministry of Environment and Forests
MHRD: Ministry of Human Resources Development
MoWR, RD&GR: Ministry of Water Resources, River Development and Ganga Rejuvenation
GRBMP: Ganga River Basin Management Plan
IITC: IIT Consortium
PMB: Project Management Board
PICC: Project Implementation and Coordination Committee

EQP: Environmental Quality and Pollution
WRM: Water Resources Management
ENB: Ecology and Biodiversity
FGM: Fluvial Geomorphology
EFL: Environmental Flows
SEC: Socio Economic and Cultural
PLG: Policy Law and Governance
GDM: Geospatial Database Management
COM: Communication

Project Management Board [PMB]

Expert Members:

- Sri Swami Avimukteshwaranand Saraswati
 - Dr Madhav A Chitale
 - Dr Bharat Jhunjunwala
-

Project Implementation and Coordination Committee [PICC]

Representatives from IIT Consortium:

- Dr Shyam Asolekar, IIT Bombay
- Dr A K Mittal, IIT Delhi
- Dr Mohammad Jawed, IIT Guwahati
- Dr Vinod Tare, IIT Kanpur
- Dr D J Sen, IIT Kharagpur
- Dr Ligy Philip, IIT Madras
- Dr I M Mishra, IIT Roorkee

Thematic Group Leads:

- Dr Purnendu Bose, Environmental Quality and Pollution (EQP)
 - Dr A K Gosain, Water Resources Management (WRM)
 - Dr R P Mathur, Ecology and Biodiversity (ENB)
 - Dr Rajiv Sinha, Fluvial Geomorphology (FGM)
 - Dr Vinod Tare, Environmental Flows (EFL)
 - Dr S P Singh, Socio Economic and Cultural (SEC)
 - Dr N C Narayanan and Dr Indrajit Dube, Policy Law and Governance (PLG)
 - Dr Harish Karnick, Geospatial Database Management (GDM)
 - Dr T V Prabhakar, Communication (COM)
-

Composition of Thematic Groups

1. Environmental Quality and Pollution (EQP)

Lead: Purnendu Bose, IIT Kanpur

Members: Shyam R Asolekar, Suparna Mukherjee (IIT Bombay); A K Mittal, A K Nema, Arun Kumar, T R Sreekrishanan (IIT Delhi); Ajay Kalmhad (IIT Guwahati); Saumyen Guha, Vinod Tare (IIT Kanpur); A K Gupta, M M Ghangrekar, Sudha Goel (IIT Kharagpur); Ligy Philip, Mukesh Doble, R Ravi Krishna, S M Shrivnagendra (IIT Madras); A AKazmi, B R Gurjar, Himanshu Joshi, Indu Mehrotra, I M Mishra, Vivek Kumar (IIT Roorkee); Anirban Gupta (BESU Shibpur); P K Singh (IIT BHU); Rakesh Kumar (NEERI Nagpur); S K Patidar (NIT Kurukshetra); Sanmit Ahuja (ETI Dynamics, New Delhi)

2. Water Resources Management (WRM)

Lead: A K Gosain, IIT Delhi

Members: Rakesh Khosa, R Maheswaran, B R Chahar, C T Dhanya, D R Kaushal (IIT Delhi); Subashisa Dutta, Suresh Kartha (IIT Guwahati); Shivam Tripathi, Gautam Rai, Vinod Tare (IIT Kanpur); Anirban Dhar, D J Sen (IIT Kharagpur); B S Murty, BalajiNarasimhan (IIT Mdras); C S P Ojha, P Perumal (IIT Roorkee); S K Jain (NIH, Roorkee); Pranab Mohapatra (IIT Gandhi Nagar); Sandhya Rao (INRM, New Delhi)

3. Fluvial Geomorphology (FGM)

Lead: Rajiv Sinha, IIT Kanpur

Members: Vinod Tare (IIT Kanpur); Vikrant Jain (IIT Gandhi Nagar); J K Pati (Allahabad University); Kirteshwar Prasad, Ramesh Shukla (Patna University); Parthasarthi Ghosh, Soumendra Nath Sarkar, Tapan Chakarborty (ISI Kolkata); KalyanRudra (WBPCB); S K Tandon, Shashank Shekhar (University of Delhi); Saumitra Mukherjee (JNU Delhi)

4. Ecology and Biodiversity (ENB)

Lead: R P Mathur, IIT Kanpur

Members: A K Thakur, Vinod Tare (IIT Kanpur); Utpal Bora (IIT Guwahati); M D Behera (IIT Kharagpur); Naveen Navania, Partha Roy, PruthiVikas, R P Singh, Ramasre Prasad, Ranjana Pathania (IIT Roorkee); Sandeep Behera (WWF-India)

5. Socio Economic and Cultural (SEC)

Lead: S P Singh, IIT Roorkee

Members: Pushpa L Trivedi (IIT Bombay); Seema Sharma, V B Upadhyay (IIT Delhi); P M Prasad, Vinod Tare (IIT Kanpur); Bhagirath Behera, N C Nayak, Pulak Mishra, T N Mazumder (IIT Kharagpur); C Kumar, D K Nauriyal, Rajat Agrawal, Vinay Sharma (IIT Roorkee)

6. Policy Law and Governance (PLG)

Lead: N C Narayanan, IIT Bombay and Indrajit Dube, IIT Kharagpur

Members: Shyam Asolekar, Subodh Wagle (IIT Bombay); Mukesh Khare (IIT Delhi); Vinod Tare (IIT Kanpur); Deepa Dube, Uday Shankar (IIT Kharagpur); G N Kathpalia, Paritosh Tyagi (IDC, New Delhi)

7. Geo-Spatial Database Management (GDM)

Lead: Harish Karnick, IIT Kanpur

Members: N L Sharda, Smriti Sengupta (IIT Bombay); A K Gosain (IIT Delhi); Arnab Bhattacharya, Kritika Venkatramani, Rajiv Sinha, T V Prabhakar, Vinod Tare (IIT Kanpur)

8. Communication (COM)

Lead: T V Prabhakar, IIT Kanpur

Members: Purnendu Bose, Rajiv Sinha, Vinod Tare (IIT Kanpur)

9. Environmental Flows (EFL)

Lead: Vinod Tare, IIT Kanpur

Members: Shyam Asolekar (IIT Bombay); A K Gosain (IIT Delhi); P M Prasad, R P Mathur, Rajiv Sinha, Shivam Tripathi (IIT Kanpur); M D Behara (IIT Kharagpur); B S Murthy, N Balaji (IIT Madras); Pranab Mohaparta, Vikrant Jain (IIT Gandhinagar); S K Jain (NIH Roorkee); Nitin Kaushal (WWF-India, New Delhi); Sandeep Behera (NMCG, MoWR, RD & GR, New Delhi); A P Sharma K D Joshi (CIFRI, Barrackpore); Ravindra Kumar (SWaRA-UP); Ravi Chopra (PSI, Dehradun); Paritosh Tyagi, (IDC, New Delhi)

Abbreviations and Acronyms

1.	BBM	:	Building Block Method.
2.	BCM	:	Billion Cubic Metres.
3.	CGWB	:	Central Ground Water Board.
4.	CWC	:	Central Water Commission.
5.	E-Flows	:	Environmental Flows.
6.	ET	:	Evapo-Transpiration.
7.	FAO	:	Food and Agricultural Organization.
8.	GRBMP	:	Ganga River Basin Management Plan.
9.	IITC	:	IIT Consortium.
10.	MLY	:	Middle and Lower Yangtze (river).
11.	MoEF	:	Ministry of Environment and Forests.
12.	MoEFCC	:	Ministry of Environment, Forests & Climate Change
13.	MoWR	:	Ministry of Water Resources.
14.	MoWRRDGR	:	Ministry of Water Resources, River Development & Ganga Rejuvenation
15.	NCIWRD	:	National Commission on Integrated Water Resources Development
16.	NGO	:	Non-Governmental Organization.
17.	NGRBA	:	National Ganga River Basin Authority.
18.	NMCG	:	National Mission for Clean Ganga.
19.	NRGB	:	National River Ganga Basin.
20.	NRGBMC	:	National River Ganga Basin Management Commission.
21.	ROR	:	Run-of-the river.
22.	UNEP	:	United Nations Environment Programme.

Contents

	Page
Preface	i
Organizational Structure for Preparing GRBMP	iii
Composition of Thematic Groups	v
Abbreviations and Acronyms	vii
List of Figures	xi
List of Tables	xii
Summary	xiii
1 Introduction	1
2 Objective	3
3 Importance of Aviral Dhara for Ganga River Basin Management	3
4 Status of Aviral Dhara in the Ganga River Network	4
4.1 Dams and Barrages	5
4.2 Water Withdrawals and Discharges	9
4.3 Hydrological Status of NRGB	11
5 Measures to Restore Aviral Dhara of National River Ganga	16
5.1 Water Storage	16
5.2 Water Use Efficiency	21
5.3 Water Resource Policy	22
5.4 Environmental Flows	23
6 Hydrological Modeling of GRBMP and Inferences	30
7 Sediment Resources of National River Ganga	36
8 Summary of Recommended Actions	40
References	43
Appendix I: Hydrographs of 30 Years' Maximum, Average and Minimum 10-Daily Flows Under Virgin and Actual (Present) Conditions for Sub-Basins of NRGB	49
Appendix II: Annual Sediment Load Variation in National River Ganga	59

List of Figures

Figure	Page
4.1 Major structural obstructions on River Ganga and her tributaries within India	7
5.1 Reservoir Evaporation	16
5.2 Storm-water Runoff Storage Options – Concentrated and Distributed Storages	20
5.3 Location Map of Flow Monitoring Stations and E-Flows Sites	26
5.4 Flows Assessment – Conceptual Diagram	27
5.5 River Cross-section at Ranari, Dharasu	27
5.6a E-Flows at Ranari, Dharasu	28
5.6b E-Flows during Non-Monsoon Season at Ranari, Dharasu	28
5.7 Some Existing and Under-Construction Barrages in Upper Ganga	30
6.1 Groundwater Model Area of Ganga Basin	31
6.2a Average (1969-2006) Annual Water Balance of the Modeled Ganga Basin	32
6.2b Average (1969-2006) Monthly Water Balance Components of the Basin	32
6.3 Line Diagram of Ganga River Network	34
6.4a Annual Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions	35
6.4b Wet Season Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions	35
6.4c Dry Season Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions	35
7.1 A Sediment Budget (in 10^6 tons/yr) for Ganga River Basin	37

Figure		Page
7.2	Comparison of the Annual Average Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga	38
7.3	Comparison of the Average Wet Season Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga	38
7.4	Comparison of the Average Dry Season Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga	39

List of Tables

Table		Page
4.1a	Water Resources Potential (in Billion Cubic Metres) in Indian River Basins	11
4.1b	Projected Water Demand in India in Billion Cubic Metres (BCM)	11
4.2	Groundwater Abstraction Rate and Depletion (with ranges of uncertainty) and Non-Renewable Irrigation Use per Country for Year 2000	15
5.1	Criteria for Permissibility of Dams and Other Projects on Rivers	17
5.2	Percentage of Virgin River Flow required as E-Flows at Ranari, Dharasu	28
7.1	Sediment Measuring Stations and Periods of Data Availability	38

Summary

The Ganga River Network was adopted in GRBMP as the primary indicator of health of National River Ganga Basin (NRGB), and human-technology-environment interactions were factored in to assess the basin's resource dynamics. While NRGB's present water status is poorly understood, a broad hydrological review indicates declining water availability in the river network due to large-scale water withdrawals from the basin's rivers and aquifers over many decades. Besides, the river network is extensively intercepted by dams and barrages into disjointed channel stretches with highly altered water, sediment and nutrient flows, thereby affecting river morphology and ecology. The depleted water availability of NRGB is borne out by hydrological modelling. The present-day sediment loads are also found to be much less than previous estimates. The main recommendations are: (1) Determination of NRGB's hydrological status more accurately and in greater detail. (2) Preparation of water resources plan for NRGB with emphasis on wetlands, forests and distributed groundwater and surface water storages rather than large impounded reservoirs. (3) Increase in water use efficiency through (i) realistic pricing of fresh water, (ii) incentives, technical assistance, and allocation of water rights and entitlements to consumers, and (iii) reuse and recycling of water. (4) Governmental policy shift to bring NRGB's water resources under natural resource management, with emphasis on resource preservation, stakeholder control, expert guidance and regulation. (5) Ensuring longitudinal river connectivity and environmental flows (of water, sediments and other natural constituents of flow) at dams, barrages and other manmade interferences, and adoption of new criteria for approving such projects. (6) Control of water withdrawals in water-depleting regions. (7) Assessment and monitoring of sediment resources of the network including assessment of quantity, quality and nutrient value of sediments trapped behind dams. (8) Research to determine the ecological limits, thresholds and interconnections of NRGB's water resources, and river flow health assessments within the framework of ecohydrology.

1. Introduction

Indian civilization grew up under the care of River Ganga, nourished by her bounties for thousands of years. The Ganga river – along with her many tributaries and distributaries – provided material, spiritual and cultural sustenance to millions of people who lived in her basin or partook of her beneficence from time to time. To the traditional Indian mind, therefore, River Ganga is not only the holiest of rivers and savior of mortal beings, she is also a living Goddess. Very aptly is she personified in Indian consciousness as “MOTHER GANGA”. This psychic pre-eminence of River Ganga in the Indian ethos testifies to her centrality in Indian civilization and her supreme importance in Indian life.

The Ganga river basin is the largest river basin of India that covers a diverse landscape, reflecting the cultural and geographical diversity of the India. It is also a fertile and relatively water-rich alluvial basin that hosts about 43% of India’s population [MoWR, 2014]. It is fitting, therefore, that the Indian government declared River Ganga as India’s **National River** in the year 2008. But the declaration was none too early. River Ganga had been degrading rapidly for a long time, and national concern about her state had already become serious in the twentieth century. It was against this backdrop that the Ministry of Environment and Forests (Govt. of India) assigned the task of preparing a Ganga River Basin Management Plan (GRBMP) to restore and preserve National River Ganga to a “Consortium of Seven IITs”. The outcome of this effort – the GRBMP – evolved an eight-pronged action plan, with each prong envisaged to be taken up for execution in mission mode.

A river basin is the area of land from which the river provides the only exit route for surface water flows. For understanding its dynamics, a basin may be viewed as a closely-connected hydrological-ecological system. Hydrological connections include groundwater flow, surface runoff, local/ regional evapotranspiration-precipitation cycles and areal flooding, while ecological links are many and varied (such as the food web and transport by biological agents). These linkages provide for extensive material transfer and communication between the river and her basin, which constitute the

functional unity of a river basin. Directly and indirectly, therefore, National River Ganga (along with her tributaries and distributaries), is a definitive indication of the health of the basin as a whole. Hence, GRBMP adopted the Ganga River Network as the primary environmental indicator of the National River Ganga Basin (NRGB).

River basin management needs to ensure that a basin's natural resources (biotic and abiotic) are adequately preserved over time. The main abiotic (or physical) resources of a river basin are *soil* and *water*, along with a multitude of minerals and compounds bound up with them. Now, water is a highly variable resource. Barring variations from year to year, the water in a basin follows an annual cycle of replenishment (primarily through atmospheric precipitation and groundwater inflows) and losses (primarily through river and groundwater outflows, evaporation, transpiration, and biological consumption). In contrast to water, formation of mature soils – from the weathering of parent material (rocks) to chemical decomposition and transformation – is a drawn-out process that may take hundreds or thousands of years [*Jenny, 1994; Wikipedia, 2014*]; but, once formed, soils can be fairly durable. Thus, changes in a basin's water resource status tend to be relatively faster and easily detected, while those of soils are slow and often go unnoticed for long periods. However, soil and water are affected by each other through many biotic and abiotic processes. Being thus interrelated, degradation of either soil or water has a concurrent effect on the other; hence neither can be considered in isolation.

It is not only soil and water that are mutually interactive, living organisms also interact with them and help shape the basin's environment. The biotic resources of a basin consist of plants, animals and micro-organisms. Since biota evolve over time to achieve a stable balance in a given environmental setting, the biotic resources of a river basin depend on its constituent ecosystems – rivers, wetlands, forests, grasslands, etc. However, with significant human activity in many ecosystems (as, for example, in agro-ecosystems and urban ecosystems), the complexity of human-technology-environment systems has increased manifold [*Pahl-Wostl, 2006*]. Nonetheless, GRBMP attempts to incorporate interactive natural resource dynamics and human-technology-environment considerations in the Basin Plan. For, with human activities multiplying and diversifying in the basin, the resulting environmental

consequences have also been pronounced in recent times. In sum, GRBMP focuses on the basin's overall resource environment and the major factors affecting it (especially diverse anthropogenic activities), and seeks ways and means to protect the basin and its resources against identifiable adverse impacts. For, only thus can we secure the environmental foundation of NRGB for the good of one and all.

2. Objective

The objective of Mission “Aviral Dhara” is to ensure that the flow of water – along with sediments, nutrients and other natural constituents of the flow – are continuous and adequate throughout the Ganga river network.

3. Importance of Aviral Dhara for Ganga River Basin Management

Climatically and geomorphologically NRGB is a large and diverse basin characterized by a network of large perennial rivers and smaller perennial or seasonal streams – the Ganga River Network – traversing from their upland sources to the sea. The basin is very fertile and has provided the natural resource needs of the basin's ecosystems and human settlements for ages. But the river network (and the basin as a whole) has seen declining water availability over the decades. In addition, there have been increasing spatial interruptions in river flows over many decades due to a host of manmade dams and barrages. The overall changes in the flow regimes of the rivers of the network have been lopsided – with greatly reduced lean season flows, but undiminished or probably even enhanced flood flows in the wet seasons – which have gone hand-in-hand with various other changes in the natural resources of rivers, notably of sediments, nutrients and biodiversity.

The above changes are found to be linked to major anthropogenic activities in the river basin rather than to natural processes. As a result, the Ganga basin and its river network are being functionally worn-out and emaciated, as reflected in the loss of biodiversity in the river network and the strain on goods and services emanating from the rivers. This underscores the urgent need to

rectify or compensate for deleterious human activities in the basin in order to maintain “Aviral Dhara” in the river system.

4. Status of Aviral Dhara in the Ganga River Network

For a given geological setting and climatic pattern, alluvial rivers – as characterized by their morphologies, drainage network and fluvial patterns – achieve stability through long-term physical balance between various dynamic parameters such as basin runoff and erosion rates, river water and sediment flow volumes, and influent/ effluent seepage rates. “Aviral Dhara” is a consequence of this long-term stability of rivers. Anthropogenic activities have violated this aspect of Ganga river’s integrity in several ways – by erecting obstacles to flow, by significant water withdrawals, by increased waste disposal into rivers, and by altering the natural water recharge/ outflow rates into/ from the basin. Regarding the last point, it may be noted that, since much of the basin is hydraulically connected by groundwater flow (besides other hydrological connections), water withdrawals/ recharges are not only those directly from/to the rivers but also those from/to different parts of the basin. Thus, while longitudinal connectivity in the river network is an essential first step to maintain “Aviral Dhara”, having adequate river flows depends much on the basin’s overall water status.

Box 4.1

“Damming and flood control can have negative impacts (in rivers), such as declining fish catches, loss of freshwater biodiversity, increases in the frequency and severity of floods, loss of soil nutrients on floodplains, and increases in diseases such as schistosomiasis and malaria. ... On the Mississippi River, the rising frequency and severity of flooding – attributed to local flood control structures – have reduced the river’s ability to support native flora and fauna, while a dramatic increase in floods on River Rhine has been attributed to increased urbanization, engineering, and the walling off of the river from its floodplain.”
– UNEP [2008]

Dams, barrages and other manmade structures block or constrict rivers, thereby interrupting the flow of water, sediments and aquatic species. While the short-term and local benefits of such structures can be reasonably estimated, the long-term, basin-wide environmental losses in terms of river instability, fertility of the river and its floodplains, ecological balance, nature of

flood events, health effects, and other facets of basin performance are difficult to predict [UNEP, 2008; WWC, 2000]. Similar adverse effects are also caused by anthropogenic activities that significantly alter river flows or sediment loads. The UNEP document cited in Box 4.1 discusses some of these aspects in terms of “*river fragmentation*” defined as “the interruption of a river’s natural flow by dams, inter-basin transfers or water withdrawal ... by man.” However, it is not only interruptions or changes in water flow rate that cause physical imbalance in a river; the balance may also be easily upset by alterations in sediment load and changes in seepage inflow/ outflow rates and overland inflow rates.

The two main anthropogenic factors that have increasingly dented Aviral Dhara in the Ganga River Network over the past two centuries are: (i) the large number of dams and barrages that have interrupted the flow of water, sediments and nutrients in the river network, and (ii) the excessive withdrawal of water for human needs from the river network and the basin. Besides, there are other human factors (such as those causing changes in land use and land cover) that have, directly or indirectly, affected Aviral Dhara in the National River Ganga. The main factors are discussed below.

4.1 Dams and Barrages

Figure 4.1 shows major dams and barrages erected in the Ganga River Network [MoWR, 2014]. Dams and barrages often help to meet several anthropogenic needs such as water supply, hydropower generation, flood control and navigation. But these obstructions have divided National River Ganga and her tributaries into small segments, thereby interrupting the flow of water, nutrient, sediments and aquatic species in the rivers. In the Upper Ganga Basin, the obstructions include cascades of *run-of-the-river* (ROR) hydro-electric projects in the Bhagirathi and Alaknanda head streams. Many of these projects are constructed or planned end to end, i.e. the tail waters of one project are head waters of the next one, so that the river gets transformed into a series of reservoirs. Moreover, the water stored behind a dam is sent through tunnels to turbines and released as tail waters at downstream points of the rivers. Thus, long stretches of rivers between dams and tail-water releases are almost devoid of water. Overall, an estimated 86 km length of

River Bhagirathi is thus without any flow whatsoever [IITC, 2014a]. Besides, sediments get trapped behind the dams, thereby disrupting the downstream river's water-sediment balance and affecting nutrient flow and fertility of the downstream river.

More than 70 hydropower projects (large and small dams) have been conceived in the Upper Ganga Basin, many of which are still in the planning stage. While there have been environmental impact studies of some individual dams, the only comprehensive study of their cumulative environmental impact in the river sub-basins was made by the Wildlife Institute of India [*Rajvanshi, 2012*]. However, the study was limited in scope. For instance, its focus did not extend beyond the Bhagirathi and Alaknanda sub-basins, so that the impact of the dams over the downstream river's ecology remained unexplored. It may be also noted here that, while many of these dams are small, the common notion that small dams have relatively insignificant impacts on river ecosystems is a misconception. In some cases, the cumulative impact of small dams may be more damaging to river ecosystems than those of large dams of equivalent power generation capacity [*Kibler and Tullos, 2013*].

