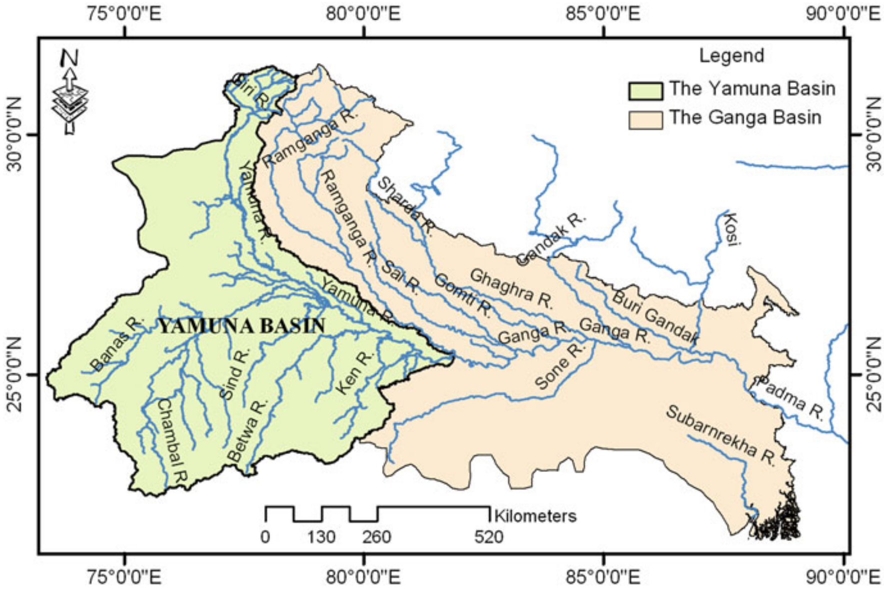
# The Yamuna River Basin



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# The Yamuna River Basin

## Water Resources and Environment

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# Preface

Challenges faced by more and more countries in their struggle for economic and social development are increasingly related to water. Water shortages, quality deterioration and flood impacts are among the problems which require greater attention and action. Globally the good quality of water for various uses has been scarce. Therefore, its management and allocation to meet out the various demand such as domestic, agriculture, industrial and environmental become important. However, in many cases due to involvement of inter-state and inter-country boundaries, the water disputes have been become a common feature leading to poor management of water resources and trans-boundary issues in the basin. To overcome this issue, various river basin authorities have been come into picture worldwide. India has also constituted various river basin authorities for better integrated water resources managements (IWRM), such as Ganga River Basin Authority, Narmada Valley Development Authority, Bhagirathi River Valley Development Authority, Upper Yamuna River Board, etc under Ministry of Environment and Forests and Ministry of Water Resources of Government of India; and State Governments. The IWRM is a participatory planning and implementation process, based on sound science, which brings stakeholders together to determine how to meet the society's long term needs for water resources while maintaining the essential ecological services and economic benefits. IWRM helps to protect the world's environment, foster economic growth and sustainable agricultural development, promote democratic participation in governance, and improve the human health. In IWRM, evaluation of natural resources is one of the major components, which requires scientific approaches.

Further to this, in India several river basins exist. Among many others, the Ganga River Basin forms nearly twenty six percent of total geographical area of the country which supports forty three percent of its population; of which Yamuna basin contributes approximately 40.2% of the drainage area of the Ganga River basin. Beside this, Yamuna River is amongst the most polluted rivers of India, which carries huge magnitude of wastewater from various urban centers and industrial towns. More than 14 towns/cities are civilized along the river banks, of which National Capital Region of Delhi (NCR-Delhi) is one of them. Due to wastewater disposal in the river, water quality has been deteriorated and is further aggravated due to less water availability during the lean periods (i.e. November to June). Considering this situation, the importance of detailed study on Yamuna River Basin has been increased, which form the basis to write a book that follows the concept of IWRM. This book "The Yamuna River Basin: Water Resources & Environment" has been designed from our continuous efforts from last three years. This book not only provides the good understanding and insight into the Yamuna River basin but also can be used as guidelines for carrying out the integrated evaluation of water resources for other river basins of India.

This book has been organized into thirteen chapters starting from the introduction to the River Basins of India to the Crop Management Plan for Yamuna basin for water resources management. Chapter 2 provides brief idea of Yamuna River basin along with inter-state water sharing. The detailed analyses of climatic characteristics of the basin have been presented in Chapter 3. This chapter also includes the development of isopluvial map along with the spatial variation of climatic parameters important to the water resources and agricultural planning. In recent years, the climate change has been come out as a major issue, and therefore, the impact of climate change is included in Chapter 4 of this book. This chapter presents detailed statistical methods for investigating the changes in climatic pattern in the Yamuna basin. The spatio-temporal variability in the climatic parameters has been adequately described through mapping and tabular results.

In Chapter 5, topography, geomorphology and geology of basin have been addressed in details. This chapter also includes the detailed analysis of geomorphological characteristics of the basin and their catchments, which are further used to derive the catchment wise unit hydrographs in Chapter 7. The soil, landuses and agriculture of the basin have been covered in Chapter 6. Detailed analyses of spatial variability of these parameters are presented in this chapter. Chapter 7 include the detailed analysis of socio-economics of the Yamuna basin starting from the demographic variation to employment followed by the poverty index and human development index (HDI) for the basin.

Chapter 8 include the catchment wise water budgeting for analyzing the surplus and deficit catchments in terms of water resources, so that adequate attention can be made for integrated water resources management. A brief methodology of flood estimation based on the approach suggested by Central Water Commission and Geomorphological Unit Hydrograph has been presented for hydrological design in the catchments.

Water pollution is the major concern of the Yamuna River, and therefore, thoroughly covered in Chapters 9, 10 and 11. The Chapter 9 presents the critical issues of the Yamuna River as far as the quality is concern. This chapter also includes the water quality parameters and their role on human body and aquatic system with their standard limits given by Bureau of Indian Standard (BIS), World Health Organization (WHO) and Central Pollution Control Board (CPCB). However, the wastewater analysis including the available treatment capacities, trends and gap has been discussed in Chapter 10.

The Chapter 11 gives a better insight into the water quality indices (WQI) and their application for assessing the water quality. In this chapter, little mathematical expression has been added for fast computations. Beside the use of WQI, the water quality trend in the river has been analyzed using the actual data. The water quality analysis has been further carried out using the bio-mappings of dissolved oxygen through the river length.

In Chapter 12, a detailed methodology on the environmental flow estimation has been presented along with the applications. A methodology for polluted and over exploited rivers has been developed and applied for the Yamuna. The developed methodology is highly useful for such other rivers in India and other countries. In India, nearly 75 percent of utilizable water resources are used in irrigation. Also due to intensive agriculture and changes in climatic patterns, water scarcities are becoming frequent for agriculture, industry, energy and households. Therefore, it is imperative to implement cropping patterns that can lead to reduced agricultural water demand, while preserving farmers' economic returns. To consider this issue, a detailed analysis of crop water demand has been carried out at district level in Chapter 13, and suitable crop plan has been suggested for entire basin at district level.

For writing this book, a vast analysis of data has been done. The data agencies, such as Central Pollution Control Board (CPCB), Central Water Commission (CWC), State Pollution Control Boards (SPCBs), Planning Commission of India, Survey of India, Agricultural Departments, Indian Council of Agricultural research (ICAR), Census Department, etc are duly acknowledge for supplying the good quality of data. Published literatures and documents were also used while writing the manuscript and are duly referred at the last of each chapter. If by chance the reference is missing, we are highly acknowledged to them.

The book will be useful to the engineers, agricultural scientists, environmentalist, planners, managers and administrators who are concerned with water resources.

Authors would like to take this opportunity to express their deep gratitude to our colleagues for their constructive suggestions and encouragement throughout the work. Special thanks are also due to Dr. R. C. Trivedi, Former Director, Central Pollution Control Board; Dr. Ajay Pradhan, Managing Director, DHI (India) Water & Environment Pvt Ltd, New Delhi; Dr. R. Dalwani, Director and Mr. S. K. Srivastava, Deputy Director of National River Conservation Directorate, Ministry of Environment & Forests, Government of India; Mr. Praveen K. Gupta, Former Director, Central Water Commission; Mr. Nitin Joshi, Research Scholar, Indian Institute of Technology Roorkee; and Mr. Prashant Eknath Kadam, Mr. Pankaj Sinha and Ms. Sagarika Rath from DHI (India) Water & Environment Pvt Ltd, New Delhi for their support and kind cooperation.

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# Chapter 1
# River Basins of India and Water Resources

**Abstract** This chapter deals with a brief description of river basins of India and their water resources, including two ways of river basin classification. The basis for classification comprises geological and topographical conditions, and catchment size. Both surface and ground water resource potential are summarized in order to understand the baseline of river basins of India.

A drainage basin is defined by the point on the stream or river, meaning the land area that drains into this point, called outlet. This land area receives water from precipitation (i.e., rainfall or snowfall) and drains downhill into river, lake, reservoir, sea or ocean. The drainage basin acts like a funnel, collecting all the water within the area covered by the basin and channeling it into a waterway. It is the drainage basin where much of the hydrologic action takes place. Indeed it can be called as the natural laboratory of hydrology. India is the land of various water bodies running from north to south and east to west.

## 1.1 River Systems

India's rivers are classified as Himalayan, peninsular, coastal, and inland-drainage basin rivers. Himalayan rivers are snow fed and maintain a high to medium rate of flow throughout the year. The heavy annual average rainfall amounts in the Himalayan catchments further add to their flow. During the monsoon months of June to September, the catchments are prone to flooding. The peninsular rivers are rainfed, whereas coastal rivers are found in the western part of India and they are short and periodic. Coastal streams, especially in the west, are short and episodic. Rivers of the Inland system, centered in western Rajasthan, are few and frequently disappear in years of scant rainfall. The majority of South Asia's major rivers flow through broad, shallow valleys and drain into the Bay of Bengal. The river systems of India, including the Indus basin, are shown in Fig. 1.1.

### *1.1.1 Himalayan Rivers*

The principal Himalayan Rivers are the Indus, the legendary Ganga and the Brahmaputra. These rivers are both naturally snow fed and rainfed and hence perennial throughout the year. Himalayan rivers discharge approximately 70% of

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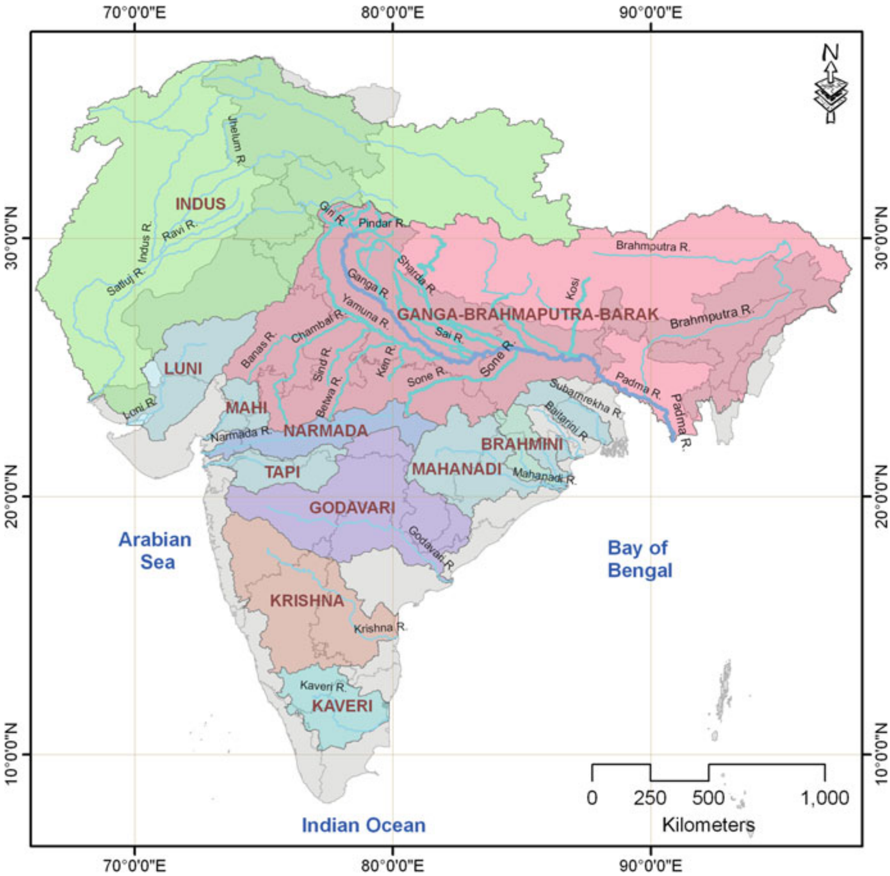


**Fig. 1.1** Important river basins of India, including part of Pakistan

their flow into the sea. The other rivers that chalk out their origin and course in the Himalayan ranges include: Sutlej, Chenab or Chandra Bhaga, Beas, Ravi, Jhelum, Yamuna, and Spiti. The principal Himalayan Rivers in India are given in Table 1.1.

The Indus originates near Mansarovar in Tibet, which flows through Kashmir and enters in Pakistan and finally terminates in the Arabian Sea near Karachi. During the course of travel, a number of tributaries, such as the Sutlej, the Beas, the Ravi, the Chenab and the Jhelum, join the Indus. These tributaries flow through India.

The Ganga River basin, India's largest, includes approximately 25% of the nation's area; it is bounded by the Himalayas in the north and the Vindhya Range to the south. The Ganga has its source in the glaciers of the Greater Himalayas, which form the frontier between India and Tibet in northwestern Uttar Pradesh (now called Uttarakhand). Many Indians believe that the source of the legendary Ganga, and several other important Asian rivers, lies in the sacred Mapam Yumco Lake (known to

**Table 1.1** Principal Himalayan rivers of India (Jain et al., 2007)

| Group No. | Drainage area ($km^2$) | Name | Himalayan area ($km^2$) |
|---|---|---|---|
| I | >256,000 | Indus | 265,728 |
| II | 128,000–256,000 | Brahmaputra | 253,952 |
| III | 38,400–128,000 | Kosi | 61,184 |
| | | Karnali | 52,736 |
| | | Sutlej | 47,360 |
| IV | 25,600–38,400 | Gandak | 37,376 |
| | | Jhelum | 33,280 |
| | | Manas | 30,720 |
| | | Chenab | 26,880 |
| | | Raidak | 26,112 |
| V | 12,800–25,600 | Ganga | 22,784 |
| | | Luhit | 20,480 |
| | | Subansiri | 17,920 |
| | | Kali | 16,128 |
| | | Beas | 14,336 |
| | | Dibang | 12,800 |
| VI | <12,800 | Tista | 12,228 |
| | | Yamuna | 11,520 |
| | | Ravi | 7,936 |
| | | Rapti | 7,680 |
| | | Ramganga | 6,656 |
| | | Baghmati | 3,840 |

the Indians as Manasarowar Lake) of western Tibet located approximately 75 km northeast of the India-China-Nepal tripoint. In the northern part of the Ganga River basin, practically all of the tributaries of the Ganga are perennial streams. However, in the southern part, located in the states of Rajasthan and Madhya Pradesh, many of the tributaries are not perennial.

Of all the rivers in India, the Brahmaputra has the greatest volume of water because of heavy annual rainfall in its basin. At Dibrugarh the annual rainfall averages 2,800 mm, and at Shillong it averages 2,430 mm. Rising in Tibet, the Brahmaputra flows south into Arunachal Pradesh after breaking through the Great Himalayan Range and dropping rapidly in elevation. It continues to fall through gorges impassable by man in Arunachal Pradesh until finally entering the Assam Valley where it meanders westward on its way to joining the Ganga in Bangladesh.

### *1.1.2 Coastal Rivers*

Coastal regions in India are primarily designated by the areas that lie close to or nearby sea and oceans. The coastal regions comprise the states lying by the Bay of Bengal and Indian Ocean; and are Odissa, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Maharashtra, Goa, and part of Gujrat. The coastal rivers, which can almost be regarded as streams, especially on the west coast, are short in length,

**Table 1.2** Important coastal rivers of India

| States | Rivers |
|---|---|
| West Bengal Coastal Rivers | Subarnarekha, Kharkai, Kamgasabati |
| Andhra Pradesh Coastal Rivers | Vamsadhara, Nagavati, Sharada |
| Tamil Nadu Coastal Rivers | Thamirabarani, Palar, Vaigai, Vellar, Vasishta, Sweta |
| Karnataka Coastal Rivers | Netravati, Sharavathi, Aghanashini rivers |
| Maharashtra Coastal Rivers | Shastri, Gad, Vashishti, Savitri, Patalganga, Ulhas, Thane Creek, Vasai Creek, Mithi, Oshiware, Dahisar, Tansa, Vaitarna, Surya |

episodic, ephemeral and have small catchments. There are as many as six hundred rivers on the west coast. Some of the important coastal rivers are given in Table 1.2.

### *1.1.3 Deccan Rivers*

The southern section of India is predominated by the Deccan plateau, the Western Ghats, the Eastern Ghats, the Vindhyan range and the Satpura range. The Deccan region is also known as Peninsular India, which mainly holds the vast plateau regions of the western and southern India. The Deccan Rivers are primarily rain-fed and as a consequence immensely fluctuate in volume. All of these rivers are non-perennial in nature. Peninsular rivers contribute 30% of the total surface water resources of India. The Deccan or Peninsular rivers behave according to the providential wish, at times overwhelming in their course and at times, running dry most of the year. The major rivers in this region are Godavari, Krishna, Cauveri, Mahanadi, Narmada, Tapi, Indravati, Tungabhadra and Bhima. Among these Narmada and Tapi are the west flowing rivers which terminate into the Arabian Sea. Pennar, Damodar, Sharavati, Netravati, Bharathapuzha, Periyar, and Pamba rivers are other secondary rivers of this region. Most of these rivers are east flowing into the Bay of Bengal except the Pamba. These rivers, generally seasonal and dependent on rainfall, cause trouble during the occurrence of rainfall.

The Mahanadi, rising in the state of Madhya Pradesh, is an important river in the state of Orissa. In the upper drainage basin of the Mahanadi, which is centered on the Chhattisgarh Plain, periodic droughts contrast with the situation in the delta region where floods may damage the crops in what is known as the rice bowl of Orissa. Hirakud Dam, constructed in the middle reaches of the Mahanadi, has helped in alleviating these adverse effects by creating a reservoir.

The source of the Godavari is northeast of Bombay (Mumbai in the local Marathi language) in the state of Maharashtra, and the river follows a southeasterly course for 1,400 km to its mouth on the Andhra Pradesh coast. The Godavari River basin area is second in size only to the Ganga; its delta on the east coast is also one of the country's main rice-growing areas. It is known as the "Ganga of the South," but its discharge, despite the large catchment area, is moderate because of the medium level of annual rainfall, for example, about 700 mm at Nasik and 1,000 mm at Nizamabad.

The Narmada and the Tapti are the only major rivers that flow into the Arabian Sea. The Narmada rises in Madhya Pradesh and crosses the state, passing swiftly through a narrow valley between the Vindhya Range and spurs of the Satpura Range. It flows into the Gulf of Khambhat (or Cambay). The shorter Tapti follows a generally parallel course, between 80 and 160 km to the south of the Narmada, flowing through the states of Maharashtra and Gujarat on its way into the Gulf of Khambhat.

The Krishna rises in the Western Ghats and flows east into the Bay of Bengal. It has a poor flow because of low level of rainfall in its catchment area i.e. 660 mm annually at Pune. Despite its low discharge, the Krishna is the third longest river in India.

The source of the Kaveri is in the state of Karnataka, and the river flows southeastward. The waters of the river have been a source of irrigation since antiquity; in the early 1990s, an estimated 95% of the Kaveri was diverted for agricultural use before emptying into the Bay of Bengal. The delta of the Kaveri is so mature that the main river has almost lost its link with the sea, as the Kollidam, the distributary of the Kaveri, bears most of the flow.

### *1.1.4 Inland Drainage Basins*

The rivers in drainage basins inland consist of rivers in western Rajasthan. These rivers are very few in numbers and they flow for a very short period of time. The rivers in this category are Sambhar which vanish in the desert sands, and the Luni that drains into the Rann of Kutch. Another major river of the western region is the Mahi, which originates from the northern slope of the Vindhyan range in Madhya Pradesh. It enters the southeastern portion of Rajasthan and flows through the Banswara district, and finally terminates into the sea by a wide estuary near Cambay.

## 1.2 Classification of Indian River Basin Based on Drainage Area

On the basis of drainage area of the rivers, the Indian river can be classified into three groups: (i) major river basins: $A > 20{,}000\ km^2$, (ii) medium river basins: $2{,}000 \leq A \leq 20{,}000\ km^2$, and (iii) minor river basins: $A < 2{,}000\ km^2$. According to this classification, the number of major and medium river basins are 12 and 46, respectively (Jain et al., 2007) and these contribute nearly 92% of the total runoff in the country. The remaining 8% runoff is contributed by the minor rivers. Of the major rivers, the Ganga-Brahmaputra-Meghana (GBM) has the biggest drainage area of 1.10 million $km^2$, which is more than 43% of the total geographical area of the country. The catchment area of medium rivers is about 0.25 million $km^2$, and Subernarekha is the largest among them having a drainage area of 19,300 $km^2$. The drainage area of major and medium river basins, length of rivers and their origin are summarized in Tables 1.3 and 1.4, respectively.

**Table 1.3** Major river basins of India (CWC, 1990; MoWR, 2004)

| S. No. | Name | Origin | Length (km) | Area (km$^2$) | States falling |
|---|---|---|---|---|---|
| 1 | Indus | Mansarovar (Tibet) | 1,114+ | 321,289+ | J&K, Punjab, Himachal Pradesh, Rajasthan and Chandigarh |
| 2 | (a) Ganga | Gangotri (Uttarkashi) | 2,525+ | 861,452+ | Uttarakhand, Uttar Pradesh, Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh, Bihar, West Bengal, and Delhi |
| | (b) Brahmaputra | Kailash Range (Tibet) | 916+ | 194,413+ | Arunachal Pradesh, Assam, Meghalaya, Nagaland, Sikkim, West Bengal, Mizoram, and Tripura |
| | (c) Barak and Meghna | | | 41,723+ | Assam, Meghalaya, Nagaland, Manipur, Mizoram, and Tripura |
| 3 | Sabarmati | Aravalli Hills (Rajasthan) | 371 | 24,674 | Rajasthan and Gujarat |
| 4 | Mahi | Dhar (Madhya Pradesh) | 583 | 34,842 | Rajasthan, Madhya Pradesh and Gujarat |
| 5 | Narmada | Amarkantak (Madhya Pradesh) | 1,312 | 98,796 | Madhya Pradesh, Maharashtra and Gujarat |
| 6 | Tapi | Betul (Madhya Pradesh) | 724 | 65,145 | Madhya Pradesh, Maharashtra and Gujarat |
| 7 | Brahmini | Ranchi (Jharkhand) | 799 | 39,033 | Madhya Pradesh, Bihar and Odissa |
| 8 | Mahanadi | Nazri Town (Madhya Pradesh) | 851 | 141,589 | Madhya Pradesh, Maharashtra, Bihar, Chattisgarh and Odissa |
| 9 | Godavari | Nasik (Maharashtra) | 1,465 | 312,812 | Maharashtra, Andhra Pradesh, Madhya Pradesh, Odissa and Pondicherry |
| 10 | Krishna | Mahabaleshwar (Maharashtra) | 1,401 | 258,948 | Maharashtra, Andhra Pradesh and Karnataka |
| 11 | Pennar | Kolar (Karnataka) | 597 | 55,213 | Andhra Pradesh and Karnataka |
| 12 | Cauvery | Coorg (Karnataka) | 800 | 81,155 | Tamil Nadu, Karnataka, Kerala and Podicherry |
| | | Total | | 2,528,084 | |

**Table 1.4** Medium river basins of India (CWC, 1990; MoWR, 2004)

| S. No. | Name | Origin | State | Length (km) | Area ($km^2$) |
|---|---|---|---|---|---|
| West Flowing Rivers | | | | | |
| 1 | Ozat | Kathiawar | Gujarat | 128 | 3,189 |
| 2 | Shetrunji | Dalkania | Gujarat | 182 | 5,514 |
| 3 | Bhadar | Rajkot | Gujarat | 198 | 7,094 |
| 4 | Aji | Rajkot | Gujarat | 106 | 2,139 |
| 5 | Dhadhar | Panchmahal | Gujarat | 135 | 2,770 |
| 6 | Purna | Dhosa | Maharashtra | 142 | 2,431 |
| 7 | Ambika | Dangs | Maharashtra | 142 | 2,715 |
| 8 | Vaitarna | Nasik | Maharashtra | 171 | 3,637 |
| 9 | Dammanganga | Nasik | Maharashtra | 143 | 2,357 |
| 10 | Ulhas | Raigarh | Maharashtra | 145 | 3,864 |
| 11 | Savitri | Pune | Maharashtra | 99 | 2,899 |
| 12 | Sastri | Ratnagiri | Maharashtra | 64 | 2,174 |
| 13 | Washishthi | Ratnagiri | Maharashtra | 48 | 2,239 |
| 14 | Mandvi | Belgaum | Karnataka | 87 | 2,032 |
| 15 | Kalinadi | Belgaum | Karnataka | 153 | 5,179 |
| 16 | Gangavati or Bedti | Dharwar | Karnataka | 152 | 3,902 |
| 17 | Sharavati | Shimoga | Karnataka | 122 | 2,209 |
| 18 | Netravati | Dakshina Kannada | Karnataka | 103 | 3,657 |
| 19 | Chaliar or Baypore | Elamtalvi Hills | Kerala | 169 | 2,788 |
| 20 | Bharathapuzha | Annamalai Hills | Tamil Nadu | 209 | 6,186 |
| 21 | Periyar | Sivajini Hills | Kerala | 244 | 5,398 |
| 22 | Pamba | Devarmalai | Kerala | 176 | 2,235 |
| East Flowing Rivers | | | | | |
| 23 | Burhabalang | Mayurbahanj | Odissa | 164 | 4,837 |
| 24 | Baitarni | Keonjhar | Odissa | 365 | 12,789 |
| 25 | Rushikulya | Phulbani | Odissa | 146 | 7,753 |
| 26 | Bahuda | Ramgiri village | Odissa | 73 | 1,248 |
| 27 | Vamsadhara | Kalahandi | Odissa | 221 | 10,830 |
| 28 | Nagavali | Kalahandi | Odissa | 217 | 9,410 |
| 29 | Sarda | Vishakhapatnam | Andhra Pradesh | 104 | 2,725 |
| 30 | Eleru | Vishakhapatnam | Andhra Pradesh | 125 | 3,809 |
| 31 | Vogarivagu | Guntur | Andhra Pradesh | 102 | 1,348 |
| 32 | Gundlakamma | Kurnool | Andhra Pradesh | 220 | 8,494 |
| 33 | Musi | Nellore | Andhra Pradesh | 112 | 2,219 |
| 34 | Paleru | Nellore | Andhra Pradesh | 104 | 2,483 |
| 35 | Muneru | Nellore | Andhra Pradesh | 122 | 3,734 |
| 36 | Swarnamukhi | Koraput | Odissa | 130 | 3,225 |
| 37 | Kandleru | Vinukonda | Andhra Pradesh | 73 | 3,534 |
| 38 | Kortalaiyar | Chinglepet | Tamil Nadu | 131 | 3,521 |
| 39 | Palar | Kolar | Karnataka | 348 | 17,871 |
| 40 | Varahandi | North Arcot | Tamil Nadu | 94 | 3,044 |
| 41 | Ponnaiyar | Kolar | Karnataka | 396 | 14,130 |
| 42 | Vellar | Chithri Hills | Tamil Nadu | 193 | 8,558 |
| 43 | Vaigai | Madurai | Tamil Nadu | 258 | 7,031 |
| 44 | Pambar | Madurai | Tamil Nadu | 125 | 3,104 |
| 45 | Gundar | Madurai | Tamil Nadu | 146 | 5,647 |
| 46 | Vaippar | Tirunolvolli | Tamil Nadu | 130 | 5,288 |
| 47 | Tambraparni | Tirunolvolli | Tamil Nadu | 130 | 5,969 |
| 48 | Subarnarekha | Nagri/Ranchi | Jharkhand | 395 | 19,296 |
| | | | Total | | 248,505 |

## 1.3 Water Resources of India

The total utilizable water resources of the country are assessed as 1,086 km$^3$. A brief description of surface and groundwater water resources of India is given below.

### *1.3.1 Surface Water Resources*

In the past, several organizations and individuals have estimated water availability for the nation. Recently, the National Commission for Integrated Water Resources Development estimated the basinwise average annual flow in Indian river systems as 1953 km$^3$ (NCIWRD, 1999). The basinwise surface water resources are given in Table 1.5.

**Table 1.5** Basin wise surface water resources potential (km$^3$)

| S. No. | River basins | Average annual flows (NCIWRD, 1999) | Utilizable flows |
|---|---|---|---|
| 1 | Indus (Catchment area in Indian territory) | 73.31 | 46.00 |
| 2 | (a) Ganga | 525.02 | 250.00 |
| | (b) Brahmaputra | 629.05 | 24.00 |
| | (c) Meghna (Barak) | 48.36 | NA |
| 3 | Godavari | 110.54 | 76.30 |
| 4 | Krishna | 69.81 | 58.00 |
| 5 | Cauvery | 21.36 | 19.00 |
| 6 | Pennar | 6.32 | 6.86 |
| 7 | Mahanadi | 66.88 | 49.99 |
| 8 | Brahmani and Baitarni | 28.48 | 18.30 |
| 9 | Subarnarekha | 12.37 | 6.81 |
| 10 | Sabarmati | 3.81 | 1.93 |
| 11 | Mahi | 11.02 | 3.10 |
| 12 | Narmada | 45.64 | 34.50 |
| 13 | Tapi | 14.88 | 14.50 |
| 14 | East flowing and river from Mahanadi to Godavari and Krishna to Pennar | 22.52 | 13.11 |
| 15 | East flowing rivers between Pennar and Kanyakumari | 16.6 | 16.73 |
| 16 | West flowing rivers of Kutch and Saurashtra including Luni | 15.10 | 14.98 |
| 17 | West flowing rivers from Tapi to Tadri | 87.41 | 11.94 |
| 18 | West flowing rivers from Tadri to Kanyakumari | 113.53 | 24.27 |
| 19 | Area of inland drainage in Rajasthan desert | NA | NA |
| 20 | Minor rivers draining to Myanmar (Burma) and Bangladesh | 31.00 | |
| | Total | 1,952.8 | 690.00 |

The utilizable water resource is the quantum of withdrawable water from its place of natural occurrence. Within the limitations of physiographic conditions and socio-political environment, legal and constitutional constraints and the technology of development available at present, utilizable quantity of water from surface flow has been assessed by various authorities differently. The utilizable annual surface water of the country is 690 km$^3$ (Table 1.5). In a majority of river basins, the percent utilization is quite high and is within the range of 50–95% of utilizable surface resources (IWRS, 1996; Kumar et al., 2005). There is considerable scope for increasing the utilization of water in the Ganga–Brahmaputra basins by construction of storages at suitable locations in neighboring countries.

## *1.3.2 Ground Water Resources*

The annual potential natural groundwater recharge from rainfall in India is about 342.43 km$^3$, which is 8.56% of the total annual rainfall of the country. The annual potential groundwater recharge augmentation from canal irrigation system is about 89.46 km$^3$. Thus, the total replenishable groundwater resource of the country is assessed as 431.89%. After allotting 15% of this quantity for drinking, and 6 km$^3$ for industrial purposes, the remaining can be utilized for irrigation purposes. Thus, the available groundwater resource for irrigation is 361 km$^3$, of which utilizable quantity (90%) is 325 km$^3$. The estimates made by the Central Groundwater Board (CGWB) of the total replenishable groundwater resource, provision for domestic, industrial and irrigation uses and utilizable groundwater resources for future use are given in Table 1.6. The basin-wise per capita water availability varies between 13,393 m$^3$ per annum for the Brahmaputra–Barak basin to about 300 m$^3$ per annum for the Sabarmati basin. The basin-wise groundwater potential of the country is given in Table 1.7.

Due to increasing population, water demand for various uses such as domestic, food, industrial and power will be increased. For the year 2050, NCIWRD (1999) has estimated that the total water demand in the country will be 973–1,180 km$^3$, whereas the utilizable surface and ground water resources are 690 km$^3$ and 396 km$^3$, respectively. In spite of the spatial variability of utilizable water resources in the country, India will become a highly water stressed country, if better water management plan is not implemented at the watershed level.

**Table 1.6** Groundwater resources of India (km$^3$/annum)

| | | |
|---|---|---|
| 1 | Total replenishable groundwater resource | 432 |
| 2 | Provision for domestic, industrial and other uses | 71 |
| 3 | Available groundwater resource for irrigation | 361 |
| 4 | Utilizable groundwater resource for irrigation (90% 361 km$^3$) | 325 |
| 5 | Total utilizable groundwater resources (sum of 1–4) | 396 |

**Table 1.7** Basin wise groundwater resources potential (in km$^3$/annum)

| S. No. | Basin | Total replenishable GW resources | Provision for domestic, industrial and other uses | Available GW for irrigation | Net draft | Balance GW Potential | Level of GW development (%) |
|---|---|---|---|---|---|---|---|
| 1 | Brahmani and Baitarni | 4.05 | 0.61 | 3.44 | 0.29 | 3.16 | 8.45 |
| 2 | Brahmaputra | 26.55 | 3.98 | 22.56 | 0.76 | 21.80 | 3.37 |
| 3 | Chambal Composite | 7.19 | 1.08 | 6.11 | 2.45 | 3.66 | 40.09 |
| 4 | Cauvery | 12.30 | 1.84 | 10.45 | 5.78 | 4.67 | 55.33 |
| 5 | Ganga | 170.99 | 26.03 | 144.96 | 48.59 | 96.37 | 33.52 |
| 6 | Godavari | 40.65 | 9.66 | 30.99 | 6.05 | 24.94 | 19.53 |
| 7 | Indus | 26.49 | 3.05 | 23.43 | 18.21 | 5.22 | 77.71 |
| 8 | Krishna | 26.41 | 5.58 | 20.83 | 6.33 | 14.50 | 30.39 |
| 9 | Kutch and Saurashtra Composite | 11.23 | 1.74 | 9.49 | 4.85 | 4.64 | 51.14 |
| 10 | Madras and South Tamil Nadu | 18.22 | 2.73 | 15.48 | 8.93 | 6.55 | 57.68 |
| 11 | Mahanadi | 16.46 | 2.47 | 13.99 | 0.97 | 13.02 | 6.95 |
| 12 | Meghna | 8.52 | 1.28 | 7.24 | 0.29 | 6.95 | 3.94 |
| 13 | Narmada | 10.83 | 1.65 | 9.17 | 1.99 | 7.18 | 21.74 |
| 14 | Northeast Composite | 18.84 | 2.83 | 16.02 | 2.76 | 13.26 | 17.20 |
| 15 | Pennar | 4.93 | 0.74 | 4.19 | 1.53 | 2.66 | 36.60 |
| 16 | Subarnarekha | 1.82 | 0.27 | 1.55 | 0.15 | 1.40 | 9.57 |
| 17 | Tapi | 8.27 | 2.34 | 5.93 | 1.96 | 3.97 | 33.05 |
| 18 | Western Ghat | 17.69 | 3.19 | 14.50 | 3.32 | 11.18 | 22.88 |
| | Total | 431.43 | 71.08 | 360.35 | 115.21 | 245.13 | 31.97 |

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# Chapter 2
# Salient Features of the Yamuna River Basin

**Abstract** In this chapter, salient features of the Yamuna River basin are presented, including mythological importance, catchment area description within states, and general river flow regime. Major abstractions, including water-related issues at various locations in the main river stem, are also discussed. The drainage area of the Yamuna River basin encompasses six states, accordingly the inter-state agreement has been formulated for water sharing. A summary of the inter-state agreement is also included in the chapter. Consequences of various abstraction points in the main river are duly addressed in order to identify critical stretches.

The Yamuna River is the largest tributary of the Ganga River (Fig. 2.1). It is also considered as a sacred river in India. According to the mythological legends, Yamuna was the daughter of Surya (the Sun God), and sister of Yama (the God of Death). A popular belief is that those who take a dip in its holy waters are not tormented by the fears of death. The Yamuna River is intimately connected to Lord Krishna's life. Lord Krishna sanctified the Yamuna River from the beginning of his *avtar*

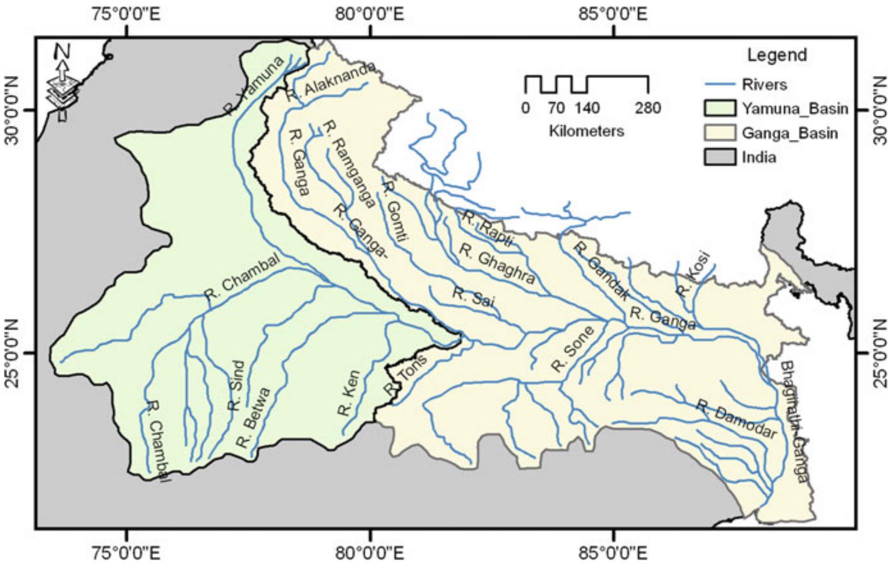


**Fig. 2.1** Gangatic River system including the Yamuna River

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(incarnation) in the world. While his father Vasudeva was crossing the Yamuna with baby lord Krishna for a safe place at the other bank of the river, the river was in spate. Legends say that the moment the rising water touched the feet of Lord Krishna, the flood receded.

The Yamuna River originates from the Yamunotri Glacier near Banderpoonch peaks (30°59′ N and 78°27′ E) in the Mussourie range of the lower Himalayas at an elevation of about 6,387 m above mean sea level in the district of Uttarkashi (Uttarakhand). Arising from the source, the Yamuna River flows through a series of valleys for about 200 km in lower Himalayas and then emerges into Indo-Gangetic plains. At this reach, the gradient of the river is steep and the entire geomorphology of the valley has been carved by the erosive action of the river water. In the head-water reach of 200 km, the Yamuna draws water from several major streams. The combined stream flows through the Shivalik range of Himachal Pradesh and Uttarakhand and enters into plains at Dak Pathar in Uttarakhand where the river water is regulated by a weir and is diverted into a canal for power generation (http://www.cwc.nic.in). From Dak Pathar, the Yamuna flows through the famous Sikh religious shrine of Poanta Sahib and reaches Hathnikund in the Yamuna Nagar district of Haryana. At Hathnikund, river water is diverted into Western Yamuna Canal (WYC) and Eastern Yamuna Canal (EYC) for irrigation and drinking water supply of Delhi. The catchment of river up to the Hathinikund headworks is nearly 12,950 km$^2$. At this point the normal high flow is of the order of 7,079 m$^3$/s, whereas the minimum flow is 70 m$^3$/s. During lean season, practically no water flows in the river downstream of Hathnikund barrage and the river remains dry in several stretches between Hathnikund and Delhi. Only approximately 160 cusec (4.53 m$^3$/s) is released downstream of Hathnikund for ecological considerations which vanish a after short distance due to losses (Fig. 2.2). Upstream of Hathnikund barrage, the ratio $Q_{max}/Q_{min}$ (where $Q_{max}$ is the flood peak discharge and $Q_{min}$ is the lowest flow rate in the year) is about 92 (with mean annual maximum and minimum of 5,042.8 and 54.5 m$^3$/s (Figs. 2.3 and 2.4) based on the data from 1994–2008), in comparison to 33 of Indus, 34 of Ganga and 4 of Amazon. This might be attributed due to the lesser glacier area in the Yamuna catchment (i.e., 125 km$^2$) as compared to the Indus basin (i.e. 14,043 km$^2$).

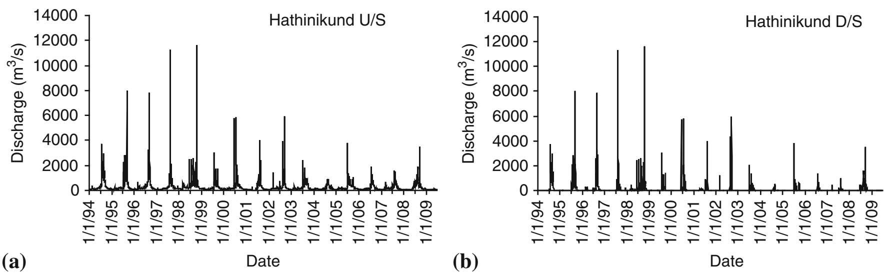



**Fig. 2.2** Discharge in the Yamuna River downstream of the Hathnikund barrage

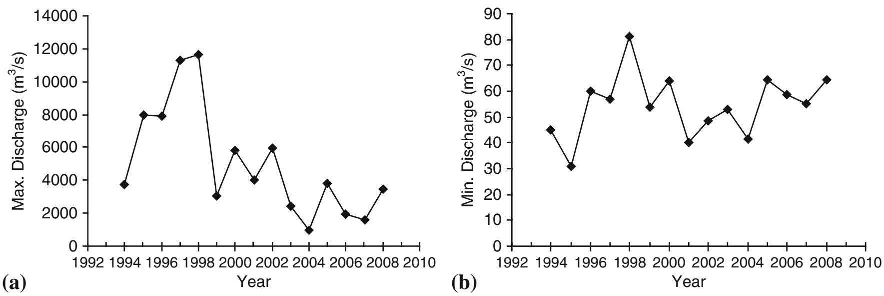
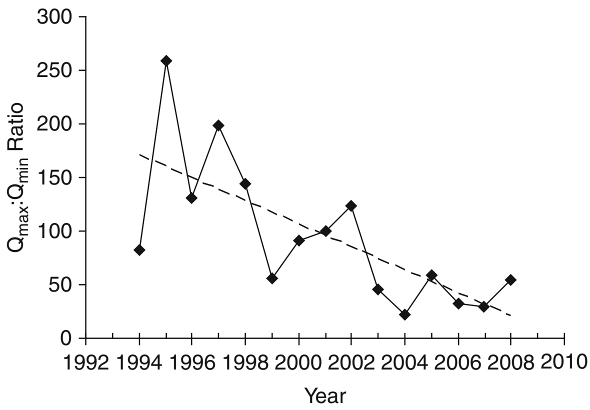



**Fig. 2.3** Annual maximum and minimum discharge upstream of the Hathnikund barrage

**Fig. 2.4** Ratio of $Q_{\max}$ and $Q_{\min}$ upstream of the Hathnikund barrage




Further, increasing trend in the minimum discharge (Fig. 2.3) and declining trend in the ratio of $Q_{\max}$ and $Q_{\min}$ (Fig. 2.4) can be seen based on the data for the period of 1994–2008 which might be due to the reduction in precipitation upstream of the Hathinikund barrage. This large ratio is indicative of a wide temporal variation in the flow. During non-monsoon period the entire inflow at Hathnikund is diverted to canal systems leaving the river dry. A canal, known as Sutlej Yamuna Link (SYL) canal, joins the Satluj with Yamuna for transferring water to Haryana and Delhi. This link canal irrigates the command areas of Sirsa branch of WYC and Hissar major distributary. Yamuna River enters Delhi near Palla village after traversing for about 224 km. At Palla, the flow in the river is received through WYC for the Delhi water supply at Wazirabad. During the dry period the flow upstream of the Wazirabad barrage is approximately 10–11 $m^3$/s and is used as raw water for Wazirabad water works and practically no water is released in the river downstream of the barrage (Fig. 2.5).

The Yamuna River flow downstream of the Wazirabad barrage consists largely of untreated or partially treated domestic and industrial wastewater contributed by numerous drains along with the water transported by Haryana Irrigation Department

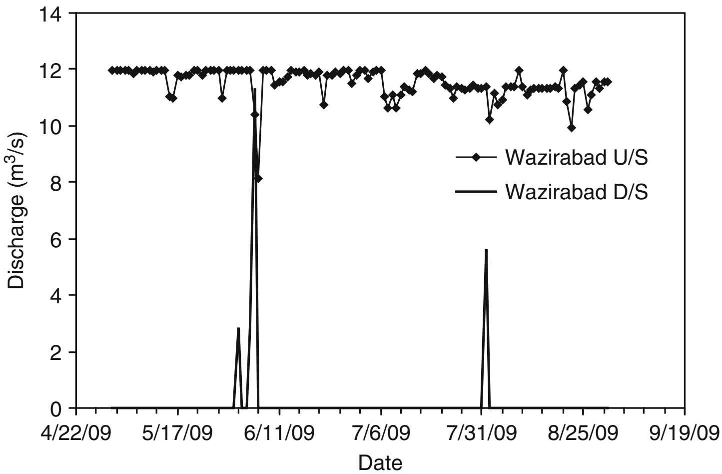



**Fig. 2.5** Discharge in the Yamuna River downstream of Wazirabad barrage (1/5/2009–28/8/2009)

from WYC to the Agra Canal via Nazafgarh drain and the Yamuna. About 22 km downstream of the Wazirabad barrage, the Yamuna water is diverted into the Agra canal for irrigation upstream of the Okhla barrage. Generally, water flow through the barrage during the dry season is small with 105 cusec (2.86 $m^3$/s) being released for ecological considerations. Whatever water flows in the river beyond the Okhla barrage is contributed through domestic and industrial wastewaters generated by East Delhi, NOIDA, Sahibabad and joins the river through the Shahdara drain.

## 2.1 Tributaries of the Yamuna River

In the upper reaches of Yamuna River, there are several hill streams joining together to form the main stream (http://www.cwc.nic.in). There are four main rivers that join Yamuna in the higher Himalayan ranges, and these are Rishi Ganga, which joins on the right bank of Yamuna, whereas Unta and Hanuman Ganga join on left bank. In the lower Himalayan ranges the Yamuna River receives Kamal, Tons, Giri and Bata on its right bank and receives Aglag and Asan on its left bank. After the Okhla barrage, the important tributary joining the Yamuna River on the left bank is Hindon. However, Hindon River hardly contributes to the Yamuna River except during the monsoon season. All the water available in the Hindon River plus the water released from Upper Ganga Canal is diverted into the Agra canal through Hindon cut via Okhla barrage. The Chambal, Betwa, Sind, Ken and Mandakini are the important tributaries joining the Yamuna on the right bank. The main tributaries of the Yamuna along with location of major cities are depicted in Fig. 2.6.

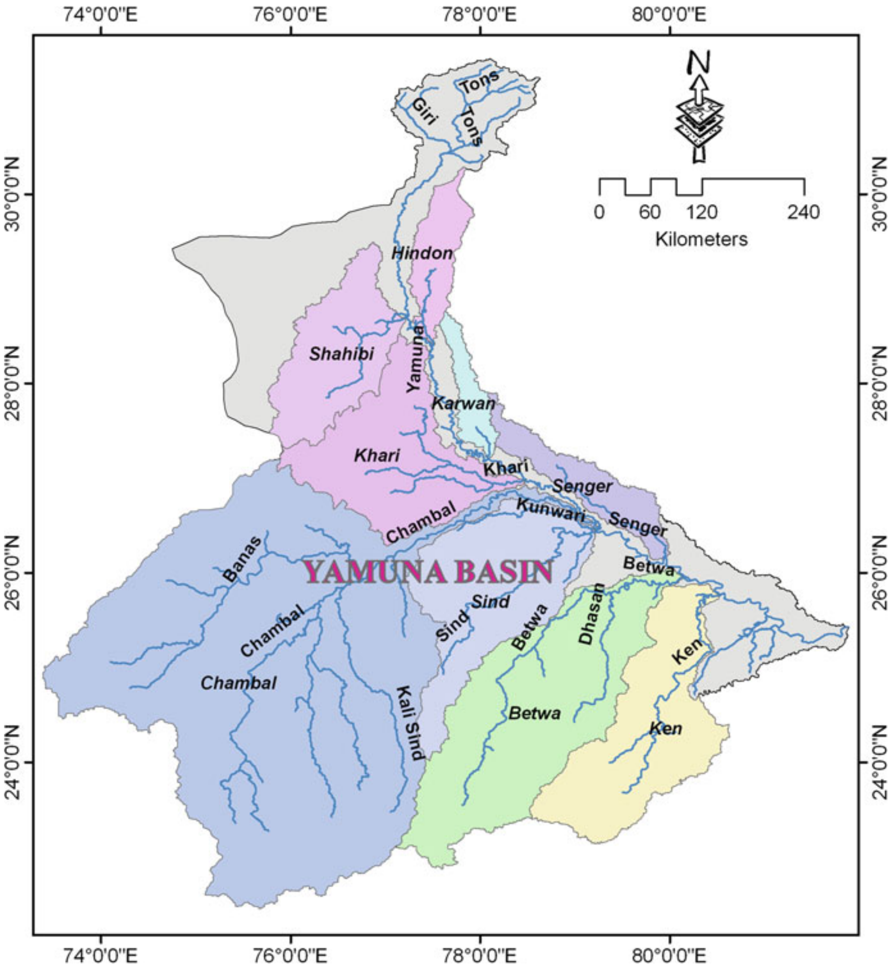



**Fig. 2.6** Important tributaries and sub-catchments of Yamuna River basin

Among all these tributaries, Tons in hills and Chambal in plains are the most important tributaries in terms of their discharges. The Tons is the principal source of water in the mountainous range and generally carries more water than mainstream. In plains, during non-monsoon period, River Chambal contributes about 5–10 times more water to the Yamuna than its own flow. However, since the year 2003, there is a significant reduction in the water quantity that Chambal River discharges into Yamuna River.

## 2.2 Yamuna River Catchment Area

The total catchment of the Yamuna River is 366,223 km$^2$ (catchment basin area in various states equals 345,848 km$^2$; the water spread area of Yamuna River is 20,375 km$^2$), which is 42.5% of the total Ganga basin area and 10.7% of the total geographical landmass of the country. The catchment of the Yamuna River system covers parts of Uttarakhand, Uttar Pradesh, Himachal Pradesh, Haryana, Rajasthan, Madhya Pradesh and National Capital Territory – Delhi. The state-wise details of catchment areas are presented in Table 2.1.

The percentage contribution of the various states to the catchment area of Yamuna River are (http://www.cwc.nic.in): Uttaranchal 1.1%; Uttar Pradesh 20.4%; Himachal Pradesh 1.7%; Haryana 6.1%; Rajasthan 29.7%; Madhya Pradesh 40.6% and NCT–Delhi 0.4%. The sub-basin tributaries of the Yamuna contributes 70.9% of catchment area and remaining 29.1% account for direct drainage into the Yamuna River through other small tributaries. The major sub-catchments of the Yamuna basin are shown in Fig. 2.6.

## 2.3 Water Allocation

Based on the contributing area of each state to the basin, the flows in the Yamuna River were regulated between Punjab (later on Haryana) and Uttar Pradesh according to May 1954 agreement and subsequent MOU of 1994 (made effective in 1995). The available supplies on the WJC system despite the augmentation of supplies from the Bhakra system through NBK link fall short of requirement. The 1954 Agreement and 1994–1995 MOU on sharing of Yamuna Water is given as follows.

The brief agreement made on March 1954 is:

> Agreement made on the 12th day of March 1954; effective the Ist of April 1950 held binding on both parties for a period of 50 years form 1/4/1950

**Table 2.1** Catchment area details of Yamuna River

| State/Territory | Contributing area in Yamuna basin (km$^2$) | Area in major sub-basin (km$^2$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | Hindon | Chambal | Sind | Betwa | Ken | Others |
| Uttarakhand | 3,771 | – | – | – | – | – | 3,771 |
| Uttar Pradesh | 70,437 | 70,83 | 452 | 748 | 14,438 | 3,336 | 44,380 |
| Himachal Pradesh | 5,799 | | | | | | 5,799 |
| Haryana | 21,265 | – | – | – | – | – | 21,265 |
| Rajasthan | 102,883 | – | 79,495 | – | – | – | 23,388 |
| Madhya Pradesh | 140,208 | – | 59,838 | 25,131 | 33,502 | 21,090 | 647 |
| NCT-Delhi | 1,485 | – | – | – | – | – | 1,485 |
| Total | 345,848 (100%) | 7,083 (2.0%) | 139,785 (40.5%) | 25,879 (7.5%) | 47,940 (13.9%) | 24,426 (7.1%) | 100,735 (29.1%) |

In the event of the river discharge being less than the total indent of the two canals, i.e. Western Canal and Eastern Canal; Supplies at Tajewala will be distributed as follows:

| Total river supplies at Tajewala (cusecs) say "$X$" | Supplies to WJC (entitlement) (cusecs) | Supplies to EJC (entitlement) (cusecs) | Remarks |
|---|---|---|---|
| Up to 5,890 | $2X/3 - 47$ | $X/3 - 47$ | WJC first |
| 5,890–8,790 | $X - 2010$ | 2010 | WJC first |
| 8,790–9,280 | 6780 | $X - 6780$ | WJC first |
| 9,280–10,900 | $X - 2500$ | 2500 | |

When the supplies are in excess of 10,900 cusecs the Punjab and U.P. to utilise the excess over 10,900 cusecs in the ratio of 2:1.

This arrangement has been in force since the formation of Haryana on 1.11.66.

Whereas, the memorandum of understanding between different states are as follows:

Memorandum of Understanding between Uttar Pradesh, Haryana, Rajasthan, Himachal Pradesh and National Capital Territory of Delhi Regarding Allocation of Surface Flow of Yamuna.

1. WHEREAS the 75% dependable notional virgin flow in the Yamuna River up to Okhla has been assessed as 11.70 Billion Cubic Meters (BCM) and the mean year availability has been assessed as 13.00 BCM.
2. AND WHEREAS the water was being utilized by the Basin States ex-Tajewala and ex-Okhla for meeting the irrigation and drinking water needs without any specific allocation.
3. AND WHEREAS a demand has been made by some Basin States on this account and the need for a specified allocation of the utilizable water resources of Yamuna River has felt for a long time.
4. AND WHEREAS to maximize the utilization of the surface flow of Yamuna River a number of storage projects have been identified.
5. AND WHEREAS the States have agreed that a minimum flow in proportion of completion of upstream storages going up to 10 cumecs shall be maintained downstream of Tajewala and downstream of Okhla Headwork throughout the year from ecological considerations, as upstream storages are built up progressively in a phased manner.
6. AND WHEREAS it has been assessed that a quantum of 0.68 BCM may not be utilizable due to flood spills.
7. NOW THEREFORE, considering their irrigation and consumptive drinking water requirements, the Basin States agree on the following allocation of the utilizable water resources of Yamuna River assessed on mean year availability.

*Subject to the following:*

(i) Pending construction of the storages in the upper reaches of the river, there shall be an interim seasonal allocation of the annual utilization flow of Yamuna River as follows:

| | Seasonal allocation of Yamuna waters (BCM) | | | |
|---|---|---|---|---|
| States | July–Oct | Nov–Feb | March–June | Annual |
| Haryana | 4.107 | 0.686 | 0.937 | 5.730 |
| Uttar Pradesh | 3.216 | 0.343 | 0.473 | 4.032 |
| Rajasthan | 0.963 | 0.070 | 0.086 | 1.119 |
| Himachal Pradesh | 0.190 | 0.108 | 0.080 | 0.378 |
| Delhi | 0.580 | 0.068 | 0.076 | 0.724 |
| Total | 9.056 | 1.275 | 1.652 | 11.983 |

Provided that the interim seasonal allocations will be distributed on a ten day basis. Provided further that the said interim seasonal allocations shall get progressively modified, as storages are constructed, to the final annual allocations as indicated in para 7 above.

(ii) Separate agreement will be executed in respect of each identified storage within the framework of overall allocation made under this agreement.

(iii) The allocation of available flows amongst the beneficiary States will be regulated by the Upper Yamuna River Board within the overall framework of this agreement.

Provided that in a year when the availability is more than the assessed quantity, the surplus availability will be distributed amongst the States in proportion to their allocations.

Provided also that in a year when the availability is less than the assessed quantity, first the drinking water allocation of Delhi will be met and the balance will be distributed amongst Haryana, U.P., Rajasthan and H.P. in proportion to their allocations.

8. This agreement may be reviewed after the year 2025, if any of the basin States so demands.
9. We place on record and gratefully acknowledge assistance and advice given by the Union Minister of Water Resources in arriving at this expeditious and amicable settlement.

## 2.4 Uses of Yamuna River Water

Water is one of the essential requirements of life. In the modern age it also plays a significant role in various economic activities. The higher growth rate is reflected during good monsoon period and availability of good amount of water in the river. The various uses of river water can be kept into two major groups. In one group the water is abstracted and transported away from the natural water bodies for beneficial uses and are called abstractive uses or uses involving collection and transportation. The other is just opposite of the first, in which withdrawal and transportation of water are not required but the water is utilized. It is known as non-abstractive or in-situ water uses.

### *2.4.1 Abstractive Uses*

The river water is abstracted at different locations for varied uses. At two places, i.e., Hathnikund/Tajewala and Okhla, the water abstraction is significant. The annual abstraction at various locations is presented in Table 2.2 and the percent use of abstracted water for various purposes is presented in Fig. 2.7, whereas, the sharing of Yamuna River water by various states is depicted in Fig. 2.8. The various abstractive uses of river water are as below (http://www.cpcb.nic.in/).

#### 2.4.1.1 Domestic Water Supplies

The large urban centers located along river banks and where suitable ground water is not available, water is abstracted for drinking water supplies after suitable treatment. The urban agglomerations, like Delhi, Mathura, Agra and Allahabad, use the Yamuna water significantly for domestic water supplies. The water abstracted for domestic water supply at various locations is presented in Table 2.2. At Wazirabad, Delhi the entire river water is diverted for this purpose along with the increase in demand of water for drinking purposes. Along with the population increase, there are plans at various locations to withdraw more and more water from the river.

**Table 2.2** Water abstraction from Yamuna River

| S. No. | Location | River water abstraction (approx. MLD) | Abstraction use |
|---|---|---|---|
| 1 | Hathinikund | 20,000 | Irrigation, drinking water supply and others |
| 2 | Wazirabad | 1,100 | Drinking water supply |
| 3 | Wazirabad to Okhla Stretch | 5,000 | Irrigation and others |
| 4 | Okhla to Etawah Stretch | 400 | Irrigation, drinking water supply and others |
| 5 | Etawah to Allahabad Stretch | 475 | Irrigation, drinking water supply and others |

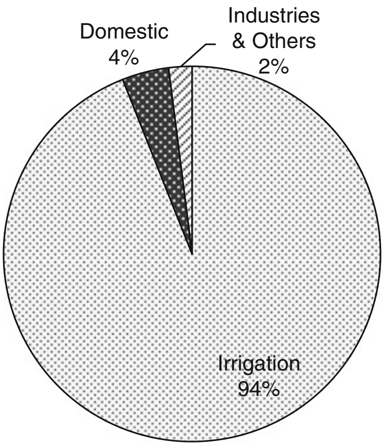



**Fig. 2.7** Percentage water abstractions from Yamuna River for various uses

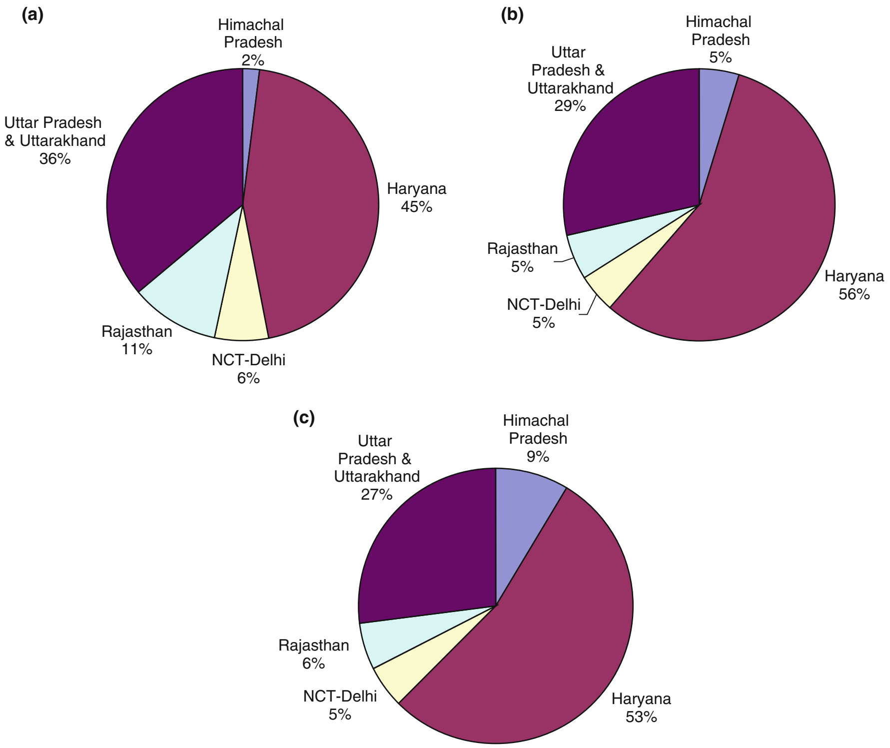



**Fig. 2.8** State wise water use of Yamuna River during (**a**) monsoon (July to October); (**b**) summer (March to June); (**c**) winter (November to February)

#### 2.4.1.2 Irrigation

Irrigation is an important use of Yamuna River water. It is estimated that about 92% of Yamuna River water is used for irrigation. In the entire Yamuna basin the irrigated land is about 12.3 million hectares and approximately half of it (about 49%) is irrigated exclusively from surface water. At present there are four irrigation canals transporting the Yamuna River water to the command areas.

#### 2.4.1.3 Western Yamuna Canal (WJC)

This canal originates from the right bank of Yamuna River at the Hathnikund/Tajewala barrage. The capacity of main canal is 163 $m^3$/s and irrigates an area of about 486,000 ha annually in Haryana State. This irrigation system is more than 100 years.

#### 2.4.1.4 Eastern Yamuna Canal (EJC)

This canal takes off from the left bank of the Yamuna River at the Hathnikund/Tajewala barrage. The canal is about 206 km long and having a capacity of 85 $m^3$/s. It irrigates an area of about 191,000 ha annually in Uttar Pradesh.

#### 2.4.1.5 Agra Canal

Agra canal originates from the right bank of Yamuna River at Okhla barrage. The canal is 163 km long and carries a discharge of about 63.5 $m^3$/s. It irrigates about 138,000 ha of land mainly in two districts of Mathura and Agra in Uttar Pradesh.

#### 2.4.1.6 Gurgaon Canal

This canal is an interstate project between Rajasthan and Haryana and takes off from Agra canal at a distance of around 8 km from its offtake at the Okhla barrage. The water flow capacity of this canal is 14.15 $m^3$/s and the land irrigated by this canal is about 40,000 ha.

### *2.4.2 In-Stream Uses*

#### 2.4.2.1 Hydropower

The total potential for hydropower development in the entire Yamuna basin is about 1,300 MW. The present utilization is only one third of the total potential. There are a few new schemes which are at various stages of construction:

#### 2.4.2.2 Fisheries

Fish is not a popular traditional food for the people residing in the Yamuna basin area except in some tribes and castes and collectively called fishing community. This is the reason that the pisciculture is neither practiced on large scale nor undertaken in an organized manner in the area. However, the entire river stretch and tributaries are being utilized for fishing in an unorganized manner. There is a large scope of farming for fish and other aquatic animals in stretches of Yamuna River.

#### 2.4.2.3 Growing Aquatic Plants

The most prevalent aquatic plants in Yamuna River is the water hyacinth. In West Bengal this plant is used as cattle fodder and composted an-aerobically on a large scale. In Kerala too there are various schemes to generate biogas from water hyacinth. Unfortunately, these practices are yet to be undertaken in the Yamuna basin.

#### 2.4.2.4 Navigation

The most of the river channel of Yamuna River and its tributaries are not suitable for Navigation. Low flow of the river further restricts this activity. At few locations the boats are playing on a need based basis, mainly for crossing the river. Earlier, the timber logs and sleepers were floated down from the Upper Himalayan areas but now this practices is also replaced by road transportation. There is a scope to use the Yamuna River stretch between Agra and Allahabad for navigation.

#### 2.4.2.5 River Bathing and Washing

River bathing and washing is one of the most important uses of river water in the country. The Hindu culture and the other cultures of Indian origin are generally considered to be river oriented. Bathing is an essential part of various Hindu rituals. Bathing in flowing water and that too on rivers like the Ganga, the Yamuna, the Narmada, the Godawari, etc. is considered superior to bathing in house with well or tap water. On religious and cultural occasions millions of people take bath especially near religious towns in a congested stretch of the river within the span of a few hours. The river water is also used for washing clothes and utensils by nearby communities, particularly by the poor inhabitants. Some of the prominent bathing centers at Yamuna River are Yamunotri, Kalpi, Paonta Sahib, Delhi, Mathura-Vrindavan, Agra, Bateshwar, Etawah and Allahabad on Yamuna River, Kota on Chambal, Orcha on Betwa and Ujjain on Shipra River.

#### 2.4.2.6 Recreational Uses

In the Yamuna basin the rivers are used very little for recreational value due to unsuitable conditions like rocky river bed and low water depth, and water sports like boating have a vast potential in future specially at urban centers and at various barrage sites in the reservoir formed by the barrages.

#### 2.4.2.7 Cattle Bathing and Washing

The cattle in most of the towns and villages along the rivers are regularly taken toward the river for drinking and bathing. It is estimated that about 70% of the total cattle population in the Yamuna basin uses flowing water of river and canals for bathing and watering purposes directly. These cattle activities impart substantial impact on water quality. This occurs not only through direct discharge of urine, dung and washed off organic inorganic materials but the bottom sediments are also churned up because of cattle wading.

Besides these uses, the river Channel of Yamuna River, particularly in Delhi stretch is also used for the transportation of water for irrigation from one water body to another or from one place to another. The Yamuna water is being transported from the Western Yamuna Canal to the Gurgaon canal via the Najafgarh drain, Yamuna River and the Agra canal. Similarly, the Ganga River water from the upper Ganga canal is transported to the Agra canal for irrigation in districts of Mathura and Agra via Hindon River, the Hindon Cut Canal and Yamuna River. The dilution that the rivers receive through this means of water transportation significantly affects the water quality of drain, canal and river.

# Chapter 3
# Climate of the Basin

**Abstract** This chapter describes important hydro-meteorological variables and their spatial analysis, including rainfall, temperature, wind, humidity, evapotranspiration. Apart from these variables, other derived variables relevant to water resources and agricultural planning, such as seasonal rainfall, number of rainydays, onset of effective monsoon, and aridity index are also critically analyzed. From a hydrological design point of view, quantile estimates of annual rainfall and daily maximum rainfall are treated. Based on the aridity index, which is an indicator of the annual soil moisture deficit, the climate classification of the basin is discussed.

India has four distinct seasons, winter: December-January; spring (Basant): February-March; summer: April-June; rainy season (or Monson): July-September; fall (Sharad): September-November. Hydro-meteorologically Yamuna basin is a heterogeneous basin having great spatial variation of rainfall pattern ranging from 200 to 2,350 mm. However, the average annual rainfall varies between 400 and 1,500 mm. The entire basin comes under the influence of the south-west monsoon and a major part of the rainfall is received between June and September. Winter rainfall is scanty. In the basin, rainfall distribution increases from North-West to the South-East direction. Broadly, climate of the basin can be classified as: (a) humid in the upstream Himalayan catchment; (b) semi-arid in north-west to western catchments; (c) sub-humid in south-west catchments and catchments located on the left bank of the river. The mean maximum temperature is 24–42.5°C and the mean minimum temperature is –1.0 to 11.0°C.

## 3.1 Rainfall

In the Yamuna River basin, rainfall is the only input to the hydrologic cycle. However, in the upper Himalayan part of the basin, the river receives water from the glacier melt runoff. During the non-monsoon period, water availability in the river is either due to glacier melt runoff and base flow. Excluding the upper Himalayan segment, the Yamuna River basin is rainfed and perennial behaviour of the river is due to upstream storages and base flow.

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### 3.1.1 Average Rainfall

Considering the one degree records of daily rainfall for the period of 1951–2003 collected from India Meteorological Department (IMD, the average annual rainfall of the basin varies from 645 to 1,175 mm with annual basin average of approximately 906 mm. The spatial variation of the annual rainfall pattern in the basin is shown in Fig. 3.1. It is apparent that the Yamuna basin comparatively receives heavy rainfall in the extreme Northern catchments of Shiwalik range (i.e. Himalayan catchments, namely Tons, Giri, Upper Yamun and Asan, Pabbar sub-catchments) followed by extreme Southern sub-catchments of Betwa, Ken,

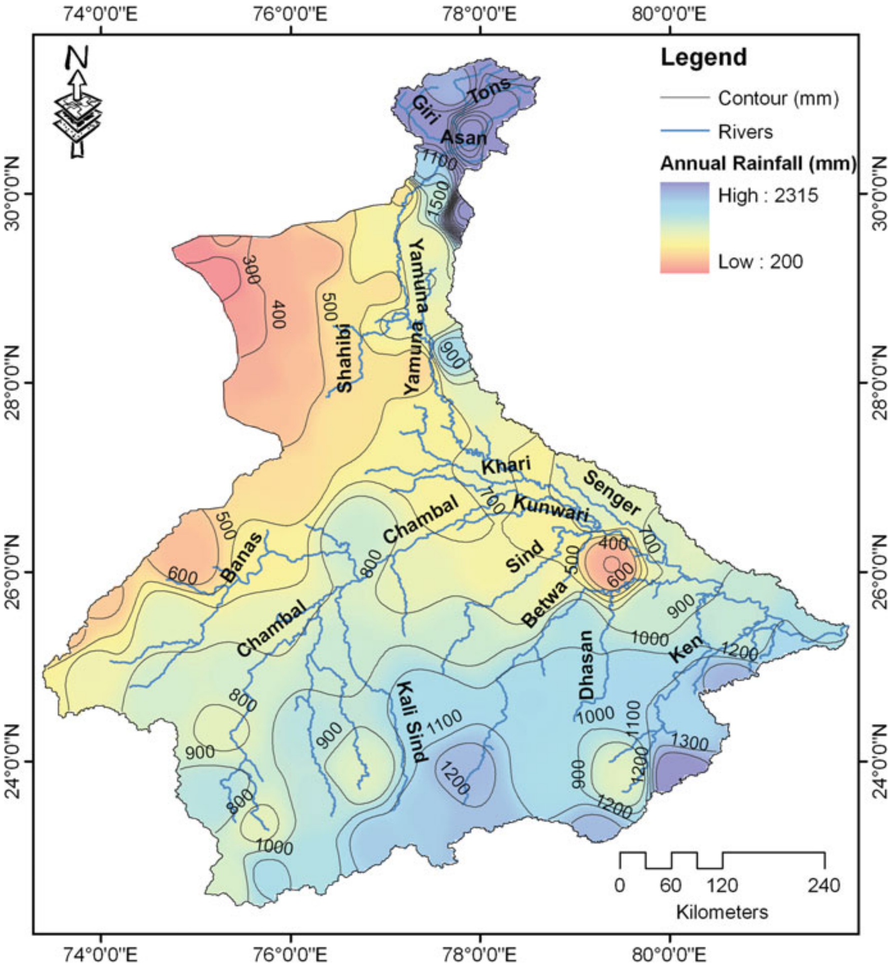


Fig. 3.1 Spatial variation of mean annual rainfall in the basin

**Table 3.1** Mean rainfall distribution in the Yamuna basin

| Mean values (mm) | Period of analysis | Betwa | Ken | Sind | Chambal | Hindon | Khari | Tons | Giri | Himalayan upper | Yamuna basin |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Annual Rainfall | 1951–2003 | 1,064.9 | 1,125.0 | 848.3 | 783.7 | 887.7 | 644.2 | 831.1 | 1,045.1 | 1,175.5 | 906.7 |
| 75% Probability of Exceedance | 1951–2003 | 892.0 | 928.9 | 705.0 | 667.1 | 752.1 | 548.5 | 583.1 | 853.0 | 994.0 | 796.3 |
| Annual Rainfall | 1994–2003 | 1,074.1 | 1,116.3 | 828.7 | 749.3 | 780.9 | 589.3 | 1,081.4 | 1,010.0 | 1,257.5 | 894.8 |
| Monsoon Rainfall | 1951–2003 | 972.1 | 1,025.6 | 769.5 | 717.4 | 734.0 | 572.1 | 323.3 | 579.1 | 707.3 | 756.4 |
| Monsoon Rainfall | 1994–2003 | 981.9 | 1,021.0 | 756.0 | 673.7 | 639.2 | 517.1 | 667.1 | 626.4 | 853.0 | 754.9 |
| Winter Rainfall | 1951–2003 | 26.0 | 29.9 | 19.4 | 10.9 | 53.8 | 19.5 | 188.4 | 175.5 | 165.8 | 47.6 |
| Winter rainfall | 1994–2003 | 23.5 | 26.6 | 16.9 | 13.8 | 62.5 | 23.3 | 135.5 | 145.7 | 138.9 | 46.4 |
| Post Monsoon Rainfall | 1951–2003 | 50.8 | 51.2 | 44.3 | 41.5 | 47.2 | 29.6 | 88.9 | 88.3 | 89.4 | 50.4 |
| Post Monsoon Rainfall | 1994–2003 | 48.6 | 50.5 | 39.6 | 47.6 | 33.8 | 25.0 | 50.5 | 51.4 | 50.7 | 41.1 |

Baghein, and Mandakini rivers. Annual rainfall in the eastern and central parts of the catchments is quite less and within the range of 300 to 600 mm.

The sub-catchment-wise rainfall was also estimated using the Theissen polygon method and are summarized in Table 3.1. The temporal variation of the weighted annual rainfall for each sub-catchment is shown in Fig. 3.2 which also include trends in annual rainfall patterns of catchments. To determine the general trend in the rainfall pattern in the basin, besides the whole record of 1951–2003, the last ten year of record (i.e., 1994–2002) are further analysed and compared with 53 years of record. The catchment-wise summarized results of analysis are given in Table 3.1. Based on this analysis, it is observed that the average rainfall in the basin has been reduced, however, the detailed statistical evidence of presence of trends and periodicities are presented in Chapter 4. Besides the analysis of annual rainfall, seasonal rainfall pattern is also studied and results are summarized in Table 3.1. It is apparent from the Table 3.1 that seasonal rainfall other than the Monsoon season is quite less, except for the upper Himalayan catchments.

The monthly distribution of the rainfall pattern for the catchments of the Yamuna basin as well as the percentage distributions are given in Tables 3.2 and 3.3.

### *3.1.2 Probability Analysis of Annual Rainfall*

For water resources planning and management, the magnitude of rainfall at 75% probability of exceedance is generally used. This analysis is performed based on the well established Weibull's plotting position formula which can be expressed as follows:

$$E = \frac{m}{N+1} \times 100\% \tag{3.1}$$

where $E$ is the probability of non-exceedance, $m$ is the rank of the observation when arranged in ascending order, and $N$ is the number of observation in the sample. The probability of exceedance can be estimated using the following equation:

$$P = 100 - E \tag{3.2}$$

where $P$ is the probability of exceedance. Using these equations [eqs. (3.1) and (3.2)], catchment rainfall at 75% probability of exceedance is estimated for all the catchments of the Yamuna basin, as given in Table 3.1.

### *3.1.3 Quantile Estimates of Daily Maximum and Annual Rainfall*

Quantile estimates of various return periods are important for designing the water resources system. For the Yamuna River basin, the quantiles were estimated for daily maximum rainfall and annual rainfall using the daily grid data for the period of 1951–2003. The quantile were estimated using Weibull's plotting position

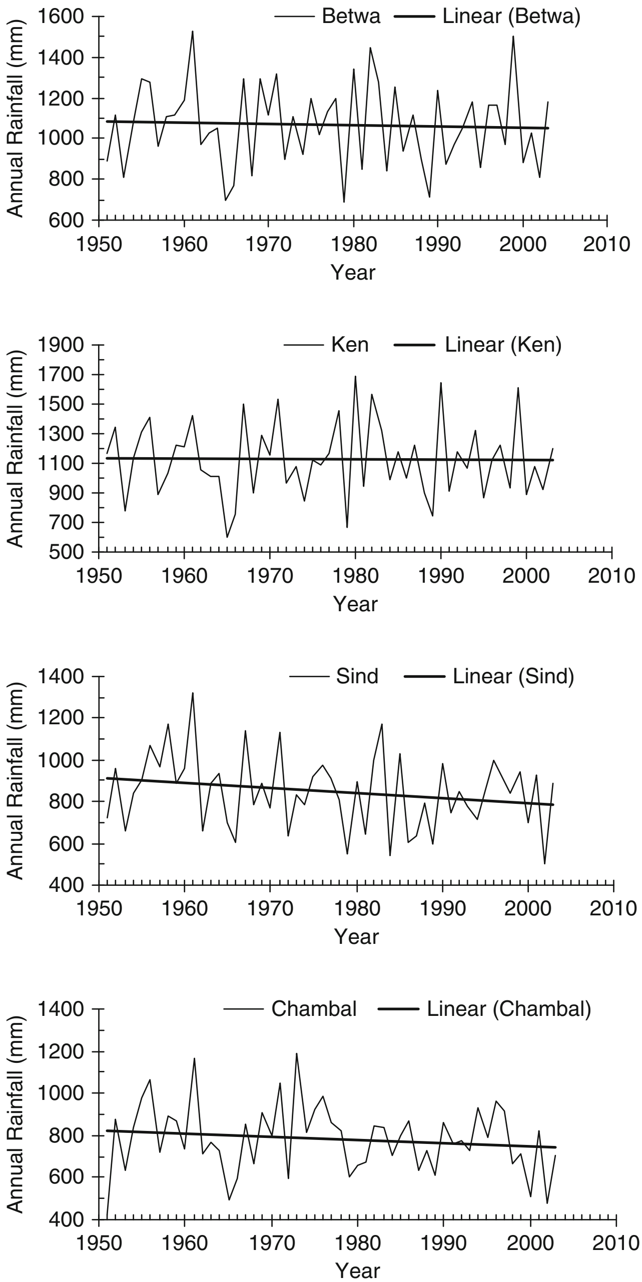


**Fig. 3.2** Annual rainfall along with the trend and 75% probability rainfall

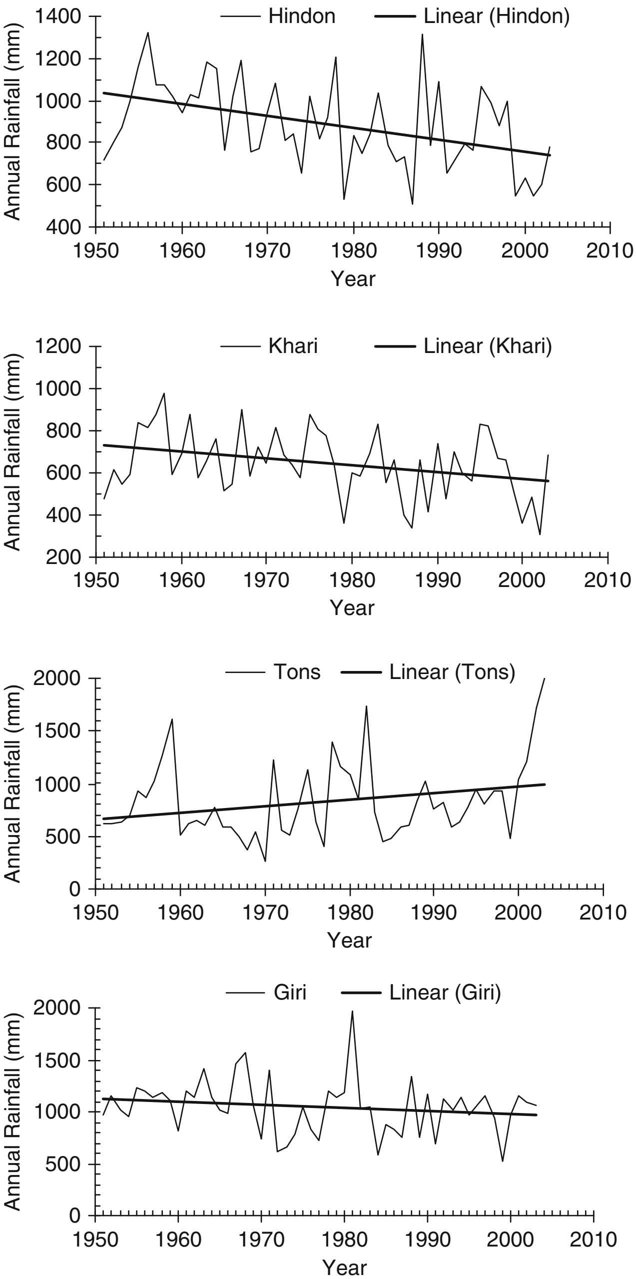


**Fig. 3.2** (continued)

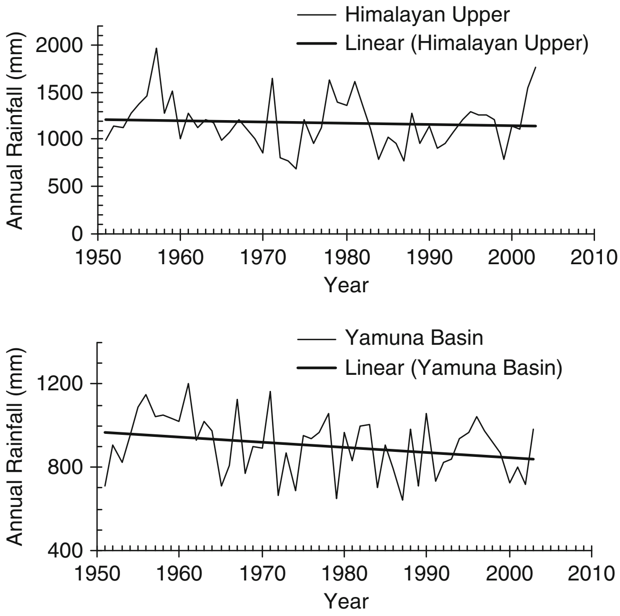


**Fig. 3.2** (continued)

**Table 3.2** Monthly distribution of mean rainfall (mm) [1951–2003] in the Yamuna basin

| Month | Betwa | Ken | Sind | Chambal | Hindon | Khari | Tons | Giri | Himalayan upper | Yamuna basin |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 15.3 | 16.9 | 10.7 | 6.2 | 27.8 | 9.8 | 91.0 | 93.4 | 81.9 | 24.6 |
| Feb | 10.7 | 13.0 | 8.8 | 4.7 | 26.1 | 9.8 | 97.5 | 82.1 | 83.9 | 23.0 |
| Mar | 6.0 | 7.4 | 4.7 | 3.6 | 21.5 | 6.0 | 100.4 | 94.1 | 92.2 | 20.9 |
| Apr | 3.1 | 3.9 | 2.8 | 3.0 | 11.6 | 4.4 | 70.2 | 48.5 | 56.5 | 12.3 |
| May | 6.8 | 7.0 | 7.6 | 7.4 | 19.6 | 12.5 | 59.7 | 59.7 | 64.3 | 19.0 |
| Jun | 100.1 | 112.4 | 71.6 | 78.5 | 78.7 | 48.6 | 52.8 | 89.6 | 101.3 | 81.9 |
| Jul | 316.1 | 319.9 | 262.6 | 254.4 | 248.6 | 199.7 | 104.6 | 210.4 | 244.5 | 257.6 |
| Aug | 370.0 | 392.4 | 283.5 | 262.1 | 281.0 | 225.6 | 93.5 | 177.9 | 231.5 | 279.2 |
| Sep | 185.9 | 200.8 | 151.8 | 122.4 | 125.7 | 98.2 | 72.4 | 101.2 | 130.0 | 137.7 |
| Oct | 33.3 | 34.2 | 30.7 | 25.7 | 28.5 | 20.5 | 29.1 | 28.2 | 36.3 | 29.5 |
| Nov | 8.8 | 8.6 | 6.3 | 8.7 | 4.6 | 3.8 | 16.5 | 14.5 | 13.9 | 7.4 |
| Dec | 8.7 | 8.5 | 7.3 | 7.1 | 14.1 | 5.4 | 43.3 | 45.5 | 39.3 | 13.5 |
| Annual | 1,064.9 | 1,125.0 | 848.3 | 783.7 | 887.7 | 644.2 | 831.1 | 1,045.1 | 1,175.5 | 906.7 |

*Monsoon*: June–September; *Post-monsoon*: October–December; *Winter*: January–February; *Summer*: March–May

**Table 3.3** Monthly percentage distribution of mean rainfall (1951–2003) in the Yamuna basin

| Month | Betwa | Ken | Sind | Chambal | Hindon | Khari | Tons | Giri | Himalayan Upper | Yamuna Basin |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 1.4 | 1.5 | 1.3 | 0.8 | 3.1 | 1.5 | 10.9 | 8.9 | 7.0 | 2.7 |
| Feb | 1.0 | 1.2 | 1.0 | 0.6 | 2.9 | 1.5 | 11.7 | 7.9 | 7.1 | 2.5 |
| Mar | 0.6 | 0.7 | 0.6 | 0.5 | 2.4 | 0.9 | 12.1 | 9.0 | 7.8 | 2.3 |
| Apr | 0.3 | 0.3 | 0.3 | 0.4 | 1.3 | 0.7 | 8.5 | 4.6 | 4.8 | 1.4 |
| May | 0.6 | 0.6 | 0.9 | 0.9 | 2.2 | 1.9 | 7.2 | 5.7 | 5.5 | 2.1 |
| Jun | 9.4 | 10.0 | 8.4 | 10.0 | 8.9 | 7.5 | 6.4 | 8.6 | 8.6 | 9.0 |
| Jul | 29.7 | 28.4 | 31.0 | 32.5 | 28.0 | 31.0 | 12.6 | 20.1 | 20.8 | 28.4 |
| Aug | 34.7 | 34.9 | 33.4 | 33.4 | 31.7 | 35.0 | 11.3 | 17.0 | 19.7 | 30.8 |
| Sep | 17.5 | 17.9 | 17.9 | 15.6 | 14.2 | 15.3 | 8.7 | 9.7 | 11.1 | 15.2 |
| Oct | 3.1 | 3.0 | 3.6 | 3.3 | 3.2 | 3.2 | 3.5 | 2.7 | 3.1 | 3.3 |
| Nov | 0.8 | 0.8 | 0.7 | 1.1 | 0.5 | 0.6 | 2.0 | 1.4 | 1.2 | 0.8 |
| Dec | 0.8 | 0.8 | 0.9 | 0.9 | 1.6 | 0.8 | 5.2 | 4.4 | 3.3 | 1.5 |
| Annual | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

formula given by eq. (3.1). The return period $T$ can be estimated using the following relationship,

$$T = \frac{1}{P} \tag{3.3}$$

where $T$ is the return period (year), $P$ is the probability of exceedance estimated from eq. (3.2). The values of daily maximum and annual rainfall for 2-, 5-, 10-, 25-, and 50-years return periods are given in Table 3.4. However, the contours of these variables are shown in Figs. 3.3, 3.4, 3.5, 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, and 3.12. For the distribution of daily maximum rainfall into shorter period (say hourly), area to point rainfall ratios (Appendix C) can be used.