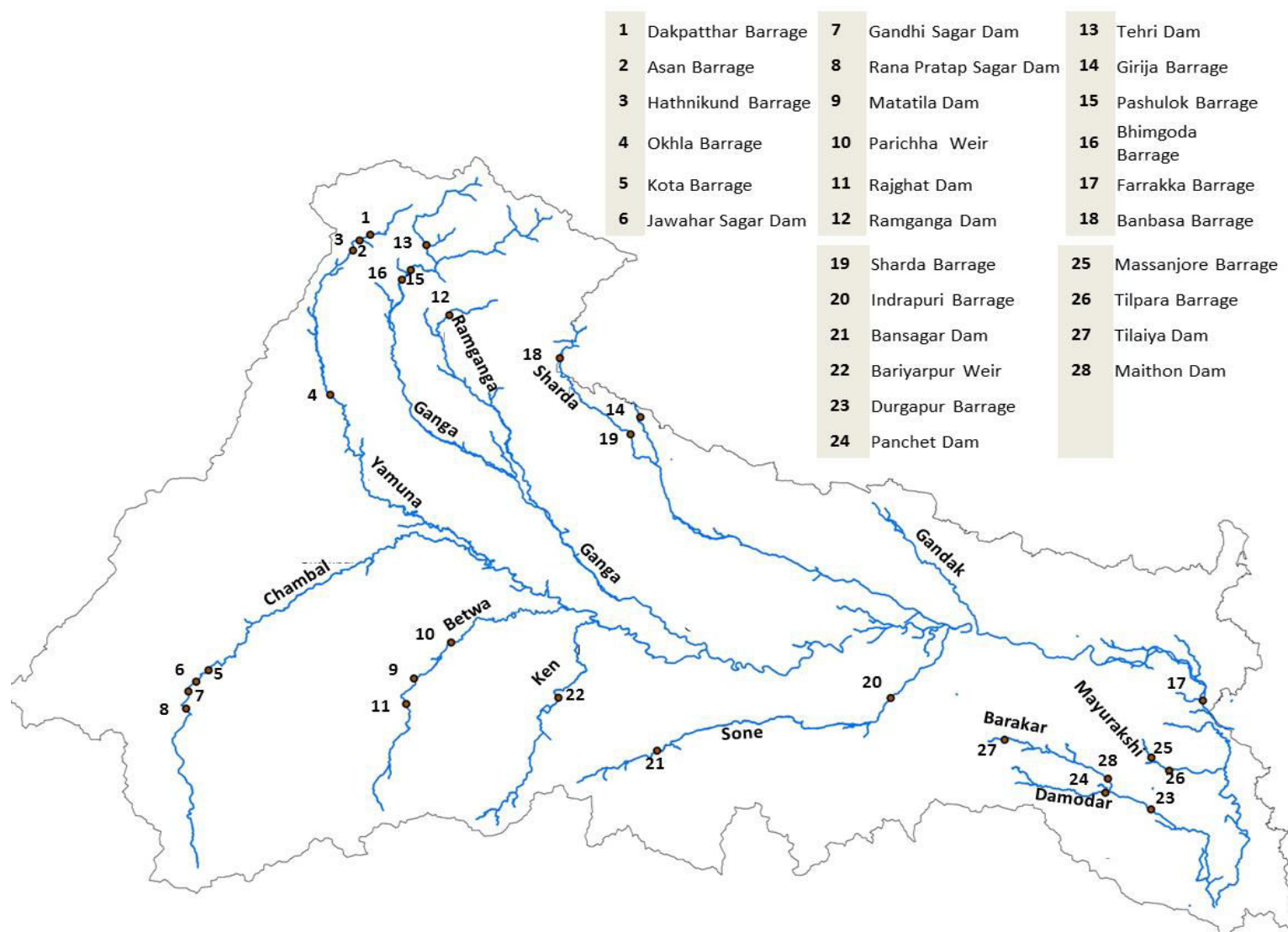


Figure 4.1: Major structural obstructions on River Ganga and her tributaries within India [MoWR, 2014]

Downstream of the hydroelectric projects in the Bhagirathi and Alaknanda basins, the Pashulok barrage on River Ganga near Rishikesh diverts nearly all the dry-weather flow of main Ganga river into the power channel of Chilla Power Station. The tail water of this power station joins the Ganga river near Bhoopatwala. Thus, a distance of about 15 km from Pashulok barrage to the junction of the tail waters with the river has essentially no flow. Further downstream, Bhimgauda Barrage, Madhya Ganga Barrage and Narora Barrage intersect the river successively to divert water to the Upper, Middle and Lower Ganga Canals. Further downstream, River Ganga is again clipped at Kanpur by the Lav-Kush Barrage. Finally, as the river heads for the estuarine reach, it is again bifurcated by the Farakka Barrage in West Bengal, which diverts part of the flow into a canal to feed the Bhagirathi-Hooghly river.

Besides the above operations on the main Ganga river, major dams and barrages on her tributaries include the Ramganga Dam on Ramganga river in Uttarakhand, the Asan Barrage, Dakpathar Barrage and Hathnikund Barrage (and the upcoming Lakhwar Dam) on River Yamuna, the Ichari Dam and Tons Barrage on River Tons, the Dhandhraul Dam on Ghaghra river, Gandhi Sagar Dam on Chambal river, the Rajghat, Parichha and Matatila Dams on Betwa river, the Rihand Dam on Rihand river in Uttar Pradesh, the Bansagar, Jawahar Sagar and Ruthai Dams on Kali Sindh, the Chandil, Tenughat, Maithon, Panchet and Tilayia dams on the Suvarnarekha and Damodar rivers in Jharkhand, and the Durgapur Barrage on River Damodar in West Bengal [NIH, 2014]. Needless to say, the innumerable intercepts in the Ganga river network have fragmented the once unified river network into disjointed stretches of flowing and stagnant waters.

Dams and barrages trap much of the river sediments, converting the downstream river water into what is called *hungry water* – “hungry water has sufficient energy to transport sediment but the sediment has been captured behind the dam. The hungry water gradually consumes the bed and banks of the river below the dam, resulting in entrenchment and armoring of the bed” [Wampler, 2012]. The long-term effects of this process significantly affect the morphology of rivers and their floodplains [Graf, 2006; Gupta et al., 2012].

In addition to the direct impacts of dams and barrages on river geomorphology, the sediments trapped behind these structures may contain

many mineral nutrients, thereby depriving the downstream river stretches of essential nutrients. It may be noted that, apart from carbon, hydrogen and oxygen, at least twenty five (and probably many more) elements are essential for plants and animals (namely, N, P, K, Ca, Mg, S, Na, Cl, B, Zn, Cu, Mn, Fe, Co, Ni, Mo, Li, I, Se, Cr, V, Si, F, As, and Sn, vide *Graham, 2008*). While knowledge of the effects of micro-nutrient deprivation in river ecosystems may be limited, the effect of deprivation of essential macro-elements (like N and P) on river biota have been studied [*refer Elser et al., 2007*]. In this context, a report by Zhou et al. [2013] on the effects of the Three Gorges Dam on phosphorus depletion in MLY (i.e. Middle and Lower Yangtze river) deserves mention. Until major dam constructions begun on River Yangtze in the 1990s, the river discharged about 940 km³/yr water and 478 Mt/yr of sediment into the East Sea, with the MLY stretch (about 2,000 km long below the Three Gorges Dam up to the estuary) getting little sediment added in the MLY reach. Zhou et al.'s study reveals that by 2011 (i.e. within 10 years of operation of the Three Gorges Project) the total sediment load in MLY reduced to only 6% of its previous long-term average, thereby resulting in extensive scouring of the river channel. Moreover, nutrient-rich fine sediment load reduced to only 8% of its long-term average. As a result, the Total P and Particulate P loads delivered to the MLY reduced to only 23% and 16.5% of their long-term values. Now P had already been a limiting nutrient for the Yangtze river's bioactivity before large dams came up on the river, hence its further reduction was critical for bioproductivity in MLY.

4.2 Water Withdrawals and Discharges

Large anthropogenic water abstractions are being effected from the Ganga River Network all over the basin, thereby dehydrating the rivers to a considerable extent. Many of the dams and barrages mentioned above are used to divert river flows for human use. After the start of the main stem of National River Ganga, the Bhimgauda Barrage diverts nearly all the river water to the Upper Ganga Canal (having head discharge capacity of about 300

cu.m/s) at Haridwar¹. Large water abstractions occur thereafter at Bijnor and Narora to divert river water into the Middle and Lower Ganga Canals respectively. Abstraction of river waters also occurs at different points for urban water supplies. In addition, many dams and barrages on the tributaries of River Ganga (mentioned in the previous section) are coupled with water diversion into irrigation canals (such as the Yamuna, Sarda, Ramganga, Kosi and Sone canal systems). Thus, even after the confluence with River Yamuna near Allahabad, the Ganga river flow is low and must be significantly less than what it was a century ago. Thus, large-scale water abstractions directly from the river network have contributed greatly to the mighty Ganga river becoming an emaciated stream during most of the lean season ever since the Upper Ganga Canal System was made operational in the mid-nineteenth century [UPID-FAO, 2008].

In addition to water withdrawals directly from rivers, there has been increased groundwater pumping in the basin in recent decades, resulting in falling water table in many places. Thus, one must take into account the additional sub-surface outflows from (or reduced base flows into) rivers due to the lowering water table in the basin.

Finally, it should be noted that water abstractions from the river network and the river basin are generally high during lean flow seasons but very low during the wet seasons. This results in the river channel carrying extremely low flows during the dry season but with the original high flows of the wet season almost intact. In fact, peak runoff rates from the basin into the rivers may have increased in many places due to urbanization and land-use/ land cover changes over the past one or two centuries, thereby increasing the river flood peaks from their earlier levels. Overall, the extremes of the river's natural hydrological regime have certainly accentuated, thus exerting further pressure on its hydro-geomorphological functioning.

¹ Note: The flow diverted into the Upper Ganga Canal is regulated at Mayapur head works. During lean seasons, only a little water is led back into the Ganga river downstream at Kankhal, with the stretch from Hardwar to Kankhal being nearly dry [IITC, 2014a].

4.3 Hydrological Status of NRGB

The water resources potential and water use in India (and in NRGB) have been evaluated by nodal government agencies under MoWR, GOI. Some relevant data are cited in Tables 4.1a and 4.1b [CWC, 2008; CWC, 2010; Jain *et al.*, 2007].

Table 4.1a: Water Resources Potential (in Billion Cubic Metres) in Indian River Basins

River Basin	Catchment Area (km ²)	Total Water Resource Potential (BCM)	Total Utilizable Water Resource Potential (BCM)	
			Replenishable Ground Water Potential (BCM)	Utilisable Surface Water Resources (BCM)
Ganga	861452	525	171	250
Total Indian	3290000	1869	433	690

Table 4.1b: Projected Water Demand in India in Billion Cubic Metres (BCM)

Sector	Standing Sub-Committee of MoWR			NCIWRD		
Year	2010	2025	2050	2010	2025	2050
Irrigation	688	910	1072	557	611	807
Drinking Water	56	73	102	43	62	111
Industry	12	23	63	37	67	81
Energy	5	15	130	19	33	70
Others	52	72	80	54	70	111
Total	813	1093	1447	710	843	1180

The above data give an indication of the critical status of water resources in India (and in the NRGB), especially when water demands are compared with the water resource potentials. The following points, however, are pertinent with regard to these data:

- How Approximate are the Water Resources Potentials? Estimates of water resources potentials made at different times and/or by different government agencies are often very different from each other [CWC, 1986;

CWC, 2008]. While the likely error margins are not indicated in the above documents, the figures have enough room for uncertainty depending on estimation methods and measurement techniques. For instance, *ground water potential* depends on estimating storages and yields of complex aquifer systems spread over large and diverse regions. On the other hand, *surface water resource potentials* do not include surface water bodies. In reviewing the government water balance estimates, Jain [2012] argued that the governmental estimates of ET (i.e. evapo-transpiration) in the Ganga basin at 23% of precipitation is too low, and suggested that it should be considered instead as 60% of precipitation as in the case for ET of most other Indian basins. The consequent estimates would reduce India's and NRGB's water resources potentials by huge amounts. In a more detailed and critical analysis, Garg & Hassan [2007] used the same government data and showed that the above water resource potentials are actually highly overestimated – by up to 88%; hence the total utilizable water resource potential of India (with the same water reservoirs deemed feasible) amounted to only 654 BCM instead of 1123 BCM, which is far short of even the present water demand of India, an issue that has already been internationally noticed [UNICEF et al., 2013].

- b) The above water estimates are for very large regions, and spatial variations of water resources potentials cannot be gauged from the above data. Such variations are large in NRGB considering the diversity in physiographic and hydrological features of the basin.
- c) As seen from Table 4.1a, India's surface water resources potential (1,869 BCM) as well as its "utilizable" part (690 BCM) are significantly greater than the ground water potential (433 BCM). On the other hand, government estimates show that, *"more than 90% of the rural and more than 50% of urban water supply is met by ground water ... with an estimated annual groundwater withdrawal of 221 BCM"* [CGWB, 2012]. Thus, groundwater usage is evidently much higher than surface water usage, although surface water potential is much higher than groundwater potential. This differential usage needs to be considered in framing India's water resource management policies.

- d) The information cited in the above paragraph also shows that India's estimated "water usage" is much less than half of the estimated "water demand" of 710 BCM or 813 BCM in 2010 (vide Col.5 and Col.2 of Table 4.1b), which suggests that India was already under severe water-stress/ water-scarcity in 2010. However, this conclusion seems untenable if "water-stress" is based on the premise of per capita water availability being less than 1000 m³/year (which seems to be the government norm, vide *India-WRIS, 2012*, whereas the international norm for hydrological water stress is when a nation's per capita water availability falls below 1700 m³/yr, vide *FAO, 2012; UN-Water, 2013*). In fact, as per CWC figures, the per capita water availability in India was 1588 m³/yr in 2010 (the per capita water availability was significantly higher in the Ganga basin at almost 2000 m³/yr in 2010) and is expected to reduce to 1434 m³/yr in 2025 [*CWC, 2010; India-WRIS, 2012*]. Table 4.1 also shows that the "utilizable" water resources of India are only 690 BCM. Likewise, NIH states that India's "utilizable" per capita water availability reduced from 1,100 m³/yr in 1998 to 938 m³/yr in 2010, and is expected to further reduce to 814 m³/yr in 2025 [*NIH, 2013*]. However, the terms "utilizable" and "replenishable" are not quantitatively explained, nor are the likely errors in determining them indicated, thus adding to overall confusion about the significance of the data. While clarity on these data and their interpretations are needed, it seems certain, however, that NRGB (like much of the country) is under increasing water stress, which calls for major changes in how NRGB's water resources are managed.
- e) The projected water demands in Table 4.1b were evidently computed without assessing the demand trends or other factors. But given binding constraints on water availability, the growth in demand must get constrained, implying a need for demand management [*UNICEF, 2013*]. Moreover, the "demands" themselves are questionable. On reviewing the demand data, Jain [2011] recommended that "*a detailed study to compute future water demand should be taken up.*" In a more detailed review of NCIWRD's estimates, Verma and Phansalkar [2007] noted, "*The commission's (i.e. NCIWRD's) estimates of 'water demand' are built on the basis of minimum norms set down by various agencies ... (instead of) the price at which the water is supplied and the quality of the supply.*" To

reiterate Verma and Phansalkar's recommendation on this issue, *"A refined prognosis of India's water future must account for two critical variables missed by the commission: (i) water demand (as against water requirement) as a function of price, availability and quality of supply; and (ii) coping mechanisms of the users of water."* In fact, the estimated "demands" are not even "requirements"; rather they seem to be estimates of "present water use" and hypothetical "future water use".

- f) The projected water demands are for human use only, and do not give any indication of the water needed to sustain healthy functioning of the basin. Generally, in most governmental water resource assessments, no attempt is made to reliably assess this requirement and it is often ignored. Or, at best, a token value is assumed. The same is the case in the above estimates. As noted by Verma and Phansalkar [2007], *"(NCIWRD) makes a 'token provision' of 5, 10 and 20 BCM for water for floods, environment and ecology (combined) for 2010, 2025 and 2050, respectively."*

Thus, a reliable picture of the present water status of India and NRGB or its sub-basins is unavailable. Evidently, NRGB's (and India's) water status needs to be determined afresh and in considerably greater detail in order to estimate its true potential and its changing impact on river flows. In NRGB, as for India as a whole, it is not only natural components like ET and groundwater recharge data that may be erroneous, reliable data on water use are also scarce. Apart from industrial water use which is declared to be uncertain [MOWR, 2008], the estimated irrigation water use in India – the highest water consuming sector at 83% of national water use [MOWR, 2008] – could be highly inaccurate due to numerous un-monitored private tube-wells operating in the basin for many decades. International studies indicate that, not only are India's estimated groundwater abstraction the highest in the world, but that the uncertainty in this estimate is also the highest ($\pm 37 \text{ km}^3/\text{yr}$) as shown in Table 4.2, vide Wada *et al.* [2012]. Wada *et al.*'s data also show that India's overall groundwater depletion and non-renewable groundwater abstractions for irrigation are exceedingly high, with almost 20% of the irrigation groundwater abstraction for the year 2000 being non-renewable. Other independent estimates [notably Tiwari *et al.*, 2009] also reveal similar unsustainable trends in India's groundwater extractions.

Table 4.2: Groundwater Abstraction Rate and Depletion (with ranges of uncertainty) and Non-Renewable Irrigation Use per Country for Year 2000 [*Wada et al., 2012*]

Country	Abstraction (km ³ /yr)	Depletion (km ³ /yr)	Gross Crop Water Demand (km ³ /yr)	Nonrenewable Abstraction (km ³ /yr)
India	190 (±37)	71 (±21)	600	68
United States	115 (±14)	32 (±7)	203	30
China	97 (±14)	22 (±5)	403	20
Pakistan	55 (±17)	37 (±12)	183	35
Iran	53 (±10)	27 (±8)	59	20
Mexico	38 (±4)	11 (±3)	71	10
Saudi Arabia	21 (±3)	15 (±4)	14	10
Globe	734 (±82)	254 (±38)	2510	234

Notwithstanding errors and uncertainties in the water resources estimates quoted above, it is fairly certain, however, that human water demands have been increasing while dry-season river discharges and ground water levels have been falling in many parts of NRGB, which implies that the hydrological status of NRGB is shifting relentlessly towards a state of critical imbalance. To overcome this impending crisis, it is imperative that either (i) water availability in the basin is increased through *increased storages*, or (ii) water consumption is reduced through more *efficient water use* (or both options are simultaneously pursued).

5. Measures to Restore Aviral Dhara of National River Ganga

5.1 Water Storage

Human interventions promote two types of water storages, viz. *concentrated (or centralized) storage* and *distributed (or decentralized) storage*. Till date, governmental focus has been mainly on “*centralized storages*” in the form of dammed reservoirs on rivers. While such storage systems have the advantage of economy of scale for capital costs, they often involve significant costs for reservoir operation, transportation

of water to end-users, human displacements, land inundation, ecological damage, and river mutilation. In fact the poor efficiencies of surface irrigation systems in India (about 35–40 % in contrast to about 60% for groundwater irrigation systems, vide CWC, 2008) may be partly attributed to conveyance losses from reservoirs to farmlands. Moreover, evaporation losses from surface reservoirs are

often high, especially in tropical climates like India's. To give an example, as per the annual water balance estimated for the Aswan Reservoir in Egypt, “*10 km³ of the entire Nile flow at Aswan, i.e. 84 km³, would (i.e. estimated to) be lost in evaporation and seepage*” [Awulachew et al., 2011]. As per UNESCO, globally more water evaporates from reservoirs than is used for industrial and domestic needs (see Figure 5.1) [UNEP, 2008]. NCIWRD assumed evaporation losses from large reservoirs at a flat rate of 15% [Verma and Phansalkar, 2007], which reflects the significant evaporation losses.

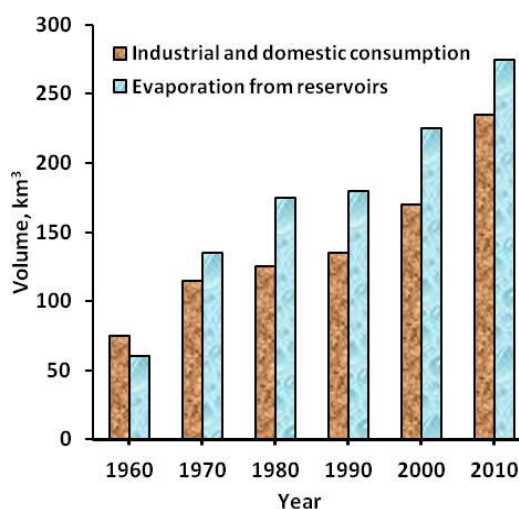


Figure 5.1: Reservoir Evaporation

Notwithstanding the above limitations, dams often fulfill several needs other than consumptive water use, such as hydropower generation, flood control and navigation. Thus, though dams (and other hydraulic structures that

fragment, constrict or otherwise mutilate rivers) may be undesirable in free-flowing rivers, their environmental impacts need to be considered in full before adopting or discarding specific projects. Accordingly four broad categories of dams, barrages and other hydraulic structures have been worked out in GRBMP [IITC, 2015] for environmental clearance based on their individual environmental impacts as presented in Table 5.1.

Table 5.1: Criteria for Permissibility of Dams and Other Projects on Rivers

Category	Type of Environmental Impact	Environmental Clearance
I	<p>MAJOR LONG-TERM, IRREVERSIBLE IMPACTS:</p> <p><u>Break in Longitudinal River Connectivity</u> leading to: (i) loss of habitat of rare or endangered species in river; <u>and/or</u> (ii) disruption in movement of biota along the river length; <u>and/or</u> (iii) disruption in sediment transport in the river.</p> <p><u>Critical Flow Reductions</u> leading to: inadequate Environmental flows needed to maintain river stability and ecological balance.</p> <p><u>Land Inundation</u>: causing loss of habitat of endangered/ rare terrestrial species living in the areas inundated.</p>	<p><i>Such projects should NOT be given Environmental Clearance*.</i></p>
II	<p>LONG-TERM, IRREVERSIBLE IMPACTS OF LESS IMPORT:</p> <p><u>Land Inundation</u> resulting in: (i) loss of terrestrial biodiversity and other ecological changes; <u>and/or</u> (ii) loss of historical, religious and cultural heritage sites.</p> <p><u>Geological Hazards</u> such as: (i) seismic hazards; <u>and/or</u> (ii) landslides, land subsidence, etc.</p>	<p><i>May be given Environmental Clearance* only after thorough study and review by domain experts.</i></p>

Table Continued on next page

Table Continued from previous page

Category	Type of Environmental Impact	Environmental Clearance
III	<p>POTENTIALLY REVERSIBLE LONG-TERM IMPACTS: <u>Land Acquisition and Inundation</u>, leading to: dislocation of human habitat, loss of livelihood, marginalization, etc. <u>Construction Activities</u>, leading to: ecological damage, disruption of local hydrology, human dislocation, loss of livelihood, etc. <u>Inadequate downstream water leading to</u>: adverse effects on livelihood, tourism (including religious tourism) and recreational activities. <u>Adverse socio-economic impacts</u>: Demographic changes, changes in livelihood patterns, unplanned “developmental activities”, tourism and other recreational activities, etc.</p>	<p>May be given Environmental Clearance subject to:</p> <p>(i) a comprehensive socio-economic and environmental impact assessment of the project by an independent agency;</p> <p>(ii) formulation of a Rehabilitation/ Resettlement Plan and an Environmental Management Plan acceptable to all stakeholders; and</p> <p>(iii) formulation of a strong monitoring mechanism to ensure implementation of the EMP (Environmental Management Plan).</p>
IV	<p>POTENTIALLY REVERSIBLE SHORT-TERM IMPACTS: <u>Construction Activities that cause</u>: noise, explosions, degradation of forests and agricultural land, pollution from debris, influx of outsiders, despoiling of nature, etc. <u>Potentially adverse socio-economic impacts</u>: Increase in crime and other social vices, tensions between local population and outsiders, etc.</p>	

**A project not cleared from the environmental angle may, however, be allowed on the basis of overriding national interest. Conversely, a project which has been cleared from the environmental angle, may be disallowed on the basis of overriding national interest. All such decisions must be made at the highest political level.*

The study by Zhou *et al.* [2013] discussed in Section 4.1 is also of relevance here. Their study showing the downstream effect of the Three Gorges Dam on phosphorous deprivation in the Yangtze river suggests that dams and barrages in the Ganga River Network may also be causing deficiencies of essential

mineral nutrients in the downstream river reaches. Without adequate data of the Ganga river's nutrient levels, however, a definite conclusion cannot be drawn in this regard. Hence there is a need to: (i) assess the availability of essential nutrient elements in different branches and stretches of the Ganga river network and identify the nutrient-starved stretches; and (ii) assess what nutrient elements are stored in the sediments trapped behind dams, and devise suitable means to release the sediments to nutrient-starved downstream reaches.

The second option of “*distributed water storage*” can be of much advantage in NRGB (see Figure 5.2). For NRGB has a vast groundwater storage capacity which can be annually replenished by capturing runoff and letting it percolate down to the water table through recharge pits, trenches, etc. Enhancing groundwater recharge would, however, need detailed basin surveying to identify suitable recharge zones. A recent report by CGWB [CGWB, 2014] in this regard is a suitable starting point. In addition, ponds and tanks (distributed surface storages) also need to be promoted in view of their broader environmental and socio-economic usefulness. Taken up at the level of small or micro-watersheds, these measures have the advantage of better decentralized management by local bodies and end-user communities, besides boosting groundwater levels and river base flows. However, both field-level technical help and relevant data (climatic, topographic, soil profile, water table, etc.) should be made available by government agencies to such users.

The “*distributed storage*” concept should also be applied to natural ecosystems of NRGB, especially wetlands, forests and grasslands. These ecosystems contribute significantly to conservation of water and other natural resources in the basin. For instance, wetlands, often referred to as “kidneys of the earth”, not only help in purifying wastewaters before they reach the rivers or groundwater, but also help in nutrient cycling, flood mitigation, and providing food, fibre and fresh water during dry periods. As noted by Pegram *et al.* [2013] “*healthy and functioning aquatic ecosystems are fundamental to rivers, in terms of the goods and services that they provide, the cultural and other social activities they support, and their inherent biodiversity value. ... Experience shows that once seriously degraded, these systems become difficult and costly to return to healthy conditions. It is therefore critical for basin*

planning to incorporate an understanding of the ecological limits, thresholds and interconnections of the entire basin water resources.” Prasad *et al.* [2002] had emphasized the great need to protect the existing wetlands in India, pointing out that “even a small country like UK could designate 161 wetlands as Ramsar sites, India ... so far managed to delineate a mere six sites till date.” The number of Ramsar wetlands in India subsequently increased to 25 out of more than 200,000 identified wetlands in the country [SAC, 2011], but hundreds of other wetlands (including many in the NRGB) are in a state of pitiable degeneration on account of urbanization and land-use changes in their catchments, wetland encroachments, water withdrawals, and agricultural, municipal and industrial pollution [Bassi *et al.*, 2014; Dhandekar, 2011].

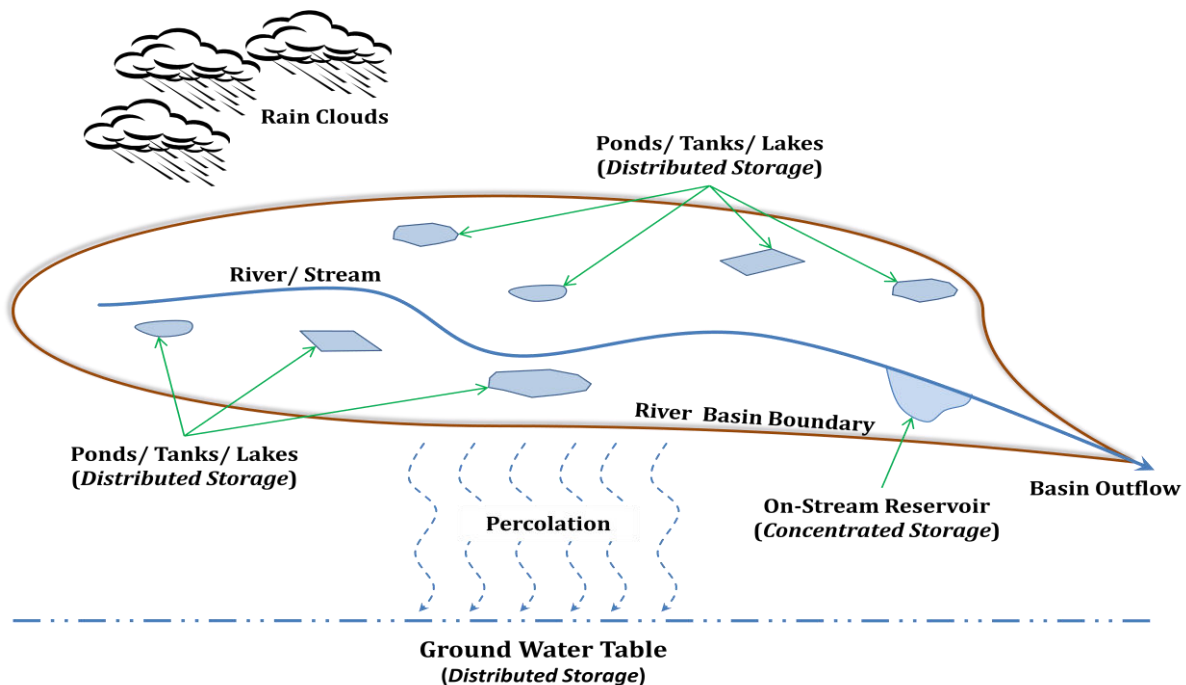


Figure 5.2: Storm-water Runoff Storage Options – Concentrated and Distributed Storages

Forests and grasslands, too, have reached minuscule proportions in the NRGB except in high altitude regions [India-WRIS, 2012]. Like wetlands, natural vegetal covers provide multiple environmental benefits including biodiversity conservation, erosion control, nutrient cycling, air and water purification, maintenance of soil health, increased groundwater recharge, flood mitigation, increased dry season flows, and increased precipitation. The last three points are particularly relevant for NRGB’s water resources. The so-called sponge effect of forests – namely the ability of forests to absorb excess waters during

floods and release them gradually later – has sometimes been questioned, but studies convincingly show that forests minimize flood peaks and increase dry season flows in rivers [see for example, *Ogden et al., 2013*]. On the last aspect concerning the effect of forests on precipitation, water resource experts typically consider forests as water-guzzling ecosystems on account of the high transpiration rates from trees; what is ignored in the water balance is the precipitation component of the regional hydrological cycle. But global field studies show that forests actually increase the precipitation in a region [*Ellison et al., 2012*]. Thus, even for the purpose of water budget only, forests can play a major role in improving the hydrological status of NRGB, especially in dry seasons.

Overall, the restoration and preservation of wetlands, forests and grasslands, combined with other water and soil conservation measures, are imperative needs in NRGB.

5.2 Water Use Efficiency

While water is a renewable resource, the renewal capacity of NRGB is limited by the region's precipitation and physiographic factors. Increasing water usage has led to progressively decreasing water availability and growing water crises in parts of the basin. More significantly, that fresh water usage in the basin as a whole may be nearing the average annual water renewal capacity may not have been realized by water-users, but this is a distinct possibility. Fresh water usage or demand control is therefore of utmost importance, effective measures for which are already pursued by many developed and developing countries. China's achievement in this regard is well-known to the Indian water establishment [*Iyer, 2012*], and her continuing efforts – such as 3-tiered water pricing for urban domestic supplies [*Spegele & Kazer, 2014*] – are worth noting. Broadly, several measures are required to ensure efficient water use, viz.:

- i) Realistic pricing of fresh water (especially for urban, industrial, commercial and affluent agricultural consumers) and disincentives for wastage of water.
- ii) Techno-economic assistance and incentives for poor and marginal sections (such as those engaged in subsistence agriculture) to improve water-use efficiencies.

- iii) Allocation of water rights and entitlements to stakeholders.
- iv) Direct reuse of water where possible, e.g. reuse of irrigation return flows.
- v) Treatment and recycling/reuse of domestic and industrial wastewaters where feasible.

5.3 Water Resource Policy

The foregoing discussions strongly suggest that the government strategy on managing NRGB's water resources needs some major changes. The desired policy changes may be stated as follows:

- A) Government agencies usually deal with NRGB's water resources independently of other natural resources; but the basin waters are intimately linked with other vital resources of the basin, such as soil (and sediments), nutrients (organic and inorganic) and biotic resources. It is imperative therefore that water resource management in NRGB should be assimilated into a broader framework of natural resource management instead of the myopic water-only focus.
- B) Thus far, governmental action on "water resources development" has meant extracting increasingly more water (and hydro-energy) from the basin for human use. This emphasis on water and energy abstractions has often led to the water resource systems themselves being endangered, as evident from many vanishing wetlands and streams. Thus, if "development" and "use" of water resources lead to their extinction, then it is evident that government priority must shift from "development" and "conjunctive use" of surface and ground water resources to their "conjunctive preservation".
- C) In recent decades, large-scale water (especially groundwater) abstractions from the environment are being effected by water-users themselves. Other aquatic resources are also being directly tapped by users. Yet, users are not entrusted with the maintenance of water resource systems, thereby creating a contradiction between ownership and usage. The obvious need to give stakeholders the rights and responsibilities to maintain water resource systems has been advocated by many experts [e.g. ADB, 2009; Sen, 2009; Thakkar, 2012; UNICEF et al., 2013]. Broadly in line with these suggestions, it is suggested that water resources

management should shift from “centralized government control” to “decentralized stakeholder control” combined with “expert guidance and regulation” for regional balance and sustainability.

5.4 Environmental Flows

Flow is one of the main drivers of biodiversity in rivers, and a river’s flow regime – the variation of high and low flows through the year as well as variation over the years – exerts great influence on its ecosystem. Environmental Flows (or E-Flows) are a regime of flow in a river that mimics the natural pattern of a river’s flow, so that the river can at least perform its minimal natural functions such as transporting water and solids received from its catchment and maintaining its structural integrity, functional unity and biodiversity along with sustaining the cultural, spiritual and livelihood activities of people. As per the 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 on these ecosystems.” In other words, E-Flows describe the

Box 5.1

Steps for Calculating E-Flows

1. Generation of Stage-Discharge curve at the E-Flows site using river cross section and hydraulic modelling.
2. Identification of keystone species for the stretch that represents the E-Flows site.
3. Assessment of temporal variations in depth of flow required to ensure survival and natural growth of keystone species.
4. Assessment of temporal variations in depth of flow from geomorphological considerations factoring longitudinal connectivity in all seasons and lateral connectivity of active flood plain for the historically observed number of days during monsoon season.
5. Assessment of minimum ecological depth of flow (higher of steps 3 and 4 above) and generation of Minimum Ecological Flows hydrograph.
6. Determination of 10-daily Average Flows and 90% Dependable Flows from historical flow data.
7. Applying the trend of variation of 90% Dependable Flows with the estimated minimum ecological flow depths to obtain 10-daily E-Flows hydrograph for dry and wet seasons.
8. Comparison of E-Flows and Ecological Requirements hydrograph with hydrographs for average and 90% dependable virgin flows.

temporal and spatial variations in quantity and quality of water required for freshwater and estuarine systems to perform their natural ecological functions (including material transport) and support the spiritual, cultural and livelihood activities that depend on them, vide IITC [2011].

After reviewing several different holistic methods of estimating E-Flows and in consultation with stakeholders and expert groups, the Building Block Method (BBM) was found to be robust and scientifically most suitable for rivers, as explained in the above report. But since it was found that the method results in Bigger Block governing E-Flows, BBM was considered to denote Bigger Block Method in GRBMP [IITC, 2011]. The method had been developed in South Africa through numerous applications in water resources development to address E-Flows requirements for riverine ecosystems under conditions of variable resources. Based on this method, E-Flows were computed for different sites of interest in the Ganga River System. It should be noted here that the BBM method quantifies only the lower bound on flow rates required at different times to sustain the river, and does not specify other conditions to be maintained in the river. One of these conditions is, of course, the connectivity in river flow. But maintaining the water-sediment balance is also an essential condition. In the absence of empirical data at specific sites, the required sediment flux has not been computed; it is suggested that E-Flows should carry suspended load and bed load in approximately the same proportions as present in the virgin flow.

To illustrate the E-Flows results, some of the selected sites on Alaknanda and Bhagirathi rivers of the Upper Ganga Segment are shown in Figure 5.3. These sites were chosen as they are considered to have high hydropower potential. The basic procedure for computing E-Flows is summarized in Box 5.1, and the detailed procedure is described in the concerned thematic report [IITC, 2015]. The geomorphological and biological features of the respective sites were analysed and the sites were physically surveyed to map the river cross-sections. The virgin river flows at these sites were considered for the period of data availability from CWC for the period 1972 to 1982 (prior to construction of Tehri Dam when the rivers could be considered 'virgin' or undisturbed). The virgin flows at the E-Flows sites were then estimated from the virgin flows at the nearest measuring stations.

E-Flows at the sites selected depend on ecological and geomorphological requirements and the minimum ecosystem goods and services of the river (including the cultural, spiritual and livelihood requirements). Referring to Figure 5.4, basic ecological flows corresponding to minimum depth D_1 are required during all seasons for general mobility of keystone river species. For the spawning period of keystone species, minimum ecological flows corresponding to depth D_2 are needed throughout the spawning season. Further, from geomorphological considerations, increased discharges corresponding to depth D_3 are needed for 18 days during the monsoon season (preferably distributed over the season). To determine these requirements, the keystone species in the given river stretches were identified, and the required depths D_1 and D_2 were determined for these species. Since flow depths at pools are higher than at riffles, hence the critical E-Flows sites were selected at riffle sections, thus ensuring that the flow depths in the entire reach would not be less than D_1 or D_2 . The flows corresponding to D_1 and D_2 were then read from the stage-discharge curves for the given sites. To determine D_3 , the average virgin flows that were exceeded for 18 days during the monsoon (i.e. between June and October, but generally between July and September) were computed. This corresponds to average virgin flows having 20% dependability during monsoons. The depth D_3 was then read from the stage-discharge curve and checked against the available river depth at the site. The flows computed thus constitute the minimum ecological requirements of the river. The Environmental Flows were obtained by mimicking the trend of annual variation of 90% Dependable Flow using the minimum ecological requirement for non-monsoon season as the minimum environmental flow for non-monsoon. For monsoon season, the 90% Dependable Flow variation was mimicked by first deducting the flows corresponding to D_3 and then adding the deducted values on the mimicked hydrograph.

It may be noted that the above procedure identifies two separate limiting flow conditions. The lower limit of Minimum Ecological Requirement may be considered essential for minimal river functioning (with survival of biota), while the higher limit of Environmental Flows would allow healthy river functioning (allowing maintenance of healthy biodiversity and production of ecosystem goods and services by the river). Thus, actual river flows above the E-Flows range would indicate a River in Good Health, while flows below this range but

above Ecological Requirements would indicate a River in Marginal Health; and below the Ecological flow limit the river would be in Grossly Unsatisfactory Health. It should be noted, however, that this distinction of River Health status pertains to hydrological quantities only, and not to river water quality. For quality aspects, the flow of sediments, nutrients and other natural constituents need to be further accommodated.

The sample results for E-Flows and Minimum Ecological Requirements for a representative site at Ranari, Dharasu are illustrated below, excluding quantitative flow data (which are classified government data).

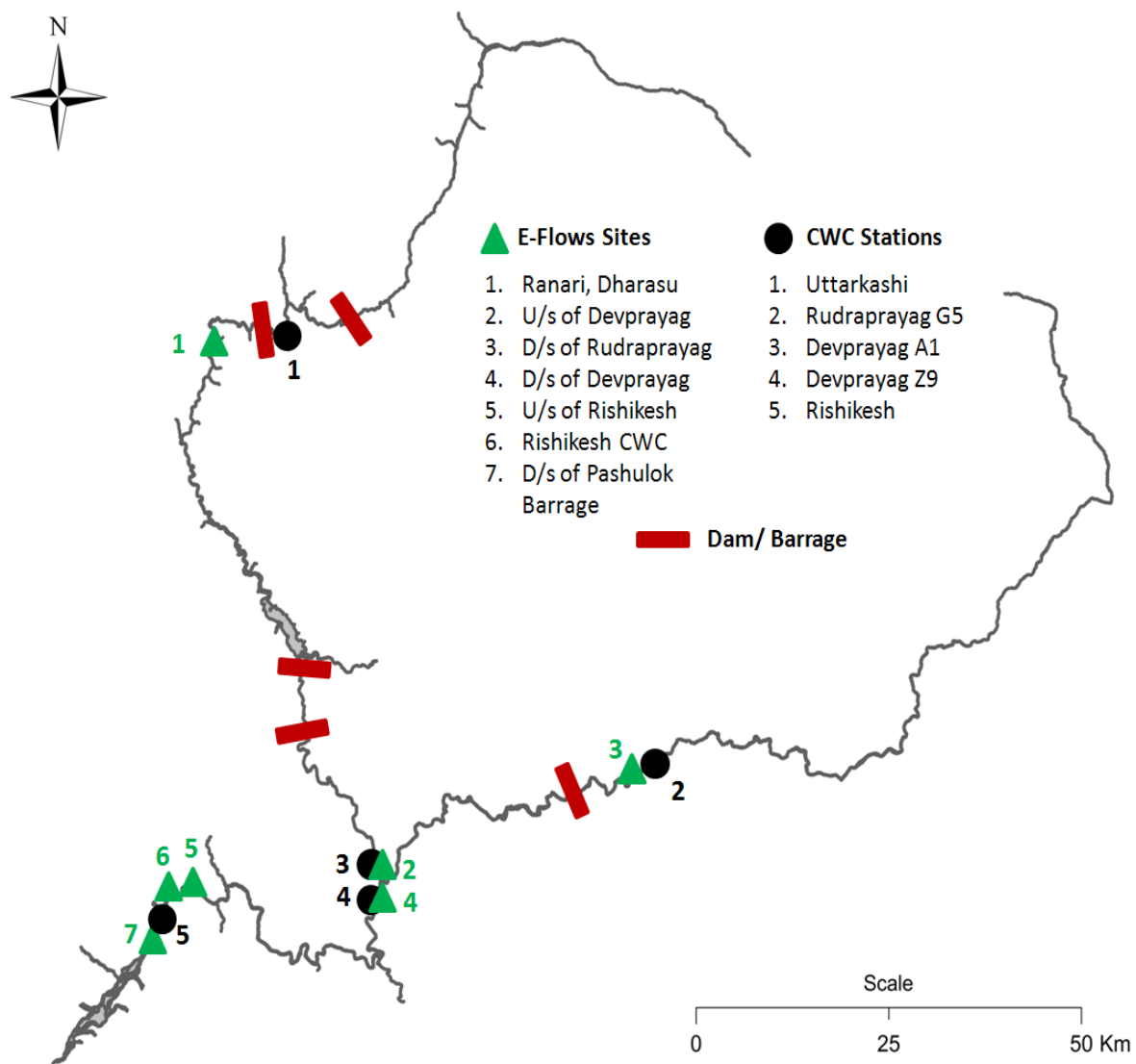
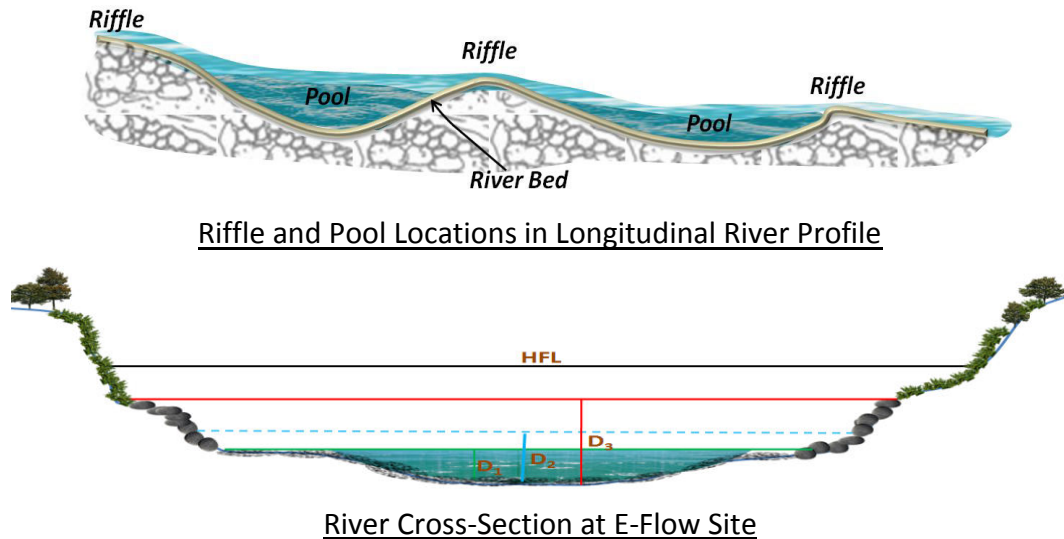


Figure 5.3: Location Map of Flow Monitoring Stations and E-Flows Sites



- D_1 – Depth of water required for mobility of keystone species during lean period.
 D_2 – Depth of water required for mobility of keystone species during spawning period.
 D_3 – Depth of water required to inundate some riparian vegetation for 18 days/year.

Figure 5.4: E-Flows Assessment – Conceptual Diagram

A. E-Flows at Site 1: Ranari, Dharasu (Lat 30°43'02"N, Long 78°21'17"E):

Geomorphic Attributes: Confined, incised river channel with coarse bed material in degradational regime in Himalayan steep valley.

Cross-Section at Site:

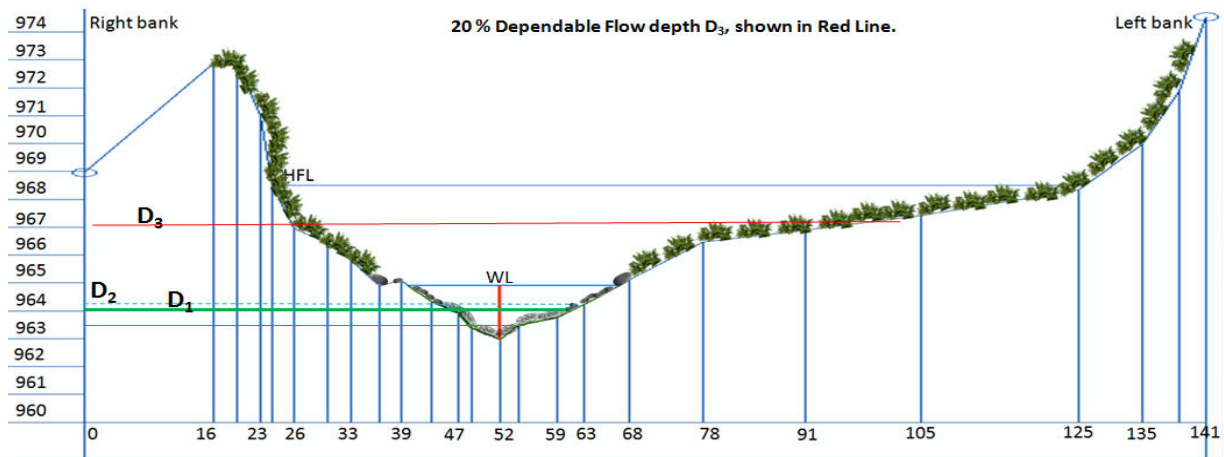
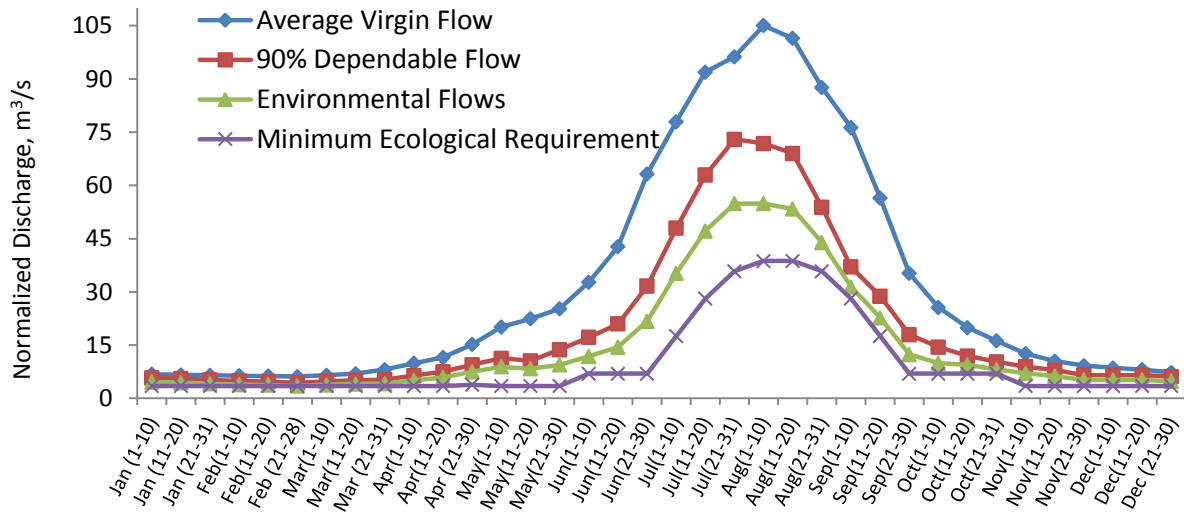
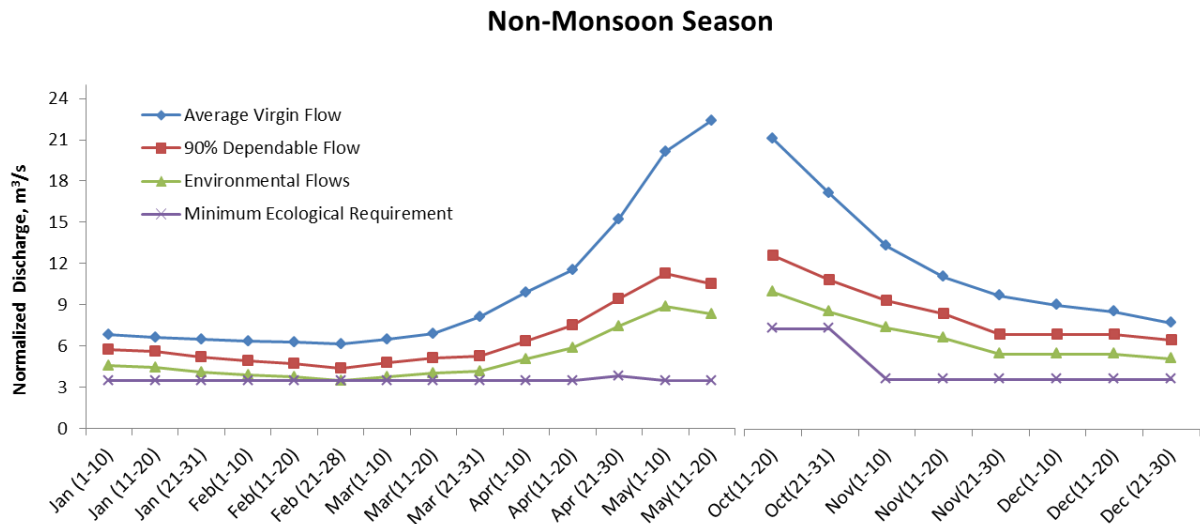


Figure 5.5: River Cross-section at Ranari, Dharasu

Keystone Species	Required Depths for E-flows		
	D_1	D_2	D_3
Snow Trout (<i>Schizothorax richardsonii</i>)	0.5 m	0.8 m	3.41 m
Golden Mahseer (<i>Tor putitora</i>)			

Computed E-Flows:**Figure 5.6a: E-Flows at Ranari, Dharasu****Figure 5.6b: E-Flows during Non-Monsoon Season at Ranari, Dharasu****Table 5.2: Percentage of Virgin River Flow required as E-Flows at Ranari, Dharasu**

Period of Year (Season)	Wet Period	Dry Period	Annual
Minimum Ecological Requirement as percentage of Average Virgin Flow	32.59%	32.96 %	32.67 %
E-Flows as percentage of Average Virgin Flow	46.13%	53.12 %	47.54 %

As seen from the above results, the minimum ecological flows required to maintain river integrity are about one-third of the average virgin flows of the river in both dry and wet seasons, while the E-Flows required are about half the average virgin flows. However, this fraction varies over the year and is relatively higher during dry season, river flows being minimum in winter.