### *3.1.4 Onset of Effective Monsoon and Number of Rainydays*

The onset of effective monsoon (OEM) is an important governing agro-climatic parameter for planning of *kharif* crops. The OEM is estimated using the Ashokraj criteria (1979), which uses daily rainfall and potential evapotranspiration data. The potential evapotranspiration (PET) can be estimated using the Thornthwaite method (1948). Details of the Thornthwaite method for estimating PET are presented later. A seven days rainfall spell satisfying the following conditions is termed as OEM. These conditions are: (i) first day rainfall in the seven days spells should be more than evaporation of that particular day; (ii) a day with more than 3 mm of rainfall is considered to be a rainy day; (iii) total rainfall during the seven day spell is more than (3× PET + 10) mm; and (iv) at least four out of seven days are rainy days. Considering this methodology, the value of OEM is estimated for the entire grid location (65 grids in the basin) for entire years. Using the annual value of OEM, the mean OEM was estimated for grid locations, and interpolated to derive the spatial pattern using the Kriging method. The spatial pattern of OEM for the basin is shown in Fig. 3.13.

**Table 3.4** Quantile estimates of daily maximum and annual rainfall for different grid points

| Grid station | | Quantile estimates of daily maximum rainfall (mm) | | | | | Quantile estimates of annual rainfall (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lat | Long | $T = 2$ yr | $T = 5$ yr | $T = 10$ yr | $T = 25$ yr | $T = 50$ yr | $T = 2$ yr | $T = 5$ yr | $T = 10$ yr | $T = 25$ yr | $T = 50$ yr |
| 21.5 | 75.5 | 68.1 | 98.9 | 123.3 | 196.8 | 223.6 | 701.9 | 938.5 | 972.3 | 10,89.8 | 1,133.0 |
| 22.5 | 74.5 | 96.8 | 151.8 | 160.3 | 205.1 | 230.7 | 791.6 | 1,123.0 | 1,212.3 | 1,348.0 | 1,530.7 |
| 22.5 | 75.5 | 85.4 | 133.2 | 148.5 | 173.6 | 254.9 | 861.5 | 1,124.9 | 1,307.2 | 1,395.3 | 1,600.2 |
| 22.5 | 76.5 | 85.8 | 121.3 | 150.2 | 162.4 | 168.8 | 979.3 | 1,109.9 | 1,271.6 | 1,488.9 | 1,625.8 |
| 22.5 | 77.5 | 126.6 | 176.0 | 225.9 | 298.0 | 326.0 | 1,125.9 | 1,491.1 | 1,633.2 | 1,835.1 | 2,021.0 |
| 22.5 | 78.5 | 138.4 | 193.9 | 225.0 | 337.3 | 364.1 | 1,655.0 | 2,053.1 | 2,372.2 | 3,020.6 | 3,273.5 |
| 22.5 | 79.5 | 81.9 | 119.4 | 163.0 | 201.5 | 231.6 | 1,084.9 | 1,297.8 | 1,509.6 | 1,624.5 | 1,633.3 |
| 23.5 | 73.5 | 93.0 | 151.7 | 212.0 | 297.1 | 425.1 | 759.1 | 962.5 | 1,262.4 | 1,341.6 | 1,454.3 |
| 23.5 | 74.5 | 116.4 | 196.2 | 274.5 | 295.3 | 304.1 | 1,005.0 | 1,281.3 | 1,456.3 | 1,645.8 | 1,683.8 |
| 23.5 | 75.5 | 84.5 | 143.3 | 156.1 | 208.6 | 261.1 | 849.4 | 1,103.9 | 1,180.9 | 1,489.3 | 1,694.9 |
| 23.5 | 76.5 | 95.5 | 146.1 | 188.3 | 246.6 | 250.6 | 922.7 | 1,114.9 | 1,359.8 | 1,732.0 | 1,802.7 |
| 23.5 | 77.5 | 96.3 | 136.3 | 188.6 | 212.8 | 233.6 | 1,170.7 | 1,465.5 | 1,585.2 | 1,748.8 | 1,853.8 |
| 23.5 | 78.5 | 101.3 | 148.2 | 191.3 | 213.5 | 221.8 | 1,192.7 | 1,470.6 | 1,675.2 | 1,929.8 | 1,978.4 |
| 23.5 | 79.5 | 90.3 | 139.1 | 158.9 | 184.8 | 246.5 | 1,229.5 | 1,485.7 | 1,650.0 | 1,996.5 | 2,139.6 |
| 23.5 | 80.5 | 85.1 | 130.6 | 170.0 | 195.0 | 229.8 | 1,294.7 | 1,563.0 | 1,681.0 | 1,956.0 | 2,142.2 |
| 24.5 | 72.5 | 95.8 | 177.9 | 278.4 | 315.2 | 332.2 | 883.5 | 1,176.1 | 1,675.2 | 1,983.0 | 2,004.9 |
| 24.5 | 73.5 | 68.3 | 95.7 | 121.8 | 158.3 | 173.8 | 638.7 | 854.3 | 940.4 | 1,067.9 | 1,232.2 |
| 24.5 | 74.5 | 80.0 | 111.4 | 130.2 | 165.1 | 195.6 | 794.7 | 1,008.7 | 1,044.1 | 1,117.5 | 1,677.2 |
| 24.5 | 75.5 | 93.1 | 127.2 | 141.0 | 165.9 | 168.9 | 825.5 | 1,057.0 | 1,169.5 | 1,301.6 | 1,317.2 |
| 24.5 | 76.5 | 87.1 | 139.9 | 176.4 | 206.7 | 225.4 | 855.0 | 1,145.2 | 1,280.4 | 1,433.7 | 2,576.4 |
| 24.5 | 77.5 | 86.6 | 143.7 | 176.6 | 243.9 | 251.9 | 1,026.6 | 1,279.8 | 1,396.7 | 1,488.8 | 1,524.2 |
| 24.5 | 78.5 | 68.0 | 102.8 | 135.6 | 168.2 | 203.5 | 988.2 | 1,223.2 | 1,423.5 | 1,463.5 | 1,564.0 |
| 24.5 | 79.5 | 93.0 | 135.3 | 151.1 | 171.1 | 177.2 | 1,125.7 | 1,273.3 | 1,578.8 | 1,877.4 | 1,949.9 |
| 24.5 | 80.5 | 96.1 | 118.3 | 142.9 | 183.7 | 204.7 | 1,130.2 | 1,367.9 | 1,480.4 | 1,610.9 | 1,709.3 |
| 24.5 | 81.5 | 102.5 | 136.2 | 159.8 | 197.1 | 224.0 | 1,088.5 | 1,325.9 | 1,447.0 | 1,530.0 | 1,713.7 |
| 24.5 | 82.5 | 83.8 | 128.7 | 150.2 | 184.5 | 281.4 | 1,101.7 | 1,281.4 | 1,460.4 | 1,691.3 | 1,875.1 |
| 25.5 | 73.5 | 80.7 | 113.4 | 179.0 | 234.3 | 260.8 | 544.9 | 803.7 | 869.6 | 1,059.5 | 1,385.3 |

**Table 3.4** (continued)

| Grid station | | Quantile estimates of daily maximum rainfall (mm) | | | | | Quantile estimates of annual rainfall (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lat | Long | $T = 2$ yr | $T = 5$ yr | $T = 10$ yr | $T = 25$ yr | $T = 50$ yr | $T = 2$ yr | $T = 5$ yr | $T = 10$ yr | $T = 25$ yr | $T = 50$ yr |
| 25.5 | 74.5 | 74.7 | 103.8 | 137.2 | 236.5 | 247.8 | 632.4 | 840.7 | 919.7 | 980.7 | 1,130.0 |
| 25.5 | 75.5 | 78.6 | 106.2 | 131.6 | 144.6 | 158.9 | 672.9 | 850.3 | 934.6 | 1,147.9 | 1,237.7 |
| 25.5 | 76.5 | 72.5 | 108.2 | 129.2 | 154.6 | 168.4 | 776.8 | 937.4 | 1,034.3 | 1,354.2 | 1,450.1 |
| 25.5 | 77.5 | 91.7 | 124.8 | 152.3 | 201.2 | 215.7 | 866.7 | 1,061.0 | 1,230.0 | 1,262.4 | 1,450.8 |
| 25.5 | 78.5 | 109.2 | 145.8 | 179.5 | 200.4 | 214.8 | 897.1 | 1,092.2 | 1,235.5 | 1,361.4 | 1,566.8 |
| 25.5 | 79.5 | 80.4 | 123.2 | 142.1 | 169.2 | 177.8 | 1,030.5 | 1,162.6 | 1,360.9 | 1,654.6 | 1,709.4 |
| 25.5 | 80.5 | 96.1 | 137.1 | 177.6 | 205.2 | 211.4 | 957.4 | 1,127.6 | 1,296.0 | 1,591.0 | 1,728.7 |
| 25.5 | 81.5 | 74.0 | 112.6 | 125.4 | 166.2 | 172.7 | 988.7 | 1,179.6 | 1,380.1 | 1,506.8 | 1,548.5 |
| 25.5 | 82.5 | 102.2 | 140.1 | 174.6 | 218.2 | 236.6 | 1,073.2 | 1,245.0 | 1,355.2 | 1,386.3 | 1,428.0 |
| 26.5 | 73.5 | 54.4 | 76.9 | 101.4 | 167.3 | 284.9 | 365.3 | 594.3 | 663.7 | 842.2 | 885.3 |
| 26.5 | 74.5 | 65.4 | 101.0 | 146.8 | 170.0 | 376.1 | 462.8 | 613.7 | 721.5 | 872.3 | 912.5 |
| 26.5 | 75.5 | 65.5 | 90.0 | 111.0 | 173.6 | 212.6 | 525.5 | 759.0 | 823.8 | 957.9 | 997.6 |
| 26.5 | 76.5 | 65.8 | 92.9 | 119.9 | 162.9 | 241.6 | 637.3 | 809.0 | 965.9 | 1,060.6 | 1,087.0 |
| 26.5 | 77.5 | 66.8 | 95.8 | 111.9 | 164.6 | 234.0 | 634.6 | 913.5 | 955.1 | 1,060.6 | 1,084.8 |
| 26.5 | 78.5 | 78.9 | 98.6 | 129.7 | 192.3 | 217.9 | 751.7 | 956.2 | 1,048.9 | 1,271.7 | 1,403.9 |
| 26.5 | 79.5 | 68.8 | 123.0 | 138.2 | 161.9 | 164.9 | 808.3 | 975.0 | 1,120.2 | 1,351.0 | 1,458.1 |
| 26.5 | 80.5 | 81.6 | 113.9 | 135.2 | 154.7 | 161.5 | 883.4 | 1,176.6 | 1,384.7 | 1,493.3 | 1,846.7 |
| 26.5 | 81.5 | 74.3 | 109.0 | 126.7 | 159.8 | 169.1 | 976.1 | 1,259.3 | 1,370.2 | 1,567.6 | 1,777.6 |
| 27.5 | 74.5 | 43.5 | 75.4 | 113.1 | 120.9 | 142.0 | 324.3 | 501.3 | 593.6 | 848.2 | 897.7 |
| 27.5 | 75.5 | 60.5 | 87.9 | 106.9 | 131.1 | 157.2 | 489.1 | 622.8 | 724.4 | 807.8 | 930.2 |
| 27.5 | 76.5 | 69.3 | 87.7 | 101.6 | 136.4 | 176.4 | 630.6 | 780.3 | 903.3 | 943.3 | 1,005.0 |
| 27.5 | 77.5 | 67.1 | 92.5 | 102.5 | 123.0 | 143.7 | 608.7 | 753.8 | 794.6 | 828.9 | 1,002.1 |
| 27.5 | 78.5 | 57.2 | 82.1 | 91.8 | 129.6 | 273.2 | 751.6 | 951.9 | 1,011.1 | 1,059.5 | 1,098.9 |
| 27.5 | 79.5 | 69.2 | 102.0 | 134.7 | 176.7 | 193.6 | 805.6 | 1,064.8 | 1,139.7 | 1,188.7 | 1,522.8 |
| 27.5 | 80.5 | 93.0 | 131.5 | 167.1 | 204.9 | 221.0 | 1,007.9 | 1,241.5 | 1,454.9 | 1,703.8 | 1,755.8 |
| 28.5 | 74.5 | 55.6 | 78.2 | 120.0 | 198.1 | 215.6 | 296.5 | 491.3 | 600.5 | 651.5 | 732.1 |
| 28.5 | 75.5 | 50.1 | 75.4 | 101.1 | 151.9 | 175.6 | 400.9 | 532.1 | 607.2 | 824.9 | 924.6 |

**Table 3.4** (continued)

| Grid station | | Quantile estimates of daily maximum rainfall (mm) | | | | | Quantile estimates of annual rainfall (mm) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Lat | Long | $T=2$ yr | $T=5$ yr | $T=10$ yr | $T=25$ yr | $T=50$ yr | $T=2$ yr | $T=5$ yr | $T=10$ yr | $T=25$ yr | $T=50$ yr |
| 28.5 | 76.5 | 60.3 | 76.6 | 87.3 | 117.2 | 139.2 | 478.0 | 685.1 | 767.0 | 937.3 | 961.5 |
| 28.5 | 77.5 | 73.8 | 115.1 | 135.1 | 171.3 | 176.9 | 735.0 | 915.1 | 1,038.7 | 1,110.4 | 1,151.2 |
| 28.5 | 78.5 | 66.2 | 93.2 | 108.1 | 141.9 | 176.2 | 785.9 | 1,071.5 | 1,146.9 | 1,236.6 | 1,273.0 |
| 29.5 | 74.5 | 46.5 | 66.4 | 91.3 | 128.7 | 133.9 | 246.9 | 344.5 | 392.1 | 486.6 | 581.3 |
| 29.5 | 75.5 | 58.6 | 79.9 | 100.0 | 121.9 | 137.0 | 378.5 | 514.9 | 560.9 | 668.6 | 773.6 |
| 29.5 | 76.5 | 51.4 | 79.0 | 99.7 | 108.0 | 136.8 | 374.3 | 555.5 | 626.7 | 803.9 | 820.4 |
| 29.5 | 77.5 | 77.6 | 102.7 | 112.6 | 154.8 | 165.0 | 839.2 | 1,017.8 | 1,107.7 | 1,274.5 | 1,342.2 |
| 29.5 | 78.5 | 108.9 | 165.6 | 188.0 | 242.2 | 325.9 | 1,140.0 | 1,425.4 | 1,622.6 | 1,800.2 | 1,906.9 |
| 30.5 | 75.5 | 69.4 | 94.7 | 119.6 | 149.2 | 206.1 | 502.6 | 703.6 | 822.1 | 980.9 | 1,011.2 |
| 30.5 | 76.5 | 78.2 | 115.1 | 142.1 | 160.2 | 264.1 | 764.9 | 911.3 | 1,021.8 | 1,449.5 | 1,546.2 |
| 30.5 | 77.5 | 118.0 | 160.0 | 177.2 | 188.4 | 219.3 | 1,490.3 | 1,975.0 | 2,282.2 | 2,982.7 | 3,269.7 |
| 30.5 | 78.5 | 90.6 | 147.6 | 188.9 | 253.8 | 531.9 | 1,615.3 | 1,973.3 | 2,244.1 | 2,318.8 | 3,527.1 |
| 31.5 | 76.5 | 67.9 | 105.8 | 124.7 | 149.0 | 171.8 | 1,230.2 | 1,554.6 | 1,717.7 | 1,876.4 | 2,052.9 |
| 31.5 | 77.5 | 54.4 | 78.9 | 104.4 | 140.7 | 154.4 | 1,063.1 | 1,187.7 | 1,375.4 | 1,552.3 | 1,914.2 |
| 31.5 | 78.5 | 49.0 | 85.2 | 119.9 | 225.1 | 338.8 | 756.6 | 1,098.4 | 1,334.7 | 1,737.0 | 1,961.3 |
| 31.5 | 79.5 | 52.5 | 77.0 | 103.8 | 170.4 | 195.7 | 1,040.0 | 1,206.1 | 1,326.4 | 1,435.1 | 1,548.3 |

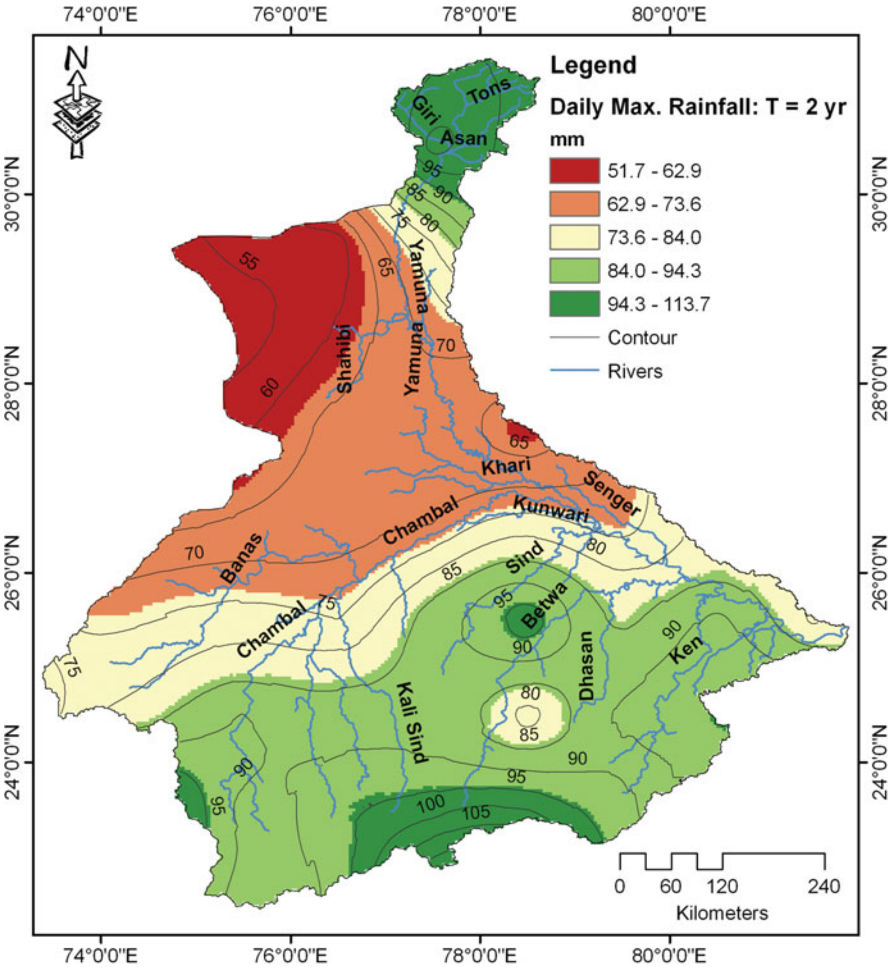


**Fig. 3.3** Daily maximum rainfall for the return period of 2 years (data period: 1951–2003)

The number of raindays from daily rainfall data is derived following the criteria of India Meteorological Department (IMD). The criterion is: "a day having rainfall of more than 3 mm is referred as the rainyday". Using this criterion, the mean values of numbers of annual, monsoon and non-monsoon rainydays are derived and depicted in Figs. 3.14, 3.15, and 3.16, respectively.

## 3.2 Temperature

Temperature is one of the driving climatic variables that govern the hydrological cycle. It directly affects the magnitude of snow melt runoff, evapotranspiration rate, water use, and water quality in the river. The Yamuna basin experiences a wide

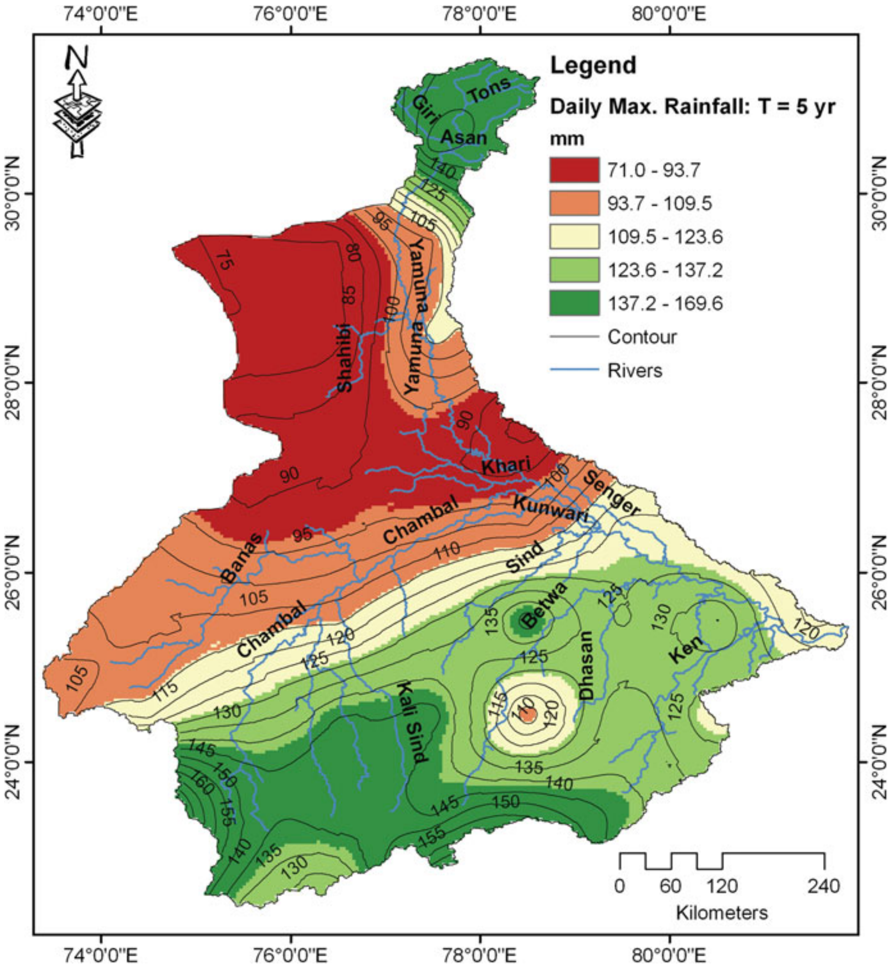


**Fig. 3.4** Daily maximum rainfall for the return period of 5 years (data period: 1951–2003)

range of spatio-temporal variability in the temperature. Mean maximum and mean minimum temperature in the basin spatially varies between 24.25 and 42.46°C and –1.05 to 10.81°C, respectively. The spatial pattern of mean maximum and minimum temperature is depicted in Figs. 3.17 and 3.18. The mean maximum and minimum isotherms are also included in Figs. 3.17 and 3.18.

Based on the available records for the period of 1983–2008 collected from National Climatic Data Center (http://www.ncdc.noaa.gov), the highest recorded daily maximum and minimum temperatures observed at different location are also identified and upscaled to the basin level using the Kriging method, and are depicted in Figs. 3.19 and 3.20. The catchment-wise estimated mean maximum and mean minimum temperature are also given in Table 3.5.

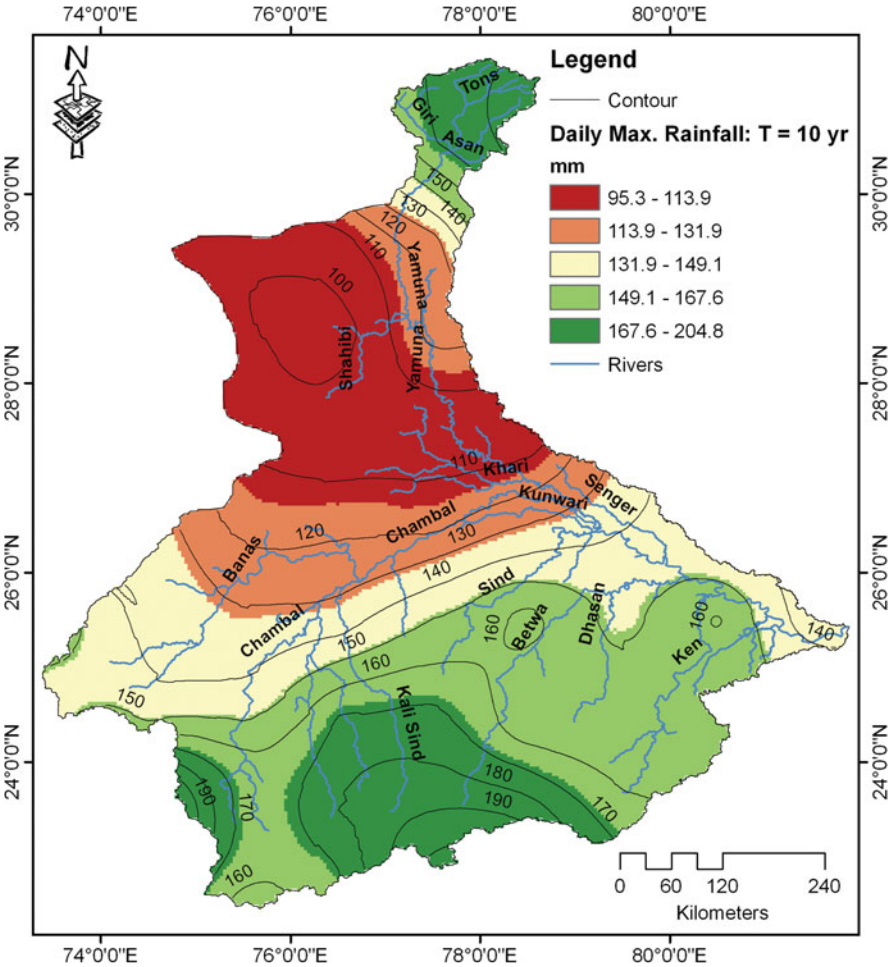


**Fig. 3.5** Daily maximum rainfall for the return period of 10 years (data period: 1951–2003)

## 3.3 Wind

Using daily values of wind speed for the period of 1980–2008 from the National Climatic Data Center (http://www.ncdc.noaa.gov) for a few stations in the Yamuna basin, average and maximum wind speed were derived and interpolated at the basin scale. The generated contours of annual mean wind speed for the Yamuna basin are depicted in Fig. 3.21.

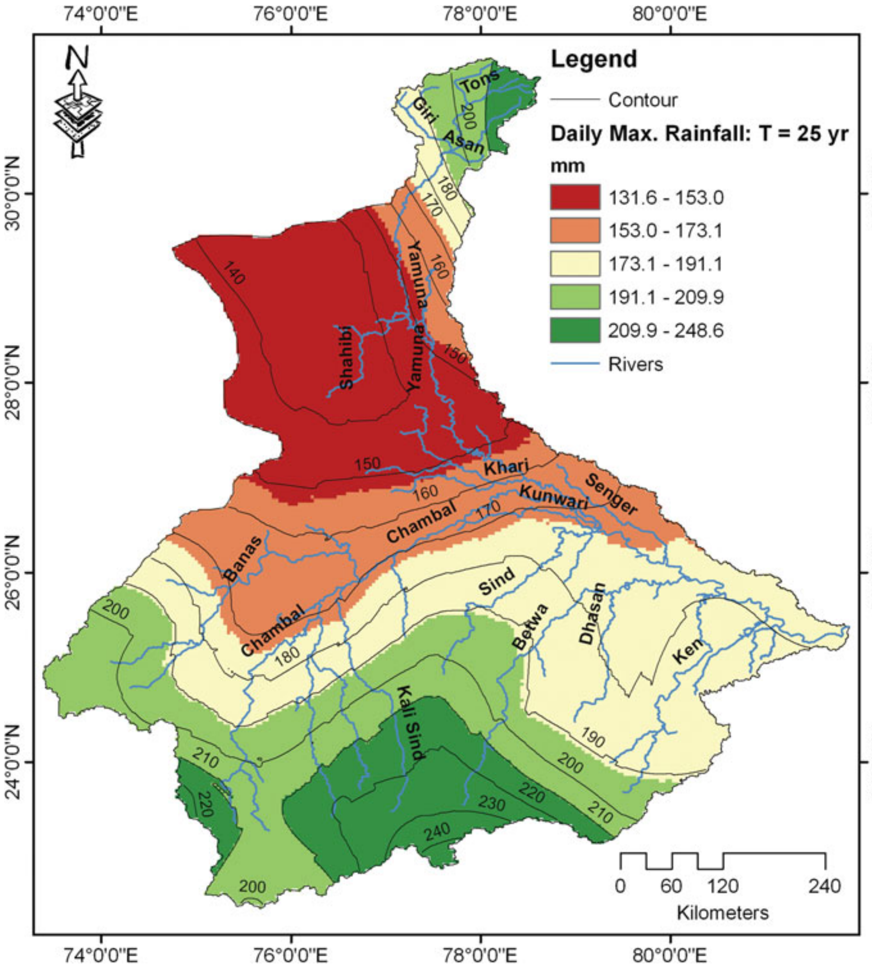


**Fig. 3.6** Daily maximum rainfall for the return period of 25 years (data period: 1951–2003)

## 3.4 Humidity

Direct measurement of humidity is not easy; therefore, it is presented through relative humidity. The relative humidity (RH) is referred to as the ratio of actual vapor pressure to the vapor pressure at saturation. Mathematically, RH is expressed as:

$$\mathrm{RH} = \frac{e_\mathrm{a}}{e_\mathrm{s}} \times 100\,\% \tag{3.4}$$

where $e_\mathrm{a}$ is the actual vapor pressure and is estimated at dew point temperature as follows:

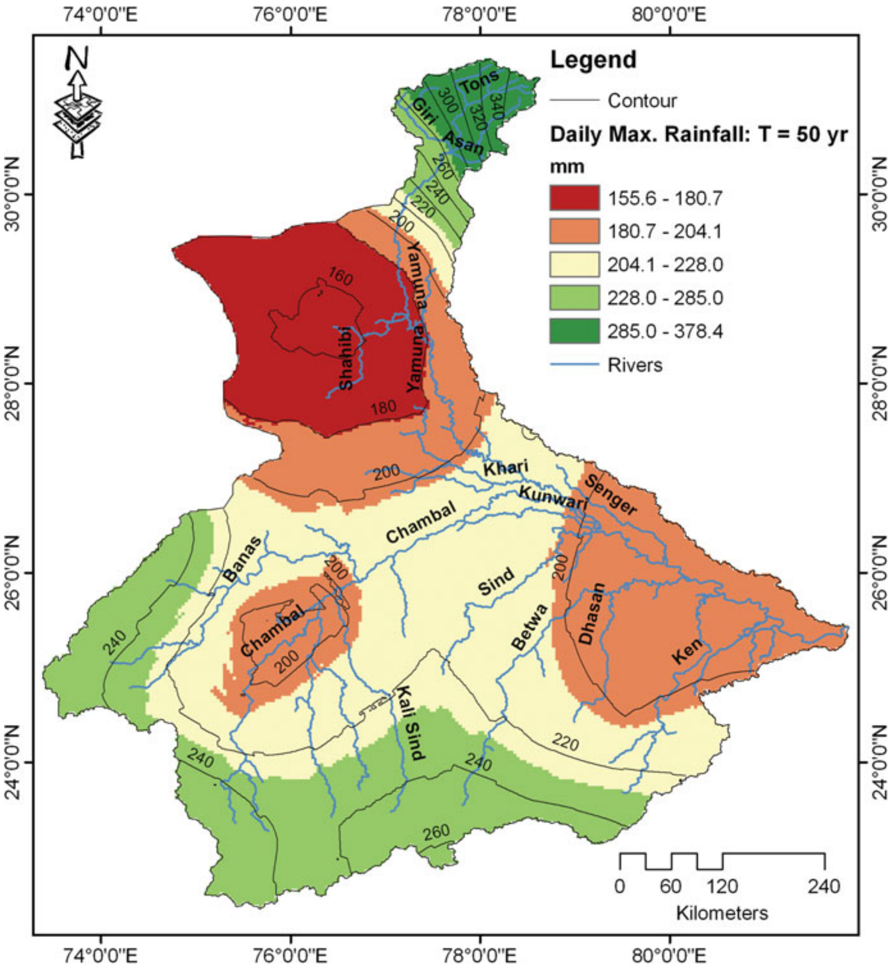


**Fig. 3.7** Daily maximum rainfall for the return period of 50 years (data period: 1951–2003)

$$e_a = 0.6108 \times \exp\left\{\frac{17.27\,T_{dew}}{T_{dew} + 237.3}\right\} \quad (3.5)$$

where $T_{dew}$ is the dew point temperature (°C).

The vapor pressure at saturation is estimated as follows:

$$e_s = \left[e_0\,(T_{max}) + e_0\,(T_{min})\right]/2 \quad (3.6)$$

$$e_0\,(T_{max}) = 0.6108 \times \exp\left\{\frac{17.27\,T_{max}}{T_{max} + 237.3}\right\} \quad (3.7)$$

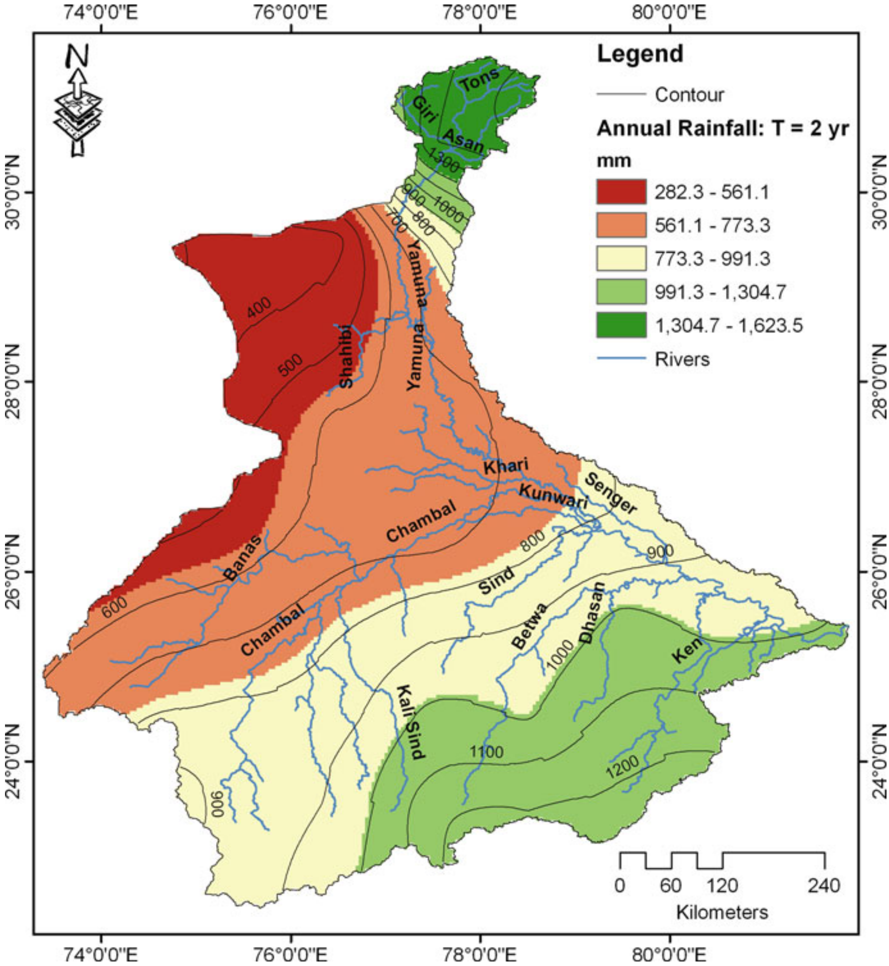


**Fig. 3.8** Annual rainfall for the return period of 2 years (data period: 1951–2003)

where $T_{\max}$ and $T_{\min}$ are the daily maximum and minimum temperatures, respectively (°C).

Using daily values of dew point temperature, minimum and maximum temperatures available from National Climatic Data Center (http://www.ncdc.noaa.gov) for a few stations in the Yamuna basin, the relative humidity is computed from eq. (3.4) with auxiliary equations [eqs. (3.5), (3.6), and (3.7)], and interpolated at the basin scale using the Kriging interpolation technique. The derived spatial variation of estimated mean RH is shown in Fig. 3.22.

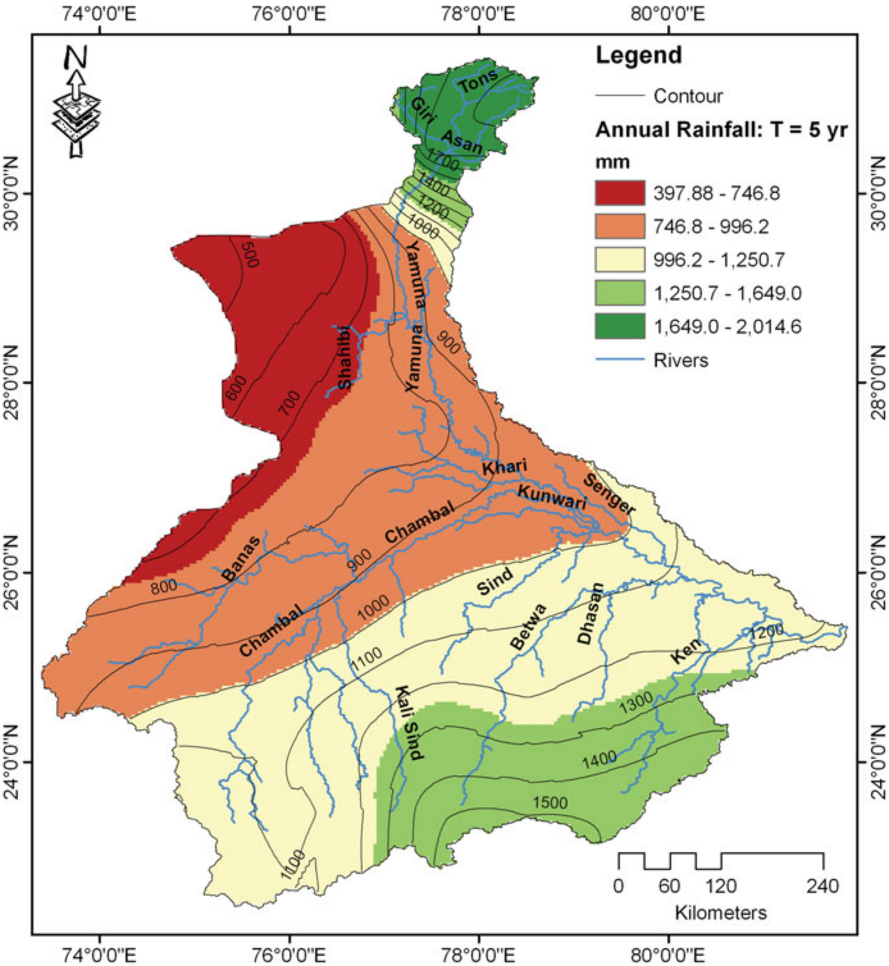


**Fig. 3.9** Annual rainfall for the return period of 5 years (data period: 1951–2003)

## 3.5 Evapotranspiration

Evapotranspiration is a process of mass transfer due to heat energy. It is the combined effect of evaporation as well as transpiration. Evaporation can be defined as the process in which liquid water is converted to water vapor from the evaporating surface, such as lakes, rivers, pavements, soil and vegetation; whereas, transpiration is a process of vaporization of liquid water from plant tissues and the vapor removal from the atmosphere. On the other hand, the evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as $ET_0$. The reference surface is a hypothetical grass reference crop that closely resembles an extensive surface of green,

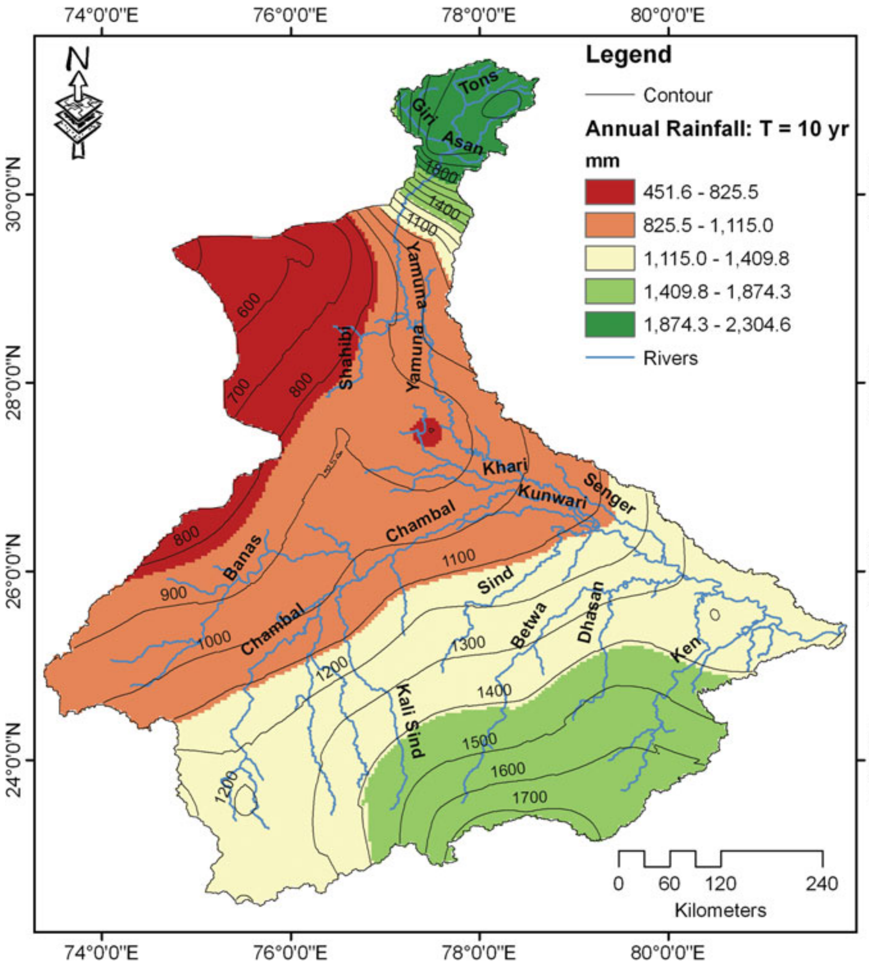


**Fig. 3.10** Annual rainfall for the return period of 10 years (data period: 1951–2003)

well-watered grass of uniform height, actively growing and completely shading the ground.

The estimation of $ET_0$ requires several climatic parameters, such as weather parameters (i.e., radiation, air temperature, wind speed, humidity); crop characteristics (type, variety, development stage); and management and environmental aspects. These data are difficult to manage for such a large basin. Under such circumstances, FAO-56 procedure based on the Penmann-Montieth approach has become limited in field application. Therefore, the Hargreaves method of $ET_0$ has been used with reliable accuracy and is described as follows. Hargreaves equation has a tendency to under-predict under high wind speed conditions ($u > 3$ m/s) and over-predict under conditions of high relative humidity.

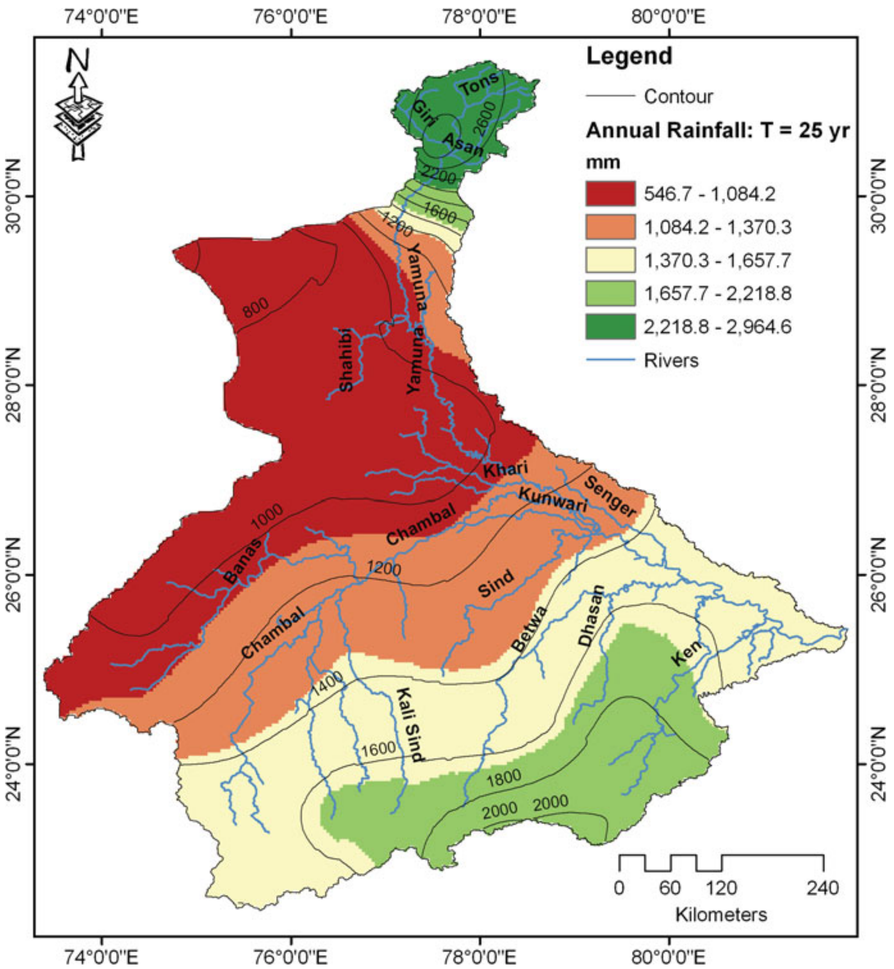


**Fig. 3.11** Annual rainfall for the return period of 25 years (data period: 1951–2003)

$$ET_0 = 0.0023\ (T_{\text{mean}} + 17.8)\ (T_{\max} - T_{\min})^{0.5} \times R_a \tag{3.8}$$

where $ET_0$ is the reference evapotranspiration (mm d$^{-1}$); $T_{\text{mean}}$, $T_{\max}$, and $T_{\min}$ are the daily mean, maximum and minimum temperatures (°C); and $R_a$ is the extra-terrestrial radiation for each day (mm d$^{-1}$). $R_a$ for each day of the year and for different latitudes can be estimated as follows:

$$R_a = 0.408 \times \frac{24\,(60)}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)\right] \tag{3.9}$$

where: $R_a$ is the extra-terrestrial radiation (mm d$^{-1}$); $G_{sc}$ is the solar constant (0.0820 MJ m$^{-2}$ min$^{-1}$); $d_r$ is the inverse relative distance (Earth-Sun); $\omega_s$ is the

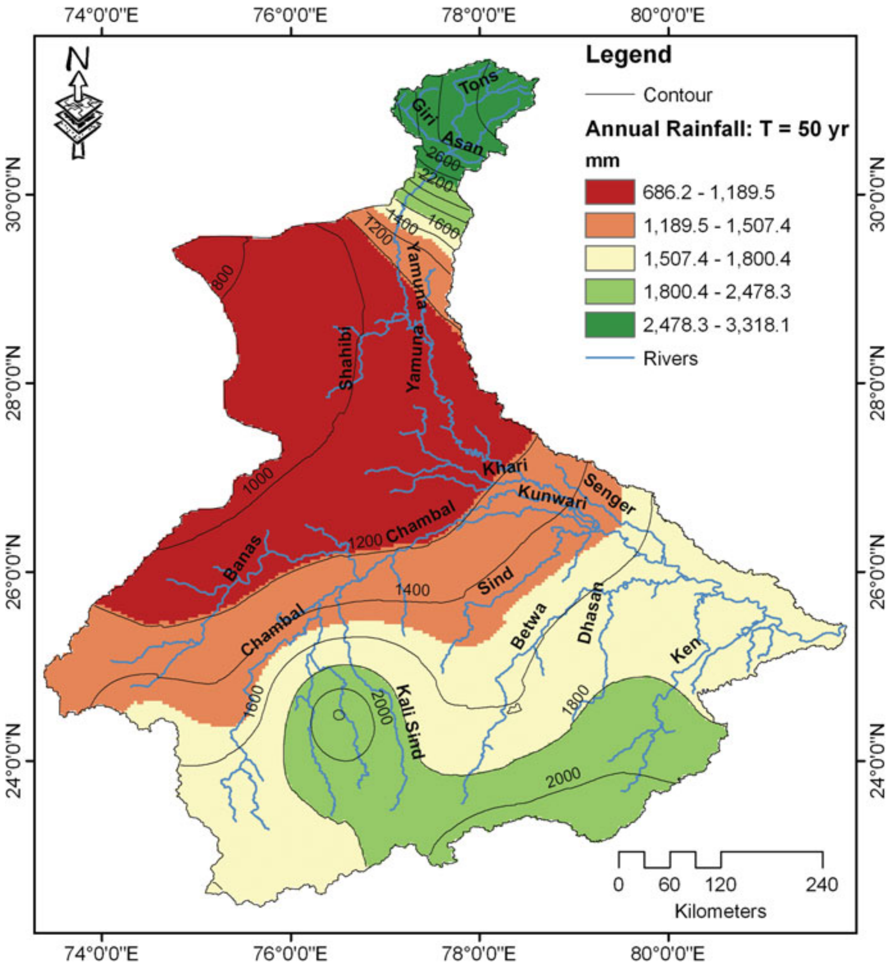


Fig. 3.12 Annual rainfall for the return period of 50 years (data period: 1951–2003)

sunset hour angle (rad); $\varphi$ is the latitude (rad); and $\delta$ is the solar declination (rad) [rad $= \pi \times$ decimal deg/180]. The inverse relative distance Earth-Sun, $d_r$ and the solar declination, $\delta$, is given as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365}J\right) \tag{3.10}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}J - 1.39\right) \tag{3.11}$$

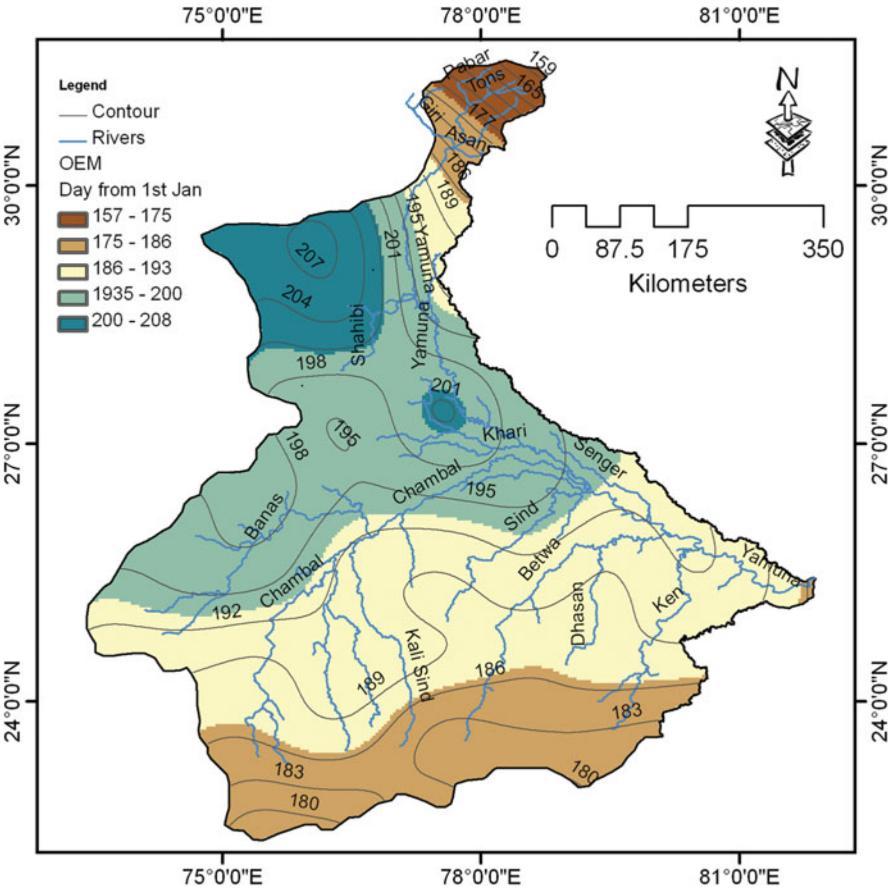


**Fig. 3.13** Date of onset of effective monsoon for the Yamuna basin

where $J$ is the number of days in the year between 1 (1st January) and 365 or 366 (31st December). The sunset hour angle $\omega_s$ is given by:

$$\omega_s = \arccos\left[-\tan(\varphi) \cdot \tan(\delta)\right] \tag{3.12}$$

Using the temperature data for the period of 1951–2002 and latitude of the district centroid, the daily reference crop evapotranspiration is estimated for the 52 year period (1951–2002). The spatial variation of estimated mean annual $ET_0$ is depicted in Fig. 3.23 which also consists of the contours of $ET_0$. Approximately, 75% of the basin area has the annual $ET_0$ varying between 1,536–1,624 mm.

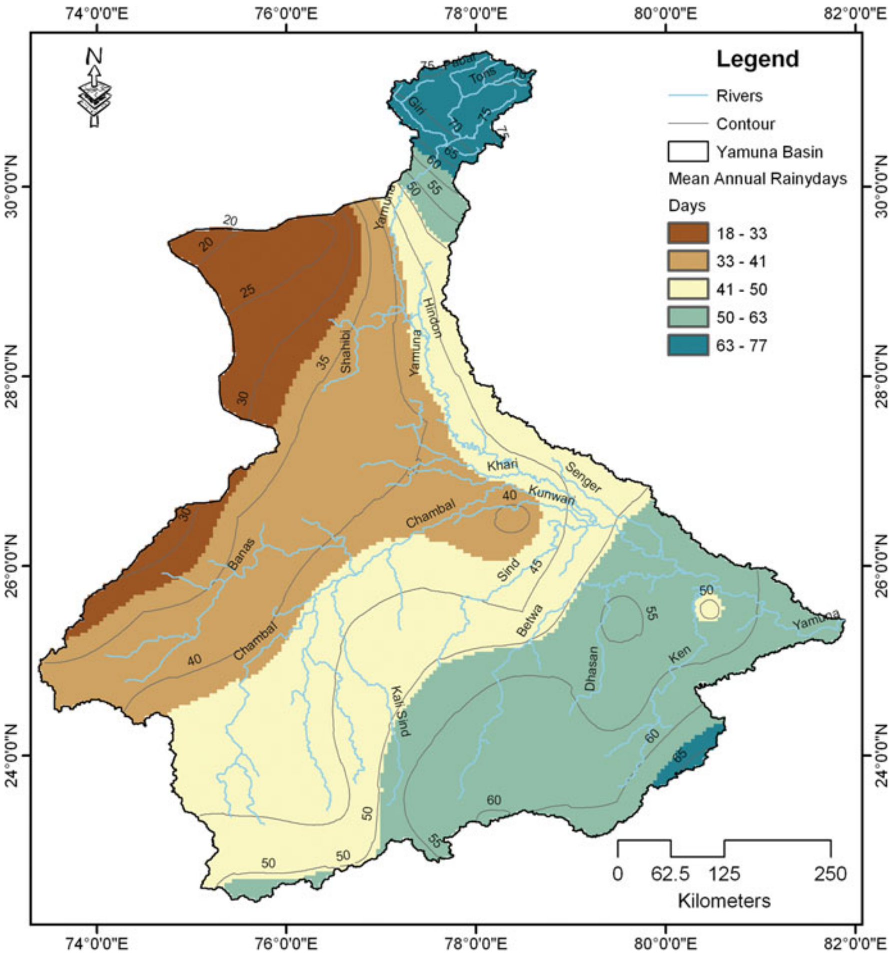


Fig. 3.14 Number of annual rainydays in the Yamuna basin

## 3.6 Aridity Index and Climate Classification

Aridity Index (AI), an indicator of the annual moisture deficit and degree of dryness, can be defined as the ratio of annual rainfall to annual potential evapotranspiration. Numerically, the aridity index (AI) can be expressed as follows (UNEP, 1993):

$$AI = \frac{\text{Annual Rainfall}}{\text{Annual Potential Evapotranspiration}} \tag{3.13}$$

Both terms appearing in eq. (3.13) are in millimeter. Using the UNEP (1993) criteria, climate can be classified as: hyper arid (AI < 0.05), arid (0.05 < AI < 0.20), semi arid (0.20 < AI < 0.50), dry sub humid (0.50 < AI < 0.65), and humid (AI > 0.65).

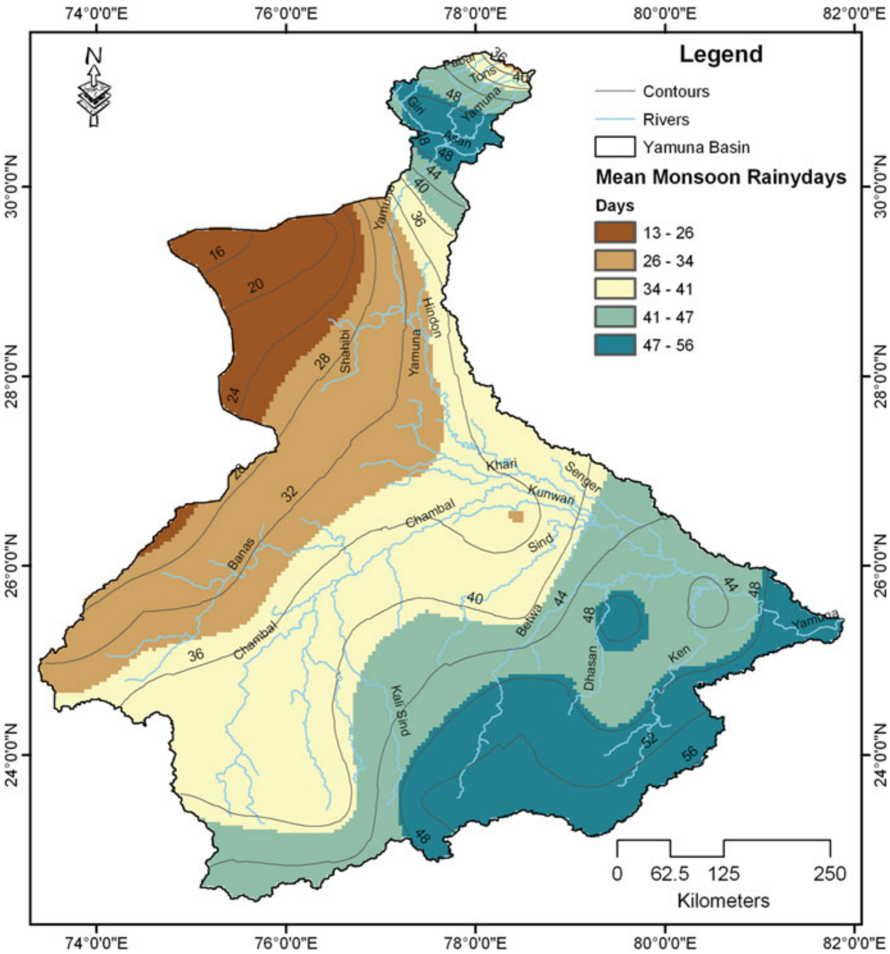


**Fig. 3.15** Number of monsoon rainydays in the Yamuna basin

The potential evapotranspiration (PET) is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapor from the ground up into the lower atmosphere. Evapotranspiration is said to equal potential evapotranspiration when there is ample water. The value of potential evapotranspiration is generally estimated using the Thornthwaite equation (Thornthwaite, 1948). The method is based on the annual temperature efficiency index $J$, defined as the sum of 12 monthly values of the mean monthly temperature $T_{mean}$ as follows:

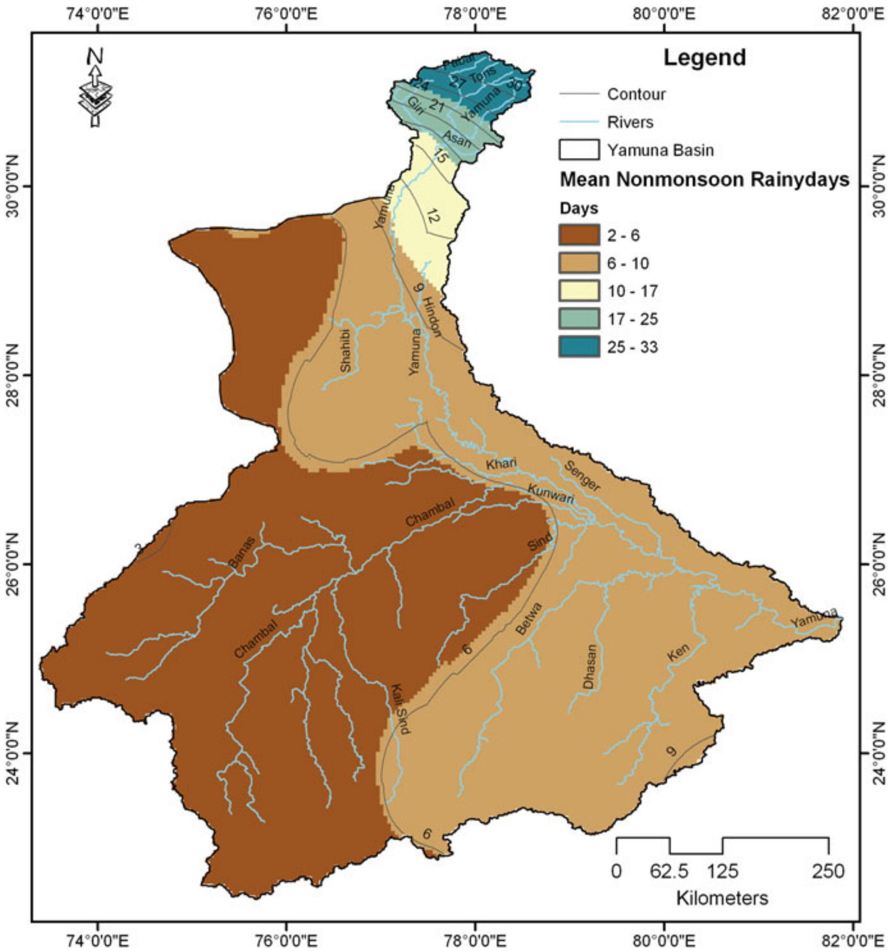


**Fig. 3.16** Number of non-monsoon rainydays in the Yamuna basin

$$\mathrm{PET}_i\left(0^\circ\right) = 1.6\left(\frac{10\,T_i}{J}\right)^c \tag{3.14}$$

where:

$$c = 0.000000675\,J^3 - 0.0000771\,J^2 + 0.0179\,J + 0.49239 \tag{3.15}$$

$$J = \sum_{i=1}^{12} I_i \tag{3.16}$$

$$I_i = \left(\frac{T_i}{5}\right)^{1.514} \tag{3.17}$$

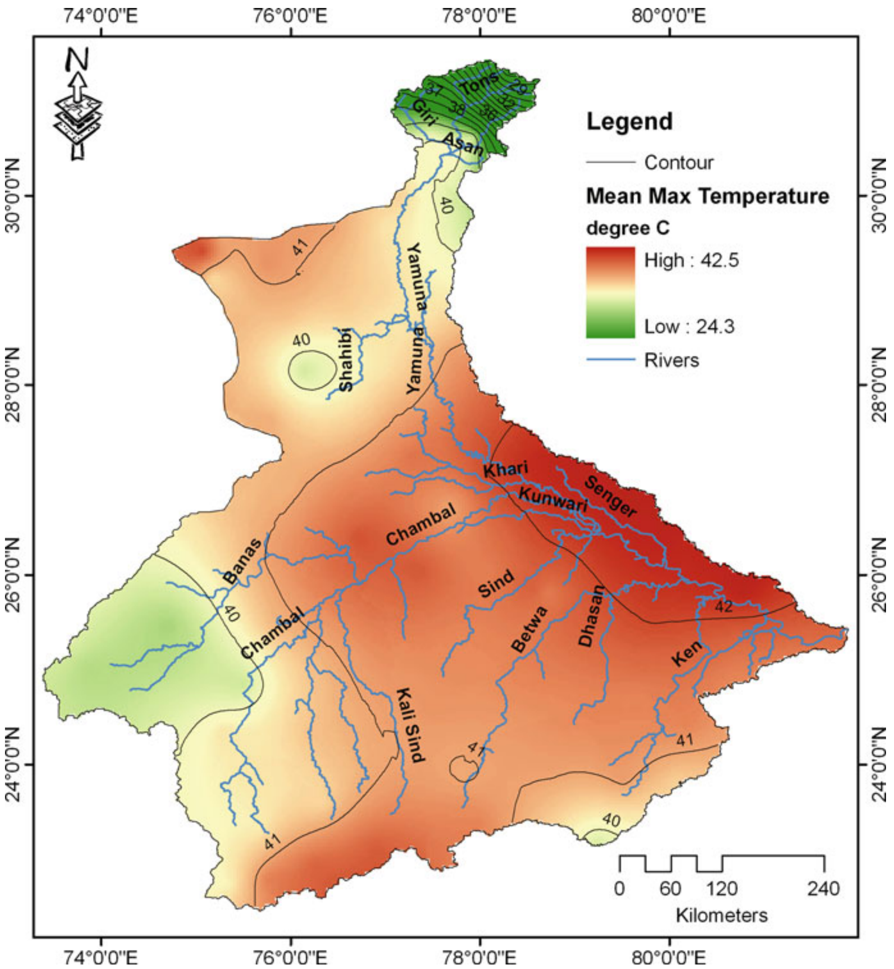


**Fig. 3.17** Spatial variation of mean maximum temperature

where $T_i$ is the mean monthly temperature (°C) for the $i$th month, and $PET_i(0°)$ is the potential evapotranspiration for the $i$th month at 0° latitude [$PET_i(0°)$]. For other latitudes, PET can be estimated as follows:

$$PET_i = k \times PET_i\left(0^{\circ}\right) \tag{3.18}$$

Where $k$ is the latitude correction factor which depends on the day light hours. It can be defined as:

$$k = \frac{N}{N'} \tag{3.19}$$

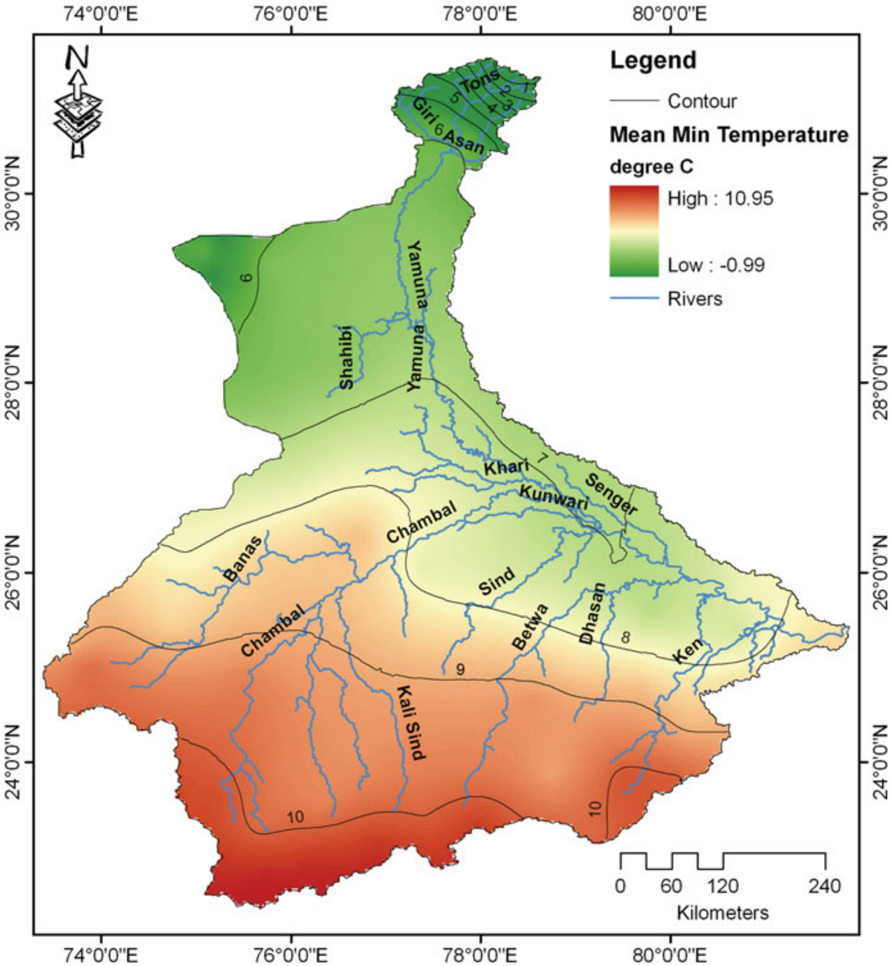


**Fig. 3.18** Spatial variation of mean minimum temperature

where, $N =$ day light hours at latitude other than 0°, and $N' =$ day light hours at 0° latitude. The value of $N$ can be obtained as:

$$N = \frac{24}{\pi} \times \omega_s. \tag{3.20}$$

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \tag{3.21}$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365}J' - 1.39\right) \tag{3.22}$$

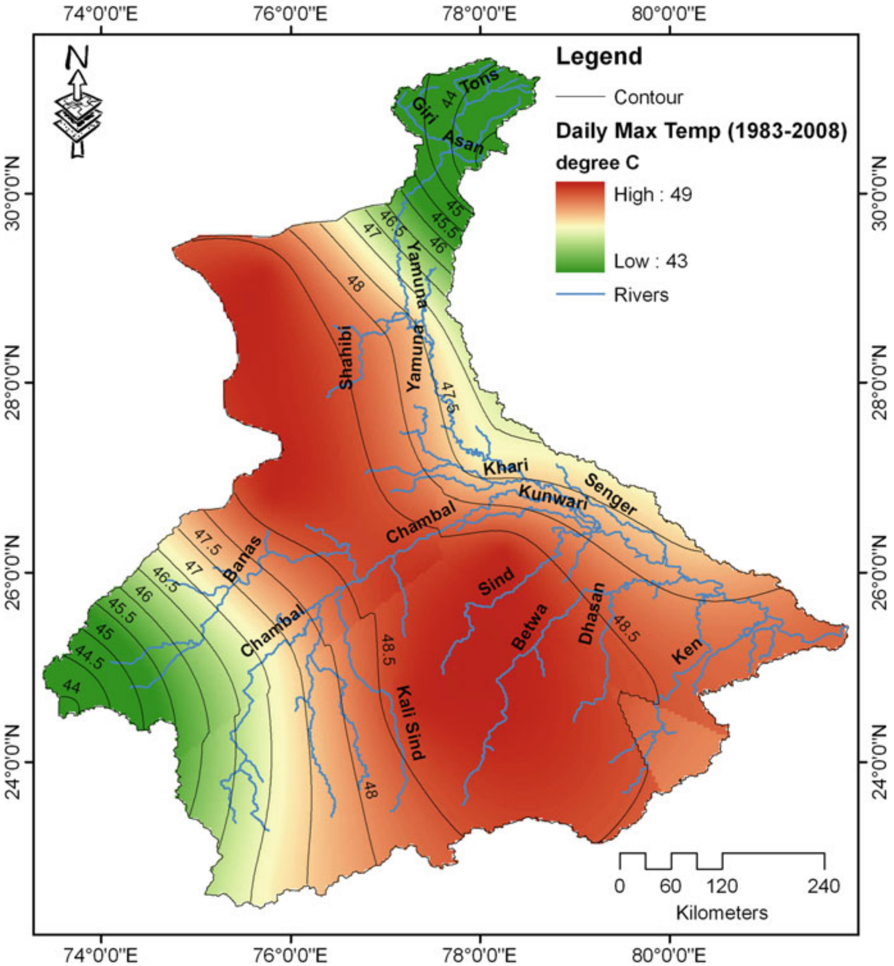


**Fig. 3.19** Spatial variation of daily maximum temperature (1983–2008)

where $J'$ is the number of days in the year between 1 (1 January) and 365 or 366 (31 December), and $\varphi$ is the latitude in radians. In the estimation of monthly PET, $J'$ is taken in the middle of the each month (Table 3.6).

Using eq. (3.13), aridity index is estimated for the entire grid locations of the Yamuna basin, and interpolated using the Kriging method. Using the aridity index, the climate of the Yamuna basin varies from arid to humid (Fig. 3.24). Based on Fig. 3.24, a majority of the catchment area in the basin falls under semi-arid climate followed by dry sub-humid and humid climate.

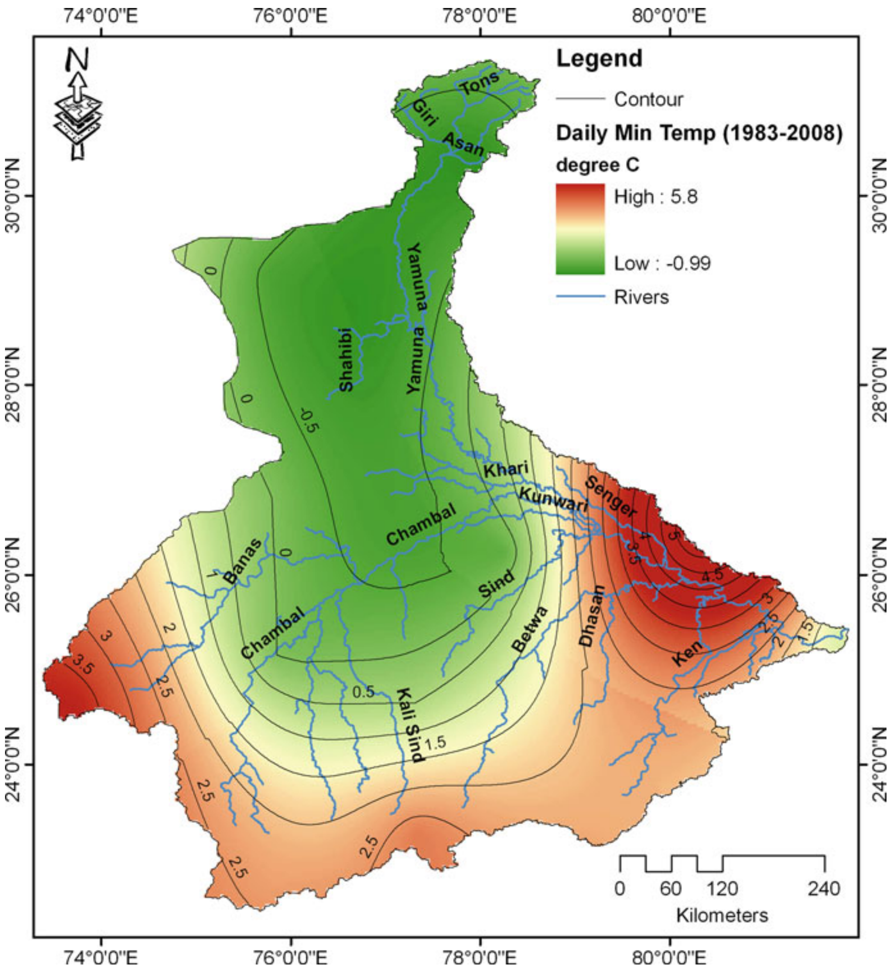


Fig. 3.20 Spatial variation of daily minimum temperature (1983–2008)

**Table 3.5** Catchment wise mean temperatures

| S. No. | Basin/sub-catchment | Maximum temperature (°C) | Minimum temperature (°C) |
|---|---|---|---|
| 1 | Upper Himalaya | 34.72 | 3.53 |
| 2 | Betwa | 41.53 | 8.80 |
| 3 | Ken | 41.28 | 8.90 |
| 4 | Sind | 42.00 | 7.86 |
| 5 | Chambal | 40.80 | 9.08 |
| 6 | Hindon | 40.31 | 6.55 |
| 7 | Khari | 41.19 | 7.33 |
| 8 | Yamuna basin | 40.52 | 7.60 |

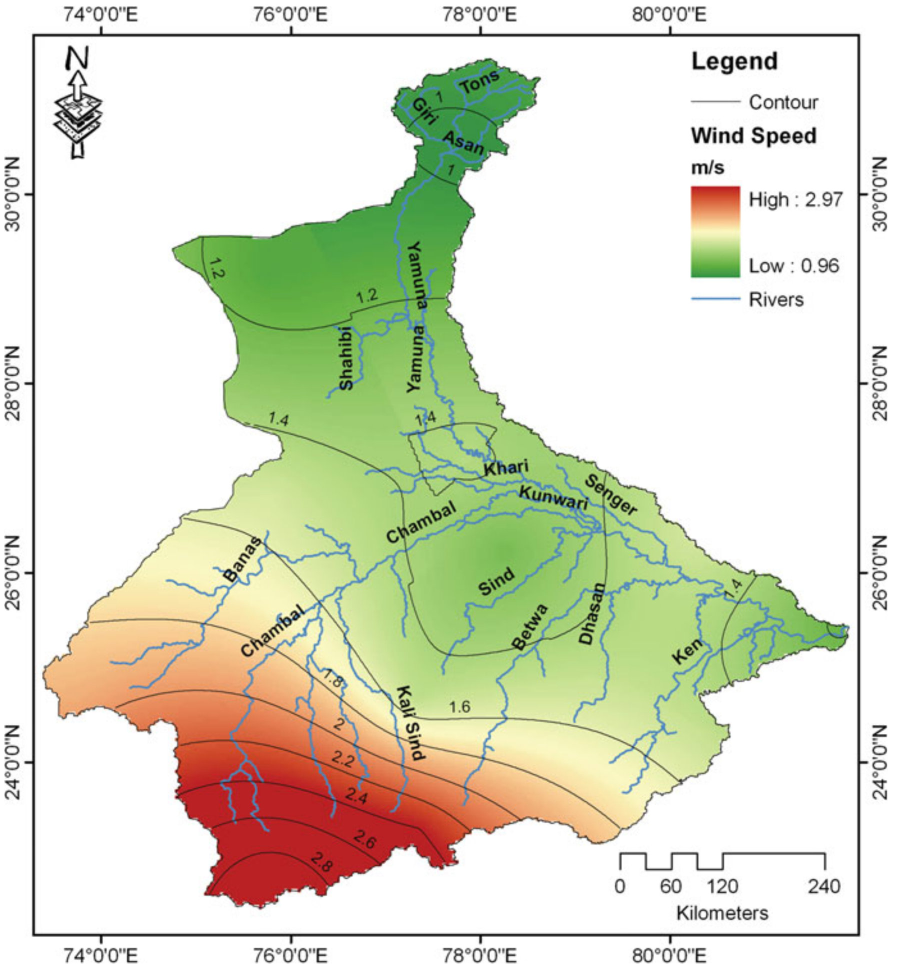


**Fig. 3.21** Spatial variation of average wind speed in Yamuna basin (1980–2009)

## 3.7 Concluding Remarks

Based on the above analysis, Yamuna basin has a wide spatial variability in the climate. Rainfall, temperature and evapotranspiration along with the aridity index are highly variable. Therefore, planning of water or natural resources is quite difficult, when the whole basin is considered as a single hydrologic unit. Under such circumstance, planning should be made at the watershed scale. However, based on topography, soil characteristics and climate, homogeneous watersheds can be identified for regional planning.