Adoption of E-Flows at Dams and Barrages:

It is evident from the preceding results that, although river flows vary significantly round the year, except for the high flows needed 18 days a year, the required ecological flows at a given site vary much less over the year if D_1 and D_2 are of the same order of magnitude (in the sample case presented above, D_1 and D_2 are 0.5 m and 0.8 m, respectively). Correspondingly, the mimicked E-Flows will also vary over a limited range. Hence, *prima facie*, it should be possible to allow a river passage of adequate dimensions through (or bypassing) a dam to transport sediment-laden E-flows and allowing the natural migration of aquatic species. For high flows needed 18 days a year corresponding to depth D_3 , passage of aquatic species is not required, and that of river sediments is not essential since their primary purpose is to flush excess river bed deposits and enable bank wetting. Hence these higher E-flows can be passed through the gates of the dam/ barrage.

It must also be noted that in the case of discharges from hydropower plants, contrary to the conventional practice of sudden and voluminous releases of tail waters, the releases should be moderated in accordance with the river's natural flow regime. It is suggested that, in general, the maximum rate of tail water discharge should be within the maximum flows in dry and wet seasons respectively, with allowance being made for discharges corresponding to depths D_1 , D_2 , or D_3 being released through the dam or river passage. The moderation of tail water discharges can be suitably achieved by use of tail-end balancing reservoirs.

To gauge the overall feasibility of the proposed scheme, photos of some existing and under-construction barrages are presented in Figure 5.7. It may be noted here, however, that while river passage through a dam/ barrage can be designed and constructed integrally with the dam/ barrage for new projects, for existing dams/ barrages the required changes may be difficult; hence

alternative means may need to be explored in such cases to ensure river connectivity capable of carrying E-Flows.



Maneri Bhali-1 Barrage



Srinagar Dam



Singoli-Bhatwari Barrage



Vishnuprayag Barrage Site

Figure 5.7: Some Existing and Under-Construction Barrages in Upper Ganga

6. Hydrological Modeling of GRBMP and Inferences

In order to obtain a quantitative picture of the hydrological status of NRGB and its likely change under various scenarios, hydrological modeling was carried out for the surface water and ground water system of the combined Ganga basin area in India (i.e. NRGB) and Nepal covering 1,028,468,63 sq. km. area [IITC, 2014c]. The SWAT (Soil and Water Assessment Tool) Model was adopted to simulate the surface water response of the basin, the basin being subdivided into 1045 sub-basins for model computations. The model results were calibrated with observed river discharge data at 30 locations on the main stem and tributaries of the Ganga river network. The raw data used included

static spatial data (digital elevation data, drainage network data, soil maps, soil characteristics, and land use data), dynamic hydro-meteorological data, and water demand and abstraction data. The model simulation was carried out for the period 1969–2006 (37 years) over the basin. The groundwater model was set up for the alluvium part of the basin (shown in Figure 6.1) using MODFLOW computer model.

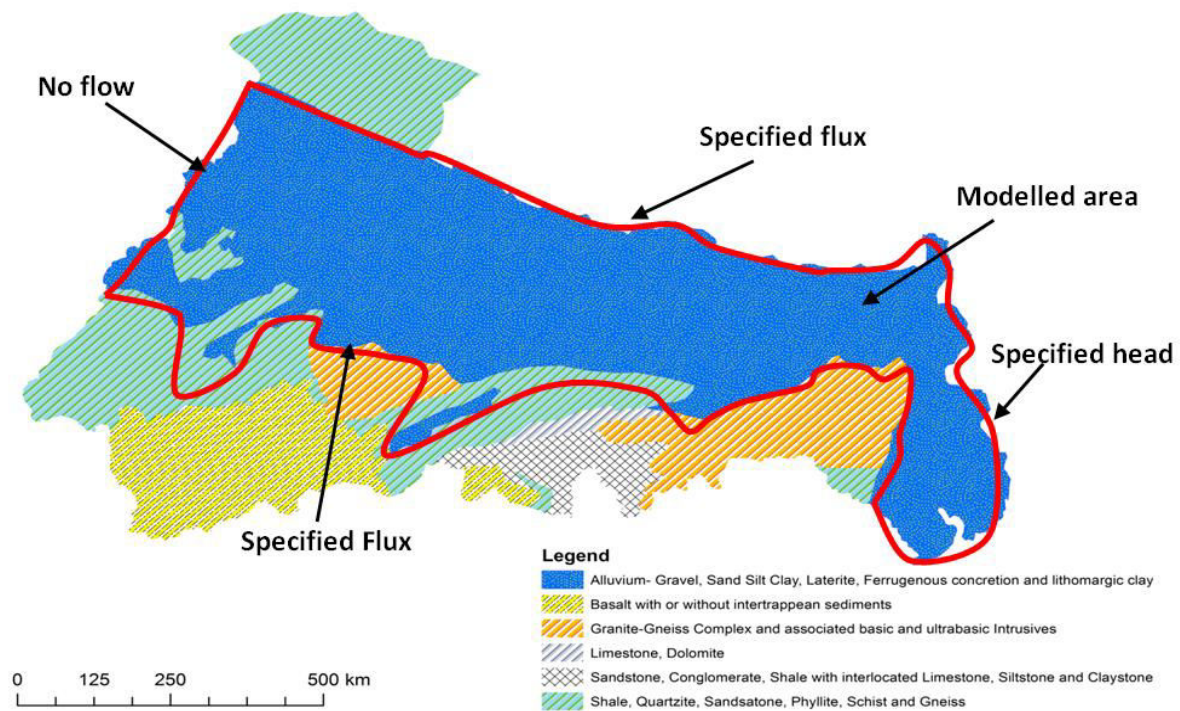


Figure 6.1: Groundwater Model Area of Ganga Basin [IITC, 2014c]

The modeling effort was constrained by data limitations such as absence of precipitation data for higher elevation areas, of canal water diversions, and of crop management (irrigation) practices. Besides, out of about 206 dams/reservoirs in the basin, information was available on only 104 such structures, and canal command area information was also missing in some cases. Limitations are also likely on the quality of data used for other anthropogenic parameters such as land use and groundwater abstractions. Subject to such constraints, the computational model was calibrated and validated against observed streamflow data at about 24 flow measuring stations and groundwater data at about 100 observation wells. The summary outcome of surface water modeling is shown in Figure 6.2a in terms of the basin's 37-year average annual water balance components, viz.: (i) Total Streamflow (Water Yield) consisting of surface runoff, lateral and base flow, (ii) Precipitation, and

(iii) Evapotranspiration. The monthly variation of the average water balance components are shown in Figure 6.2b. As evident from the figures, streamflow and evapotranspiration are the two main components of water outgo from the modeled area. It may be noted that, on an annual basis, the average ratio of evapotranspiration to precipitation is found to be about 41-42%, which is much higher than the government norm of 23% for the Ganga basin but much lower than 60% suggested by Jain [2012] which were cited earlier in Section 4.3.

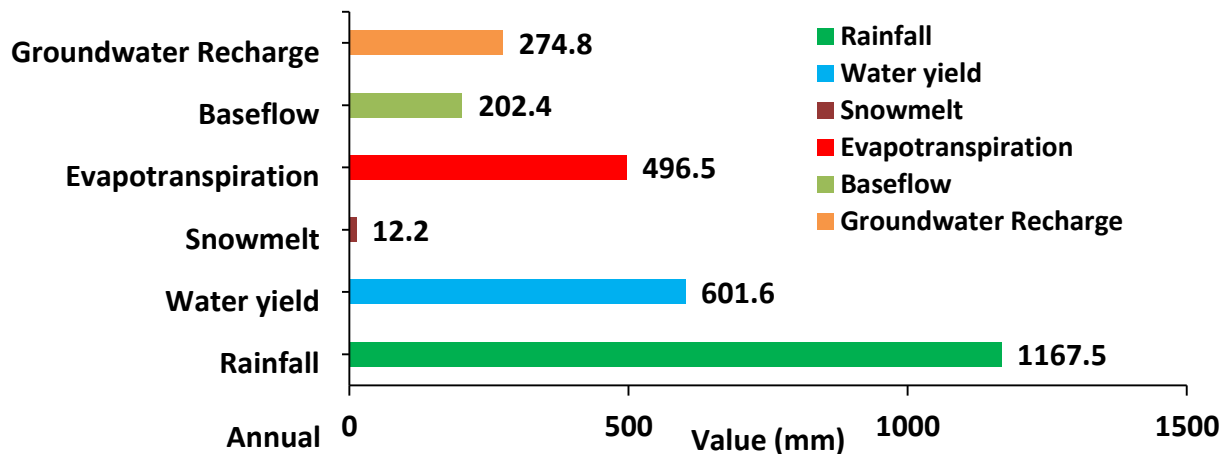


Figure 6.2a: Average (1969-2006) Annual Water Balance of the Modeled Ganga Basin

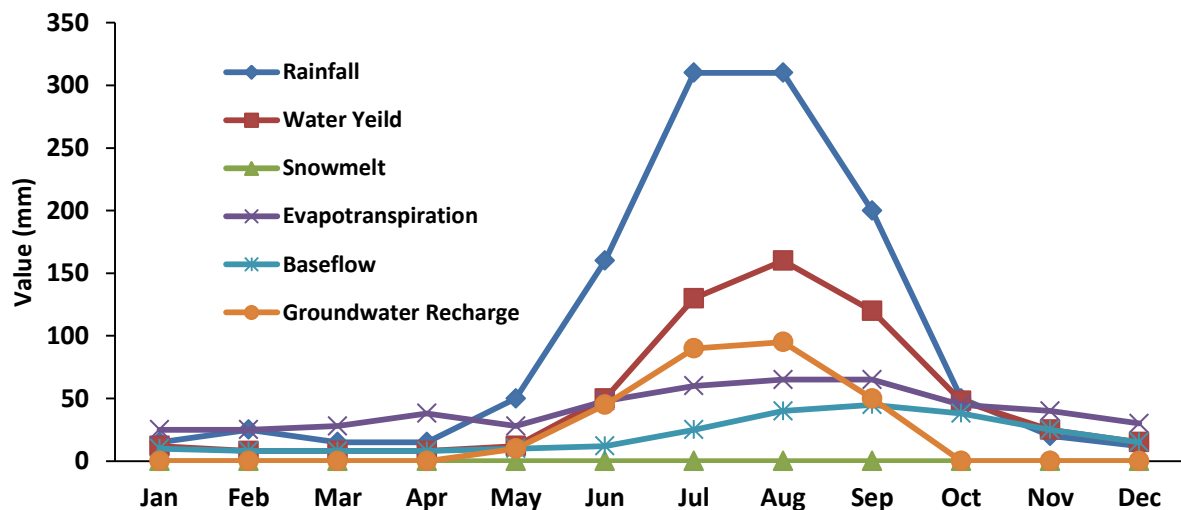


Figure 6.2b: Average (1969-2006) Monthly Water Balance Components of the Basin.

Based on the above model results, an analysis of the hydrologic flow health of the Ganga river and its important tributaries had also been carried out to obtain annual “flow health scores” of the rivers [IITC, 2014b]. In general, the study showed that the flow health scores had significantly altered in several

stretches of National River Ganga and her tributaries due to the present system of river water management. However, the analysis does not cover many aspects of river health such as functional needs of ecosystems and habitats. Considering this work as a first step to understand the significance of hydrology on the health of National River Ganga, it is envisaged that a more comprehensive assessment including ecological and geomorphological considerations of river health can be developed in future within the broader framework of ecohydrology.

The hydrological model was also run to simulate the hypothetical virgin river flows under the present climatic and land-use conditions by switching off all water resource projects and considering no groundwater abstraction in the basin. The “virgin flows” of different rivers of the network and their contributions to the main stem of the river were thus obtained for the hypothetical virgin conditions over a 30-year period of model run to enable quantitative comparison with actual flows over this period. The main tributaries of the Ganga river network (and some important flow and water quality measuring stations of CWC) are shown in the line diagram of Figure 6.3. Based on the model results, Figure 6.4a shows the estimated changes in annual flows of the major tributaries of the network. The results indicate that, while the changes in flow volumes are very small in the headstreams of National River Ganga, river flows are considerably reduced in her major tributaries such as Yamuna, Ghaghra, Gandak, Kosi, Chambal, Sone, etc., thereby reducing the flow in the main Ganga river through most of her reach. Figures 6.4b and 6.4c show the comparisons of average virgin flows and actual flows for the wet season (mid-June to mid-October) and dry season (mid-October to mid-June of following year), respectively. As evident from the figures, the differences between virgin and present flows in most rivers are much more pronounced in the dry season than the wet period, with dry season flows having drastically reduced in some rivers such as Ramganga, Chambal, Yamuna and Damodar. Thus, it can be definitively concluded that anthropogenic hydrological interventions have significantly curtailed the annual flows in the Ganga river network below the Himalayan Upper Ganga Region, especially in the dry season. Further anthropogenic uses must be immediately curtailed in critical sub-basins, and corrective measures applied where possible.

The model simulation results were also analysed in further detail to compare the average hydrographs of maximum 10-daily flows, average 10-daily flows and minimum 10-daily flows under virgin and present conditions, respectively in the major sub-basins. Appendix 1 presents figures showing the comparative changes, and their significance is self-evident from the figures.

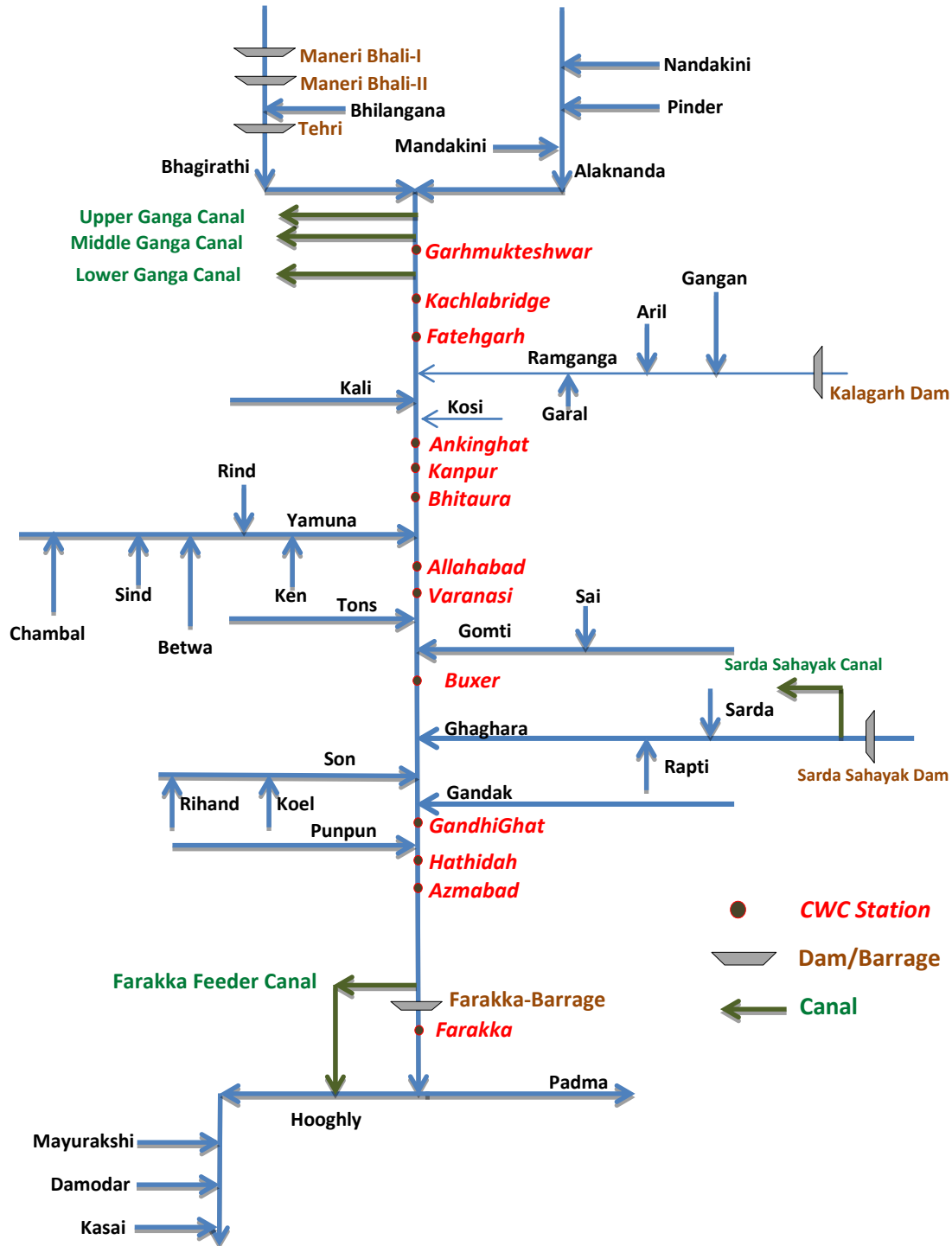


Figure 6.3: Line Diagram of Ganga River Network (with major

dams/barrages, canals, and flow and water quality measuring stations).

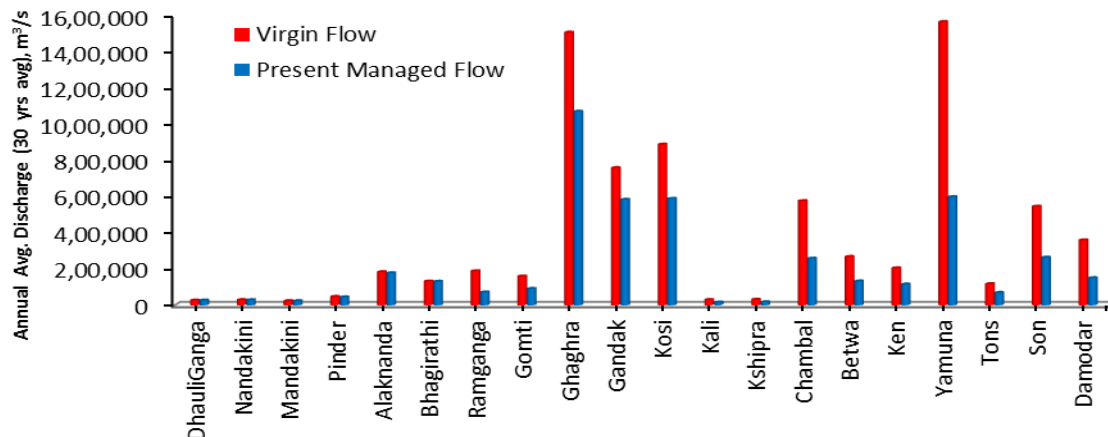


Figure 6.4a: Annual Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions

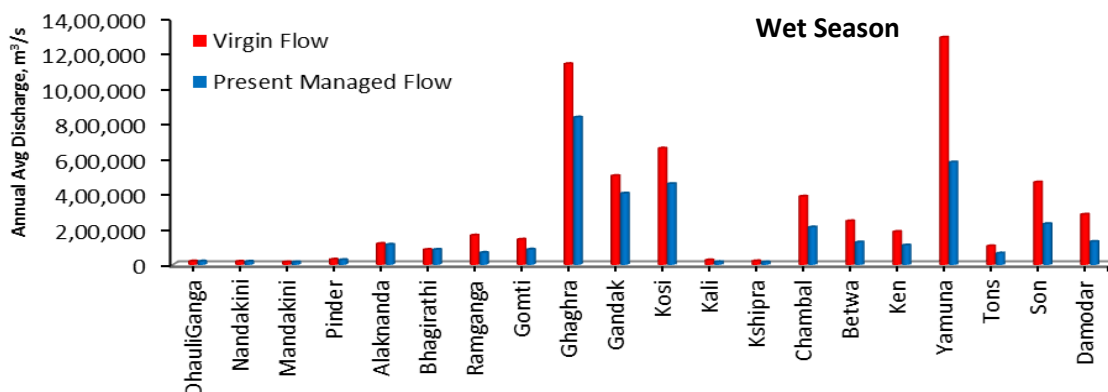


Figure 6.4b: Wet Season Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions

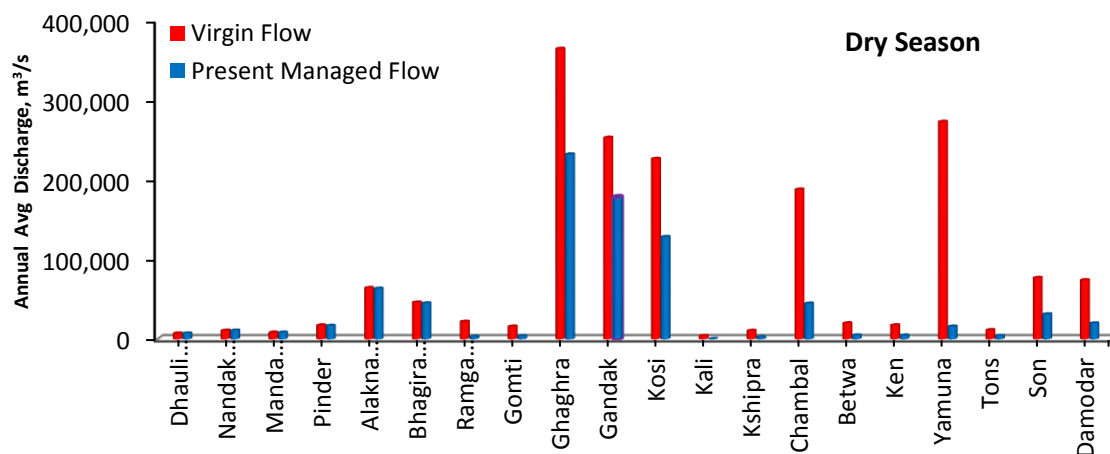


Figure 6.4c: Dry Season Flow Contributions of Different Tributaries (sub-basins) to National River Ganga under Present Flow Conditions and under Virgin Flow Conditions

7. Sediment Resources of National River Ganga

Water-borne sediments play a vital role in the dynamics and ecology of the Ganga River Network. The river's suspended sediment load – generally estimated at between 500 to 800 million T/yr (e.g. 524 million T/yr vide *Tandon et al., 2008*; 729 million T/yr vide *Abbas & Subramanian, 1984*) – is probably the third highest among the world's rivers, after the Yellow and Amazon rivers' loads [*Milliman & Meade, 1983*; *Singh et al., 2003*]. The total sediment load estimated at 2400 million T/yr [IITC, 2012] is also very high for any river, but since bed load measurements are few in the river network, the figure is very uncertain. Wasson [2003] reasoned that the long-term average of total sediment load of the combined Ganga-Brahmaputra rivers is between 1600 to 3500 million T/yr, which suggests that the total sediment load of National River Ganga could be much less than 2400 million T/yr. Nonetheless, the sediment load is exceptionally high, and it evidently plays a key role in maintaining the network of rivers in dynamic equilibrium from their sources to the delta.

Apart from their geomorphological significance, river sediments deposited on plains during floods replenish soils lost from the plains through erosion. Besides, sediments are also a potentially major source of key nutrient elements such as phosphorous as well as most of the micro-nutrient elements discussed in Section 4.1. These elements provide long-term fertility to the rivers and the delta (for maintaining healthy biota) as well as to the plains by flood deposits [*Dixit et al., 2008*]. The possibility of heavy metals being present in harmful proportions in the sediments has also been studied in the field, but their concentrations in sediments from upland sources are generally found to be benign in the Ganga river network [*Jha et al., 1988*; *Purushothaman & Chakrapani, 2007*; *Singh et al., 2003*]. In fact, considering the sediment load at 744 million tons/ year, Singh et al.'s [2003] estimate includes significant annual transport of many sedimentary micro-nutrients to the Bay of Bengal (e.g. 1.3×10^6 tons Mn, 30.0×10^6 tons Fe, 110×10^3 tons Cr, 14×10^3 tons Co, 35×10^3

tons Ni, 41×10^3 tons Cu, and 78×10^3 tons Zn). Given the known deficiency of many of these micro-nutrients in agricultural soils in NRGB (vide Mission Report on Sustainable Agriculture), the sediments deposited on flood plains would be a natural mechanism to replenish such nutrients.

Wasson [2003] conducted a sediment budget analysis and estimated that most of the long-term sediment load in the Ganga river system derives from the Himalaya mountain range (especially from the High Himalayas), with probably less than 10% coming from the Siwaliks, plains and peninsular regions of the basin, vide Figure 7.1. While the exact figures may be uncertain, the Himalayas – on account of their litho-tectonic characteristics – undoubtedly contribute the major sediment load in the river network. Thus many of the Himalayan tributaries of National River Ganga (such as the Kosi, Ghaghra, and Gandak) are known to carry enormous sediment loads, some of which tend to deposit on the plains during floods. The Himalayan ranges are therefore important not only for the hydrological regime, but also for the geomorphological stability and fertility of the basin.

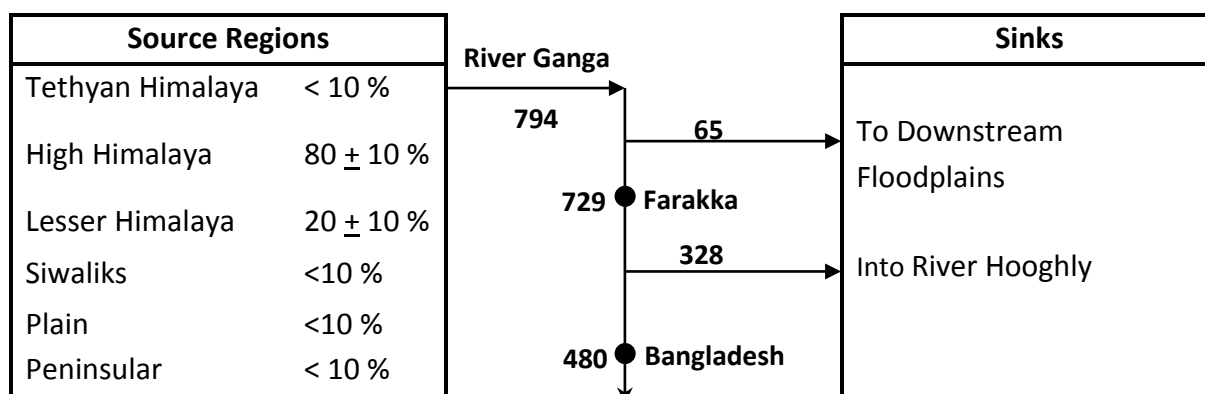


Figure 7.1: A Sediment Budget (in 10^6 tons/yr) for Ganga River Basin [from Wasson, 2003].

In view of the above available information, it is first and foremost necessary to estimate the correct sediment loads in the Ganga River System. To this end, river discharges and suspended sediment concentrations measured continually at 13 measuring stations along the main stem of the National River Ganga for varying periods were availed from CWC. The said measuring stations and the period of sediment data availability are given in Table 7.1 below. Data were also available for 3 measuring stations on tributaries, but these have not been used here since such stations are too few. Based on data of the preceding 13

stations, the average sediment loads at different stations for the common period of data availability (1999–2006) were computed for annual, wet season and dry season sediment loads respectively, and are shown in Figures 7.2, 7.3 and 7.4. However, it may be noted that at Garhmuketswar data were available only up to 2003, so the average of the 1999-2003 period was used for this station. For further reference, the annual sediment load data for different stations are shown in Appendix II.

Table 7.1: Sediment Measuring Stations and Periods of Data Availability

Station No.	1	2	3	4	5	6
Station Name	Garhmukteshwar	Kachlabridge	Fatehgarh	Ankinghat	Kanpur	Bhithaura
Data Period	1981–2003	1981–2010	1981–2010	1981–2010	1981–2010	1981–2010

Station No.	7	8	9	10	11	12	13
Station Name	Allahabad	Varanasi	Buxer	Gandhighat	Hathidah	Azimabad	Farakka
Data Period	1981–2010	1981–2010	2001–10	2001–10	2001–10	2001–10	1999–2006

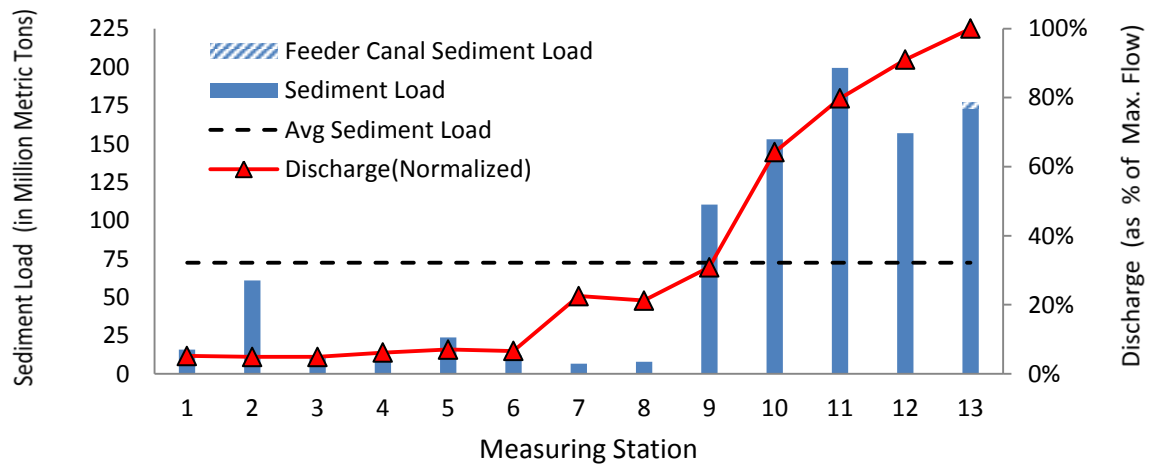


Figure 7.2: Comparison of the Annual Average Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga

Sediment Load (in Million Metric Tons)

Discharge (as % of Max. Flow)

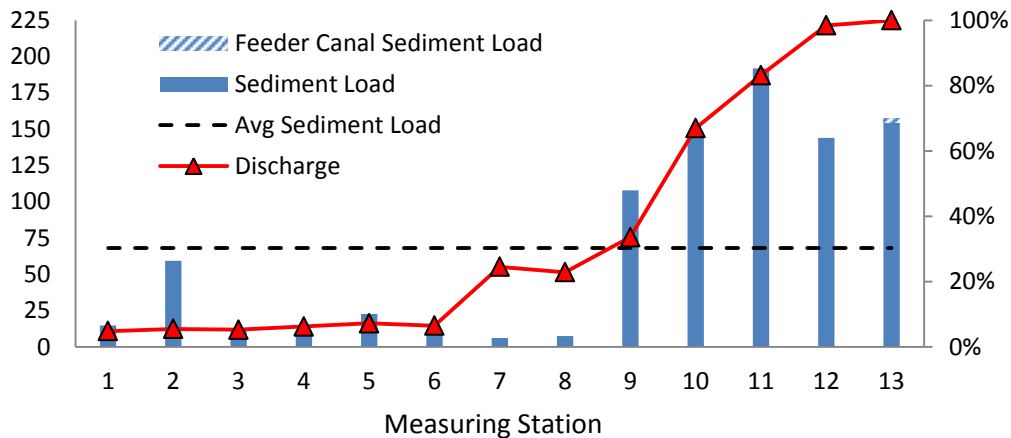


Figure 7.3: Comparison of the Average Wet Season Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga

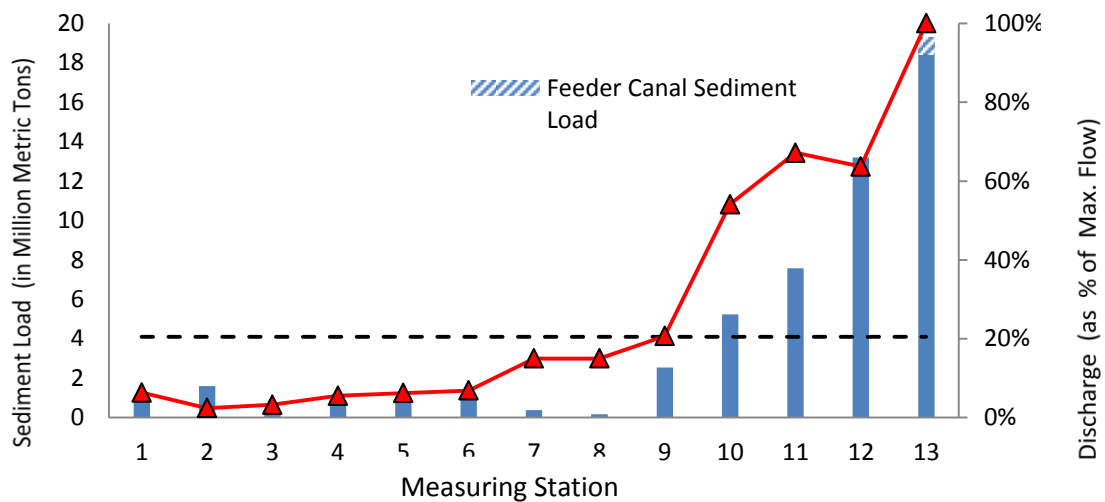


Figure 7.4: Comparison of the Average Dry Season Sediment Loads (for period 1999-2006) at Different Locations of National River Ganga

Overall, it may be noted that the common period of data availability is very limited, hence the computed results are of limited significance. But some provisional conclusions can be drawn from the figures. Firstly, the average suspended sediment load at Farakka (i.e. passing the Farakka Barrage into the Ganga/ Padma river as well as flowing into the canal feeding River Bhagirathi/Hooghly) during the period 1999–2006 is only about 177 million T/year which is much less than values between 500 to 800 million T/year commonly cited in literature. But, in consonance with observations cited in literature, most of the sediment load carried by the river occurs during the wet season.

Secondly, the sediment load variation along the main river stem is somewhat intriguing, and they suggest varying aggrading–degrading stretches along the

length of the river. Generally the load increases downstream, but it jumps sharply between Garhmukteswar and Kachla bridge (despite the Lower Ganga Canal taking off in this zone) and drops at Fatehgarh, suggesting a degrading river stretch before Kachla bridge and an aggrading stretch after it. Between Kanpur and Varanasi, the river stretch again appears to aggrade to some extent with the sediment load reducing downstream (despite the Yamuna river joining below Allahabad). After Varanasi, the sediment load increases steeply at Buxar (probably due to significant sediment inflows from the Tons and Gomti rivers) and increases progressively up to Hathidah (with major tributaries like Ghaghra, Sone, Gandak and Punpun joining National River Ganga). But the sediment load decreases before Azimabad (except in the dry season), again suggesting channel aggradation in this zone. Finally there is some further increase in load at Farakka (presumably with sediment inputs from River Kosi.) It may be also seen that most of the sediment outflow from Farakka barrage carries over to the Ganga/ Padma river, with only a very small fraction entering the feeder canal of the Bhagirathi-Hooghly river.

In summing up, the above discussions throw up many questions regarding National River Ganga's sediment resources. At the minimum, they underscore the need for long-term monitoring of sediment loads in the Ganga river system including all her major tributaries, sediment budget assessments of her major sub-basins, understanding the dynamics of sediment flow in the network, and sediment quality estimates.

8. Summary of Recommended Actions

The main recommendations of the mission are summarized below:

1. While water withdrawals from rivers and aquifers have affected the basin's water status and accentuated the rivers' hydrological extremes, NRGB's present hydrological status is very inadequately known, especially in terms of water availability and usage. The hydrological status needs to be determined afresh and in much greater detail in order to estimate its true potential and its changing impact on different regions of the basin.
2. Considering the significant costs of land inundation, human displacements, ecological damage, operation, transportation, and evaporation losses of

large in-stream reservoirs, NRGB's water resource management plan must adopt distributed water storage in the basin's groundwater, lakes, tanks and ponds, and promote wetlands and forests.

3. Increasing anthropogenic water usage needs to be checked by increased water use efficiency through realistic pricing of fresh water, incentives, technical assistance, allocation of water rights and entitlements to stakeholders, and promotion of water reuse and recycling.
4. A major policy shift in NRGB's water resource management should bring it under the ambit of natural resource management in the basin with emphasis on resource preservation before exploitation, decentralized stakeholder control, and expert guidance and regulation.
5. Dams and barrages have altered or disrupted the flow of water, sediments, nutrients and biota in the Ganga river network, severely affecting the morphology and ecology of rivers, floodplains and river valleys. Hence, all dams/ barrages must ensure longitudinal river connectivity and environmental flows (of water, sediments and other natural constituents), and new projects should be approved or rejected on the basis of a set of 4 categories of their environmental impacts as detailed in Table 5.1.
6. Hydrological model studies show significant anthropogenic effects in many sub-basins of NRGB and NRGB as a whole. Increasing water withdrawals must be checked on a priority basis in critical regions.
7. The sediment resources of the Ganga river system need monitoring on a long-term basis and assessed comprehensively in terms of both quantity and quality. The quantity and nutrient value of sediments trapped behind dams also need to be assessed, and nutrient-rich sediments need to be delivered to downstream river stretches and floodplains.
8. Major research needs include the determination of ecological limits, thresholds and interconnections of water resources in NRGB, and river flow health assessments within the framework of ecohydrology.

References

1. Abbas, N. & V. Subramanian [1984], “Erosion and Sediment Transport in the Ganges River Basin (India),” Journal of Hydrology, Vol. 69, pp 173–182.
2. ADB (Asian Development Bank) [2009], “Water Resources Development in India”. [Accessed May 09, 2013 from: <http://www.indiaenvironmentportal.org.in/reports-documents/water-resources-development-india-critical-issues-and-strategic-options.>]
3. Awulachew, S. B. [2011], “Hydrological Water Availability, Trends and Allocation in the Blue Nile Basin”, in “Nile River Basin: Hydrology, Climate and Water Use” by A.M. Melese (editor), Springer, pp 283–296.
4. Bassi, N. et al. [2014], “Status of wetlands in India: A review of extent, ecosystem benefits, threats and management strategies,” Jour. of Hydrology: Regional Studies 2, pp 1–19.
5. Brisbane Declaration [2007], “Environmental Flows are Essential for Freshwater Ecosystem Health and Human Well-Being”, 10th International River Symposium and International Environmental Flows Conference, Brisbane.
6. CGWB (Central Ground Water Board, MoWR, GOI) [2012], “Aquifer Systems of India”.
7. CWC (Central Water Commission, MoWR, GOI) [1986], “Ganga Basin Water Resources Development – A Perspective Plan”, Vol. 1/1.
8. CWC (Central Water Commission, Govt. of India) [2008], “Integrated Water Resources Development and Management”, Water Resources Day–2008: Theme Paper.
9. CWC (Central Water Commission) [2010], “Water and Related Statistics”. [Accessed May 09, 2013 from: www.cwc.nic.in/ISO_DATA_Bank/W&RelatedStatistics_2010.pdf].
10. Dhandekar, P et al. [2011], “India’s Wetlands in Peril”, South Asia Network on Dams, Rivers and People. [Accessed May 06, 2013 from http://www.sandrp.in/rivers/Indias_wetlands_in_peril_Feb_2011.pdf.]
11. Dixit, A. et al. (2008), “Costs and Benefits of Flood Mitigation in the Lower Bagmati Basin: Case of Nepal Tarai and North Bihar,” From Risk to Resilience – Working Paper No. 6, Institute for Social and Environmental Transition - Nepal and ProVention, Kathmandu.
12. Ellison, D., M.N. Futter and K. Bishop [2012], “On the forest cover–water yield debate: from demand- to supply-side thinking”, Global Change Biology, 18, pp 806–820.

13. Elser, J.J. et al. [2007], *“Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems”*, Ecology Letters, Vol.10, Issue 12, pp 1135–1143.
14. Garg, N.K. & Q. Hassan [2007], *“Alarming Water Scarcity in India,”* Current Science, Vol.93, No.7, pp 932–941.
15. Graf, W.L. [2006], *“Downstream hydrologic and geomorphic effects of large dams on American rivers,”* Geomorphology, Vol. 79, pp 336–360.
16. Graham, R.D. [2008], *“Micronutrient Deficiencies in Crops and Their Global Significance”*, in *“Micronutrient Deficiencies in Global Crop Production”*, by B.J. Alloway (editor), Springer.
17. Gupta, H., S-J. Kao and M. Dai [2012], *“The role of mega dams in reducing sediment fluxes: A case study of large Asian rivers”*, Journal of Hydrology, 464–465, pp 447–458.
18. IITC [2011], *“Environmental Flows: State-of-the-Art with special reference to Rivers in the Ganga River Basin”*, 022_GBP_IIT_EFL_SOA_01_Ver 1_Dec 2011
19. IITC [2012], *“Riparian Vegetation in Ganga River Basin”*, 032_GBP_IIT_ENB_DAT_10_Ver 1_Jun 2012
20. IITC [2014a], *“Measures for Ecological Revival of River Ganga”*, 051_GBP_IIT_ENB_DAT_14_Ver 1_May 2014
21. IITC [2014b], *“Hydrological Flow Health Assessment of the River Ganga”*, 056_GBP_IIT_WRM_ANL_02_Ver 1_Jun 2014
22. IITC [2014c], *“Surface and Groundwater Model of the Ganga River Basin”*, 055_GBP_IIT_WRM_ANL_01_Ver 1_Aug 2014
23. IITC [2015], *“Criteria for Dams and Barrages and Environmental Flow Estimates in the Ganga River Network”*,
24. India-WRIS (MoWR, GOI) [2012], *“River Basin Atlas of India – 2012”*, RRSC-West, NRSC, ISRO, Jodhpur, India.
25. Iyer, R.R. [2012], *“River Linking Project – A Disquieting Judgement”*, Economic & Political Weekly, Vol.XLVII, No.14, pp.33–40.
26. Jain, S. K. [2011], *“Population rise and growing water scarcity in India – revised estimates and required initiatives”*, Current Science, Vol. 101 No.3, pp 271–276.
27. Jain, S. K. [2012], *“India’s Water balance and evapotranspiration”*, Current Science, Vol. 102 No.7, pp 914–967.
28. Jain, S. K., P. K. Agarwal and V. P. Singh [2007], *“Hydrology and Water Resources of India”*, Springer (Netherlands).

29. Jha, P. K., V. Subramanian & R. Sitasawad [1988], *“Chemical and Sediment Mass Transfer in the Yamuna River – A Tributary of the Ganges System”*, Jour. Of Hydrology, Vol. 104, pp 237–246.
30. Jenny, H. [1994], *“Factors of soil formation: a system of quantitative pedology”*, Dover Publication. [Accessed May 28, 2014 from: <http://www.soilandhealth.org/01aglibrary/010159.Jenny.pdf>.]
31. Kibler, K.M. and D.D. Tullos [2013], *“Cumulative Biophysical Impact of Small and Large Hydropower Development in Nu River, China”*, Water Resources Research, Vol. 49, pp 3104–3118. [Information source: *“Small dams on Chinese river harm environment more than expected, study finds”* in ScienceDaily accessed January 30, 2014 from <http://www.sciencedaily.com/releases/2013/05/130530095018.htm>.]
32. Milliman, J. D. & R. H. Meade [1983], *“Worldwide Delivery of River Sediments to the Oceans”*, Jour. of Geology, Vol. 91, No.1, , pp 1–21.
33. MoWR (Min. of Water Resources, Govt. of India) [2014], *“Ganga Basin – Version 2.0”*.
34. NIH (National Institute of Hydrology) [2014], *“Ganga Basin.”* [Accessed April 28, 2014 from: http://www.nih.ernet.in/rbis/basin%20maps/ganga_about.htm]
35. Pahl-Wostl, C. [2007], *“The implications of complexity for integrated resources management”*, Environmental Modelling & Software, Vol. 22, pp 561–569.
36. Ogden, F. L., T. D. Crouch, R. F. Stallard, and J. S. Hall [2013], *“Effect of land cover and use on dry season river runoff, runoff efficiency, and peak storm runoff in the seasonal tropics of Central Panama”*, Water Resources Research, Vol. 49, pp 8443–8462.
37. Prasad, S.N. et al. [2002], *“Conservation of Wetlands of India – A Review”*, Tropical Ecology, Vol. 43(1), pp 173–186. [Accessed February 21, 2013 from: http://www.ces.iisc.ernet.in/energy/water/paper/Conservation_of_wetlands_of_India.pdf]
38. Pegram, G. et al. [2013], *“River Basin Planning: Principles, Procedures and Approaches for Strategic Basin Planning”*, UNESCO, Paris.
39. Purushothaman, P. & G. J. Chakrapani [2007], *“Heavy Metals Fractionation in Ganga River Sediments, India,”* Environ Monit Assess, Vol. 132, pp 475–489.
40. Rajvanshi, A. et al. [2012], *“Assessment of Cumulative Impacts of Hydroelectric Projects on Aquatic and Terrestrial Biodiversity in Alaknanda and Bhagirathi Basins, Uttarakhand”*, Wildlife Institute of India.

41. SAC (Space Application Centre, ISRO) [2011], "National Wetland Atlas", Ahmedabad. [Accessed May 10, 2013 from: http://www.indiawaterportal.org/sites/indiawaterportal.org/files/NWIA_National_atlas.pdf.]
42. SANDRP (South Asia Network on Dams, Rivers and People) [2012], "*WII's Cumulative Impact Assessment of Ganga Hydel Projects on Biodiversity: A Small Step in the Right Direction, a Long Way to Go*", Dams, Rivers and People, Vol.10, Issue 3-4-5. [Accessed April 28, 2014 from: http://sandrp.in/drp/April_May_June_2012.pdf].
43. Sen, S. [2009], "Water Resource Management: Social Discourse, Governance & Technology Development", Pre-Proceedings of Intl. Conference on Water Harvesting, Storage & Conservation, IIT, Kanpur.
44. Singh, M., G. Muller & I. B. Singh [2003], "*Geogenic distribution and baseline concentrations of heavy metals in sediments of the Ganges River, India*," Jour. Of Geochemical Exploration, Vol. 80, pp 1–17.
45. Singh, M., I.B. Singh & G. Muller [2007], "*Sediment Characteristics and Transportation Dynamics of the Ganga River*," Geomorphology, Vol. 86, pp 144–175.
46. Spegele, B. & W. Kazer [2014], "*To Conserve Water, China Raises Prices for Top Users*" The Wall Street Journal, January 08, 2014. [Accessed February 02, 2014 from: <http://www.wsj.com/articles/SB10001424052702303870704579297410328066466>.]
47. Thakkar, H. [2012], "Water Sector Options for India in a Changing Climate", South Asia Network on Dams, Rivers and People (SANDRP). [Accessed May 09, 2013 from: http://sandrp.in/wtrsect/Water_Sector_Options_India_in_Changing_Climate_0312.pdf].
48. Tiwari, V.M., J. Wahr & S. Swenson [2009], "Dwindling groundwater resources in northern India, from satellite gravity observations", Geophysical Research Letters, Vol. 36, L18401, doi:10.1029/2009GL039401.
49. UNEP (United Nations Environment Program) [2008], "Vital Water Graphics", 2nd Ed. [Accessed May 10, 2013 from: <http://www.unep.org/dewa/vitalwater/rubrique21.html>]
50. UNICEF, FAO and SaciWATER [2013], "Water in India: Situations and Prospects". [Accessed June 11, 2013 from: http://www.unicef.org/india/Final_Report.pdf.]
51. UPID-FAO [2008], "Main Ganga Canal System", Uttar Pradesh Irrigation Dept. & FAO, Meerut. [Accessed May 01, 2014 from:

<http://www.fao.org/nr/water/docs/masscote/applications/masscotemeerutreport.pdf>]

52. Verma, S. and S.J. Phansalkar [2007], *“India's Water Future 2050: Potential Deviations from 'Business-as-Usual'”*, Intl. Journal of Rural Management, Vol. 3(1), pp 149–179. (Note: A modified and updated version of the article also available at <http://www.iwmi.cgiar.org/Publications/Other/PDF/Paper%202%20of%20NRLP%20series%201.pdf> – accessed on September 03, 2014).
53. Wada, Y., L.P.H. van Beek & M.F.P. Bierkens [2012], *“Nonsustainable groundwater sustaining irrigation: A global assessment”*, Water Resources Research, Vol. 48, W00L06, doi:10.1029/2011WR010562.
54. Wampler, P.J. [2012], *“Rivers and Streams - Water and Sediment in Motion”*, Nature Education Knowledge 3(10):18. [Accessed April 02, 2014 from: <http://www.nature.com/scitable/knowledge/library/rivers-and-streams-water-and-26405398>.]
55. Wasson, R.J. [2003], *“A Sediment Budget for the Ganga-Brahmaputra Catchment,”* Current Science, Vol. 84, No. 8, pp 1041–1047.
56. Wikipedia [2014], *“Soils”*. [Accessed May 28, 2014 from: <http://en.wikipedia.org/wiki/Soil>.]
57. WWC (World Water Council) [2000], *“World Water Vision – Chap. 2: The Use of Water Today”*. [Accessed March 19, 2013 from: http://www.worldwatercouncil.org/fileadmin/world_water_council/documents_old/Library/WWVision/Chapter2.pdf.]
58. Zhou, J., M. Zhang, & P. Lu [2013], *“The effect of dams on phosphorus in the middle and lower Yangtze river”*, Water Resources Research, Vol. 49, pp 3659–3669.