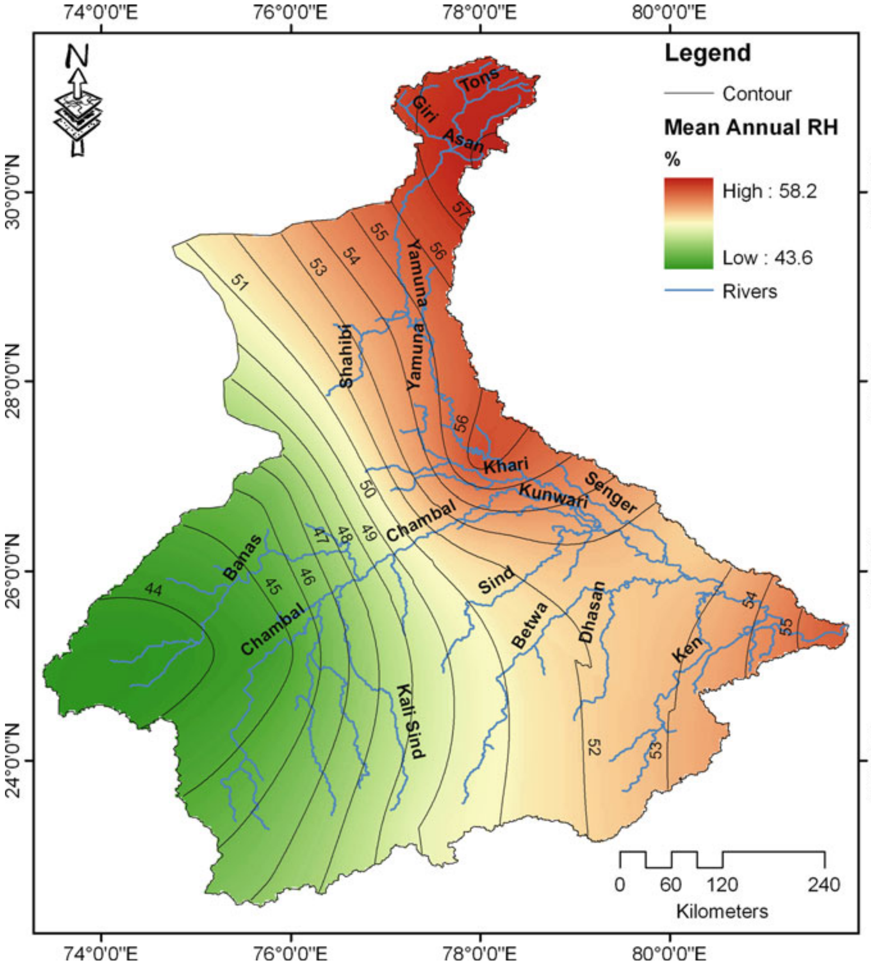


Fig. 3.22 Spatial variation of average relative humidity in Yamuna basin (1980–2009)

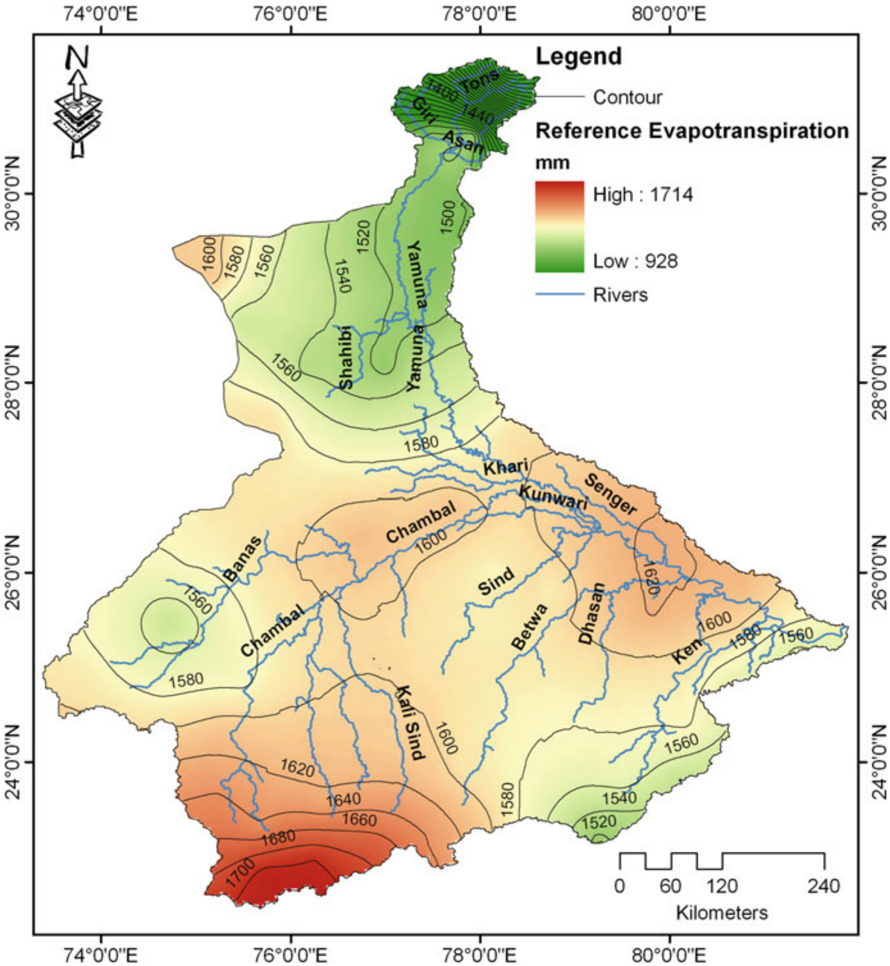


Fig. 3.23 Spatial variation of $ET_0$

**Table 3.6** $J'$ value used for the estimation of the solar declination, $\delta$ (rad)

| Month | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $J'$ (Normal) | 15 | 46 | 74 | 105 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 |
| $J'$ (Leap) | 15 | 46 | 75 | 106 | 136 | 167 | 197 | 228 | 259 | 289 | 320 | 350 |

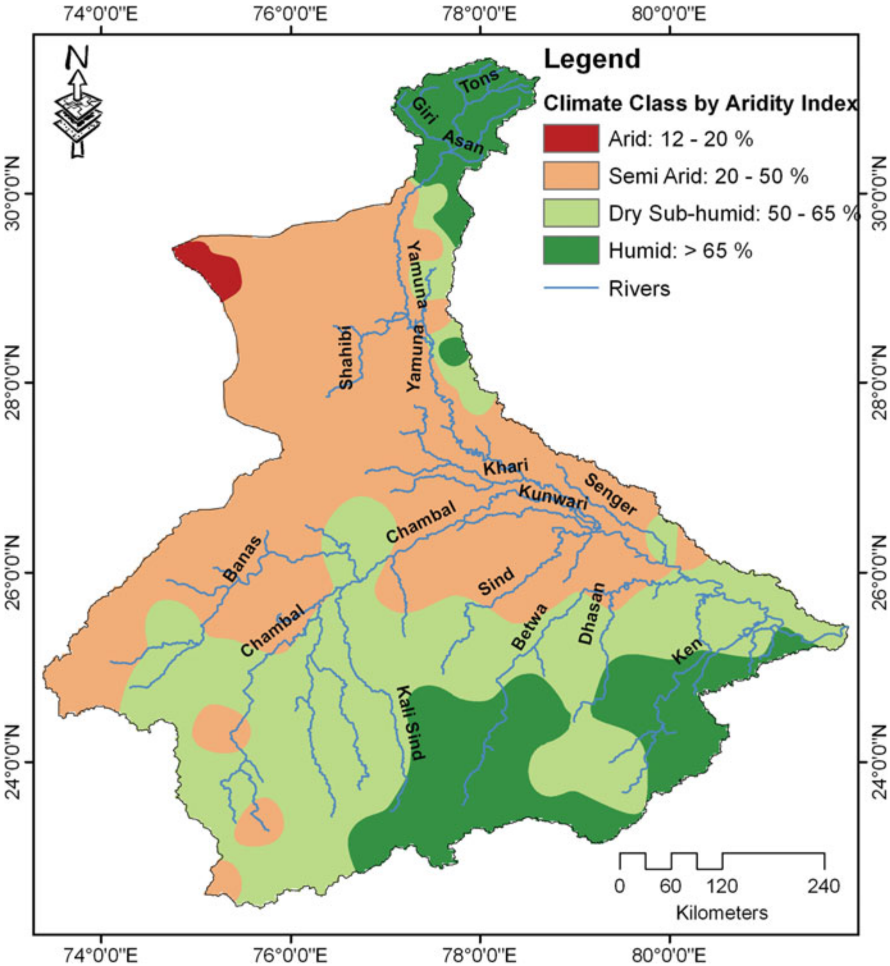


**Fig. 3.24** Climate classification of Yamuna basin

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# Chapter 4
# Pattern Changes in Climatic Variables

**Abstract** This chapter describes a methodology for identifying the nature and attributes of the time series of climatological variables, which is usually the first step for water resources planning and management. A detailed description of the statistical approach used to investigate the presence and extent of persistence, trend and periodicity in climatic time series is presented. Results of persistence and trend analysis are reported spatially for the basin. The hydro-climatic variables considered for analysis are annual rainfall; monsoon and non-monsoon rainfall; annual, monsoon and non-monsoon rainy days; onset of effective monsoon; and aridity index.

Climate is the most important driving parameter that causes year-to-year variability in socio-economic and environmental systems including the availability of water resources. It affects the development and planning of water resources schemes, such as flood prevention and control, drought management, food and fiber production, etc. Further, any change in climate will increase the uncertainty in water resources planning. Apart from this, changes in climatic pattern will have profound effects and consequences for natural and agricultural ecosystems and for society as whole. These changes could even alter the location of the major crop production regions on the earth (Reddy and Hodges, 2000). The shifting from "normal weather", with its associated extreme events will surely change the zones of crop adaptation and cultural practices required for successful crop production. Climate and weather induced instability in food and fibre supplies will alter social and economic stability and regional competitiveness (Reddy and Hodges, 2000). Therefore, analysis of hydro-climatic variables such as rainfall, potential evapotranspiration, etc., becomes a prerequisite to understand the climatic changes.

In recent years, there has been a considerable concern about the possibility of global warming and climatic changes. Alteration in our climate is governed by a complex system of atmospheric, land surface and oceanic processes and their interactions. Atmospheric processes also result in an increase in surface-level ultraviolet radiation and changes in temperature and rainfall pattern. Human activities on the other hand are responsible for changes in ecosystems due to increased emissions rate of $CO_2$ and other green house gases. The evidence using state-of-art computer models incorporating as much of the theoretical understanding of the earth's weather suggests that global warming is occurring along with shifting patterns of rainfall and incidents of extreme weather events (IPCC, 2007). It has been demonstrated that global surface warming has been taking place at a rate of $0.74 \pm 0.18°C$

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over the period of 1906–2005 (IPCC, 2007) and it is expected to be more in the next century than what has occurred during the past 10,000 years (IPCC WG II, 2007). The increased atmospheric moisture content associated with warming might be expected to increase the global mean precipitation.

The global annual land mean precipitation shows a small, but uncertain, upward trend of approximately 1.1 mm per decade (uncertainty ±1.5 mm) over 1901–2005. During the 20th century, precipitation has generally increased from latitudes 30° to 85°N over land; but notable decreases have occurred between latitudes 10°S and 30°N in the last 30–40 years. In western Africa and southern Asia, linear trends in the rainfall decrease during 1900–2005 are 7.5% per century (significant statistically at <1% level), whereas much of northwest India shows an increase in rainfall with more than 20% per century (IPCC, 2007). At lower latitudes, especially in seasonally dry and tropical regions, the crop productivity is projected to decrease for even small local temperature increases (1–2°C), which would increase food risk (IPCC WG II, 2007). Based on the data for the period of 1901–2005, it is demonstrated that all-India mean annual temperature has been rising at 0.05°C/decade, with maximum temperature at +0.07°C/decade and minimum temperature at +0.02°C/decade (Kothawale and Kumar, 2005). As a result, the diurnal temperature range shows an increase of 0.05°C/decade. However, in northern India, the average temperature is falling at a rate of −0.38°C unlikely to rise in all-India average temperature (i.e., at +0.42°C/Century) (Arora et al., 2005).

Change in the precipitation pattern is also reported for the 21st century. Kripalani et al. (2007) reported an increasing trend in South-Asian mean monsoon precipitation associated with intensification of land–ocean pressure gradient during the establishment phase of the monsoon. At a regional scale, diversified precipitation pattern have been investigated by various scientists/agencies. A declining trend in precipitation has been observed over Greece (Giakoumakis and Baloutsos, 1997), Canadian Prairies (Gan, 1998), Bologna in Italy (Ventura et al., 2002); whereas North Carolina (Boyles and Raman, 2003), Mainland Spain (Mosmann et al., 2004) experienced rising trends. No trend has been identified in precipitation over the Iberian Peninsula (Serrano et al., 1999) and Japan (Xu et al., 2003). Besides these, a comprehensive review of precipitation changes has also been carried out at global and regional levels, and decreasing precipitation trends have been identified in Russia, Kazakhstan, China and Thailand with a global increase in variance (Dore, 2005). Probable causes of change in rainfall may be due to: (a) global climate shift (Baines, 2006) or weakening global monsoon circulation (Chase et al., 2003; Duan and Yao, 2003; Pant, 2003); (b) reduction in forest cover (Meher-Homji, 1991; Hingane, 1996; Kothyari et al., 1997; Chen et al., 2001; Lawton et al., 2001; Nair et al., 2003; Ray et al., 2003; Avissar and Werth, 2005; Gupta et al., 2005; Ray et al., 2006; etc.) and change in land use, including introduction of irrigated agriculture (Pielke, 2001; Douglas et al., 2006; Ramankutty et al., 2006; Pielke et al., 2007; etc.); and (c) increasing aerosol due to anthropogenic activities (Ackerman et al., 2000; Ramanathan et al., 2001; Ramanathan et al., 2005; Sarkar and Kafatos, 2004; etc.).

In India, a diverse climate with large variations in rainfall is experienced. Rainfall variability of the Indian monsoons has been extensively studied by several investigators (Kripalani and Kulkarni, 1997, 2001; Kulkarni et al., 2007). An extensive review of studies on rainfall patterns in India excluding the Himalayan region, is well presented by Basistha et al. (2009). Based on these studies, a consensus regarding evidence of insignificant trend in annual rainfall series can be reported, though divergences do exist depicting an increasing (Parthasarathy and Dhar, 1976a) or decreasing trend (Singh et al., 2005). Regional analyses of data reveal increasing rainfall trends over the Indus, the Ganga, the Brahmaputra, the Krishna and the Cauvery basin (Singh et al., 2005), the west coast (Alvi and Koteswaram, 1985), north Andhra Pradesh and northwest India (Kumar et al., 1992), Rohtak and Kurukshetra of Haryana (Lal et al., 1992), Delhi (Rao et al., 2004), west Madhya Pradesh (Parthasarathy and Dhar, 1976b), coastal Orissa (Senapati and Misra, 1988) and peripheries of the Rajasthan desert (Pant and Hingane, 1988), but decreasing trends in the central Indian basins of Sabarmati, Mahi, Narmada, Tapi, Godavari and Mahanadi (Singh et al., 2005), east Madhya Pradesh and adjoining areas, northeast India (Zveryaev and Aleksandrova, 2004) and parts of Gujarat (Kumar et al., 1992), south Kerala (Singh et al., 1989; Singh and Soman, 1990) and central north Indian divisions (Subbaramayya and Naidu, 1992). Singh et al. (2007) have indicated increasing trends in annual rainfall and relative humidity in north Indian River basins, though the least variation has been observed in monsoon rainfall. Studies by Kothyari and Singh (1996) and Kothyari et al. (1997) report a decreasing rainfall trend over the Ganga basin, beginning around the second half of the 1960s. This is elaborated by Singh and Sontakke (2002) to be increasing over western Indo-Gangetic Plains and decreasing (statistically insignificant, though) over the central part. IINC (2004) depicts a decreasing summer monsoon rainfall trend over the state of Uttarakhand.

Exploring changes in rainfall pattern in the Indian Himalayas during the 20th century, Basistha et al. (2009) have found that the most probable year of change in annual as well as monsoon rainfall in the region is 1964. There is an increasing trend up to 1964 (corroborating with all India and nearby plains), followed by a decreasing trend in 1965–1980 (exclusive to this region). In the entire region, changes are most conspicuous over the Shivaliks and the southern part of the Lesser Himalayas. Chase et al. (2003) indicated a consistent reduction in the intensity of all tropical monsoon systems since 1950. A decrease in monsoon precipitation in the central Himalayas (Tibet, China) has been identified from early 1920s to the present (Duan and Yao, 2003). However, a substantial global climate shift has been reported in the late 1960s affecting South America–Africa (Baines, 2006). Apart from the rainfall pattern, other meteorological parameters show significant variations. Jhajharia et al. (2008) have analyzed the temporal characteristics of pan evaporation (Epan) under the humid conditions for northeast India and reported general decreasing trends in pre- and monsoon seasons. A declining trend in sunshine hours and wind speed, and increasing trend in relative humidity is also reported for most of the stations. Bandyopadhyay et al. (2009) reported similar results for India in case of reference evapotranspiration (ETo) for the period of 1971–2002, which is mainly caused by a significant increase in relative humidity and a consistent significant decrease in the wind speed throughout the country. However, a general increase in rainfall has not been found in recent years.

Considering the aforesaid studies, it can be stated that there is no consensus among the studies. Possibly, it may be due to the analysis of climatic variables at the regional scale, which induces loss of spatial information about the variables. Therefore, for water resources planning, it seems to be logical and compulsory to analyze the hydro-climatic variables at small scale that it can be rationalized at the river basin scale. Though the change in climate is governed by the complex system of atmosphere and oceanic processes and their interaction, but due to limitations on the availability of wide variety of atmospheric data, this study focuses on the analysis of indicative hydro-climatic parameters to demonstrate the climate change or changes in weather patterns.

In this chapter, the Yamuna River basin is investigated to demonstrate the climatic fluctuation/variability which exhibits high spatio-temporal variability in terms of climate (semi-arid to humid subtropical climates) and topography. Parameters that directly influence water resources and agricultural planning (viz., annual, monsoon and non-monsoon rainfall; number of annual, monsoon and non-monsoon rainydays; onset of effective monsoon; and aridity index) are considered.

## 4.1 Statistical Test for Climatological Data

To define the climatic fluctuations exhibited in the hydro-climatic time series is important. From a statistical point of view, the study of climatic fluctuations is a problem of time series analysis. Statistical evidence of persistence in such time series is equated with evidence of bona fide climatic fluctuations and is said to be dependent. In many instances, a time series is generally not statistically independent but is comprised of persistence, cycles, trends or other non-random components. A steady and regular movement in a time series through which the values are on average either increasing or decreasing is termed a trend. This type of behavior can be local, in which case the nature of the trend is subject to change over short intervals of time, or, on the other hand, it can be visualize a global trend that is long lasting. If a trend in a hydrologic time series appears, then it is, in effect, part of a low frequency oscillatory movement induced by climatic factors or through the change in land use and catchment characteristics. Looking into the importance of the deterministic components of climatic series, statistical tests for persistence, trend and periodicity are discussed, and analyzed for the hydro-climatic variables of the Yamuna River basin.

### *4.1.1 Persistence*

For climatic variability and changes, the definition of persistence given by WMO (1966) is commonly used. According to this definition, persistence is a “tendency for successive values of the series to “remember” their antecedent values, and to be influenced by them." The value of $r_1$ has been used to detect the possible persistence in the observed year-to-year variations of normalized anomaly series and to examine its nature and magnitude. The approach proposed by WMO (1966) and Matalas (1967) is widely used in many studies related to long-term climatic variations (Rodhe and Virji, 1976; Granger, 1977; Ogallo, 1979; Anyadike, 1993; Drosdowsky, 1993; Nicholson and Palao, 1993; Türkes, 1998; Türkes et al., 2002). To test the persistence in the climatological time series normalized anomaly of the time series is used, which is obtained as:

$$X_t = (x_t - \bar{x})/\sigma \tag{4.1}$$

where $X_t$ is the normalized anomaly of the series, $x_t$ is the observed time series, and $\bar{x}$ and $\sigma$ are the long-term mean and standard deviation of annual/seasonal time series. All serial correlation coefficients of the normalized climatic series are computed for lags $L = 0$ to $m$, where $m$ is the maximum lag (i.e. $m = n/3$); $n$ is the length of the series. The serial correlation coefficient is computed from eq. (4.2):

$$r_L = \frac{\sum_{t=1}^{n-L} \left(X_t - \bar{X}_t\right) \cdot \left(X_{t+L} - \bar{X}_{t+L}\right)}{\left[\sum_{t=1}^{n-L} \left(X_t - \bar{X}_t\right)^2 \cdot \sum_{t=1}^{n-L} \left(X_{t+L} - \bar{X}_{t+L}\right)^2\right]^{1/2}} \tag{4.2}$$

where $r_L$ is the lag-$L$ serial correlation coefficient of the series. To test the significance of serial correlation, eq. (4.3) is used (Yevjevich, 1971):

$$(r_L)_{t_g} = \frac{-1 \pm t_g\ (n - L - 1)^{1/2}}{n - L} \tag{4.3}$$

where, $(r_L)_{t_g}$ is the normally distributed value of $r_L$, $t_g$ is the normally distributed statistic at $g$ level of significance. The value of $t_g$ are 1.645, 1.965 and 2.326 at a significance level of 0.10, 0.05 and 0.01, respectively.

The hypothesis test is carried out at the 0.05 significance level as this level is sufficient from an engineering point of view. The "null" hypothesis of the randomness of climatic series against the serial correlation is rejected for the large value of $r_1$. If $r_1$ of the series is not statistically significant or is significant but has a negative sign, it is assumed that the series does not contain the persistence and the appropriate null continuum is termed as "white noise". On the other hand, the persistence in the time series is characterized by a positive serial correlation. In this case, a "Markov red noise" type "null" continuum is ensured using $r_2$ and $r_3$ (WMO, 1966). In addition to this significant negative $r_1$ is very likely to be indicative of high-frequency oscillations, whereas significant positive $r_1$ is likely to be indicative of low-frequency fluctuations and persistence in climatic series. Therefore, in the study serial correlation coefficients up to lag-3 are assessed.

## *4.1.2 Trend*

There are several approaches for detecting the trend in the time series. These approaches can be either parametric or non-parametric. Parametric methods assume the data should normally distributed and free from outliers. On the other hand, non-parametric methods are free from such assumptions. The most popularly used non-parametric tests for detecting a trend in the time series is the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1955). It is widely used for different climatic variables (Hirsch et al., 1982; Hirsch and Slack, 1984; Lettenmaier et al., 1994; Gan, 1998; Lins and Slack, 1999; Douglas et al., 2000; Burn and Elnur, 2002; Yue et al., 2002; Yue and Pilon, 2004; Burn et al., 2004; Zhang et al., 2005; Aziz and Burn, 2006; Chen et al., 2007; etc.).

For the original Mann-Kendall test, the time series must be serially independent in nature. However, in many real situations, the observed data are serially dependent (i.e., autocorrelated). The autocorrelation in the observed data results in misinterpretation of trend test results. Cox and Stuart (1955) stated that "positive serial correlation among the observations would increase the chance of significant error, even in the absence of a trend". A closely related problem that has been studied is the case where seasonality exists in the data (Hirsch et al., 1982). By dividing the observations into separate classes according to the season and then performing the Mann-Kendall trend test on the sum of the statistics from each season, the effect of seasonality can be eliminated. This modification is called the seasonal Mann-Kendall test (Hirsch et al., 1982; Hirsch and Slack, 1984). Although the seasonal test eliminates the effect of seasonal dependence, it does not account for the correlation in the series within the season (Hirsch and Slack, 1984). The same problem exists when yearly time series is considered for analysis, as it significantly autocorrelated. Therefore, in this paper, the original Mann-Kendall test is described along with its modified versions that accounts for the serially dependent in the data.

#### 4.1.2.1 Mann-Kendall Test

The Mann-Kendal (MK) test (Mann, 1945; Kendall, 1955) searches for a trend in a time series without specifying whether the trend is linear or nonlinear (Khaliq et al., 2009). The Mann-Kendall test for detecting monotonic trends in hydrologic time series is described by Yue et al. (2002). It is based on the test statistics $S$, which is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{4.4}$$

where $x_j$ are the sequential data values, $n$ is the length of the data set, and

$$\text{sgn}\ (t) = \begin{cases} 1, & \text{for}\, t > 0 \\ 0, & \text{for}\, t = 0 \\ -1, & \text{for}\, t < 0 \end{cases} \tag{4.5}$$

The value of $S$ indicates the direction of trend. A negative (positive) value indicates a falling (rising) trend. Mann and Kendall have documented that when $n \geq 8$, the test statistics $S$ is approximately normally distributed with mean and variance as follows:

$$E\,(S) = 0 \tag{4.6}$$

$$\text{Var}\ (S) = \frac{1}{18}\left[n\ (n-1)\ (2n+5) - \sum_{i=1}^{m} t_i\,(t_i - 1)\,(2t_i + 5)\right] \tag{4.7}$$

where $m$ is the number of tied groups and $t_i$ is the size of the $i$th tie group. The standardized test statistics $Z$ is computed as follows.

$$Z_{\text{MK}} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}\,(S)}}, & \text{for}\, S > 0 \\ 0 \quad , & \text{for}\, S = 0 \\ \frac{S+1}{\sqrt{\text{Var}\,(S)}}, & \text{for}\, S < 0 \end{cases} \tag{4.8}$$

The standardized Mann-Kendall statistics $Z$ follows the standard normal distribution with zero mean and unit variance. If $|Z| \geq Z_{1-(\alpha/2)}$, the null hypothesis about no trend is rejected at the significance level $\alpha$ (10% in this study).

#### 4.1.2.2 Modified Mann-Kendall Test

For Modified Mann-Kendall's test, statistic $S$ tends to normality for large $n$, with mean and variance given by:

$$E\,(S) = 0 \tag{4.9}$$

$$\text{Var}\ (S) = n\ (n-1)\ (2n+5)\,/18 \tag{4.10}$$

Statistic $S$ is given by eq. (4.8):

$$S = a_{ij} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\ \left(x_j - x_i\right) \tag{4.11}$$

With the same mean and variance as in eqs. (4.9) and (4.10), a modified version of the Mann-Kendall test which is robust in the presence of autocorrelation is proposed based on the modified variance of $S$ given by eq. (4.12):

$$V^*\,(S) = \text{Var}\ (S) \cdot \frac{n}{n_s^*} = \frac{n\,(n-1)\,(2n+5)}{18} \cdot \frac{n}{n_s^*} \tag{4.12}$$

where $n/n_s^*$ represents a correlation due to the autocorrelation in the data. The $n/n_s^*$ term is evaluated using eq. (4.13):

$$\frac{n}{n_s^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{i=1}^{n-1} (n-i)(n-i-1)(n-i-2)\,\rho_s(i) \tag{4.13}$$

In eq. (4.13), $n$ is the actual number of the observations, and $\rho_s(i)$ is the autocorrelation function of the ranks of observations. The advantage of using eqs. (4.12) and (4.13) for the evaluation of variance of $S$ is that there is no need of either normalized data or their autocorrelation function. The autocorrelation of ranks of observations $\rho_s(i)$ is related with the parent autocorrelation function and is given as follows (Kendall, 1955):

$$\rho(i) = 2\sin\left(\frac{\pi}{6}\rho_s(i)\right) \tag{4.14}$$

Inverse of eq. (4.14) can therefore be used to evaluate the autocorrelation of rank $\rho_s(i)$ that appears in eq. (4.13) and is given by eq. (4.15):

$$\rho_s(i) = \frac{6}{\pi}\sin^{-1}\left(\frac{\rho(i)}{2}\right) \tag{4.15}$$

The significance of the trends is tested by comparing the standardized test statistics $Z$.

$$Z = \frac{S}{[V^*(S)]^{0.5}} \tag{4.16}$$

A significant level of $\alpha = 0.1$ for the autocorrelation of ranks $\rho_s(i)$ is used, which produces the best overall empirical significance level. The serial correlation of ranks of the series and their significance test can be computed from eqs. (4.2) and (4.3).

#### 4.1.2.3 Mann-Kendall Test with Pre-whitening

An alternate approach to perform trend analysis of a time series in the presence of serial correlation using the Mann-Kendall test is to first remove the serial correlation from data and then apply the test. Several approaches have been suggested for removing the serial correlation from a data set prior to applying the test. The pre-whitening approach is most common which involves computation of serial correlation and removing the correlation if the calculated serial correlation is significant at the 0.05 significance level (Burn and Elnur, 2002). The pre-whitening is accomplished as follows:

$$X_t' = x_{t+1} - r_1 \times x_t \tag{4.17}$$

where $x_t$ = original time series with autocorrelation for time interval $t$; $X'_t$ = the pre-whitened time series; and $r_1$ = the lag-1 autocorrelation coefficient. This pre-whitened series is then subjected to the Mann-Kendall test [i.e., eqs. (4.4) to (4.8)] for detecting the trend.

### *4.1.3 Periodicity*

Periodicity is one of the deterministic components in the time-series. Most of the climatic, atmospheric and hydrological time-series would consist of a combination of stochastic and deterministic components. The power spectrum is a method of analysis that was developed to handle the problem of periodicity in variations of natural events observed in time, such as in climatological and hydrological time series. Power spectrum analysis, also called generalized harmonic analysis, is derived from the principles first developed by Wiener (1930, 1949). It is based on the premise that the time series are not necessarily composed of a finite number of oscillations each with a discrete wavelength, but rather they consist of virtually an infinite number of small oscillations spanning a continuous distribution of wavelengths. The spectrum therefore, gives the distribution of variations in a time series over a continuous domain of all possible wavelengths.

Procedures for computing the power spectra may vary. Here, in this study an approach described in WMO (1966), developed by Tukey (1950) and Blackman and Tukey (1958) is employed. A detailed description of this approach can also be found in various textbooks (Blackman and Tukey, 1958; Jenkins and Watts, 1968; Julian, 1967). It can be summarized through the following steps:

(i) First, all serial correlation coefficients of normalized climatic series (eq. (4.1)) are computed for lags from $L = 0$ to $m$, where $m$ is the maximum lag ($m = n/3$). The serial correlation coefficient can be computed using eq. (4.2).

(ii) Using the values of $r_L$, the "raw" spectral estimates, $\hat{s}_k$, are computed using the following set of equations:

$$\hat{s}_0 = \frac{1}{2m}(r_0 + r_m) + \frac{1}{m}\sum_{L=1}^{m-1} r_L \tag{4.18}$$

$$\hat{s}_k = \frac{r_0}{m} + \frac{2}{m}\sum_{L=1}^{m-1} r_L \,\mathrm{Cos}\left(\frac{\pi kL}{m}\right) + \frac{1}{m} r_m (-1)^k \,;\, \text{for}\ k = 1, 2, \ldots, m-1 \tag{4.19}$$

$$\hat{s}_m = \frac{1}{2m}\left[r_0 + (-1)^m\ r_m\right] + \frac{1}{m}\sum_{L=1}^{m-1} (-1)^L\ r_L \tag{4.20}$$

Smallest is the value of $k$ longest will be the wavelength of the spectrum, i.e., the shortest wavelength is achieved at $k = m$.

(iii) The raw spectrum $\hat{s}_k$ is then smoothened with a 3-term weighted average. For smoothing, procedure suggested by Hanning is used (WMO, 1966):

$$s_0 = \left(\hat{s}_0 + \hat{s}_1\right)/2 \tag{4.21}$$

$$s_k = \left(\hat{s}_{k-1} + 2\,\hat{s}_k + \hat{s}_{k+1}\right)/4; \quad \text{for}\, k = 1,\, 2,\, \ldots\ldots,\, m - 1 \tag{4.22}$$

$$s_m = \left(\hat{s}_{m-1} + \hat{s}_m\right)/4 \tag{4.23}$$

The averaging procedure is performed to derive a constant estimate of the final spectrum in terms of $m + 1$ discrete estimates (WMO, 1966).

#### 4.1.3.1 Statistical Significance Test

The procedure for evaluating the results of power spectrum analysis mentioned in WMO (1966) is described below:

(i) A "null" hypothesis continuum is fitted to the computed spectrum. To start with, the significance of the lag-1 serial correlation coefficient $r_1$ of the climatic series is tested at the 90% confidence level. The "null" hypothesis of the randomness of climatic series against the serial correlation is rejected for the large value of $(r_1)_t$. If $r_1$ is not significantly different from zero, then series is regarded to be free from persistence. In this case, the appropriate null continuum is "white noise". In other words, a horizontal straight line, the value of which is everywhere equal to the average of the values of all the $m + 1$ "raw" spectral estimates (i.e., $\bar{s}$) in the computed spectrum (i.e., $S_k = \bar{s}$), is taken as the most suitable theoretical approach.

(ii) If the computed $r_1$ is positive and statistically significant, serial correlation coefficients for lag-2 and lag-3 are checked to see whether they approximate the exponential relations $r_2 \cong r_1^2$ and $r_3 \cong r_1^3$ (WMO, 1966). If these relations are ensured with the computed serial coefficients, the approximate "null" continuum is assumed as the simple "Markov red noise", whose shape depends on unknown value of the lag-1 serial correlation coefficient for a population $\rho$. Then the "null" continuum can be created by following an approximate procedure. By assuming that the sample $r_1$ is an unbiased estimation of $\rho$, various choices of the Harmonic number of $k$ between $k = 0$ to $m$ are assessed:

$$S_k = \bar{s}\left(\frac{1 - r_1^2}{1 + r_1^2 - 2\,r_1\,\mathrm{Cos}\left(\frac{\pi k}{m}\right)}\right) \tag{4.24}$$

where $\bar{s}$ is the average of all $m + 1$ "raw" spectral estimates $\hat{s}_k$ in the computed spectrum. The resulting values of $S_k$ can be superposed on the sample spectrum, and a smoothed curve passes through these values to reach the required null continuum.

(iii) If $r_1$ is statistically significant but a few serial correlation coefficients for higher lags do not show the required exponential relations (i.e., $r_2 \cong r_1^2$ and $r_3 \cong r_1^3$) with $r_1$, then doubt arises as to whether the simple Markov-type persistence is the dominant form of non-randomness in the series of climatic observations. Nevertheless, WMO (1966) suggested that this procedure could be continued with just as before to compute the red noise continuum for $r_1$.

(iv) At this stage of the power spectrum analysis a first choice of the null continuum is made, and this selected continuum is superposed on the studied spectrum. In this case, it would be possible to make an assessment of the spectrum for its consistency with the chosen continuum. Then, the value of each spectral estimate $s_k$ is compared with the local value of the null continuum.

The statistic associated with the each spectral estimate is the ratio of the magnitude of the spectral estimate to the local magnitude of the continuum (red noise continuum). Tukey (1950) found that the quantity of this ratio is distributed as Chi-square divided by the degree of freedom. The degree of freedom, $\nu$, of each estimate of a computed spectrum is given as follows:

$$\nu = (2n - m/2)/m \tag{4.25}$$

The ratio of any sample spectral estimate $s_k$ to its local value of the red noise continuum is then compared with the critical percentage-point levels of $\chi^2/\nu$ distribution for the proper $\nu$ value. This comparison produces the required statistical significance level. The $\chi^2$ value can be obtained from standard statistical books.

(v) In a sample spectrum, critical percentage-point levels of the $\chi^2/\nu$ distribution, e.g., the 0.95 confidence level, is the same for all spectral estimates $s_k$. The confidence limits are finally derived by multiplying the "null" continuum (i.e., $S_k$) with the $\chi^2/\nu$.

(vi) Finally, the cycle associated in the time series is computed as:

$$P = 2m/L \tag{4.26}$$

## 4.2 Application

### *4.2.1 Data Processing*

The climatic series subjected to the analysis are: (i) annual rainfall; (ii) monsoon and non-monsoon rainfall; (iii) annual rainydays; (iv) monsoon and non-monsoon rainydays; (v) onset of effective monsoon (OEM); and (vi) annual aridity index (AI). For rainfall data, one degree grid data of daily rainfall for the period 1951–2002 maintained by the India Meteorological Department (IMD) is used. Sixty five rain-grids points that fall under the Yamuna basin with 1° buffer are used in the analysis. The monsoon rainfall is derived from daily data for the period July to October and the rest of the period is considered as non-monsoon. The estimation procedure of OEM, rainydays, and the aridity index are presented in Chapter 3.

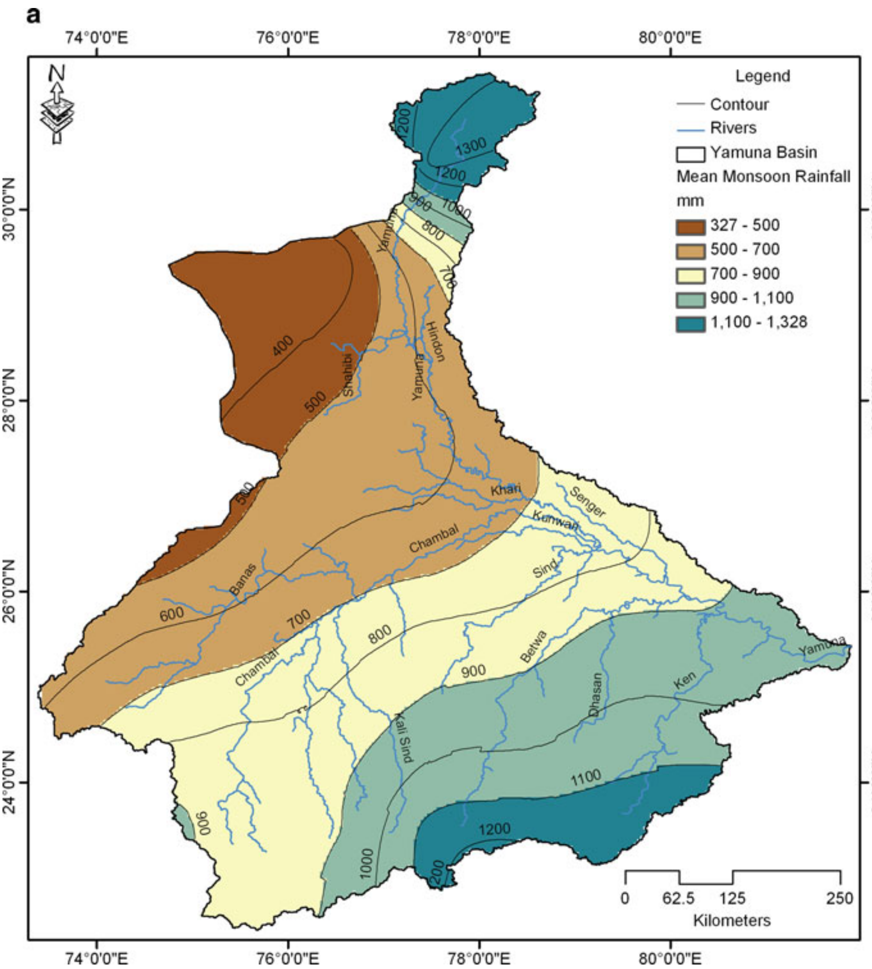


**Fig. 4.1** (**a**) Spatial variability of monsoon rainfall in the Yamuna basin

The spatial distribution pattern of these hydro-climatic parameters is depicted in Chapter 3 except for monsoon mean and non monsoon mean rainfall. The monsoon and non-monsoon rainfall pattern is shown in Figs. 4.1a and 4.1b.

## 4.3 Results and Discussions

### *4.3.1 Persistence*

Persistence is evident in a long time series of climatic observations characterized by a positive serial correlation. Significant negative $r_1$ is likely to be indicative of high-frequency oscillations, whereas significant positive $r_1$ is likely to be indicative of

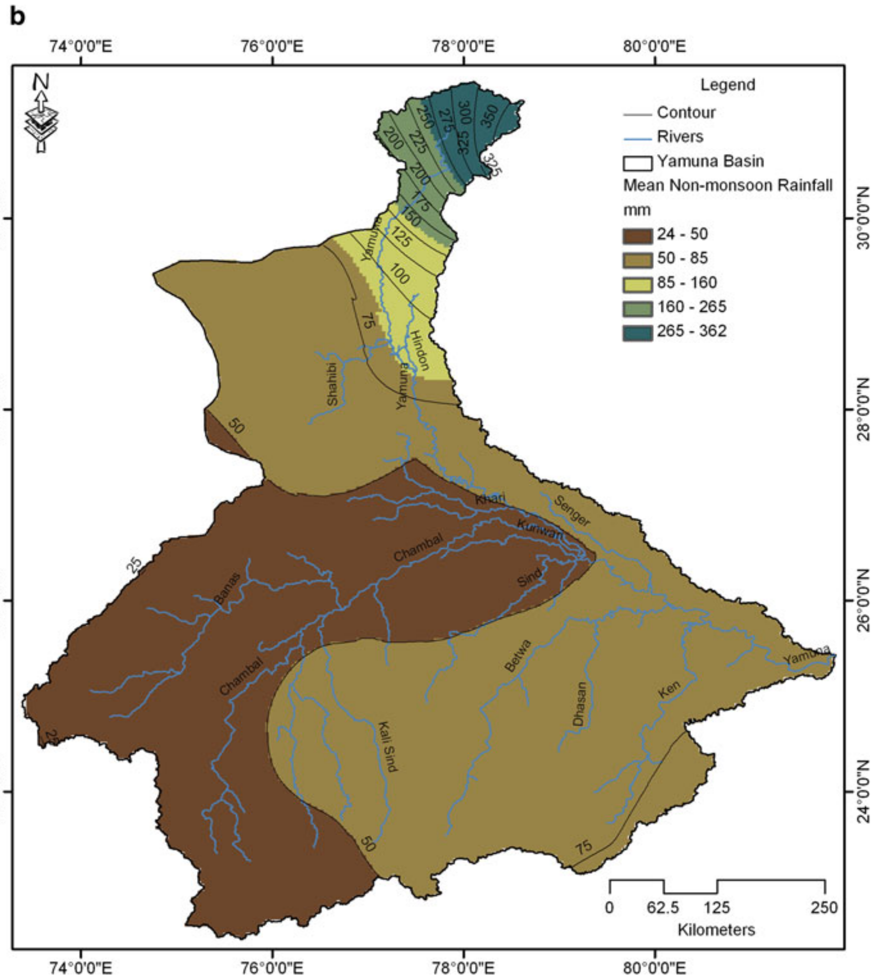


**Fig. 4.1** (**b**) Spatial variability of non-monsoon rainfall in the Yamuna basin

low-frequency fluctuations and persistence in climatic series. This feature is further elaborated in the following section (i.e. "periodicity"). In the study, serial correlation for all the lags (i.e. $L = 0$ to $m$) is computed for all the grid points.

However, serial correlation coefficients up to lag 3 is also assessed. Serial correlation coefficient up to lag-3 is plotted for all the climatic variables except non-monsoon, although all the variables are analyzed. These plots are shown in Figs. 4.2, 4.3, and 4.4, which give the spatial distributions pattern of lag-1 to lag-3 serial correlation coefficients for the considered variables over the Yamuna River basin. A Kriging method is used as an interpolation technique to produce the spatial distribution pattern of the variables.

It is evident from Figs. 4.2, 4.3, and 4.4 that most of the grid point data show statistically insignificant serial correlation coefficient (SC) for all the hydro-climatic

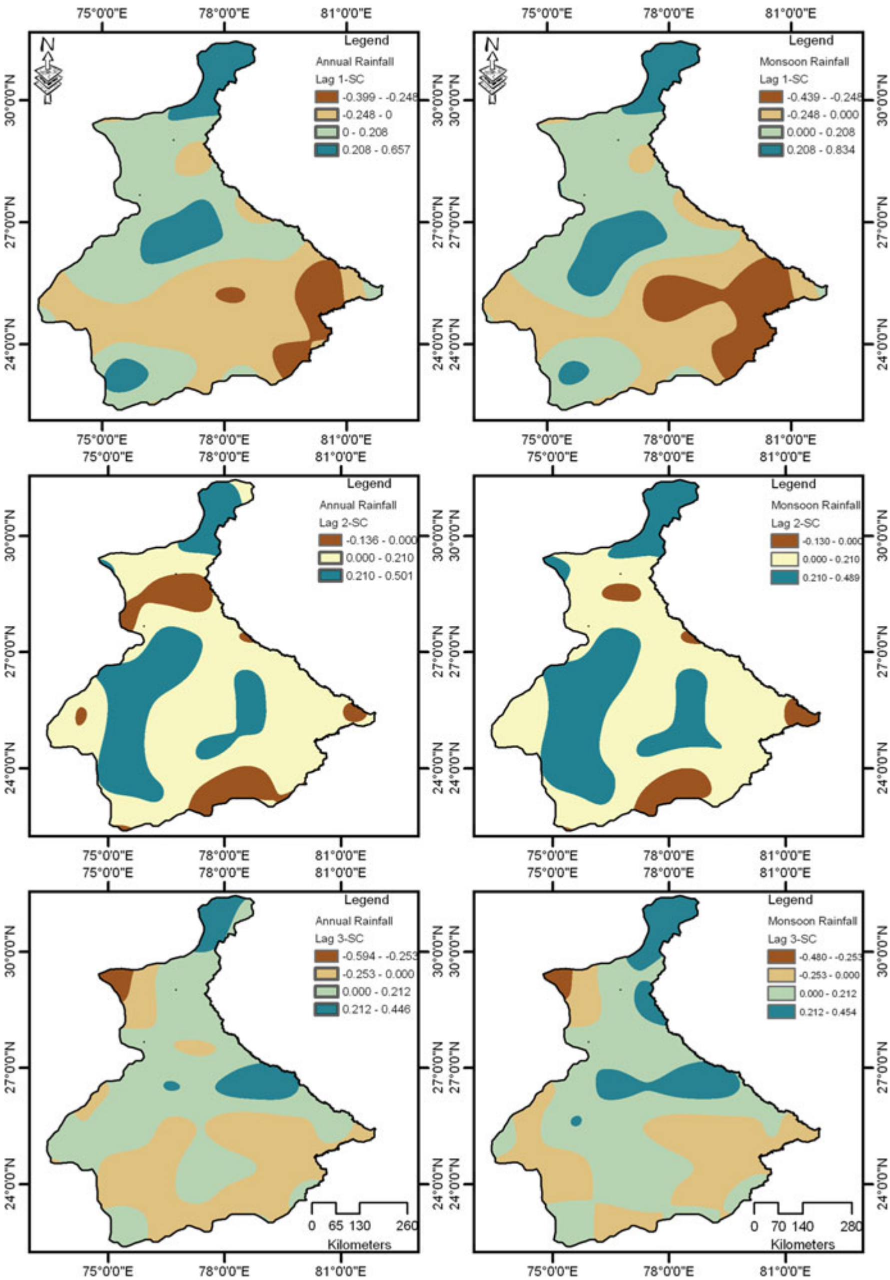


**Fig. 4.2** Spatial distribution pattern of serial correlation of annual mean and monsoon mean rainfall up to lag 3

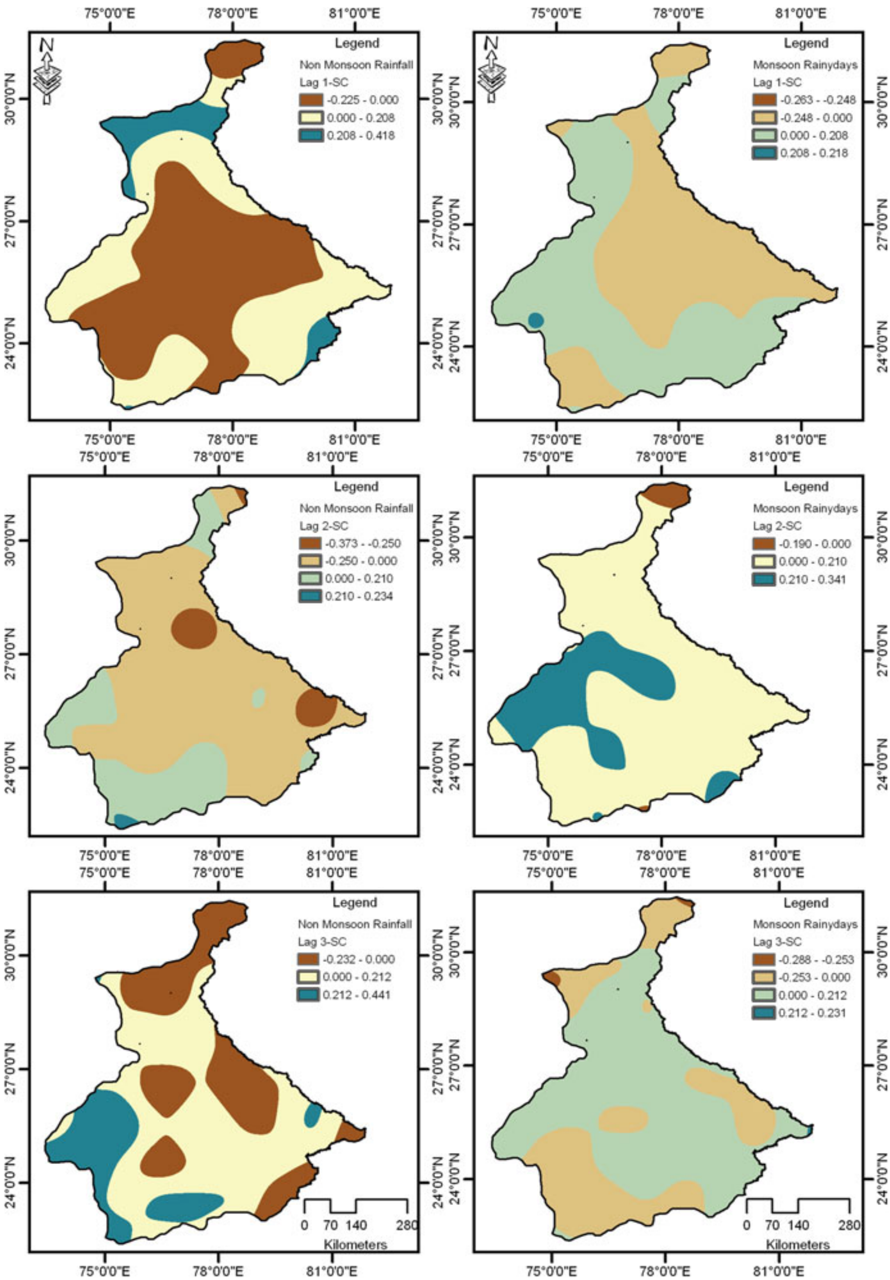


**Fig. 4.3** Spatial distribution pattern of serial correlation of non-monsoon rainfall and monsoon rainydays up to lag 3

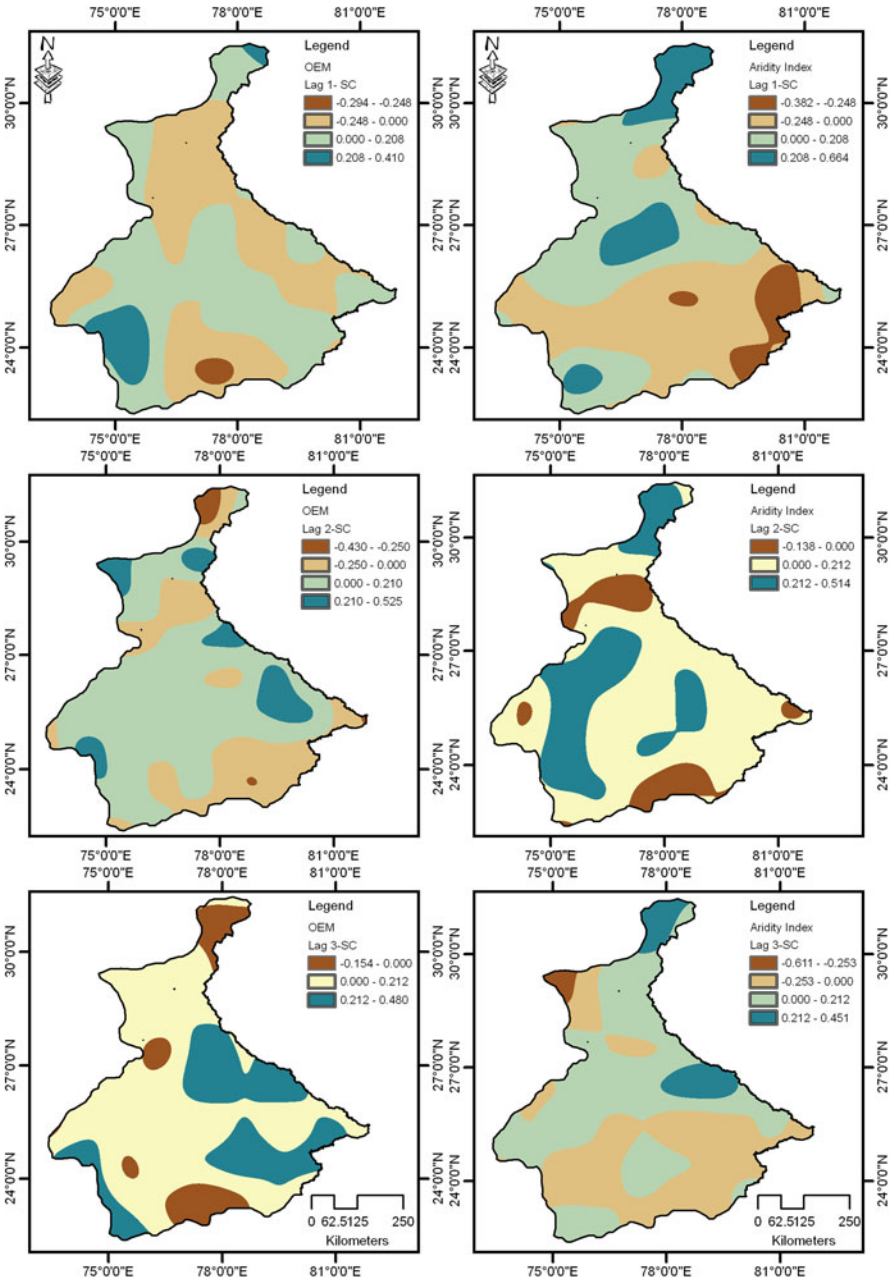


**Fig. 4.4** Spatial distribution pattern of serial correlation of OEM and aridity index up to lag 3

variables (i.e. annual, monsoon and non monsoon rainfall; annual, monsoon and non monsoon rainydays; OEM and aridity index). However, a few grid data of annual and monsoon rainfall near the central and northern parts of the basin show the existence of persistence characterized by significant lag-1 SC; whereas, a few grid data points in the south-east part of the basin shows high frequency variability as characterized by significant negative lag 1-SC (Fig. 2.2). The spatial distribution of lag 1-SC of non monsoon (Fig. 2.3) indicates the presence of persistence in the few grid data in the northern part of the basin. Lag-1 SC of annual rainfall and aridity index show similar distribution pattern, which might be due to the more dependence of aridity index on annual rainfall (Figs. 4.2 and 4.4).

Based on Figs. 4.2, 4.3, and 4.4, a little positive spatial coherence characterized by lag-1 SC is identified for annual and monsoon rainfall, annual rainydays and aridity index. Looking into the Figs. 4.2, 4.3, and 4.4 and by comparing the spatial pattern of lag-2 SC with lag-1 SC, it was indicated that coherent area of significant positive lag-2 SC is greater than that of lag-1 SC. The lag-2 SC coefficients are mostly positive but insignificant for all the variables except for the non-monsoon rainfall, non-monsoon rainydays and OEM. On the other hand, by analyzing the lag-3 SC of the hydro-climatic variables, it is evident that the percentage coherent area is significantly reduced for all the variables. However, it is an increase in the case of non-monsoon rainfall, non-monsoon rainydays and OEM. Apart from this, a detailed table of the serial correlation coefficients up to lag-3 is also prepared for all the variables. But serial correlation coefficients up to lag-3 are presented for monsoon rainfall, rainydays and OEM only (Tables 4.1, 4.2, and 4.3), though the summarized table (Table 4.4) is prepared to visualize the overall temporal characteristics of the variables.

### *4.3.2 Trend Analysis*

In the trend analysis, time series of the entire variable from 1951 to 2002 is subjected to three non-parametric statistical tests, viz. Mann-Kendall test, Modified Mann-Kendall test and Mann-Kendall test with pre-whitening of series. Two later tests are basically designed for the series having a significant lag-1 SC. Comparative results were obtained from all the three tests for all the considered variables. However, the sample results of trend analysis for monsoon rainfall and OEM are presented (Tables 4.5 and 4.6). These Tables (Tables 4.5 and 4.6) also include the value of lag-1 SC along with their lower and upper limits at the 95% confidence level. Based on Tables 4.5 and 4.6, it is apparent that the times series with significant negative lag-1 SC do not have the significant trend.

**Table 4.1** Results of serial correlation (lag 1 to 3) and power spectrum analysis for monsoon rainfall ($r_1$ = lag-1 SC, $r_2$ = lag-2 SC, $r_3$ = lag-3 SC, $L$ = lag corresponding to significant spectral estimates, Cycles = periodicity (2 *m*/*L*), Cont. = null continuum, WN = white noise, RN = Markov red noise)

| | | | | | Cycles | | |
|---|---|---|---|---|---|---|---|
| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | 90% | 95% | Cont. |
| 1 | 0.00 | −0.18 | −0.18 | 7 | 4.9 | | WN |
| | | | | 8 | 4.3 | | |
| 2 | 0.05 | −0.01 | 0.04 | 2 | 17.0 | | WN |
| 3 | 0.05 | 0.02 | 0.08 | 2 | 17.0 | | WN |
| 4 | −0.09 | 0.11 | −0.05 | | | | WN |
| 5 | −0.12 | −0.07 | −0.05 | | | | WN |
| 6 | 0.40 | 0.37 | 0.42 | 12 | 2.8 | | RN |
| 7 | −0.04 | 0.03 | −0.12 | | | | |
| 8 | −0.04 | −0.02 | 0.18 | 11 | 3.1 | | RN |
| | | | | 12 | | 2.8 | WN |
| 9 | −0.05 | 0.13 | 0.02 | 2 | | 17.0 | |
| 10 | 0.22 | 0.24 | 0.01 | 1 | 34.0 | | |
| | | | | 2 | | 17.0 | WN |
| | | | | 3 | 11.3 | | |
| 11 | 0.15 | 0.23 | 0.01 | 2 | | 17.0 | WN |
| | | | | 3 | | 11.3 | |
| 12 | −0.03 | −0.03 | 0.04 | | | | WN |
| 13 | −0.02 | −0.11 | −0.02 | | | | WN |
| 14 | −0.34 | 0.07 | 0.01 | 14 | | 2.4 | WN |
| | | | | 15 | | 2.3 | |
| 15 | −0.18 | −0.02 | 0.12 | | | | WN |
| 16 | −0.14 | 0.10 | −0.01 | | | | |
| 17 | 0.07 | 0.05 | −0.01 | 2 | 17.0 | | WN |
| 18 | −0.20 | 0.15 | −0.03 | 14 | 2.4 | | WN |
| | | | | 15 | | 2.3 | |
| 19 | −0.08 | 0.39 | −0.11 | 2 | | 17.0 | WN |
| | | | | 3 | | 11.3 | |
| | | | | 15 | 2.3 | | |
| | | | | 16 | | 2.1 | |
| 20 | −0.04 | 0.17 | 0.13 | 2 | | 17.0 | WN |
| | | | | 3 | | 11.3 | |
| 21 | −0.22 | 0.23 | 0.13 | 2 | 17.0 | | WN |
| | | | | 3 | 11.3 | | |
| | | | | 13 | 2.6 | | |
| | | | | 14 | | 2.4 | |
| 22 | −0.21 | 0.20 | 0.01 | 12 | 2.8 | | WN |
| | | | | 13 | 2.6 | | |
| | | | | 14 | 2.4 | | |
| 23 | −0.22 | 0.20 | −0.09 | 14 | 2.4 | | WN |
| | | | | 15 | | 2.3 | |
| 24 | −0.37 | 0.07 | −0.03 | 13 | 2.6 | | WN |
| | | | | 14 | | 2.4 | |
| | | | | 15 | | 2.3 | |
| 25 | −0.21 | 0.09 | −0.13 | 15 | | 2.3 | WN |

**Table 4.1** (continued)

| | | | | | Cycles | | |
|---|---|---|---|---|---|---|---|
| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | 90% | 95% | Cont. |
| | | | | 16 | 2.1 | | |
| 26 | −0.15 | 0.20 | 0.13 | 2 | 17.0 | | WN |
| | | | | 12 | | 2.8 | |
| 27 | 0.04 | 0.08 | −0.04 | 2 | 17.0 | | WN |
| | | | | 5 | 6.8 | | |
| 28 | 0.20 | 0.43 | 0.21 | 1 | | 34.0 | WN |
| | | | | 2 | | 17.0 | |
| 29 | 0.23 | 0.20 | 0.06 | 2 | | 17.0 | WN |
| | | | | 3 | | 11.3 | |
| 30 | −0.26 | 0.12 | −0.01 | 14 | | 2.4 | WN |
| | | | | 15 | | 2.3 | |
| 31 | −0.27 | 0.25 | −0.10 | 13 | 2.6 | | WN |
| | | | | 14 | | 2.4 | |
| | | | | 15 | | 2.3 | |
| | | | | 16 | 2.1 | | |
| 32 | −0.25 | 0.10 | −0.08 | 14 | | 2.4 | WN |
| | | | | 15 | | 2.3 | |
| 33 | −0.41 | 0.07 | 0.00 | 13 | | 2.6 | WN |
| | | | | 14 | | 2.4 | |
| | | | | 15 | | 2.3 | |
| 34 | −0.02 | −0.06 | −0.06 | 7 | 4.9 | | WN |
| 35 | −0.12 | 0.11 | −0.04 | 15 | | 2.3 | WN |
| 36 | 0.00 | 0.02 | 0.04 | | | | WN |
| 37 | 0.20 | 0.18 | −0.07 | 1 | | 34.0 | WN |
| | | | | 2 | | 17.0 | |
| 38 | 0.12 | 0.28 | 0.09 | 1 | 34.0 | | WN |
| | | | | 2 | 17.0 | | |
| 39 | 0.35 | 0.30 | 0.27 | 2 | 17.0 | | RN |
| | | | | 12 | 2.8 | | |
| 40 | 0.26 | 0.14 | 0.22 | 12 | | 2.8 | RN |
| | | | | 13 | | 2.6 | |
| 41 | 0.11 | 0.23 | 0.31 | 1 | 34.0 | | WN |
| 42 | 0.02 | 0.12 | 0.27 | | | | WN |
| 43 | −0.14 | 0.06 | 0.06 | 13 | | 2.6 | |
| | | | | 14 | | 2.4 | |
| 44 | −0.13 | 0.15 | 0.04 | 13 | 2.6 | | WN |
| | | | | 14 | | 2.4 | |
| | | | | 15 | 2.3 | | |
| 45 | 0.40 | 0.30 | 0.13 | 13 | 2.6 | | RN |
| 46 | 0.18 | 0.04 | 0.19 | 2 | | 17.0 | WN |
| 47 | 0.11 | 0.24 | 0.10 | 2 | 17.0 | | WN |
| | | | | 3 | 11.3 | | |
| 48 | 0.14 | 0.15 | 0.06 | 4 | 8.5 | | WN |
| | | | | 5 | 6.8 | | |
| 49 | −0.10 | −0.01 | 0.13 | 12 | 2.8 | | WN |
| 50 | −0.07 | 0.06 | 0.09 | 13 | | 2.6 | WN |
| 51 | 0.06 | 0.04 | −0.16 | 4 | 8.5 | | WN |

**Table 4.1** (continued)

| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | Cycles 90% | Cycles 95% | Cont. |
|---|---|---|---|---|---|---|---|
| | | | | 5 | | 6.8 | |
| 52 | 0.15 | 0.09 | −0.17 | 4 | 8.5 | | WN |
| 53 | 0.07 | −0.02 | 0.07 | 3 | 11.3 | | WN |
| | | | | 4 | 8.5 | | |
| 54 | −0.03 | 0.04 | 0.26 | 13 | | 2.6 | WN |
| 55 | 0.21 | 0.34 | 0.23 | 1 | | 34.0 | WN |
| 56 | 0.17 | 0.22 | 0.11 | 2 | | 17.0 | WN |
| | | | | 3 | | 11.3 | |
| 57 | 0.13 | 0.22 | 0.20 | 13 | 2.6 | | WN |
| 58 | 0.13 | 0.29 | −0.01 | 14 | 2.4 | | WN |
| 59 | −0.12 | −0.11 | 0.06 | 13 | 2.6 | | WN |
| | | | | 14 | 2.4 | | |
| 60 | 0.59 | 0.48 | 0.41 | 14 | 2.4 | | WN |
| 61 | 0.44 | 0.28 | 0.13 | 14 | 2.4 | | RN |
| 62 | 0.28 | 0.14 | 0.14 | 14 | 3.4 | | RN |
| 63 | −0.25 | −0.01 | 0.06 | 14 | | 2.4 | WN |
| | | | | 15 | 2.3 | | |
| 64 | 0.40 | 0.20 | 0.01 | 15 | | 2.3 | RN |
| 65 | 0.48 | 0.41 | 0.24 | 15 | 2.3 | | RN |

**Table 4.2** Results of serial correlation (lag 1 to 3) and power spectrum analysis for monsoon rainydays ($r_1$ = lag-1 SC, $r_2$ = lag-2 SC, $r_3$ = lag-3 SC, $L$ = lag corresponding to significant spectral estimates, Cycles = periodicity (2 *m*/*L*), Cont. = null continuum, WN = white noise, RN = Markov red noise)

| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | Conf. Level 90 | Conf. Level 95 | Cont. |
|---|---|---|---|---|---|---|---|
| 1 | 0.10 | 0.11 | 0.00 | 2 | 17.0 | 0.0 | WN |
| 2 | –0.03 | 0.14 | 0.14 | | | | WN |
| 3 | 0.01 | 0.10 | 0.00 | | | | WN |
| 4 | −0.04 | 0.20 | −0.04 | | | | WN |
| 5 | 0.07 | −0.12 | −0.18 | 6 | 5.7 | 0.0 | WN |
| | | | | 7 | 4.9 | 0.0 | |
| 6 | 0.08 | 0.15 | 0.06 | 2 | 17.0 | 0.0 | WN |
| 7 | 0.32 | 0.12 | −0.09 | | | | RN |
| 8 | 0.10 | 0.26 | 0.19 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 0.0 | |
| | | | | 13 | 2.6 | 0.0 | |
| 9 | −0.04 | 0.15 | −0.01 | 12 | 2.8 | 0.0 | WN |
| 10 | −0.07 | 0.16 | −0.13 | | | | WN |
| 11 | 0.06 | 0.15 | −0.09 | 2 | 17.0 | 0.0 | WN |
| 12 | 0.04 | 0.18 | 0.01 | 2 | 17.0 | 17.0 | WN |
| 13 | 0.02 | 0.03 | −0.08 | 5 | 6.8 | 0.0 | WN |
| 14 | 0.09 | 0.27 | 0.10 | 1 | 34.0 | 0.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 15 | 0.01 | 0.15 | 0.14 | 2 | 17.0 | 17.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |

**Table 4.2** (continued)

| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | Conf. Level | | Cont. |
|---|---|---|---|---|---|---|---|
| | | | | | 90 | 95 | |
| 16 | −0.01 | 0.01 | 0.08 | 12 | 2.8 | 2.8 | WN |
| 17 | 0.04 | 0.09 | 0.02 | 2 | 17.0 | 0.0 | WN |
| 18 | 0.21 | 0.22 | −0.03 | 1 | 34.0 | 0.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| | | | | 3 | 11.3 | 0.0 | |
| 19 | 0.07 | 0.07 | −0.13 | 2 | 17.0 | 0.0 | WN |
| 20 | 0.03 | 0.28 | 0.08 | 2 | 17.0 | 17.0 | WN |
| 21 | −0.05 | 0.11 | 0.12 | 2 | 17.0 | 0.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |
| 22 | 0.13 | 0.14 | 0.12 | 2 | 17.0 | 17.0 | WN |
| 23 | 0.01 | 0.04 | 0.06 | | | | WN |
| 24 | 0.14 | 0.12 | 0.07 | 5 | 6.8 | 0.0 | WN |
| 25 | 0.01 | 0.11 | 0.18 | 14 | 2.4 | 0.0 | WN |
| 26 | 0.09 | 0.20 | 0.09 | 1 | 34.0 | 34.0 | WN |
| 27 | 0.16 | 0.28 | 0.06 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 28 | 0.07 | 0.32 | 0.02 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 29 | −0.05 | 0.11 | −0.01 | 14 | 2.4 | 0.0 | WN |
| 30 | −0.06 | 0.17 | 0.00 | 14 | 2.4 | 2.4 | WN |
| 31 | −0.08 | 0.20 | 0.10 | 14 | 2.4 | 0.0 | WN |
| 32 | −0.03 | 0.11 | 0.05 | | | | WN |
| 33 | −0.05 | 0.05 | −0.06 | | | | WN |
| 34 | −0.01 | 0.12 | 0.15 | 14 | 2.4 | 0.0 | WN |
| 35 | −0.24 | 0.10 | 0.06 | 14 | 2.4 | 2.4 | WN |
| | | | | 15 | 2.3 | 2.3 | |
| 36 | 0.11 | 0.12 | 0.00 | 2 | 17.0 | 17.0 | WN |
| 37 | 0.15 | 0.28 | 0.15 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 38 | 0.08 | 0.24 | 0.05 | 2 | 17.0 | 17.0 | WN |
| 39 | −0.07 | 0.21 | 0.06 | 2 | 17.0 | 17.0 | WN |
| 40 | −0.09 | 0.27 | 0.06 | 2 | 17.0 | 0.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |
| | | | | 15 | 2.3 | 0.0 | |
| 41 | −0.07 | 0.18 | 0.00 | 15 | 2.3 | 0.0 | WN |
| 42 | −0.03 | 0.11 | −0.01 | 5 | 6.8 | 0.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |
| 43 | −0.05 | 0.06 | 0.03 | 15 | 0.0 | 0.0 | |
| 44 | 0.06 | 0.05 | 0.08 | 5 | 6.8 | 0.0 | WN |
| 45 | 0.13 | 0.12 | 0.18 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 46 | 0.19 | 0.17 | 0.13 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 17.0 | |
| 47 | 0.02 | 0.21 | 0.09 | 2 | 17.0 | 17.0 | WN |
| | | | | 3 | 11.3 | 0.0 | |
| 48 | −0.08 | 0.12 | 0.11 | | | | WN |
| 49 | −0.13 | 0.09 | 0.06 | 14 | 2.4 | 2.4 | WN |

**Table 4.2** (continued)

| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | Conf. Level 90 | Conf. Level 95 | Cont. |
|---|---|---|---|---|---|---|---|
| 50 | −0.01 | 0.14 | 0.11 | 2 | 17.0 | 0.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |
| 51 | 0.14 | 0.07 | −0.01 | 2 | 17.0 | 0.0 | WN |
| | | | | 5 | 6.8 | 0.0 | |
| | | | | 14 | 2.4 | 0.0 | |
| 52 | 0.11 | 0.05 | −0.06 | 3 | 11.3 | 11.3 | WN |
| | | | | 4 | 8.5 | 8.5 | |
| 53 | 0.08 | 0.11 | 0.15 | | | | WN |
| 54 | −0.11 | 0.20 | −0.01 | | | | WN |
| 55 | 0.10 | 0.11 | 0.16 | | | | WN |
| 56 | −0.01 | 0.19 | −0.02 | 2 | 17.0 | 0.0 | WN |
| | | | | 3 | 11.3 | 0.0 | |
| 57 | 0.04 | 0.16 | 0.06 | 2 | 17.0 | 0.0 | WN |
| 58 | 0.37 | 0.28 | 0.08 | | | | RN |
| 59 | 0.05 | 0.16 | 0.09 | 1 | 34.0 | 0.0 | WN |
| 60 | 0.01 | 0.08 | −0.06 | | | | WN |
| 61 | 0.08 | 0.07 | −0.10 | 5 | 6.8 | 0.0 | WN |
| 62 | 0.05 | −0.02 | −0.01 | | | | WN |
| 63 | −0.18 | 0.27 | −0.09 | 15 | 2.3 | 0.0 | WN |
| | | | | 16 | 2.1 | 0.0 | |
| 64 | 0.28 | 0.10 | 0.03 | | | | RN |
| 65 | 0.43 | 0.36 | 0.27 | 14 | 2.4 | 0.0 | RN |

**Table 4.3** Results of serial correlation (lag 1 to 3) and power spectrum analysis for OEM ($r_1$ = lag-1 SC, $r_2$ = lag-2 SC, $r_3$ = lag-3 SC, $L$ = lag corresponding to significant spectral estimates, Cycles = periodicity (2 $m/L$), Cont. = null continuum, WN = white noise, RN = Markov red noise)

| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | Conf. Level 90 | Conf. Level 95 | Cont. |
|---|---|---|---|---|---|---|---|
| 1 | 0.10 | 0.06 | 0.08 | 4 | 8.5 | 0.0 | WN |
| 2 | 0.08 | −0.07 | 0.38 | 10 | 3.4 | 3.4 | WN |
| 3 | 0.05 | −0.03 | 0.42 | 1 | 34.0 | 0.0 | WN |
| | | | | 2 | 17.0 | 0.0 | |
| | | | | 12 | 2.8 | 0.0 | |
| | | | | 13 | 2.6 | 2.6 | |
| 4 | 0.03 | 0.06 | 0.12 | | | | WN |
| 5 | 0.00 | −0.18 | −0.03 | 7 | 4.9 | 4.9 | WN |
| | | | | 8 | 4.3 | 4.3 | |
| 6 | 0.17 | 0.07 | 0.06 | 1 | 34.0 | 0.0 | WN |
| 7 | 0.23 | −0.04 | −0.03 | 6 | 5.7 | 0.0 | WN |
| | | | | 9 | 3.8 | 0.0 | |
| 8 | 0.12 | −0.09 | −0.06 | | | | WN |
| 9 | 0.04 | 0.13 | 0.34 | 1 | 34.0 | 34.0 | WN |
| 10 | 0.32 | 0.13 | 0.12 | 7 | 4.9 | 0.0 | RN |

**Table 4.3** (continued)

| | | | | | Conf. Level | | |
|---|---|---|---|---|---|---|---|
| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | 90 | 95 | Cont. |
| 11 | −0.14 | −0.05 | 0.01 | | | | WN |
| 12 | −0.29 | 0.06 | −0.12 | 15 | 2.3 | 0.0 | WN |
| | | | | 16 | 2.1 | 2.1 | |
| | | | | 17 | 2.0 | 2.0 | |
| 13 | −0.10 | −0.21 | −0.02 | 9 | 3.8 | 0.0 | WN |
| | | | | 10 | 3.4 | 3.4 | |
| 14 | 0.01 | −0.19 | 0.17 | 8 | 4.3 | 0.0 | WN |
| | | | | 9 | 3.8 | 3.8 | |
| | | | | 10 | 3.4 | 0.0 | |
| 15 | 0.04 | 0.03 | 0.06 | | | | WN |
| 16 | 0.07 | −0.02 | −0.11 | | | | WN |
| 17 | −0.10 | −0.15 | 0.21 | 10 | 3.4 | 0.0 | WN |
| | | | | 11 | 3.1 | 3.1 | |
| | | | | 12 | 2.8 | 0.0 | |
| 18 | 0.31 | 0.29 | 0.30 | | | | RN |
| 19 | 0.32 | 0.04 | −0.01 | 8 | 4.3 | 4.3 | |
| 20 | −0.04 | 0.04 | 0.14 | 11 | 3.1 | 0.0 | WN |
| 21 | 0.02 | 0.04 | 0.21 | | | | WN |
| 22 | 0.05 | −0.10 | 0.35 | 9 | 3.8 | 3.8 | WN |
| 23 | 0.14 | −0.06 | 0.24 | 9 | 3.8 | 0.0 | WN |
| 24 | 0.00 | −0.13 | 0.24 | | | | WN |
| 25 | 0.17 | −0.15 | 0.18 | 8 | 4.3 | 4.3 | WN |
| | | | | 9 | 3.8 | 3.8 | |
| 26 | −0.16 | −0.05 | −0.08 | 10 | 3.4 | 0.0 | WN |
| 27 | −0.11 | 0.03 | 0.15 | 13 | 2.6 | 2.6 | WN |
| 28 | 0.12 | 0.10 | 0.15 | | | | WN |
| 29 | 0.03 | 0.12 | 0.14 | 14 | 2.4 | 2.4 | WN |
| 30 | 0.03 | 0.09 | 0.10 | 14 | 2.4 | 0.0 | WN |
| 31 | 0.10 | 0.13 | 0.22 | | | | WN |
| 32 | −0.10 | 0.26 | 0.14 | 13 | 2.6 | 2.6 | WN |
| 33 | 0.01 | 0.20 | 0.21 | 12 | 2.8 | 0.0 | WN |
| | | | | 13 | 2.6 | 2.6 | |
| 34 | 0.02 | −0.21 | 0.17 | 8 | 4.3 | 0.0 | WN |
| | | | | 9 | 3.8 | 0.0 | |
| 35 | −0.12 | −0.25 | 0.20 | 9 | 3.8 | 3.8 | WN |
| | | | | 10 | 3.4 | 3.4 | |
| 36 | 0.04 | −0.16 | 0.09 | | | | WN |
| 37 | 0.17 | 0.08 | 0.16 | 1 | 34.0 | 0.0 | WN |
| | | | | 2 | 17.0 | 0.0 | |
| 38 | 0.16 | 0.11 | 0.08 | 2 | 17.0 | 0.0 | WN |
| 39 | −0.04 | 0.14 | 0.10 | 14 | 2.4 | 0.0 | WN |
| 40 | 0.14 | 0.02 | 0.33 | 1 | 34.0 | 0.0 | WN |
| | | | | 9 | 3.8 | 0.0 | |
| 41 | −0.19 | −0.02 | 0.22 | 13 | 2.6 | 0.0 | WN |
| | | | | 14 | 2.4 | 0.0 | |
| 42 | 0.09 | 0.29 | 0.29 | 1 | 34.0 | 0.0 | WN |
| | | | | 13 | 2.6 | 0.0 | |

**Table 4.3** (continued)

| | | | | | Conf. Level | | |
|---|---|---|---|---|---|---|---|
| S. No. | $r_1$ | $r_2$ | $r_3$ | $L$ | 90 | 95 | Cont. |
| 43 | −0.07 | −0.13 | 0.17 | 9 | 3.8 | 3.8 | WN |
| | | | | 13 | 0.0 | 0.0 | |
| 44 | −0.19 | −0.14 | −0.02 | 14 | 2.4 | 2.4 | WN |
| 45 | −0.01 | −0.01 | 0.19 | | | | WN |
| 46 | 0.03 | −0.08 | 0.10 | | | | WN |
| 47 | −0.07 | 0.00 | −0.04 | 8 | 4.3 | 4.3 | WN |
| | | | | 9 | 3.8 | 0.0 | |
| 48 | 0.00 | 0.19 | 0.32 | 1 | 34.0 | 0.0 | WN |
| | | | | 13 | 2.6 | 0.0 | |
| 49 | −0.03 | 0.29 | 0.19 | 13 | 2.6 | 0.0 | WN |
| 50 | 0.03 | −0.10 | 0.22 | 9 | 3.8 | 3.8 | WN |
| | | | | 10 | 3.4 | 0.0 | |
| 51 | −0.14 | −0.11 | 0.09 | 9 | 3.8 | 0.0 | WN |
| | | | | 13 | 2.6 | 0.0 | |
| 52 | 0.05 | 0.19 | 0.17 | 1 | 34.0 | 34.0 | WN |
| | | | | 2 | 17.0 | 0.0 | |
| 53 | −0.10 | −0.02 | 0.20 | 11 | 3.1 | 0.0 | WN |
| 54 | −0.15 | −0.19 | 0.13 | 6 | 5.7 | 0.0 | WN |
| | | | | 11 | 3.1 | 3.1 | |
| | | | | 12 | 2.8 | 2.8 | |
| | | | | 13 | 2.6 | 0.0 | |
| 55 | 0.19 | 0.30 | 0.07 | 1 | 34.0 | 34.0 | WN |
| 56 | −0.05 | 0.06 | 0.08 | | | | WN |
| 57 | −0.07 | 0.33 | 0.07 | 2 | 17.0 | 0.0 | WN |
| | | | | 15 | 2.3 | 2.3 | |
| 58 | 0.02 | 0.03 | −0.25 | 4 | 8.5 | 8.5 | WN |
| | | | | 5 | 6.8 | 6.8 | |
| 59 | 0.01 | 0.13 | 0.08 | 13 | 2.6 | 0.0 | WN |
| 60 | 0.05 | −0.28 | −0.04 | 8 | 4.3 | 4.3 | WN |
| | | | | 9 | 3.8 | 3.8 | |
| 61 | 0.12 | 0.12 | −0.13 | 2 | 17.0 | 0.0 | WN |
| 62 | 0.16 | −0.03 | 0.02 | | | | WN |
| 63 | 0.12 | −0.19 | −0.08 | 5 | 6.8 | 0.0 | |
| | | | | 6 | 5.7 | 5.7 | WN |
| 64 | −0.06 | −0.19 | 0.08 | 8 | 4.3 | 0.0 | WN |
| | | | | 9 | 3.8 | 3.8 | |
| 65 | −0.04 | −0.14 | 0.13 | 9 | 3.8 | 0.0 | WN |