Appendix I

Hydrographs of 30-Years' Maximum, Average and Minimum 10-Daily Flows Under Virgin and Actual (Present) Conditions for Sub-Basins of NRGB

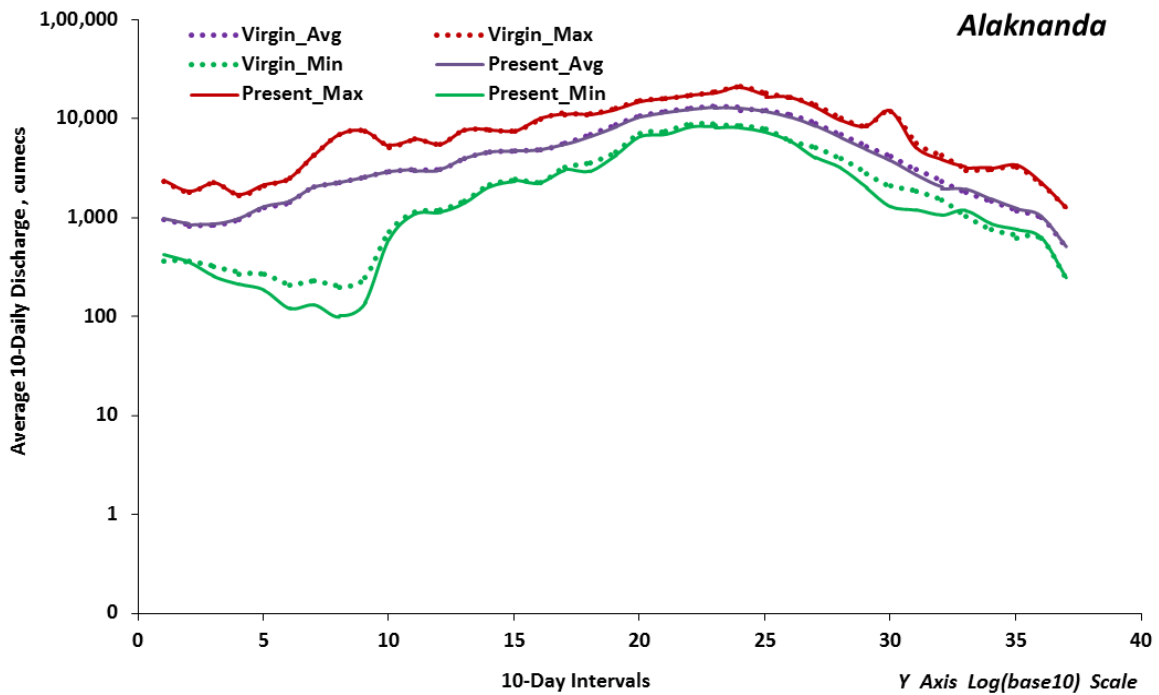


Figure A1.1: 10-Daily Hydrographs for River Alaknanda

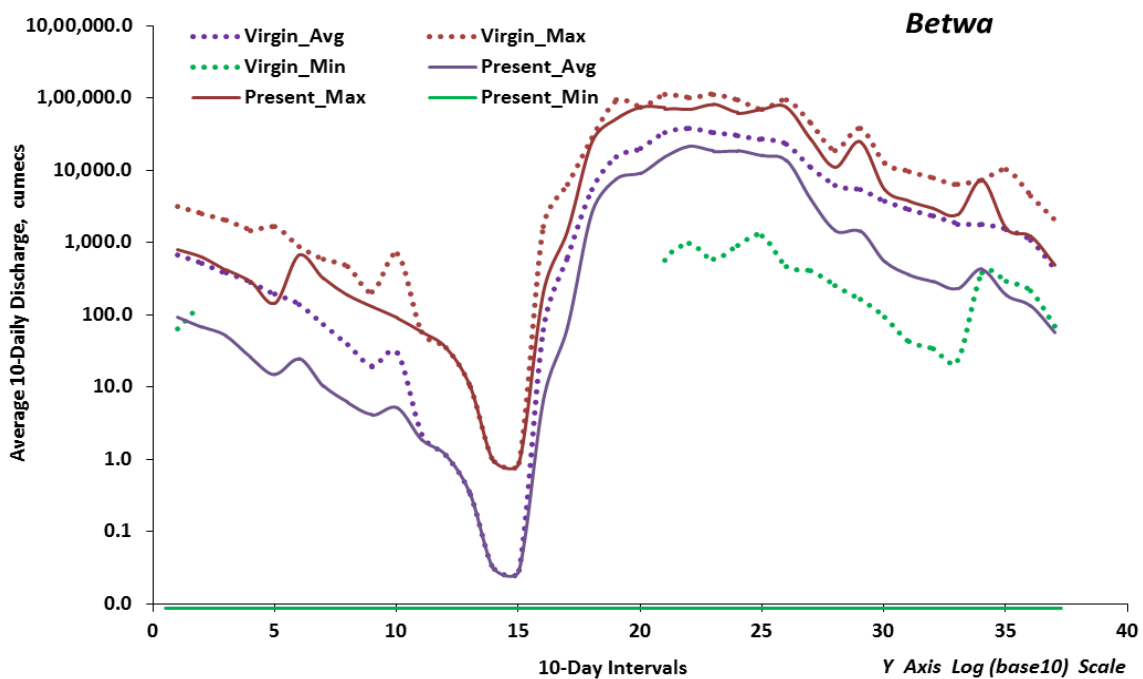


Figure A1.2: 10-Daily Hydrographs for River Betwa

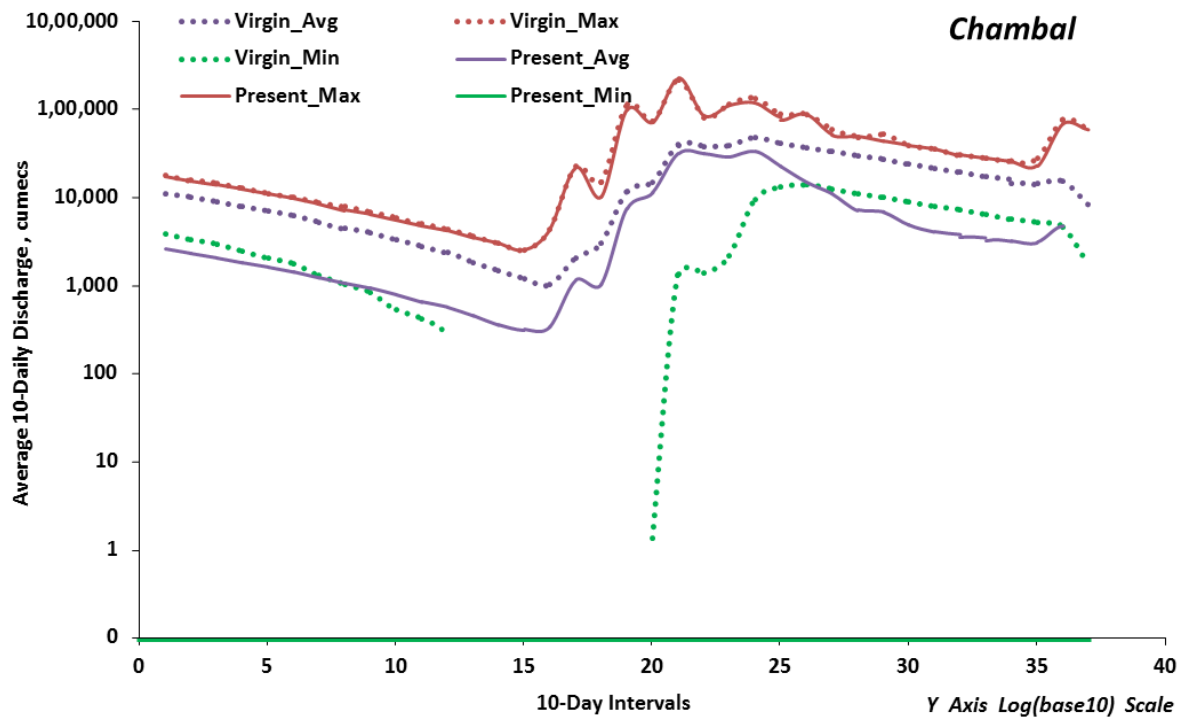


Figure A1.3: 10-Daily Hydrographs for River Chambal

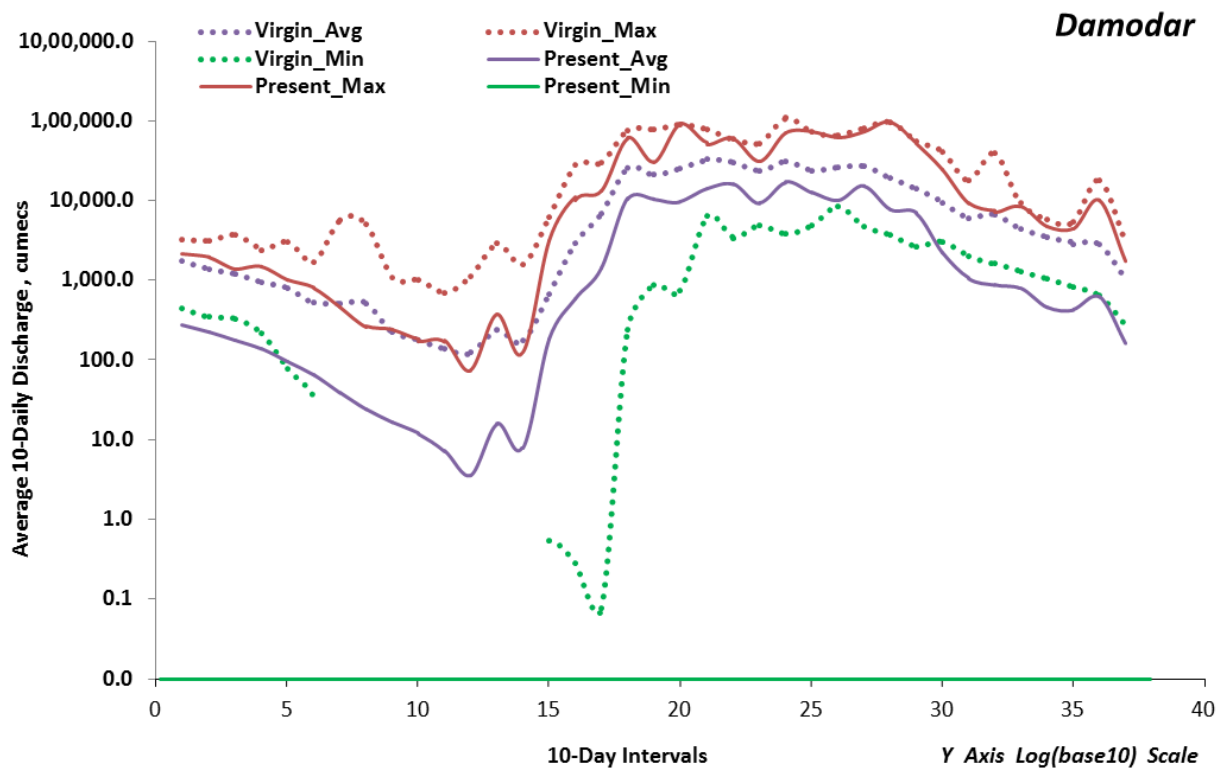


Figure A1.4: 10-Daily Hydrographs for River Damodar

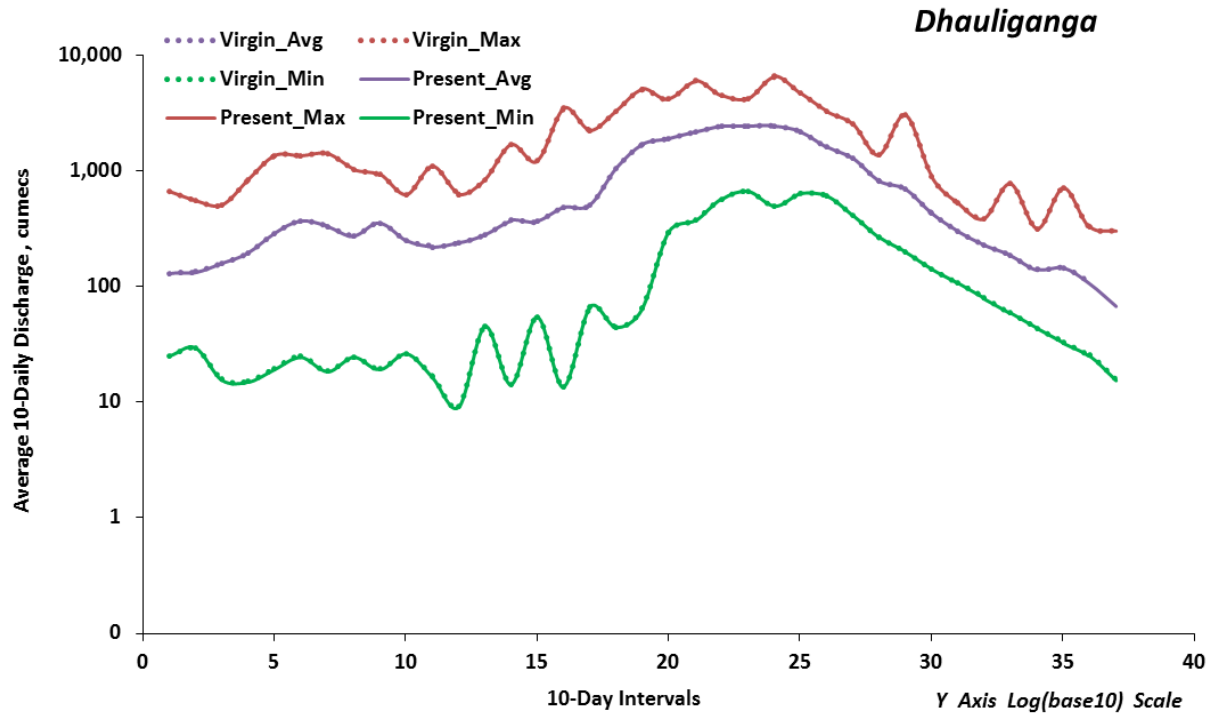


Figure A1.5: 10-Daily Hydrographs for River Dhauliganga

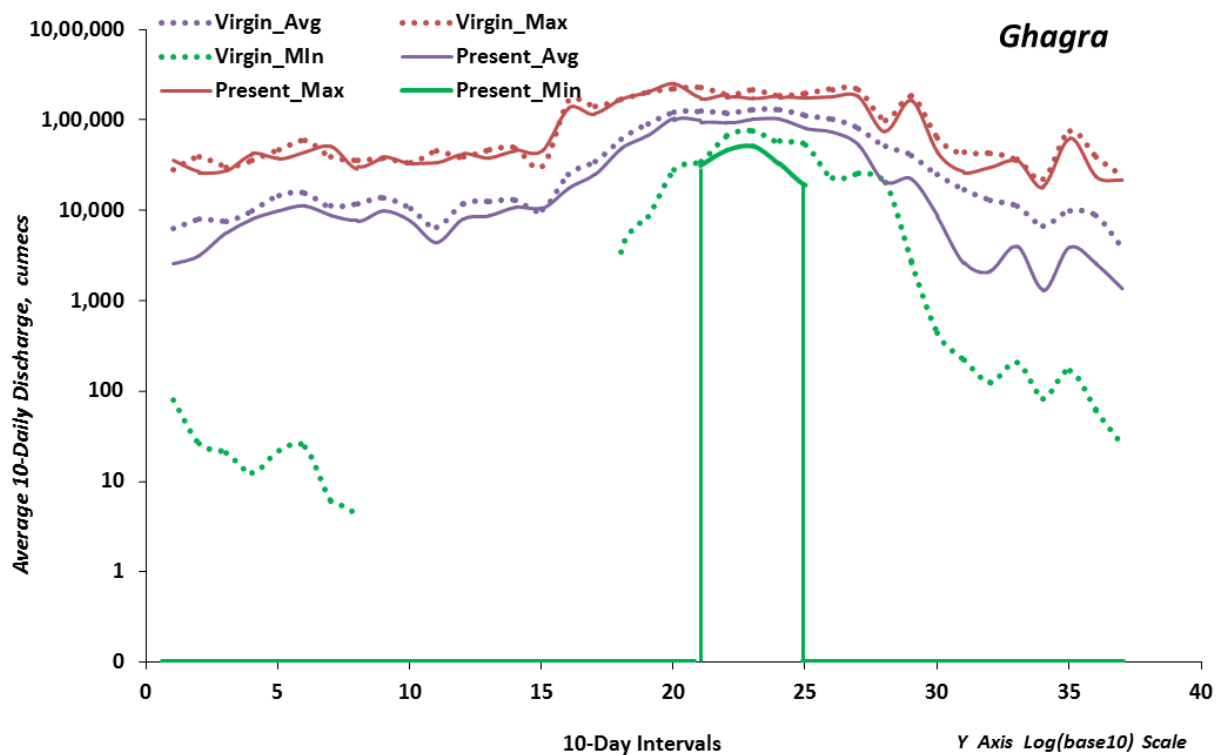


Figure A1.6: 10-Daily Hydrographs for River Ghaghra

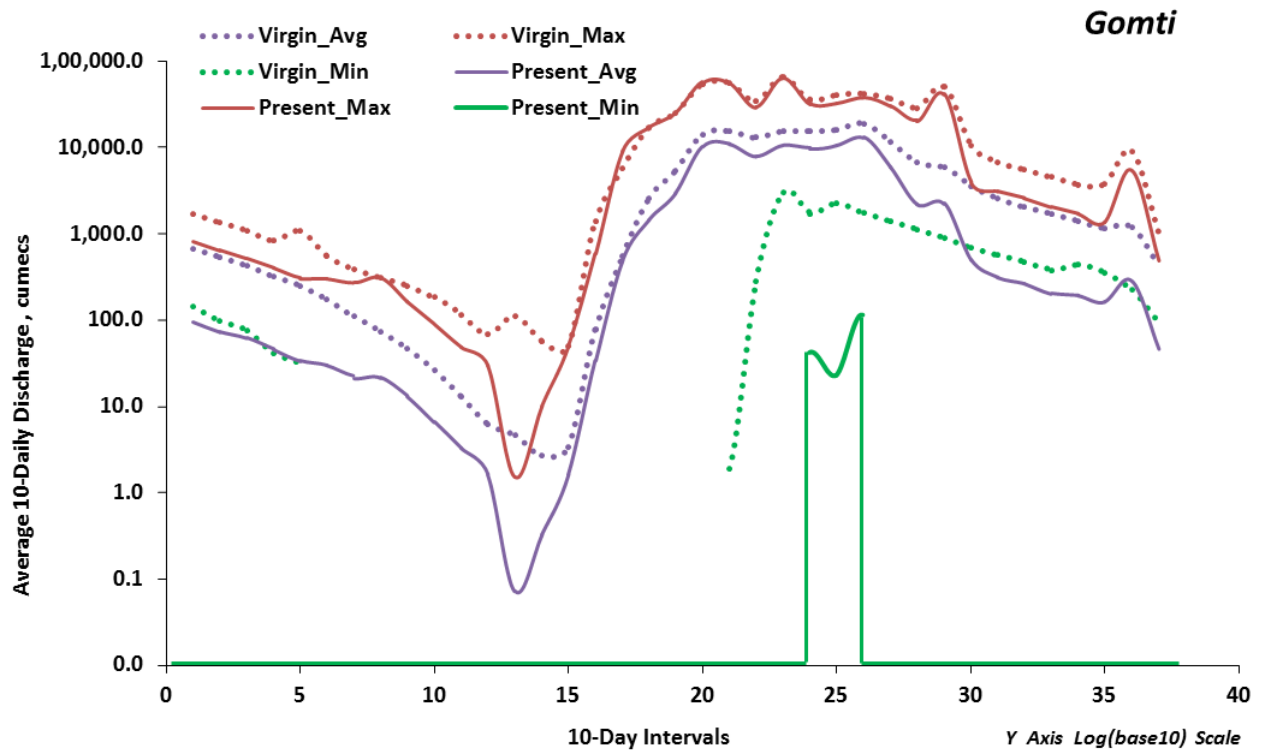


Figure A1.7: 10-Daily Hydrographs for River Gomti

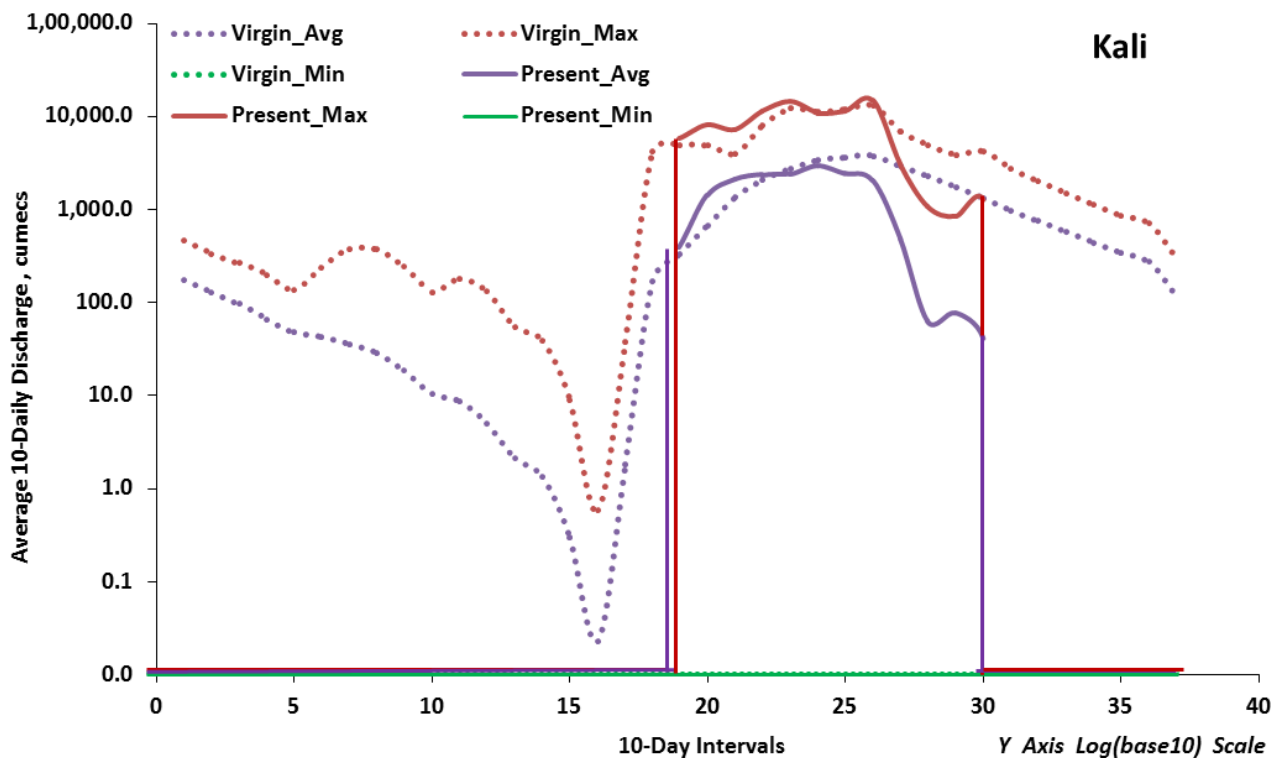


Figure A1.8: 10-Daily Hydrographs for River Kali

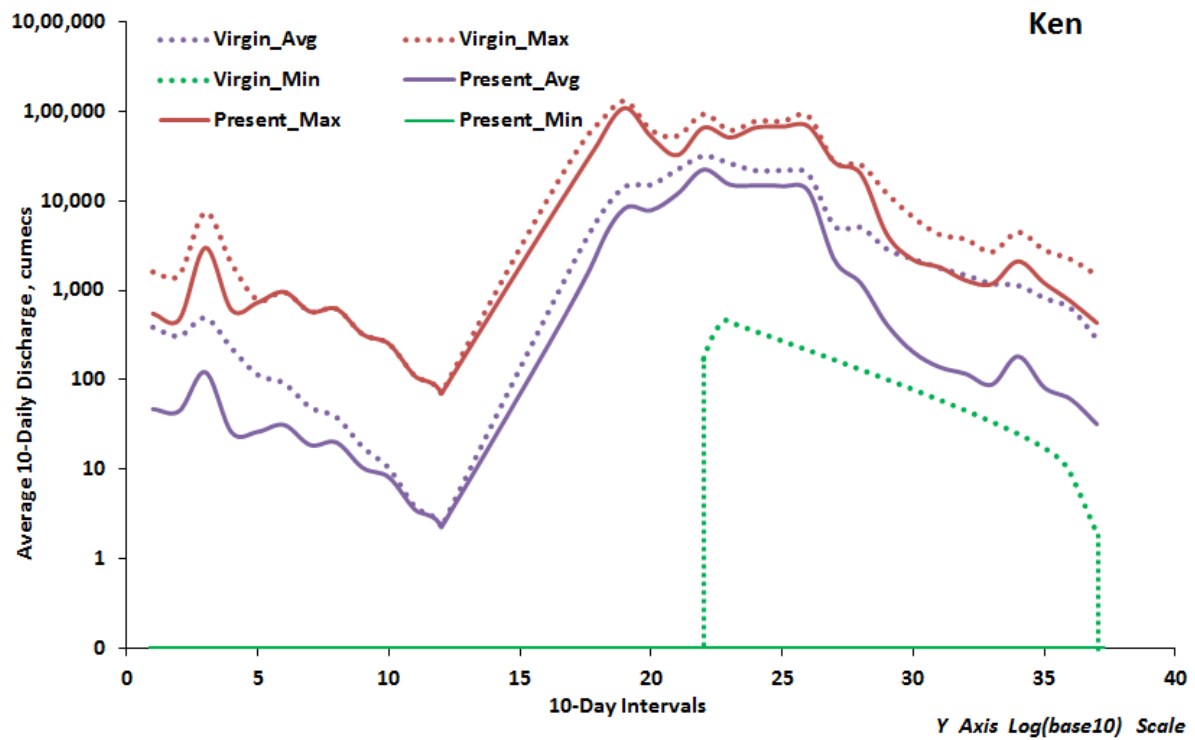


Figure A1.9: 10-Daily Hydrographs for River Ken

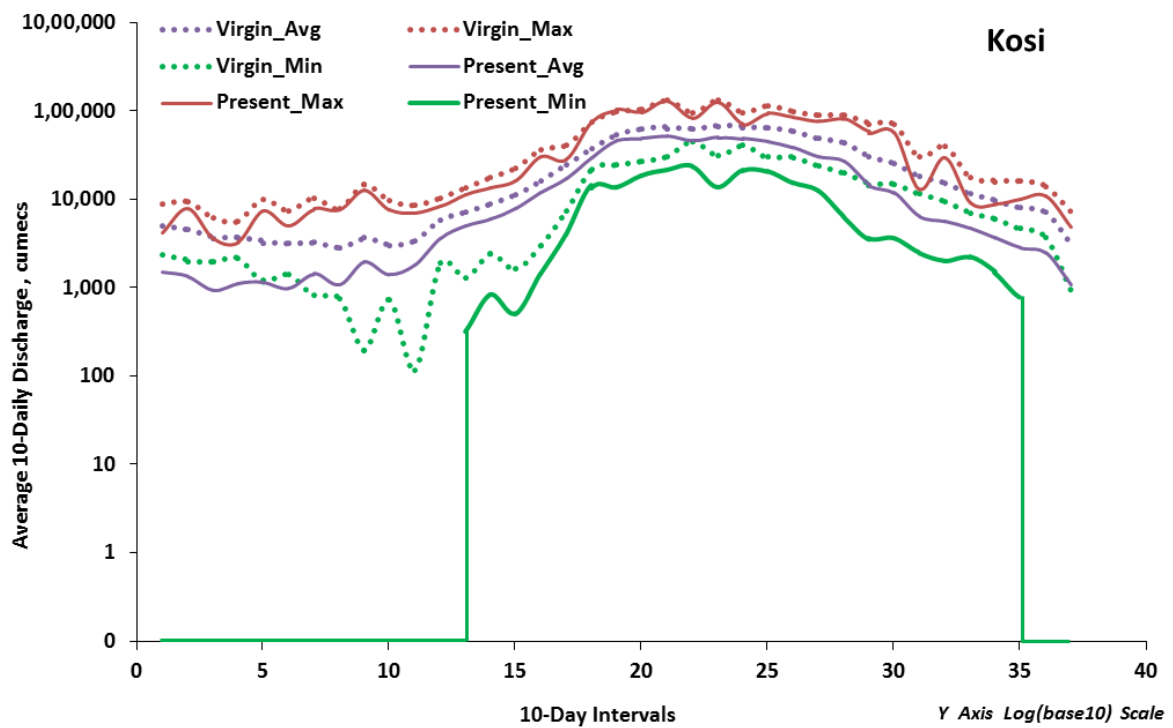


Figure A1.10: 10-Daily Hydrographs for River Kosi

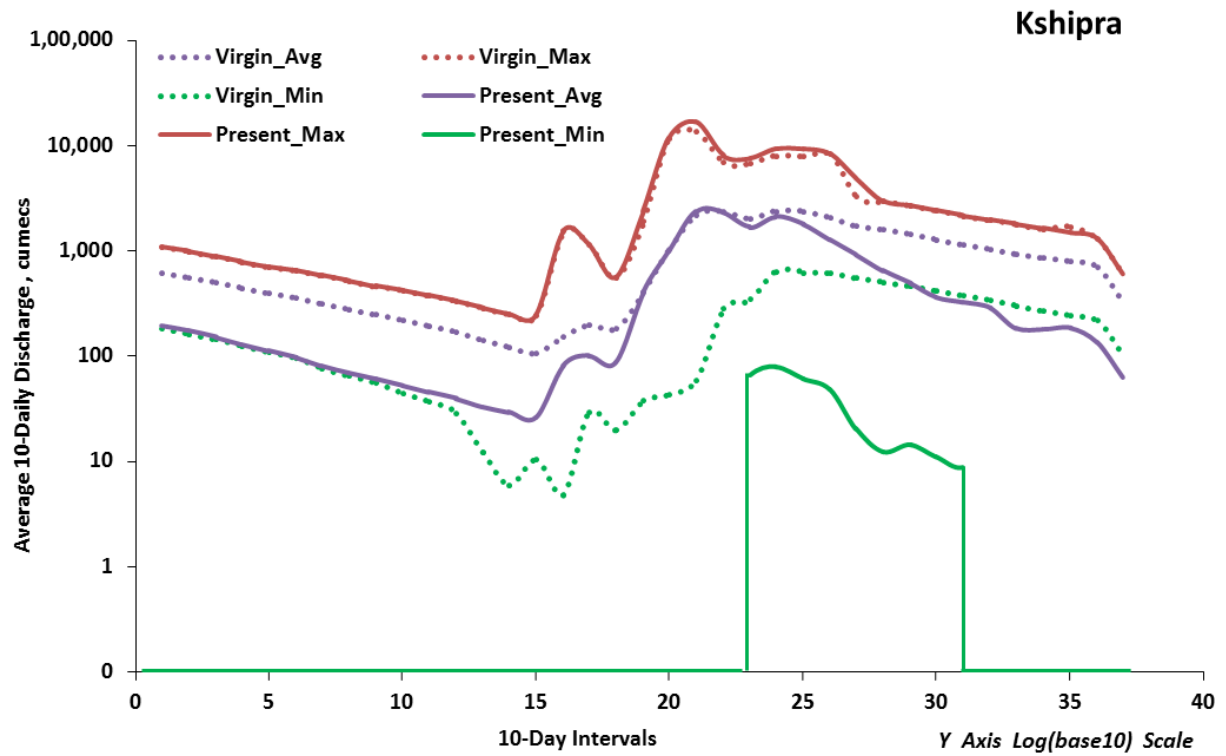