The spatial pattern of lag-1 SC of the hydro-climatic variables is depicted in Figs. 4.2, 4.3, and 4.4. The summarized statistics of trend analysis is given in Table 4.7. Though the trend results are produced using all the tests but the spatial pattern of $Z$-statistics was presented using the results obtained from the modified Mann-Kendall test. For pattern analysis, the Kriging method is used for the interpolation of data. The spatial pattern of the trend statistics for the hydro-climatic variables is shown in Fig. 4.5 (annual, monsoon, and non-monsoon

**Table 4.4** Summarized result of persistence analysis

| S. No. | Variable | No. series sowing significant positive | | | No. (%) series sowing persistence | No. (%) series sowing significant negative | | |
|---|---|---|---|---|---|---|---|---|
| | | $r_1$ | $r_2$ | $r_3$ | | $r_1$ | $r_2$ | $r_3$ |
| 1 | Annual Rainfall | 13 (20.00) | 16 (24.60) | 5 (7.69) | 13 (20.00) | 3 (4.61) | 0 (0.00) | 0 (0.00) |
| 2 | Monsoon Rainfall | 12 (18.46) | 19 (29.23) | 9 (13.84) | 12 (18.46) | 6 (9.23) | 0 (0.00) | 0 (0.00) |
| 3 | Non-Monsoon Rainfall | 13 (20.00) | 2 (3.07) | 14 (21.50) | 13 (20.00) | 0 (0.00) | 3 (4.61) | 1 (1.54) |
| 4 | Annual Rainydays | 17 (26.15) | 12 (18.46) | 2 (3.07) | 17 (26.15) | 0 (0.00) | 0 (0.00) | 2 (3.07) |
| 5 | Monsoon Rainydays | 5 (7.69) | 14 (21.54) | 1 (1.54) | 5 (7.69) | 0 (0.00) | 0 (0.00) | 0 (0.00) |
| 6 | Non-Monsoon Rainydays | 22 (33.84) | 2 (3.07) | 10 (15.38) | 22 (33.84) | 0 (0.00) | 2 (3.07) | 2 (3.07) |
| 7 | OEM | 4 (6.15) | 6 (9.23) | 14 (21.5) | 4 (6.15) | 1 (1.54) | 1 (1.54) | 0 (0.00) |
| 8 | Aridity Index | 13 (20.00) | 16 (24.60) | 4 (6.15) | 13 (20.00) | 3 (4.61) | 0 (0.00) | 0 (0.00) |

Values in the parenthesis are the percentage of total time series

**Table 4.5** Lag-1 serial correlation and Mann-Kendall's $Z$-statistics of Monsoon rainfall of the Yamuna River basin [$r_1(l) = -0.248$ and $r_1(u) = 0.208$]

| Grid Location | | | *Z*-MK | | |
|---|---|---|---|---|---|
| Lat | Long | $r_1$ | Org | Mod | PW |
| 21.5N | 75.5E | 0.003 | 0.3 | 0.3 | 0.3 |
| 22.5N | 74.5E | 0.052 | −0.655 | −0.655 | −0.655 |
| 22.5N | 75.5E | 0.047 | −0.513 | −0.513 | −0.513 |
| 22.5N | 76.5E | −0.09 | −0.923 | −0.923 | −0.923 |
| 22.5N | 77.5E | −0.121 | −0.702 | −0.702 | −0.702 |
| 22.5N | 78.5E | **0.396** | **−4.34** | 0.021 | **−3.338** |
| 22.5N | 79.5E | −0.039 | 0.016 | 0.016 | 0.016 |
| 23.5N | 73.5E | −0.036 | −0.971 | −0.971 | −0.971 |
| 23.5N | 74.5E | −0.049 | −0.371 | −0.371 | −0.371 |
| 23.5N | 75.5E | **0.218** | −0.608 | 0.017 | −1.16 |
| 23.5N | 76.5E | 0.152 | −1.302 | −1.302 | −1.302 |
| 23.5N | 77.5E | −0.029 | 1.065 | 1.065 | 1.065 |
| 23.5N | 78.5E | −0.018 | −0.339 | −0.339 | −0.339 |
| 23.5N | 79.5E | **−0.344** | −0.813 | 0.061 | −1.239 |
| 23.5N | 80.5E | −0.177 | −0.687 | −0.687 | −0.687 |
| 24.5N | 72.5E | −0.144 | −0.915 | −0.915 | −0.915 |
| 24.5N | 73.5E | 0.066 | −0.229 | −0.229 | −0.229 |
| 24.5N | 74.5E | −0.203 | −0.734 | 0.01 | −0.734 |
| 24.5N | 75.5E | −0.084 | −0.592 | −0.592 | −0.592 |
| 24.5N | 76.5E | −0.041 | 0.024 | 0.024 | 0.024 |

**Table 4.5** (continued)

| Grid Location | | | *Z*-MK | | |
|---|---|---|---|---|---|
| Lat | Long | $r_1$ | Org | Mod | PW |
| 24.5N | 77.5E | −0.217 | −0.418 | −0.418 | −0.418 |
| 24.5N | 78.5E | −0.211 | −1.176 | −1.176 | −1.176 |
| 24.5N | 79.5E | −0.224 | 0.103 | 0.103 | 0.103 |
| 24.5N | 80.5E | **−0.371** | −0.418 | −0.418 | −0.718 |
| 24.5N | 81.5E | −0.21 | 0.86 | 0.86 | 0.86 |
| 25.5N | 73.5E | −0.149 | −0.166 | −0.166 | −0.166 |
| 25.5N | 74.5E | 0.04 | 0.229 | 0.229 | 0.229 |
| 25.5N | 75.5E | 0.202 | ***−2.951*** | ***−2.951*** | ***−2.951*** |
| 25.5N | 76.5E | **0.227** | −1.586 | −1.586 | **−1.996** |
| 25.5N | 77.5E | **−0.255** | −0.039 | −0.039 | −0.481 |
| 25.5N | 78.5E | **−0.272** | −1.207 | 0.009 | **−2.123** |
| 25.5N | 79.5E | −0.247 | −1.192 | −1.192 | −1.192 |
| 25.5N | 80.5E | **−0.409** | −0.797 | −0.034 | −1.097 |
| 25.5N | 81.5E | −0.022 | −0.387 | −0.387 | −0.387 |
| 25.5N | 82.5E | −0.123 | 1.065 | 1.065 | 1.065 |
| 26.5N | 73.5E | −0.004 | 0.292 | 0.292 | 0.292 |
| 26.5N | 74.5E | 0.204 | −0.181 | −0.181 | −0.181 |
| 26.5N | 75.5E | 0.119 | −1.405 | −1.405 | −1.405 |
| 26.5N | 76.5E | 0.346 | −1.981 | 0.005 | −2.359 |
| 26.5N | 77.5E | 0.257 | −2.044 | −2.044 | −2.438 |
| 26.5N | 78.5E | 0.107 | −1.681 | −1.681 | −1.681 |
| 26.5N | 79.5E | 0.022 | −2.486 | −2.486 | −2.486 |
| 26.5N | 80.5E | −0.144 | −1.57 | −1.57 | −1.57 |
| 26.5N | 81.5E | −0.128 | −1.413 | −1.413 | −1.413 |
| 27.5N | 74.5E | 0.401 | −1.349 | 0.015 | −1.176 |
| 27.5N | 75.5E | 0.181 | −1.199 | −1.199 | −1.199 |
| 27.5N | 76.5E | 0.105 | −1.933 | −1.933 | −1.933 |
| 27.5N | 77.5E | 0.144 | −2.178 | −2.178 | −2.178 |
| 27.5N | 78.5E | −0.1 | −0.955 | −0.955 | −0.955 |
| 27.5N | 79.5E | −0.072 | −1.665 | −1.665 | −1.665 |
| 27.5N | 80.5E | 0.062 | −2.075 | −2.075 | −2.075 |
| 28.5N | 75.5E | 0.145 | 0.039 | 0.039 | 0.039 |
| 28.5N | 76.5E | 0.071 | −0.174 | −0.174 | −0.174 |
| 28.5N | 77.5E | −0.025 | −1.247 | −1.247 | −1.247 |
| 28.5N | 78.5E | 0.211 | −3.717 | −3.717 | −3.764 |
| 29.5N | 76.5E | 0.169 | −1.618 | −1.618 | −1.618 |
| 29.5N | 77.5E | 0.13 | −3.306 | −3.306 | −3.306 |
| 29.5N | 78.5E | 0.125 | −2.044 | −2.044 | −2.044 |
| 30.5N | 76.5E | −0.123 | 0.055 | 0.055 | 0.055 |
| 30.5N | 77.5E | 0.593 | −1.223 | 0.013 | −1.381 |
| 30.5N | 78.5E | 0.444 | −2.517 | 0.046 | −1.996 |
| 31.5N | 76.5E | 0.281 | −1.428 | 0.015 | −1.507 |
| 31.5N | 77.5E | −0.253 | −1.081 | −1.081 | −1.87 |
| 31.5N | 78.5E | 0.395 | 2.888 | 0.04 | 1.728 |
| 31.5N | 79.5E | 0.475 | 1.476 | −0.013 | 0.245 |

$r_1$ = lag-1 SC, *Z-MK* = Mann-Kendall's *Z*-statistics, *Org* = original MK test, *Mod* = modified MK test, *PW* = MK test with pre-whitening of data

**Table 4.6** Lag-1 serial correlation and Mann-Kendall's *Z*-statistics of OEM of the Yamuna River basin [$r_1(l) = -0.248$ and $r_1(u) = 0.208$]

| Grid Location | | | *Z*-MK | | |
|---|---|---|---|---|---|
| Lat | Long | $r_1$ | Org | Mod | PW |
| 21.5N | 75.5E | 0.099 | 1.320 | 1.321 | 1.321 |
| 22.5N | 74.5E | 0.084 | 1.785 | 1.785 | 1.785 |
| 22.5N | 75.5E | 0.050 | 1.335 | 1.335 | 1.335 |
| 22.5N | 76.5E | 0.028 | ***1.990*** | ***1.991*** | ***1.991*** |
| 22.5N | 77.5E | 0.001 | 0.917 | 0.918 | 0.918 |
| 22.5N | 78.5E | 0.168 | ***2.354*** | ***2.356*** | ***2.356*** |
| 22.5N | 79.5E | **0.234** | **2.110** | **2.111** | 1.184 |
| 23.5N | 73.5E | 0.117 | ***3.776*** | 0.056 | ***3.777*** |
| 23.5N | 74.5E | 0.035 | ***2.678*** | ***2.679*** | ***2.679*** |
| 23.5N | 75.5E | **0.323** | **2.472** | **2.473** | 1.097 |
| 23.5N | 76.5E | −0.136 | 1.517 | 1.519 | 1.519 |
| 23.5N | 77.5E | **−0.291** | 1.146 | 0.031 | 0.963 |
| 23.5N | 78.5E | −0.101 | 1.406 | 1.407 | 1.407 |
| 23.5N | 79.5E | 0.014 | 1.763 | 1.766 | 1.766 |
| 23.5N | 80.5E | 0.037 | ***2.433*** | ***2.433*** | ***2.433*** |
| 24.5N | 72.5E | 0.074 | ***1.998*** | ***1.999*** | ***1.999*** |
| 24.5N | 73.5E | −0.097 | 1.240 | 1.241 | 1.241 |
| 24.5N | 74.5E | **0.307** | **3.658** | 0.020 | **1.965** |
| 24.5N | 75.5E | **0.320** | **2.441** | −0.025 | 1.515 |
| 24.5N | 76.5E | −0.043 | 1.651 | 1.652 | 1.652 |
| 24.5N | 77.5E | 0.019 | ***3.792*** | ***3.793*** | ***3.793*** |
| 24.5N | 78.5E | 0.051 | ***3.160*** | ***3.162*** | ***3.162*** |
| 24.5N | 79.5E | 0.136 | ***3.106*** | ***3.108*** | ***3.108*** |
| 24.5N | 80.5E | 0.004 | ***2.782*** | ***2.786*** | ***2.786*** |
| 24.5N | 81.5E | 0.167 | 2.938 | 2.939 | 2.939 |
| 25.5N | 73.5E | −0.157 | 0.537 | 0.538 | 0.538 |
| 25.5N | 74.5E | −0.106 | 1.509 | 1.509 | 1.509 |
| 25.5N | 75.5E | 0.115 | ***2.566*** | ***2.566*** | ***2.566*** |
| 25.5N | 76.5E | 0.030 | ***2.812*** | ***2.813*** | ***2.813*** |
| 25.5N | 77.5E | 0.030 | ***2.173*** | ***2.174*** | ***2.174*** |
| 25.5N | 78.5E | 0.096 | ***3.238*** | ***3.239*** | ***3.239*** |
| 25.5N | 79.5E | −0.104 | ***3.100*** | ***3.107*** | ***3.107*** |
| 25.5N | 80.5E | 0.014 | ***2.964*** | ***2.966*** | ***2.966*** |
| 25.5N | 81.5E | 0.020 | ***2.647*** | ***2.648*** | ***2.648*** |
| 25.5N | 82.5E | −0.118 | 1.358 | 1.359 | 1.359 |
| 26.5N | 73.5E | 0.042 | −1.153 | −1.154 | −1.154 |
| 26.5N | 74.5E | 0.172 | 0.569 | 0.569 | 0.569 |
| 26.5N | 75.5E | 0.155 | ***2.559*** | ***2.559*** | ***2.559*** |
| 26.5N | 76.5E | −0.036 | ***1.991*** | ***1.993*** | ***1.993*** |
| 26.5N | 77.5E | 0.144 | ***3.002*** | ***3.003*** | ***3.003*** |
| 26.5N | 78.5E | −0.188 | ***2.606*** | ***2.607*** | ***2.607*** |
| 26.5N | 79.5E | 0.085 | ***3.502*** | ***3.507*** | ***3.507*** |
| 26.5N | 80.5E | −0.065 | ***2.141*** | ***2.141*** | ***2.141*** |
| 26.5N | 81.5E | −0.194 | 0.924 | 0.924 | 0.924 |
| 27.5N | 74.5E | −0.007 | 0.079 | 0.079 | 0.079 |
| 27.5N | 75.5E | 0.032 | 1.193 | 1.193 | 1.193 |

**Table 4.6** (continued)

| Grid Location | | | Z-MK | | |
|---|---|---|---|---|---|
| Lat | Long | $r_1$ | Org | Mod | PW |
| 27.5N | 76.5E | −0.069 | 0.371 | 0.372 | 0.372 |
| 27.5N | 77.5E | 0.003 | ***3.270*** | ***3.271*** | ***3.271*** |
| 27.5N | 78.5E | −0.025 | ***3.341*** | ***3.343*** | ***3.343*** |
| 27.5N | 79.5E | 0.026 | 1.808 | 1.808 | 1.808 |
| 27.5N | 80.5E | −0.141 | 1.011 | 1.012 | 1.012 |
| 28.5N | 75.5E | 0.046 | 1.125 | 1.131 | 1.131 |
| 28.5N | 76.5E | −0.100 | 0.537 | 0.537 | 0.537 |
| 28.5N | 77.5E | −0.153 | 0.134 | 0.134 | 0.134 |
| 28.5N | 78.5E | 0.194 | ***4.447*** | 0.000 | ***4.448*** |
| 29.5N | 76.5E | −0.047 | 1.047 | 1.096 | 1.096 |
| 29.5N | 77.5E | −0.071 | 1.936 | 1.937 | 1.937 |
| 29.5N | 78.5E | 0.024 | 0.672 | 0.673 | 0.673 |
| 30.5N | 76.5E | 0.009 | 1.698 | 1.699 | 1.699 |
| 30.5N | 77.5E | 0.051 | ***2.156*** | ***2.157*** | ***2.157*** |
| 30.5N | 78.5E | 0.118 | 0.387 | 0.387 | 0.387 |
| 31.5N | 76.5E | 0.158 | ***2.267*** | ***2.268*** | ***2.268*** |
| 31.5N | 77.5E | 0.115 | 1.216 | 1.216 | 1.216 |
| 31.5N | 78.5E | −0.056 | −0.348 | −0.348 | −0.348 |
| 31.5N | 79.5E | −0.035 | 0.963 | 0.963 | 0.963 |

$r_1$ = lag-1 SC, Z-MK = Mann-Kendall's Z-statistics, Org = original MK test, Mod = modified MK test, PW = MK test with pre-whitening of data

rainfall; and annual, monsoon, and non-monsoon rainydays) and Fig. 4.6 (OEM and aridity index). The patterns are classified based on the 90% confidence level (i.e., $Z < -1.645$; $-1.645 < Z < 0.0$; $0.0 < Z < 1.645$; and $Z > 1.645$). These interval ($Z < -1.645$; $-1.645 < Z < 0.0$; $0.0 < Z < 1.645$; and $Z > 1.645$) show the significant negative trend, insignificant negative trend, insignificant positive trend, and significant positive trend at the 90% confidence interval, respectively.

Based on analysis (Fig. 4.5 and Table 4.7), it can be observed that annual rainfall and monsoon rainfall values show an overall declining trend, although the scattered patches of the basin shows insignificant rising trend. The trend statistics for annual rainfall pattern and annual rainydays, and monsoon rainfall and monsoon rainy days are −0.832 and −0.362, and −0.874 and −0.62, respectively. On the other hand, the magnitude of non-monsoon rainfall has been insignificantly increased though few grid data show the significant rising trend in the north and north-west portion of the basin, which can be evident from the average Z-statistic of +0.209 and +0.258 for non-monsoon rainfall and rainy days, respectively. The spatial distribution pattern of rainydays is more or less similar to that of rainfall. Most of the area in the central to South-east and central to south experiences declination in rainfall. Since OEM is dependent on the rainfall pattern and potential evapotranspiration, and both the variables have shown a general falling trend in the basin. Therefore, an increasing trend in OEM is the resulting effect of rainfall and evapotranspiration patterns. The overall mean Z-statistic for OEM is +1.81. Similarly, the aridity index

**Table 4.7** Summary of trend analysis based on Modified Mann-Kendall test

| S. No | Variable | Mean value | | | No. of series indicating significant lag-1 serial correlation | No. of series indicating significant | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Spatial mean | Range | SD | | Rising trend | Falling trend | No trend | Overall trend |
| 1 | Annual rainfall | 893.3 | 372.2–1653.5 | 280.3 | 13 | | 6 (8) | 59 (57) | − ve |
| 2 | Monsoon rainfall | 806.8 | 327.0–1568.9 | 259.7 | 12 | | 8 (13) | 57 (52) | − ve |
| 3 | Non-monsoon rainfall | 86.5 | 19.5–479.0 | 100.1 | 13 | 3 (2) | | 62 (63) | + ve |
| 4 | Annual rainydays | 88 | 46.0–160.0 | 25 | 17 | 4 (2) | 7 (11) | 54 (52) | − ve |
| 5 | Monsoon rainydays | 70 | 43–96 | 15 | 5 | | 5 (6) | 60 (59) | − ve |
| 6 | Non-monsoon rainydays | 17 | 1–72 | 14 | 22 | 6 (2) | 1 (2) | 58 (61) | + ve |
| 7 | OEM | 190 | 173–207 | 7 | 4 | 29 (30) | | 36 (35) | + ve |
| 8 | Aridity Index (AI) | 38.0 | 14.9–74.6 | 12.9 | 13 | | 6 (8) | 59 (57) | − ve |

Values in the parenthesis are the results from Mann-Kendall with pre-whitening test

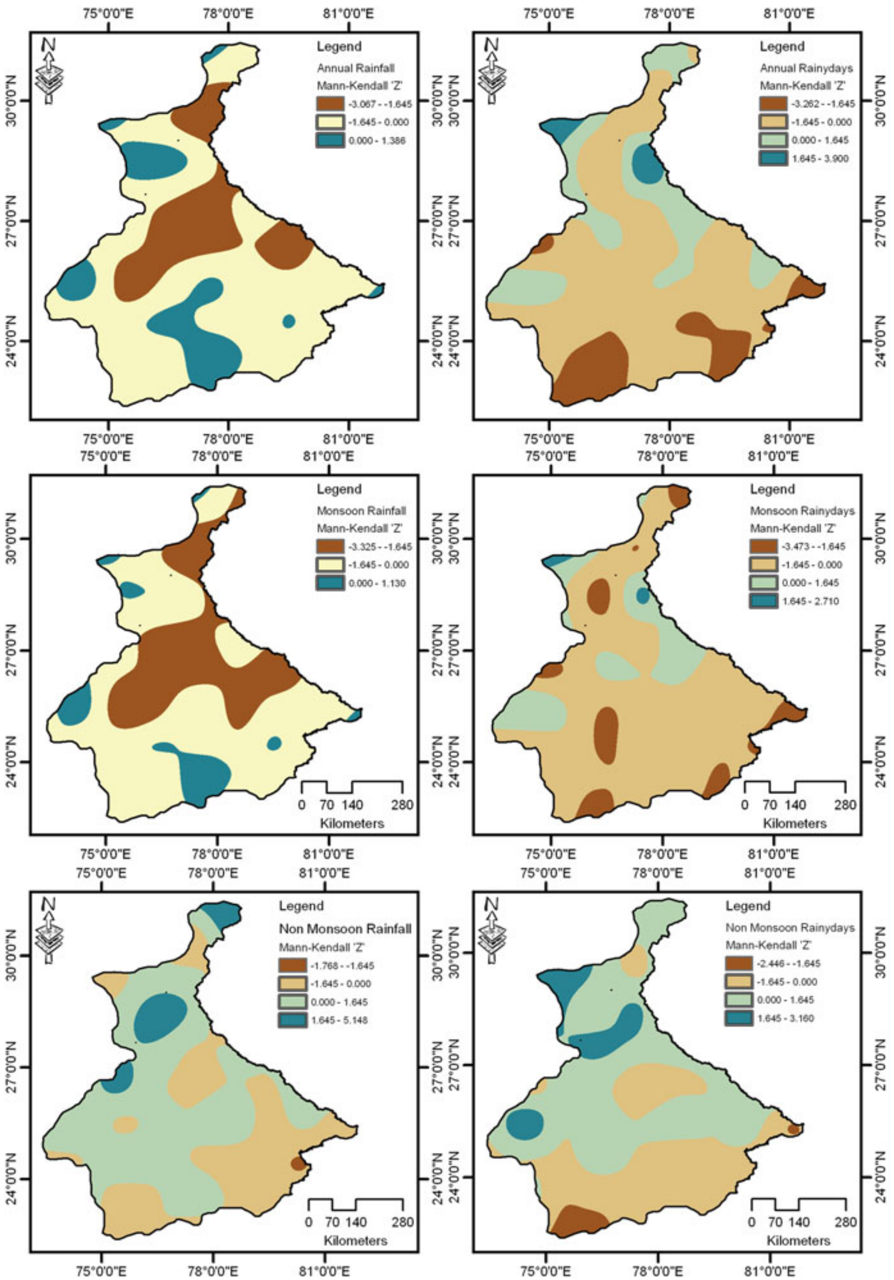


**Fig. 4.5** Spatial distribution pattern of Mann-Kendall's *Z*-statistics of rainfall (annual, monsoon and non-monsoon) and rainydays (annual, monsoon and non-monsoon)

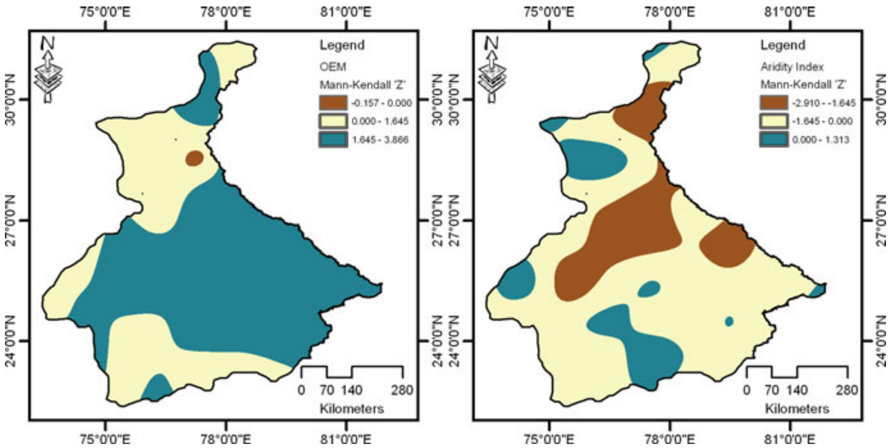


**Fig. 4.6** Spatial distribution pattern of Mann-Kendall's $Z$-statistics of OEM and aridity index

is the ratio of annual rainfall and potential evapotranspiration. The falling trend observed in the aridity index is associated with the overall falling trend in the rainfall pattern of the Yamuna River basin (Table 4.7 and Fig. 4.5). The overall mean $Z$-statistic value for the aridity index is $-0.78$. Based on the trend analysis, it can be stated that the water resources potential of the Yamuna River basin is declining.

### *4.3.3 Periodicity*

The significance of spectral estimates is evaluated at 90 and 95% confidence levels of the appropriate null continuum (red or white noise). The relationship between the correlogram and spectral estimates is shown in Fig. 4.7 for sample time series of annual rainfall of the Yamuna River basin. If a time series has persistence, the spectrum changes over all the wavelengths and the amplitude of the spectrum has a decreasing trend from long to short wavelengths (i.e. corresponding to increasing order of lags); and the spectrum is termed as "red noise" (Fig. 4.7a). For the spectrum of a time series having persistence with necessary exponential relationship between $r_1$, $r_2$ and $r_3$ (i.e., Markov-type persistence), the appropriate null appropriate is assumed to be a Markov red noise continuum (Fig. 4.7b). A series characterized by an insignificant positive lag-1 SC or a series that has a significant positive lag-1 SC but not a simple Markov-type, and any series with a negative lag-1 serial correlation coefficient is evaluated as a white noise continuum (Figs. 4.7c and 4.7d). From Fig. 4.7d, it may be stated that times series with negative lag-1 SC shows the high frequency variability (i.e. $L = 14$, and $P = 2\ m/L = 2.4$ years). For all the variables, power spectrum plots and the tables are prepared. However, for presentation sample power spectrum plots of monsoon rainfall, OEM and AI are given (Figs. 4.8, 4.9, and 4.10). To evaluate the power spectrum results, generally

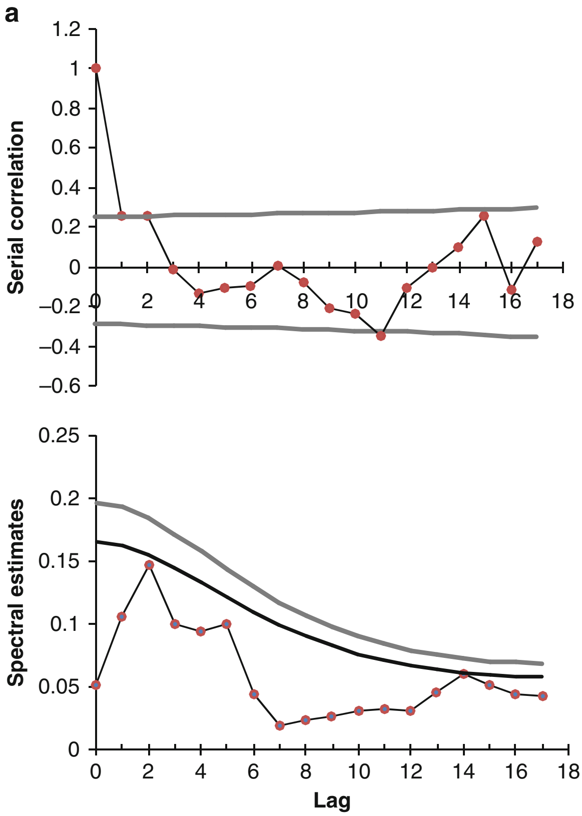


**Fig. 4.7** (**a**) Relation between correlogram and spectral estimates: Series with persistence (red noise)

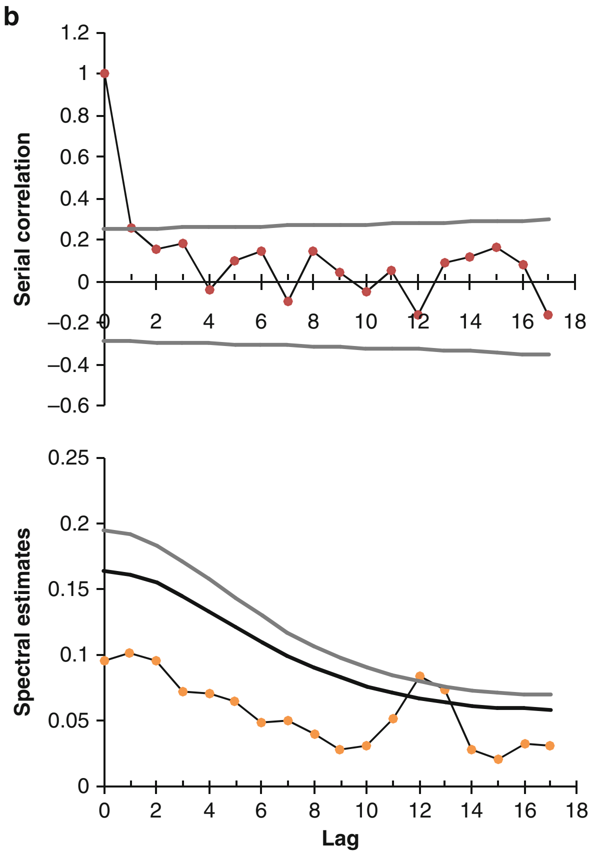


**Fig. 4.7** (**b**) Relation between correlogram and spectral estimates: Series with persistence and sowing necessary exponential relationship (Markov red noise)

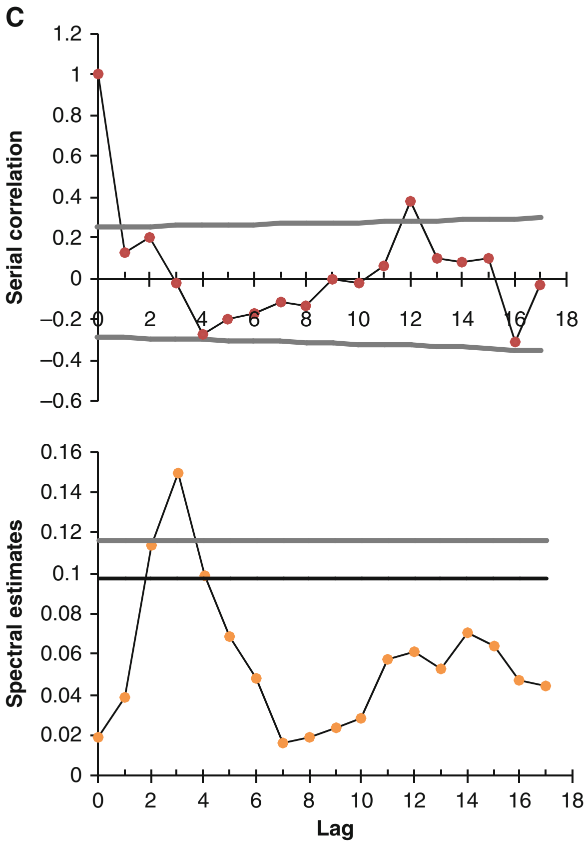


**Fig. 4.7** (**c**) Relation between correlogram and spectral estimates: Series with insignificant positive lag-1 SC (white noise)

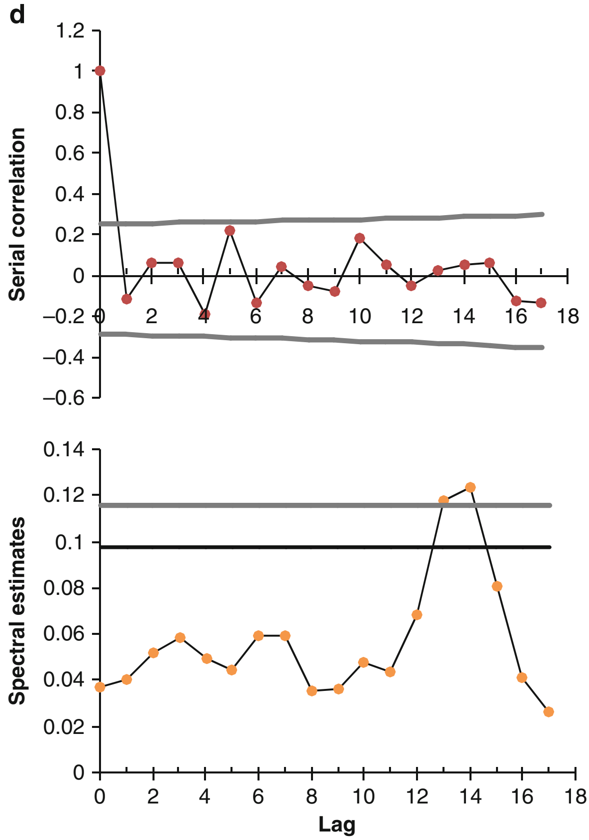


**Fig. 4.7** (**d**) Relation between correlogram and spectral estimates: Series with negative lag-1 SC (white noise)

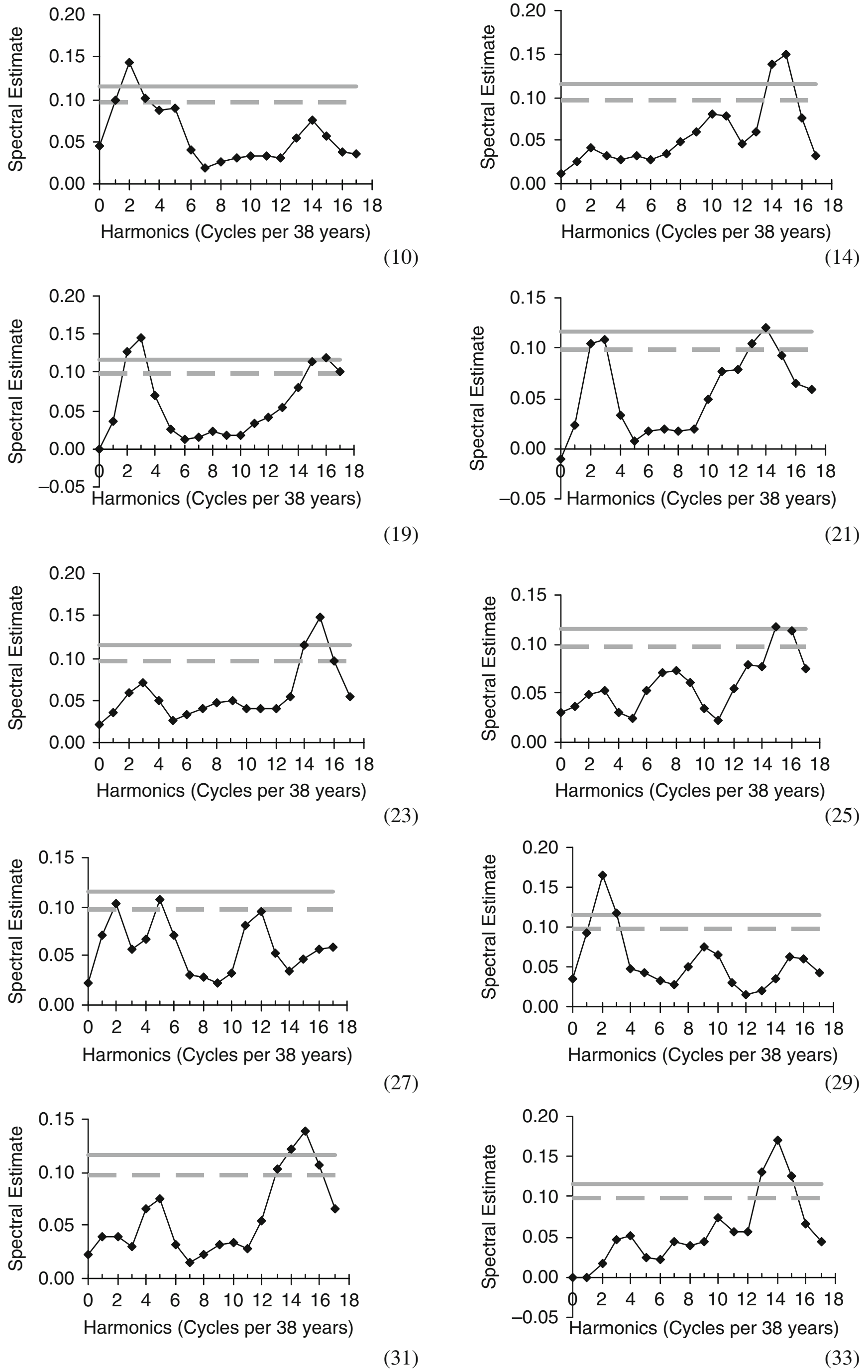


**Fig. 4.8** Power spectrum plot for monsoon rainfall (——: 95% confidence limit; - - - - - -: 90% confidence limit)

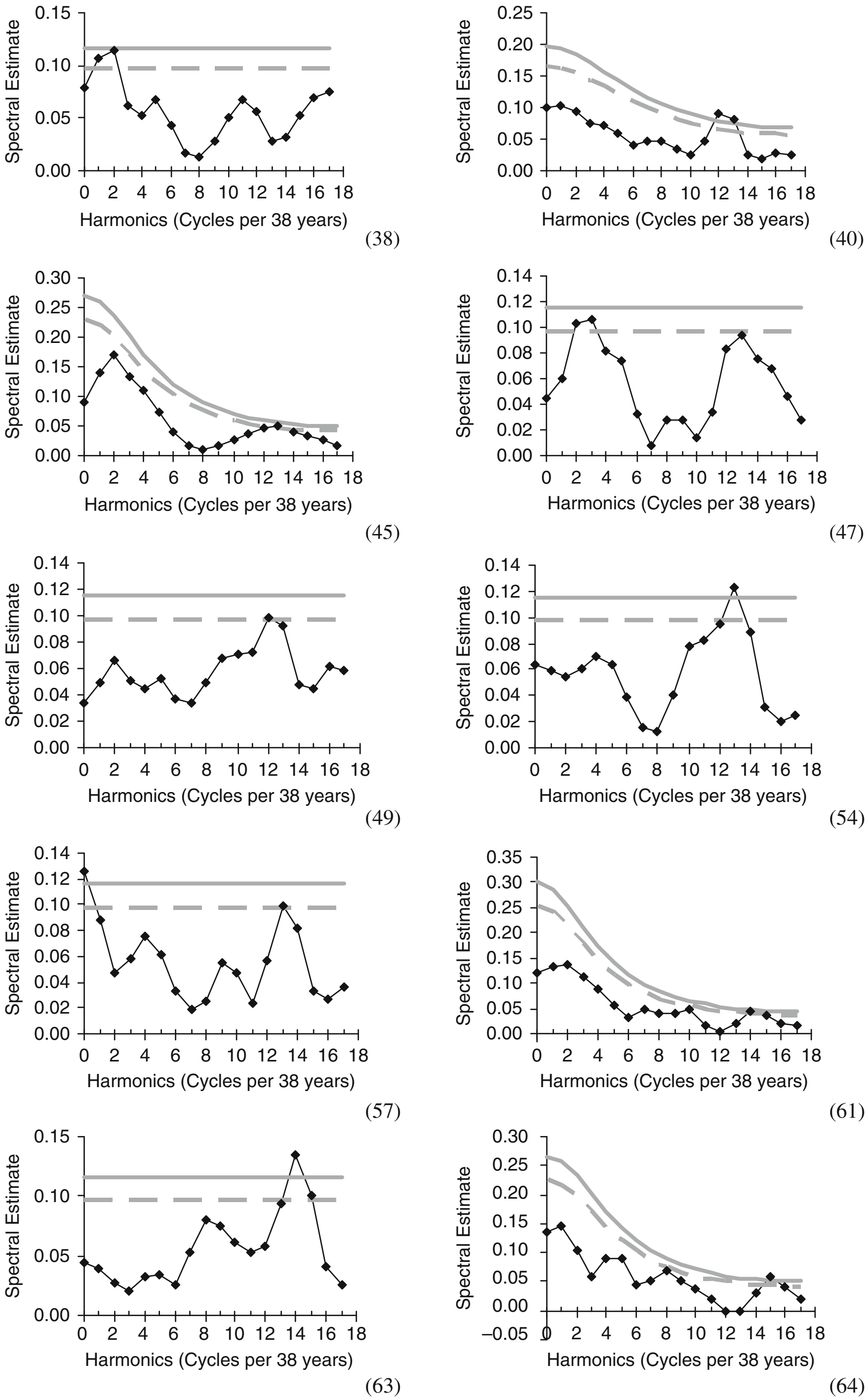


**Fig. 4.8** (continued)

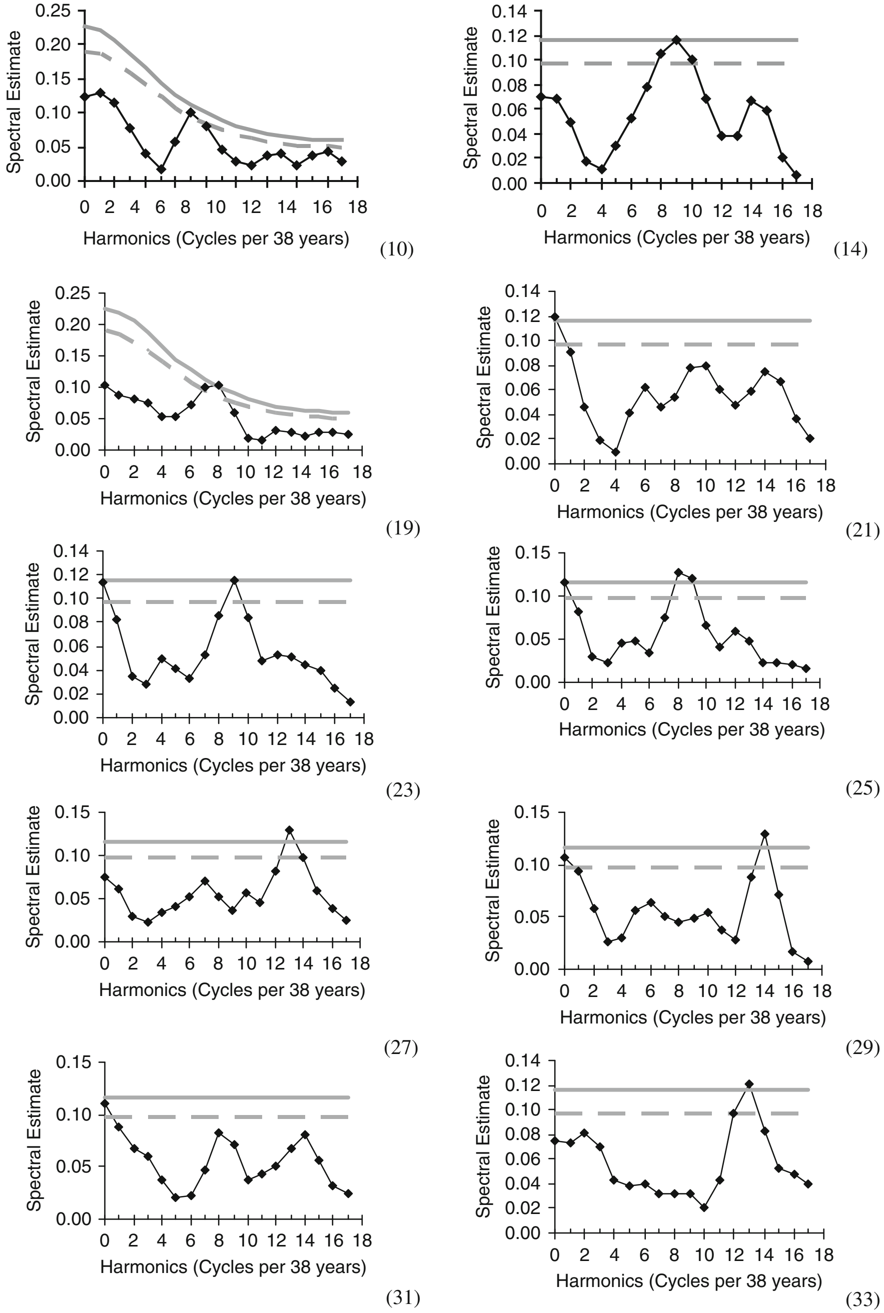


**Fig. 4.9** Power spectrum plot for OEM

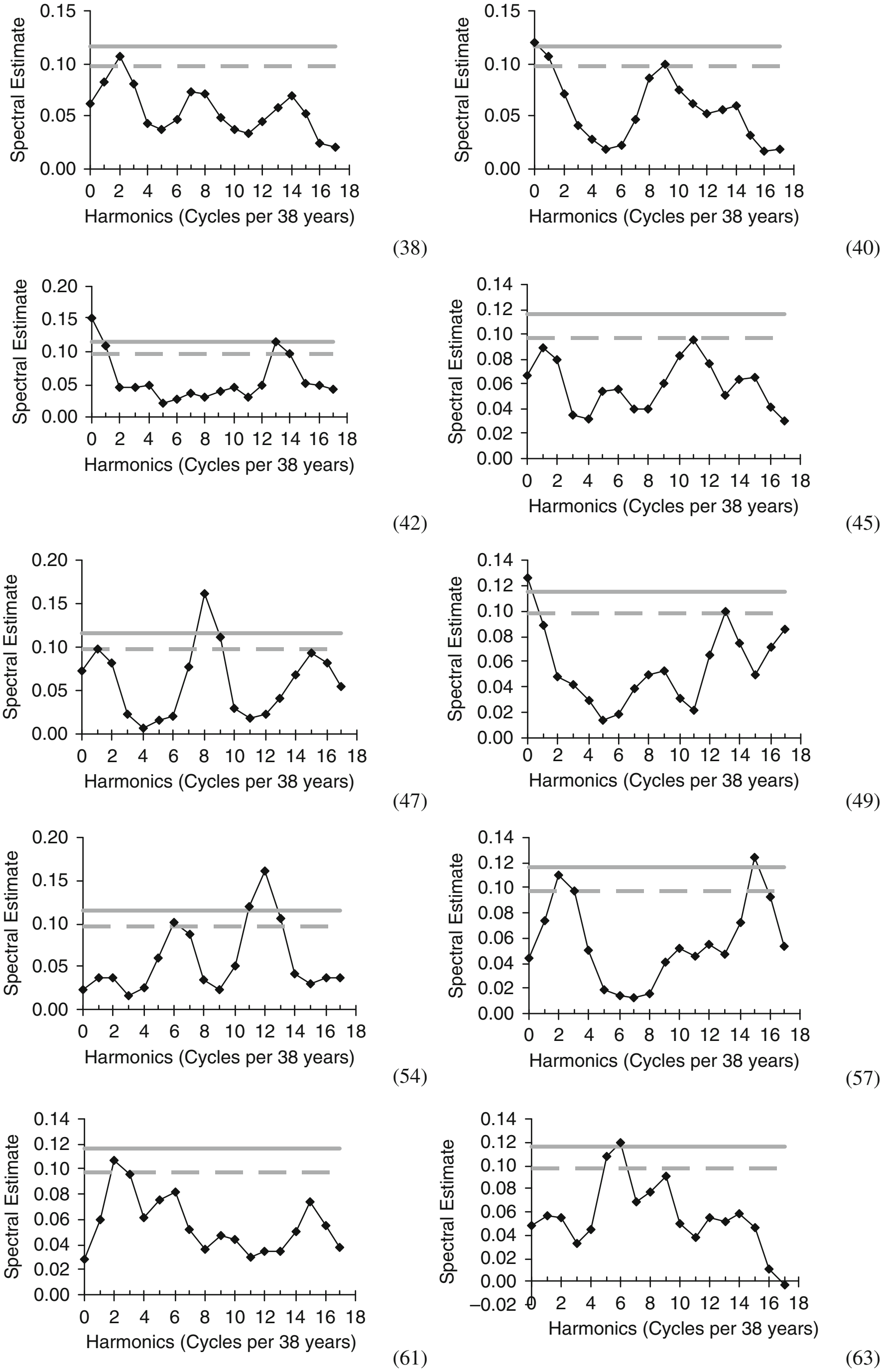


**Fig. 4.9** (continued)

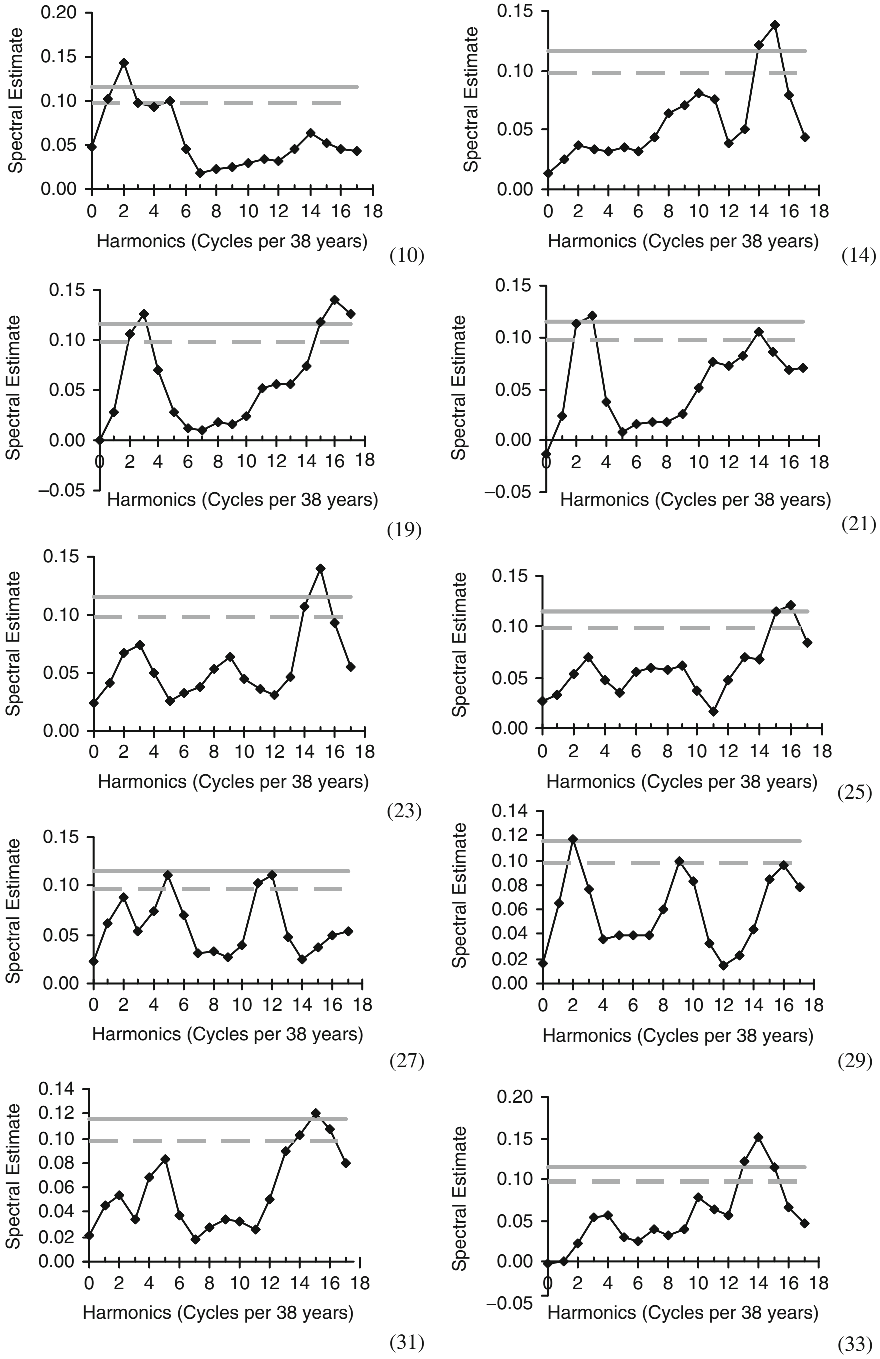


**Fig. 4.10** Power spectrum plot for aridity index (AI)

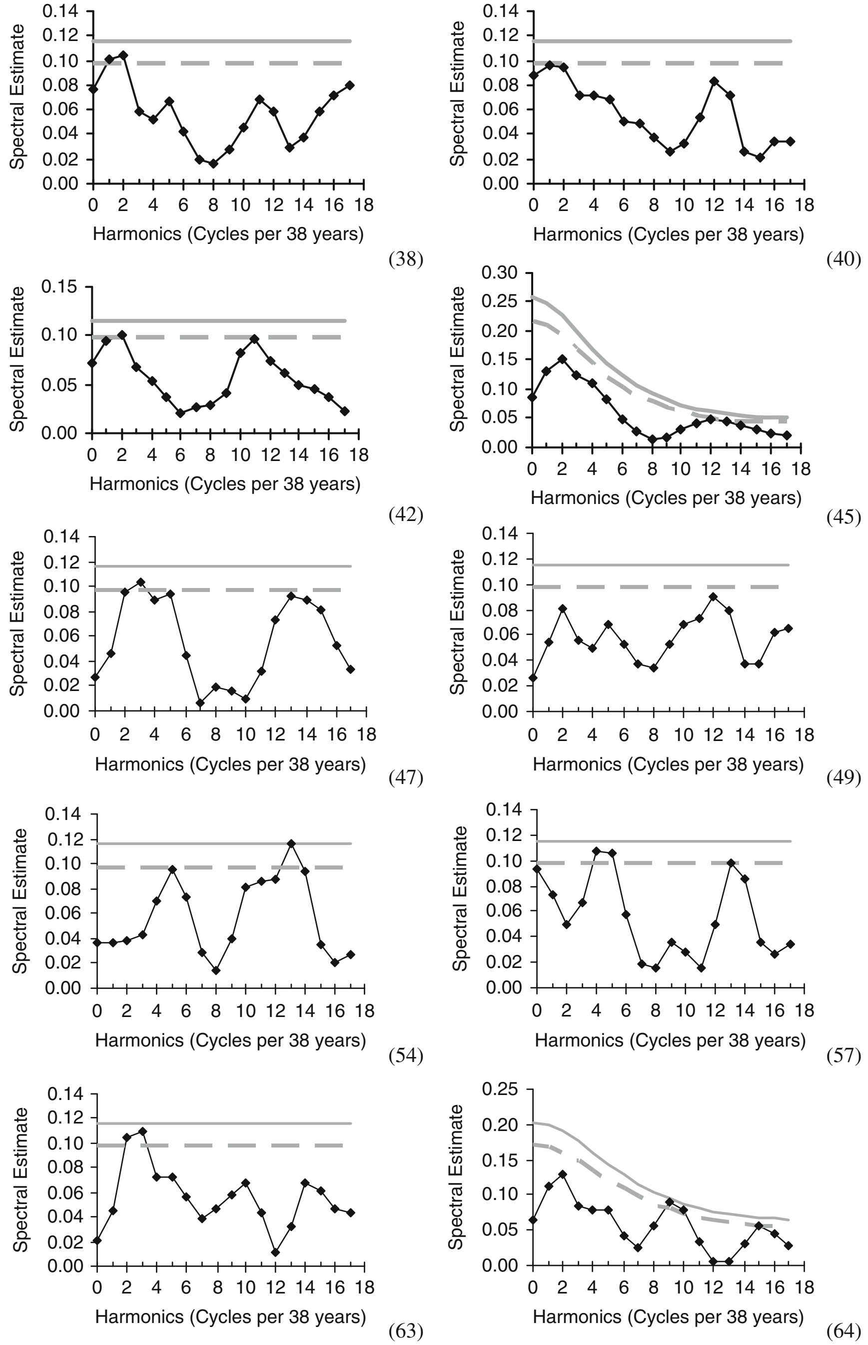


**Fig. 4.10** (continued)

period values are computed using eq. (4.26) (i.e., $P = 2\ m/L$) for all the time series. The computed values of the period along with their significance level for monsoon rainfall, rainydays and OEM are given in Tables 4.1, 4.2, and 4.3 which also comprise serial correlation coefficients up to lag-3. Analysis revealsthat the short-term period fluctuation of 2.0–4.9 years is dominant in the annual and monsoon rainfall, whereas medium and long-term period of 5.0–34.0 years is dominant in case of non-monsoon rainfall. This short term periodic behavior (high frequency) of rainfall pattern in the Yamuna River basin should be kept in mind while preparing the water resources plan. In the case of number of rainydays, the long-period is dominated over the short- periodicity. Results of the power spectrum analysis of OEM and AI indicate that OEM and AI have dominating short-period fluctuations of 2.0–3.0 years, which lead to a high probability of meteorological and agricultural droughts and will frequently disturb the planning of *Kharif* crops in the Yamuna River basin.

## 4.4 Concluding Remarks

Based on the analysis, following conclusion can be drawn:

(i) There is a considerable difference in the monsoon and non-monsoon rainfall patterns in terms of persistence and periodicity.
(ii) Approximately 20% rainfall time series shows the presence of persistence characterized by lag-1 serial correlation.
(iii) The presence of serial correlation in the time series significantly affects Mann-Kendall's trend analysis.
(iv) The original Mann-Kendall test overestimates the presence of significant trend in the series than the modified Mann-Kendall and Mann-Kendall with pre-whitening tests. Based on the overall trend results, the original Mann-Kendall test results in approximately 37% more presence of significant trend than the modified Mann-Kendall test.
(v) Overall falling trend is observed in the annual rainfall, monsoon rainfall, annual rainydays, monsoon rainydays, and AI. In sixty five grid locations, the spatial mean of Mann-Kendall's $Z$-statistics for annual rainfall and monsoon rainfall were −0.832 and −0.874, respectively. Regardless of a few series having significant trends, most of the series have higher values of $Z$-statistic.
(vi) An increasing trend with overall mean $Z$-statistic of +1.81 is observed in OEM which shows the gradual delay in the onset of effective monsoon in the Yamuna River basin.
(vii) It may be remarked that the declining monsoon rainfall and number of monsoon rainydays along with the delay in the onset of effective monsoon (i.e. rising trend in OEM) should be of the great concern while preparing the river basin management plan.
(viii) It is observed that high frequency fluctuations associated with short-period cycle is dominating over the basin for annual and monsoon rainfall, OEM

and AI. However, for non-monsoon rainfall low frequency fluctuations are identified.

(ix) There is a good consistency between the lag-1 serial correlation and results of the power spectrum analysis. A positive lag-1 serial correlation coefficient gives low frequency fluctuations, whereas a negative one is an indicator for high frequency (Fig. 4.7).

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# Chapter 5
# Geomorphology and Geology

**Abstract** A detailed analysis of topography, geomorphology, and geology are presented in this chapter. The analysis comprises the classification of the Yamuna basin based on topography. The tributaries contributing to the Yamuna River are duly addressed. The chapter also provides a discussion of sub-catchment wise geomorphological characteristics, followed by spatial analysis of geological and hydrogeological formations.

Besides climate, topography, geomorphology and geology are the other important characteristics of the basin which are not only important for addressing water resources related issues but also the type of habitation. These parameters are highly important for watershed management, flood and drought estimation/management, water logging, erosion estimation/mitigation, identification of recharge zone, installation of hydropower system, construction of rainwater harvesting structure, other structural development, etc. In this chapter, a detailed description of these parameters is presented. This chapter also includes the description of major tributaries and river morphology of the Yamuna.

## 5.1 Topographic Characteristics

Topography of the Yamuna basin varies between steep topography in the Himalayan segment to almost flat in the middle and lower segments (Fig. 5.1). The elevation in the Yamuna River basin varies from about 6,320 m above mean sea level (msl) near Yamunotri Glacier to around 100 m (above msl) near the confluence of Yamuna River with River Ganga at Allahabad. The topography of the Yamuna basin can be classified into three groups, i.e., hilly region (more than 600 m above msl); foot hills and Plateau region (300–600 m); and plains and valleys (100–300 m above msl). On the basis of this topographic classification 11,700 $km^2$ basin area (about 3.19%) can be classified as hilly, while remaining equally divided between plains and plateau regions with 161,231 $km^2$ and 172,917 $km^2$, respectively. In the Himalayan segment (upper Yamuna catchment), the drainage system and the characteristics of landforms are closely interdependent and inter-related. The upper Yamuna catchment falls into three defined physiographic belts: the Lesser Himalaya, the Siwalik, and the Doon Valley. On the other hand, catchments of the Chambal, the Sind, the Betwa and the Ken experience undulating topography with

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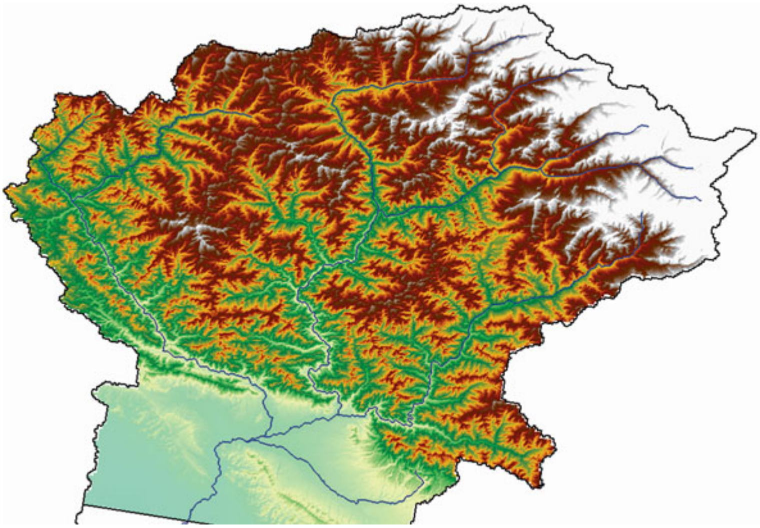

Fig. 5.1 Topography of Himalayan catchment of Yamuna River basin

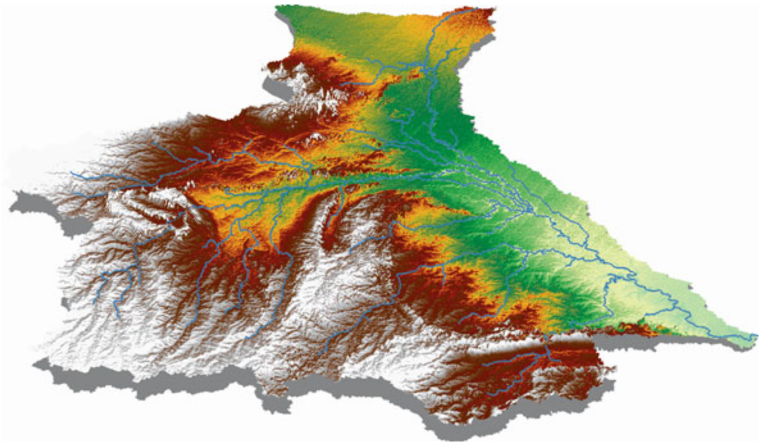

Fig. 5.2 Topography of the Yamuna River basin excluding the Himalayan catchment

ravines (Fig. 5.2). The digital elevation model showing the elevations is shown in Fig. 5.3.

*Lesser Himalaya* has a mild topography with gentle slopes and deeply dissected valleys which suggest that rivers and streams are still furiously at work. Elevation in this region ranges from 4,000 to 1,000 m. The upper part of this area has high mountains, most of which have seasonal snow capped peaks and glaciated ranges. Prominent glaciers are Bandarpunch, Jamadar Bamak and Deokhera Bamak. The retreating movement of these glaciers and their tributary glaciers may still be observed in the form of "V" shaped valleys with moraines and smooth and

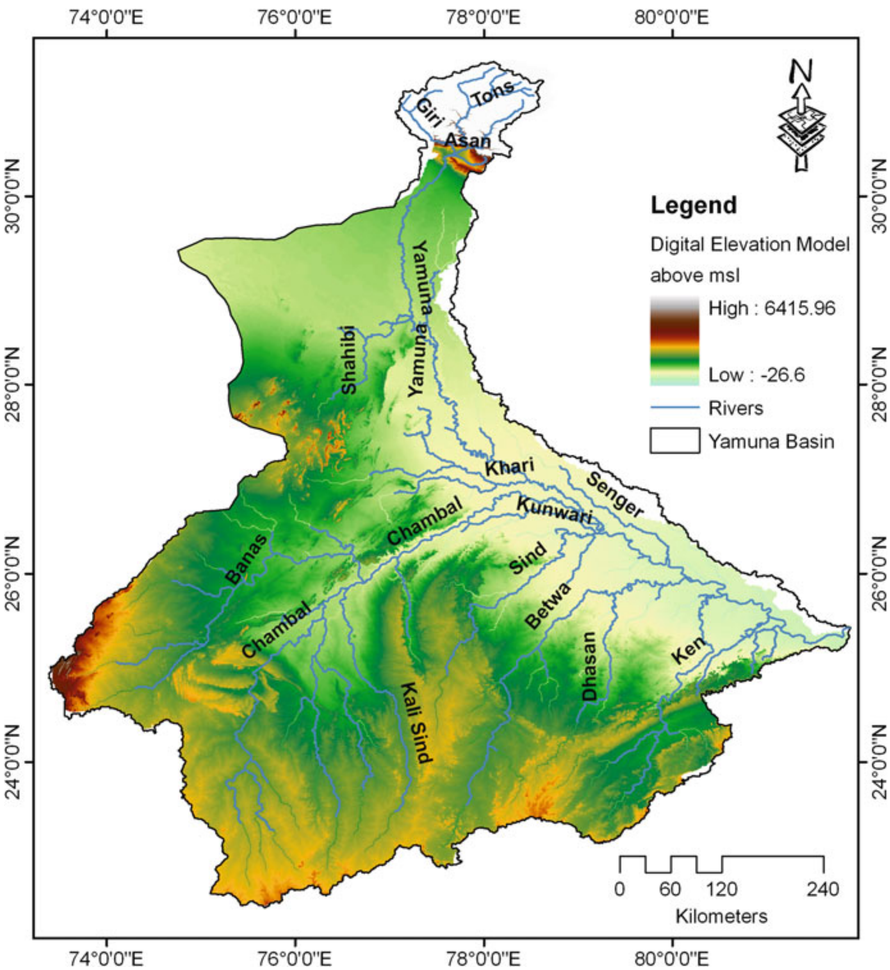


**Fig. 5.3** Digital Elevation Model and major tributaries of Yamuna River basin

aggradational slope (Jain et al., 2007). Low to moderately high mountains occur between the altitudes of 1,000 and 3,000 m. Actually, the Lesser Himalayas region is a massive mountainous tract with a series of ridges and spurs divided by river valleys. The slope varies from 25 to 50% but may rise even up to 80%. The rivers and their tributaries have carved out entrenched valleys with steep slopes in higher reaches, while flatter valleys are found in lower reaches. At a number of places, rivers have formed depositional terraces. A large part of this region is made up of sedimentary rock formations encroached by granite and basic volcanic rocks. The northern part has been subjected to low-grade metamorphism.

*The Siwalik Hills* are formed as a result of intense dissection by fine textured pattern of drainage lines. They are long prominent ridge trending NW-SE with altitudes

**Table 5.1** Average slopes in Yamuna River stretches

| S. No. | Stretch | Stretch length (km) | Rate of fall (m/km) | Slope (%) |
|---|---|---|---|---|
| 1 | Upper Himalaya | 25 | 59.0 | 5.90 |
| 2 | Himalaya Stretch | 152 | 19.1 | 1.91 |
| 3 | Total Plain Stretch | 1,224 | 0.20 | 0.02 |
| 4 | Lower Plain Stretch | 768 | 0.08 | 0.008 |

ranging from 750 to 1,500 m. The main ridge is composed of a gentle northern slope and a steeper southern slope. A water divide is located more or less half way through this ridge. It is drained with numerous parallel to sub-parallel streams flowing towards north or south in consequent entrenched channels. The Shiwalik or the outer Himalayan range is a youthful range separated from the lesser Himalayas by the main boundary fault.

*The Doon Valley* is a long tectonic synclinal structure of the outer Himalaya. It lies within the ranges of lesser Himalaya to the north and the Shiwalik range of the Outer Himalaya towards north. It is a low-lying region between the two ranges with altitudes not more than 500–750 m. The Doon gravels, composed of boulder and gravel beds with this clay bands, constitute the piedmont slopes. Stream frequency and drainage density is low here because of the poor development of drainage, possibly due to porous and permeable characteristics of bed rocks.

In the plains stretch the river flattens gradually with an average slope of 0.02%. The stretch wise average slope of the river is given in Table 5.1 which reflects a remarkable difference in rate of fall in valley profile of the Himalaya and the plain stretch. The maximum rate of fall of 59 m/km is experienced in the first 25 km of river from its origin, while it is minimum (i.e., 0.08 m/km) in the 768 km long tail end starting from Agra.

## 5.2 Major Tributaries

The important tributaries of the Yamuna River are the Tons, the Chambal, the Hindon, the Sind, the Betwa, the Ken, the Baghein, and the Mandakini. Other small tributaries of the Yamuna River include Rishiganga, the Uma, the Hanuman Ganga, the Giri, the Karan, the Sagar and the Rind. The main Yamuna and the Tons are fed by glaciers, viz., the Bandar Punch Glacier and its branches and originate from the Great Himalayan range. Many smaller streams in the Yamuna basin, viz., the Chautang, the Sahibi, the Dohan, the Kantili, the Bapah and the Banganga end up in the sandy tracts. Major tributaries of the Yamuna River system are shown in Fig. 5.4.

*Tons River*: The Tons River is the longest tributary of the Yamuna in the upper Himalayan segment. It flows through Garhwal, the western part of the Himalayan

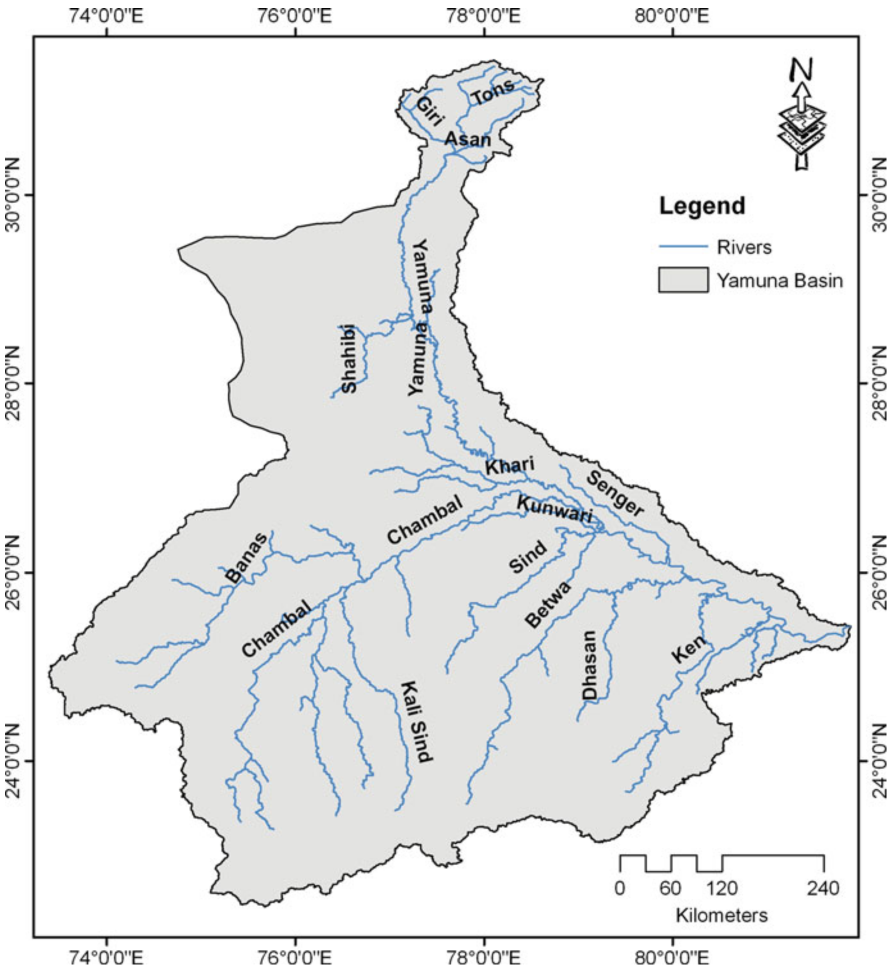


**Fig. 5.4** Major tributaries of Yamuna River

state of Uttarakhand. The river originates at an elevation of 3,900 m and joins the Yamuna below Kalsi. In fact, Tons carries more water than Yamuna itself.

*Kali River*: The Kali River originates from the Doon Valley in the western part of Uttarakhand. The catchment covers a drainage area of approximately 750 $km^2$ within the latitude of 29°13′30″ N and longitude of 77°32′45″ E. From its origin up to the confluence with Hindon River, the river travels a distance of approximately 150 km through Saharanpur and Muzaffarnagar, Meerut and Ghaziabad districts. Despite a significant drainage area, mostly lying in plains, the river does not carry any significant flow. The city of Muzaffarnagar is situated on the left bank of the Kali River.

Kali River is a highly polluted river which receives pollutants including heavy metals and industrial sludge from a dozen of towns along the river from Saharanpur to Kannauj. The presence of salt of cyanide has resulted in over 100 species of getting extinct from river over the past 40 years.

*Hindon River*: Hindon is an important tributary of Yamuna River. In fact, this river is sand-witched between two major rivers: the Ganga on the left and Yamuna on the right. Hindon originates from upper Shiwalik (Lower Himalayas). It is purely a rainfed river with catchment area of about 7,083 $km^2$. This river has a total run of about 400 km. The width of Hindon River ranges from 20 to 160 m.

*Banganga River*: The Banganga River originates in the Aravali hills, near Arnasar and Bairath in Jaipur District. It flows towards the south up to the village of Ghat, then east through partly hilly and partly plain terrain. The length of the river is 240 km. The main tributaries of the Banganga River are Gumti Nala (latitude: 25°0.5′–25°53′ N; longitude: 75°52′–76°01′ E; length: 24 km; drainage area: 102 $km^2$), Suri River (latitude: 26°44′–26°53′ N; longitude: 76°25′–76°30′ E; length: 18 km; drainage area: 76 $km^2$), Sanwan (latitude: 26°59′–27°22′ N; longitude: 76°16′–76°46′ E; length: 29 km; drainage area: 660 $km^2$) and Palasan River (latitude: 27°02′–27°18′ N; longitude: 76°25′–76°49′ E; length: 24 km; drainage area: 539 $km^2$).

*Chambal River*: The Chambal River, called Charmanvati in ancient times, is the largest of the rivers flowing through Rajasthan. This tributary of Yamuna River is 960 km long draining 134,689 $km^2$ areas between the latitudes of 22°27′–27°20′ N and longitudes of 73°20′–79°15′ E. The Chambal River rises in northern slopes of Vindhyan Mountain, about 15 km West-South-West of Mhow in Indore district in Madhya Pradesh at an elevation of about 853 m. The river flows first in a northerly direction in Madhya Pradesh for a length of about 346 km and after passing the historic fort of Chaurasigarh, it flows in a generally north-easterly direction for a length of around 225 km through Rajasthan. The Chambal River flows for another 217 km between Madhya Pradesh and Rajasthan and further 145 km between Madhya Pradesh and Uttar Pradesh. The Chambal River enters Uttar Pradesh near the Charak Nagar village and flows for about 32 km before joining the Yamuna River, south east of the Sahon village in Etawah district at an elevation of about 122 m. Three dams, namely, Gandhi Sagar, Rana Pratap Sagar and Jawahar Sagar have been constructed in its basin.

From the source to its confluence with the Yamuna River, the Chambal has a fall of about 732 m. Out of this approximately 305 m is within the first 16 km reach. It falls for another 195 m in the next 338 km, where it enters the gorge past the Chaurasigarh Fort. In the next 97 km of its run from Chaurasigarh Fort to Kota city, the bed falls by another 91 m. In the rest of its 523 km, the river passes through the flat terrain of the Malwa Plateau and later in the Gangetic Plain with an average gradient of 0.21 m/km. River Chambal flows through the deep gorge and has, therefore, a large scope to build the storage capacity. Up to Kota barrage, three large storages have been built namely, Gandhi Sagar, Rana Pratap Sagar and Jawahar Sagar. The Kota barrage is located near the Kota town, where the river emerges from the gorge section into the plateau. The total area draining at the Kota barrage is 27,319 $km^2$. Important tributaries of the Chambal River are summarized in Table 5.2.

**Table 5.2** Description of important tributaries of the Chambal River

| S. No. | Name | Tributary/River | Description |
|---|---|---|---|
| 1 | Alnia | Chambal | Origin: North-western slopes of Mukindwara hills<br>Length: 58 km<br>Confluence: with Chambal near Notana village in Kota<br>Catchment area: 792 $km^2$ |
| 2 | Kalisindh | Chambal | Origin: Northern slopes of Vindhyan hills<br>Length: 145 km<br>Confluence: joins Chambal near Nonera village in Kota<br>Catchment area: 7,944 $km^2$<br>Extend: Jhalwar and Kota |
| 3 | Parwan | Kalisindh | Origin: Malwa Plateau<br>Length: It enter Rajasthan near Kharibor village of Jhalawar district after 186 km run in Madhya Pradesh<br>Confluence: joins Kalisindh near ramgarh village in Kota. Chambal near Notana village in Kota<br>Catchment area: 2,892 $km^2$ |
| 4 | Mej | Chambal | Origin: Mandalgarh Tehsil in Bhilwara District<br>Confluence: joins Chambal near Bhaius Khana village in Kota district<br>Catchment area: 5,860 $km^2$<br>Extend: Bhilwara, Bundi, Tonk |
| 5 | Chakan | Chambal | Origin: formed by the confluence of many small rivulets.<br>Flow direction: South-easterly<br>Confluence: Chambal near Karanpura village in Sawai Madhopur district.<br>Catchment area: 789 $km^2$<br>Extend: Sawai Madhopur, Tonk, Bundi, and Kota |
| 6 | Parwati | Chambal | Origin: northern slopes of Vindhyan hills in Madhya Pradesh<br>Flow direction: South-easterly<br>Length: 159 km<br>Confluence: Chambal at Pali village in Kota district.<br>Catchment area: 5,001 $km^2$<br>Tributaries: Lhasi, Berni, Bethli, Andheri, Retri, Dubraj, Bilas and Kunu |
| 7 | Kunu | Parwati | Origin: north of Guna town in Madhya Pradesh<br>Confluence: Chambal at Gordhanpura village in Kota district.<br>Catchment area: 726 $km^2$<br>Tributaries: Karal and Rempi |
| 8 | Banas | Chambal | Origin: Khamnor hills of the Aravali range (about 5 km from Kumbhalgarh)<br>Length: 512 km<br>Confluence: Chambal at Rameshwar village in Khandar block of Sawai Madhopur district.<br>Catchment area: 45,833 $km^2$<br>Tributaries: Berach (R), Menali (R), Kothari (L), Khari (L), Dai (L), Dheel (L), Sohadara (L), Morel (L) and Kalisil (L) |

**Table 5.2** (continued)

| S. No. | Name | Tributary/River | Description |
|---|---|---|---|
| 9 | Berach | Banas | Origin: in the hills northeast of Udaipur city.<br>Length: 157 km (flows in a hilly region up to Badgaon reservoir and then through plains).<br>Direction: northeast<br>Confluence: Banas near Bigod village in Mandalgarh village of Bhilwara district.<br>Catchment area: 7,502 km$^2$<br>Tributaries: Ayar, Wagli Wagon, Gambhiri and Orai |
| 10 | Mashi | Banas | Origin: Kishangarh in Ajmer district.<br>Length: 96 km (flows east and then south in partly hilly and partly plain areas of Ajmer and Tonk district).<br>Direction: east<br>Confluence: Banas near Tonk.<br>Catchment area: 6,335 km$^2$ |
| 11 | Khari | Banas | Origin: hills near Deogarh in Rajsamand district.<br>Length: 192 km (through Udaipur, Bhilwara and Ajmer district).<br>Direction: northeast<br>Confluence: Banas near Chosala village in Ajmer district.<br>Catchment area: 6,268 km$^2$ |
| 12 | Dai | Banas | Origin: southeast slopes of Aravali range near Nasirabad Tehsil of Ajmer district.<br>Length: 96 km<br>Confluence: Banas river near Bisalpur village of Tonk district.<br>Catchment area: 3,015 km$^2$ |
| 13 | Morel | Banas | Origin: in the hills near Dharla and Chaibnpura villages in Bassi Tehsil of Jaipur district.<br>Length: 147 km<br>Confluence: Banas river near Hadoli village in Karauli Tehsil of Sawai Madhopur district.<br>Tributaries: Dhund, Kankrauli and Kalisil |
| 14 | Kothari | Banas | Origin: in the eastern slopes of the Aravali range near Horera village in Bhilwara district.<br>Length: 151 km<br>Confluence: Banas river near Nandrai village in Bhilwara district<br>Catchment area: 2,341 km$^2$ |

*Betwa River*: The Betwa River is a tributary of Yamuna River. Its basin extends from longitude 77°00′ to 81°00′ E and latitude 23°08′ to 26°00′ N. The Betwa River originates at an elevation of 706 m in the Bhopal district in Madhya Pradesh. After traversing a distance of 590 km, the river joins the Yamuna River near Hamirpur of Uttar Pradesh at an elevation of 106.68 m. The total catchment area of the Betwa

River catchment is 46,580 km$^2$ of which 31,971 km$^2$ (68.64%) lies in Madhya Pradesh and 14,609 km$^2$ (31.36%) lies in Uttar Pradesh. The basin is saucer (bowl) shaped with sandstone hills around the perimeter. The river has 14 principal tributaries out of which 11 are completely in Madhya Pradesh and 3 lie in Madhya Pradesh and partly in Uttar Pradesh. The Halali and Dhasan Rivers are the important tributaries of the Betwa River. The Halali is the largest tributary having a length of 180.32 km.