Figure A1.11: 10-Daily Hydrographs for River Kshipra

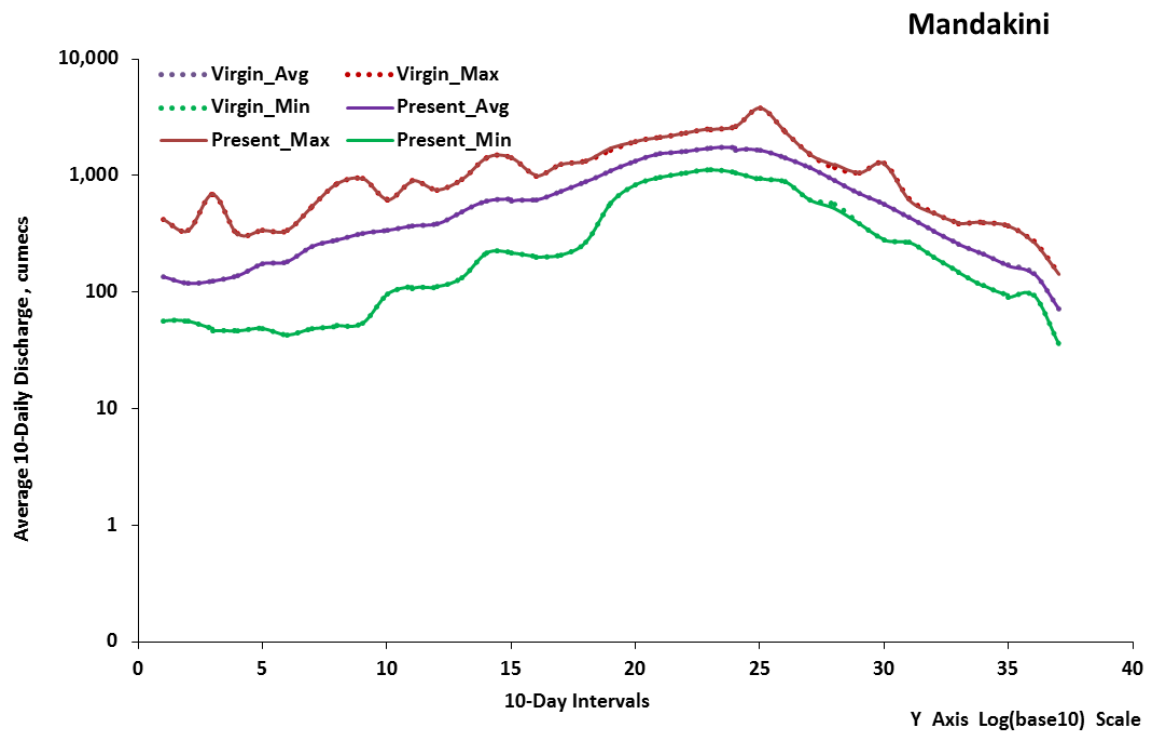


Figure A1.12: 10-Daily Hydrographs for River Mandakini

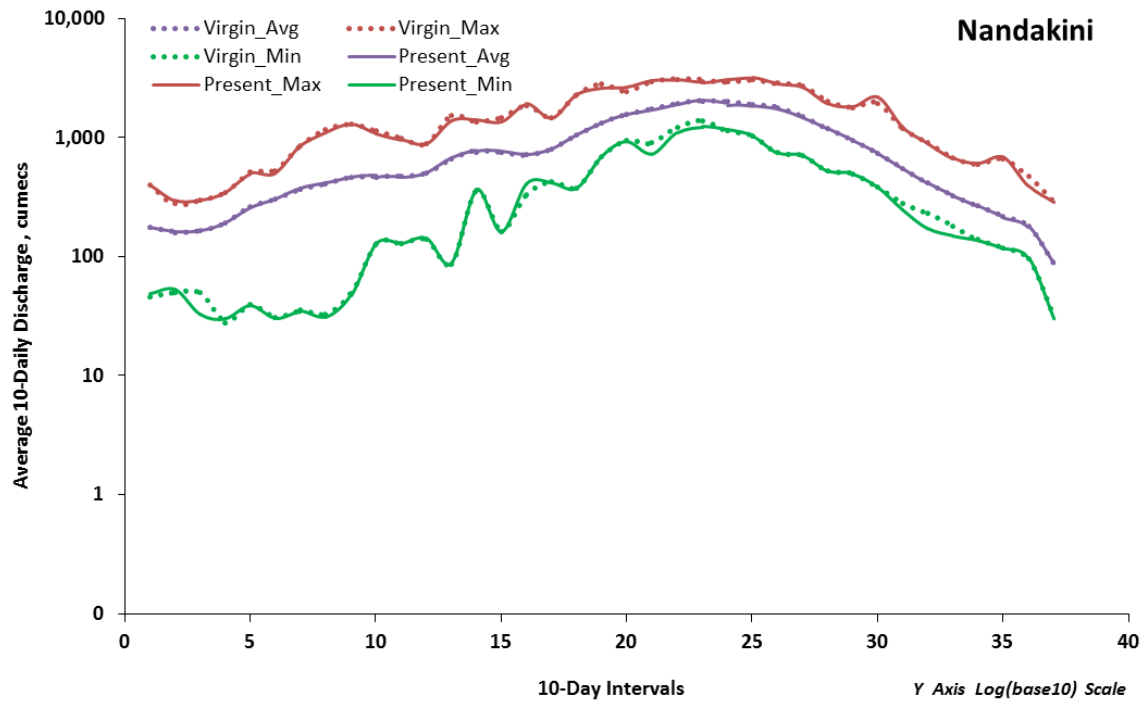


Figure A1.13: 10-Daily Hydrographs for River Nandakini

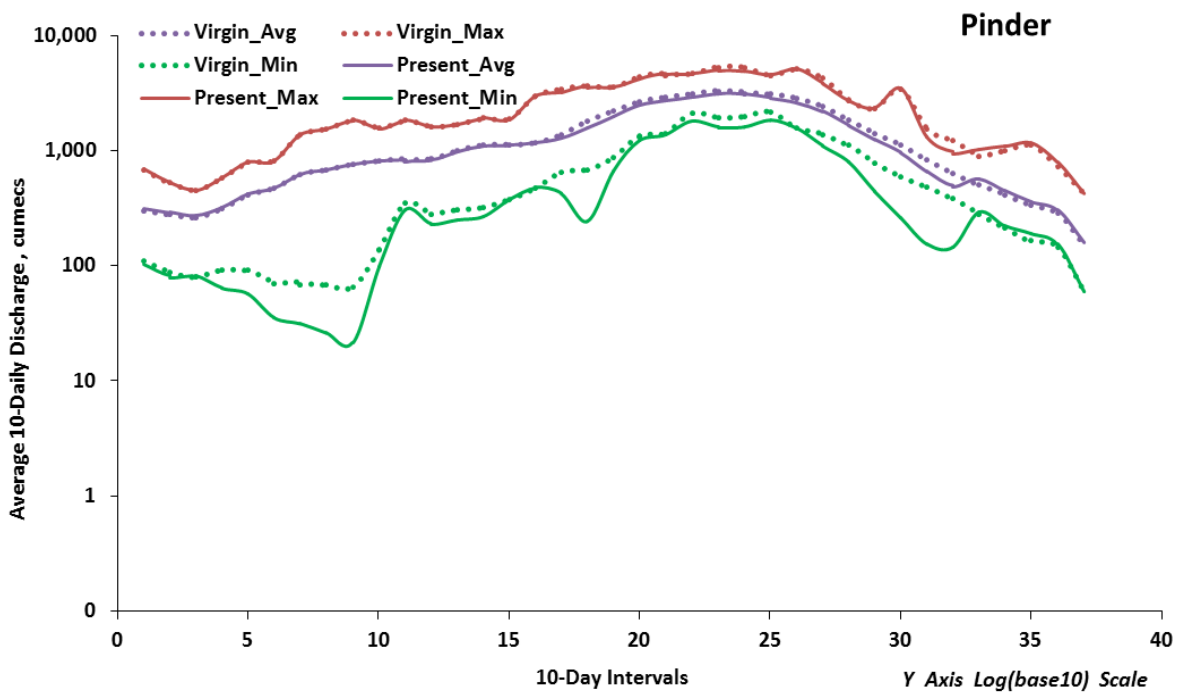


Figure A1.14: 10-Daily Hydrographs for River Pinder

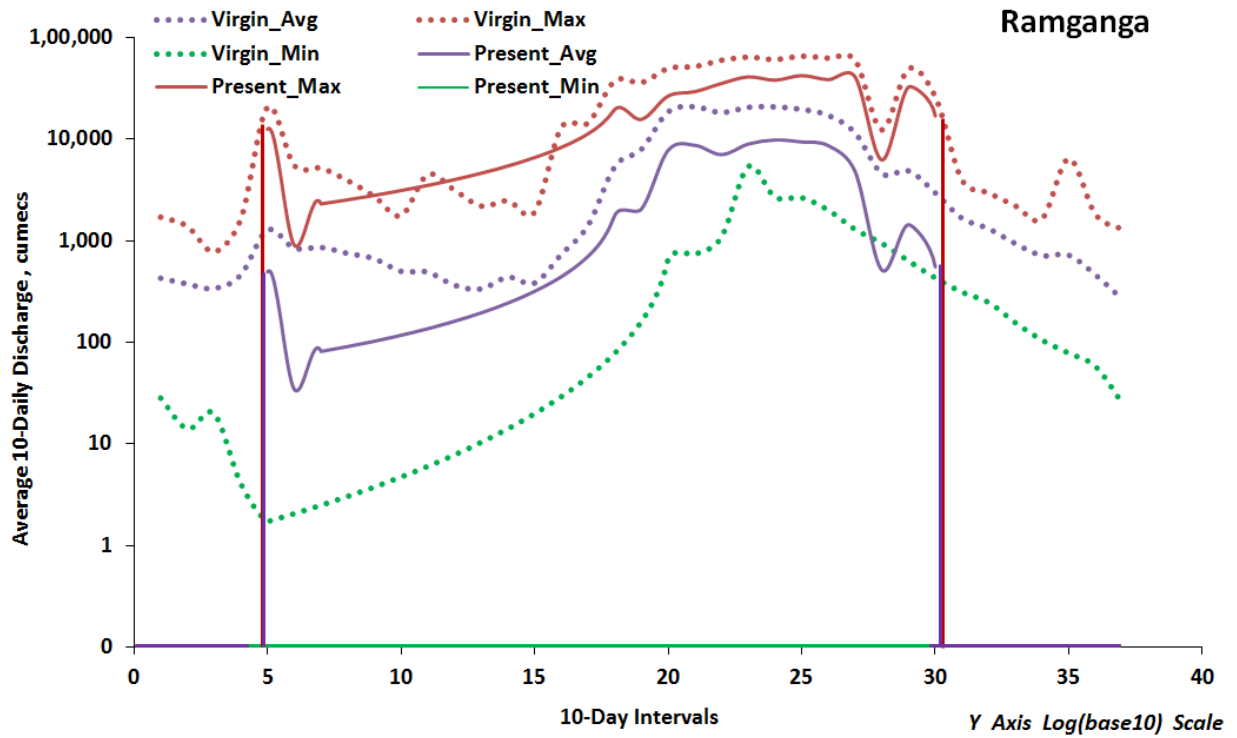


Figure A1.15: 10-Daily Hydrographs for River Ramganga

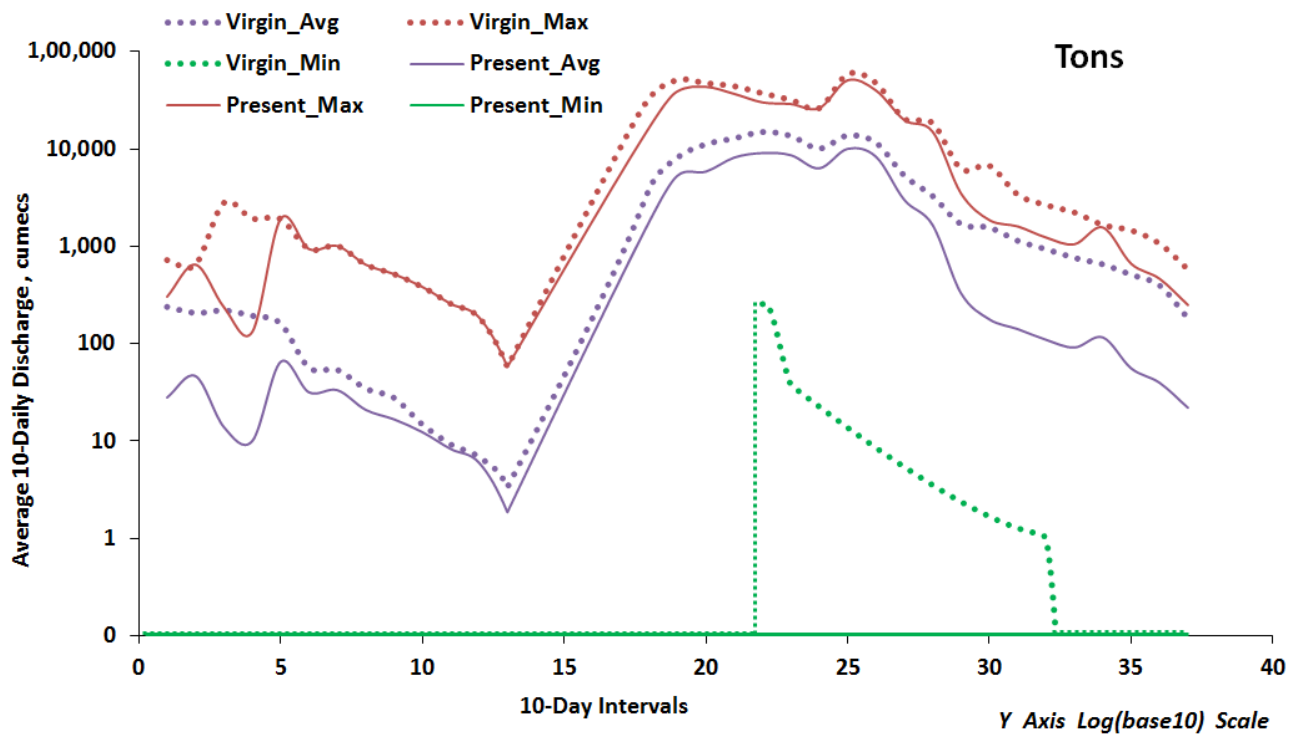


Figure A1.16: 10-Daily Hydrographs for River Tons

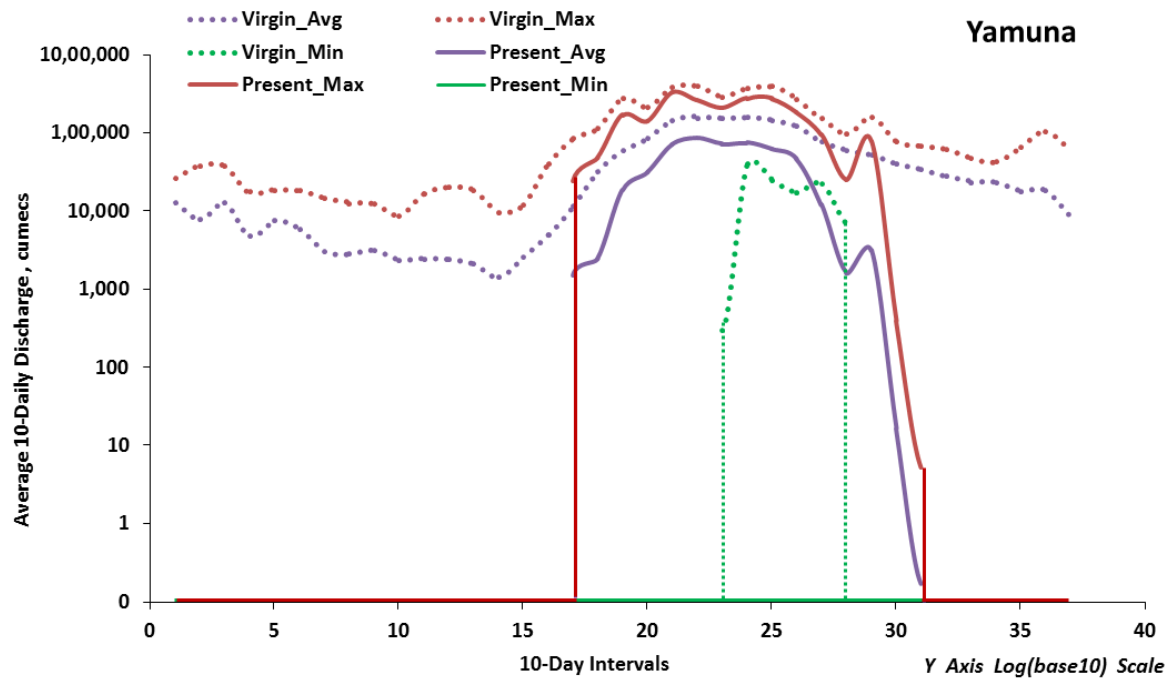


Figure A1.17: 10-Daily Hydrographs for River Yamuna

Appendix II

Annual Sediment Load Variation in National River Ganga

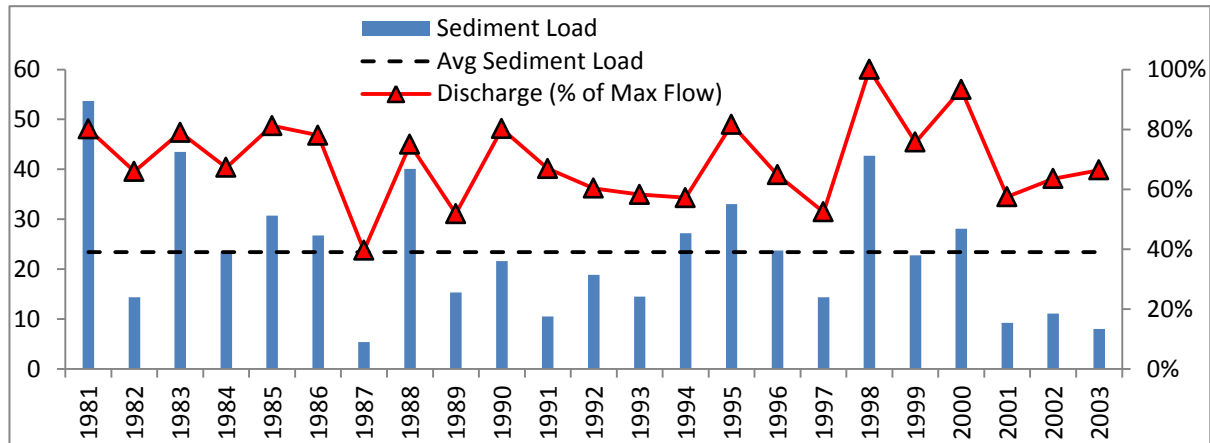


Figure A2.1: Annual Sediment Loads (in million metric tons) at Garhmukteswar

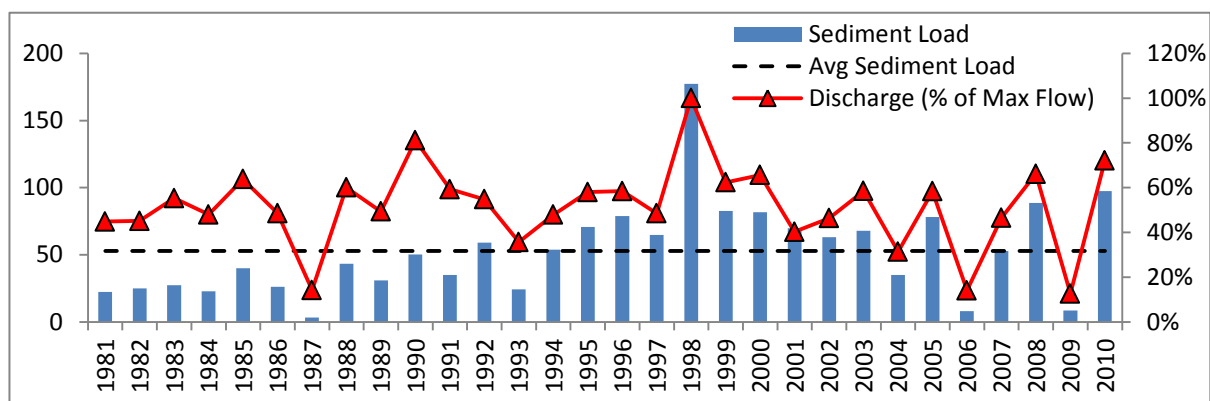


Figure A2.2: Annual Sediment Loads (in million metric tons) at Kachlabridge

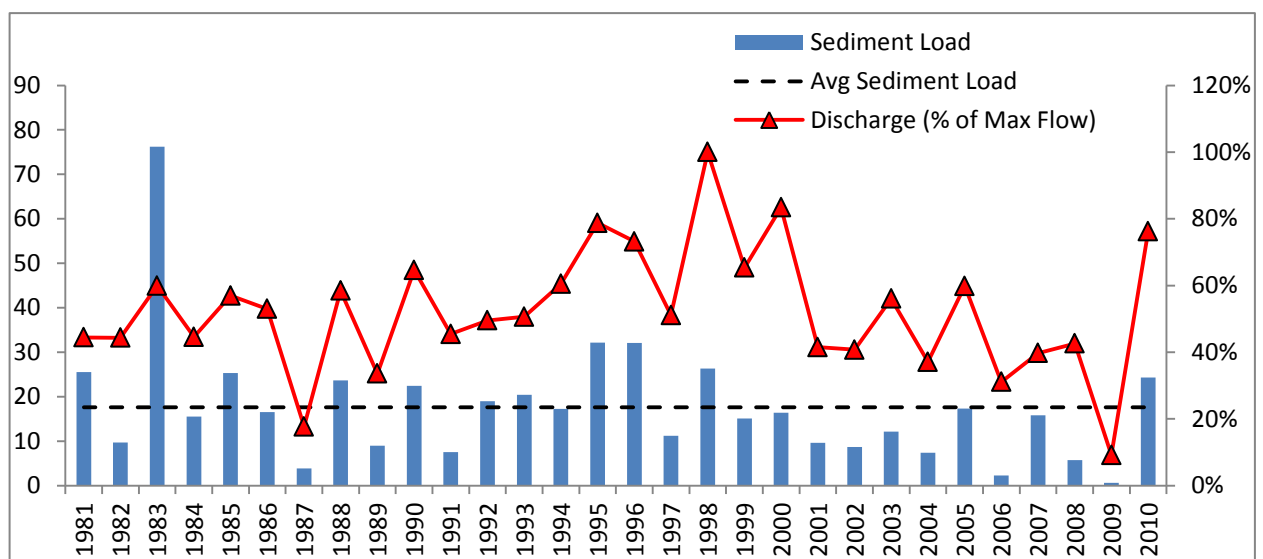


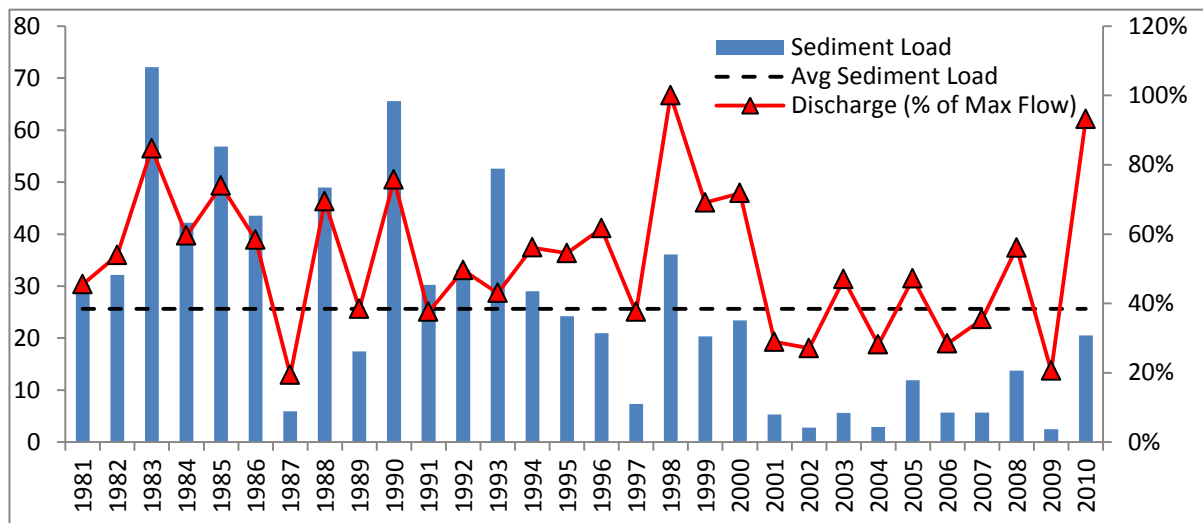
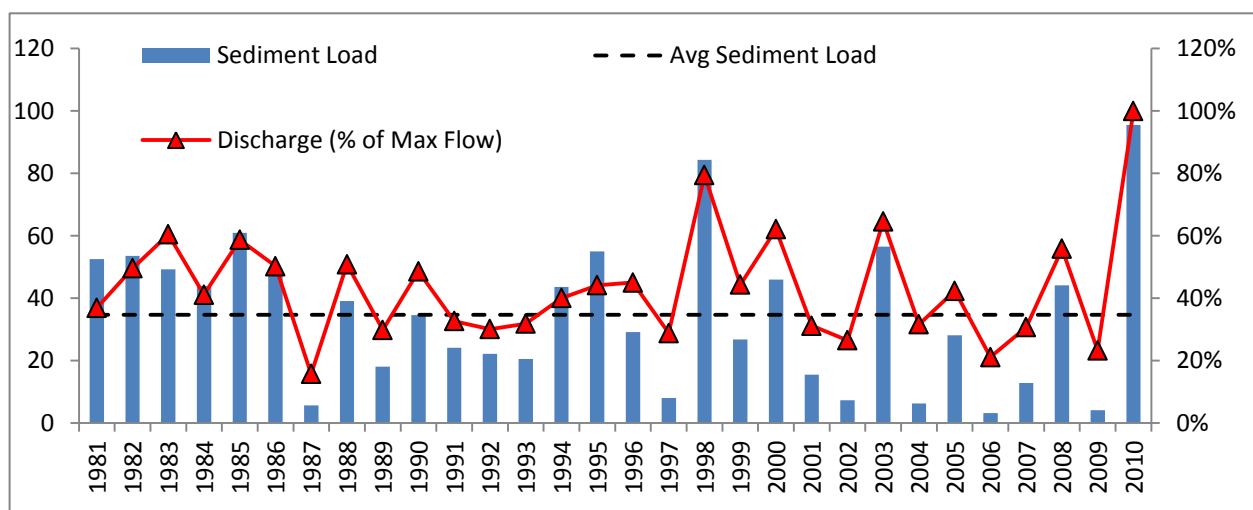
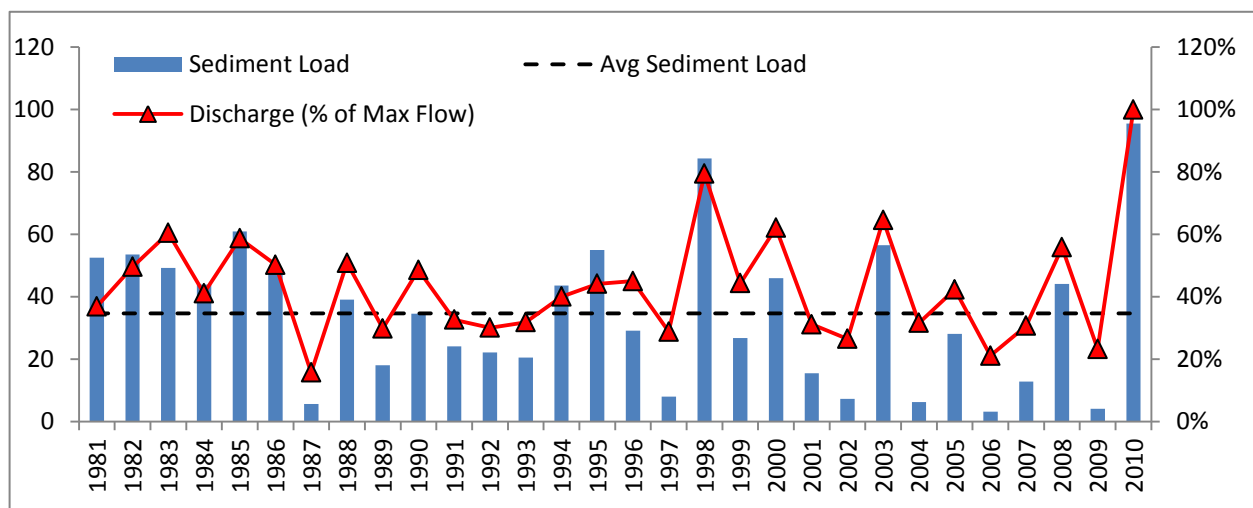