*Ken River*: Ken is an inter-state river, flowing through the states of Madya Pradesh and Uttar Pradesh. Its basin lies between north latitudes of 23°20′and 25°20′ and east longitudes of 78°30′ and 80′32′. The river originates near the village Ahirgawan in north-west slopes of Kaimur hills of Jabalpur district of Madhya Pradesh at an altitude of 550 m above mean sea level and joins the Yamuna near Chilla village in Uttar Pradesh at an elevation of about 95 m. The river has a total length of 427 km, out of which 292 km lies in Madhya Pradesh, 84 km in Uttar Pradesh and 51 km forms the common boundary between Madhya Pradesh and Uttar Pradesh. The drainage area of the Ken River catchment is 28,058 km$^2$, out of which 24,472 km$^2$ lies in Madhya Pradesh and the balance 3,586 km$^2$ in Uttar Pradesh. The important tributaries of Ken River are Sonar, Bearma, Kopra, Bewas, Urmil, Mirhasan, Kutni, Kail, Gurne, Patan, Siameri, Chandrawal, Banne, etc. In terms of catchment area, Sonar is the largest tributary which traverses a distance of 227 km and drains approximately 6,550 km$^2$ areas. The Sonar River catchment fully lies in Madhya Pradesh, extends between 23°20′ and 23°50′ N latitudes and 78°30′–79°15′ E longitudes. It is a leaf shaped elongated catchment, with an average width of about of 40 km. The Sonar catchment is bounded by Bearma catchment in the east side and Dhasan catchment on the west side and the Vindhyan ranges on the south. Sagar and Damoh are the major district falling in the catchment, and parts of Panna, Chhatarpur and Raisen districts also falls in the catchment.

## 5.3 Geomorphologic Characteristics

Geomorphology of a river basin describes the status of topographic features of the surfaces and streams, and its relationship with geomorphometry provides the geomorphological control on basin hydrology (Rai et al., 2009). Geomorphology reflects the topographic and geometric properties of the watershed and its drainage channel network. It controls the hydrologic processes from rainfall to runoff, and the subsequent flow routing through the drainage network. The role of basin geomorphology in controlling the hydrological response of a river basin is known for a long time. Moreover, for any infrastructural development, it is a very useful tool for the first hand overview of the basin. It is advantageous in the case of laying out the urban drainage and irrigation canal systems, aqueducts; study the physiographic impacts on environment, and selection of silt disposal site, hydropower site, recharge zone, percolation tank, retention tank, dam site, etc. This drainage network analysis of the river basin can provide a significant contribution towards flood management and water logging program (Rai et al., 2009). Earlier works have provided an understanding of basin geomorphology-hydrology relationship through empirical relationships (Snyder, 1938; Horton, 1945; Taylor and Schwartz, 1952; Singh, 1988b; Singh, 1989; Jain and Sinha, 2003; etc.). Snyder (1938) proposed a synthetic unit hydrograph approach (SUH) for ungauged basin as a function of catchment area, basin shape, topography, channel slope, stream density and channel storage; and derived the basin coefficient by averaging out other parameters.

## *5.3.1 Geomorphologic Parameters*

Certain characteristics of the drainage basins reflect hydrologic behavior and are, therefore, useful, when quantified, in evaluating the hydrologic response of the basins. These characteristics relate to either the physical drainage basin of channels. Physical characteristics of the drainage basin include drainage area, basin shape, ground slope, and centroid (i.e. centre of gravity of the basin). Channel characteristics include channel order, channel length, channel slope, channel profile, and drainage density.

### 5.3.1.1 Basin Order and Channel Order

Drainage areas may be characterized in terms of the hierarchy of stream ordering. The order of the basin is the order of its highest-order channel. An inspection of a drainage basin channel network reveals that as one traces the flow from one of the uppermost channels in the basin towards the outlet. This upper most channel joins another channel, which in turn joins another channel and so on. The first order channel is defined as those channels that receive water entirely from surface overland flow and does not have tributaries. The junction of two first order streams forms the second order stream. A second order channel receives flow from the two first order channels and from overland flow from surface and it might receive the flow from another first order stream. Thus, a second order channel must carry much more flow of water than a first order channel. When the two second order streams join, together they form the third order stream, and so on. This scheme of stream ordering is referred to as the Horton-Strahler ordering scheme (Horton, 1945; Strahler, 1957). A watershed is described as first-, second-, third-, or higher order, depending upon the stream order at the outlet (i.e., highest-order stream within the watershed area).

### 5.3.1.2 Basin Area

Basin area is defined as the area contained within the vertical projection of the drainage divide on a horizontal plane. Some areas in the drainage basin do not contribute to the runoff and are termed as closed drainage. These areas may be lakes, swamps, etc.

#### 5.3.1.3 Basin Shape

The watershed shape may influence the hydrograph shape, especially for small watersheds. For example, if the watershed is long and narrow, then it will take longer time for water to travel from the most extreme point to the outlet and the resulting hydrograph shape is flatter. For more compacted watershed, the runoff hydrograph is expected to be sharper with a greater peak and shorter duration. Numerous symmetrical and irregular forms of drainage areas are encountered in practice. To define the basin shape, a multitude of dimensionless parameters are used to quantify and these are: form factor, shape factor, elongation ratio, circulatory ratio, and compactness coefficient (Table 5.3). These factors involve watershed length, area and perimeter. The watershed length can be defined as the length of the main stream from its source (projected to the perimeter) to the outlet. Clearly, the form factor is less than unity and its reciprocal, the shape factor, is grater than unity. A square drainage basin has the shape factor equal to unity, whereas the long narrow drainage basin would have a shape factor greater than unity. The elongation ratio, circulatory ratio, and compactness coefficient approach to unity as the watershed shape approaches a circle.

#### 5.3.1.4 Basin Slope

Basin slope has a pronounced effect on the velocity of overland flow, watershed erosion potential, and local wind systems. The average basin slope is defined as

$$S = h/L \tag{5.1}$$

where $S$ is the average basin slope (m/m), $h$ is the fall (m), and $L$ is the horizontal distance (m) over which the fall occurs.

**Table 5.3** Watershed shape parameters (Singh, 1988b)

| Parameter | Definition | Formula | Value |
|---|---|---|---|
| Form factor | $\frac{\text{Watershed area}}{(\text{Watershed length})^2}$ | $= A/L^2$ | <1 |
| Shape factor, $B_s$ | $\frac{(\text{Watershed length})^2}{\text{Watershed area}}$ | $L^2/A$ | >1 |
| Elongation ratio | $\frac{\text{Diameter of circle of watershed area}}{\text{Watershed length}}$ | $\frac{1.128A^{0.5}}{L}$ | ≤1 |
| Circulatory ratio | $\frac{\text{Watershed area}}{\text{Area of circle of watershed area}}$ | $\frac{12.57A}{P_r^2}$ | ≤1 |
| Compactness coefficient | $\frac{\text{Watershed perimeter}}{\text{Perimeter of circle of watershed area}}$ | $\frac{0.2821P_r}{A^{0.5}}$ | ≥1 |

$A$ watershed area, $L$ watershed length, $P_r$ watershed perimeter

#### 5.3.1.5 Drainage Basin Similarity

Strahler (1957) hypothesized the drainage basin similarity as follows:

$$A/L_{\mathrm{b}}^2 = C \tag{5.2}$$

where $A$ is the area of the drainage basin [$L^2$], $L_{\mathrm{b}}$ is the length of the basin [$L$] and $C$ is the constant for basin similarity.

#### 5.3.1.6 Drainage Density

Drainage density is defined as the length of drainage per unit area. This term was first introduced by Horton (1932) and is expressed as

$$D_{\mathrm{d}} = L/A \tag{5.3}$$

or

$$D_{\mathrm{d}} = \frac{\sum_{i=1}^{\Omega}\sum_{j=1}^{N_i} L_{i,j}}{A} \tag{5.4}$$

The above relationships can be simplified as follows

$$D_{\mathrm{d}} = \frac{\bar{L}_1 R_{\mathrm{b}}^{\Omega-1}}{A} \cdot \frac{r^{\Omega} - 1}{r - 1} \tag{5.5}$$

where

$$r = R_{\mathrm{l}}/R_{\mathrm{b}} \tag{5.6}$$

### 5.3.2 *Determination of Horton's Ratio*

Three Horton's ratios, namely bifurcation ratio ($R_{\mathrm{b}}$), stream-length ratio ($R_{\mathrm{l}}$) and stream-area ratio ($R_{\mathrm{a}}$) are unique representative parameters for a given watershed and are fixed values for a given watershed system. These parameters play an important role in deriving the geomorphologic instantaneous unit hydrograph and thus the unit hydrograph and flood hydrographs for catchments.

#### 5.3.2.1 Bifurcation Ratio $R_{\mathrm{b}}$

The number of channels of a given order in a drainage basin is a function of the nature of the surface of that drainage basin. In general, the greater the infiltration of the soil material covering the basin, the fewer will be the number of channels required to carry the remaining runoff water. Moreover, the larger the number of channels of a given order, the smaller is the area drained by each channel order. A dimensionless parameter based on the number of channels with respect to their order is termed as bifurcation ratio and is useful in defining the watershed response. The bifurcation ratio is given as follows:

$$R_b = N_i/N_{i+1} \tag{5.7}$$

where $R_b$ is the bifurcation ratio, $N_i$ and $N_{i+1}$ are the number of streams in order $i$ and $i$+1 respectively, $i = 1, 2, \ldots, \Omega$ and $\Omega$ is the highest stream order of the watershed. The value of $R_b$ for watersheds varies between 3 and 5. This law is an expression of topological phenomenon, and is a measure of drainage efficiency.

#### 5.3.2.2 Stream-Length Ratio $R_l$

This refers to length of channels of each order. The average length of channels of each higher order increase as a geometric sequence, which can be further explained as follows: the first order channels are the shortest of all the channels and the length increases geometrically as the order increases. This relation is called Horton's law of channel length and can be formulated as follows:

$$\bar{L}_i = \bar{L}_1 R_l^{i-1} \tag{5.8}$$

where $\bar{L}_i$ is the average length of channel of order $i$, $R_l$ is the stream-length ratio. The $R_l$ is mathematically expressed as follows:

$$R_l = \bar{L}_{i+1}/\bar{L}_i \tag{5.9}$$

where

$$\bar{L}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} L_{j,\,i} \tag{5.10}$$

The lengths of channels of a given order are determined largely by the type of soil covering the drainage basin. Generally, more pervious the soil, longer will be the channel length of a given order. Also, higher is the $R_l$ more will be the imperviousness. Generally it varies between 1.5 and 3.5.

#### 5.3.2.3 Stream-Area Ratio $R_a$

The Channel area of order $i$, $A_i$ is the area of the watershed that contributes to the channel segment of order $i$ and all lower order channels. It can be quantified as:

$$\bar{A}_i = \bar{A}_1 R_a^{i-1} \tag{5.11}$$

where $\bar{A}_i$ is the average area of order $i$ and $R_a$ is the stream area ratio. These are given as follows:

$$R_a = \bar{A}_{i+1}/\bar{A}_i \tag{5.12}$$

$$\bar{A}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} A_{j,\,i} \tag{5.13}$$

where $A_{j,\,i}$ is the total area that drains into the $j$th stream area of order $i$.

**Table 5.4** Geomorphologic characteristics of the Yamuna basin

| | | | |
|---|---|---|---|
| Area (km$^2$) | 366,394.0 | Minimum elevation (m) | 62.0 |
| Perimeter (km) | 5,414.7 | Relief (m) | 6,226.0 |
| Length of basin (km) | 1,376.0 | Mean slope (m/km) | 4.525 |
| Maximum elevation (m) | 6,288.0 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area (km$^2$) |
| 1 | 6053 | 36,805.61 | 23,5948.5 |
| 2 | 2775 | 17,727.18 | 29,6485.8 |
| 3 | 890 | 9,068.76 | 329,752.3 |
| 4 | 72 | 5,464.85 | 34,9845.5 |
| 5 | 21 | 2,859.14 | 360,242.5 |
| 6 | 5 | 7,94.07 | 363,315.2 |
| 7 | 2 | 886.99 | 366,394.3 |
| *Ratios* | | | |
| Bifurcation ratio | 4.63 | Shape factor | 5.17 |
| Length ratio | 2.64 | Elongation ratio | 0.496 |
| Stream-area ratio | 4.94 | Circulatory ratio | 0.157 |
| Horton ratio | 0.568 | Compactness coefficient | 2.523 |
| Drainage density | 0.20 | Basin slope (m/m) | 0.0045 |
| Drainage frequency | 0.026 | Length of overland flow (km) | 2.49 |
| Form factor | 0.193 | | |

**Table 5.5** Geomorphologic characteristics of the upper Yamuna catchment

| | | | |
|---|---|---|---|
| Area (km$^2$) | 11,359.8 | Minimum elevation (m) | 297 |
| Perimeter (km) | 718.56 | Relief (m) | 5,991 |
| Length of basin (km) | 210 | Mean slope (m/km) | 28.5286 |
| Maximum elevation (m) | 6,288 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area (km$^2$) |
| 1 | 177 | 964.0 | 6,988.995 |
| 2 | 39 | 485.8 | 9,278.07 |
| 3 | 7 | 373.4 | 10,893.92 |
| 4 | 1 | 120.9 | 11,359.8 |
| *Ratios* | | | |
| Bifurcation ratio | 5.703 | Shape factor | 3.882 |
| Length ratio | 2.945 | Elongation ratio | 0.572 |
| Stream-area ratio | 6.622 | Circulatory ratio | 0.276 |
| Horton ratio | 0.516 | Compactness coefficient | 1.902 |
| Drainage density | 0.171 | Basin slope (m/m) | 0.02853 |
| Drainage frequency | 0.0197 | Length of overland flow (km) | 2.921 |
| Form factor | 0.258 | | |

**Table 5.6** Geomorphologic characteristics of the Chambal basin

| | | | |
|---|---|---|---|
| Area (km$^2$) | 134,689.4 | Minimum elevation (m) | 87 |
| Perimeter (km) | 3,202.1 | Relief (m) | 1,219 |
| Length of basin (km) | 960 | Mean slope (m/km) | 1.704 |
| Maximum elevation (m) | 1,306 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area (km$^2$) |
| 1 | 2,260 | 13,541.5 | 88,190.4 |
| 2 | 1,412 | 63,88.9 | 110,464.7 |
| 3 | 102 | 2,843.1 | 120,959.8 |
| 4 | 27 | 2,064.7 | 128,594.7 |
| 5 | 8 | 1,061.9 | 132,482.9 |
| 6 | 2 | 193.2 | 133,165.2 |
| 7 | 1 | 389.1 | 134,689.4 |
| *Ratios* | | | |
| Bifurcation ratio | 4.76 | Shape factor | 3.79 |
| Length ratio | 1.361 | Elongation ratio | 0.578 |
| Stream-area ratio | 5.12 | Circulatory ratio | 0.165 |
| Horton ratio | 0.286 | Compactness coefficient | 2.461 |
| Drainage density | 0.197 | Basin slope (m/m) | 0.0017 |
| Drainage frequency | 0.028 | Length of overland flow (km) | 2.543 |
| Form factor | 0.263 | | |

**Table 5.7** Geomorphologic characteristics of the Sind sub-basin

| | | | |
|---|---|---|---|
| Area (km$^2$) | 27,940.0 | Minimum elevation (m) | 93.0 |
| Perimeter (km) | 1,308.71 | Relief (m) | 469.0 |
| Length of basin (km) | 440.0 | Mean slope (m/km) | 1.066 |
| Maximum elevation (m) | 562.0 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area (km$^2$) |
| 1 | 442 | 2,562.91 | 17,395.7 |
| 2 | 80 | 1,147.96 | 21,560.2 |
| 3 | 20 | 738.09 | 24,352.9 |
| 4 | 6 | 603.76 | 26,782.6 |
| 5 | 2 | 293.2 | 27,936.3 |
| 6 | 1 | 2.92 | 27,946.6 |
| *Ratios* | | | |
| Bifurcation ratio | 3.55 | Shape factor | 6.93 |
| Length ratio | 1.86 | Elongation ratio | 0.428 |
| Stream-area ratio | 4.01 | Circulatory ratio | 0.205 |
| Horton ratio | 0.524 | Compactness coefficient | 2.21 |
| Drainage density | 0.191 | Basin slope (m/m) | 0.00106 |
| Drainage frequency | 0.02 | Length of overland flow (km) | 2.61 |
| Form factor | 0.144 | | |

**Table 5.8** Geomorphologic characteristics of the Betwa sub-basin

| | | | |
|---|---|---|---|
| Area ($km^2$) | 43,651.6 | Minimum elevation (m) | 79.0 |
| Perimeter (km) | 1,689.4 | Relief (m) | 627.0 |
| Length of basin (km) | 590.0 | Mean slope (m/km) | 1.063 |
| Maximum elevation (m) | 706.0 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area ($km^2$) |
| 1 | 725 | 4,186.97 | 28,538.37 |
| 2 | 317 | 1,922.3 | 35,381.33 |
| 3 | 32 | 1,039.55 | 39,691.11 |
| 4 | 8 | 513.43 | 41,701.67 |
| 5 | 2 | 438.67 | 43,237.05 |
| 6 | 1 | 116.8 | 43,651.64 |
| *Ratios* | | | |
| Bifurcation ratio | 3.91 | Shape factor | 7.97 |
| Length ratio | 2.15 | Elongation ratio | 0.40 |
| Stream-area ratio | 4.33 | Circulatory ratio | 0.192 |
| Horton ratio | 0.55 | Compactness coefficient | 2.28 |
| Drainage density | 0.188 | Basin slope (m/m) | 0.00106 |
| Drainage frequency | 0.021 | Length of overland flow (km) | 2.656 |
| Form factor | 0.125 | | |

**Table 5.9** Geomorphologic characteristics of the Ken sub-basin

| | | | |
|---|---|---|---|
| Area ($km^2$) | 28,572.85 | Minimum elevation (m) | 76 |
| Perimeter (km) | 1,411.62 | Relief (m) | 663 |
| Length of basin (km) | 427 | Mean slope (m/km) | 1.5527 |
| Maximum elevation (m) | 739 | | |
| *Stream characteristics* | | | |
| Stream order | Number | Length (km) | Area ($km^2$) |
| 1 | 486 | 2,594.4 | 18,143.7 |
| 2 | 102 | 1,219.5 | 22,709.3 |
| 3 | 24 | 758.9 | 25,763.4 |
| 4 | 7 | 255.9 | 26,759.7 |
| 5 | 2 | 185.8 | 27,443.1 |
| 6 | 1 | 273.4 | 28,572.4 |
| *Ratios* | | | |
| Bifurcation ratio | 3.58 | Shape factor | 6.38 |
| Length ratio | 2.304 | Elongation ratio | 0.446 |
| Stream-area ratio | 4.00 | Circulatory ratio | 0.180 |
| Horton ratio | 0.642 | Compactness coefficient | 2.356 |
| Drainage density | 0.185 | Basin slope (m/m) | 0.00155 |
| Drainage frequency | 0.022 | Length of overland flow (km) | 2.702 |
| Form factor | 0.157 | | |

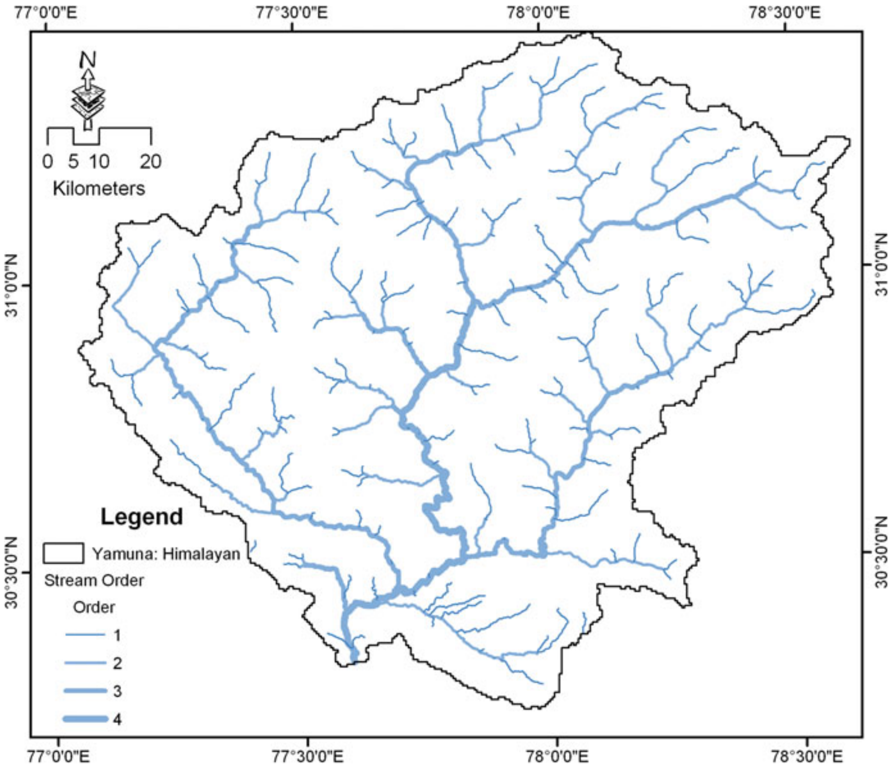


**Fig. 5.5** Stream order and drainage network of Upper Yamuna Catchment (Himalayan)

Using the digital elevation model (DEM) of 30 m resolution of the basin, geomorphologic characteristics of the Yamuna basin has been extracted using the ArcGIS and are summarized in Table 5.4. Similarly, the geomorphologic characteristics of other sub-basins, viz., Upper Himalayan Catchment (up to Hathnikund barrage), Chambal, Sind, Betwa and Ken are summarized in Tables 5.5, 5.6, 5.7, 5.8, and 5.9. The stream network of the sub-basins is shown in Figs. 5.5, 5.6, 5.7, 5.8, and 5.9.

## 5.4 Geology of the Basin

The geological formation of the Yamuna basin has five major classes, viz., Proterozoic, Paleozoic, Mesozoic, Cenozoic and Deccan Volcanics/Sediments (Fig. 5.10). A brief description of these classes is given as follows.

*Cenozoic*: The Cenozoic "means the new life" is the most recent of the three classic geologic eras and covers the period from 65.5 million years (myrs) to the present. It is marked by the Cretaceous-Tertiary extinction event at the end of the

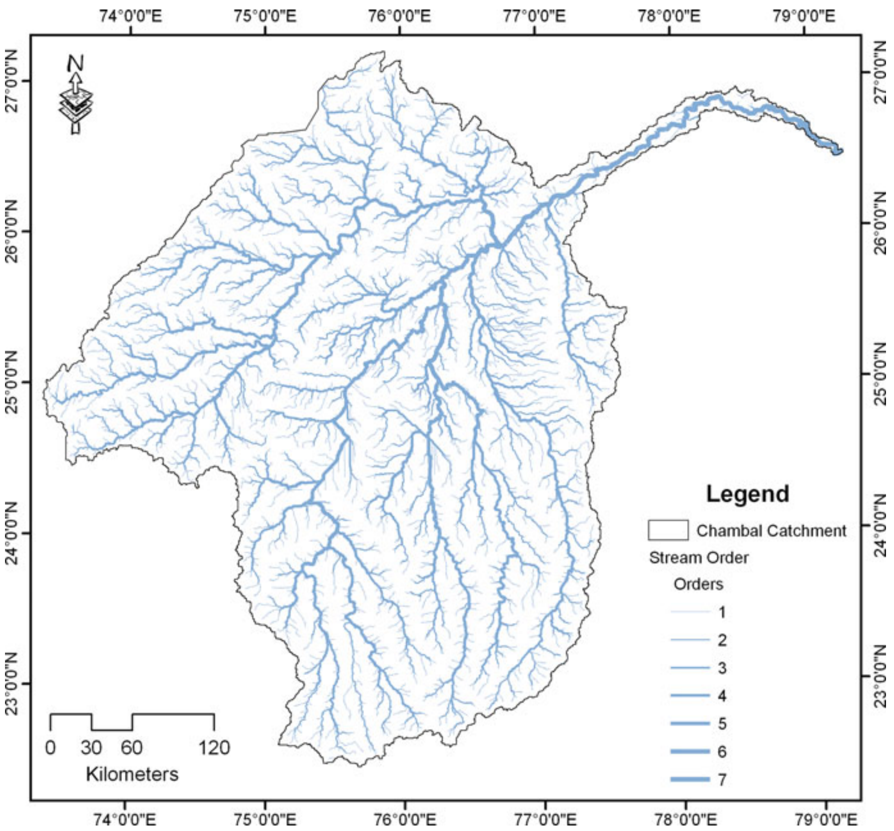


**Fig. 5.6** Stream order and drainage network of Chambal sub-basin

Cretaceous that saw the demise of the last non-avian dinosaurs and the end of the Mesozoic era. The Cenozoic era is ongoing. Major Gangetic plain (i.e., duab area of the Ganga-Yamuna system) and trans-Yamuna catchments come under this category. A few parts of the other catchment before the confluence with higher order streams also have this formation. This plain has a deeply incised river with 15–30 m of cliff sections along the river banks. Repeated degradation and aggradations events separated by the stratigraphic discontinuities are recognized in the alluvial sequence, which represents relatively slow rates of accumulation (Sinha et al., 2005).

*Mesozoic*: The Mesozoic era is an interval of geological time from about 250 myrs ago to about 65 myrs ago. It is called the age of Dinosaurs.

*Deccan Volcanics/Sediments*: Close to the Mesozoic era is marked by the outcropping of enormous lava flows which spread over vast areas of the Western, Central and Southern India. They issue through long narrow fissures or cracks in the earth's crust, from a large magma basin and are, therefore, called fissure eruptions. The lava spread out far and wide as nearly horizontal sheets, the earliest flows filling up the irregularities of the pre-existing topography. They appear to have erupted sub-aerially. The Deccan traps are thus the most extensive geological formation of

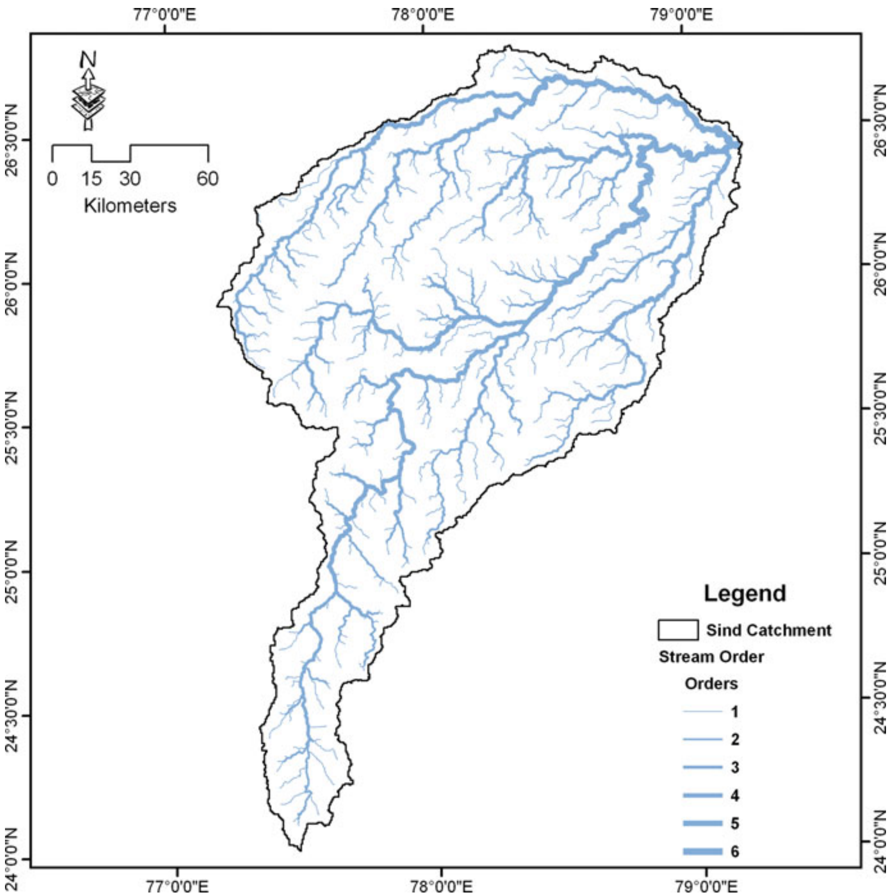


**Fig. 5.7** Stream order and drainage network of Sind sub-basin

Peninsular India at present, with the exception of the metamorphic and igneous complex of Achaean age. The existence of Deccan volcanic rocks or sediments is evident in the upstream part of the Chambal, Betwa and Ken catchment, as shown in Fig. 5.10.

*Paleozoic*: The Paleozoic or Paleozoic era is the earliest of three geological eras of the Phanerozoic Eon. The Paleozoic spanned from roughly 542–251 myrs ago, and is subdivided into six geologic periods; from oldest to youngest these are: the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian Fish population exploded in the Devonian. During the late Paleozoic, great forests of primitive plants thrived on land forming the great coal beds of Europe and Eastern North America. From the beginning of Paleozoic, shallow seas began to encroach on the continents. As the era proceeded, the marginal seas periodically washed over the stable interior, leaving sedimentary deposits to mark their incursions. In this era, evidence of glaciers is also experienced.

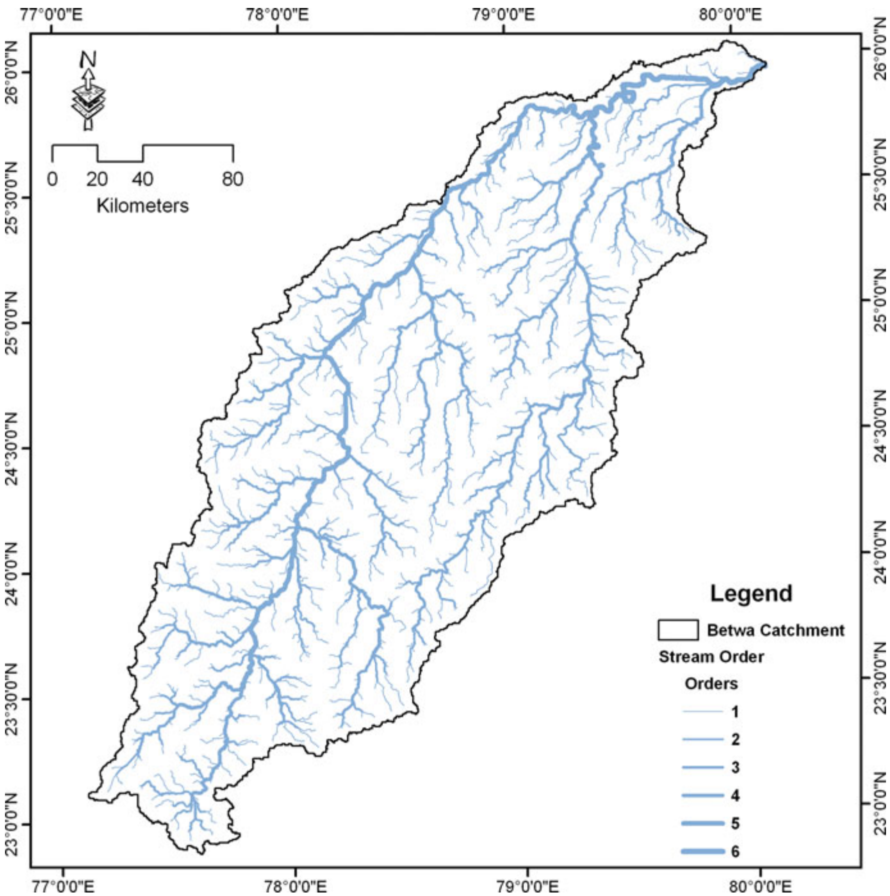


**Fig. 5.8** Stream order and drainage network of Betwa sub-basin

*Proterozoic*: The Vindhyan range is a classical example of Proterozoic intercontinental basin that developed in the central part of the Indian shield along with several other basins such as Cuddapah, Chhattisgarh, etc. The strata are exposed in three major areas: Son Valley, Bundelkhand and Rajasthan. Substantially thick Vindhyan rocks have also been recognized under the Gangetic alluvium. The constituent stratigraphic units of the Vindhyan Supergroup are laterally correlated and vertically stacked in a similar fashion in individual areas, but their stratigraphic and sedimentologic attributes vary from one area to the other. The dominant lithologies include conglomerate, sandstone, shale, limestone as well as volcaniclastics. The strata lie uncomfortably on the Achaean-early Proterozoic gneisses, high grade rocks, granite-greenstones or metasedimentaries of Proterozoic mobile belts. Most parts of the Vindhyas are composed of horizontally bedded sedimentary rocks of ancient age, the contemporaries of the Torridon sandstone of Scotland.

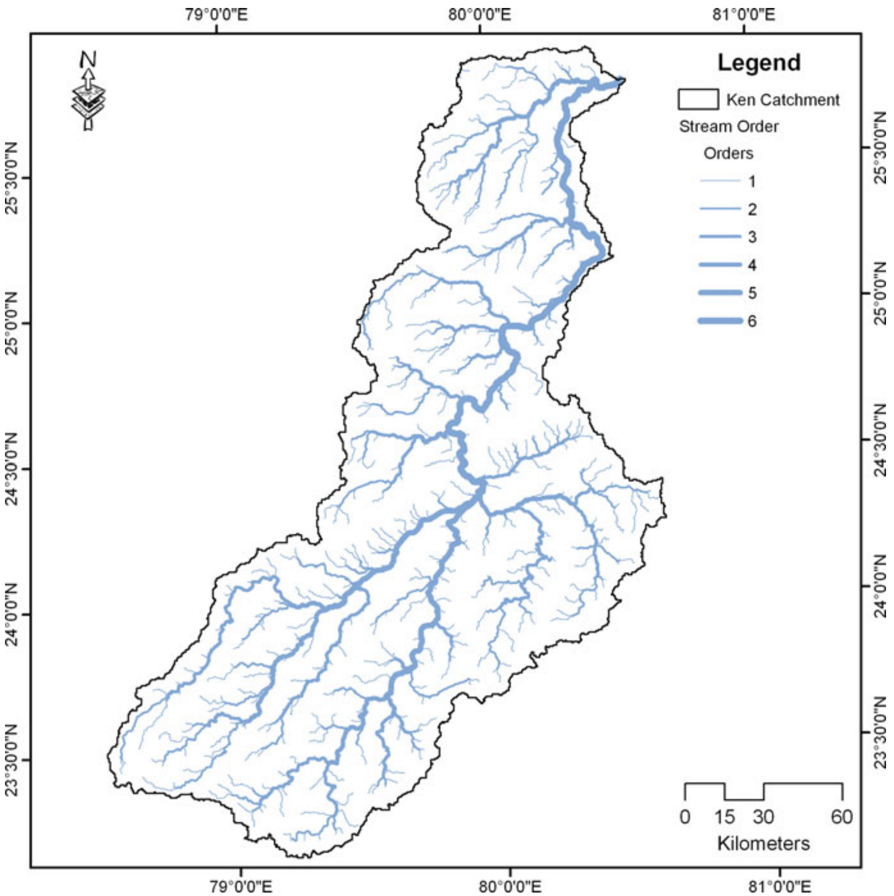


**Fig. 5.9** Stream order and drainage network of Ken sub-basin

The Vindhyan system is marked by a major ENE-WSW trending lineament termed Narmada-Son lineament south of which occurs the Satpura orogen. The western margin of the system in Rajasthan is also marked by an NE-SW trending major lineament known as Great Boundary Fault separating the Aravalli-Delhi orogen from the Vindhyan. Nearly half of the basin area belongs to this geological formation category. As sown in Fig. 3.1, significant portions of the Chambal, Sind, Betwa, and Ken catchments are constituted under the Proterozoic era.

In general granitoid gneisses are common in the Bundelkhand, and are generally referred to as the Bundelkhand gneisses. It looks like a typical pink granite in hand specimens, the foliation being very rude, if at all developed. Granulites and crystalline limestone (i.e. marbles) are another important composition of this category which is exposed in the Alwar district of Rajasthan.

Aravalii chains of the Cuddapah system is mainly composed of much indurated and compacted shales, slates, quartzites and limestones. The shales have acquired a

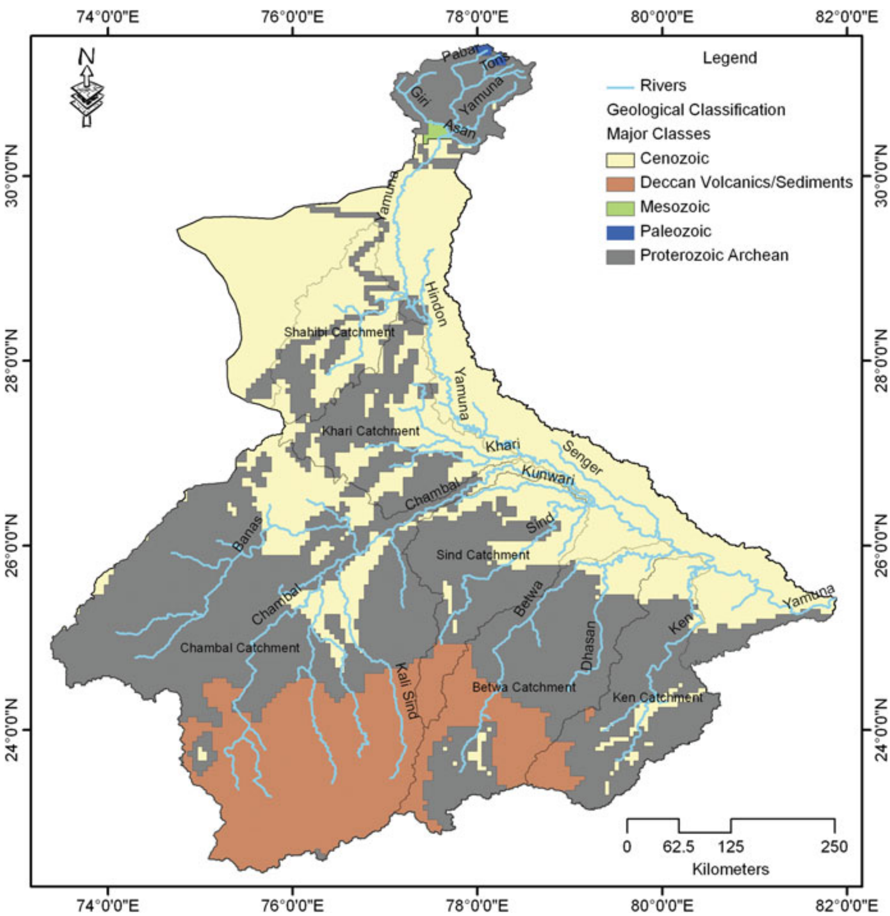


**Fig. 5.10** Major classification of geological formation

slaty cleavage, but beyond that there is no further metamorphism (i.e., action of heat and pressure) into phyllites or schists; such secondary minerals as mica, chlorite, andalusite, staurolite, gamets, etc, have not been developed in them; nor are the limestone recrystallized into marbles, as in the Dharwar rocks.

The catchment-wise summary of geological formation is given in Table 5.10. Further to the geology of the basin, a detailed catchment-wise description of lithology and hydrogeology is presented in the following section.

## 5.5 Lithology and Hydrogeology of the Basin

The Yamuna River system is bounded by the Himalayas on the north and the Vindhyas on the south. In the east, it is separated by the ridge from the main Ganga catchment and on the west by the ridge separating it from the Luni and the

**Table 5.10** Catchment wise distribution of geological formation

| Sub basin | Predominant formation type | Geological formation | Areal extent ($km^2$) | Remarks |
|---|---|---|---|---|
| Chambal/Betwa/Ken/Kali Sind (plateau region) | Hard rock | Crystalline: granite/gneiss, phyllite/schist Deccan trap-basalt sedimentary-lime stone/sand stone | 196,232 | Alluvium deposits are found in patches near and along the major rivers. |
| Yamuna/Hindon/Khari/Sahibi, i.e., Yamuna-Ganga and Yamuna-Ghaghar Doab (Indo-Gangatic plain) | Alluvium | Older to recent alluvium sand, silt, gravel, clay, boulder | 158,629 | |

Ghaggar basins. Most parts of catchment in Haryana and Uttar Pradesh lie in the Gangetic alluvial plains. The catchment/region wise lithological and hydrogeological features of the Yamuna basin are described as follows. A brief summary of the hydrogeological characteristics of the basin is given in Table 5.11.

### 5.5.1 Himalayan Region

A significant part of the Yamuna basin is contained in the Lesser Himalaya. The Yamuna originates from the Yamunotri Glacier at the base of the Bandapunch peak in the Higher Himalaya (Negi, 1991; Dalai et al., 2002); and many tributaries, such as the Tons, the Giri, the Aglar, the Asan and the Bata join in the Himalayan segment. Near its source in the Higher Himalaya, the Yamuna drains mainly the crystallines of Ramgarh and Almora groups (Gansser, 1964). Occurrences of calc-schists and marble with sulphide mineralization have been reported in the areas upstream of Hanuman Chatti (Jaireth et al., 1982). From the Higher Himalayas, the Yamuna flows in the southwest direction and enters the Lesser Himalayas where it drains a variety of lithologies. It flows through a large stretch of quartzite of Berinag Formation. Downstream, it passes through the massive dolomitic limestone and marble of Mandhali and Deoban Formations. The Yamuna then enters a large stretch of the sedimentaries of the Chakrata Formation, Chandpur Formation and Nagthat Formation. Barites occur in the silisiclastic sediments of Nagthat Formations in the Tons river section (Sachan and Sharma, 1993) and in the lower horizons of Krol limestones at Maldeota and Shahashradhara, where they occur as veins (Anantharaman and Bahukhandi, 1984). Southwest of Kalsi, the Yamuna enters the Siwaliks comprising the channel and floodplain deposits by the Himalayan Rivers in the past. In the Lesser Himalaya, occurrences of shales are reported into the Infra Krol, the Lower Tal, the Deoban and the Mandhali Formations (Gansser, 1964; Valdiya, 1980). These are exposed at a number of locations in the Yamuna and

**Table 5.11** Hydro-geological features of different formations in terms of groundwater development, use and prospect to recharge

| Predominant geological formations zones | Water bearing features | Well yield range (lps) | Feasible well types | Depth range (m) | Areal extent ($km^2$) |
|---|---|---|---|---|---|
| Hilly and Tarai Region | Tarai, Alluvium, Fracture/weather Hard Rock | 0.1–15 | Hand pumps, Spring, kunds, shallow large diameter dug well to deep tube wells in Tarai, Bhabar zone | Varying | 11,528 |
| Younger Alluvium (Unconsolidated formation of sand, silt, clay, deposited closer to major rivers-mainly low land area; Khader) | Porous voids | 25–55 | Tube well | 20–300 | 63,083 |
| Older Alluvium (Unconsolidated to Semi consolidated layers of sand, gravel, silts, kanker with occasional gravel bed–Upland area Bhanger | Porous voids | 10–15 | Tube well/Dug well | 65–150/20–40 | 95,546 |
| Consolidated Sedimentary (Sand stone/lime stone, shale, slate) | Weathered/Fractured/Jointed | 2–3 | Tube well/Dug well | 100–150/30–50 | 52,177 |
| Crystalline rock (Igneous and Metamorphic)-Granite/Gneiss, Phyllite/Schist, Quartzite | Fractured/Weathered | 0.5–1.0 | Dug well | 30–40 | 55,284 |
| Deccan Trap-Basaltic | Vesicles/Fractures/Joints | 0.35–0.9 | Dug well | 15–20 | 88,771 |

the Tons catchments, the largest being at Maldeota and Durmala, around Dehradun, where phosphorite is mined economically. Gypsum occurs in the Krol Formation in the form of pockets and bands (Anantharaman and Bahukhandi, 1984; Valdiya, 1980).

The soils in these regions have been grouped as brownhill soils (Devi, 1992), which form from the weathering of granite, gneiss and schist. Soils on the slope (15–40%) are shallow due to erosion and mass wasting processes and usually have very thin surface horizons.

### *5.5.2 National Capital Region (NCR) Region*

The physiography of the NCR region is characterized by the presence of the Ganga skirting it as its eastern boundary, the Yamuna traversing north-south forming the boundary between Uttar Pradesh and Haryana, and the sand dunes and barren low hills of the Aravalli chain and its outcrops in the west, flat topped prominent and precipitous hills of the Aravalli range enclosing fertile valleys and high table lands in the south-west, and the rolling plains dominated by rainfed torrents in the south. The rest of the region is plain with a gentle slope of north-east to south and south-west.

The rock type exposed in the area belongs to Delhi Super-group of Lower Proterozoic age and consists of Quartzite of the Alwar Group, Phyllite and Slate of the Ajabgarh Group. The Quartzites are massive, thickly bedded, hard, and compact, and highly jointed and are intercalated with thin beds of Phyllite and Slates.

The strike of the beds is NNE-SSW and dip westerly at moderate angles. These rocks are mostly covered by quaternary sediments and are exposed in isolated residual and structural hills and pediments.

These hills are exposed in south and south-west of Delhi at Delhi, Gurgaon, Rewari and Alwar. The rocks near Delhi consist of narrow strike-ridges and are moderately folded and they are over-folded in the southeast as a series of isoclines.

The quartzite and its associated rocks of the Delhi series are traversed by joints and are folded, faulted and fractured. The joints persist deeper down often to about 100 m depth, which is the maximum depth to which most of the tube wells to date exist. The joints and fractures are open, often filled with debris and mutually interconnected; cavities created by the erosion of mica-schist add to the secondary porosity developed by these joints and fractures.

Ground water occurs in the consolidated rocks both in confined and semi-confined conditions. Mostly the top water table zone and the deeper semi-confined aquifer have the same static water level surface because of their interconnections. The depth of water table below ground level varies in general between 5 and 20 m. A number of ground water structures by way of open wells and shallow tube wells (60–70 m deep) exist in this formation in different parts of NCR with varying degrees of discharge rates. On the whole, discharges around 2–3 $m^3$/h and at times even less (down to one cubic meter) or more (up to 4–5 $m^3$), with an average of about 15–20 m of the aquifer-zone, are available.

The thickness of the alluvium and the proportion of clean granular zones in aggregate within the same are the two main criteria, which determine the availability of ground water in the alluvium. A major portion of NCR is covered by alluvium, which is fairly thick. It is more than 450 m thick in some parts of Haryana in the upper Yamuna basin (Sonepat, Panipat, etc.). In general, the thickness increases as we proceed towards the northern and eastern areas of NCR away from the hard-rock outcrops, with modifications resulting from tectonics or the bedrock topography sub-surface. Depending upon the thickness of the alluvium, one or more aquifer zones have been identified in the alluvium. The occurrence of ground water sub-area wise, under water tabl, and confined to semi-confined conditions has been described as follows.

Phreatic water surface is generally shallow, about 3–5 m below ground level (mbgl). It could be even as low as one meter or so, in the newer alluvium along the present day flood plains or the low level terraces. Such shallow water levels may be encountered even in the older alluvium. Deeper confined aquifers or medium deep semi-confined aquifers have their piezometric surfaces within about 20–25 mbgl in general.

Open wells, shallow tube wells, gravity wells and deep tube wells are abundant in the areas covered by the alluvium. Their discharges vary anywhere from 18 to 25 $m^3$/h for about 2–3 m drawdowns in the open wells to about 162 per cubic metre per hour for about 8–12 m drawdowns in the deep tube wells tapping granular zones about 70–100 m in aggregate thickness. As far as ground water quality is concerned, there are a few fresh water pockets in the north-east and the south-east corners of NCR area, otherwise in these areas the Total Dissolved Solids (TDS) are more than the desirable limits and the other quality parameters are within the desirable range. The TDS, nitrate and fluorides are more than the desirable limits in the NCT-Delhi area and most parts of the north-west and south-west portions of NCR. However, in the central part of the north-west zone of NCR, fluorides are within the desirable limits.

### *5.5.3 Ken and Betwa Catchment*

The Ken basin covers the areas of Jabalpur, Sagar, Damoh, Panna, Satna, Chhatarpur and Raisen districts of Madhya Pradesh and Hamirpur and Banda districts of Uttar Pradesh. It is bounded by Vindhyan range in the south, Betwa basin on west, free catchment of Yamuna below Ken on east, the Yamuna River on north. The upper reaches of Ken River are flanked by undulating plateau with sandstone, shale and limestone. Down below recent alluvium is experienced in the river up to Daudhan dam site. The stratigraphy of rock formations found in the region is mostly alluvial soil, Deccan traps, Lameta beds and Vindhyan system (Valdiya et al., 1982).

The Betwa basin covers the areas of Bundelkhand uplands, the Malwa plateau and the Vindhyan scrap lands in the districts of Tikamgarh, Sagar, Vidisha, Raisen, Bhopal, Guna, Shivpuri and Chhatarpur of Madhya Pradesh and Hamirpur, Jalaun, Jhansi and Banda districts of Uttar Pradesh.

The following types of hydrogeological formations are found in the Ken and Betwa basins:

*The older metamorphies* occur in Panna, Chhatarpur and Tikamgarh districts of Madhya Pradesh. Ground water occurs in them only in the weathered mantle and the fractured zone underlying them. The wells are recorded to be generally up to 25–30 m in depth with water levels in the lean part of the year exceeding 10–15 mbg1. The specific capacity of wells in these formations ranges from 20 to 100 lpm/m of drawdown, where the thickness of the aquifer is commendable. The hydraulic conductivity is generally less than 1 m/d and the specific yield is generally less than 5%.

*The purana formations* of both Vindhyan and Cuddapah age comprise orthoquartzites, limestones and shale sequence are found in parts of Panna, Raisen and Bhopal districts. The wells located in these areas are easily capable of yielding 100–500 $m^3$/d for a drawdown of 3 m. The specific capacity is in the range from 100 to 300 lpm/m of drawdown, and the hydraulic conductivity varies from 5 to 15 m/d. Similarly, the specific yield is generally in the range of 5 to 15%.

*The Deccan traps* cover the Guna, Vidisha, Damoh, Sagar, Bhopal and Raisen districts. They are generally simple and a type of flow, where each flow is separable into vesicular and massive units. These flows are generally 10–20 m in thickness, of which 25–40% is generally vesicular. The characteristics of red bole beds generally form the masker horizons between successive flows. The wells of these areas are capable of yielding 250–750 $m^3$/d for a drawdown of 3 to 6 m. The specific capacity ranges from 50 to 150 lpm/m of drawdown. The hydraulic conductivity ranges from 5 to 15 m/day. The specific yield in the area is generally in the range of 5 to 10%.

### 5.5.4 Chambal Catchment

Chambal is the principal tributary of the Yamuna and rises in the Vindhyan range just south of Mhow, at an elevation of 354 m. The Vindhyan range traverses nearly the whole width of Peninsular India with a length of about 1,050 km and an average elevation of some 300 m. The Deccan Trap lava flows cover the major areas in the upstream of the Chambal River. Large inliers of old rocks, belonging to the Archaeans, Vindhyan and Gondwanas, outcrop within the Deccan Trap. The Vindhyan Mountain forms the prominent plateau-like range of sandstones to the north of the Narmada valley, particularly Bundelkhand and Malwa (Krishnan, 1982).

A large part of the soils in the alluvial plains of the Chambal River system (where the annual rainfall is <100 cm) is impregnated with alkaline and saline soils (Sarin et al., 1989). The Chambal catchment exhibits a wide range of land-use types, with large areas of intensely farmed agricultural land, urbanized and industrial regions and open uplands (CBPCWP, 1982). The river water is of variable quality, containing effluents from industries and urban conurbations and sediments, nutrients and agrochemicals from the land surfaces (Rangarajan and Sarin, 2004).

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# Chapter 6
# Soil, Landuse and Agriculture

**Abstract** This chapter deals with soil characteristics, land use and agricultural activities involved in the Yamuna basin. Spatial analysis of the USDA soil group for characterizing soils in the basin is provided. Landuse classification and biodiversity (i.e., flora and fauna) analysis, followed by agricultural practices, are also included. Following the agro-climatic zoning in the basin, a detailed analysis is presented for crop seasons, crop calendar, cropping patterns, cropping intensity, and fertilizer and pesticide application, including the integrated pest management.

This chapter deals with soil characteristics, landuses and agricultural activities involved in the Yamuna basin. A detailed spatial variation of the above features is also included in the chapter. To start with, a detailed analysis of soil and its spatial variability in the basin has been presented in the following section.

## 6.1 Soil Classification

Based on geography and geology, the Yamuna basin has three distinct regions: (i) the Hilly and Tarai which is part of Uttarakhand, Himachal Pradesh, and Uttar Pradesh lies in the extreme north side of the basin, (ii) the Indo-Gangetic alluvium region i.e., Yamuna-Ganga and Yamuna–Ghaghar doab (Interfluves) which is the part of Uttar Pradesh, Delhi, Hayana and Rajasthan and lies mainly in the central and eastern side of the basin, and (iii) the plateau region consisting of Deccan trap, Vindhyan range, crystalline rocks which are part of mainly Madhya Pradesh, Rajasthan and Uttar Pradesh, and lies in the south western part of the basin. A detailed description of these features is given in Chapter 5. The geological formations play an important role in the soil formation at the upper surface.

On the basis of soil types there are eight types of soils present in the entire Yamuna River basin (Table 6.1). The majority of soil type is alluvial and covers about 42% of the basin area, whereas calcareous sierozemic soils contribute a minimum with about 0.5% of the basin area. Based on the United States Department of Agriculture (USDA, 1999), the soils of the Yamuna basin can be classified into 35 categories. The spatial pattern of the soil category in the basin is shown in Fig. 6.1, whereas a description of each soil categories is presented in Tables 6.2 and 6.3.

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**Table 6.1** Soil types in the Yamuna River basin

| Soil type | % of total basin area covered | Locations |
|---|---|---|
| Red Sandy | 2.5 | Along Uttar Pradesh-Madhya Pradesh border in districts of Jhansi, Hamirpur, Chhattarpur, etc. |
| Red and Yellow | 5.0 | Parts of Jaipur, Alwar, Sawai Madhopur, Banda, Panna districts and along western boundary of basin in Rajasthan |
| Calcareous sierozemic | 0.5 | Parts of Mohindergarh and Bhiwani districts in Haryana |
| Deep Black | 5.5 | On the southern boundary of the basin in Sehore, Bhopal, Raisen, Vidisha, Sagar and Damoh districts |
| Medium black | 25.5 | Most of the basin in MP and strips north of river Chambal in Rajasthan |
| Mixed red and black | 15.0 | Chittaurgarh, Bhilwara, Banda, Mandasaur, Shivpuri, Lalitpur, Tikamgarh, Panna and Chattarpur districts |
| Brown hill | 4.0 | Hills and foothills in the north |
| Alluvial | 42.0 | Plains and valley |

## 6.2 Landuse

Major landuse in the basin can be classified as agriculture, forest, non-agriculture, barren land, permanent pasture, cultivable wasteland, cultivable fallow, etc. (Fig. 6.2). Out of total reported area, more than 50% area is under agriculture followed by the forest area. Other categories of landuses have almost equal distribution in the basin. The existing landuse pattern of the districts that fall under the Yamuna basin have been further analysed to arrive at the catchment-wise landuses. The catchment wise statistics of the landuse category is given in Table 6.4. It can be stated that the Chambal basin has a large forest area in the Yamuna basin followed by the Betwa, Ken and Sind catchments. The percentage of cultivable waste and fallow land are also high in these catchments which follow the similar sequence.

### *6.2.1 Forests and Protected Areas*

Forests provide multiple benefits to environment, people, and animals. The variety of cultural values and symbolic functions ascribed to the forests are as numerous and diverse as the communities and cultures of the region. Forests provide important sources of income. India has 76.84 million ha of recorded forest area in March 1999. This accounts for 23.38% of the total geographic area. The per capita availability of forests in India is 0.07 ha, which is much lower than the world average of 0.8 ha (Table 6.5).

Asia has the highest deforestation rate of any major tropical region in the world. In many parts of the world forests are shrinking at an unprecedented rate, due to agricultural expansion, urban development and accelerating demands for fuel and fibre.

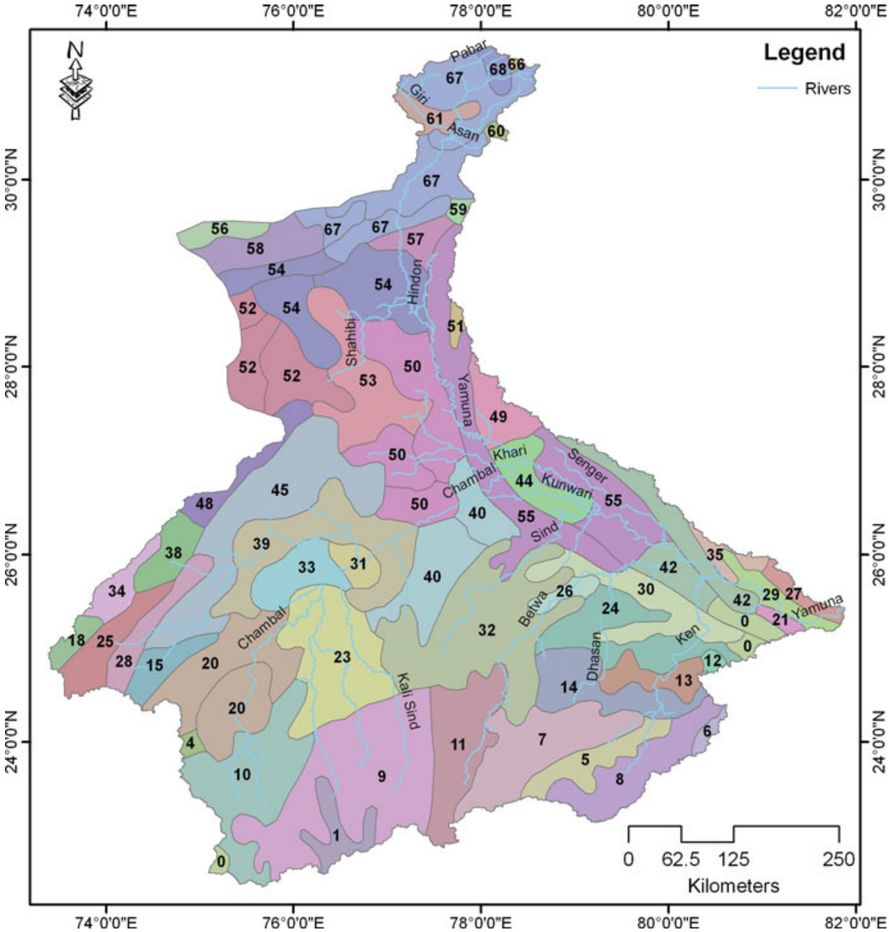


**Fig. 6.1** USDA soil classification of Yamuna River basin

Many key forest ecosystems are endangered, with critical consequences for the survival of traditional communities, wildlife, land degradation, soil erosion, flooding, and climatic change.

Forest conservation is one of the most important environmental and social challenges facing the community. Strict forest reserves must be expanded, but the problem can be solved only by implementing sustainable forest management in all forest areas. The Yamuna River basin area also has a rapid increase of population and urbanization. Therefore, care of natural resource and forest is important. State wise we find that conservation steps have been taken by the government for protecting forest lands. Table 6.6 provides state wise forest in Yamuna basin. Tables 6.7 and 6.8 show threatened species and total species in India.

**Table 6.2** Description of USDA soils groups

| Soil order | Sub-order | Description | Soil order | Sub-order | Description |
|---|---|---|---|---|---|
| 2 | 7, 8, 9 | Aqualfs + Aquepts + Udalfs | 58 | 1, 2 | Orthents + Ochrepts |
| 8 | 5, 1 | Ustalfs + Orthents | 59 | 1, 2, 5 | Orthents + Ochrepts + Ustalfs |
| 9 | 5, 2 | Ustalfs + Orchrepts | 60 | 1, 4 | Orthents + Rockout Crops |
| 10 | 5, 6 | Ustalfs + Fluvents | 64 | 8, 2 | Aquepts + Ochrepts |
| 18 | 5, 2, 1 | Ustalfs + Orchrepts + Orthents | 70 | 2 | Ochrepts |
| 20 | 9 | Udalfs | 71 | 2, 14 | Ochrepts + Gullied Land |
| 24 | 9, 2 | Udalfs + Ochrepts | 72 | 2, 1 | Ochrepts + Orthents |
| 27 | 10 | Orthids | 73 | 2, 12 | Ochrepts + Psamments |
| 30 | 10, 1 | Orthids + Orthents | 75 | 2, 1, 4 | Ochrepts + Orthents + Rockout Crops |
| 32 | 10, 6 | Orthids + Fluvents | 77 | 2, 8, 5 | Ochrepts + Aquepts + Ustalfs |
| 33 | 11, 6 | Aquents + Fluvents | 78 | 2, 3, 5 | Ochrepts + Usterts + Ustalfs |
| 35 | 12 | Psamments | 79 | 2, 6, 3 | Ochrepts + Fluvents + Ustalfs |
| 36 | 12, 6 | Psamments + Fluvents | 86 | 2, 6, 1 | Ochrepts + Fluvents + Orthents |
| 37 | 12, 6, 10 | Psamments + Fluvents + Orthids | 92 | 3 | Usterts |
| 38 | 12, 6, 11 | Psamments + Fluvents + Aquents | 98 | 3, 2, 1 | Usterts + Ochrepts + Orthents |
| 40 | 12, 10 | Psamments + Orthids | 100 | 3, 2 | Usterts + Ochrepts |
| 42 | 12, 6, 2 | Psamments + Fluvents + Ochrepts | 103 | 15 | Glaciers and Snowcaps |
| 53 | 1, 13 | Orthents + Argids | | | |

*Source*: NBSS and LUP

### 6.2.2 *National Parks and Sanctuaries*

The National Forest Policy (MoEF, 1988), emphasizes creating massive people's movement through the involvement of village communities living close to the forest in protection and development of forests. Pursuant to this policy, the Government of India issued a notification in June 1990 requesting the State Governments to involve local communities in the management of forests. This led to the development of Joint Forest Management (JFM) programmes. For in situ conservation of bio-diversity of the country, 87 National Parks and 485 Wildlife Sanctuaries have been created so far with a total area of 4.06 million ha and 11.54 million ha, respectively. These together constitute 15.60 million ha and form 4.75% of the geographic area of the country and are referred to as Protected Areas (PA). National Parks and Wildlife sanctuaries in the states falling under the Yamuna basin are shown in Table 6.9.

**Table 6.3** USDA soil classification of Yamuna basin

| Sub-order No. | Sub-order | Description |
|---|---|---|
| 1 | Orthents | Soil texture is loamy and clayey, surface is erosional, better drained than Aquents, regular decrease in content of organic matter with depth, without podegenic horizons that have retained original structure of parent materials. |
| 2 | Ochrepts | Soil organic matter content is low, weakly developed horizons showing alteration of parent materials. |
| 3 | Usterts | Soil moisture is limited but present at the time needed by crops, high clay content of cracking nature and dark gray colours, cracks are open for at least 90 cumulative days per year. |
| 4 | Rockout Crops | |
| 5 | Ustalfs | Soil moisture is limited but present at the time needed by crops, moisture moves through soil to deeper layers only in occasional years, minerals have been strongly weathered, medium to high base status and subsurface horizons of clay accumulation. |
| 6 | Fluvents | Soil texture is loamy and clayey (finer in texture than loamy fine sand), soils formed on alluvium, without podegenic horizons that have retained original structure of parent materials. |
| 7 | Aqualfs | Wet soils that are seasonally or permanently saturated with moisture which affects plant growth (this may be due to higher water table or low hydraulic conductivity), medium to high base status and subsurface horizons of clay accumulation. |
| 8 | Aquepts | Wet soils that are seasonally or permanently saturated with moisture which affects plant growth, usually have cambic horizons, weakly developed horizons showing alteration of parent materials. |
| 9 | Udalfs | Moist soils that are not dry for a long time that affect plant growth, the undisturbed soil has a thin horizon darkened by humus, medium to high base status and subsurface horizons of clay accumulation. |
| 10 | Orthids | Generally surface is erosional, dry soils with pedogenic horizons, very low organic matter. |
| 11 | Aquents | Wet soils that are seasonally or permanently saturated with moisture which affects plant growth, without podegenic horizons that have retained original structure of parent materials. |
| 12 | Psamments | Soil texture is loamy fine sand or coarser, subject to the movement by wind if dry, without podegenic horizons that have retained original structure of parent materials. |
| 13 | Argids | Usually hot and dry, very low moisture and organic matter. |
| 14 | Gullied Land | Gully erosion is prominent, ravine. |
| 15 | Glaciers and Snowcaps | Covered with snow. |

*Source*: NBSS and LUP

The periodic assessment of forest cover provides a quantitative measure of the extent of land area under forest/tree cover along with the density. It helps in monitoring the changes in the cover. The forest cover information serves useful purpose for national and state policy planning. The National Forest Policy (MoEF, 1988)

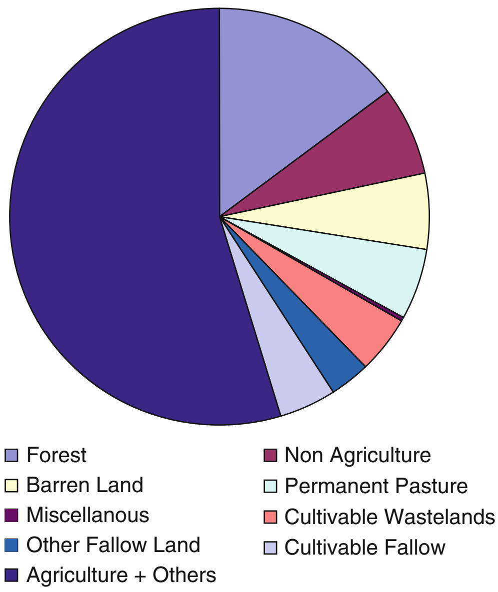


**Fig. 6.2** Distribution of landuse categories in the Yamuna basin

envisages bringing one-third of the geographic area of the country under forest/tree cover for maintaining ecological balance and environmental stability.

Following a different classification, the forest cover can be divided into three categories: dense, open and mangroves. The forests are called as dense when the canopy density is 40% and higher; whereas if the canopy density is between 10 and 40%, forests are termed as the Open forests. Besides these two categories, the Mangroves are salt-tolerant forest ecosystems found mainly in the tropical and subtropical inter-tidal regions in estuaries and coasts. They are a reservoir of a large number of plants and animal species. Mangroves exhibit a remarkable capacity for salt tolerance, stabilize the shoreline, and act as a barrier against encroachments by the sea. Based on this classification, the Yamuna River basin comprises two classes, namely the dense and opens (Table 6.10).

The forest area can further be classified into reserved and protected forests. The percentage of these two categories in the forest area for the states of Yamuna basin is given in Table 6.11.

The Yamuna basin state has various national parks and sanctuaries some of these are illustrated as follows.

(i) Kalesar National Park and Sanctuary, Yamuna Nagar (100.28 $km^2$)
(ii) Sultanpur National Park, Gurgaon (1.49 $km^2$)
(iii) Bhindawas Bird Sanctuary
(iv) Hastinapur Wild life Sanctuary (2,073.00 $km^2$),
(v) National Chambal Wildlife Sanctuary (635 $km^2$)
(vi) Okhla Wildlife Sanctuary (4 $km^2$), Ghaziabad

**Table 6.4** Landuse in the Yamuna Basin (in $km^2$)

| Basin/ sub-basin | Shape area | Rural area | Urban area | Reported area | Forest | Non-agric. | Barren | Permanent pasture | Miscellaneous | Cl. wasteland | Other fallow | Cl. fallow |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sahibi | 17,561.3 | 16,962.6 | 598.63 | 15,943.3 | 866.1 | 1,227.8 | 715.6 | 614.7 | 26.4 | 208.0 | 462.0 | 908.4 |
| Hindon | 6,975.74 | 6,396.5 | 579.3 | 7,153.0 | 491.1 | 1,067.5 | 156.7 | 13.2 | 50.4 | 99.0 | 106.8 | 116.1 |
| Khri | 25,738.0 | 24,656.0 | 1,082.0 | 21,510.4 | 1,566.1 | 2,052.5 | 1,380.2 | 718.2 | 34.3 | 405.2 | 640.7 | 1,318.0 |
| Chambal | 134,650.4 | 131,292.6 | 3,357.9 | 124,873.6 | 17,085.8 | 8,140.4 | 10,686.7 | 8,317.4 | 97.3 | 7,812.1 | 4,447.3 | 5,937.4 |
| Sind | 27,940.0 | 27,188.5 | 751.5 | 26,316.2 | 4,091.8 | 1,769.4 | 1,845.4 | 817.3 | 74.0 | 1,281.9 | 333.5 | 1,184.5 |
| Betwa | 43,637.8 | 43,429.2 | 965.3 | 47,563.9 | 9,509.6 | 3,009.0 | 1,660.8 | 2,030.3 | 75.4 | 2,291.6 | 883.0 | 1,251.0 |
| Ken | 28,527.1 | 28,336.6 | 769.6 | 30,072.0 | 7,498.8 | 1,862.8 | 797.1 | 1,285.3 | 62.4 | 1,262.5 | 639.3 | 829.4 |
| Karwan | 4,058.4 | 4,296.6 | 187.0 | 4,587.8 | 126.2 | 474.4 | 95.3 | 12.7 | 30.6 | 112.0 | 115.5 | 117.7 |
| Sengar | 4,058.4 | 4,296.6 | 187.0 | 4,587.8 | 126.2 | 474.4 | 95.3 | 12.7 | 30.6 | 112.0 | 115.5 | 117.7 |
| Yamuna | 365,870 | 356,790 | 9,309 | 342,541 | 50,346 | 24,180 | 20,057 | 18,580 | 1,039 | 15,371 | 9,976 | 15,082 |

**Table 6.5** Forest cover and per capita availability in different regions/countries

| Region/country | Percentage of forest cover to land area (1995) | Per capita forest (ha) |
|---|---|---|
| World | 26.6 | 0.64 |
| Asia | 16.4 | 0.1 |
| Africa | 17.7 | 0.7 |
| Europe | 41.3 | 1.3 |
| China | 14.3 | 0.1 |
| Pakistan | 2.3 | 0.01 |
| Bangladesh | 7.8 | 0.02 |
| Japan | 66.8 | 0.2 |
| USA | 23.2 | 0.8 |
| India | 15.7 | 0.06 |

*Source*: FAO (1999)

**Table 6.6** State wise forest cover in Yamuna basin (Area in km$^2$)

| State/UT | 1999 Assessment | 1997 Assessment | 1995 Assessment | Changes in 1999 | Changes in 1997 |
|---|---|---|---|---|---|
| Delhi | 88 | 26 | 26 | 62 | 0 |
| Haryana | 964 | 604 | 603 | 360 | 1 |
| Himachal Pradesh | 13,082 | 12,521 | 12,501 | 561 | 20 |
| Madhya Pradesh | 131,830 | 131,195 | 135,164 | 635 | −3,969 |
| Rajasthan | 13,871 | 13,353 | 13,280 | 518 | 73 |
| Uttar Pradesh | 34,016 | 33,994 | 33,986 | 22 | 8 |

*Source*: MoEF (1999a)

**Table 6.7** Globally threatened animal occurring in India by status category

| 1994 IUCN Red list threat category | | | | | |
|---|---|---|---|---|---|
| | Endangered | Vulnerable | Rare | Indeterminate | Insufficiently known |
| Mammals | 13 | 20 | 2 | 5 | 13 |
| Birds | 6 | 20 | 25 | 13 | 5 |
| Reptiles | 6 | 6 | 4 | 5 | 2 |
| Amphibians | 0 | 0 | 0 | 3 | 0 |
| Fishes | 0 | 0 | 2 | 0 | 0 |
| Invertebrates | 1 | 3 | 12 | 2 | 4 |
| Total | 26 | 49 | 45 | 28 | 24 |

*Source*: Groombridge (1993)

(vii) Indira Privadarshini (Asola) Wildlife Sanctuary (13.2 km$^2$)
(viii) Ranthambore National Park, Sawai Madhopur
(ix) Kumbhalgarh Wildlife Sanctuary, Udaipur
(x) Keoladeo Ghana National Park, Bharatpur
(xi) Sariska Wildlife Sanctuary, Alwar
(xii) Darrah Wildlife Sanctuary, Kota

**Table 6.8** Comparison between the number of species in India and the World

| | No. of species in India (SI) | No. of species in worlds (SW) | SI/ SW |
|---|---|---|---|
| Mammals | 350 | 4,629 | 7.6 |
| Birds | 1,224 | 9,702 | 12.6 |
| Reptile | 408 | 6,550 | 6.2 |
| Amphibians | 197 | 4,522 | 4.4 |
| Fishes | 2,546 | 21,730 | 11.7 |
| Flowering Plants | 15,000 | 250,000 | 6.0 |

**Table 6.9** National parks and wildlife sanctuaries

| | National park | | Wildlife sanctuaries | | |
|---|---|---|---|---|---|
| States | Number | Area ($km^2$) | Number | Area ($km^2$) | Total area ($km^2$) |
| Delhi | 0 | 0 | 1 | 27.60 | 27.60 |
| Haryana | 1 | 1.43 | 9 | 278.32 | 279.75 |
| Himachal Pradesh | 2 | 1,429.40 | 32 | 5,736.85 | 7,166.25 |
| Madhya Pradesh | 11 | 6,474.69 | 35 | 10,704.05 | 17,178.74 |
| Rajasthan | 4 | 3,856.53 | 24 | 5,712.83 | 9,569.36 |
| Uttar Pradesh | 7 | 5,410.82 | 29 | 7,594.54 | 13,005.36 |
| **India** | **87** | **40,631.64** | **485** | **115,374.42** | **156,006.06** |

**Table 6.10** Extent of forest covers in states of Yamuna basin

| State/UT | Dense forest, % | Open forest, % | Forest cover, % |
|---|---|---|---|
| Delhi | 39.77 | 60.23 | 5.93 |
| Haryana | 46.58 | 53.42 | 2.18 |
| Himachal Pradesh | 69.71 | 30.29 | 23.50 |
| Madhya Pradesh | 61.91 | 38.09 | 29.73 |
| Rajasthan | 31.06 | 68.94 | 4.05 |
| Uttar Pradesh | 67.33 | 32.67 | 11.55 |
| Total | | | **19.39** |

*Source*: MoEF (1997)

**Table 6.11** Forest area and protected area in states falling under Yamuna basin

| States | Reserved forests (%) | Protected forests (%) | Forest to geographic area (%) |
|---|---|---|---|
| Delhi | 90.70 | 8.14 | 5.73 |
| Haryana | 15.88 | 73.85 | 3.52 |
| Himachal Pradesh | 5.12 | 89.23 | 66.52 |
| Madhya Pradesh | 61.68 | 37.37 | 30.89 |
| Rajasthan | 36.78 | 54.98 | 9.49 |
| Uttar Pradesh | 30.08 | 60.8 | 6.98 |
| Uttarakhand | 68.74 | 30.79 | 54.81 |
| India | 51.62 | 30.78 | 23.57 |

*Source*: MoEF (2003)

**Table 6.12** Area under joint forest management

| State | No. of JFM committees | Area under JFM ('000 ha) |
|---|---|---|
| Haryana | 350 | 60.73 |
| Himachal Pradesh | 203 | 62.00 |
| Madhya Pradesh | 12,038 | 5,800.00 |
| Rajasthan | 2,705 | 235.63 |
| Uttar Pradesh | 197 | 34.59 |
| India | 36,130 | 64 |

*Source*: MoEF (1999b, 2002)

The Joint Forest Management Scheme (JFMS) encourages the involvement of village institutions for the forest development. The local institutions engaged in the task are known by different names in different states like Forest Protection Committee (FPC), Village Forest Committee (VFC), *Van Sanrakshan Samiti* (VSS), Village Forest Protection Management Committee (VFPMC) etc. In JFM, the user (local communities) and the owner (Government) manage the resource and share the cost equally. After the National JFM guidelines were issued in 1990, 22 States are now implementing the programme. The JFM programme has evolved to different levels across these States. The area under joint forest management is shown in Table 6.12. Table 6.12 provides information of per capita availability of forests in different categories.

## *6.2.3 Biodiversity*

India is rich in biodiversity as evident that the country is included in the list of 12 mega-diversity nations. Country has a 7% of the world's biodiversity and supports 16 major vegetation types. A wide variety of flora and fauna exists in the Yamuna basin, and their spatial variability largely depends on the geo-physical environment. The state-wise status of the flora and fauna in the Yamuna River basin is given as follows:

### 6.2.3.1 Haryana

***Flora*****:** Haryana forest cover is mostly dry deciduous which comprises pine and thorny shrubs. Chief trees are Kikar *(Acacia nilotica)*, Khair *(Acacia catechu)*, Neem *(Azadirachta indica)*, Shisham or Indian Rosewood *(Dalbergia sissoo)*, Pipal *(Ficus religiosa)*, Mango *(Mangifera indica)*, Jamun *(Syzygium cumini)*, Tamarind *(Tamarindus indica)*, Banyan (*Ficus indicus)*, Sagwan or Teak *(Tectona grandis)*, Ber or Indian Jujube *(Zizyphus mauritiana)*, Mitha Jal or Pillu *(Salvadora indica)*, Khara Jal or Pillu *(Salvador persica)*, Semul, Khejri *(Prosopis cineraria)*, Lahswa (*Cordia dichotoma*), Amla, Dhak (*Butea frondosa)*, Shahtoot or mulberry (*Morus alba atropurpurea)*, eucalyptus, Guava *(Psidium guajava)*, pine and poplar.

The Kalesar forest is full of Sal trees. The Ritha tree can be found in the Morni Hills as well as the Kalesar forest. Another relatively bigger forest is the Saraswati Plantation near Pehowa. An important shrub species of the state is the leafless Kair or Teat *(Capparis decidua).* Another important plant that has religious and medicinal value, is the *Tulsi*. A beautiful flowering tree is the Kachnar, whose flowers are used for many purposes. Other trees that are found in Haryana are Tun (Red Cedar), Baheda and Bel.

Among small tree species, *Careya arboreal, Holarrhena antidysenterica, Mallotus philippinensis, Murraya exotica, Randia dumetorum, Wrightia tomentosa, Zizyphus mauritiana*, etc. are common.

**Shrubs:** *Adhatoda sp., Callicarpa macrophylla, Carissa opaca, Clerodendron viscosum, Colebrookia oppositifolia, Euphorbia royleana, Ixora sp., Murraya sp., Woodfordia sr. Zizyphus sp. etc.*

**Climbers and Grasses:** *Acacia pinnata, Arundo donex, Bauhinia vahlii, Caesalpinia sepiaria, Cenchrus setigerus, Chrysopogon sp., Clematis gouriana, Cymbopogon martini, Oendrocalamus strictus, Oesmostachya bipifJnata, Oioscorea belophylla, Erianthus munja, Heteropogon contortus, Eulolopsis binanta, Ichnocarpus sp., Milletia ovaldolia, Mimosa himalayan, Pueraria tuberosa, Saccharum spontaneum, Smilex sp., Vallaris solanacea, Vetiveria zizanioides* etc.

**Ferns Species:** *Adiantum lunulatum., Adiantum caudatum, Adiantum cappilisveneris, Athyrium spo, Oryopteris sp., Ophioglossum, Salvia, Azolla, Nephrolepsis, Oyptris, Amphilopteres.*

***Fauna*** **– Mammals:** Black Buck *(Antelope cervicapra)*, blue bull *(Boselaphus tragocamelus Pallas),* leopard *(Panthera pardus)*, striped Hyena *(Hyena hyena), w*ild boar *(Sus scrofa)*, mongoose *(Herpestes edwardsi)*, Jackals *(Canis aureus)* and wild dogs *(Cuon alipnus)*, Monkey (*Rhesus macaque*), langur *(Presbytis entellus),* jungle cat *(Felis chaus)*, the small Indian civet *(Viverricula indica)* and Indian fox are common wild animals. The state has deer like the barking deer *(Muntiacus muntjak)*, Sambar (*Cervus unicolor*), Chital (*Axis axis*) and antelopes like Neelgai (Blue Bull) and black buck. Other common mammal species are gray musk shrew or chachunder *(Suncus murinus),* common yellow bat, Tickell's bat, five stripped palm squirrel *(Funambulus palmarum)*, Sehi *(Hystrix indica)*, Indian gerbil, common house rat *(Rattus rattus)*, house mouse, Indian Hare (*Lepus nigricollis).*

**Birds:** Various types of ducks and geese such as *Graylag Goose, Bar-headed Goose, Brahminy Duck, Northern Pintail, Common Shelduck, Mallard, Gadwall, Eurasian Wigeon, Blue winged Teal, Shoveller, Common Pochard, Ferruginous Duck* and *Tufted Duck* can be seen at river and tanks during winter. Some other ducks such as *Comb Duck, Common Teal, Spot-billed Duck, Tree duck* are found throughout the year at suitable habitat. *Dabchick* is also a residential bird. Other Game Birds like *Grey Francolin (Teetar), Black Francolin (Kala Teetar)* and *quails* are also common. *Sand grouse* has been noted as a resident (*Indian Sand grouse*) as well as visitor birds. Common *Green Pigeon (Hariyal)* is found in vicinity of villages chiefly on *Ficus* trees and *Blue Rock Pigeon* occurs in almost all the villages.

*Oriental Turtle Dove* is a winter visitor, whereas the Laughing Dove is found near cultivated fields.

Among scavenger and predator birds, *Black Kite, Brahmin Kite, White backed Vulture, King Vulture, Tawny Eagle, Greater Spotted Eagle, White Eyed Buzzard Eagle, House Crow* and *Jungle Crow, Vulture, Black-winged Kite, Shikara, Lagger Falcon, Shahin Falcon, Merli, Kestrel*, *Booted Eagle, Eastern Steppe Eagle, Pale Harrier, Spotted Owlet, Eurasian Eagle* and *Owl.*

The common colorful birds, such as *Indian Roller (Neelkanth), Northern Green Barbet, Coppersmith Barbet, Northern Golden backed Woodpecker, Eurasian Golden Oriole, Alexandrine Parakeet, Rose-ringed Parakeet, Pied Crested Cuckoo, Asian Koel, Kingfishers* such as *Common Kingfisher, White breasted Kingfisher, Indian Pied Kingfisher, Red vented Bulbul, Lal munia (Red Avadat), Purple sunbird, Indian Spotted Munia*, *White Storks, storks, cranes, White Ibis* and *Crested Bunting* etc., along with National Bird of India, the *Blue Peafowl*, add beauty to the varied wildlife of the state.

**Snakes:** The poisonous snakes, like common Indian Krait, Russell's Viper, Phoosra and other snakes, like *Blind Snake, Indian Python, John's sand boa, wolf snake, rat snake* and *sand snake* are found in Haryana.

**Fish:** Feather back fish *Parri, Katla, Mrigal, Chunni, Bata, Siriha, Ghally, Mallee*, and the snake-head fish, *Dolla* and *Curd*.

#### 6.2.3.2 Rajasthan

***Flora*:** Forests are mostly confined to the east of the Aravali range. Vegetation in the desert region is limited to very slow growing stunted trees, thorny shrubs and some grasses. The other natural vegetation type in Rajasthan is ephemeral, occurring only during the monsoon season.