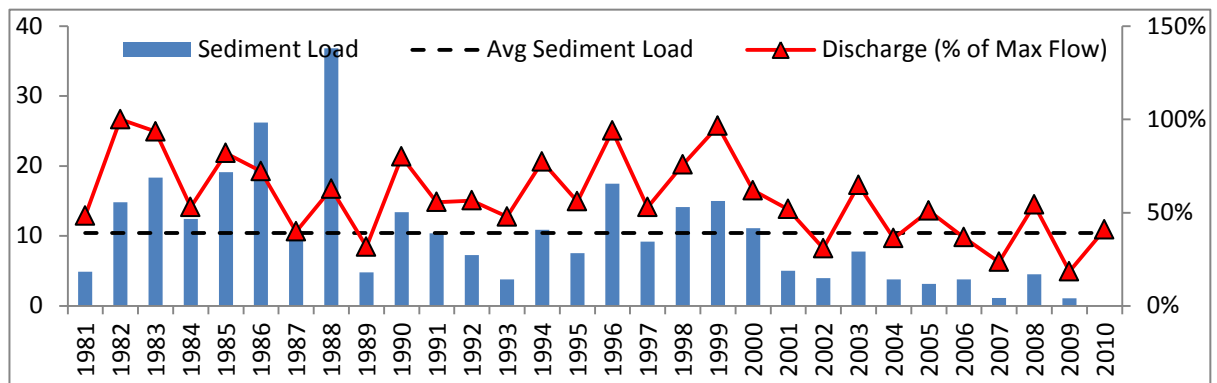
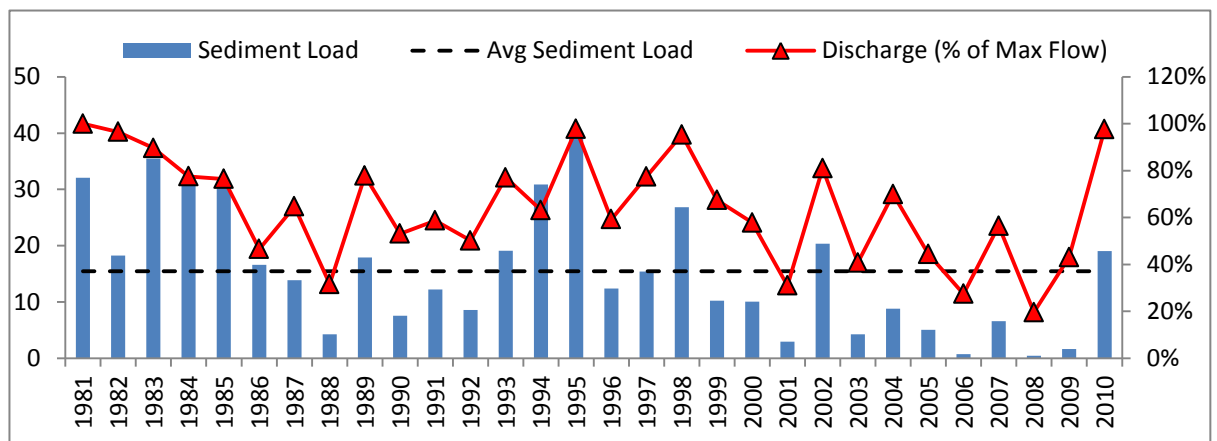
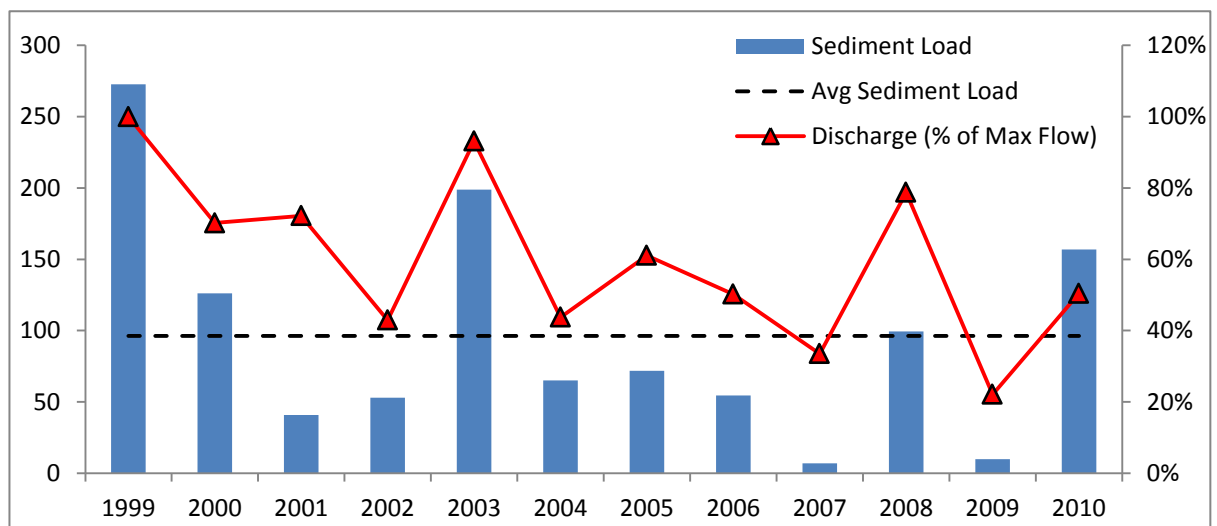
Figure A2.3: Annual Sediment Loads (in million metric tons) at Fatehgarh**Figure A2.4: Annual Sediment Loads (in million metric tons) at Ankinghat****Figure A2.5: Annual Sediment Loads (in million metric tons) at Kanpur**

Figure A2.6: Annual Sediment Loads (in million metric tons) at Bhitaura**Figure A2.7: Annual Sediment Loads (in million metric tons) at Allahabad****Figure A2.8: Annual Sediment Loads (in million metric tons) at Varanasi****Figure A2.9: Annual Sediment Loads (in million metric tons) at Buxar**

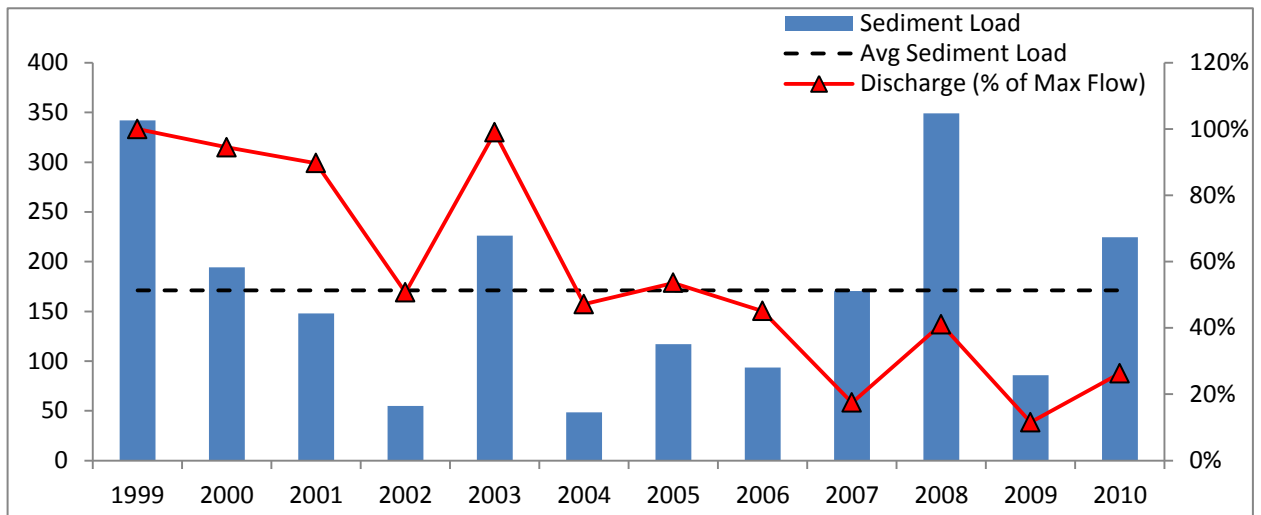


Figure A2.10: Annual Sediment Loads (in million metric tons) at Gandhigat

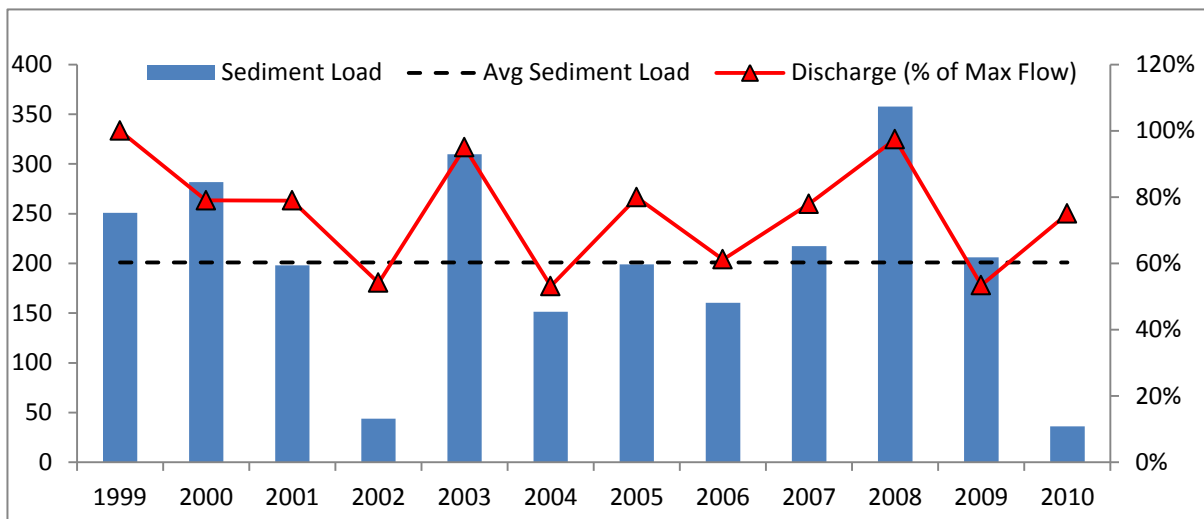


Figure A2.11: Annual Sediment Loads (in million metric tons) at Hathidah

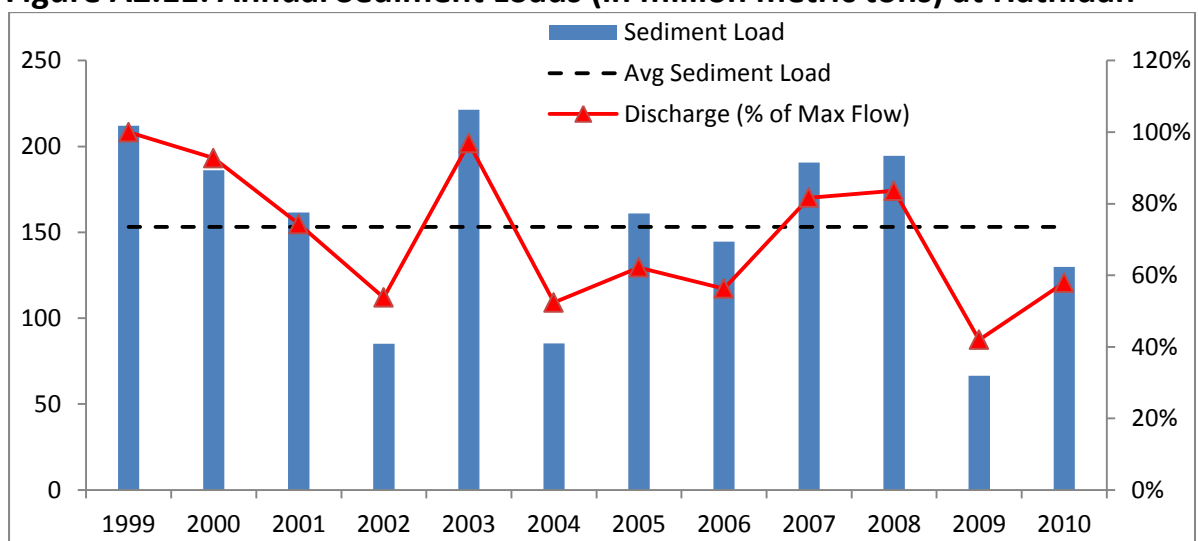


Figure A2.12: Annual Sediment Loads (in million metric tons) at Azimabad

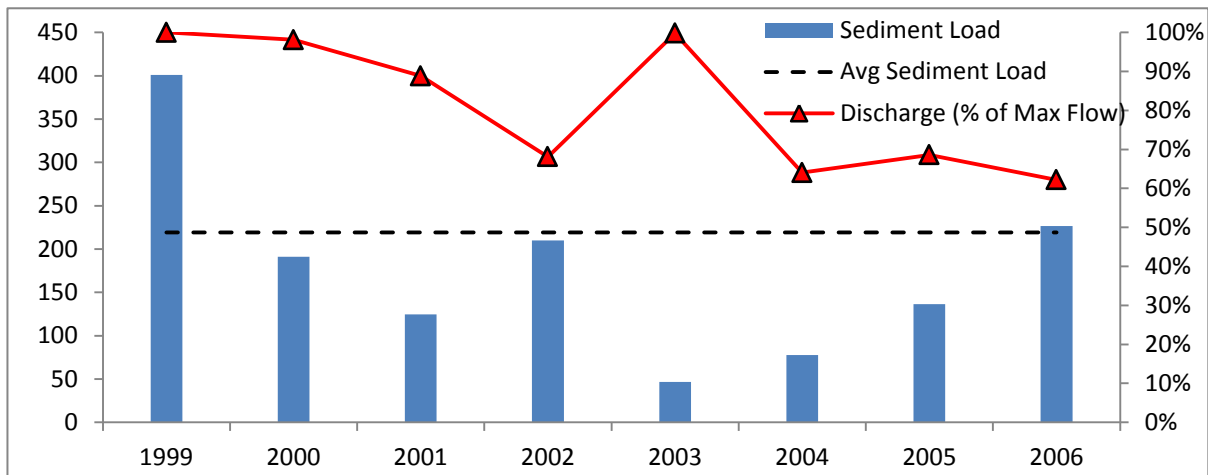


Figure A2.13: Annual Sediment Loads (in million metric tons) at Farakka (including Feeder Canal)