Kejri (*Prosopis cineraria*), ker, akaro (*Calotropis precera*), thor (*Euphorbia caduca*), bordi (*Zizyphus nummularia*), babul (*Acacia nilotica*), anwal (*Cassia aureculata*), Dhak (*Butea monosperma*), peepal (*Ficus religiosa*), banyan (*Ficus benghalensis*), ber (*Zizyphus mauritiana*) and khajur (*Phoenix sylvestris*). salar (*Bowellia seriata*), bamboo (*Dendor calamus strictus*), dhok (*Anogeisrus pendula*), mango (*Mangifera indiaca*)and jamun (*Syzygium cumini*), guggal (*Commiphora*), brahmi (*Bacopa monnieri*), shatawari (*Asparagus*) and adusa (*Adathoda vassica*) are common species.

Among perennial grasses sewan (*Lasiurus sindicus*), dhaman (*Cenhrus ciliaris*), boor (*Cenchrus jwarancusa*) and bharut (*Cenchrus catharficus*) are common.

***Fauna*:** Mammal species in wild life include Black buck (kala hiran), Indian gazelle (chinkara), blue bull (Nilgai), four horned antelope (*Chau singha*), sambar, spotted deer (chital), monkeys (rhesus macaque), langur, Indian tiger (bagh), tigers, panthar (baghera), jungle cat, caracal (*Syiagosh*), jackal, wolf, desert fox, wild boar, sloth bear, common mangoose and smaller Indian mangoose . Other fauna species include Indian python, Indian chameleon and the garden lizard, crocodile and ghariyal. Bharatpur has almost 375 bird species and of great interest is the world's tallest black necked stork standing up to 1.8 m tall and its black and white wings span up to 2.5 m. The rare Indian bustard and the grey partridge are the birds of open scrub forests of Rajasthan.

#### 6.2.3.3 Uttar Pradesh and Uttarakhand

***Flora*:** The plains of Uttar Pradesh have been very rich in natural vegetation which has, however, diminished due to wide-ranging needs of the people. Only a few patches of natural forest are now found scattered here and there in the plains, while such forests are extensively found on a very large scale in sub-mountain and mountain regions in Uttrakhand.

*Tropical Moist Deciduous Forests* are found in the moist region of Terai. They grow in regions which record 100–150 cm of rainfall annually, have an average temperature between 26 and 27°C and have considerable degree of humidity. A special feature of forests is that deciduous trees of uneven size grow on higher altitude regions. Lower regions have several species interspersed with Bamboo, Climbers, Cand and ever green shrubs. Main trees are Sal, Ber, Gular, Jhingal, Palas, Mahua Semal, Dhak, Amla, Jamun, etc.

*Tropical Dry Deciduous Forests* are found in all parts of the plains, and usually in central eastern and western regions. The trees are mostly deciduous. Since sunlight reaches the ground in abundance, shrubs and grasses also grow here. Large tracts of these forests have been cleared for cultivation. Important trees are Sal, Palas, Amaltas, Bel, Anjeer etc. Neem, Peepal, Sheesham. Mango, Jamun, Babool, Tamarind, etc. grows along river banks and in other moist regions.

*Tropical Thorny Forests* are mostly found in south-western parts of the State. Such forests are confined to the areas which have low annual rainfall (50–70 cm), mean annual temperature between 25 and 27°C and low humidity (less than 47%). Widely scattered thorny trees, mainly, Babool, Thorny, legumes and Euphorbias are extensively found here. During rains, short grasses also grow here. The trees are generally small here forming open dry forests. Important trees of the region are Phulai, Khair, Kokke, Dhaman, Danjha, Neem, etc. Various types of resin and gum are obtained from these trees.

***Fauna*:** The population of the wild animals includes various species of animals including *Antelope, Sambhar, Cheetal, Blue bull, Leopard, Hyena, Wild cat*, Shrew, Porcupine, Squirrel, Hare, Mongoose, Cow, Buffalo and Mouse. Other common species found here are Tiger, Panther, Snow Leopard, Sambhar, Cheetal, Kastura, Chinkara, Black Deer, Nilgai, Back-brown Bear, Mountain Goat, Hyena, Hill Dog, Elephant etc.

Among the birds, Fowl, Pheasant, Partridge, Florican, Duck, Goose and Wader are common.

*Fish species* commonly found are Mahaser, Hilsa, Saul, Tengan, Parthan, Rasela, Vittal, Rohu, Mirgal, Kata, Labi, Mangur, Cuchia, Eel, Einghi, Mirror Carp, and Trout.

*Reptiles*: Bamania, Pit-viper, Lizard, Goh, Cobra, Tortoise, Krait, Dhaman and Crocodile. *Birds*: Cheel, Vulture, Peacock, Nightingale, Pigeon, Parrot, Owl, Nilkanth and Sparrow.

## 6.3 Agriculture in the Basin

Agriculture is the dominant sector in India and it constitutes a significant part of the national economy. It contributes 23% of Gross Domestic Product (GDP) and employs about 64% of the workforce. Of course, in recent times, the share of agriculture in the economy is declining and will continue in the near future. Even then agriculture will have important bearings on India's economy, as it helps feed a growing population, employs a large labour force, and provides raw material to agro-based industries. In recent years, it has been confirmed that India has largely been unaffected by the world-wide recession because of its agriculture based economy. India has the potential to produce crops in almost all climatic classes namely, dry, arid, semiarid, sub-humid and humid.

To start with, The Yamuna basin has been analysed with the agro-climatic zones followed by crop seasons, cropping pattern and production.

### *6.3.1 Agro-climatic Zones*

India has a large number of complex agro-climatic conditions. The Planning Commission has demarcated the geographical area of India into 15 agro-climatic regions for resource development. The basis of the zonalization is soil type, climate including temperature and rainfall and its variability, and water resources availability. These are further divided into 72 more homogeneous sub-zones. The 15 agro-climatic zones are given as follows:

1. Western Himalayan Region: J&K, HP, UP, Uttarakhand
2. Eastern Himalayan Region: Assam Sikkim, W. Bengal and all North-Eastern states
3. Lower Gangetic Plains Region: W. Bengal
4. Middle Gangetic Plains Region: UP, Bihar
5. Upper Gangetic Plains Region: UP
6. Trans-Gangetic Plains Region: Punjab, Haryana, Delhi and Rajasthan
7. Eastern Plateau and Hills Region: Maharashtra, UP, Orissa and W. Bengal
8. Central Plateau and Hills Region: MP, Rajasthan, UP
9. Western Plateau and Hills Region: Maharashtra, MP and Rajasthan
10. Southern Plateau and Hills Region: AP, Karnataka, Tamil Nadu
11. East Coast Plains and Hills Region: Orissa, AP, TN, and Pondicherry
12. West Coast Plains and Ghat Region: TN, Kerala, Goa, Karnataka, Maharashtra
13. Gujarat Plains and Hills Region: Gujarat
14. Western Dry Region: Rajasthan
15. The Islands Region: Andaman and Nicobar, Lakshadweep

The Yamuna river basin comprises mainly five agro climatic zones (Fig. 6.3): (i) Western Himalayan Region: Himachal Pradesh, Uttar Pradesh and Uttarakhand; (ii) Upper Gangetic Plains Region: Uttar Pradesh; (iii) Trans-Gangetic Plains Region: Haryana, Delhi and Rajasthan; (iv) Central Plateau and Hills Region:

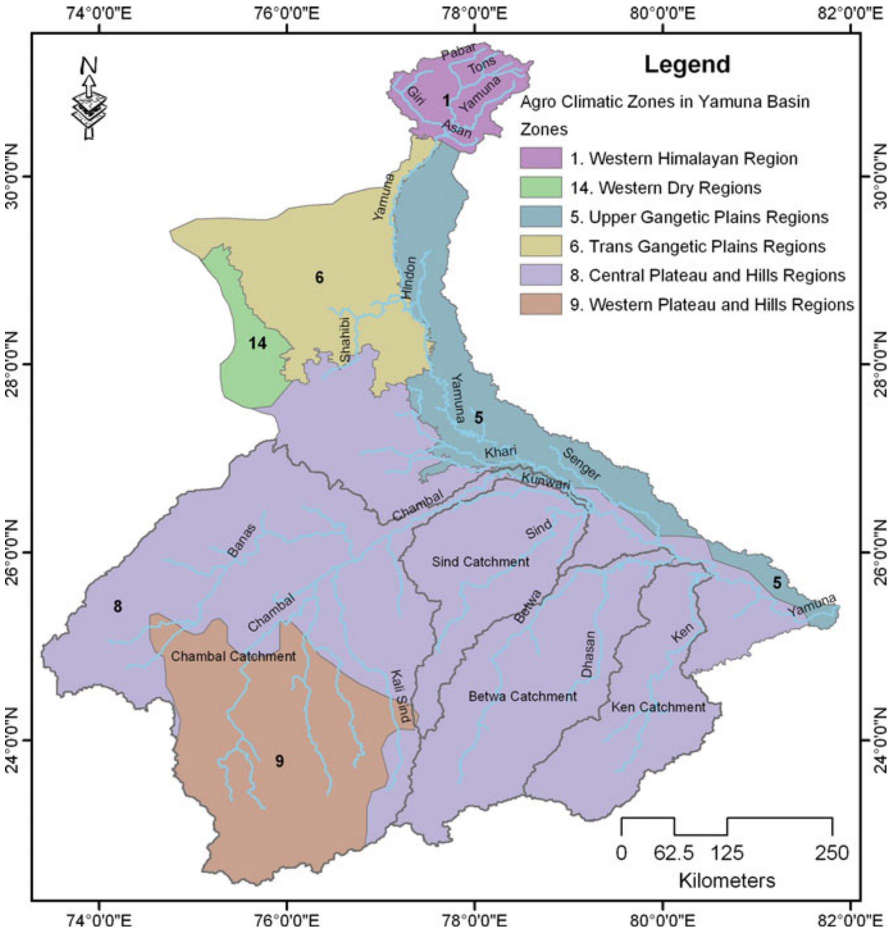


**Fig. 6.3** Agro-climatic zone of Yamuna basin

Madhya Pradesh, Rajasthan, and Uttar Pradesh; and (v) Western Plateau and Hills Region: Madhya Pradesh and Rajasthan. However, a major part of the basin area falls under zone 8 (i.e. Central Plateau and Hills Region: MP, Rajasthan, UP). State wise agriculture status is discussed in the following section.

Considering agricultural planning in India, Chowdhury et al. (1993) demarcated another type of 15 classes, which is summarized in Table 6.13. Based on this category the Yamuna River basin comprises three categories: The Satluj-Yamuna Alluvial Plains, the Central Semi-Arid Zone, and Lower Ganga basin.

### *6.3.2 Crop Seasons*

In the basin, three distinct crop seasons can be identified, viz., *Kharif* (July-October), *Rabi* (October-March) and *Zaid* (April-June) and majority of agricultural land are sown more than once in a single calendar year, and therefore

**Table 6.13** Agro-climatic zones of India (Chowdhury et al., 1993)

| S. No. | Name | Area coverage | Rainfall | Major soil type | Major crops |
|---|---|---|---|---|---|
| 1 | Northern most zone | Jammu and Kashmir | 50–75 cm | Podsolic type | Maize and Paddy |
| 2 | Eastern Himalayan zone | Areas of eastern Himalayas | About 250 cm | Alluvial and deep black soils | Paddy |
| 3 | Western Himalayan zone | Hilly region of western Himalayas (outside Ladakh) and its foothills | Much diversity from Eastern Himalayan zone | Brown hilly and alluvial soils | Paddy |
| 4 | Lower Assam Hills | Tripura, Mizoram, Manipur | About 250 cm | – | Paddy |
| 5 | Sutlej, Yamuna Alluvial plains | Haryana, Punjab, adjoining areas of Jammu and Kashmir and Uttar Pradesh | Low rainfall zone | Alluvial and calcareous soil | Paddy, cotton |
| 6 | The arid west zone | Areas of Thar Desert, Western Rajasthan and adjoining areas | Low rainfall (20–30 cm annually) | Sandy soil | Jowar, Bajra |
| 7 | The Central semi-arid zone | Eastern Rajasthan, West Madhya Pradesh and adjoining areas of Uttar Pradesh and Gujarat | Over 75 cm | Medium black to red black soil | Sorghum, Jowar, Maize |
| 8 | Lower Ganga basin | Ganga basin in Uttar Pradesh, hills and plains of east Madhya Pradesh | 100–150 cm | Medium black to red black soil | Paddy |
| 9 | Eastern Ganga and Mahanadi basin | Gangetic plains in Bihar and West Bengal, The Bihar Plateau and Mahanadi basin | Moderate rainfall | Rich alluvial intercepted by red, yellow and lateritic soils | Paddy and Jute |
| 10 | Gujarat and neighbourhood | Parts of Gujarat and Maharashtra | Low rainfall (50–70 cm) | Sandy loam to loamy soil | Groundnut, Jowar, Bajra and cotton |
| 11 | The northern and central Western Ghats | Coastal areas of Maharashtra and Karnataka | Heavy rainfall | Acidic soil (pH $\leq 3$) | Paddy |
| 12 | Central highlands | Leeward side of Western Ghats | Drought prone area | Medium black in north and red sandy in south | Jowar, cotton, ground nut |
| 13 | Godavari basin | Andhra Pradesh | High rainfall | Sandy coastal alluvial to red soil | Paddy ground nut, Jowar |
| 14 | Lower Western Ghats | Kerala, adjoining hills of Tamil Nadu and Karnataka | High rainfall | – | Topioca and Paddy |
| 15 | Semi arid Tamil Nadu tract | Areas of Tamil Nadu | High rainfall | Red sandy to deltaic alluvial soils | Jowar, ground nut |

the cropping intensity of the basin is more than 100%. A detailed description of cropping intensity is given in the subsequent section. Based on crop seasons, the cropping pattern in the Yamuna basin is very diverse because of large variation in the hydro-climatic, soil and topographic conditions.

#### 6.3.2.1 Cropping Pattern

A diverse cropping system exists in the Yamuna basin. Cropping pattern depends on climate, soil, overall agro-ecological setting and economic conditions. At farmers' level, potential productivity and monetary benefits act as guiding principles, while opting for a particular crop/cropping system. These decisions with respect to choice of crops and cropping systems are further narrowed down under the influence of several other forces related to infrastructure facilities, socio-economic factors and technological developments, all operating interactively at micro-level. Table 6.14 shows details of crops according to cropping season in the basin. However, in most parts of the basin *Kharif* and *Rabi* are the two cropping season. Crops can also be categorized on the basis of life cycle, such as annual biennials and perennial (Table 6.14).

Due to different climatic and soil characteristics, and water availability in the basin, a wide variation in the cropping pattern exists in Yamuna basin. The sub-basin wise cropping pattern is presented in Table 6.15.

#### 6.3.2.2 State-Wise Agro-ecosystem

State wise agro ecosystem and cropping pattern (1998–1999) with percentage of cultivated area is shown in Table 6.16 based on which it may be remarked that crop diversity is low in the states of Yamuna basin (MoAg, 2000). Lower the crop

**Table 6.14** Crop type according to season and life cycle

| S. No. | Season | Crop |
|---|---|---|
| 1 | Kharif | Rice, Bajra, Maize, Cotton, Ground nut, Urd, Moong, Lobia, Sorghum, Sweet potato, Til, Guar, Jute, Sanai, Arhar, Dhaincha, Sugarcane, Soyabean, Lady's finger |
| 2 | Rabi | Wheat, Mustard, Lentil, Gram, Joe, Potato, Peas, Barseem, Rijka, Tobacco, Lahi, Jai |
| 3 | Zaid | Pumpkin, water melon, melon, bottle gourd, Chili, Tomato, Sunflower, Kheera, Kakri, Mung, Sunflower |
| **Life cycle** | | |
| 1 | Annual | Rice, Wheat, Gram, Dhaincha, Bajra, Moong, Cotton, Ground nut, Mustard, Potato, Sweet Potato, Bottle gourd, Pumpkin, Soyabean |
| 2 | Biennials | Beet root, Onion |
| 3 | Perennial | Napier grass, Rijka, fruit crops |

*Source*: http://www.krishisewa.com/articles/crops.html

**Table 6.15** Cropping pattern in the Yamuna Basin (ha)

| Basin/ Sub-Basin | Paddy | Jowar | Maize | Bajra | Arhar | Wheat | Barley | Gram | Potato | Sugarcane | Groundnut | Mustard | Soybean | Cotton | Fruit | Veg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sahibi | 128,363 | 12,203 | 1,678 | 78,880 | 7,264 | 406,702 | 29,434 | 33,690 | 442 | 14,001 | 25,246 | 317,486 | 7 | 55,681 | 2,600 | 17,355 |
| Hindon | 80,039 | 3,455 | 28,546 | 8,048 | 7,395 | 247,228 | 6,243 | 305 | 6,833 | 190,080 | 1,646 | 7,970 | 4 | 258 | 21,134 | 17,545 |
| Khri | 42,968 | 6,046 | 4,738 | 47,588 | 8,693 | 508,938 | 48,227 | 11,297 | 32,476 | 7,540 | 27,834 | 544,117 | 361 | 15,285 | 4,969 | 57,197 |
| Chambal | 67,128 | 498 | 35,090 | 27,770 | 60,133 | 1,225,290 | 66,759 | 304,471 | 40,487 | 10,556 | 124,862 | 1,034,715 | 1,853,005 | 114,305 | 15,021 | 90,032 |
| Sind | 58,492 | 78 | 5,165 | 258 | 59,156 | 440,795 | 10,468 | 86,689 | 6,776 | 6,598 | 42,638 | 205,271 | 165,451 | 1 | 958 | 16,130 |
| Betwa | 23,337 | 49 | 2,117 | 306 | 145,474 | 692,390 | 19,000 | 271,202 | 4,825 | 9,320 | 67,692 | 77,099 | 538,850 | 70 | 1,116 | 26,197 |
| Ken | 64,360 | 6 | 22 | 0 | 53,377 | 357,176 | 5,163 | 190,438 | 5,403 | 17,775 | 7,596 | 19,992 | 167,414 | 1 | 2,352 | 25,503 |
| Karwan | 37,127 | 259 | 33,652 | 6,554 | 7,084 | 216,751 | 16,493 | 1,921 | 14,267 | 27,060 | 120 | 37,950 | 0 | 681 | 8,343 | 21,741 |
| Sengar | 63,421 | 246 | 24,634 | 3,065 | 11,554 | 255,487 | 18,839 | 3,284 | 23,153 | 6,755 | 222 | 51,596 | 25 | 600 | 5,787 | 31,063 |
| Yamuna | 1,352,681 | 101,460 | 190,169 | 246,619 | 351,229 | 5,601,043 | 396,779 | 869,132 | 156,664 | 575,661 | 239,483 | 2,593,843 | 2,579,040 | 611,744 | 125,104 | 362,503 |

**Table 6.16** State-wise agro-ecosystems cropping pattern for 1998–1999 (% of the total cultivated area of the country)

| | | Crops | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Climatic Zones | State | Rice | Wheat | Jowar | Bajra | Maize | Other coarse cereals | Gram | Tur | Other Pulses | Groundnut | Rapeseed and Mustard | Other Oilseeds | Sugarcane |
| Arid and Semi Arid | Haryana | 2.4 | 8 | Neg | 6.6 | Neg | 2.7 | 4.3 | 1.2 | 1.8 | Neg | 7.4 | 2.1 | 3.2 |
| Humid | HP | Neg | 1.4 | Neg | Neg | 5.1 | 1.2 | Neg | Neg | Neg | Neg | Neg | Neg | Neg |
| Semi Arid | MP | 11.9 | 17 | 8.1 | 1.5 | 14 | 9.4 | 31.7 | 11.5 | 21.2 | 3.4 | 10.5 | 23.1 | 1.2 |
| Arid and Semi Arid | Rajasthan | Neg | 10.1 | 5.4 | 44.9 | 15.6 | 19.9 | 33.5 | Neg | 19.5 | 4.3 | 45.5 | 16.1 | 0.5 |
| Semi Arid and Sub Humid | UP | 13.3 | 33.7 | 3.3 | 8.6 | 14.8 | 8.9 | 9.8 | 12.1 | 11.4 | 1.6 | 5.2 | 6 | 48.3 |
| | All India-acreage | 44.6 | 27.4 | 9.98 | 9.28 | 29.54 | 29.54 | 8.41 | 3.47 | 23.82 | 7.57 | 6.6 | 26.71 | 4.08 |

Neg. = negligible; acreage = million hectare
*Source*: Agricultural Statistics at a Glance (2000)

diversity, lesser will be the crop and economic sustainability of the farmers. For example, Himachal Pradesh and Haryana have low crop diversity followed by Uttar Pradesh, Rajasthan and Madhya Pradesh. Haryana has a high dependency on wheat, mustard and sugarcane. Rajasthan is more dependent on bajra, gram and mustard. Uttar Pradesh has a high dependency on sugarcane, wheat, maize and rice.

The crop time is dependent on temperature, light, and growing environment. The crop calendar is intended as a general reference for growing plants common to any area. It does not include all crops that can be grown, nor does it represent the only way those crops listed can be grown. Table 6.17 provides sowing time of different cereal crops. Sowing time for oilseeds, vegetable crops and pulses has been shown in Tables 6.18, 6.19 and 6.20, respectively (ICAR, 2007).

Besides the above descriptions, a few crops can be sown in more than one season. For example, Soybean and Sunflower crops which can be sown during autumn (Zaid Kharif) as well as spring (Zaid Rabi), though the main crop is spring season.

**Table 6.17** Sowing time of cereal crops

| S. No | Crop | Sowing time | Reaping time (Transplanting) |
|---|---|---|---|
| 1 | Wheat | 10 Nov–10 Dec | – |
| 2 | Barley (Joe) | Irrigated Area: 15 Nov–15 Dec<br>Un-irrigated Area: 20 Oct–7 Nov | – |
| 3 | Maize | | – |
| 4 | Pearl Millet (Bajra) | May–June–July: Northern Plains<br>Apr–May: North West Hilly areas<br>March: North East Hilly areas | July |
| 5 | Paddy | June–July | July–August |
| 6 | Sorghum (Jowar) | 15 June–15 July | – |

*Source*: ICAR (2007)

**Table 6.18** Sowing time for oil seeds

| S. No. | Crop | Sowing time |
|---|---|---|
| 1 | Indian mustard/ Brown mustard/ Laha | 30 Sept–15 Oct |
| 2 | Toria/ Lahi | 1 Sept–15 Sept |
| 3 | Yellow sarson, Brown sarson | 25 Sept–15 Oct |
| 4 | Taramira/ Rocket salad | Oct |
| 5 | Sesamum/ Sesame | Jun–July (Kharif) |
| 6 | Ground nut | Mid Jun–July |
| 7 | Linseed | Oct–Nov |
| 8 | Soybean | Mid Jun–Mid July |
| 9 | Castor | Mid June– Mid July |
| 10 | Sunflower | Spring: 20 Feb–10 Mar<br>Kharif: July–Aug<br>Rabi: Nov |

*Source*: ICAR (2007)

**Table 6.19** Sowing time of vegetable crops

| S. No. | Crop | Sowing time | Transplanting time | Harvest period |
|---|---|---|---|---|
| 1 | Amaranthus | Feb–July | – | April–Oct |
| 2 | Beat Root | Oct–Nov | – | Dec–Feb |
| 3 | Bitter Gourd | Feb–March | – | May–July |
| | | June–July | | Aug–Oct |
| 4 | Bottle Gourd | Feb–March | – | April–June |
| | | June–July | | Oct–Dec |
| 5 | Brinjal | Jan–Feb | Feb–Mar | April–June |
| | | May–June | June–July | Sept–Nov |
| | | Oct–Nov | Jan | March–May |
| 6 | Cabbage | Sept–Oct | Oct–Nov. | Dec–March |
| 7 | Capsicum | Nov–Jan | Jan–Feb | April–May |
| | | June–July | July–Aug | Sept–Oct |
| 8 | Carrot | Aug–Oct | – | Dec–March |
| 9 | Cauliflower – Early | Early June | July | Nov. |
| 10 | Cauliflower – Mid season | July–Sept | Aug–Oct | Nov–Jan |
| 11 | Cauliflower – Late | Sept–Oct | Oct–Nov | Jan–March |
| 12 | Chillies | Nov–Jan | Jan–March | April–June |
| | | May–June | June–July | Sept–Nov |
| 13 | Cluster Bean | Feb–March | – | April–June |
| | | June–July | | Aug–Oct |
| 14 | Cowpea | June–July | – | Aug–Oct |
| | | Feb–March | | April–June |
| 15 | Cucumber | Feb–March | – | May–July |
| | | June–July | | Aug–Oct |
| 16 | Dolichos Bean | June–July | – | Oct–Dec |
| 17 | Fenu Greek | Sept–Nov | – | Nov–Feb |
| 18 | French Bean | Feb–March | – | April–May |
| 19 | Knol-Knol | Sept–Oct. | Oct–Nov. | Dec–Feb. |
| 20 | Lettuce | Sept–Oct | Oct–Nov | Dec–Feb |
| 21 | Muskmelon | Jan–Feb | – | April–June |
| 22 | Okra | Feb–March | – | March–June |
| | | June–July | | Aug–Nov |
| 23 | Onion | Oct–Nov | Dec–Jan | April–June |
| | | May–June | June–July | Oct–Nov |
| 24 | Peas-Early | Sept–Oct | – | Nov–Jan |
| | Peas | Oct–Nov | – | Jan–March |
| 25 | Potato | Sept–Nov | – | Jan–March |
| | | Dec–Feb | – /td> | March–April |
| 26 | Radish | April–Aug. | – | May–Sept |
| | | Sept–Oct | | Nov–Jan |
| | | Nov–Jan | | Dec–March |
| 27 | Palak | Sept–Nov | – | Nov–Feb |
| | | Feb | | March–April |
| 28 | Sponge Gourd | Feb–March | – | April–June |
| 29 | Ridge Gourd | June–July | – | Aug–Oct |
| 30 | Round melon | Feb–March | – | May–June |
| | | June–July | | Sept–Oct |
| 31 | Tomato | June–Aug | Aug–Sept | Oct–Dec |
| | | Nov–Dec | Dec–Feb | April–June |
| 32 | Turnip | Oct–Nov | – | Dec–March |
| 33 | Watermelon | Jan–March | – | May–June |

*Source*: ICAR (2007)

**Table 6.20** Sowing time of pulses

| S. No. | Crop | Sowing time |
|---|---|---|
| 1 | Gram/Chickpea | Unirrigated-15–20 Oct<br>Irrigated–15 Nov |
| 2 | Pea | Mid Oct–Mid Nov |
| 3 | Lentil | Mid Oct–Mid Nov |
| 4 | Moong bean | Summer: Mid April<br>Kharif: July |
| 5 | Urd bean | Summer: Mar- April<br>Kharif: July |
| 6 | Pigeon pea/Red gram/Tur | Spring: Feb<br>Kharif: Jun-July |
| 7 | Cowpea | Spring: Feb last<br>Summer: Mid April<br>Kharif: July |

*Source*: ICAR (2007)

Similarly, maize is the Kharif season crop but can be sown during the spring season, if soil moisture condition is good. Fruit crops, such as Banana and Guava, can be grown as multiple season crops (Kharif and Rabi).

#### 6.3.2.3 Cropping Intensity

Cropping intensity can be defined as number of times a land is cultivated within the single crop calendar year. For example, if a piece of land is sown two times in a single crop calendar year, the cropping intensity will be 200%. To reflect this feature the term cropping intensity is used as an indicator. The spatial variation in the cropping intensity of the basin is derived from the district wise average value of cropping intensity and is shown in Fig. 6.4. It is evident from Fig. 6.4 that the number of crops taken from a particular land per calendar year is more either along the river or in the irrigation command area. It might be due to the availability of surface water through the Yamuna and Ganga canal system. The cropping intensity in the extreme North-West area is very high (i.e. of the order of 200%) and it is due to the support of Bhakhra canal system (i.e. SYL and Narwana Canals). The average cropping intensity of the Yamuna basin is of the order of 141%. The catchment-wise cropping intensity is summarized in Table 6.21.

## 6.4 Irrigation

Irrigation plays a major role in the integrated water resources management as a majority of water resources is used for the agricultural irrigation. Irrigation is the replacement or supplementation of rainfall with water from other sources in order

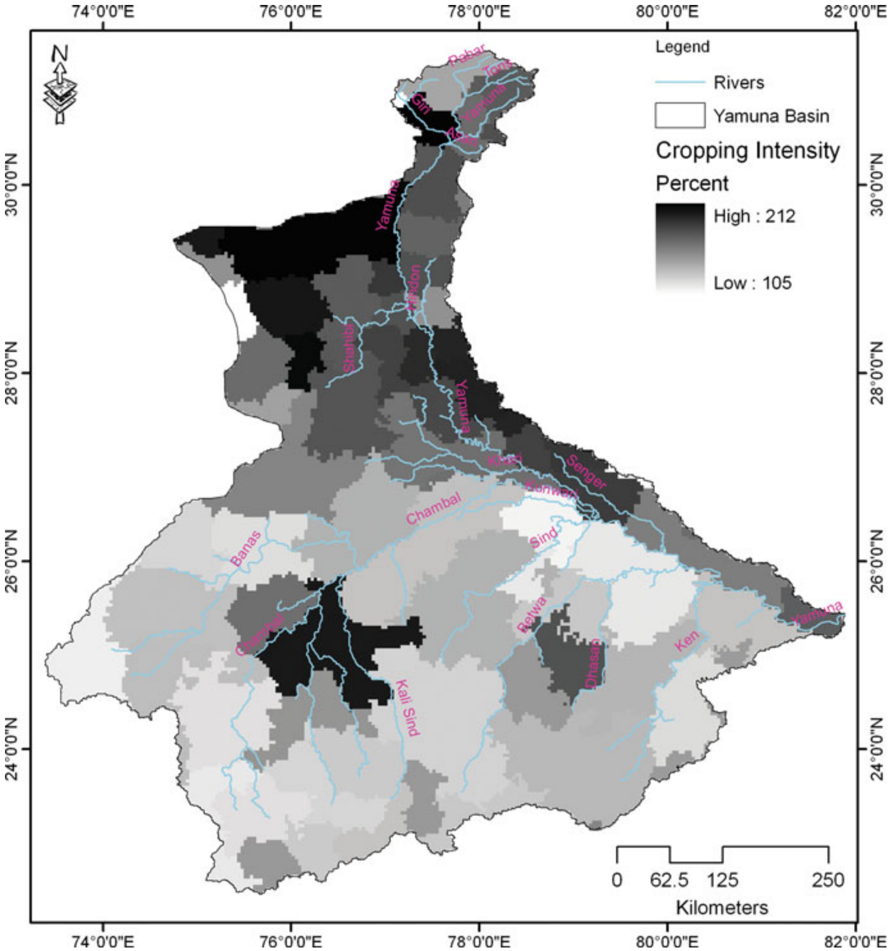


**Fig. 6.4** Spatial variation of cropping intensity in the Yamuna basin

to grow crops. In contrast, agriculture that relies only on direct rainfall is sometimes referred to as dry land farming. Irrigation demand is either fulfilled by surface water or groundwater. Irrigation is available from various sources and canals are the major water suppliers from large and small rivers. Dams, barrages, and anicuts are constructed on the rivers to regulate the flow of rivers and large storage reservoirs are developed to use water at times of deficiency. The storage in different basins varies according to its flow. The storage capacity in the Ganga basin is the largest due to its vast size. Major irrigation projects use surface water through canals. The percentage of the net irrigated area to the cultivable area is maximum in the alluvial plais of Ganga and Trans Yamuna plains. Uttar Pradesh ranks highest in area irrigated by canal followed by Andhra Pradesh, Punjab and Haryana. Minor irrigation schemes

**Table 6.21** Agriculture and irrigation sources in the Yamuna basin (All the units in ha)

| Catchment | Net sown area | Area sown more than once | Grass area | Net irrigated area (NIA) | NIA by canal | NIA by tube well | NIA by other sources | Cropping intensity (%) |
|---|---|---|---|---|---|---|---|---|
| Sahibi | 1,091,428 | 625,734 | 1,717,161 | 768,541 | 163,584 | 604,543 | 414 | 164 |
| Hindon | 505,223 | 268,794 | 774,016 | 451,932 | 83,396 | 360,982 | 7,554 | 153 |
| Khri | 1,339,520 | 631,598 | 1,971,118 | 1,027,059 | 102,467 | 918,136 | 6,456 | 148 |
| Chambal | 6,234,917 | 1,423,958 | 7,658,875 | 2,775,368 | 422,908 | 2,113,435 | 239,026 | 125 |
| Sind | 1,491,835 | 328,336 | 1,820,171 | 733,527 | 248,823 | 421,145 | 63,560 | 123 |
| Betwa | 2,685,310 | 630,452 | 3,315,761 | 1,212,924 | 274,703 | 734,686 | 203,535 | 126 |
| Ken | 1,583,438 | 404,388 | 1,987,825 | 664,013 | 100,532 | 444,868 | 118,614 | 127 |
| Karwan | 350,343 | 2,00,049 | 550,392 | 316,077 | 58,049 | 253,185 | 4,843 | 157 |
| Sengar | 413,643 | 239,900 | 653,543 | 360,722 | 93,560 | 266,397 | 765 | 158 |
| Yamuna | 18,790,861 | 6,609,467 | 25,400,328 | 10,517,828 | 2,856,924 | 7,040,012 | 620,893 | 141 |

Cropping Intensity = 100×[(Net Sown Area + Area Sown More than Once)/Net Sown Area] include groundwater development through the construction of dugwells, deep tube wells, and private shallow tubewells and lift irrigation projects.

The Yamuna River basin can be further classified based on the canal command area into four categories: arable land within command area, arable land outside the command area, water bodies and non-arable land (Fig. 6.5). For crop irrigation different sources are being practiced in the basin. These sources can be categorized as canal, tube well, and others (i.e. tanks, ponds, etc.). Approximately 67% area is irrigated through groundwater resources. Only 27% agriculture water demand is met by canal systems and the rest 6% area is irrigated through tanks, ponds, etc. Details of areas irrigated by different sources are given in Table 6.21. However, the state wise irrigation sources in the Yamuna basin is given in Table 6.22.

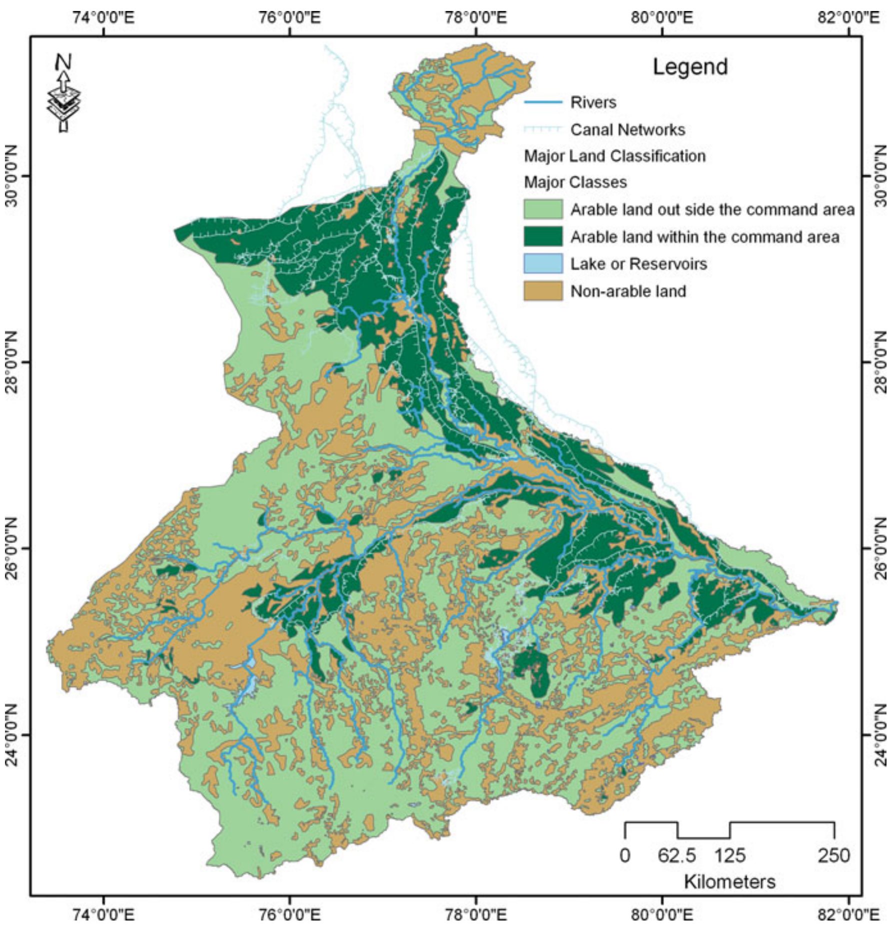


**Fig. 6.5** Land classification based on canal command area in Yamuna basin

**Table 6.22** State-wise irrigation system in the Yamuna basin

| State | Area (1,000 ha) | NSA (1,000 ha) | Total IA (1,000 ha) | % IA | Irrigated area by source (%) Canal | Tank | TW | Well | Other sources |
|---|---|---|---|---|---|---|---|---|---|
| Haryana | 4,421 | 3,696 | 2,350 | 63.7 | 53.5 | | 45.7 | 0.5 | 0.3 |
| Himachal Pradesh | 5,567 | 571 | 93 | 16.3 | 2.1 | 1.2 | 6.4 | | 90.3 |
| Madhya Pradesh | 44,345 | 19,027 | 2,656 | 13.9 | 43.7 | 7.0 | 2.0 | 40.3 | 7.0 |
| Rajasthan | 34,224 | 15,660 | 3,218 | 20.5 | 31.8 | 4.4 | 5.2 | 56.9 | 1.7 |
| Uttar Pradesh[a] | | 17,226 | 9,884 | 57.4 | 33.7 | 1.7 | 54.4 | 7.0 | 3.2 |
| Delhi | 148 | 65 | 52 | 80 | 7.7 | 1.9 | 84.7 | 1.9 | 3.8 |

[a] Uttar Pradesh including Uttarakhand

## 6.5 State-Wise Agriculture

### *6.5.1 Uttar Pradesh*

The economy of Uttar Pradesh is predominantly agrarian and the performance of agriculture and allied activities, such as horticulture, animal husbandry, dairying and fisheries, are critical in determining the growth rate of the State. The primary sector (inclusive of mining) contributes 36.8% to the State's income in 2003–2004 and provides employment to 66% of total workers. However, the share of this sector in State income has been progressively declining.

Out of an estimated number of 22.15 million rural households in Uttar Pradesh, 77.4% are farmer households. According to data released by National Sample Survey Organization (NSSO) based on 59th round of NSS, 24% of UP farmers (27% at all India level) de not like farming and feel that agriculture is not profitable. In all 41% farmers in UP (40% at all India level) feel that given a choice, they would take up some other career. This indicates a serious problem, wherein the main protagonist are suffering from low self-esteem and do not believe that what they are doing is worthwhile economically or even socially. In the social hierarchy, farming as a profession now figures considerably low in the social order.

***Indebtedness of Farmers*****:** The data released by NSSO provides useful insights regarding indebtedness of farmers in the country as a whole as well as Uttar Pradesh. In Uttar Pradesh, out of 17.16 million farmer households, 6.92 million (40.3%) are reported to be indebted while for the country as a whole, 48.6% (43.42 million) of 89.35 million farmer households were reported to be indebted. The estimated prevalence of indebtedness among farmer households is highest in Andhra Pradesh (82%) followed by Tamil Nadu (74.5%) and Punjab (65.4%). In UP, households with one hectare or less land account for 74% of all farmer households and about 39% of them are indebted. Tables 6.23 and 6.24 show the agricultural production and productivity in Uttar Pradesh as whole. Agricultural production has increased from

**Table 6.23** Agricultural production in Uttar Pradesh (000 tonnes)

| | | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S.No. | Crop | 1995–1996 | 1996–1997 | 1997–1998 | 1998–1999 | 1999–2000 | 2000–2001 | 2001–2002 | 2002–2003 | 2003–2004 | 2004–2005 |
| 1 | Paddy | 9,788 | 11,197 | 11,678 | 10,826 | 12,633 | 11,679 | 12,856 | 9,596 | 13,022 | 9,559 |
| 2 | Total Kharif foodgrains | 12,967 | 14,374 | 15,082 | 13,212 | 15,681 | 14,998 | 15,877 | 12,003 | 15,996 | 12,498 |
| 3 | Wheat | 21,077 | 23,287 | 22,147 | 22,781 | 25,551 | 25,168 | 25,498 | 23,748 | 25,567 | 22,514 |
| 4 | Total Rabi foodgrains | 23,705 | 26,321 | 24,939 | 25,612 | 28,580 | 27,777 | 28,310 | 26,370 | 28,442 | 253,05 |
| 5 | Total Food grains | 36,672 | 40,695 | 40,021 | 38,824 | 44,261 | 42,775 | 44,187 | 38,373 | 44,438 | 37,803 |
| 6 | Oilseeds | 1,389 | 1,520 | 984 | 1,070 | 1,268 | 1,145 | 1,110 | 851 | 928 | 946 |
| 7 | Pulses | 2,163 | 2,591 | 2,282 | 2,308 | 2,551 | 2,160 | 2,377 | 2,182 | 2,380 | 2,366 |

**Table 6.24** Crop productivity in Uttar Pradesh (Quintal/ha)

| | | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S. No. | Crop | 1995–1996 | 1996–1997 | 1997–1998 | 1998–1999 | 1999–2000 | 2000–2001 | 2001–2002 | 2002–2003 | 2003–2004 | 2004–2005 |
| 1 | Rice | 18.54 | 22.21 | 21.46 | 19.42 | 21.85 | 19.77 | 21.17 | 18.4 | 21.87 | 17.9 |
| 2 | Total Kharif foodgrains | 16.06 | 17.74 | 18.29 | 16.04 | 18.73 | 17.53 | 18.25 | 15.7 | 18.27 | 16.01 |
| 3 | Wheat | 24.69 | 27 | 25.25 | 25.51 | 28.03 | 27.24 | 27.55 | 25.9 | 27.94 | 25.02 |
| 4 | Total Rabi foodgrains | 21.02 | 23.39 | 21.99 | 22.15 | 24.55 | 23.59 | 24.14 | 22.8 | 24.75 | 22.05 |
| 5 | Total foodgrains | 18.95 | 21.02 | 20.43 | 19.61 | 22.12 | 21.04 | 21.63 | 20 | 21.95 | 19.6 |
| 6 | Oilseeds | 8.67 | 8.98 | 6.08 | 7.01 | 8.74 | 8.25 | 8.69 | 7.72 | 8.19 | 8.4 |
| 7 | Pulses | 7.74 | 9.32 | 8.27 | 8.29 | 9.57 | 8.03 | 8.86 | 8.26 | 8.9 | 8.5 |

1995 to 2005 for crops except paddy and oilseeds. Productivity has also declined from 2003–2004 to 2004–2005, except for pulses and oilseeds as it is a drought year.

***Irrigation in Uttar Pradesh*:** In Uttar Pradesh, the proportion of net irrigated area to net cropped area has increased from 36.12% in 1966–1967 to 54.89% in 1980–1981 and 76.30% in 2001–2002. However, the net irrigated area by private sources such as private tube well/ pump sets constitute nearly 87.09 lakh hectares, which is 68% of the net irrigated area. There are 35 lakh private tube wells/pump sets in Uttar Pradesh of which about 28 lakh are diesel operated and 7 lakh electricity operated. Canal irrigation provides irrigation facilities to only 27.19 lakh hectares, which is about 21% of net irrigated area. 28,123 State Tube wells account for just 8% of the net irrigated area.

The area irrigated by canals has been continually declining over the years. Further, the water use efficiency in most irrigation systems is low in the range of 30–40% as against an ideal value of 60%. There has also been steady decline in the water table due to over-exploitation of ground water and insufficient recharge from rainwater. Declining trend of groundwater has been observed in 559 of 819 blocks in the State. Between 1987 and 2000, the percentage of groundwater used for irrigation has gone up from 30 to 57.31% for the State as a whole. It is also noteworthy that against created irrigation potential of 31,063.73 thousand hectares, the actual utilization of potential was only 22,404.48 thousand hectares in 2002–2003. This lag of nearly 90 lakh hectares is a cause of serious concern. It could be due to several reasons, such as non-construction of on-farm development works below the outlet, change in cropping patterns to more water intensive crops, loss in live storage due to sedimentation, low water use efficiency due to disrepair of the system etc. Heavy load of silt in river waters and thereby excessive siltation of the canals has reduced the carrying capacity of the canal system and hence there is a decline of water use at tail end areas of canals. Further, the irrigation potential created can be described as "protective irrigation" rather than "assured irrigation". The difference in operating costs of canal irrigation and tube well based irrigation is in the ratio of 1:7 and rising cost of diesel is placing a heavy burden on small and marginal farmers. Consequently, farmers provide only that much irrigation as required to save the crop rather than meet the full requirement of water for the crop.

### *6.5.2 Madhya Pradesh*

Madhya Pradesh has about 73% rural population depending largely on agriculture. Approximately 70% of the geographical area is under cultivation. Of the total gross cropped area cereals covers 42%, pulses 21% and oilseed 21%, commercial (cotton and sugarcane etc.) 3% and the remaining is covered by other crops e.g. vegetables, fruit, fodder and medicinal crops. Of the total gross cropped area 59% is sown in Kharif season, 41% in Rabi season and multiple cropped area is about 24%. The major agriculture and horticulture crops grown in Madhya Pradesh are summarized in Table 6.25.

**Table 6.25** Major agriculture and horticulture crops of Madhya Pradesh

| S. No | Crop type | Crop |
|---|---|---|
| 1 | Cereals | Wheat, sorghum (jowar), maize and paddy |
| 2 | Oilseeds | Soya bean, mustard, linseed |
| 3 | Pulses | Gram, pigeon pea (tur), lentil (masoor) |
| 4 | Vegetables | Green peas, cauliflower, okra, tomato, onion, potato |
| 5 | Fruits | Mango, guava, orange, papaya, banana |
| 6 | Spices | Chilies, garlic, coriander, ginger, turmeric |

The state share (2004–2005) in the total national production of oilseeds is 18.8% (soybean 50%), pulses 25% (gram 44%) and the state is ranked Number 01 in the country in production of oilseeds and pulses. Madhya Pradesh also leads in spices production with the largest production of garlic, accounting for 37% of the total national production and is second largest producer of coriander in the country.

Among vegetables, Malwa potato has gained reputation for processing into potato chips. The state's share in the total national production of pea is 15%.

***Irrigation in Madhya Pradesh*:** There are several small and large dams constructed in the Chambal, Sind, Ken and Betwa sub-basins of Madhya Pradesh that have increased the irrigation potential of the state. The Rajghat irrigation project is a major interstate development with water from the Rajghat Dam on the Betwa River being shared equally between Uttar Pradesh and Madhya Pradesh. The water allocated to Madhya Pradesh is planned to irrigate 121,450 ha in the districts of Guna, Shivpuri, Tikamgarh, Bhind, Gwalior and Datia.

### *6.5.3 Rajasthan*

Seventy six percent (76%) of the population of Rajasthan reside in the rural area, and their economy is agriculture based. In Rajasthan, cereal crops, such as bajra, juar, wheat and barley cover the largest cultivated area. Salient features of Rajasthan as whole for agriculture is given in Table 6.26. The main crops of the Rajasthan are as follows:

(i) Bajra (*Pennisetum typhoideum*) is consumed by the rural poor, particularly the nomads. Rajasthan is the largest producer of bajra in India.
(ii) Juar (*Sorghum vulgare*) is an important crop during the monsoon.
(iii) Gram (*Cicer arietinum*) is another major pulse crop grown in rabi.
(iv) Wheat (*Triticum sp.*) is cultivated on the irrigated land.
(v) Barley (*Hordeum vulgare*) is the second largest crop in Rajasthan.
(vi) Maize (*Zea mays*) is a stable crop for the Bhil tribes in the Aravallis.
(vii) In northern Rajasthan, maize is a delicacy eaten with butter and the green leaf of the mustard plant.
(viii) Groundnut is a major kharif oilseed crop.

**Table 6.26** Salient features of Rajasthan agriculture

| S. No. | Item | Year | Unit | |
|---|---|---|---|---|
| 1 | Average size of Operational holding | 2000–2001 | ha | 3.65 |
| 2 | Gross irrigated area to gross cropped area | 2007–2008 | % | 36.42 |
| 3 | Net irrigated area to net sown area | 2007–2008 | % | 37.69 |
| 4 | Net area sown to total reporting area | 2007–2008 | % | 49.89 |
| 5 | Consumption of fertilizers per hectare of cropped area | 2006–2007 | kg/ha | 49.45(F) |
| 6 | Average yield per hectare (F) | | | |
| | (i) Food grains | 2007–2008 | kg | 1,177 |
| | (ii) Oil seeds | 2007–2008 | kg | 1,045 |
| | (iii) Sugarcane | 2007–2008 | kg | 57,089 |
| | (iv) Cotton (Lint) | 2007–2008 | kg | 397 |

(ix) Sesame Rajasthan provides the second highest quantum of sesame (*Sesamum indicum*) in India. One of its common uses is as an ingredient in sweetmeats.

(x) Cotton (*Gossypium sp.*) used to make the famous Rajasthan textiles, is a major cash crop.

***Irrigation in Rajasthan*:** The Indira Gandhi or Rajasthan canal provides irrigation to the arid western districts of Bikaner and Jaisalmer. Ganganagar district is irrigated with water from the Ganga canal in the Punjab. Irrigation projects have also developed on the Chambal and Luni rivers. The western region grows predominantly kharif (monsoon) crops, while the eastern belt, which has better rains and soil, grows both kharif and rabi (winter) crops. The latter is grown under rain-fed farming conditions or in irrigated areas.

In the central and eastern region of Rajasthan, the Persian wheel method is popular where the ground water table is comparatively high. One Persian wheel can irrigate up to one hectare of land. For groundwater abstraction through pumps, nearly 80% villages have electricity supply. The canal density in the Rajasthan is quite low. Canal command area in the Chambal basin is due to the canal networks of Kota barrage and Bisalpur dam. However, a few parts of the Shahibi and Khari river catchment are partly fed by the Agra canal.

### *6.5.4 Delhi*

Important crops grown in the union territory are wheat, gram, Bajra and Jowar. The important sources of irrigation are tube wells, wells and canals. On the floodplain of Yamuna, agriculture is based on excessive use of groundwater, agrochemicals and

**Table 6.27** Irrigated area in Delhi (ha)

| Source of Irrigation | 1994–1995 | 1995–1996 | 1996–1997 | 1997–1998 | 1998–1999 |
|---|---|---|---|---|---|
| Canals | 2,304 | 2,425 | 2,102 | 3,179 | 2911 |
| Tanks | – | – | – | – | – |
| Wells | 36,600 | 42,306 | 34,698 | 37,988 | 36,159 |
| (a)Tubewells | 35,887 | 41,055 | 33,481 | 34,214 | 34,972 |
| (b)Other Sources | 713 | 1,251 | 1,217 | 3,774 | 1,187 |
| Net Area Irrigated | 38,904 | 44,731 | 36,800 | 41,165 | 39,070 |
| Area Irrigated under more than one crop | 11,292 | 2,724 | 428 | 2,836 | 8,968 |
| Gross Area Irrigated | 50,196 | 47,455 | 37,228 | 44,001 | 48,038 |

*Source*: Directorate of Economics and Statistics (2000) Delhi

**Table 6.28** Salient features of agriculture in Delhi

| Year | Net sown area (ha) | Gross cropped area (ha) | Cropping Intensity |
|---|---|---|---|
| 1994–1995 | 47,409 | 68,613 | 145 |
| 1999–2000 | 41,386 | 60,886 | 147 |
| 2005–2006 | 23,809 | 36,041 | 161 |

organic manures, which is not sustainable. The revival of earlier water bodies along with creation of new water bodies to "harvest" floodwaters during the monsoon, and the accompanying change in land use from agriculture to semi intensive aquaculture and pasture greater economic returns per unit of land area can be achieved. Tables 6.27 and 6.28 show trends in agriculture in Delhi. It was observed that the net sown area in Delhi has reduced though the cropping intensity has been increased. This trend shows the completely unsustainable use of natural resources.

### *6.5.5 Haryana*

Due to adequate irrigation facilities in state, intensive agriculture is being practiced. Considering agricultural statistics of Haryana, it is evident that the cropping intensity is close to 200% (Table 6.29). The percentage net irrigated area is 82.3%. Haryana contributes 69.11 lakh tone of wheat to central pool. This is mainly due to high infrastructure developed for irrigation.

Haryana state has a good canal density, and most of the cultivated areas are well connected with canal system fed by either the Western Yamuna Canal or Bhakra canal. Apart from this source, groundwater exploitation in the state is very high causing most of the area under dark with respect to the stage ground water development percentage.

**Table 6.29** Agricultural statistics of Haryana

| Item | |
|---|---|
| Cultivable area ("000" ha) | 3,809 |
| Percent Cultivable area | 86.2 |
| Net area sown ("000" ha) | 3,566 |
| Percent Net area sown | 93.6 |
| Area sown more than once ("000" ha) | 2,938 |
| Gross cropped area ("000" ha) | 6,504 |
| Cropping Intensity | 182.39 |
| Net area irrigated (Total) ("000" ha) | 2,936 |
| • By canal | 1,331 (45.3%) |
| • Tube well | 1,591 (54.2%) |
| • Others | 14 (0.5%) |
| Gross irrigated area ("000" ha) | 5,446 |
| Intensity of Irrigation | 185.49 |
| Percent net irrigated sown area | 82.3 |
| Fertilizer consumption (kg/ha.) (2007–2008) | 209 (NP ratio 3.2:1) |
| Foodgrains Prod. (Lakh Tonnes) (2008–2009) Kharif- 44.88 and Rabi- 116.78) | 161.66 |
| Contribution of Haryana to central pool of Wheat. (lakh tonnes) 2008–2009 | 69.11 |

## 6.6 Fertilizer and Pesticides Application

The key role of fertilizers and their judicious use in cropping is well understood, when one is familiar with the general facts about plant nutrition. In one study in New Delhi 28 kg N, 4.4 kg P, 41 kg K, 4.9 kg S, 5.9 kg Ca, 4.2 kg Mg, 400 g Fe, 100 g each of Mn and Zn and 30 g Cu are removed from the soil for each tonne of wheat grain produced. Similarly, from the International Rice Research Institute, Philippines it is reported that 10–31 kg N, 1–5 kg P and 8–35 kg K were removed from the soil per tonne of rice grain produced. When crop yields of 5–8 t grain $ha^{-1}$ are taken as with the high yielding varieties of crops, it is not possible for most soils to supply the needed amounts of plant nutrients and that is why fertilizers are needed.

Such heavy removal of plant nutrients from soil leads to the depletion of soil fertility, which shows up in the crop yield decline and lowered factor productivity. For example, in a long-term study at four research centers rice yields have declined by 32% in plots receiving nitrogen and phosphate fertilization; the decline in unfertilized plots has been 57%.

From the dry land rain fed areas where yields are low and very little fertilizer applied, a negative balance between crop removal and plant nutrient application of 6.37 million tonnes $yr^{-1}$ ($N + P_2O_5 + K_2O$) in India has been reported. Thus, contrary to lowering the rates of fertilizer application, Indian farmers may have to think of fertilizing for crop production as well as for soil fertility resilience. Thus, fertilizer has been and will continue to be the main input in India's achieving self sufficiency in food grain production.

Among the seven states of the Yamuna basin, Uttar Pradesh and Haryana are the big users of fertilizer.

***Pesticide*:** The use of synthetic pesticides in agriculture is world-wide still the most widespread method for pest control. Environmental and human health problems related to the use of synthetic pesticides have created an increasing pressure against their use. Therefore, non chemical alternatives for pest control have been developed and modern pesticides have become safer and more specific. Technical developments of the application equipment have kept pace, ensuring an adequate application of these modern products. However, those technical developments regarding modern application equipment and their professional use have not been transferred satisfactorily to field practice. In order to improve these situations, the Agricultural Engineering Service of FAO has initiated a programme to create awareness for the issue on a government level, introduce adequate practical training programmes for farmers and equipment operators and improve equipment quality through the introduction of standards and regular tests.

***Potential Adverse Effects of Pesticides*:** Despite their many advantages, there are some potential hazards or risks when using farm chemicals. These risks may be associated with all chemicals whether they be industrial chemicals, pesticides, household products or even natural chemicals found in the environment. Undesirable side effects of farm chemical use usually stem from a lack of understanding of the impact of chemicals on the environment, compounded by indiscriminate and overuse of the product. These side effects do not always occur when farm chemicals are used and damage does not necessarily result. Some of these effects may be:

- Reduction of beneficial species. Non-target organisms, including predators and parasites of pests, can also be affected by chemical application. The reduction of these beneficial organisms can result in changes in the natural biological balances. Losses of honeybees and other pollinating insects can also be a problem.
- Drift of sprays and vapour during application can cause severe damage and residue problems in crops, livestock, waterways and the general environment. Care in the methods of application and the weather conditions under which it is carried out can reduce drift. Environmental pollution from careless application and runoff can result in wildlife and fish losses. This should be a concern for all of us.
- Residues in food for humans and feed for livestock can be a consequence of direct application of a chemical to the food source, by the presence of pollutants in the environment or by transfer and biomagnifications of the chemical along a food chain. Not all residues are undesirable although good agricultural practice must be observed to prevent unnecessary and excessive levels of residues.
- Ground water contamination by leached chemicals can occur in high use areas if persistent products are used.

- Resistance to the pesticide used can develop in target pests due to the overuse and incorrect use of the chemical.
- Poisoning hazards and other health effects to operators can occur through excessive exposure if safe handling procedures are not followed and protective clothing not worn. Poisoning risks depend on dose, toxicity, duration of exposure and sensitivity.
- Other possible health effects due to indiscriminate use of farm chemicals also concern many people in the community.

The Indian pesticide industry with 85,000 MT of production during year 2007 is ranked second in Asia (behind China) and twelfth globally. The per hectare consumption of pesticide is low in India at 381 grams when compared to the world average of 500 g. Low consumption can be attributed to fragmented land holdings, low level of irrigation, dependence on monsoons, low awareness among farmers about the benefits of usage of pesticides, etc. India, being a tropical country, the consumption pattern is also more skewed towards insecticides which accounted for 64% of the total pesticide consumption in year 2007. Table 6.30 shows state-wise distribution points in the Yamuna basin for pesticides. Consumption in all the concerned states has reduced from year 2002–2003 to 2006–2007 except Uttar Pradesh and Uttarakhand (Table 6.31).

**Table 6.30** Distribution points for pesticides (Year 2007)

| State | State department | Cooperative | Other institutions | Private | Total |
|---|---|---|---|---|---|
| Haryana | – | 870 | – | 6,080 | 6,950 |
| Himachal Pradesh | 570 | 59 | – | 942 | 1,571 |
| Madhya Pradesh | – | 503 | – | 1,557 | 2,060 |
| Rajasthan | – | 951 | – | 7,337 | 8,288 |
| Uttar Pradesh | 868 | 443 | 520 | 11,857 | 13,688 |
| Uttarakhand | 267 | 177 | – | 963 | 1,407 |
| Delhi | 14 | 08 | – | 175 | 197 |

*Source*: PMU (2007–2008)

**Table 6.31** Consumption of pesticides

| States | 2002–2003 | 2003–2004 | 2004–2005 | 2005–2006 | 2006–2007 |
|---|---|---|---|---|---|
| Haryana | 5,012 | 4,730 | 4,520 | 4,560 | 4,600 |
| Himachal Pradesh | 380 | 360 | 310 | 300 | 290 |
| Madhya Pradesh | 1,026 | 662 | 749 | 787 | 879 |
| Rajasthan | 3,200 | 2,303 | 1,628 | 1,008 | 1,523.20 |
| Uttar Pradesh | 6,775 | 6,710 | 6,855 | 6,672 | 7,022 |
| Uttarakhand | 129 | 147 | 132 | 141 | 139 |
| Delhi | 60 | 56 | 53 | 39 | 57 |

## 6.7 Practice of IPM and IPNM

Site-specific nutrient management considers indigenous nutrient supply of the soil and productivity targets capable of sustained high yields on one hand, and assured restoration of soil fertility on the other hand. With this approach, the present food grain production could be achieved from half of the presently irrigated area. Practice of Integrated Pest Management (IPM) and Integrated Pest & Nutrient Management (IPNM) is very little in the basin, still traditional practices for fertilizer and pesticides consumption are on in the entire area.

***Integrated Pest and Nutrient Management (IPNM)*****:** The basic purpose of inducting this component has been to popularize and practice the balanced use of fertilizers based on soil testing. In general farmers have been using more and more nitrogenous and phosphatic fertilizers with less emphasis on the use of potash fertilizers and other micronutrients.

***Integrated Pest Management (IPM)*****:** Integrated Pest Management, or IPM, "is a sustainable approach to managing pests by combining biological, cultural, physical and chemical tools in a way that minimizes economic, health, and environmental risks" (National Coalition on Integrated Pest Management). Integrated Pest Management strategies have been used for many years in agriculture.

In technical terms, Integrated Pest Management (IPM) is the coordinated use of pest and environmental information with available pest control methods to prevent unacceptable levels of pest damage by the most economical means and with the least possible hazard to people, property, and the environment.

***Integrated Nutrient Management (INM)*****:** The main objective of Integrated Nutrient Management (INM) is to ensure adequate availability of quality fertilizers to farmers through periodic demand assessment and timely supply, promoting integrated nutrient management, which is soil test based, judicious and balanced use of chemical fertilizers in conjunction with organic manures and bio-fertilizers, promotion of organic farming and ensuring quality control of fertilizers through implementation of Fertilizer (Control) Order, 1985.

India is the third largest producer and consumer of fertilisers in the world after China and the USA. Against 18.4 million tonnes of fertiliser nutrients (Nitrogen, Phosphorous and Potassium, NPK) consumed during 2004–2005, the nutrient consumption is estimated at 20.2 million tonnes during 2005–2006. The consumption of major fertilisers, namely, Urea, DAP, MOP, SSP and Complexes are estimated to be 22.2, 6.8, 2.6, 2.8 and 6.7 million tonnes, respectively, during 2005–2006. India is, by and large, self sufficient in respect of Urea and about 90% in case of DAP.

The all-India average fertiliser consumption is 96.4 kg/ha of NPK nutrients through there is a wide variation from state to state varying from 197 kg/ha in Punjab, 164 kg/ha in Haryana to less than 10 kg/ha in States like Arunachal Pradesh, Nagaland, Sikkim, etc. Considering the skewed pattern of fertiliser use, Government of India is promoting balanced and integrated use of fertiliser nutrients through various initiatives. As a result, NPK consumption ratio has now improved to 5.7: 2.2: 1 during 2004–2005 from 7: 2.7: 1 during 2000–2001.

***Promotion of Bio-fertiliser*:** With a view to promote the use of bio-fertilisers as an environment-friendly and cheaper source of plant nutrients, Government of India had earlier taken up a “National Project on Development and Use of Bio fertilisers” during the Sixth Plan and was continued till Ninth Plan.

***Organic Farming*:** Organic farming is becoming increasingly popular worldwide and global demand for organic products is increasing rapidly. Organic farming is not only expected to increase the income of farmers but also helps in moving towards sustainable agriculture and environmentally friendly and healthy food. Many farmers are practicing organic cultivation but not in an organized manner properly. Hence, they need proper scientific knowledge, management and certification system.

For promotion of organic farming, it is advocated that an area and cluster based approach be adopted by the state governments. This will help in concentrating activities of target groups and also help in creation of awareness and educating the farmers easily, making a quick assessment of the demand and arranging the supplies etc. There is a need to identify and appoint adequate committed service providers who will act as a technology transfer vehicle to farmers and will serve as a link between certification agencies and farmers.

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# Chapter 7
# Socio-economic Status

**Abstract** This chapter addresses major issues of socio-economic status of the Yamuna River basin, including demography, population growth, urbanization, migration, sex ratio, literacy, classification of workers, agricultural labor and farmers, and population below poverty line. Various health indicators are discussed to assess the health status in the basin. For overall spatial socio-economic status in the basin, various indicators, such as human development index and technical efficiency, are described. Other important parameters, such as livelihood and employment, livestock population, water supply, and water auditing, are also covered.

The World Summit on Sustainable Development (WSSD, 2002) recommended that integrated water resources management and water efficiency planning should be an essential element in all national or regional development strategies. The success of Integrated Water Resources Management (IWRM) and planning depends on institutional and human resources capacity, awareness and leadership.

Monitoring at all levels is important to ascertain progress in meeting the IWRM targets and to alert agencies and organizations capable of providing support to those areas lagging behind and in need of assistance.

The disparity between the areas that are making progress and those that are left behind in the process of implementing IWRM is increasing. Most monitoring efforts to date have tended to rely upon largely subjective assessments and have focused more on planning than implementation aspects. IWRM planning requires a variety of socio-economic data of the basin. Some indicative parameters in the Yamuna basin are elaborated in this chapter.

The Yamuna River basin covers seven states partly or completely, viz. Uttarakhand, Himachal Pradesh, Haryana, Uttar Pradesh, Delhi, Rajasthan and Madhya Pradesh. The basin area comprises 89 districts from these states. The administrative boundary in the basin is shown in Fig. 7.1.

## 7.1 Demography

Demography results can be used in many different ways, ranging from very general to very specific technical applications. From a strictly statistical viewpoint, the census data represents one of the most important components of the information system and can serve as a basis for many other statistical activities related to food,

R.K. Rai et al., *The Yamuna River Basin*, Water Science and Technology Library 66,
DOI 10.1007/978-94-007-2001-5_7, 

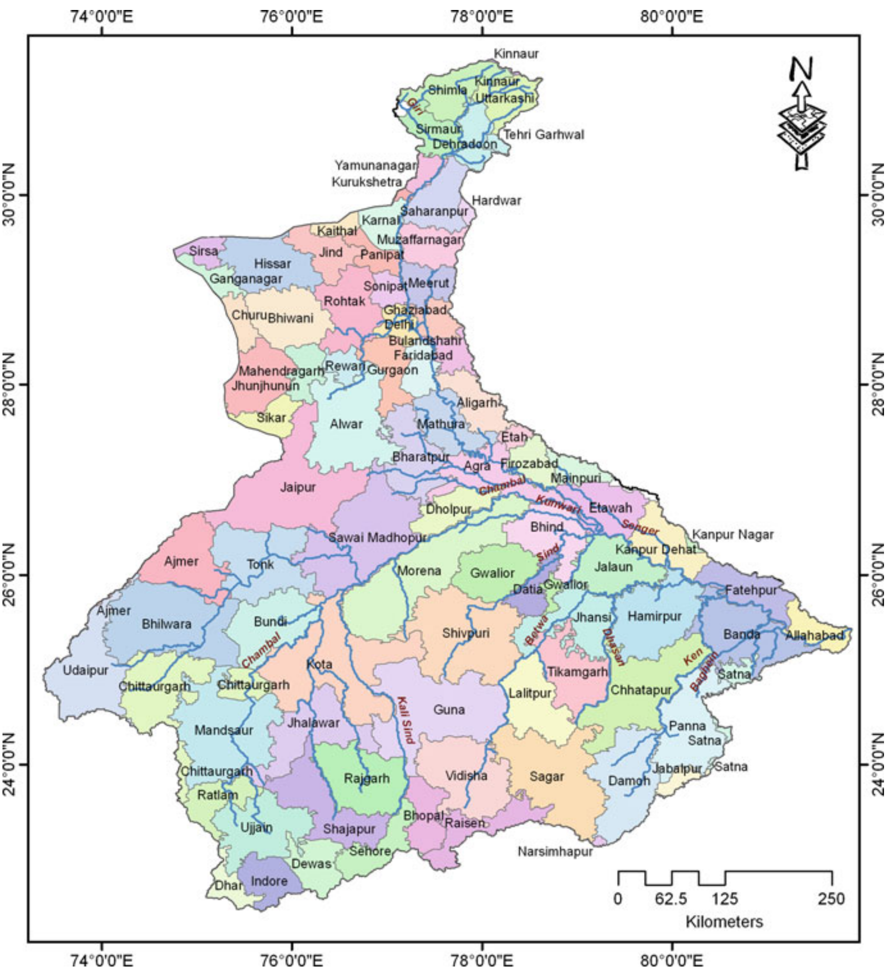


**Fig. 7.1** Administrative setup (districts) of the Yamuna River basin

agriculture, education and infrastructure. While the reason for census data collection is no doubt the use of census data for agriculture and infrastructural development planning and formulation of policies, a much wider application of census results is possible.

As stated above, seven states form the drainage area (approximately 3,65,868 km$^2$) of the Yamuna basin. The state-wise population share estimated from the population data of Census-2001 in the basin is shown in Fig. 7.2. The total population of the basin is estimated to be 127,524,051 (i.e., 127.5 million). Among these states, Uttar Pradesh alone contributes 32.95% of the basin population followed by Madhya Pradesh, Rajasthan, Haryana, Delhi, Uttarakhand and Himachal Pradesh; though the geographical area contribution of Uttar Pradesh (19.19%) in the basin is less as compared to the Madhya Pradesh (38.25%) (Fig. 7.3). By comparing

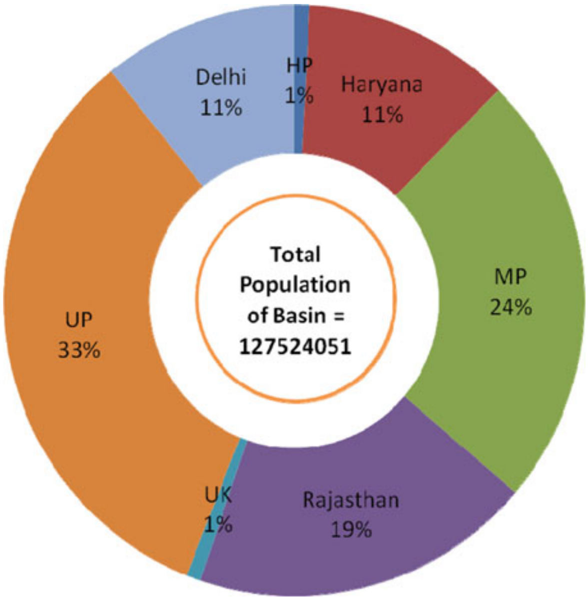


**Fig. 7.2** State wise share of population in the Yamuna basin

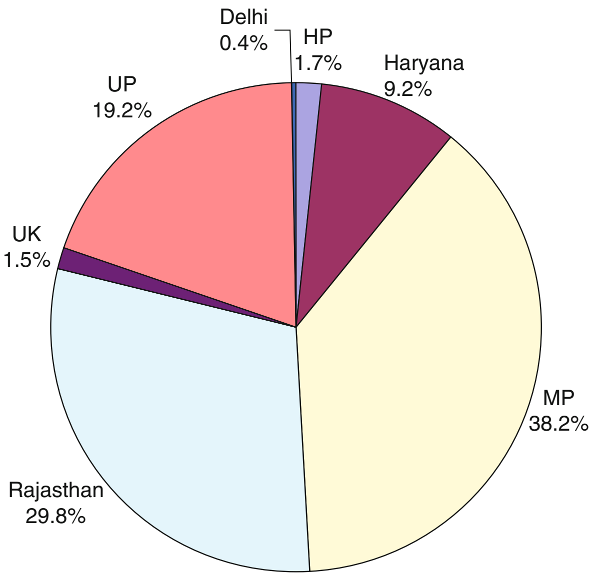


**Fig. 7.3** State wise share of area in the Yamuna basin (%)

Figs. 7.2 and 7.3, it can be seen that Delhi has highest population density, which shares only 0.40% area while the population share of Delhi is 11% close to that of Haryana which results in severe pollution in the Yamuna River.

### *7.1.1 Urban and Rural Population*

The Yamuna River basin comprises 92 districts, and a few of them partly contribute to the area. Out of 92 districts, approximately 32 districts have industrial influence. Rural areas are dominantly agricultural communities. In the Yamuna basin, more than half of the population (i.e. 62.3%) is categorized as rural population, and the rest of the population (i.e., 37.6%) are urban population (Census, 2001). However, the national average percentage of the rural population is of the order of 70%. This difference is caused due to large population of Delhi. The state-wise categorized population residing in the Yamuna basin is given in Table 7.1.

Analysis of Census (Census, 1991, 2001) shows that population in rural areas is shrinking mainly due to migration to urban areas for employment opportunity, and will further continue because of better living standard and other reasons. The overall distribution of the total urban population in the basin is the highest in Uttar Pradesh followed by Delhi, Madhya Pradesh, Rajasthan, Haryana, Uttarakhand and Himachal Pradesh as 27.51, 26.85, 19.83, 15.5, 8.91, 1.01 and 0.40%, respectively (Fig. 7.4). The rural population is also highest in Uttar Pradesh (i.e., 36.49%) followed by Madhya Pradesh and Rajasthan (Fig. 7.5).

### *7.1.2 Population Density*

Population density is commonly represented as people per square kilometer. Several of the most densely populated city-states share a relatively small area and a high urbanization level, with an economically specialized city population drawing also on rural resources outside the area, illustrating the difference between high population density and over-population. The population density of India in 2001 was 324

**Table 7.1** Population in the Yamuna basin (Census, 2001)

| State | Population | Urban population | Rural population |
|---|---|---|---|
| Himachal Pradesh | 1,107,815 | 191,589 | 916,226 |
| Haryana | 14,733,152 | 4,272,975 | 10,460,177 |
| Madhya Pradesh | 30,363,417 | 9,512,468 | 20,850,949 |
| Rajasthan | 24,213,470 | 7,432,741 | 16,780,729 |
| Uttarakhand | 1,033,572 | 482,496 | 551,076 |
| Uttar Pradesh | 42,227,667 | 13,193,488 | 29,034,179 |
| Delhi | 13,844,958 | 12,875,811 | 969,147 |
| Total | 127,524,051 | 47,961,568 | 79,562,483 |

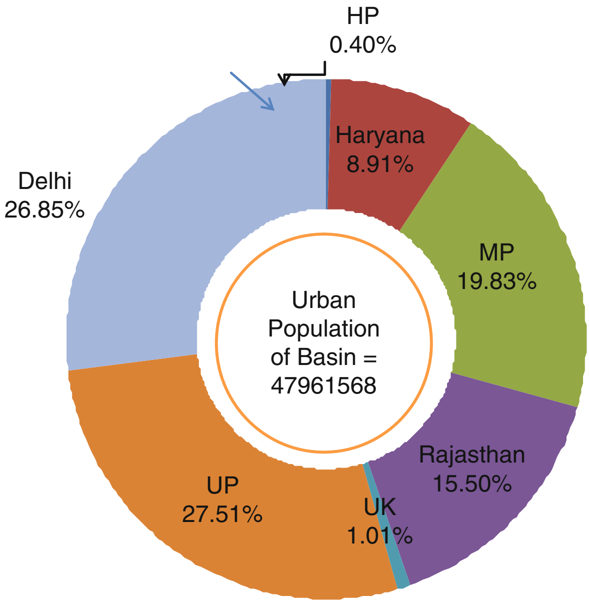


**Fig. 7.4** State wise share of urban population in the Yamuna basin (%)

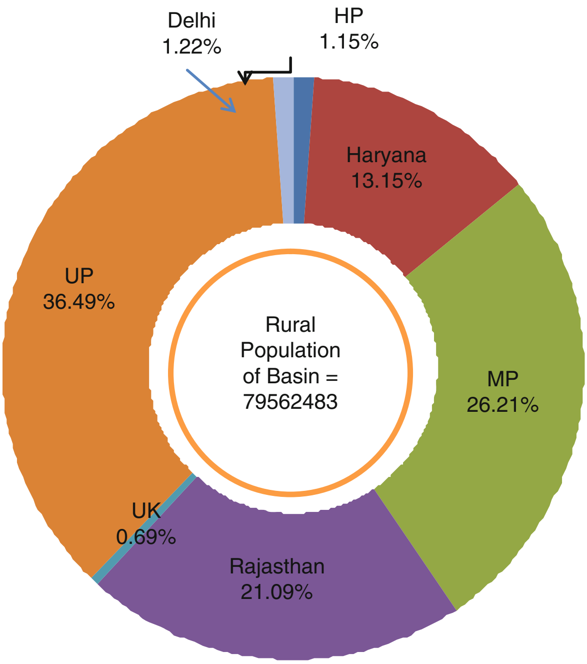


**Fig. 7.5** State wise share of rural population in the Yamuna basin (%)

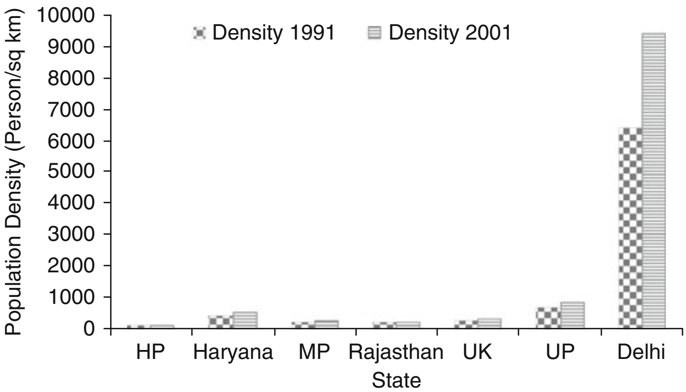


**Fig. 7.6** State-wise average population density in the Yamuna basin

people per sq. km. The density of population has been increased in all the States and Union Territories during the census year 1991 and 2001. Among major states, West Bengal is still the most densely populated state with a population density of 903 (Census, 2001). Bihar is now the second most densely populated state, pushing Kerala to the third place.

In the Yamuna basin, Delhi has the highest population density (Fig. 7.6) followed by Uttar Pradesh and Haryana. In the Yamuna River basin, most of the cities are located along the river due to better availability of water resources. Even most of the industrial and urban developments are taking place near the river banks. Similar to states, the population density of the Yamuna basin has been significantly increased during the census year 1991–2001 (Fig. 7.6). The density of Delhi has increased from 6,402 per sq. km (Census, 1991) to 9,412 per sq. km (Census, 2001). It is indeed a great challenge to protect the natural environment of the river and its catchment. Population in Delhi has been so increased in last two decades that all the natural resources have been over-exploited, even the intra-basin natural resource transfer gets shortened for adequate livelihood and eco-system functioning. The spatial pattern of the population density of the basin for the years 1991 and 2001 are shown in Fig. 7.7. It is clear from Fig. 7.7 that population growth is significant in 1991–2001 along the main river course as well as the major tributaries of the Yamuna basin such as Hindon and Chambal.

### *7.1.3 Population Growth Rate*

The decadal population growth is estimated using the population census data. This helps in planning for the infrastructure development. It can also be used for population projections for long term integrated water resources management plan. Again Delhi has the highest decadal growth rate from year 1981 to 1991 and from 1991 to 2001 (Fig. 7.8). However, it has slightly decreased for 1991–2001 than 1981–1991.

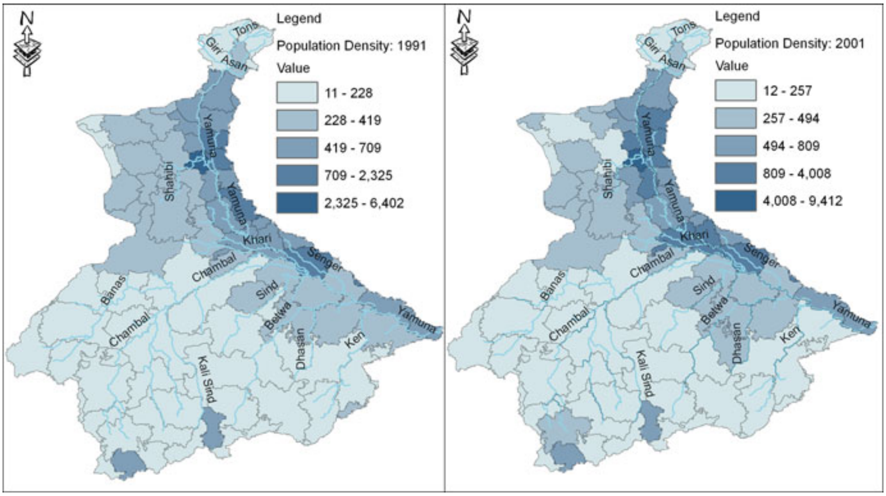


**Fig. 7.7** Comparison of population density in the Yamuna River basin

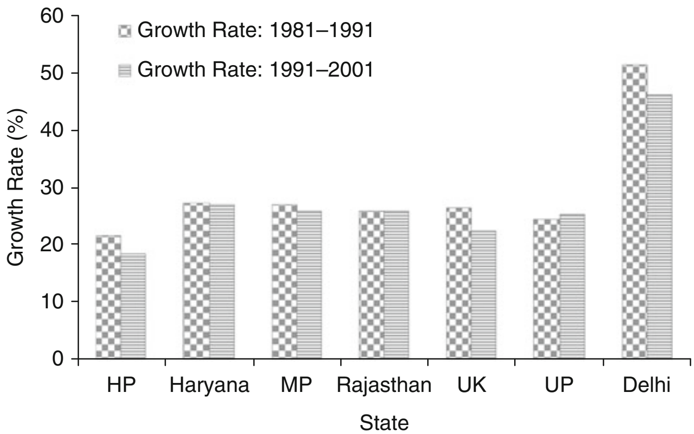


**Fig. 7.8** Population growth rate in the Yamuna basin

The spatial decadal growth rate in the Yamuna basin is shown in Fig. 7.9 for the periods of 1981–1991 and 1991–2001, respectively. Comparing Fig. 7.9, a similar remark can be made as for the population density.

### *7.1.4 The Rate of Urbanization*

Urbanization is also defined by the United Nations as the movement of people from rural to urban areas with population growth equating to urban migration. The population growth in urban areas is mainly due to infrastructure development and the lack

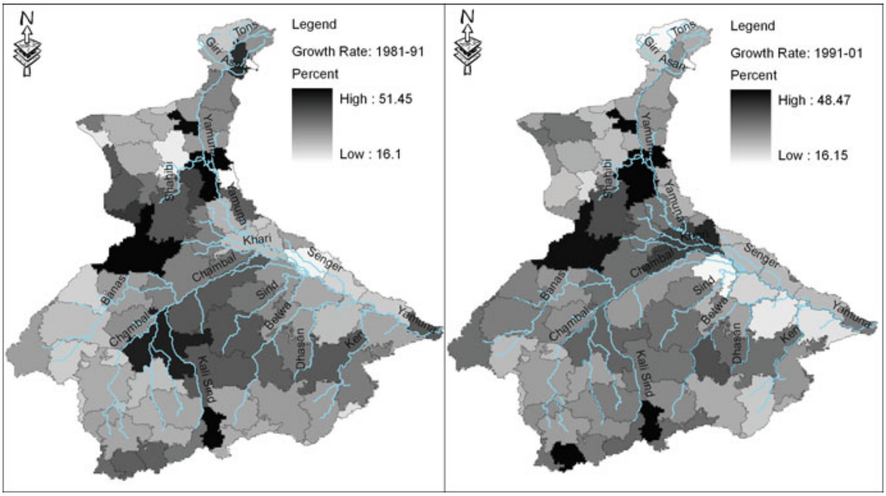


**Fig. 7.9** Comparison of population growth rate in the Yamuna River basin

of development and insecurity in agriculture. Urbanization is the physical growth of urban areas.

Urbanization occurs naturally from individual and corporate efforts to reduce time and expense in commuting and transportation while improving opportunities for jobs, education, housing, and transportation. Living in cities permits individuals and families to take advantage of the opportunities of proximity, diversity, and marketplace competition.

In rural areas, often on small family farms, it is difficult to improve one's standard of living beyond basic sustenance. Farm living is dependent on unpredictable environmental and climatic conditions. Urban areas, on the other hand have better basic services as well as other specialist services that are rarely available in rural areas. Similarly, urban centers have better employment opportunities for different qualification levels.

Health is another major factor that causes migration to urban centers. People, especially the elderlies are often forced to move to cities where there are doctors and hospitals that can cater for their health needs. It is also a result of industrialization that farms become more mechanized, putting many laborers out of work. This is currently occurring rapidly in India.

According to the 1981 census, 75% of male workers in non-agricultural activities are required for a settlement to be declared as urban.

The sources of urban growth comprise a natural increase in urban areas, migration, reclassification of rural areas into urban areas and the change in the boundaries of existing towns.

Intra-city migration from smaller to bigger cities is continuing along with the migration from rural to urban areas besides an enormous natural population pressure. Cities are facing a serious shortage of power, water, sewerage, housing, transportation, and communication mixed with dramatic pollution, poor public health, unemployment and poverty. Thus, understanding and monitoring past and current urbanization processes is the basis for future predictions and preparedness, and thus for sustainable urban planning.

Focus on the urban growth of the cities in the Yamuna basin shows interesting features (Fig. 7.9). It shows that population growth is not only in the cities adjacent to main Yamuna River but the development of incipient towns has also started. It might be due the migration of population to adjacent urban centre. This may continue longer, which will be beneficial for metropolitan cities in reducing the population load due to migration.

### *7.1.5 Migrants*

The complexity of movement of population in different parts of the country helps in understanding the dynamics of the society. At this crucial juncture in economic development study on migration assumes special importance. A person is considered as migrant by place of birth if the place in which he is enumerated during the census is other than his place of birth (Census, 2001).

The total migrant population in the basin is 3,90,51788 (Table 7.2) and its state wise distribution is shown in Fig. 7.10. Uttar Pradesh shares the largest population of migrants of 27.7% and Himachal Pradesh lowest as 1.1%.

State wise data shows that the population of Delhi comprises the highest number of migrants as 43.4% followed by Himachal Pradesh and Haryana (Table 7.3). Urban and rural categories of migrants shows the highest urban migrants as 92.46% in Delhi whereas, rural migrants are highest in Rajasthan as 71.4% followed by HP, Uttar Pradesh, Madhya Pradesh, Haryana, Uttarakhand and Delhi.

Urban and rural both type of migration are mainly for better standard of living. In rural areas, a lack of agriculture infrastructure, source of income, poor standard of amenities and monsoon failure mainly lead to migration. However, urban areas face migration because of the lack of job and infrastructure for development.

**Table 7.2** Urban and rural migrant population

| State | Total migrant | Rural migrant | Urban migrant |
|---|---|---|---|
| Himachal Pradesh | 412,274 | 289,709 | 122,565 |
| Haryana | 5,117,618 | 3,117,546 | 2,000,071 |
| Madhya Pradesh | 9,229,246 | 6,035,624 | 3,193,622 |
| Rajasthan | 7,003,496 | 5,002,008 | 2,001,488 |
| Uttarakhand | 466,216 | 216,447 | 249,769 |
| Uttar Pradesh | 10,810,933 | 7,489,107 | 3,321,826 |
| Delhi | 6,012,006 | 453,243 | 5,558,763 |
| Total | 39,051,788 | 22,603,684 | 16,448,105 |

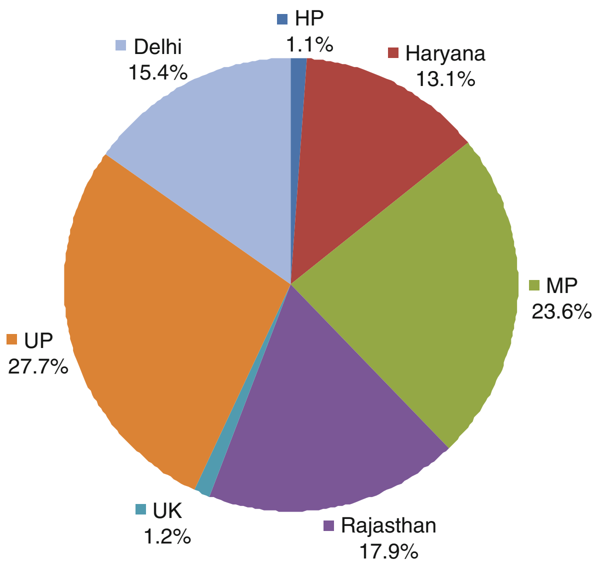


**Fig. 7.10** State wise distribution of migrants in the Yamuna basin

**Table 7.3** State wise migrants in the Yamuna basin (%)

| State | Migrant | Rural migrant | Urban migrant |
|---|---|---|---|
| Himachal Pradesh | 37.3 | 70.3 | 29.7 |
| Haryana | 34.6 | 60.9 | 39.1 |
| Madhya Pradesh | 30.1 | 65.4 | 34.6 |
| Rajasthan | 30.1 | **71.4** | 28.6 |
| Uttarakhand | 34.2 | 46.4 | 53.6 |
| Uttar Pradesh | 25.6 | 69.3 | 30.7 |
| Delhi | **43.4** | 7.54 | 92.5 |

## 7.2 Sex Ratio

Sex ratio is an important social indicator to measure the extent of prevailing equity between males and females at a given point of time. It is mainly the outcome of the interplay of sex differentials in mortality, sex selective migration, sex ratio at birth and at times the sex differential in population enumeration.

Sex ratio is defined as the number of females per thousand of males. According to the Census of India (2001), the sex ratio of India stands at 933. This is a marginal improvement from the 1991 Census, which had recorded 927 females for every 1000 males. Considering the Census (2001), the sex ratio among the major States ranged between 861 in Haryana to 1058 in Kerala. State wise analysis of sex ratio in the Yamuna basin shows the best status for Uttarakhand as the sex ratio is 938 (Fig. 7.11).

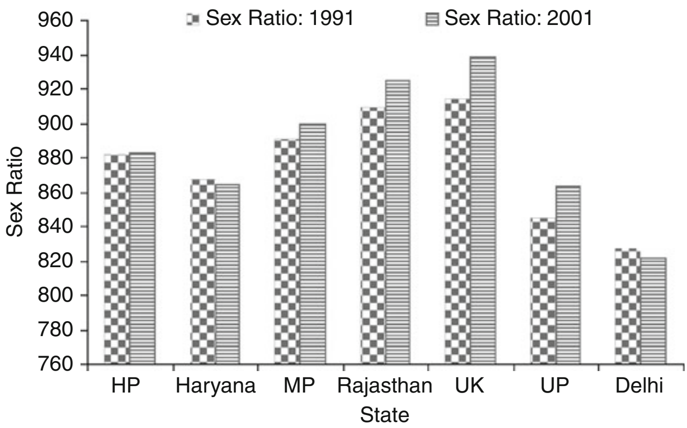


**Fig. 7.11** Sex Ratio in the Yamuna basin

In the Yamuna basin, the sex ratio has been considerably increased from census year 1991 to 2001 (Fig. 7.11). The spatial variability in the sex ratio for the Yamuna basin is also shown in Fig. 7.12. It was observed from Fig. 7.12 that the sex ratio is highly dependent on the topography. The sex ratio is generally high in the hilly and forest area as compared to the plains. A gradual reduction in the sex ratio is taking place from hilly region to the plains. It might be due to non-availability of resources and inadequate employment opportunity in the hilly regions. Another region of this variation is the migration of population from hilly areas to plains for employment. In spite of the sex ratio of India (i.e. 933 females per 1000 males), the average sex ratio in the basin is estimated to be 891 with a minimum of 821 in Delhi and a maximum of 1051 in Tehri Garhwal (Census, 2001).

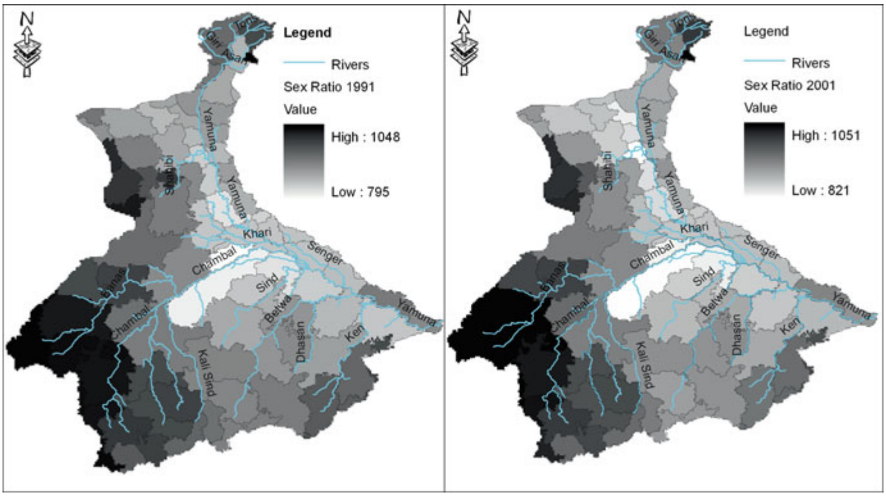


**Fig. 7.12** Spatial pattern of sex ratio and comparison for the census years 1991 and 2001

## 7.3 Literacy

Literacy, in its simplest definition, is the ability to read and write. Literacy is more than just being able to read and write. The literate use reading to learn about a wide range of subjects, share their ideas and tend to have rich imaginations and many interests. Literacy widens a person's world; illiteracy narrows it. Literacy is calculated by Census using the population of the persons of more than 7 years of age having knowledge of reading and writing.

Literacy campaigns have helped spread the knowledge about health care and nutrition, thereby enabling mothers to keep their family in better health and to care better for their children. The National Literacy Mission seeks to achieve 75% literacy goal by imparting functional literacy to illiterates in the 15–35 age group. This age group has been the focus of attention because they are in the productive and reproductive period of life. The basic objective is to create a generation which will ensure that their children are educated, to realize the dream of "education for all."

The literacy rate in the states of the Yamuna basin is the highest in Delhi as 81.67, followed by Himachal Pradesh and Uttarakhand (Table 7.4). It is the lowest in Uttar Pradesh as 56.27. The literacy rate for women is poor in the state of Uttar Pradesh, Rajasthan and Madhya Pradesh (lower than national average). It might be attributed due to gender based inequality, occupation of girl child in domestic tasks, and low enrolment of girls in schools.

**Table 7.4** Literacy Rate in State falling under the Yamuna basin

| India/state | Category | Person | Male | Female |
|---|---|---|---|---|
| India | Total | 64.84 | 75.26 | 53.67 |
| | Rural | 58.74 | 70.7 | 46.13 |
| | Urban | 79.92 | 86.27 | 72.86 |
| Himachal Pradesh | Total | 76.48 | 85.35 | 67.42 |
| | Rural | 75.08 | 84.51 | 65.68 |
| | Urban | 88.95 | 92.04 | 85.03 |
| Uttarakhand | Total | 71.62 | 83.28 | 59.63 |
| | Rural | 68.07 | 81.78 | 54.7 |
| | Urban | 81.44 | 87.05 | 74.77 |
| Haryana | Total | 67.91 | 78.49 | 55.73 |
| | Rural | 63.19 | 75.37 | 49.27 |
| | Urban | 79.16 | 85.83 | 71.34 |
| Delhi | Total | 81.67 | 87.33 | 74.71 |
| | Rural | 78.05 | 86.6 | 67.39 |
| | Urban | 81.93 | 87.39 | 75.22 |
| Rajasthan | Total | 60.41 | 75.7 | 43.85 |
| | Rural | 55.34 | 72.16 | 37.33 |
| | Urban | 76.2 | 86.45 | 64.67 |
| Uttar Pradesh | Total | 56.27 | 68.82 | 42.22 |
| | Rural | 52.53 | 66.59 | 36.9 |
| | Urban | 69.75 | 76.76 | 61.73 |
| Madhya Pradesh | Total | 63.74 | 76.06 | 50.29 |
| | Rural | 57.8 | 71.7 | 42.76 |
| | Urban | 79.39 | 87.39 | 70.47 |

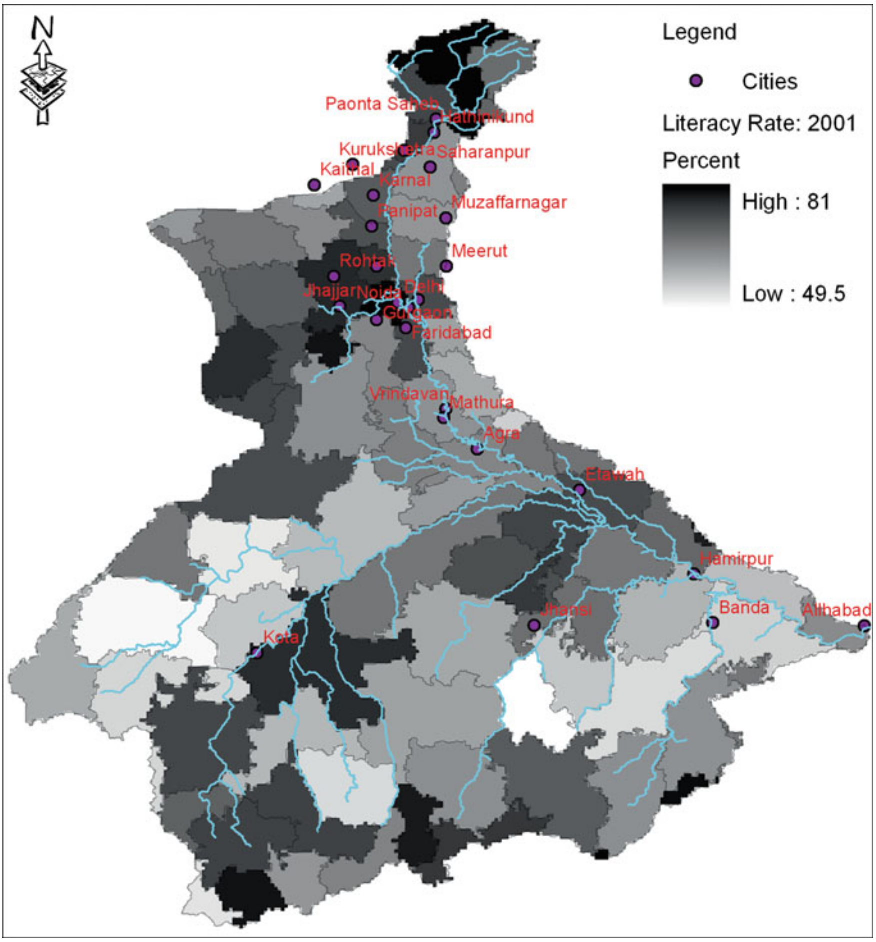


**Fig. 7.13** District-wise variation of average literacy rate in the Yamuna basin

The variation of average district wise literacy rate can be seen from Fig. 7.13. The figure shows that the literacy rate is generally high in urban areas. Delhi has the highest literacy rate, among other districts. Shimla (79.1) and Dehradun (79.0) also have very high literacy rate as compared to other districts. District Lalitpur has the lowest literacy rate in the basin as 49.5.

## 7.4 Main and Marginal Workers

Work is defined as participation in any economically productive activity. All persons engaged in "work" are workers. Persons who are engaged in cultivation or milk production even solely for domestic consumption are also treated as workers. The reference period for determining a person as a worker and a non-worker is one year preceding the date of enumeration (Census, 2001).

All those workers who had worked for a major part of the reference period (i.e. 6 months or more) are termed as Main Workers and workers who had not worked for the major part of the reference period are termed as Marginal Workers.

Yamuna basin has total 47,922,103 workers (Table 7.5). These comprise 36,857,018 Main and 11,065,085 Marginal workers.

State wise distribution of workers shows the highest workers in Uttar Pradesh followed by Madhya Pradesh, Rajasthan, and Delhi as 29.27, 24.82 and 21.75%, respectively (Fig. 7.14). The lowest share of workers is by Uttarakhand as 0.86% in the Yamuna basin.

**Table 7.5** Workers in the Yamuna basin

| State | Workers | Main workers | Marginal workers |
|---|---|---|---|
| Himachal Pradesh | 556,944 | 448,721 | 108,224 |
| Haryana | 5,856,832 | 4,298,415 | 1,558,417 |
| Madhya Pradesh | 12,575,951 | 9,519,908 | 3,056,043 |
| Rajasthan | 10,227,216 | 7,600,473 | 2,626,743 |
| Uttarakhand | 402,803 | 334605.1 | 68,198 |
| Uttar Pradesh | 13,758,975 | 10,339,141 | 3,419,834 |
| Delhi | 4,543,381 | 4,315,756 | 227,625 |
| Total | 47,922,103 | 36,857,018 | 11,065,085 |

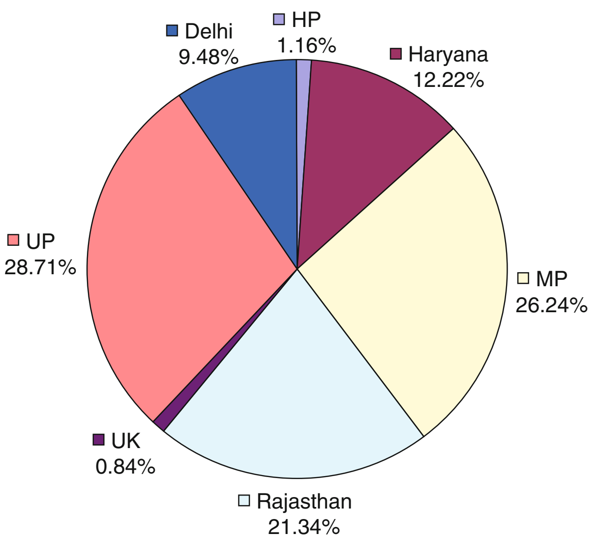


**Fig. 7.14** State wise distribution of workers in the Yamuna basin (%)

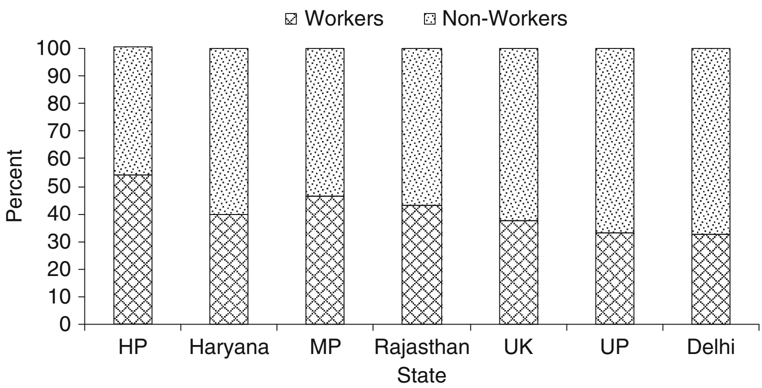


**Fig. 7.15** Workers and non workers percentages

A person who does not work at all during the reference period is treated as a non-worker. The non-workers broadly constitute students, those performing household duties, such as daily household chores like cooking, cleaning utensils, looking after children, fetching water, etc. and the unpaid work in the family farm, cultivation or milching, dependents, such as infants or very elderly people are not included in the category of worker. Delhi, Uttar Pradesh and Madhya Pradesh share most of the non-worker population of the basin (Fig. 7.15).

### *7.4.1 Cultivator and Agricultural Labourer*

According to Census, a person is classified as cultivator if he or she is engaged in the cultivation of land for payment in money, kind or share. Cultivation includes effective supervision or direction in cultivation. A person who works on another person's land for wages in money or kind or share is regarded as agricultural laborers. The worker population shows a total 55.5% population of cultivators and agricultural laborers in the Yamuna basin. Cultivator and agriculture laborers are 18,755,795 and 7,855,485, respectively, in the Yamuna basin (Table 7.6).

**Table 7.6** Cultivator and agricultural labour in the Yamuna basin

| State | Cultivator | Agricultural labor |
|---|---|---|
| Himachal Pradesh | 3,74,895 | 14,529 |
| Haryana | 21,91,334 | 8,40,500 |
| Madhya Pradesh | 54,19,816 | 29,83,682 |
| Rajasthan | 54,58,481 | 10,03,340 |
| Uttarakhand | 1,14,264 | 31,744 |
| Uttar Pradesh | 51,59,589 | 29,65,922 |
| Delhi | 37,415 | 15,766 |
| Total | 1,87,55,795 | 78,55,485 |

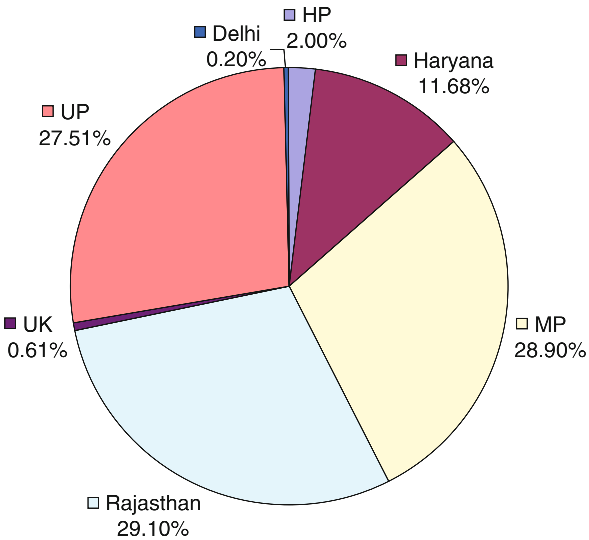


**Fig. 7.16** Distribution of cultivators in the Yamuna basin (%)

Cultivator's population is distributed as the highest among workers in Rajasthan which is 29.1% followed by Madhya Pradesh, Uttar Pradesh and Haryana as 28.9, 27.5 and 11.0, 68.0%, respectively (Fig. 7.16). In the Yamuna basin, Delhi has the lowest percentage of cultivators (i.e. 0.2%). Madhya Pradesh and Uttar Pradesh

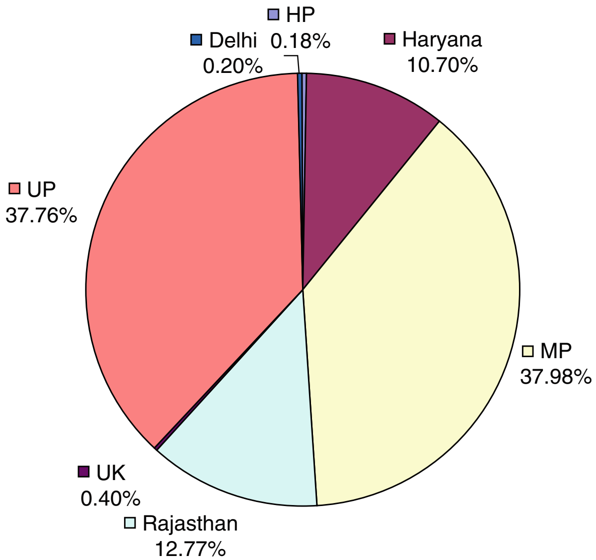


**Fig. 7.17** Distribution of agricultural labor in the Yamuna basin (%)

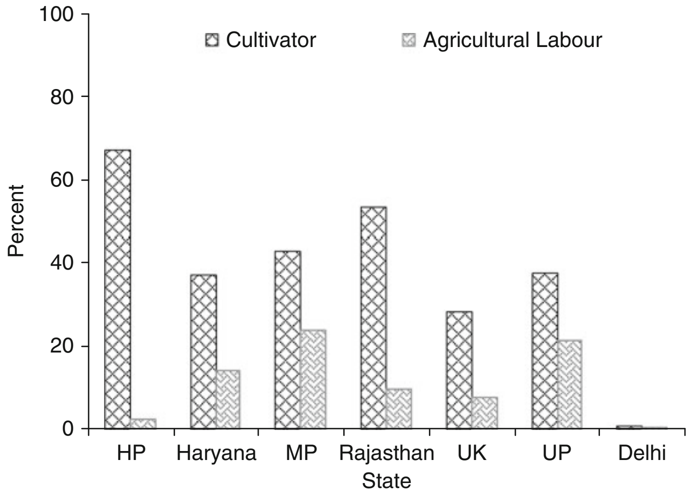


**Fig. 7.18** Status of cultivators and agricultural labor among workers in the Yamuna basin

share almost equal percentages of agricultural labor in the worker category in the Yamuna basin (Fig. 7.17).

State wise analysis of workers show Himachal Pradesh has a higher percentage of cultivators followed by Rajasthan, Madhya Pradesh, Uttar Pradesh, Haryana, Uttarakhand, and Delhi (Fig. 7.18).

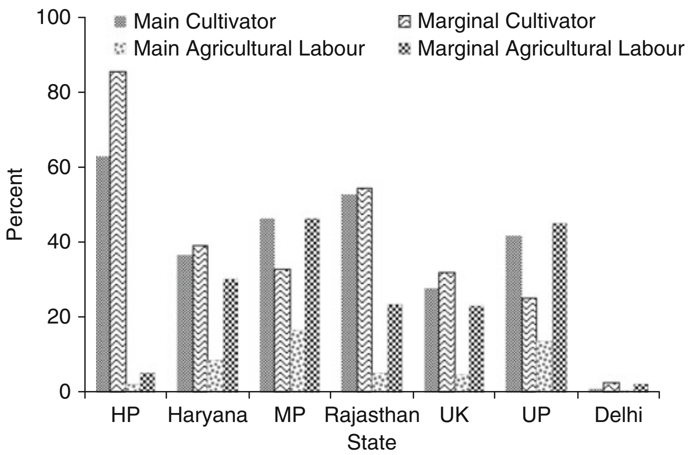


**Fig. 7.19** State wise cultivator and agricultural labor (%)

Analysis of main and marginal categories of population shows that Uttar Pradesh and Madhya Pradesh comprise a higher main category of cultivators than marginal category (Fig. 7.19). Main Agricultural laborers are lower in all cases than in marginal category.

## 7.5 Health: Vital Statistics

***Infant Mortality*****:** Infant Mortality is defined as the number of infant deaths that occur per thousand live births in any population in one calendar year, the infant being a child of 1 year or less. The various factors involved in infant mortality are the immediate direct medical causes that lead to the death of infants, economic, socio-cultural, environmental and nutritional factors that play a contributory or predisposing role in the epidemiology of infant mortality. Infant deaths are more frequent among poor families. The poorest live in slum areas where the civic administration spends the least on public amenities, such as safe water supply, sanitation, drainage and personal health services.

The infant mortality rate is the highest in Madhya Pradesh (i.e. 74) followed by Uttar Pradesh and Rajasthan (i.e., 71 and 67, respectively). In these three states it is higher than the national average of 57. Infant mortality is lowest in Delhi (Table 7.7).

***Expectation of Life*****:** Expectation of life at birth is the highest for Delhi. Himachal Pradesh and Haryana have almost equal life expectation at birth as 65.9 and 65.2 which are higher than the national average 62.5.

***Birth Rate and Death Rate*****:** Comparison of health indicators among the states of the Yamuna basin shows a higher birth rate in Uttar Pradesh, Madhya Pradesh

**Table 7.7** Health indicators

| | 2005 | | | 2006 | | | |
|---|---|---|---|---|---|---|---|
| India/State | Birth rate | Death rate | Infant mortality rate | Birth rate | Death rate | Infant mortality rate | Expectation of life at birth (1998–2002) |
| **India** | **23.8** | **7.6** | **58** | **23.5** | **7.5** | **57** | **62.5** |
| Delhi | 18.6 | 4.6 | 35 | 18.4 | 4.7 | 37 | **70** |
| Haryana | 24.3 | 6.7 | 60 | 23.9 | 6.5 | 57 | 65.2 |
| Himachal Pradesh | 20 | 6.9 | 14 | 18.8 | 6.8 | 50 | 65.9 |
| Madhya Pradesh | 29.4 | 9 | 76 | 29.1 | 8.9 | **74** | 56.9 |
| Rajasthan | 28.6 | 7 | 68 | 28.3 | 6.9 | 67 | 61.1 |
| Uttar Pradesh | 30.4 | 8.7 | 73 | 30.1 | 8.6 | 71 | 59.1 |
| Uttrakhand | 20.9 | 7.4 | 42 | 21 | 6.7 | 43 | – |

*Source*: SRS Bulletin (2008)

**Table 7.8** Index of "A long and healthy life" based on infant mortality rate and life expectancy at age 1

| State | 2006 | 1996 |
|---|---|---|
| Haryana | 0.733 | 0.685 |
| Himachal Pradesh | 0.747 | 0.709 |
| Madhya Pradesh | 0.628 | 0.559 |
| Rajasthan | 0.678 | 0.618 |
| Uttar Pradesh | 0.651 | 0.598 |
| Uttarakhand | 0.721 | 0.643 |
| Delhi | 0.759 | 0.731 |
| India | 0.706 | 0.653 |

and Haryana as compared to the national average of 23.5. The death rate is higher in Uttar Pradesh and Madhya Pradesh than the national average (SRS, 2006).

***Life Expectancy Index*:** The Life Expectancy Index is a statistical measure used to determine the average lifespan of the population of a certain area. Life expectancy is one of the factors in measuring the Human Development Index (HDI), along with adult literacy, education, and standard of living. Life expectancy is also a factor in finding the physical quality of life of an area. Table 7.8 shows the highest index for Delhi followed by Himachal Pradesh, Haryana, Uttarakhand, Rajasthan, Uttar Pradesh and Madhya Pradesh (UNDP, 2006). Uttar Pradesh, Rajasthan and Madhya Pradesh has lower life expectancy index than national average.

***Maternal Mortality*:** For India, the National Family Health Survey of 1992–1993 was the first to provide a national-level estimate of 437 maternal deaths per 100,000 births for the two-year period preceding the survey (International Institute for Population Sciences, 1995). Bhat (2001) estimated the values of maternal mortality using sex-differentials in adult mortality (SDAM). Results are depicted in Table 7.9. The maternal mortality rate in the Yamuna basin states is higher than the country level status.

**Table 7.9** Maternal mortality rate

| S. No. | State | MMR | Year |
|---|---|---|---|
| 1 | Madhya Pradesh | 532 | 1987–1996 |
| 2 | Haryana | 472 | 1987–1996 |
| 3 | Rajasthan | 399 | 1987–1996 |
| 4 | Uttar Pradesh | 579 | 1987–1996 |
| 5 | India – Total | **410** | 1987–1991 |
| 6 | India – Total | **341** | 1992–1996 |

*Source*: Bhat (2001)

***Health Facilities*****:** Health facilities are required for preventing disease, prolonging life and promoting health through the organized efforts and informed choices of society, organizations, public and private, communities and individuals. Government runs various schemes for prevention of the spread of communicable diseases. The goal of public health is to improve lives through the prevention and treatment of disease. For sustaining the achievement for communicable disease control, particularly HIV/AIDS, tuberculosis, malaria and meningitis; vigilance and surveillance for epidemic-prone diseases and advancing emergency preparedness infrastructure is required. Table 7.10 shows the yearly statistics of the number of hospital beds per lakh of population for the states of Yamuna basin during the period of 1961 to 1998. Tables 7.11 and 7.12 show the total number of hospital beds in rural and urban areas, respectively. Considering these statistics, status of Madhya Pradesh is poor as compared to other states. Based on Table 7.10, the status of the Uttar Pradesh is still poor as the population is very high for this state.

**Table 7.10** Total number of hospital beds in Yamuna basin states per 1,00,000 population

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| State | 1961 | 1966 | 1971 | 1976 | 1981 | 1986 | 1988 | 1991 | 1996 | 1998 |
| Delhi | | | | | | | | | 168.24 | 150.5 |
| Haryana | * | 52.01 | 61.28 | 69.91 | 62.27 | 51.33 | 51.12 | 45.38 | 38.45 | 38.23 |
| Himachal Pradesh | 48.32 | 148.23 | 132.64 | 136.62 | 81.76 | 89.4 | 89.7 | 87.79 | 83.85 | 88.51 |
| Madhya Pradesh | 30.75 | 39.39 | 36.7 | 39.64 | 32.24 | 34.59 | 36.03 | 38.27 | 26.58 | 26.59 |
| Rajasthan | 52.27 | 63.77 | 67.38 | 64.23 | 52.16 | 54.73 | 53.15 | 44.11 | 42.33 | 41.63 |
| Uttar Pradesh | 35.76 | 38 | 43.87 | 47.29 | 45.74 | 42.47 | 40.65 | 38.2 | 37.83 | 42.41 |
| All India | 52.28 | 60.75 | 63.6 | 72.79 | 73.64 | 77.79 | 78.19 | 78.7 | 66.4 | 71.5 |

**Table 7.11** Total number of beds in hospitals in rural area per 1,00,000 population

| | Year | | | | | |
|---|---|---|---|---|---|---|
| State | 1981 | 1986 | 1988 | 1991 | 1996 | 1998 |
| Delhi | * | * | * | * | 4.17 | * |
| Haryana | 10.05 | 4.91 | 4.92 | 4.57 | 3.86 | 3.93 |
| Himachal Pradesh | 26.7 | 17.31 | 16.51 | 16.8 | 9.95 | 12.46 |
| Madhya Pradesh | 3.21 | 2.99 | 4.37 | 43.38 | 11.79 | 11.79 |
| Rajasthan | 5.93 | 6.02 | 5.84 | 3.11 | 2.89 | 2.95 |
| Uttar Pradesh | 7.83 | 7.63 | 7.34 | 6.93 | 2.55 | 7.62 |
| All India | 16.51 | 18.18 | 18.49 | 22.26 | 17.54 | 23.25 |

*Not Available

**Table 7.12** Total number of beds in hospitals in urban area per 100,000 population

| | Year | | | | | |
|---|---|---|---|---|---|---|
| | 1981 | 1986 | 1988 | 1991 | 1996 | 1998[1] |
| Delhi | * | * | * | * | 186.68 | * |
| Haryana | 248.71 | 202.43 | 196.99 | 169.19 | 144.48 | 132.87 |
| Himachal Pradesh | 749.76 | 895.7 | 886.19 | 832.46 | 859.41 | 830.24 |
| Madhya Pradesh | 146.28 | 147.18 | 145.26 | 21.37 | 75.53 | 75.55 |
| Rajasthan | 225.63 | 226.67 | 216.86 | 182.3 | 174.81 | 159.55 |
| Uttar Pradesh | 219.01 | 191.55 | 180.15 | 165.38 | 189.2 | 191.7 |
| All India | 261.56 | 260.27 | 256.59 | 241.96 | 207.64 | 188.55 |

*Sources*: Health Information of India
*Notes*: Beds includes beds in hospitals and dispensaries
* Not Available, CBHI, MOHFW, GOI, respective years
[1] Figures based on Statistical Abstract India 2000 and Denominator Population used for obtaining Hospital- Population ratio refers to reference period given in the source

## 7.6 Population Below Poverty Line (BPL)

According to a 2005 World Bank estimate, 42% of India's population falls below the International poverty line of $1.25 a day (Purchasing Power Parity (PPP), in nominal terms Rs. 21.6 a day in urban areas and Rs 14.3 in rural areas). In India after 2002, below poverty line (BPL) estimation is done considering the thirteen socio-economic parameters: (i) size of operational landholding, (ii) type of house, (iii) availability of cloths, (iv) food security, (v) sanitation, (vi) ownership of consumer durables, (vii) literacy status, (viii) status of household labour force, (ix) means of livelihood, (x) status of children (going to school), (xi) type of indebtedness, (xii) reason for migration from household, and (xiii) preference for assistance.

State wise statistics of the BPL population is given in Table 7.13. It evident that the BPL percentage in Madhya Pradesh is high as compared to other states. It

**Table 7.13** State wise percentage of population below poverty line

| States/UT | 1973–1974 | 1977–1978 | 1983 | 1987–1988 | 1993–1994 | 1999–2000 |
|---|---|---|---|---|---|---|
| Haryana | 35.36 | 29.55 | 21.37 | 16.64 | 25.05 | 8.74 |
| Himachal Pradesh | 26.39 | 32.45 | 16.4 | 15.45 | 28.44 | 7.63 |
| Madhya Pradesh | 61.78 | 61.78 | 49.78 | 43.07 | 42.52 | 37.43 |
| Punjab | 28.15 | 19.27 | 16.18 | 13.2 | 11.77 | 6.16 |
| Rajasthan | 46.14 | 37.42 | 34.46 | 35.15 | 27.41 | 15.28 |
| Uttar Pradesh | 57.07 | 49.05 | 47.07 | 41.46 | 40.85 | 31.15 |
| Delhi | 49.61 | 33.23 | 26.22 | 12.41 | 14.69 | 8.23 |
| All India | 54.88 | 51.32 | 44.48 | 38.86 | 35.97 | 26.1 |

*Source*: Planning Commission (2005)

forms the order as Madhya Pradesh, Uttar Pradesh, Rajasthan, Haryana, Himachal Pradesh, respectively.

***Rural BPL Household*:** In spite of agricultural, industrial and economic evolution of India, 32.98% of rural families come below the poverty line. In the Yamuna basin the total number of rural households is 2,178,612 (Census-2001). The highest rural households have been reported for Allahabad of the Yamuna basin followed by Udaipur, Alwar and Aligarh; however, BPL households are maximum in Delhi (i.e. 438,015 households) followed by Sagar in Madhya Pradesh and Allahabad in Uttar Pradesh and Udaipur in Rajasthan. Figure 7.20 shows the district wise rural household and BPL percentage in Yamuna basin. Information is based on the database of Ministry of Rural Development, GoI. The estimates are based on the methodology outline in the Report of the Expert Group on the estimation of proportion and number of Poor (Ministry of Rural Development, GoI).

***Share of Poor*:** India still has the world's largest number of poor people in a single country. Of its nearly 1 billion inhabitants, an estimated 350–400 million are below the poverty line, 75% of them in the rural areas. More than 36% of the population is illiterate, with women, tribal and scheduled castes particularly affected. Economic development and urbanization are closely linked. In India, cities contribute over 55% to country's GDP and urbanization has been recognized as an important factor driving economic growth.

It is interesting to note that the ratio of urban poverty in some of the larger states is higher than that of rural poverty leading to the phenomenon of "Urbanization of Poverty". Urban poverty poses the problem of housing and shelter, water, sanitation, health, education, social security and livelihoods along with special needs of vulnerable groups like women, children and aged people. Poor people live in slums which are overcrowded, often polluted and lack basic civic amenities like clean drinking water, sanitation and health facilities.

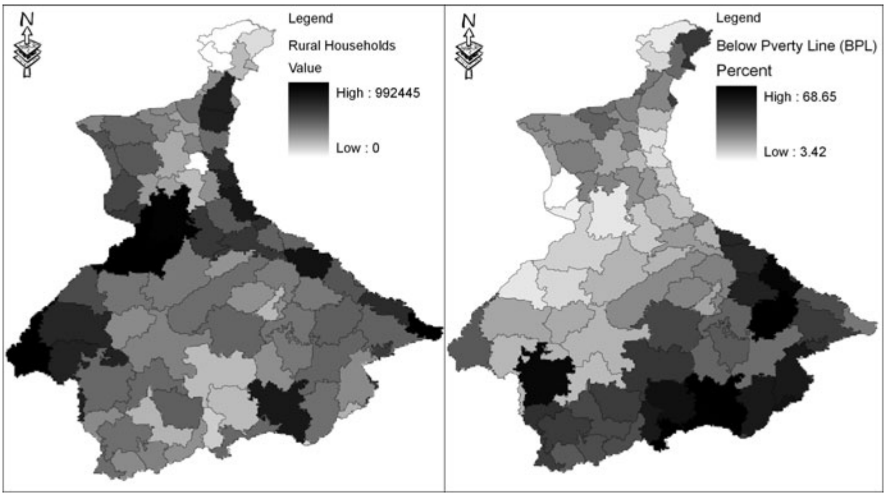


**Fig. 7.20** Rural household and BPL percentage in theYamuna River basin

**Table 7.14** Trend in percentage (expressed as a percentage of the total population) share of poor in the two groups of States individually and collectively

| States | 1983–1984 | 1987–1988 | 1993–1994 | 1999–2000 |
|---|---|---|---|---|
| ***Forward Group*** | | | | |
| Andhra Pradesh | 5.10 | 5.22 | 4.81 | 4.57 |
| Gujarat | 3.65 | 3.98 | 3.28 | 2.61 |
| Haryana | 0.92 | 0.83 | 1.37 | 0.67 |
| Karnataka | 4.64 | 5.17 | 4.88 | 4.01 |
| Kerala | 3.31 | 2.88 | 2.39 | 1.58 |
| Maharashtra | 9.01 | 9.65 | 9.53 | 8.76 |
| Punjab | 0.89 | 0.82 | 0.78 | 0.56 |
| Tamil Nadu | 8.05 | 7.53 | 6.31 | 5.01 |
| Total for forward States | 35.57 | 36.08 | 33.35 | 27.77 |
| ***Backward Group*** | | | | |
| Assam | 2.41 | 2.47 | 3.01 | 3.63 |
| Bihar | 14.31 | 13.71 | 15.40 | 16.36 |
| Madhya Pradesh | 8.61 | 8.61 | 9.32 | 11.47 |
| Orissa | 5.62 | 5.40 | 5.01 | 6.50 |
| Rajasthan | 3.93 | 4.65 | 4.01 | 3.14 |
| Uttar Pradesh | 17.24 | 17.47 | 18.87 | 20.36 |
| West Bengal | 9.87 | 9.24 | 7.95 | 8.20 |
| Total for Backward States | 61.99 | 61.55 | 63.57 | 69.66 |
| All India | 100.00 | 100.00 | 100.00 | 100.00 |

*Source*: Planning Commission (2005)

Table 7.14 shows the percentage share of poor. Forward and backward groups are on the basis of their economic status. The sharp decline in the share of poor in the forward States since 1987–1988, especially after 1993–1994 is commendable. Table 7.14 shows that the share of poor in backward group has gone up, whereas in forward group has reduced. As the table indicates, each one of the states in this group, except for West Bengal, experiences a considerable increase in the share of the poor. West Bengal's exceptional experience was mainly on account of the fast growth in agricultural production and the associated rural prosperity. It may, however, be mentioned that since the overall poverty in the country has come down substantially in the nineties, an increase in the State share in poverty need not imply an increase in the number of poor. Indeed, between 1993–1994 and 1999–2000, the absolute numbers of poor in all the States have come down.

## 7.7 Human Development Index

Human Development is a development paradigm that is about much more than the rise or fall of national incomes. It is about creating an environment in which people can develop their full potential and lead productive, creative lives in accord with their needs and interests. People are the real wealth of nations. Dr. Mahbub ul Haq, the Pakistani economist played a key role in formulating the human development paradigm, Prof. Amartya Sen and others provided the conceptual foundation for an alternative and broader human development approach.

***Human Development Index***: Human Development Index (HDI) introduced a new way of measuring development by combining indicators of life expectancy, educational attainment and income into a composite human development index, the HDI. The breakthrough for the HDI was the creation of a single statistic which was to serve as a frame of reference for both social and economic development. The HDI sets a minimum and a maximum for each dimension, called goalposts, and then shows where each country stands in relation to these goalposts, expressed as a value between 0 and 1.

The *Human Development Index* (HDI) is a simple composite measure that measures the overall achievements of a region in terms of three basic dimensions of human development; health status (measured by longevity), knowledge (measured by literacy and enrolments) and a decent standard of living (measured by per capita incomes). These three dimensions are measured by life expectancy at birth, educational attainment (adult literacy and the combined gross primary, secondary and tertiary enrolment ratio) and GDP per capita (PPP US$). Income enters the HDI as a proxy for a decent standard of living and as a surrogate for all human choices not reflected in the other two dimensions.

A few statistics of the HDI is presented through Table 7.15. It can be seen that HDI has been improved in all the states. HDI is higher in Haryana than the national average. Table 7.16 has HDI values for some nearby Asian countries. India ranks 134th position in HDI (UNDP).

District wise HDI for the Yamuna basin is shown in Fig. 7.21. The average HDI, estimated for the Yamuna basin, is 0.55, with the lowest of 0.45 being in Chhatarpur in Madhya Pradesh and maximum of 0.74 being in Delhi (National Capital of India). For Haryana district wise Human Development Index (HDI) data was not available, therefore, the total HDI average of Haryana has been mapped for all the Haryana districts. However, for Faridabad and Gurgaon this will be higher than the state average.

The socio-economic indicators for Uttar Pradesh, Rajasthan, Madhya Pradesh and Delhi are summarized in Table 7.17. It can be seen that the poverty in the urban

**Table 7.15** Trends in human development index (HDI)

| State | 1981 | 1991 | 2001 |
|---|---|---|---|
| Haryana | 0.36 | 0.44 | 0.50 |
| Madhya Pradesh | 0.24 | 0.32 | 0.39 |
| Rajasthan | 0.25 | 0.34 | 0.42 |
| Uttar Pradesh | 0.25 | 0.31 | 0.38 |
| India | 0.30 | 0.38 | 0.47 |

*Source*: Srinivasan (2004)

**Table 7.16** Human development index (HDI) (Indicators for 2007)

| Country | HDI Value | Rank | Life expectancy at birth (years) | Adult literacy rate (% aged 15 and above) | Gross enrolment ratio in education (%) | GDP per capita (PPP $) |
|---|---|---|---|---|---|---|
| India | 0.612 | 134 | 63.4 | 66.0 | 61.0 | 2,753 |
| China | 0.772 | 92 | 72.9 | 93.3 | 68.7 | 5,383 |
| Bhutan | 0.619 | 132 | 65.7 | 52.8 | 54.1 | 4,837 |
| Pakistan | 0.572 | 141 | 66.2 | 54.2 | 39.3 | 2,496 |
| Nepal | 0.553 | 144 | 66.3 | 56.5 | 60.8 | 1,049 |
| Sri Lanka | 0.759 | 102 | 74.0 | 90.8 | 68.7 | 4,243 |

*Source*: UNDP (2007)

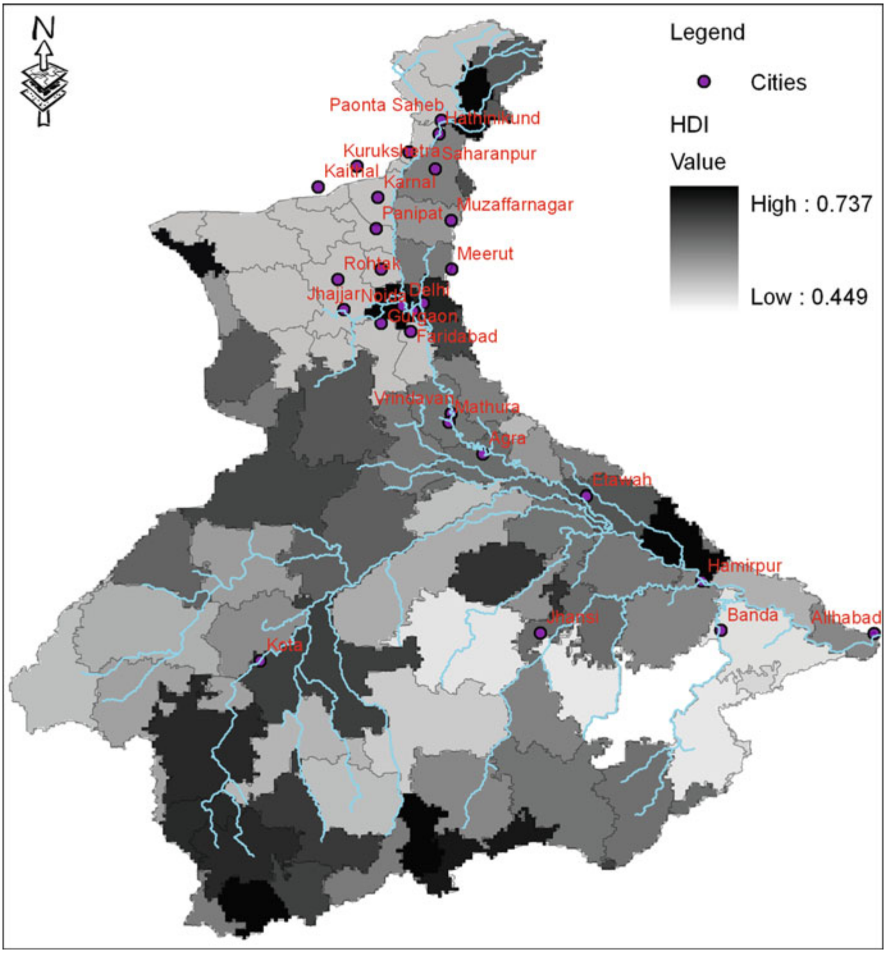


**Fig. 7.21** Human development index (HDI) in the Yamuna basin

**Table 7.17** Indicators for demography, health and amenities (State wise numbers)

| | | | |
|---|---|---|---|
| **Uttar Pradesh** | Demographic Indicators | Total Population (in million) | 166 |
| | | Urban Population (in million) | 34.5 |
| | | % Population in Urban Areas | 20.80 |
| | | Population Growth Rate (1991–2001) | 25.80 |
| | | Urban Population Growth Rate (1991–2001) | 32.90% |
| | | No. of Million Plus Cities (Kanpur, Lucknow, Agra, Varanasi, Meerut, and Allahabad) | 6 |
| | | No. of Towns with Over 1 Lakh Population | 52 |
| | | Population Below Poverty Line in Urban Areas (in million) | 10.7 |
| | | Population Below poverty line in Urban Areas | **30.90%** |
| | Health Indicators among Urban Poor | Neonatal Mortality Rate | 43.7 |
| | | Infant Mortality Rate | 79 |
| | | Child mortality rate | 130.6 |
| | | % Children Receiving All Immunization | 29.7 |
| | | % Children Receiving ORS or Recommended Home fluid during Diarrhea | 2.1 |
| | | % Children Underweight | 58.3 |
| | | % Pregnant Women Receiving the Recommended 3 ANC Visits | 9.1 |
| | | % Deliveries Attended by Health Personnel | 26.2 |
| | | % Using any Modern Method of family Planning | 21.3 |
| | | % Women Anemic | 55.1 |
| | | Total Fertility Rate (TFR) | 3.74 |
| | Environmental Health Indicators | % Having Access to Piped Water Supply | 17.7 |
| | | % Having Access to Toilets | 33.6 |
| **Rajasthan** | Demographic Indicators | Total Population (in million) | 56.5 |
| | | Urban Population (in million) | 13.2 |
| | | % Population in Urban Areas | 23.4 |
| | | Population Growth Rate (1991–2001) | 28.3 |
| | | Urban Population Growth Rate (1991–2001) | 31.5 |
| | | No. of Million Plus Cities | 1 |
| | | No. of Towns with Over 1 Lakh Population | 17 |
| | | Population Below Poverty Line in Urban Areas (in million) | 2.61 |
| | | % Population Below Poverty Line in Urban Areas | **19.8** |
| | Health Indicators among Urban Poor | Neonatal Mortality Rate | 65.5 |
| | | Infant Mortality Rate | 98.2 |
| | | Child mortality rate | 162.3 |
| | | % Children Receiving All Immunization | 7.4 |
| | | % Children Receiving ORS or Recommended Home fluid during Diarrhea | 29.0 |
| | | % Children Underweight | 62.5 |
| | | % Pregnant Women Receiving the Recommended 3 ANC Visits | 23.6 |
| | | % Deliveries Attended by Health Personnel | 33.0 |
| | | % Using any Modern Method of family Planning | 28.5 |
| | | % Women Anemic | 55.7 |

**Table 7.17** (continued)

| | | | |
|---|---|---|---|
| | Environmental Health Indicators | % Having Access to Piped Water Supply | 12.6 |
| | | % Having Access to Toilets | 18.9 |
| **Madhya Pradesh** | Demographic Indicators | Total Population (in million) | 60 |
| | | Urban Population (in million) | 16 |
| | | % Population in Urban Areas | 27 |
| | | Population Growth Rate (1991–2001) | 24 |
| | | Urban Population Growth Rate (1991–2001) | 31 |
| | | No. of Million Plus Cities | 3 |
| | | No. of Towns with Over 1 Lakh Population | 23 |
| | | Population Below Poverty Line in Urban Areas (in million) | 6.14 |
| | | % Population Below poverty line in Urban Areas | **38.4** |
| | Health Indicators among Urban Poor | Neonatal Mortality Rate | 69.7 |
| | | Infant Mortality Rate | 99.4 |
| | | Child mortality rate | 131.9 |
| | | % Children Receiving All Immunization | 20.6 |
| | | % Children Receiving ORS or Recommended Home fluid during Diarrhea | 34.7 |
| | | % Children Underweight | 72.4 |
| | | % Pregnant Women Receiving the Recommended 3 ANC Visits | 32.0 |
| | | % Deliveries Attended by Health Personnel | 38.1 |
| | | % Using any Modern Method of family Planning | NA |
| | | % Women Anemic | 55.0 |
| | Environmental Health Indicators | % Having Access to Piped Water Supply | 56.0 |
| | | % Having Access to Toilets | 13.3 |
| **Delhi** | Demographic Indicators | Total Population (in million) | 13.78 |
| | | Urban Population (in million) | 12.82 |
| | | % Population in Urban Areas | 93.1 |
| | | Population Growth Rate (1991–2001) | 46.31 |
| | | Urban Population Growth Rate (1991–2001) | 52.13 |
| | | No. of Million Plus Cities | NA |
| | | No. of Towns with Over 1 Lakh Population | NA |
| | | Population Below Poverty Line in Urban Areas (in million) | 1.14 |
| | | % Population Below poverty line in Urban Areas | **9.42** |
| | Health Indicators among Urban Poor | Neonatal Mortality Rate | 39.3 |
| | | Infant Mortality Rate | 94.4 |
| | | Child mortality rate | 135.5 |
| | | % Children Receiving All Immunization | 24.7 |
| | | % Children Receiving ORS or Recommended Home fluid during Diarrhea | 44.7 |
| | | % Children Underweight | 43.4 |
| | | % Pregnant Women Receiving the Recommended 3 ANC Visits | 35.8 |
| | | % Deliveries Attended by Health Personnel | 29.1 |

**Table 7.17** (continued)

| | | | |
|---|---|---|---|
| | | % Using any Modern Method of family Planning | 31.3 |
| | | % Women Anemic | 42.7 |
| | | Total Fertility Rate (TFR) | NA |
| | Environmental Health Indicators | % Having Access to Piped Water Supply | 84.4 |
| | | % Having Access to Toilets | 74.6 |
| **India** | Demographic Indicators | Total Population (in million) | 1,027 |
| | | Urban Population (in million) | 285.4 |
| | | % Population in Urban Areas | 27.81 |
| | | Population Growth Rate (1991–2001) | 21.34 |
| | | Urban Population Growth Rate (1991–2001) | 31.39 |
| | | No. of Million Plus Cities (Kanpur, Lucknow, Agra, Varanasi, Meerut, and Allahabad) | 35 |
| | | No. of Towns with Over 1 Lakh Population | 423 |
| | | Population Below Poverty Line in Urban Areas (in million) | 80.79 |
| | | % Population Below poverty line in Urban Areas | 25.7 |
| | Health Indicators among Urban | Neonatal Mortality Rate | 34.9 |
| | | Infant Mortality Rate | 54.6 |
| | | Child mortality rate | 72.7 |
| | | % Children Receiving All Immunization | 39.9 |
| | | % Children Receiving ORS or Recommended Home fluid during Diarrhea | 24.9 |
| | | % Children Underweight | 47.1 |
| | | % Pregnant Women Receiving the Recommended 3 ANC Visits | 54.3 |
| | | % Deliveries Attended by Health Personnel | 55.9 |
| | | % Using any Modern Method of family Planning | 48.7 |
| | | % Women Anemic | 58.8 |
| | | Total Fertility Rate (TFR) | NA |
| | Environmental Health Indicators | % Having Access to Piped Water Supply | 18.5 |
| | | % Having Access to Toilets | 47.2 |

*Source*: Planning Commission (2004)

areas is very high in Uttar Pradesh and Madhya Pradesh. Rajasthan and Madhya Pradesh are very poor in access to toilet as 18.9 and 13.3%, respectively.

***Technical Efficiency (TE)*****:** Shanmugam and Venkataramani (2006) determined the technical efficiency (TE) using district level data. The main variables used for computation of TE are rural literacy rate, rural infant mortality, villages with pacca road, electrification and landholding size. Based on his study, TE for the districts of Haryana, Uttar Pradesh, Madhya Pradesh, Rajasthan and India are 79.93, 77.27, 77.07, 77.46, and 79.23%, respectively. This study shows that the relative importance of the determinants of TE across districts depends greatly on environmental factors, such as agro-climatic zones, technological factors (such as irrigation regime), and crop mix. The policy implications are clear: interventions to improve the technical efficiency are not "one-size fits- all." Indeed, even districts within the same state would benefit differently from the same set of interventions. Study indicated that health, education, and infrastructure are powerful drivers of efficiency at the district level. In that sense, it might be wise to develop policy interventions at a more localized level.

## 7.8 Livelihood and Employment

The most crucial need for sustainable livelihoods for an individual or household is employment, or being gainfully employed over a period of time, that ensures a level of remuneration satisfying basic needs and a quality of life. It is difficult to estimate the level of earning/ income/ inflow of money goods or services to a household that ensures a particular standard livelihood. The most widely used measure is one of income poverty. Households subsisting below this level of income (calculated using expenditure estimates) would be the most vulnerable and deprived households. The other measures would be employment figures, employment in different categories.

Livelihoods, in many ways would then be a sum total of both the employment portfolio of a household and what it earns in monetary terms, or as services and goods, and what a household receives as entitlements being a citizen of the state, or gram panchayat.

Agriculture is the main source of employment in the Yamuna basin. Industrial development is higher in Haryana and cities along Yamuna River.

***Special Employment Programmes and Development Schemes*****:** Panchayats as institutions and Human Development as the goal of all planned development have the following three dimensions:

(a) as decentralised institutions that play an effective role in furthering the national goal of human development as representative institutions that are able to express the local concerns for human development and undertake consequent action;
(b) eabling institutions that create opportunities for the local human resource to practice their skills for self-governance; and
(c) generating the development and employment.

The following schemes are working for rural areas:

(a) IRD: Integrated Rural Development
(b) NREP: National Rural Employment Programme
(c) DRDA: District Rural Development Agency
(d) TRYSEM: Training of Rural Youth for Self Employment
(e) IRDP: Integrated Rural Development Programme
(f) SLDP: Special Livestock Development Programme
(g) NAREGA: National Rural Employment Guarantee

## 7.9 Livestock Population

Livestock Census work has been carried out by Department of Animal Husbandry & Dairying, Ministry of Agriculture. Livestock (also cattle) refers to one or more domesticated animals raised in an agricultural setting to produce commodities such as food and work. The term "livestock" does not include poultry or farmed fish; however the inclusion of these, especially poultry, within the meaning of "livestock" is common. Livestock generally are raised for subsistence or for profit. Raising animals (animal husbandry) is an important component of modern agriculture. It has been practiced in many cultures since the transition to farming from hunter-gather lifestyles. Cattle include bovines such as cow, bull, etc.

Table 7.18 shows cattle, livestock and poultry population. Total cattle population in the Yamuna basin is about 19 million. State wise distribution shows highest cattle population in Madhya Pradesh followed by Uttar Pradesh and Rajasthan as 45, 28 and 18%, respectively (Fig. 7.22). Total 38 million livestock population exist in Yamuna basin. Its state wise distribution (Fig. 7.23) is the highest for Rajasthan as 32%. Haryana ranks first with 48% poultry population in the Yamuna basin (Fig. 7.24).

## 7.10 Water Supply

Globally, 1 billion people have a lack of access to improved water supply and 2.6 billion people have a lack of adequate sanitation (WHO, 2004). Water provision cannot be separated from two other inter-related factors, sanitation and health. The primary cause of contamination of water is the inadequate or improper system for disposal of human (and animal) excreta. This often leads to a cycle of infection (resulting primarily in diarrhoeal diseases) and contamination which remains one of the leading

**Table 7.18** Cattle, livestock and poultry population ('000) for year 2003

| | Total cattle | | Total livestock | | Total poultry | |
|---|---|---|---|---|---|---|
| State | State | Basin | State | Basin | State | Basin |
| Himachal Pradesh | 2,236 | 245.36 | 2,881 | 316.13 | 767 | 84.16 |
| Haryana | 1,540 | 1,170.88 | 7,345 | 5,584.50 | 13,619 | 10,354.71 |
| Madhya Pradesh | 18,913 | 8,589.04 | 16,704 | 7,585.86 | 11,705 | 5,315.64 |
| Rajasthan | 10,854 | 3,459.92 | 38,284 | 12,203.78 | 6,192 | 1,973.82 |
| Uttarakhand | 2,188 | 221.57 | 2,755 | 278.99 | 1,984 | 200.91 |
| Uttar Pradesh | 18,551 | 5,460.02 | 39,980 | 11,767.12 | 11,718 | 3,448.90 |
| Delhi | 92 | 92.25 | 282 | 279.71 | 459 | 455.28 |
| Total | 54,374 | 19,057.51 | 108,231 | 37,933.81 | 46,444 | 16,278.12 |
| India | 185,181 | | 485,002 | | 489,012 | |

*Source*: Ministry of Agriculture, Department of Animal Husbandry Dairying & Fisheries, GoI.

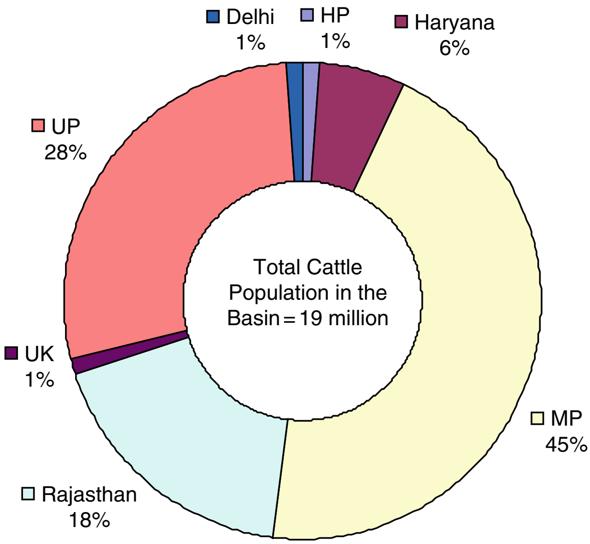


**Fig. 7.22** State wise distribution of cattle in the Yamuna basin

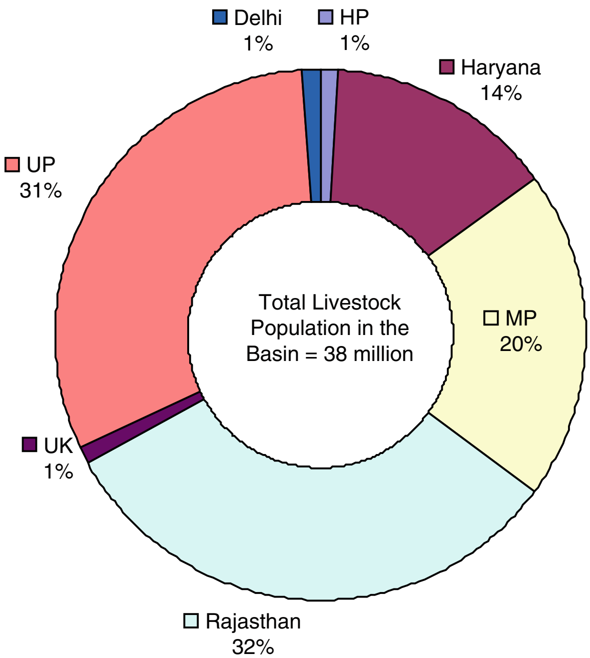


**Fig. 7.23** State wise distribution of livestock in the Yamuna basin

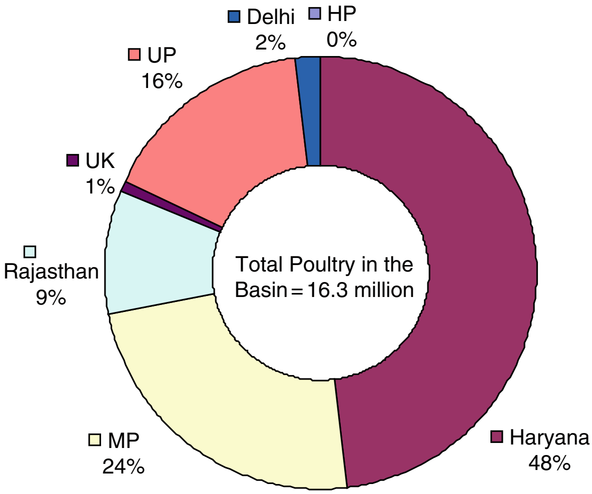


**Fig. 7.24** State wise distribution of poultry in the Yamuna basin

causes of illness and death in the developing world. Inadequate water supply is both a cause and an effect of poverty. Invariably adequate and affordable water supplies are poor in the society.

***Per capita Water Requirement*:** Potable drinking water is still not available to various areas. The quantity of water required for domestic purposes depends mainly on habits, social status, climatic conditions and customs of the people. The per capita water requirement in urban areas is more than that in the rural areas. As per yardstick of the Union Ministry of Urban Development & Poverty Alleviation, water requirement for domestic purposes in urban areas is 40 litres per capita per day (lpcd) in case of supply through public stand posts and 70 lpcd in the case of supply through house service connections, where no sewerage system is existing or contemplated. Where sewerage system exists or contemplated, water supply would be 135 lpcd in urban areas. In the case of metropolitan cities having a population more than 1 million, the domestic water supply would be 150 lpcd. Over and above the aforesaid demand, 15% losses may be allowed for determining the quantity of raw water required.

The Department of Drinking Water Supply was created in the Ministry of Rural Development by the Central government, and is acknowledged as the nodal agency with the responsibility of providing safe drinking water to all rural habitations. Technology Mission (presently known as Rajiv Gandhi National Drinking Water Mission) works with the broad objective of providing sustainable and safe drinking water to all uncovered/"no source" villages and creating awareness among the rural people about the hazards of using unsafe water.

***Water Supply Rate*:** The Five Year Plan documents and the National Sample Survey provide official figures about the percentage of population, having access to drinking water in rural and urban areas. The Planning Commission states that these figures are far from the ground realities, which means that the situation is not as projected in the official circles. Traditionally water supply is limited to major towns and cities and that too within the boundaries of state/provincial units. With the spread of the process of urbanization and declining public health standards in both urban and rural areas government has taken a serious initiative in the form of laws and policies. Water supply is done by mainly the government department of respective states. As a matter of policy it is desired as 135 lpcd for urban area and 40 lpcd for rural areas.

A two-way approach is adopted in this regard, viz:

1. Legislations focusing on water supply and at times on water supply and sanitation to be driven by the state agencies
2. Policy initiatives by the central government in order to assist and supplement the states' activities with the overall objective of providing safe drinking water and thereby promoting public health.

Tables 7.19, 7.20, and 7.21 describe the total number of class I and II cities in the states falling under the Yamuna basin as whole and water supply rates. Haryana, Madhya Pradesh, Uttar Pradesh, Rajasthan receive less water supply than the prescribed limit of 135 (Table 7.20).

### *7.10.1 Water Auditing*

In domestic water supply, water audit is considered important, since the treatment of water to bring it to drinking water standard costs a lot of money to the supplier. Water audit helps in determining the amount of water lost from a distribution system due to leakages, etc.

Water audit compares the amount of water supplied with the amount billed and accounts for the water loss. Draft Guidelines for Water Audit and Water Conservation, jointly produced by the Central Water Commission and the Central Ground Water Board are as follows:

**Table 7.19** Water supply in class–I cities

| State | No. of cities | Water supply in MLD | Per capita supply |
|---|---|---|---|
| Delhi | 1 | 4,346 | 292.49 |
| Haryana | 20 | 783.39 | 142.59 |
| Himachal Pradesh | 1 | 36.18 | 221.3 |
| Madhya Pradesh | 25 | 1,560.91 | 144.6 |
| Rajasthan | 24 | 1,727.96 | 179.78 |
| Uttar Pradesh | 61 | 4,382.58 | 170.12 |
| Uttarakhand | 6 | 221.21 | 177.06 |

*Source*: CPCB (2009)

**Table 7.20** Water supply in class–II cities

| State | No. of cities | Water supply in MLD | Per capita supply |
|---|---|---|---|
| Haryana | 7 | 49.68 | 91.32 |
| Madhya Pradesh | 23 | 163.64 | 93.77 |
| Rajasthan | 21 | 184.76 | 115.53 |
| Uttar Pradesh | 46 | 432.19 | 127.77 |
| Uttarakhand | 1 | 11.34 | 163.26 |

*Source*: CPCB (2009)

**Table 7.21** Water supply in state wise class–I and II cities (aggregate)

| State | No. of cities | Water supply in MLD |
|---|---|---|
| Delhi | 1 | 4,346 |
| Haryana | 27 | 833.07 |
| Himachal Pradesh | 1 | 36.18 |
| Madhya Pradesh | 48 | 1,724.55 |
| Rajasthan | 45 | 1,912.72 |
| Uttar Pradesh | 107 | 4,814.77 |
| Uttarakhand | 7 | 232.55 |

*Source*: CPCB (2009)

(i) Water audit is an important management tool for effective conservation of water. Broadly water audit should be conducted categorically in two systems, resource audit or supply side audit and the other one as consumption audit on demand side. All efforts should be made for improvement of not only water use efficiency and distribution system, but also on the efficient development and management of the source of water.

(ii) It has been strongly advocated that the water audit system needs to be framed and incorporated in every significant water resources project as a routine exercise during operation and maintenance of the project by the project authorities.

(iii) The periodicity of water audit and its report may be determined in advance at the commencement of commissioning the project by the project authority and the concerned Governments and appropriate provision of fund may be made for its implementation.

(iv) The recommendations in the water audit report for corrective measures of the system may be considered on priority for implementation by the competent authority. All efforts should also be made to provide all technical and financial provisions in a time bound manner.

(v) The irrigation sector utilizes about 83% of water as a major stakeholder. Due to the thrust on account of rapid urbanization and modernization, the demands for domestic and industrial uses are progressively increasing, thus creating a situation of competing of demands from value added sectors of water use and threatening irrigation sector even in maintaining current level of water use whereas more water is needed for growing more to meet the demand of growing population.

(vi) A systematic comprehensive water audit is useful in bringing out the trend of changes in demand and supply scenario which will help in deciding the methodology for improving the efficiency of the system by adopting conjunctive use of surface and ground water, application of modern irrigation techniques, including drip and sprinkler irrigation wherever feasible and other improvised agricultural devices in addition to development of wasteland and waterlogged areas.

(vii) Due to over-exploitation of ground water, the water table at vulnerable places like thickly populated urban areas are depleting at a very fast rate. Private tube wells are mushrooming without control to meet the growing demand. Industries should be discouraged to exploit ground water on their own.

(viii) As far as possible supplies to industries should be from surface water and if ground water supply is considered essential, it should be managed by a Government Agency. There is general apathy towards conjunctive use of ground water and surface water. Specific water audit needs to be conducted on a regular basis for realistic assessment of ground realities and initiating remedial measures under the umbrella of holistic approach.

(ix) Pollution level of fresh surface water and ground water resources are alarmingly increasing due to the excessive use of pesticides and fertilizers in agriculture and discharge of untreated waste by industries and sewage disposal leading to health hazards and scarcity of fresh water. Water audit from this angle needs to be conducted strategically and periodically. The existing laws regarding pollution control need to be strictly observed by not only imposing penalties but also restricting the polluters.

(x) To prevent wastage of water, pricing of water for irrigation, domestic and industrial uses needs to be revised and updated periodically so that subsidy is phased out as quickly as possible and at least operation and maintenance cost is recovered for sustainability of the system. Further, the pricing of water at flat rate system needs to be replaced gradually by actual cost rate by volume. The differential pricing system should also be suitably introduced keeping in view the socio-economic aspects of the people and the region in addition to their life style and ethnic background.

(xi) Benchmarking system of various suitable parameters for all sectors of water use may be developed and introduced for optimizing and enhancing the efficiency of the system. It is an effective tool for water audit and measurement of relative performance and suggests ameliorative measures for performance improvement.

(xii) To identify the source of water loss due to leakage, the approach of bulk metering system should be installed at various well defined macro and micro systems like various zones, districts, towns, colonies and even large group-consumers to single unit consumers so that water audit can be effectively conducted.

#### 7.10.1.1 Transmission Losses

A study undertaken by the Ministry of Urban Development & Poverty Alleviation through NEERI, Nagpur, has revealed that about 30 to 50% of the water produced and supplied in the cities goes as waste through leakages in the distribution system. About 80% of the aforesaid losses are estimated in the household connections due to worn out pipes, etc.

In view of this, the Ministry of Urban Development & Poverty Alleviation has emphasized the need for control of unaccounted supply of water (non-revenue water) through leak detection programmes for identifying leakages and rectifying the same through suitable replacement of pipelines. A manual containing details of various aspects of operations and maintenance (O&M) of water supply systems has been brought out by the Ministry of Urban Development & Poverty Alleviation recently.

#### 7.10.1.2 Water Conservation

(i) Water Conservation is a prime and challenging concern. There is a gap on the application of the appropriate technologies, which needs to be removed. Due to lack of proper operation and maintenance in irrigation, industry and domestic water distribution system, there is a huge loss of water. Hence, it is emphasized to improve the operation and maintenance (O&M) system.

(ii) For developing water resources, age-old traditional water conservation methods need to be judiciously adopted in conjunction with the latest modern conservation technology. Keeping this in view, rain water harvesting, revival of traditional water storages, check dams and other similar structures need to be adopted. Building byelaws should be suitably modified to introduce mandatory roof top rain water harvesting.

(iii) In order to conserve precious fresh water, recycling of waste water may be incorporated wherever feasible. The dual water supply system, one for treated wastewater and the other for fresh water may be introduced so that treated waste water can be used for secondary purposes, such as toilets flushing, gardening, agriculture and selective industries, etc. New urban colonies, big hotel industries and other similar establishments should have mandatory dual water supply systems.

(iv) Cropping patterns and crops water requirement varies from time to time due to the dynamic socio-economic condition of the people and the region in addition to geo-morphological, climatic and metrological changes. Hence, for effective management, appropriate base line data for water demand under different situations need to be brought out for optimum crop water management and field activities considering effective rainfall in different physiological stages.

(v) Night irrigation practice may be introduced to minimize evaporation loss thus conserving irrigation water. Timely and need based irrigation should be done to minimize loss of water. Further, for boosting productivity, rotational

**Table 7.22** Norms for providing potable drinking water

| Purpose quantity | lpcd |
|---|---|
| Drinking | 3 |
| Cooking | 5 |
| Bathing | 15 |
| Washing utensils and house | 7 |
| Ablution | 10 |

cropping pattern may be introduced for balancing fertility of soil and natural pest control.

(vi) Various water saving devices are being developed under various ongoing R&D programmes. These devices may be suitably adopted in the system.

(vii) Strategic mass awareness campaign should be conducted regularly to cover all stakeholders, including service providers and consumers, for water conservation in irrigation, domestic and industrial sectors. Special attention must be given so that the fruits of the campaign must reach children, housewives and farmers effectively.

Drinking water supply is a state subject. *Accelerated rural water supply programme (ARWSP) certain guidelines and norms* that have been adopted since the inception of the programme (1972) for providing potable drinking water to the rural population based on basic minimum need is as follows: 40 lpcd for humans to meet the following requirements based on basic minimum need as defined under the ARWSP guideline (Table 7.22). The implementing agencies for the programme may be decided by the State Government. The implementation may be through the PHED or Rural Development Department/Panchayati Raj Department/Board, Corporation or Authority. In addition, provision should be allowed at 30 lpcd for animals in hot and cold desert ecosystems.

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# Chapter 8
# Water Resources and Water Budgeting

**Abstract** This chapter presents a catchment-wise water resource analysis of the Yamuna River basin. Both surface and ground water resources are included. Over-exploitation of ground water resources is causing persistent lowering of the water table in the basin. This major issue is discussed using the indicator of the stage of ground water development. In order to know the exact status of the basin in terms of water resources, surplus and deficit analyses are also presented. Furthermore, catchment wise flood estimation techniques, based on the synthetic unit hydrograph and geomorphological unit hydrograph approaches, are also presented.

Water resources are sources of water that is vital for life. Uses of water include agricultural, industrial, household, recreational and environmental activities. Virtually all these human uses require fresh water. Globally, nearly 97% of the water on the earth is salt water, and only about 3% of the water exists as fresh water of which nearly two third is frozen in glaciers and polar ice caps. The remaining unfrozen fresh water is mainly found as groundwater, with a small fraction (or percent) above ground or in the air.

Although fresh water is a renewable resource, but the supply of the clean and fresh water is steadily decreasing as a result of exceeding water demand and increasing pollution in many parts of the world, and Yamuna River basin is no exception. Besides, the availability of water greatly varies in time and space. Therefore, it becomes vital to estimate the extent and availability of surface and ground water for economic and optimum utilization, planning, design and operation of water resources.

This chapter discusses the availability of water in the Yamuna basin, including catchment wise water budgeting for analysing surplus and deficit catchments in terms of water resources needed for integrated water resources management, and methodology for flood estimation for hydrological design.

## 8.1 Water Resources Assessment

Water resources of a basin are equal to the volume of average annual flow of surface water generated from precipitation and groundwater. However, if human intervention in the catchment has been done in the form of surface storages, then the water resource of a catchment can be estimated using the following formula.

R.K. Rai et al., *The Yamuna River Basin*, Water Science and Technology Library 66,
DOI 10.1007/978-94-007-2001-5_8, 

$$\mathrm{WR} = Q_{\mathrm{S}} + \mathrm{GW}_{\mathrm{rec}} - (Q_{\mathrm{out}} - Q_{\mathrm{in}}) + S_{\mathrm{s}} + S_{\mathrm{sm}} \tag{8.1}$$

where WR is the water resources availability in the basin, $Q_{\mathrm{s}}$ is the surface runoff volume, i.e., the total volume of the long term average annual flow of surface runoff due to precipitation, $\mathrm{GW}_{\mathrm{rec}}$ is the groundwater recharge generated from precipitation, $Q_{\mathrm{out}}$ is the groundwater contribution to the base flow, and $Q_{\mathrm{in}}$ is the seepage from river or canal to the aquifer, $S_{\mathrm{s}}$ is the surface storages, $S_{\mathrm{sm}}$ is the soil moisture storage generally filled up during the monsoon period; however, it supplies water to meet agricultural demands.

Introduction of the term net recharge simplifies eq. (8.1) as

$$\mathrm{WR} = Q + \mathrm{GW}_{\mathrm{Net}} + S_{\mathrm{s}} + S_{\mathrm{sm}} \tag{8.2}$$

where $Q$ is the total volume of long term average annual flow in the river, which includes surface runoff and base flow in the river (i.e. $Q_{\mathrm{s}} + Q_{\mathrm{out}}$), and $\mathrm{GW}_{\mathrm{Net}}$ is the net annual groundwater recharge, which includes $\mathrm{GW}_{\mathrm{rec}}$, $Q_{\mathrm{in}}$ and $Q_{\mathrm{out}}$. All the variables appearing in eqs. (8.1) and (8.2) are in volumetric unit.

### *8.1.1 Surface Water Resources*

The surface water resources of the basin are assessed based on stream flow measured at a terminal site (i.e. site either close to the sea or confluence with the other higher order stream). The average annual flow at the terminal point of river is normally denoted as the water resources of the basin.

When water resources in the basin have been developed, the surface water resources availability would be estimated as the sum of $Q$ and $S_{\mathrm{s}}$. The long term average annual runoff volume, $Q$ is estimated using the discharge data at different sites. The locations of the gauge-discharge sites maintained by Central Water Commission are shown in Fig. 8.1, and their salient features are given in Table 8.1.

The steps involved in the estimation of surface water are to first derive the flow duration curve (FDC) followed by estimation of 50, 75 and 90% dependable flow. The FDCs for the discharge sites of the Yamuna River are derived using the Weibull's plotting position formula which is described in Chapter 3. The derived FDCs for various sites of the Yamuna River are shown in Figs. 8.2, 8.3, and 8.4; and the estimated values of dependable flows are given in Table 8.2. The table also includes dependable water availability (in volumetric terms) used to estimate the surface water availability for different dependabilities, and mean annual discharge with the corresponding values of surface water availability at different locations in the basin and sub-basins. For Yamuna basin, an attempt is to establish the relationship between catchment area and mean discharge (Fig. 8.5), catchment area and water availability (Fig. 8.6), and catchment area and dependable flows (Fig. 8.7). These relationships can be used as ready reference for the Yamuna basin.

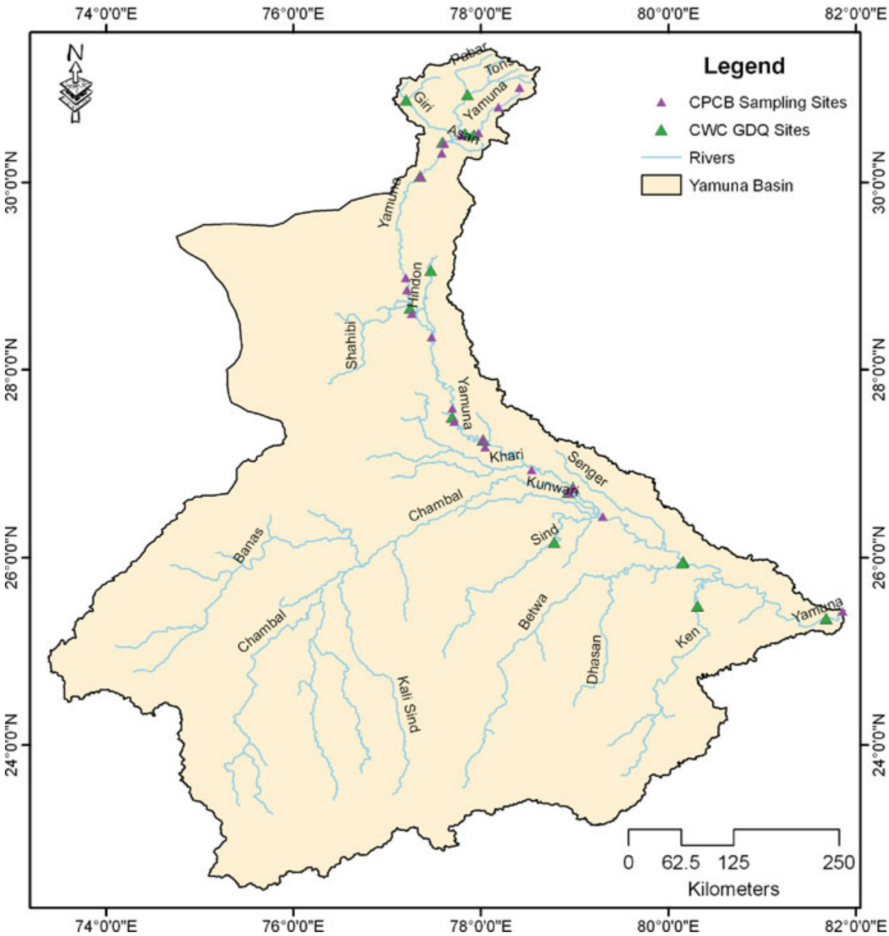


**Fig. 8.1** CWC GD and CPCB WQ sites of Yamuna River and its tributaries

#### 8.1.1.1 Surface Water Storage

There are large number of reservoirs and dams constructed in the Yamuna River basin. The list of water storages along with salient features of dams and reservoirs in the basin are given in Appendix A. The location of important dams in the basin is shown in Fig. 8.8. Therefore, the catchment wise surface water availability in the basin estimated by summing up the mean annual surface runoff in the river (Table 8.2), and live storages in the catchments (Appendix A) is given in Table 8.3.

Based on the above analysis (Table 8.3), the total estimated surface water resources availability in the Yamuna basin is 61,219.2 MCM, of which Chambal River basin 43.67% contribution has followed by Betwa (19.28%), Ken (13.21%) and Sind (3.08%) catchments.

**Table 8.1** Salient features of CWC GD sites

| S. No. | Site | River | Latitude | Longitude | Type | Catchment Area (km$^2$)[a] | % Area |
|---|---|---|---|---|---|---|---|
| 1 | Paonta | Yamuna | 30.4306 | 77.5911 | GDSQ | 10,875.50 | 3.27 |
| 2 | Kalanaur | Yamuna | 30.0696 | 77.3528 | GDSQF | 12,720.50 | 3.83 |
| 3 | Delhi Rly. Bridge | Yamuna | 28.6624 | 77.2459 | GDSQWF | 30,793.84 | 9.27 |
| 4 | Mathura | Yamuna | 27.4984 | 77.6956 | GDSQ | 41,703.84 | 12.55 |
| 5 | Agra | Yamuna | 27.2556 | 78.0226 | GDSQ | 42,572.24 | 12.81 |
| 6 | Etawah | Yamuna | 26.7500 | 78.9833 | GDSQWF | 71,999.24 | 21.67 |
| 7 | Hamirpur | Yamuna | 25.9572 | 80.1601 | GDQWF | 247,432.20 | 74.47 |
| 8 | Pratappur | Yamuna | 25.3556 | 81.6841 | GDSQ | 331,318.80 | 99.72 |
| 9 | Naini Bridge | Yamuna | 25.4244 | 81.8616 | GF | 332,264.8 | 100.00 |
| 10 | Galeta | Hindon | 26.0667 | 77.4667 | GDQ | | |
| 11 | Udi | Chambal | 26.7000 | 78.9333 | GDSQ | 134,679 | 99.99 |
| 12 | Seondha | Sind | 26.1667 | 78.7833 | GDSQ | 16,701 | 59.77 |
| 13 | Sahjina | Betwa | 25.9455 | 80.1507 | GDSQF | 43,651.0 | 99.99 |
| 14 | Banda | Ken | 25.4864 | 80.3122 | GDSQWF | 27,616 | 96.65 |

*G* Gauge, *S* Silt, *W* Wireless, *D* Discharge, *Q* Water Quality, *F* Flood Forecasting
[a] Catchment area does not include the WYC command area, but it is based on flow direction

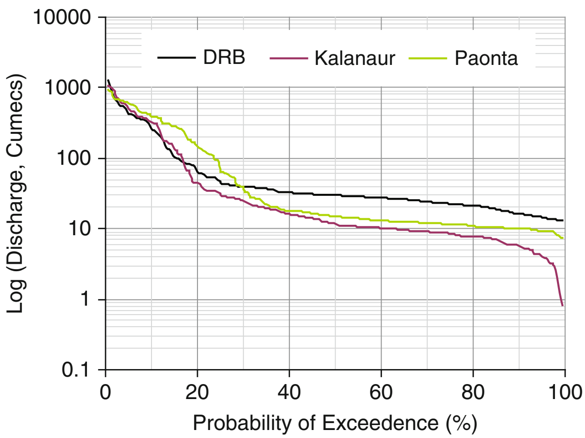


**Fig. 8.2** Flow duration curve for different locations in the Yamuna basin

## 8.1.2 Groundwater Resources

Groundwater resources are important for water resources planning as they supplement surface water resources. In the Yamuna basin more than 65% of water supply is dependent on the groundwater potential. The total annual groundwater potential for a unit refers to the available annual recharge after allowing for the natural

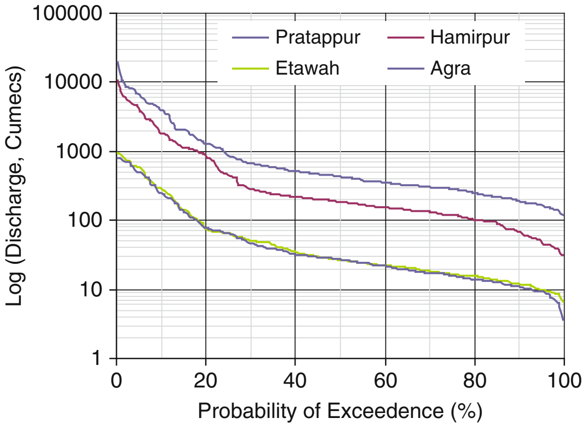


**Fig. 8.3** Flow duration curve for different locations in the Yamuna basin

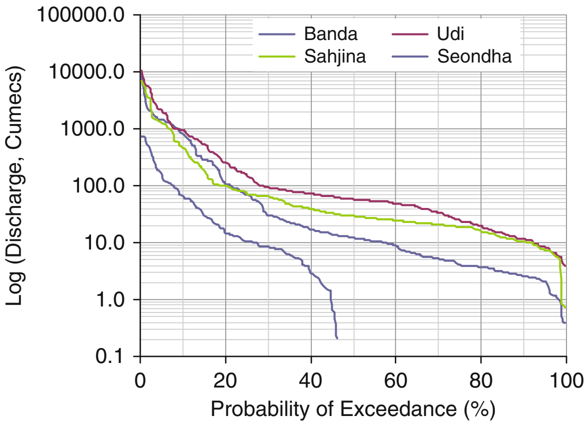


**Fig. 8.4** Flow duration curve for different locations in the Yamuna basin

discharge during the monsoon and non-monsoon season through base flow and sub-surface inflow/outflow. In the study, the groundwater potential is estimated using the methodology presented in GEC-97 of Central Ground Water Board (CGWB). The district wise groundwater potential is shown in Fig. 8.9 which reveals that the groundwater availability is high along the course of the Yamuna due to alluvial geological formation. The district-wise groundwater information is summarized in Appendix B which also includes total recharge, groundwater flow, net availability, total draft and stage groundwater development.

A large fraction of water demand that is being fulfilled by ground water is resulting in ground water depletion. Further, due to the over-exploitation of groundwater for intensive agriculture, a large part of the basin has fallen under dark zone, and it can be assessed through the stage of ground water development.

**Table 8.2** Discharge and runoff water availability at different locations in the Yamuna basin

| Site | River | Area ($km^2$) | Dependable flow ($m^3/s$) | | | Dependable water availability (MCM) | | | Mean annual flow ($m^3/s$) | Mean annual availability (MCM) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 50% | 75% | 90% | 50% | 75% | 90% | | |
| Paonta | Yamuna | 10,875.5 | 14.95 | 11.50 | 10.12 | 471.46 | 362.66 | 319.14 | 114.32 | 3,605.20 |
| Kalanaur | Yamuna | 12,720.5 | 11.73 | 8.53 | 5.76 | 369.92 | 269.00 | 181.65 | 80.35 | 2,533.92 |
| DRB | Yamuna | 30,793.8 | 30.34 | 22.52 | 16.53 | 956.80 | 710.19 | 521.29 | 88.71 | 2,797.56 |
| Mathura | Yamuna | 41,703.8 | – | – | – | – | – | – | – | – |
| Agra | Yamuna | 42,572.2 | 27.01 | 15.68 | 10.79 | 851.90 | 494.44 | 340.27 | 85.26 | 2,688.76 |
| Etawah | Yamuna | 71,999.2 | 26.78 | 16.56 | 11.91 | 844.58 | 522.08 | 375.47 | 87.31 | 2,753.41 |
| Hamirpur | Yamuna | 247,432.2 | 183.84 | 119.14 | 66.98 | 5,797.50 | 3,757.07 | 2,112.38 | 644.87 | 20,336.62 |
| Pratappur | Yamuna | 331,318.8 | 428.41 | 283.43 | 188.84 | 13,510.47 | 8,938.30 | 5,955.31 | 1,249.53 | 39,405.18 |
| Allahabad | Yamuna | 332,264.8 | – | – | – | – | – | – | – | – |
| Udi | Chambal | 134,679 | 57.70 | 24.00 | 11.65 | 1,819.63 | 756.86 | 367.39 | 353.71 | 11,154.60 |
| Seondha | Sind | 16,701 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 22.91 | 722.49 |
| Shahjina | Betwa | 43,651 | 29.50 | 19.15 | 10.34 | 930.31 | 603.91 | 326.08 | 235.57 | 7,428.94 |
| Banda | Ken | 27,616 | 12.03 | 4.13 | 2.60 | 379.38 | 130.24 | 81.99 | 234.57 | 7,397.40 |

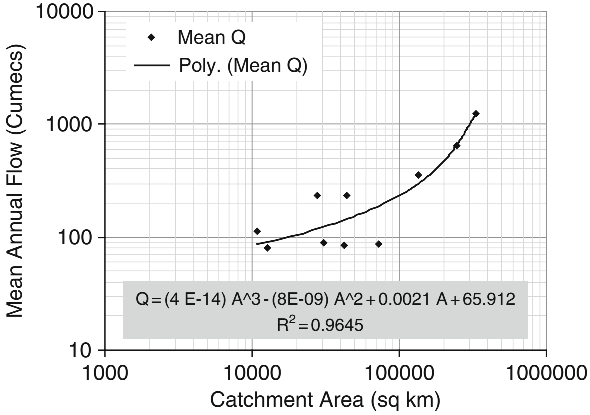


**Fig. 8.5** Catchment area vs mean annual flow relation for the Yamuna basin

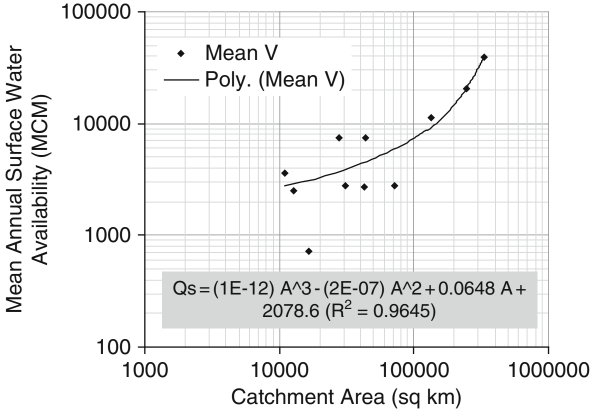


**Fig. 8.6** Catchment area vs water availability relation for the Yamuna basin

The stage groundwater development of the unit area can be estimated using the following relationship:

$$\text{Stage GW Development } (\%) = \frac{\text{Annual GW Draft}}{\text{Annual Net GW Recharge}} \times 100\% \tag{8.3}$$

The district wise stage groundwater development for the Yamuna basin is shown in Fig. 8.10 from which it is observed that most part of the basin in the southwestern and central parts are under dark zone. Most of the Haryana area is either under grey zone or dark zone, though it is the richest in terms of canal networks in the basin. It is also reported that 90% of groundwater draft is used for irrigation; only 10% is being used for domestic and other purposes (GEC, 1997).

Further, the catchment wise groundwater resource availability is summarized in Table 8.4 which also includes the status of GW development in the basin, and it is observed that the Chambal basin is critical in terms of the ground water exploitation followed by the whole Yamuna basin (82.3%) and the Betwa catchment (51.2%).

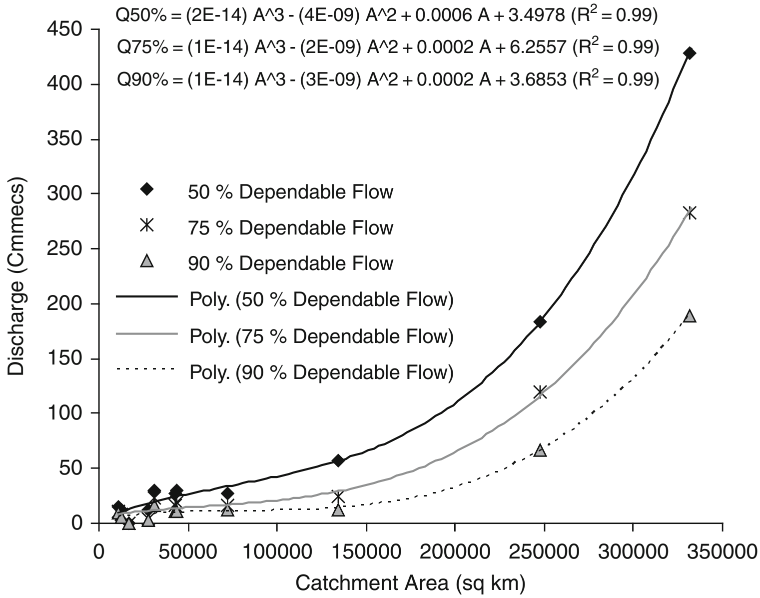


**Fig. 8.7** Area-Discharge relations for Yamuna basin at 50-, 75-, and 90% probability

### *8.1.3 Soil Moisture Storage*

In the Yamuna basin annual soil moisture storage varies between 100 and 250 mm (http://www.iwmi.cgiar.org/). For the Yamuna River basin, 18% of mean annual rainfall of the catchment is considered in the analysis.

Considering individual estimates of water resources (i.e., surface water, ground water and soil moisture storage) described under section 8.1, the total water resources of the catchments and the basin that have been estimated are presented in Table 8.5.

## 8.2 Water Demand Estimation

The water uses in the basin can be broadly categorized as: (i) domestic, (iii) agriculture, (iii) industrial, (iv) power, (v) livestock, etc. In the Yamuna basin, domestic, agriculture, industrial and livestock water use are important.

*The domestic water demand* is estimated from the population data. The standard water use of 135 lpcd in urban, 175 lpcd for Delhi (average), and 40 lpcd in rural area is considered for the domestic water requirement. According to the water supply of Delhi master Plan: (a) domestic = 135 lpcd, (b) industrial and commercial = 70 lpcd, (c) public use = 10 lpcd, (d) losses and thefts = 55 lpcd,

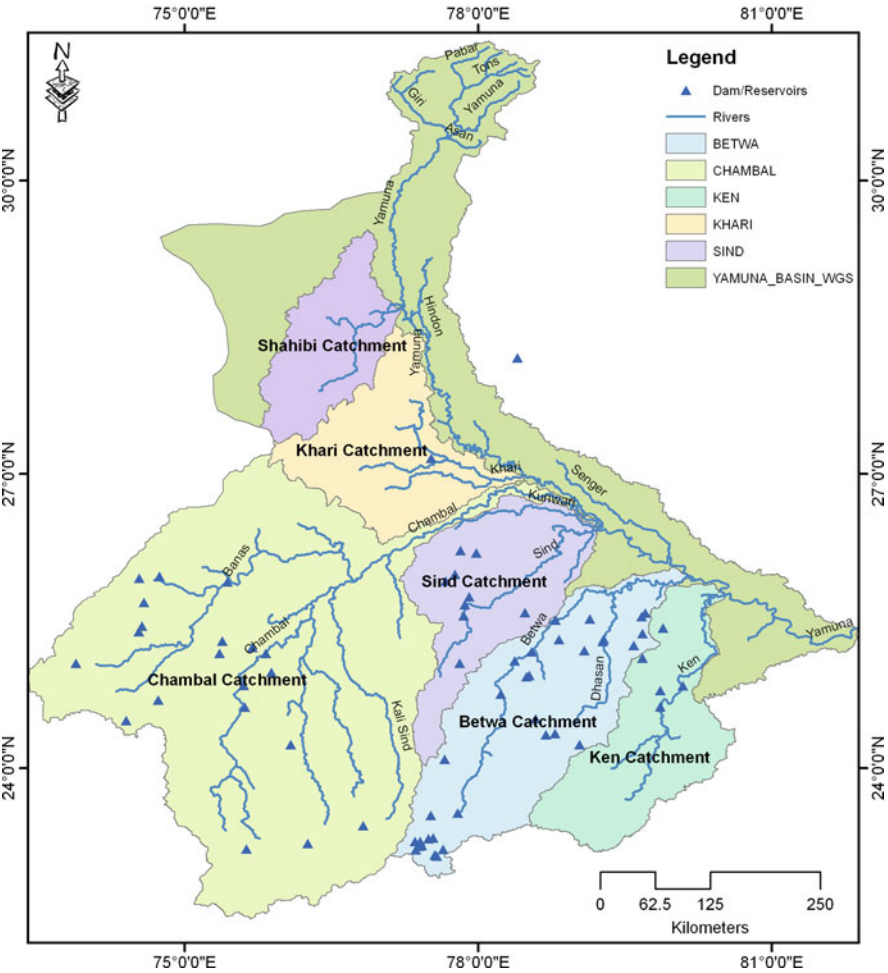


**Fig. 8.8** Location of important dams in the Yamuna basin

(e) total = 270 lpcd. The district wise estimated domestic water demand is given in Appendix B. The catchment wise estimates of domestic demand are summarized in Table 8.6. The spatial distribution of domestic water demand in the basin is shown in Fig. 8.11 based on which it can be stated that the domestic water demand is high along the Yamuna Riveras compared to the other area. The domestic water demand is the largest in the Delhi state and NCR region.

*For industrial water demand*, a thumb rule of nearly 20–30% of municipal water is being utilized to meet industrial demand. Since the whole basin cannot be set at the same level of industrialization like Delhi, the 20% of municipal water demand can be taken as the industrial demand (Table 8.6).

**Table 8.3** Surface water resources of the Yamuna River basin

| S. No. | Site | Catchment | Area (km²) | Mean annual flow (m³/s) | Mean annual availability (MCM) | Gross storage (MCM) | Live storage (MCM) | Surface water resources (MCM) |
|---|---|---|---|---|---|---|---|---|
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) |
| 1 | Paonta | Yamuna | 10,875.5 | 114.32 | 3,605.20 | 3,550 | 1,556[a] | 3,605.2 (5,162.2) |
| 2 | Kalanaur | Yamuna | 12,720.5 | 80.35 | 2,533.92 | | | |
| 3 | DRB | Yamuna | 30,793.8 | 88.71 | 2,797.56 | | | |
| 4 | Mathura | Yamuna | 41,703.8 | – | – | | | |
| 5 | Agra | Yamuna | 42,572.2 | 85.26 | 2,688.76 | | | |
| 6 | Etawah | Yamuna | 71,999.2 | 87.31 | 2,753.41 | | | |
| 7 | Hamirpur | Yamuna | 247,432.2 | 644.87 | 20,336.62 | | | |
| 8 | Pratappur | Yamuna | 331,318.8 | 1,249.53 | **39,405.18** | | | |
| 9 | Allahabad | Yamuna | 332,264.8 | – | – | | | |
| 10 | Udi | **Chambal** | 134,679 | 353.71 | 11,154.60 | 19,613 | 15,582 | **26,736.6** |
| 11 | Seondha | **Sind** | 16,701 | 22.91 | 722.49 | 1,248 | 1,166 | **1,888.5** |
| 12 | Shahjina | **Betwa** | 43,651 | 235.57 | 7,428.94 | 4,923 | 4,374 | **11,802.9** |
| 13 | Banda | **Ken** | 27,616 | 234.57 | 7,397.40 | 812 | 692 | **8,089.4** |
| | | **Yamuna Basin** | | | **39,405.18** | | **21,814** (23,371) | **61,219.2** (62,776.0) |

[a] Refers to the proposed

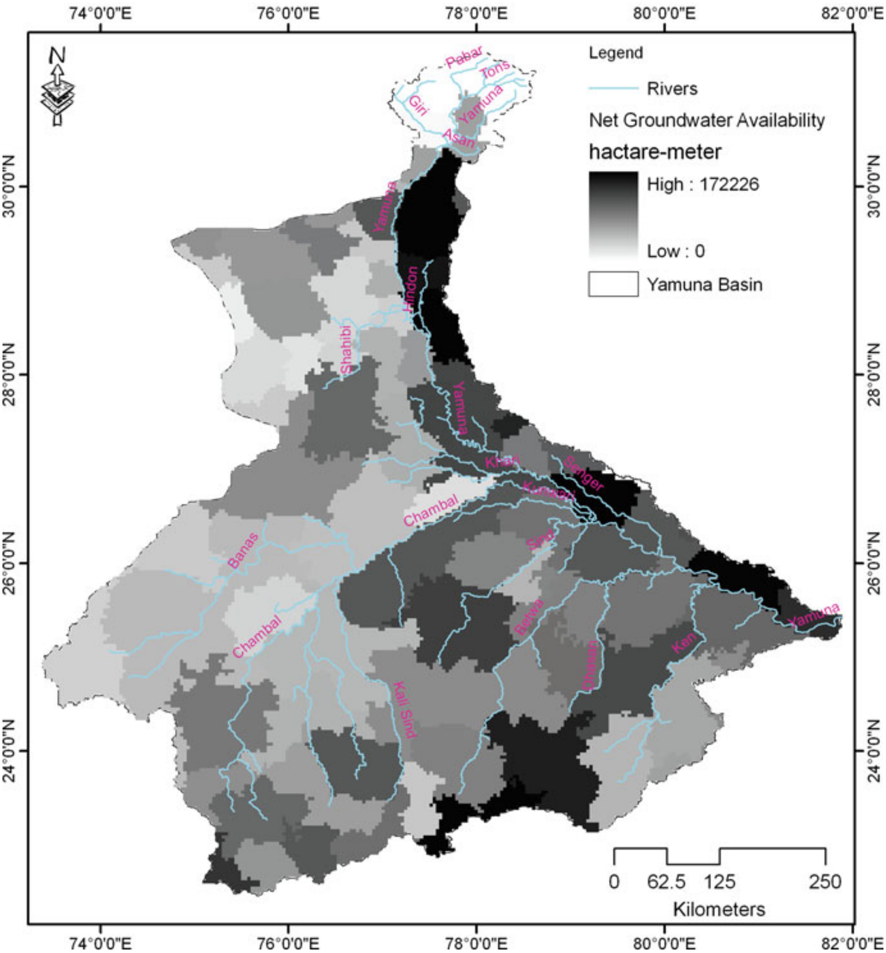


**Fig. 8.9** District-wise net groundwater availability in the basin (ha-m)

## 8.2.1 Agricultural Water Demand

Agricultural demand is estimated using the following relationship (FAO, 1998) [however, a detailed procedure of crop water demand is presented in Chapter 13]:

$$\mathrm{CWR} = \sum_{i=1}^{N} \sum_{j=1}^{M} (K_{\mathrm{c}})_{i,j} \times (ET_0)_j \tag{8.4}$$

where CWR is the crop water requirement (mm), $(K_{\mathrm{c}})_{i,j}$ is the crop coefficient [dimensionless] for the $j$th day of the $i$th crop, $(ET_0)_j$ is the reference crop evapotranspiration (mm) of the $j$th day, $N$ is the number of crops, and $M$ is the

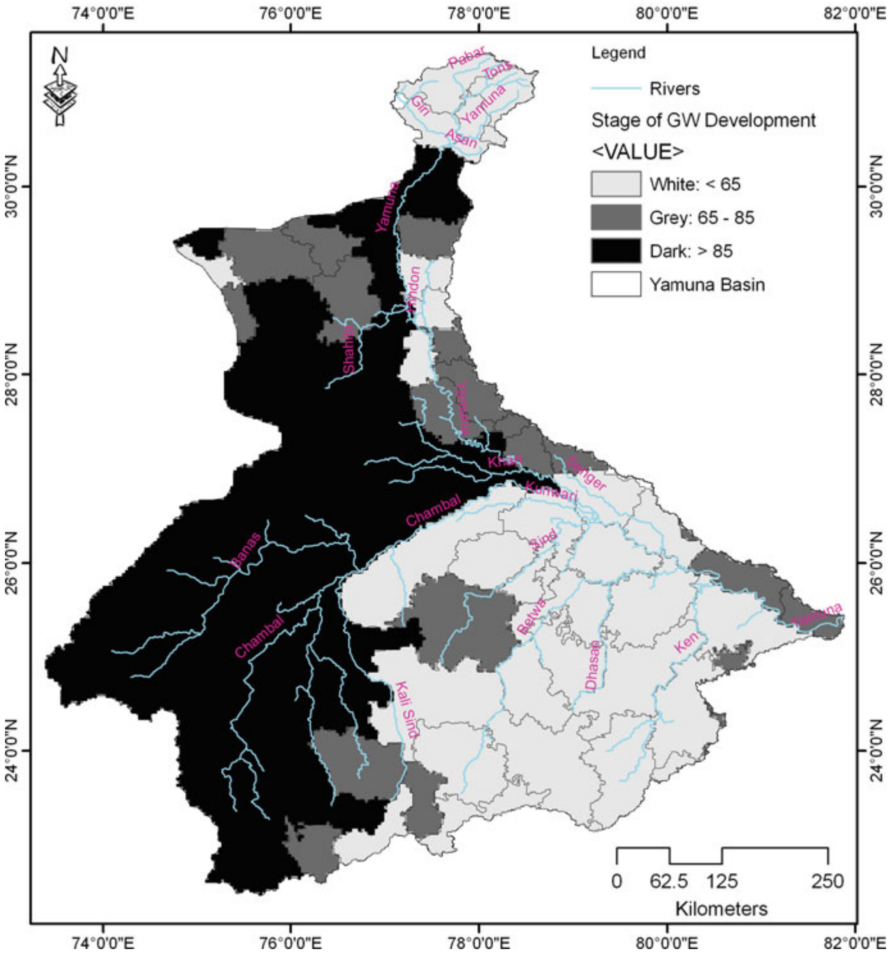


**Fig. 8.10** District-wise stage groundwater developments in the basin (%)

crop duration. Approximate date of sowing, growth stage and crop coefficients for important crops of Yamuna basin are given in Table 8.7. Considering the cropping patter of the district, the crop water demand is estimated using eq. (8.4).

The spatial variability of crop water demand in the basin is shown in Fig. 8.12 [detailed estimates are presented in Chapter 13]. It is observed that the crop water demand is high along the alluvial plains of the basin. Based on Figs. 8.11 and 8.12, it can be stated that the demand is very high along the main river course and alluvial system of major tributaries, resulting high ground water abstraction and induced pollution. Further to this, crop water demand is less in the Ken catchment followed by Betwa catchment. The catchment wise summary of the crop water demand is presented in Table 8.6.

**Table 8.4** Sub-basin-wise groundwater resources availability

| S. No. | Catchment | Area (km$^2$) | Total recharge (MCM) | GW flow (MCM) | Net GW availability (MCM) | Total draft (MCM) | Stage GW development (%) |
|---|---|---|---|---|---|---|---|
| 1 | Upper Yamuna | 11,058.4 | 487.0 | 30.1 | 457.0 | 40.5 | 12.1 |
| 2 | Chambal | 134,967.6 | 10,075.4 | 692.5 | 9,382.9 | 9,133.9 | 101.2 |
| 3 | Sind | 27,940.0 | 3,630.7 | 189.0 | 3,441.7 | 1,413.8 | 40.9 |
| 4 | Betwa | 43,835.9 | 6,050.3 | 349.2 | 5,701.0 | 2,837.3 | 51.2 |
| 5 | Ken | 28,806.5 | 3,293.7 | 180.7 | 3,113.0 | 1,497.9 | 50.2 |
| 6 | Yamuna | 365,870.7 | 48,907.2 | 3,478.4 | 45,428.8 | 34,669.6 | 82.3 |

**Table 8.5** Sub-basin-wise estimates of demand and groundwater resources

| S. No. | Catchment | Area (km$^2$) | Soil moisture storage (MCM) | Net GW availability (MCM) | Surface water resources (MCM) | Total water resources (MCM) |
|---|---|---|---|---|---|---|
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) = (iv)+(v)+(vi) |
| 1 | Upper Yamuna | 11,058.4 | 1,935.0 | 457.0 | 3,605.2 (5,162.2) | 5,997.0 (7,554.0) |
| 2 | Chambal | 134,967.6 | 23,619.0 | 9,382.9 | 26,736.6 | 59,739.0 |
| 3 | Sind | 27,940.0 | 4,890.0 | 3,441.7 | 1,888.5 | 10,220.0 |
| 4 | Betwa | 43,835.9 | 7,671.0 | 5,701.0 | 11,802.9 | 25,175.0 |
| 5 | Ken | 28,806.5 | 5,041.0 | 3,113.0 | 8,089.4 | 16,244.0 |
| 6 | Yamuna | 365,870.7 | **640,27.0** | **45,428.8** | **61,219.2** (**62,776**) | 170,675.0 (172,231.0) |

Values in the parenthesis are the estimates after functioning of three dams in the upper Himalayan segment

## 8.2.2 *Surplus and Deficit Analysis*

In the Sections 8.1 and 8.2, the water availability and water demand has been estimated; and used to estimate the surplus and deficits in the basin/catchments. The estimated gross water demand in the basin is 205,216 MCM, of which 98.2% water is used for agriculture in the basin; whereas the water availability in the basin is 170,675 MCM. Therefore, total deficit in the basin is of the order of 34,541 MCM (Table 8.6).

From analysis it may be concluded that all catchments of the basins are experiencing water deficits, except the upper Himalayan and Ken catchments as the crop water demand is quite low in these catchments due to their prevailing geographic conditions.

**Table 8.6** Catchment wise estimates of demand and groundwater resources

| S. No. | Catchment/ basin | Domestic water demand (MCM) | Crop water demand (MCM) | Industrial water demand (MCM) | Gross water demand (MCM) | Soil moisture storage (MCM) | Net GW availability (MCM) | Surface water resources (MCM) | Total water resources (MCM) | Surplus/deficit |
|---|---|---|---|---|---|---|---|---|---|---|
| (i) | (ii) | (iii) | (iv) | (v) | (vi) = (iii)+(iv)+(v) | (vii) | (viii) | (ix) | (x) = (vii)+(viii)+(ix) | (xi) = (x)–(vi) |
| 1 | Upper Yamuna | 54.3 | 1,332 | 10.86 | 1,397.16 | 1,935 | 457 | 3,605.2 (5,162.2) | 5,997 (7,554) | 4,599.8 (6,157.0) |
| 2 | Chambal | 721 | 62,771 | 144.2 | 63,636.2 | 23,619 | 9,382.9 | 26,736.6 | 59,739 | −3,897.2 |
| 3 | Sind | 166.8 | 13,786 | 33.36 | 13,986.16 | 4,890 | 3,441.7 | 1,888.5 | 10,220 | −3,766.1 |
| 4 | Betwa | 287.5 | 26,456 | 57.5 | 26,801 | 7,671 | 5,701 | 11,802.9 | 25,175 | −1,626.0 |
| 5 | Ken | 137.2 | 12,808 | 27.44 | 12,972.64 | 5,041 | 3,113 | 8,089.4 | 16,244 | 3,271.4 |
| 6 | Yamuna | 3,712.9 | 200,761 | 742.58 | 205,216.48 | 64,027 | 45,428.8 | 61,219.2 (62,776) | 170,675 (172,231) | –34,541.5 (–32,984.7) |

Values in the parenthesis are the estimates when proposed dams are considered

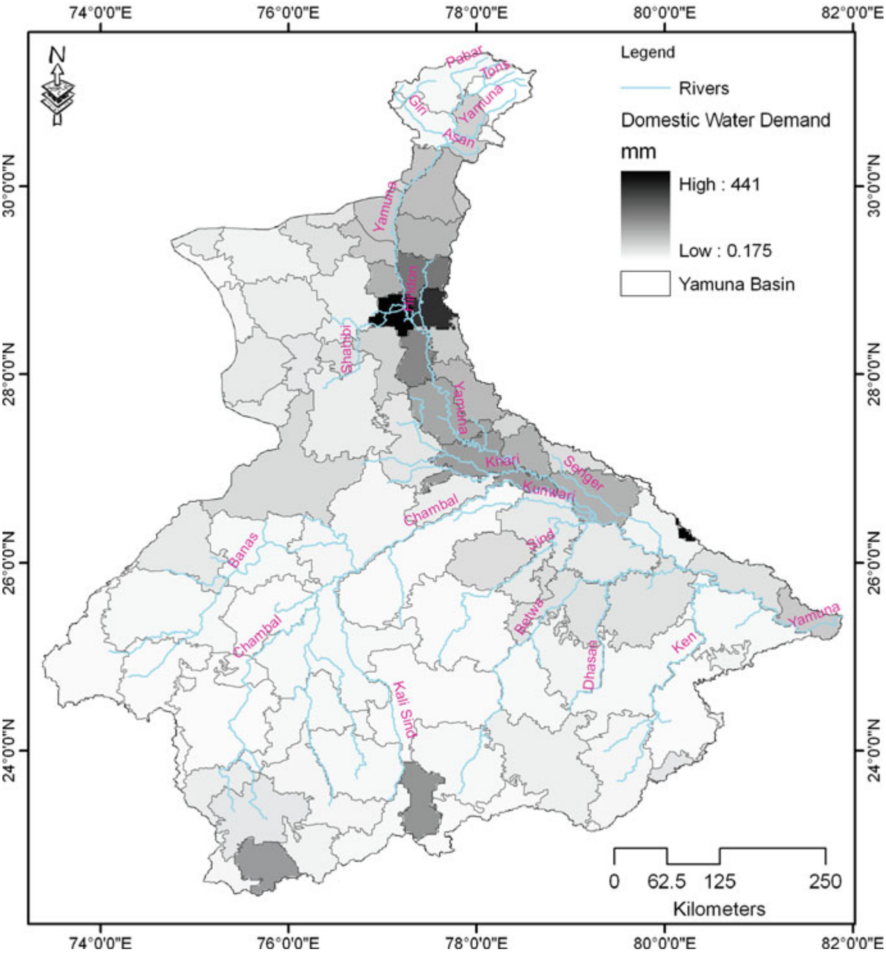


**Fig. 8.11** Spatial distribution of domestic water demand in the Yamuna basin

## 8.3 Flood Hydrograph Estimation for the Catchments

Accurate estimation of flood hydrograph is important for hydrological design, such as design of culverts, design of the spillway capacity of reservoirs, hydropower design, etc. It requires a variety of data, including climatic, topographic, soils, land use information along with event based hydrologic data for model calibration. However, practically most of the small streams are ungauged in India; and it becomes difficult to estimate the flood hydrograph using sophisticated models (Singh and Frevert, 2002a, b). Under such circumstances, regional flood estimation becomes more useful for the derivation of flood hydrograph. Apart from this, the geomorphology based conceptual models have become popular for the estimation of synthetic hydrographs.

**Table 8.7** Approximate date of sowing, growth stage and crop coefficients for important crops of the Yamuna basin

| Crop | Sowing date (approx) | Growth stage (days) | | | | Total duration (Days) |
|---|---|---|---|---|---|---|
| | | Initial | Development | Middle | Late | |
| Wheat | 1st November | 20 | 60 | 20 | 50 | 150 |
| $K_c$ | | 0.40 | 1.00 | 1.20 | 0.60 | |
| Barley | 1st November | 15 | 25 | 50 | 30 | 120 |
| $K_c$ | | 0.20 | 1.00 | 1.15 | 0.25 | |
| Gram | 20th October | 20 | 30 | 30 | 20 | 100 |
| $K_c$ | | 0.35 | 0.75 | 1.05 | 0.50 | |
| Potato | 25th October | 25 | 30 | 30 | 30 | 115 |
| $K_c$ | | 0.52 | 0.81 | 1.10 | 0.70 | |
| Mustard | 1st November | 25 | 35 | 35 | 40 | 135 |
| $K_c$ | | 0.38 | 0.38 | 1.00 | 0.56 | |
| Bajra | 10th June | 20 | 35 | 25 | 30 | 110 |
| $K_c$ | | 0.41 | 1.00 | 1.20 | 0.40 | |
| Paddy | 20th June | 30 | 30 | 60 | 30 | 150 |
| $K_c$ | | 1.05 | 1.20 | 1.20 | 0.75 | |
| Jowar | 20th June | 20 | 40 | 45 | 20 | 125 |
| $K_c$ | | 0.42 | 1.00 | 1.20 | 0.40 | |
| Maize | 15th May | 20 | 35 | 40 | 30 | 125 |
| $K_c$ | | 0.42 | 0.95 | 1.00 | 0.50 | |
| Arhar | 15th June | 20 | 35 | 40 | 30 | 125 |
| $K_c$ | | 0.63 | 0.63 | 0.63 | 0.63 | |
| Soybean | 15th May | 20 | 35 | 60 | 25 | 140 |
| $K_c$ | | 0.40 | 1.00 | 1.15 | 0.50 | |
| Groundnut | 15th May | 35 | 45 | 35 | 25 | 140 |
| $K_c$ | | 0.52 | 0.85 | 1.00 | 0.55 | |
| Cotton | 10th April | 30 | 50 | 60 | 55 | 195 |
| $K_c$ | | 0.43 | 1.00 | 1.15 | 0.60 | |
| Sugarcane | 15th November | 30 | 50 | 180 | 60 | 320 |
| $K_c$ | | 0.47 | 1.00 | 1.25 | 0.70 | |

*Source*: FAO (1998)

This section, therefore, discusses the application of a regional flood estimation technique given by Central Water Commission (CWC, 1983) as well as the geomorphology based conceptual modelling technique for the generation of synthetic hydrograph (Rai et al., 2009; Singh, 1988). Both of these techniques follow the assumptions of Unit Hydrograph.

### *8.3.1 Regional Synthetic Unit Hydrograph Technique*

The CWC (1983) method is well accepted by field engineers and hydrologists for the derivation of unit hydrograph (UH) for ungauged catchments in India for the estimation of design floods for installing waterway of bridges/cross drainage

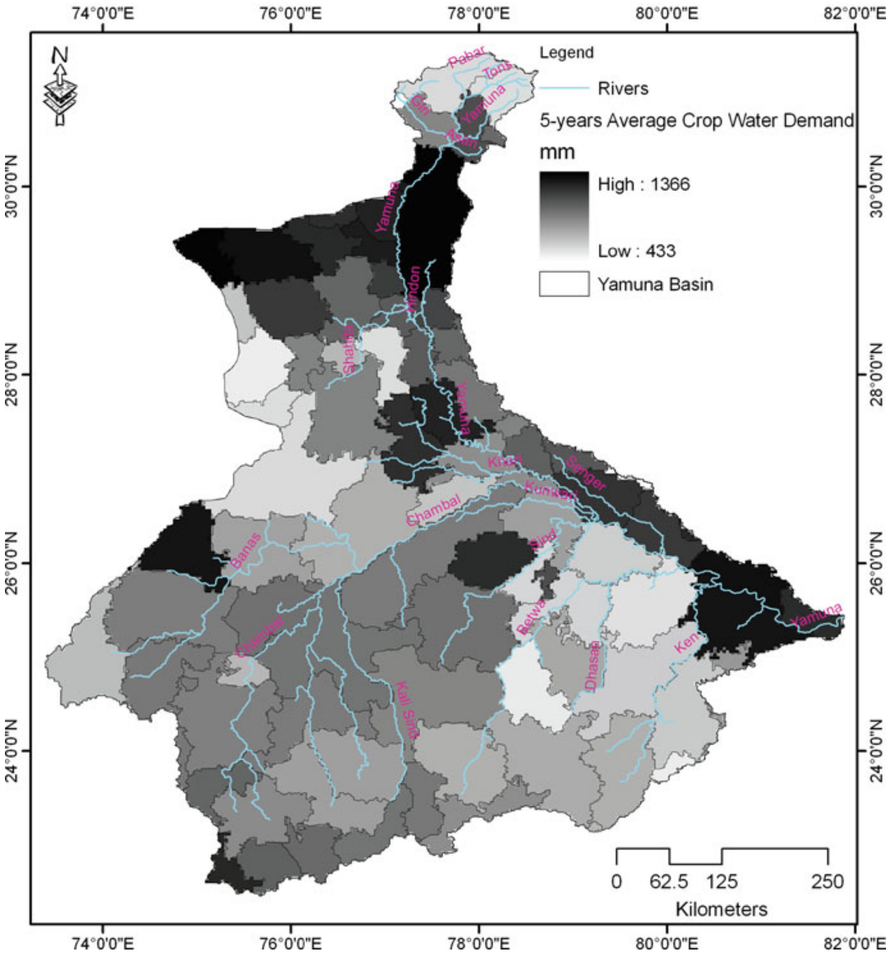


**Fig. 8.12** Spatial distribution of crop water demand in the basin

structures across small and medium streams. In this method a set of equations for UH parameters (viz., peak flow rate, time to peak flow rate and time base of the hydrograph) as a function of slope, length of the longest stream and drainage area are developed for the regions, based on the regional analysis of observed data from 42 representative sub-watersheds (40 sub-watersheds data were collected by Northern and North-eastern Railways, India; and 2 sub-watersheds data were collected by Ministry of Transport, India).

Considering the hydro-climate and geography and soil characteristics of the area, India has been divided into seven hydro-meteorologically homogeneous zones, and is further divided into twenty six hydro-meteorological sub-zones [i.e. sub-zones

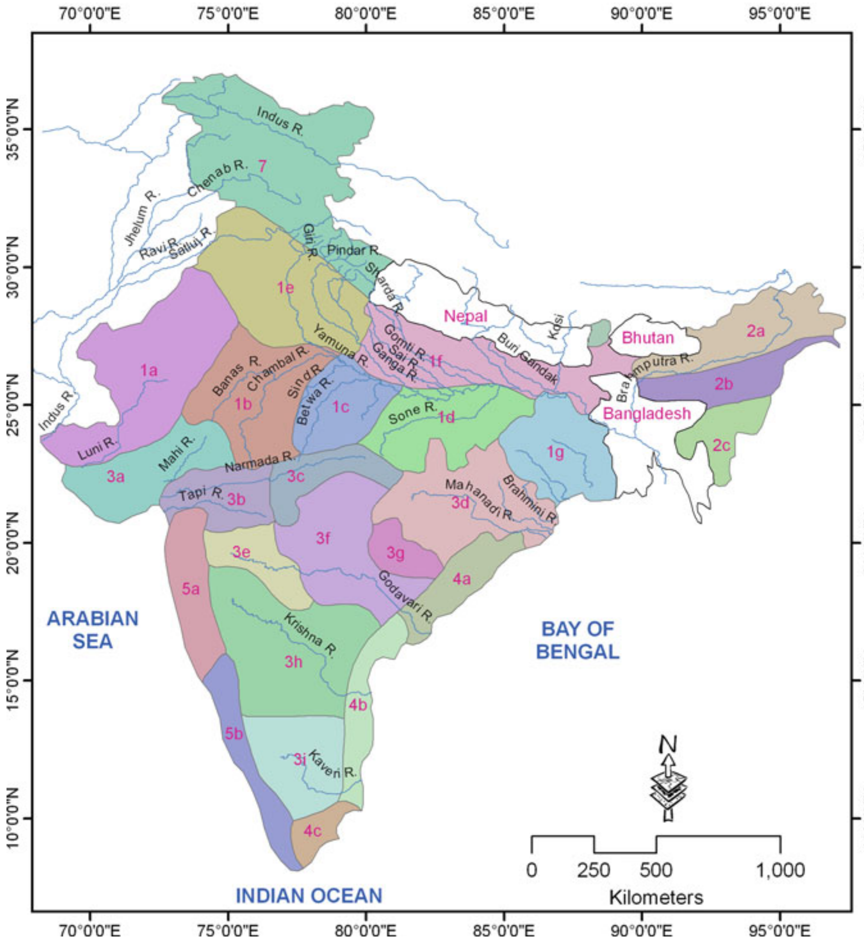


**Fig. 8.13** Hydro-meteorological sub-zones of India

1(a) to 1(g), 2(a) to 2(c), 3(a) to 3(i), 4(a) to 4(c), 5(a), 5(b), 6 and 7] (Jain et al., 2007). The hydro-meteorological sub-zones of India are shown in Fig. 8.13.

Due to varying topography and hydro-climatic conditions, the Yamuna River basin comprises five sub-zones, viz. 7, 1b, 1c, 1e and 1f (Fig. 8.13). Detailed computational steps for computing the synthetic unit hydrograph (SUH) for these sub-zones are presented in Tables 8.8, 8.9, 8.10, 8.11, and 8.12. Parameters of the synthetic unit hydrograph (SUH) are shown in Fig. 8.14. The UH parameters so derived using the procedure are used to generate the synthetic unit hydrograph by smoothing the rest of the ordinates. It should be kept in mind that the total volumetric assumption of unit depth should be preserved. If the unit depth is not achieved then adjustments can be made in the ordinates of the UH.

**Table 8.8** Relationships of 1 h SUH of ungauged catchments in hydro-meteorological sub-zone 7 (CWC, 1994)

| Steps | Equations | Remarks |
|---|---|---|
| Step-1: Analysis of "catchment physiography" | $S = \frac{\sum L_i \left(D_{i-1} - D_i\right)}{L^2}$<br>where $L_i$ is the length of the $i$ th segment in km, $D_{i-1}$, $D_i$ are the depths of the river at the point of intersection of ($i$ – 1) and $i$ th contours respectively from the base line (datum) | $A$ is the catchment area, $L$ is the length of the longest stream and $S$ is the equivalent stream slope |
| Step-2: Determination of "time from center of effective rainfall duration to the peak value for 1 h SUH" | time to peak $t_p = 2.498 \times (L \times L_c/S)^{0.156}$ (h)<br>$L_c$ is the length of the longest stream from a point opposite to the center of gravity of the catchment to the point of study. | |
| Step-3: Determination of "peak value for 1 h SUH" | unit hydrograph peak per unit catchment area<br>$q_p = 1.048 \times \left(t_p\right)^{-0.178}$ (cumec/km$^2$) | Peak discharge $Q_p = q_p \times A$ |
| Step-4: Estimation of the "time to peak ($T_m$) for 1 h SUH" | time to peak $T_m = t_p + t_r/2$ | |
| Step-5: Estimation of "time base for 1 h SUH" | time base $T_B = 7.845\left(t_p\right)^{0.453}$ | |
| Step-6: Estimation of "time widths for different % values of peak discharge of 1 h SUH" | time width parameters (in h)<br>$W_{50} = T_{50} + T\,T_{50} = 1.954 \times (L \times L_c/S)^{0.099}$<br>$W_{75} = T_{75} + T\,T_{75} = 0.972 \times (L \times L_c/S)^{0.124}$<br>$W_{R50} = T_{50} = 0.189 \times (W_{50})^{1.769}$<br>$W_{R75} = T_{75} = 0.419 \times (W_{75})^{1.246}$ | |

**Table 8.9** Relationships of 1 h SUH of ungauged catchments in hydro-meteorological sub-zone 1b (CWC)

| Steps | Equations | Remarks |
|---|---|---|
| Step-1: Analysis of "catchment physiography" | $S = \frac{\sum L_i (D_{i-1} - D_i)}{L^2}$ where $L_i$ is the length of the $i$ th segment in km, $D_{i-1}$, $D_i$ are the depths of the river at the point of intersection of $(i-1)$ and $i$ th contours respectively from the base line (datum) | $A$ is the catchment area, $L$ is the length of the longest stream and $S$ is the equivalent stream slope |
| Step-2: Determination of "time from center of effective rainfall duration to the peak value for 1 h SUH" | time to peak $t_p = 0.339 \times \left(L/\sqrt{S}\right)^{0.829}$ (h) | |
| Step-3: Determination of "peak value for 1 h SUH" | unit hydrograph peak per unit catchment area $q_p = 1.215/(t_p)^{0.610}$ (cumec/km$^2$) | Peak discharge $Q_p = q_p \times A$ |
| Step-4: Estimation of the "time to peak ($T_m$) for 1 h SUH" | time to peak $T_m = t_p + t_r/2$ | |
| Step-5: Estimation of "time base for 1 h SUH" | time base $T_B = 6.662(t_p)^{0.613}$ | |
| Step-6: Estimation of "time widths for different % values of peak discharge of 1 h SUH" | time width parameters (in h)<br>$W_{50} = T_{50} + T\,T_{50} = 2.215/(q_p)^{1.034}$<br>$W_{75} = T_{75} + T\,T_{75} = 1.191/(q_p)^{1.057}$<br>$W_{R50} = T_{50} = 0.834/(q_p)^{1.077}$<br>$W_{R75} = T_{75} = 0.502/(q_p)^{1.065}$ | |

**Table 8.10** Relationships of 1 h SUH of ungauged catchments in hydro-meteorological sub-zone 1c (CWC)

| Steps | Equations | Remarks |
|---|---|---|
| Step-1: Analysis of "catchment physiography" | $S = \frac{\sum L_i (D_{i-1} - D_i)}{L^2}$ where $L_i$ is the length of the $i$ th segment in km, $D_{i-1}$, $D_i$ are the depths of the river at the point of intersection of $(i-1)$ and $i$ th contours respectively from the base line (datum) | $A$ is the catchment area, $L$ is the length of the longest stream and $S$ is the equivalent stream slope |
| Step-2: Determination of "peak value for 1 h SUH" | unit hydrograph peak per unit catchment area $q_p = 1.331 \times (L/S)^{-0.492}$ (cumec/km$^2$) | Peak discharge $Q_p = q_p \times A$ |
| Step-3: Determination of "time from center of effective rainfall duration to the peak value for 1 h SUH" | time to peak $t_p = 2.195 \times (q_p)^{-0.944}$ (h) | |
| Step-4: Estimation of the "time to peak ($T_m$) for 1 h SUH" | time to peak $T_m = t_p + t_r/2$ | |
| Step-5: Estimation of "time base for 1 h SUH" | time base $T_B = 3.917(t_p)^{0.990}$ | |
| Step-6: Estimation of "time widths for different % values of peak discharge of 1 h SUH" | time width parameters (in h) $W_{50} = T_{50} + TT_{50} = 2.04 \times (q_p)^{-1.026}$ $W_{75} = T_{75} + TT_{75} = 1.25 \times (q_p)^{-0.864}$ $W_{R50} = T_{50} = 0.739 \times (q_p)^{-0.968}$ $W_{R75} = T_{75} = 0.500 \times (q_p)^{-0.813}$ | |

**Table 8.11** Relationships of 2 h SUH of ungauged catchments in hydro-meteorological sub-zone 1e (CWC, 1984)

| Steps | Equations | Remarks |
|---|---|---|
| Step-1: Analysis of "catchment physiography" | $S = \frac{\sum L_i\,(D_{i-1} - D_i)}{L^2}$ Where $L_i$ is the length of the $i$ th segment in km, $D_{i-1}$, $D_i$ are the depths of the river at the point of intersection of $(i - 1)$ and $i$ th contours respectively from the base line (datum) | $A$ is the catchment area, $L$ is the length of the longest stream and $S$ is the equivalent stream slope |
| Step-2: Determination of "peak value for 2 h SUH" | unit hydrograph peak per unit catchment area $q_p = 2.030/\left(L/\sqrt{S}\right)^{0.649}$ in (cumec/km$^2$) | Peak discharge is $Q_p = q_p \times A$ |
| Step-3: Estimation of the "time to peak ($T_m$) for 2 h SUH" | time lag $t_p = 1.858/\left(q_p\right)^{1.038}$ The time to peak $T_m = t_p + t_r/2$ | |
| Step-4: Estimation of "time base for 2 h SUH" | time base $T_B = 7.744\left(t_p\right)^{0.779}$ | |
| Step-5: Estimation of "time widths for different % values of peak discharge of 2 h SUH" | time width parameters (in h) $W_{50} = T_{50} + T\,T_{50} = 2.217/\left(q_p\right)^{0.990}$ $W_{75} = T_{75} + T\,T_{75} = 1.477/\left(q_p\right)^{0.876}$ $W_{R50} = T_{50} = 0.812/\left(q_p\right)^{0.907}$ $W_{R75} = T_{75} = 0.606/\left(q_p\right)^{0.791}$ | |

**Table 8.12** Relationships of 6 h SUH of ungauged catchments in hydro-meteorological sub-zone 1f (CWC)

| Steps | Equations | Remarks |
|---|---|---|
| Step-1: Analysis of "catchment physiography" | $S = \frac{\sum L_i (D_{i-1} - D_i)}{L^2}$ where $L_i$ is the length of the $i$ th segment (km), $D_{i-1}, D_i$ are the depths of the river at the point of intersection of ($i$–1) and $i$ th contours respectively from the base line (datum) [m] | $A$ is the catchment area (km$^2$), $L$ is the length of the longest stream (km) and $S$ is the equivalent stream slope (m/km) |
| Step-2: Determination of "time from center of effective rainfall duration to the peak value for 6 h SUH" | time to peak $t_p = 3.065 \times \left(L/\sqrt{S}\right)^{0.471}$ (h)<br>$t_p = 1.217/\left(q_p\right)^{1.034}$ | |
| Step-3: Determination of "peak value for 6 h SUH" | unit hydrograph peak per unit catchment area<br>$q_p = 0.409/\left(L/\sqrt{S}\right)^{0.456}$ (cumec/km$^2$)<br>$q_p = 0.138/\left(t_p\right)^{0.968}$ | Peak discharge $Q_p = q_p \times A$ |
| Step-4: Estimation of the "time to peak ($T_m$) for 6 h SUH" | time to peak $T_m = t_p + t_r/2$ | |
| Step-5: Estimation of "time base for 6 h SUH" | time base $T_B = 16.432\left(t_p\right)^{0.646}$ | |
| Step-6: Estimation of "time widths for different % values of peak discharge of 6 h SUH" | time width parameters (in h)<br>$W_{50} = T_{50} + T\,T_{50} = 1.743/\left(q_p\right)^{1.104}$<br>$W_{75} = T_{75} + T\,T_{75} = 0.902/\left(q_p\right)^{1.108}$<br>$W_{R50} = T_{50} = 0.736/\left(q_p\right)^{0.928}$<br>$W_{R75} = T_{75} = 0.478/\left(q_p\right)^{0.902}$ | |

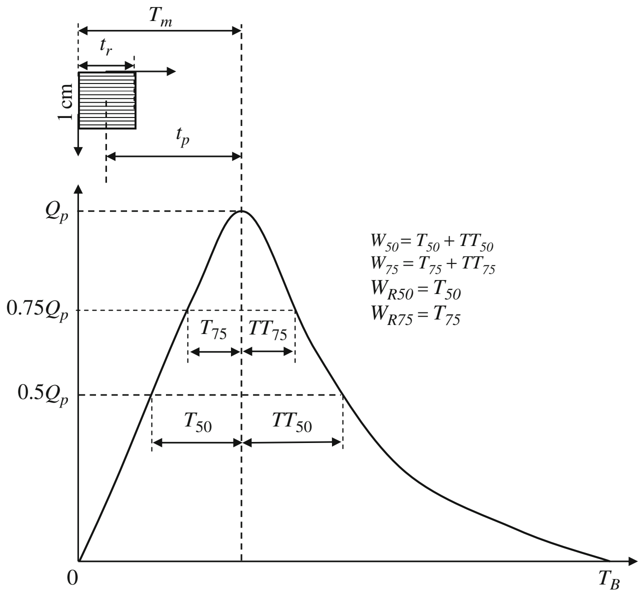


**Fig. 8.14** Components of synthetic unit hydrograph

### *8.3.2 Geomorphology Based Synthetic Unit Hydrograph Technique*

Geomorphology of a river basin describes the status of topographic features of surfaces and streams, and its relationship with hydrology provides the geomorphologic control on the basin hydrology (Jain and Sinha, 2003). Geomorphology reflects the topographic and geometric properties of the watershed and its drainage channel network. It controls the hydrologic processes from rainfall to runoff, and the subsequent flow routing through the drainage network. The role of basin geomorphology in controlling the hydrological response of a river basin is known for a long time. Earlier works have provided an understanding of basin geomorphology-hydrology relationship through empirical relationships (Snyder, 1938; Horton, 1945; Taylor and Schwartz, 1952; Singh, 1988, 1989, 1992; Jain and Sinha, 2003). Snyder (1938) proposed a synthetic unit hydrograph approach (SUH) for ungauged basins as a function of catchment area, basin shape, topography, channel slope, stream density and channel storage; and derived the basin coefficient by averaging out other parameters. Therefore, geomorphology based approach becomes one of the most popular modeling tools for the computation of runoff hydrographs (Rodriguez-Iturbe and Valdes, 1979; Rodriguez-Iturbe et al., 1982; Yen and Lee, 1997; Rai et al., 2009). The geomorphologic instantaneous unit hydrograph (GIUH) (Rodriguez-Iturbe and Valdes, 1979) and its simplification by Gupta et al. (1980) are hydrological models that relate the geomorphological features of a basin to its response to rainfall. They can be applied to ungauged basins having scarce hydrologic data (Al-Wagdany and Rao, 1998). The derivation of the GIUH uses the assumption that a stream of a certain order has a known linear response function of the familiar or complex probability distribution type (Rodriguez-Iturbe and Valdes, 1979; Fleurant et al., 2006). Thus, the GIUH based transfer function approach is applicable where rainfall data is available but runoff data is not, and it is a more powerful technique for the flood estimation than the commonly used parametric models (Yen and Lee, 1997; Bhaskar et al., 1997; Jain et al., 2000; Lohani et al., 2001; Kumar et al., 2002, 2007; Sarangi et al., 2007; Rai et al., 2009; etc.).

Another advantage of the GIUH technique is its potential for deriving the unit hydrograph (UH) using the geomorphologic characteristics obtainable from topographic map/remote sensing, possibly linked with geographic information system (GIS) and digital elevation model (DEM) (Rodriguez-Iturbe and Valdes, 1979; Rai et al., 2009).

#### 8.3.2.1 Derivation of Geomorphologic Unit Hydrograph (GUH)

The GIUH theory was introduced by Rodriguez-Iturbe and Valdes (1979) by relating the peak discharge and time to peak discharge with the geomorphologic characteristics of the catchment and a dynamic velocity parameter. This work explicitly integrates the geomorphologic details and the climatologic characteristics of the basin, in a framework of travel time distribution for stream flow synthesis in the basin having no or scanty information of flow data. This formulation of GIUH is based on the probability density function (*pdf*) of the time history of a randomly chosen drop of effective rainfall reaching the trapping state of a hypothetical basin, treated as a continuous Markovian process, where the state is the order of the stream in which the raindrop is located at any time. The value at the mode of this *pdf* produces the main characteristics of GIUH. Rodriguez-Iturbe and Valdes (1979) derived the peak and time to peak characteristics of the IUH as a function of Horton's order ratios (Horton, 1945), and are expressed as follows (Kumar et al., 2002):

$$q_{\mathrm{p}} = 1.31\, R_{\mathrm{l}}^{0.43}\, V/L_{\Omega} \tag{8.5}$$

$$t_{\mathrm{p}} = 0.44\, (L_{\Omega}/V)\, (R_{\mathrm{b}}/R_{\mathrm{a}})^{0.55} \cdot R_{l}^{-0.38} \tag{8.6}$$

where $q_{\mathrm{p}}$ is the peak flow ($\mathrm{h}^{-1}$), $t_{\mathrm{p}}$ is the time to peak (h), $L_{\Omega}$ is the length of the highest order stream (km), $V$ is the dynamic velocity parameter ($\mathrm{m\ s}^{-1}$), $R_{\mathrm{b}}$ is the bifurcation ratio, $R_{\mathrm{a}}$ is the stream area ratio, and $R_{\mathrm{l}}$ is the stream length ratio. Multiplying eqs. (8.5) and (8.6) a non-dimensional term $q_{\mathrm{p}}^{*}t_{\mathrm{p}}$ is derived at.

$$q_{\mathrm{p}}^{*}t_{\mathrm{p}} = 0.5764\, \left[R_{\mathrm{b}}/R_{\mathrm{a}}\right]^{0.55} R_{\mathrm{l}}^{0.05} \tag{8.7}$$

Term $q_{\mathrm{p}}^{*}t_{\mathrm{p}}$ is not dependent on velocity and thereby on storm characteristics and hence, it is a function of only the geomorphologic characteristics of the basin. The dynamic velocity parameter in the formulation of GIUH incorporates the effect of climatic variation. Rodriguez-Iturbe and Valdes (1979) showed that the dynamic velocity parameter of GIUH can be taken as the velocity at the peak discharge for a given rainfall-runoff event in the catchment. Rodriguez-Iturbe and Valdes (1979) compared the GIUHs for some real world basins with the IUHs derived from the discharge hydrograph produced by a physically based rainfall-runoff model of the same basin and found them to be remarkably similar. For deriving the SUH for the catchments of the Yamuna basin, the Nash model was linked with the geomorphologic characteristics of the catchments. A brief description of the Nash model and its linkage with geomorphologic parameters are now given.

#### 8.3.2.2 The Nash Model

The Nash model (Nash, 1957) is based on the concept of routing of the instantaneous inflow through a cascade of linear reservoirs with equal storage coefficient. The Nash model can be expressed as:

$$u(t) = \frac{1}{k\,\Gamma(n)}\,(t/k)^{n-1}\,\exp(-t/k) \tag{8.8}$$

where $u(t)$ is the ordinates of IUH (hour$^{-1}$), $t$ is the sampling time interval (hour), $n$ and $k$ are the parameters of the Nash model, in which $n$ is the number of linear reservoirs, and $k$ is the storage coefficient (hour).

A unit hydrograph (UH) of desired duration ($D$) may be derived by using the following expression:

$$U(D,\,t) = \frac{1}{D}\left[I(n,\,t/k) - I\,(n,\,(t-D)/k)\right] \tag{8.9}$$

where $U(D,\,t)$ denotes the ordinates of $D$ hour UH (h$^{-1}$), $t$ is the sampling time interval (h), $I\,(n,\,t/k)$ is the incomplete gamma function of order $n$ at $(t/k)$, and $D$ is the duration of UH (h).

#### 8.3.2.3 Geomorphology Based Parameter Estimation of Nash's GIUH

The complete shape of the GIUH can be obtained by linking $q_\mathrm{p}$ and $t_\mathrm{p}$ of the GIUH with scale ($k$) and shape ($n$) parameters of the Nash model. Equating the first derivative with respect to $t$ of eq (8.8) to zero, $t$ becomes the time to peak discharge, $t_\mathrm{p}$. Thus, taking the natural logarithm of both sides of eq. (8.8), differentiating with respect to $t$ and by simplification eq. (8.10) is derived.

$$\frac{\partial}{\partial t}\ln\,[u(t)] = \left[-\frac{1}{k} + \frac{(n-1)}{t}\right] \tag{8.10}$$

Equating eq. (8.10) to zero and replacing $t$ with $t_\mathrm{p}$ result in:

$$t = t_\mathrm{p} = k\,(n-1) \tag{8.11}$$

Simplifying the value of $t_p$ from eq. (8.11) in eq. (8.8) and simplifying yields

$$q_p = \frac{1}{k\Gamma(n)} \exp\left[-(n-1)\right] \cdot (n-1)^{n-1} \tag{8.12}$$

From eqs. (8.11) and (8.12), the result is:

$$q_p \cdot t_p = \frac{(n-1)}{\Gamma(n)} \exp\left[-(n-1)\right] \cdot (n-1)^{n-1} \tag{8.13}$$

Equating eq. (8.13) to eq. (8.7) one obtains:

$$\begin{aligned} \frac{(n-1)}{\Gamma(n)} \cdot \exp\left[-(n-1)\right] \cdot (n-1)^{n-1} \\ = 0.5764\left[R_b/R_a\right]^{0.55} \times R_l^{0.05} \end{aligned} \tag{8.14}$$

The Nash parameter $n$ can be obtained by solving eq. (8.14) using the Newton-Raphson method.

The Nash's parameter $k$ for the given velocity $V$ is obtained using eqs. (8.6) and (8.11) and the known value of parameter $n$ as:

$$k = \frac{0.44\,L_\Omega}{V} \cdot \left[\frac{R_b}{R_a}\right]^{0.55} \cdot R_l^{-0.38} \cdot \frac{1}{(n-1)} \tag{8.15}$$

The derived values of $n$ and $k$ are used to determine the complete shape of the Nash based GIUH using eq. (8.8). Subsequently, the D-hour UH can be derived from eq. (8.9). The direct runoff hydrograph (DRH) is estimated by convoluting the excess rainfall hyetograph with the UH.

#### 8.3.2.4 Application of the GIUH Methodology

To implement the described technique requires a geomorphologic investigation of the catchments of the Yamuna basin, and is presented in Chapter 5. However, the geomorphologic parameters required to derive the GSUH are summarized in Table 8.13.

Using Horton's ratio and Ω, parameter $n$ of the Nash model is estimated using eq. (8.14) and is given in Table 8.14 for the catchments of the basin. Using the value of $n$ and range of average velocities, the values of storage coefficients, $k$ are computed using eq. (8.15). The values of $k$ are depicted in Table 8.14. Using the values of $n$ and $k$, the GIUH is derived (eq. (8.8)) for the catchments and subsequently the 1-h SUH is generated (eq. (8.9)). The resulting SUHs are shown in Figs. 8.15, 8.16, 8.17, 8.18, and 8.19 for the Upper Himalayan Yamuna, Chambal, Sind, Betwa and Ken catchments, respectively.

The above described approach becomes difficult for field engineers because of the involvement of large computational steps. Therefore, an attempt is made to

**Table 8.13** Horton's ratio of the catchments of the Yamuna basin

| Catchment | Horton's ratio: Stream-area ratio, $R_a$ | Bifurcation ratio, $R_b$ | Length ratio, $R_l$ | Length of highest order stream, Ω (km) |
|---|---|---|---|---|
| Upper Yamuna | 6.622 | 5.703 | 2.945 | 120.9 |
| Chambal | 5.21 | 4.76 | 1.361 | 389.1 |
| Sind | 4.01 | 3.55 | 1.86 | 51.4 |
| Betwa | 4.33 | 3.91 | 2.15 | 116.8 |
| Ken | 4.00 | 3.58 | 2.304 | 273.4 |

**Table 8.14** The Nash parameters for the catchments of the Yamuna basin

| S. No. | Velocity (m/s) | Upper Yamuna *n* | Upper Yamuna *k* (h) | Chambal *n* | Chambal *k* (h) | Sind *n* | Sind *k* (h) | Betwa *n* | Betwa *k* (h) | Ken *n* | Ken *k* (h) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.25 | 3.1324 | 60.97 | 3.1084 | 274.90 | 3.1017 | 30.93 | 3.1737 | 66.84 | 3.1679 | 152.06 |
| 2 | 0.50 | | 30.48 | | 137.45 | | 15.46 | | 33.42 | | 76.03 |
| 3 | 0.75 | | 20.32 | | 91.63 | | 10.31 | | 22.28 | | 50.69 |
| 4 | 1.00 | | 15.24 | | 68.72 | | 7.73 | | 16.71 | | 38.02 |
| 5 | 1.50 | | 10.16 | | 45.82 | | 5.15 | | 11.14 | | 25.34 |
| 6 | 2.00 | | 7.62 | | 34.36 | | 3.87 | | 8.35 | | 19.01 |
| 7 | 2.50 | | 6.09 | | 27.49 | | 3.09 | | 6.68 | | 15.21 |
| 8 | 3.00 | | 5.08 | | 22.91 | | 2.58 | | 5.57 | | 12.67 |
| 9 | 4.00 | | 3.81 | | 17.18 | | 1.93 | | 4.18 | | 9.50 |
| 10 | 5.00 | | 3.05 | | 13.74 | | 1.55 | | 3.34 | | 7.60 |

establish relationships to avoid a detailed analysis. For this purpose, first the relationships between storage coefficients k and average flow velocities are developed (Fig. 8.20). Numerical expressions for the catchments are given through eqs. (8.16) through (8.20) in Table 8.15.

Coefficients ($k_{coeff}$) of the above relationships [eqs. (8.16) to (8.20)] have been further fitted for the length of the highest order stream of the catchment (Ω) using the second order polynomial (Fig. 8.21). The derived relationship can be mathematically expressed as:

$$K_{coeff} = 0.0003 \times \Omega^2 + 0.0323 \times \Omega + 6.4608 \quad (R^2 = 0.9966) \tag{8.22}$$

Using eq. (8.22), the value of $k_{coeff}$ can be estimated and substituted in eq. (8.21) to estimate the value of storage coefficient $k$ corresponding to the reliable value of velocity of flow. The value of $n$ and $k$ for the catchment are then used to derive the IUH and subsequently the UH using eqs. (8.8) and (8.9).

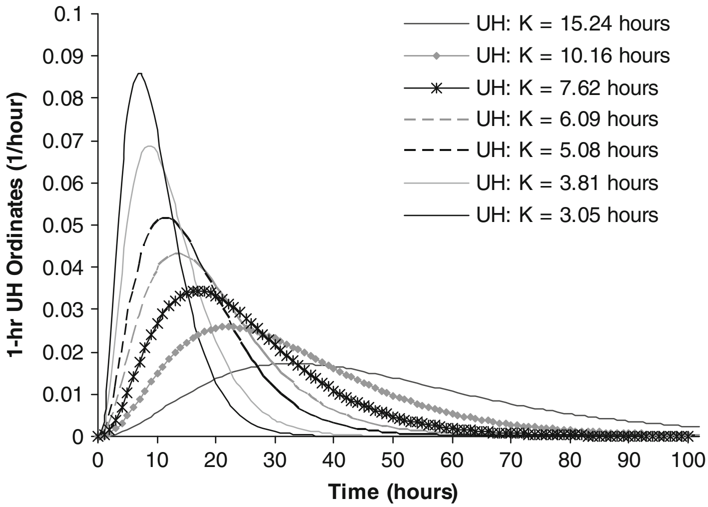


**Fig. 8.15** One-hour Unit hydrograph for the Upper Himalayan Yamuna catchment

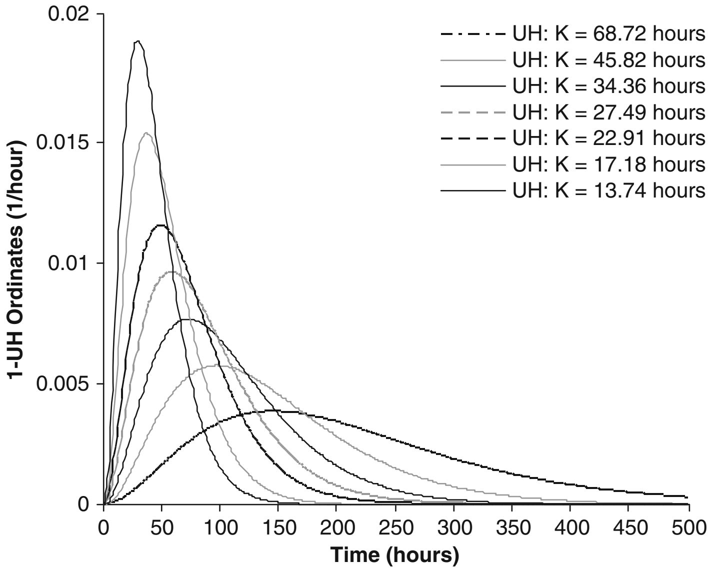


**Fig. 8.16** One-hour Unit hydrograph for the Chambal catchment

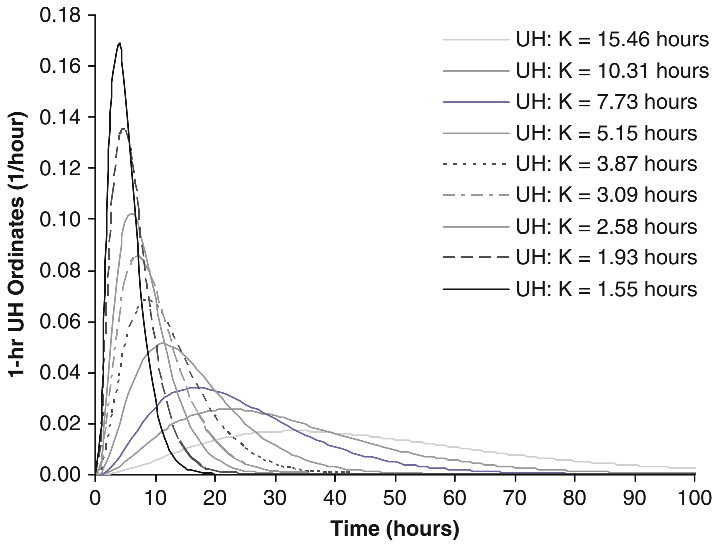


**Fig. 8.17** One-hour Unit hydrograph for the Sind catchment

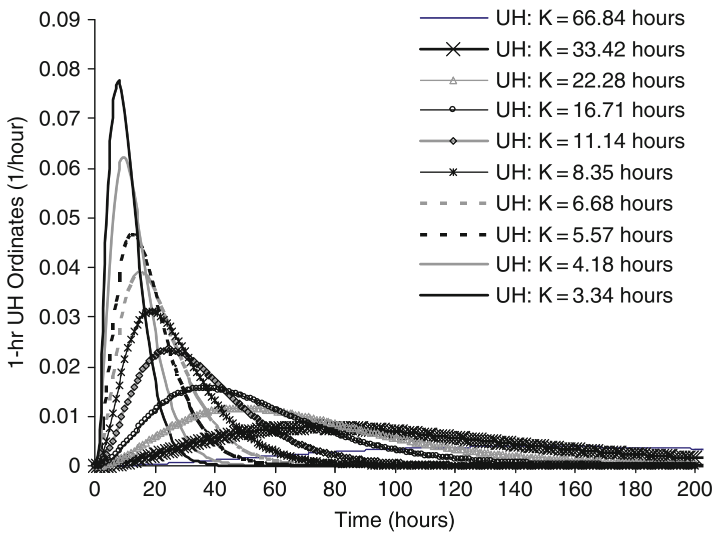


**Fig. 8.18** One-hour Unit hydrograph for the Betwa catchment

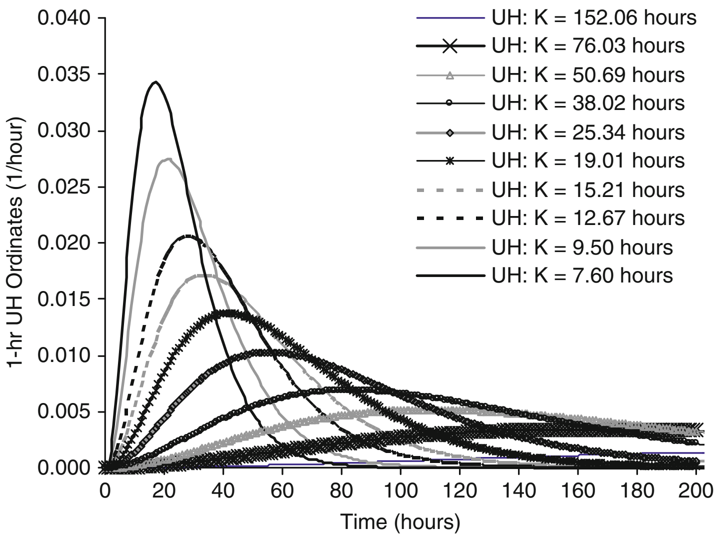


**Fig. 8.19** One-hour Unit hydrograph for the Ken catchment

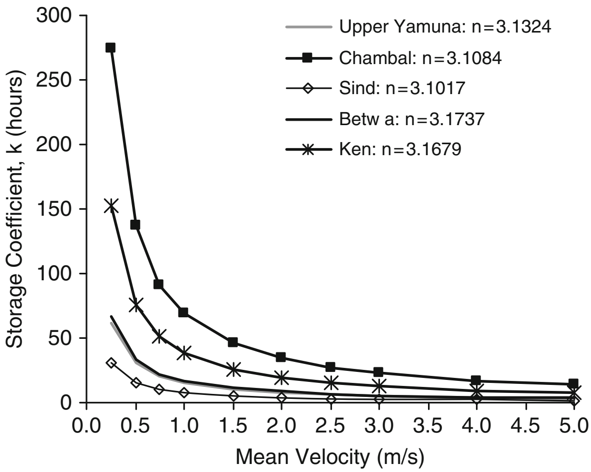


**Fig. 8.20** Relationship between the mean flow velocity and k

**Table 8.15** Relationship between flow velocity and k for different catchments

| Catchment | $n$ | Relation between $k$ and $\bar{u}$ | Eq. |
|---|---|---|---|
| Upper Himalayan Yamuna | 3.1324 | $k = 15.243/\bar{u}$ | (8.16) |
| Chambal | 3.1084 | $k = 68.726/\bar{u}$ | (8.17) |
| Sind | 3.1017 | $k = 7.7328/\bar{u}$ | (8.18) |
| Betwa | 3.1737 | $k = 16.711/\bar{u}$ | (8.19) |
| Ken | 3.1679 | $k = 38.016/\bar{u}$ | (8.20) |
| General equation | | $k = k_{\text{coeff}}/\bar{u}$ | (8.21) |

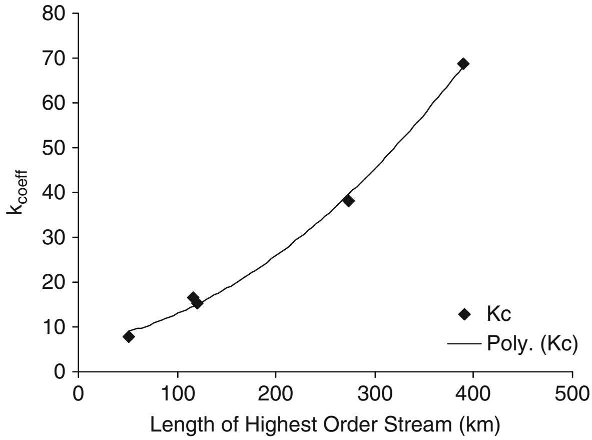


**Fig. 8.21** Relationship between $k_{\text{coeff}}$ and $\Omega$

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# Chapter 9
# Water Pollution

**Abstract** This chapter discusses the issues related to water quality in the Yamuna River basin, including the sources of pollution. The discussion includes different types of pollution sources, which are categorized into point- and non-point sources. The role of barrages on water quality and their impact on river segmentation are adequately addressed. Further, water quality monitoring sites on the river and monitoring agencies, followed by the importance of physico-chemical characteristics of the water on human and river health, are described.

## 9.1 Sources of Pollution

The entire stretch of Yamuna River from origin to confluence with Ganga River is highly used for various human activities. The accumulated results of these activities are the low flow availability in the river during the lean period and water pollution. During the course of travel, Yamuna River receives a lot of pollutants of various kinds.

Water pollution can be broadly categorized into three main classes based on the pollution sources: (i) domestic, (ii) industrial, and (iii) agricultural. Among these categories, the city sewage and industrial waste are important. These pollutants enter groundwater, rivers, and other water bodies and finally back to the households and carries disease-causing microbes. Agricultural runoff, or the water from the fields that drains into rivers, is another major water pollutant as it contains fertilizers and pesticides. Domestic sewage refers to the waste water that is discarded from households. Also referred to as sanitary sewage, the water contains a wide variety of dissolved and suspended impurities (CPCB, 1978; CPCB, 1981; CPCB, 1982–1983; CPCB, 1984–2008; CPCB, 1986; CPCB, 1994; CPCB, 2006; CPCB, 2009).

The use of land for agriculture and the practices followed in cultivation greatly affect the quality of groundwater. Intensive cultivation of crops causes chemicals from fertilizers (e.g. nitrate) and pesticides to seep into the groundwater, a process commonly known as leaching. Routine applications of fertilizers and pesticides for agriculture and indiscriminate disposal of industrial and domestic wastes are increasingly being recognized as significant sources of water pollution. These pollutants also affect surface water bodies when agricultural runoff is produced during monsoon. Generally, agricultural pollution is treated as non-point source pollution, as it is generated from diffuse sources. The high nitrate content in groundwater

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is mainly from irrigation runoff from agricultural fields where chemical fertilizers have been used indiscriminately.

Waste water from manufacturing or chemical processes in industries contributes to water pollution. Industrial waste water usually contains specific and readily identifiable chemical compounds. During the last fifty years, the number of industries has grown rapidly, but water pollution is concentrated within a few sub-sectors, mainly in the form of toxic wastes and organic pollutants. Out of this a large portion can be traced to the processing of industrial chemicals and to the food products industry. In fact, a number of large- and medium-sized industries in the region covered by the Ganga Action Plan do not have adequate effluent treatment facilities. Most of these defaulting industries are sugar mills, distilleries, leather processing industries, and thermal power stations. Most major industries have treatment facilities for industrial effluents, but this is not the case with small-scale industries, which cannot afford enormous investments in pollution control equipment as their profit margin is very slender.

## *9.1.1 Point Sources of Pollution*

When the source of pollution is single, well specified and generates a significant amount of pollutants, such a source is known as point source. Urban centers located along or near the banks of Yamuna River are the major pollution sources. The point sources of pollution cover two major categories: domestic and industrial pollution.

### 9.1.1.1 Domestic Pollution

The domestic pollution is the major source of pollution in Yamuna River. About 85% of the total pollution in the river is caused by domestic sources. The domestic pollution is mainly caused by urban centers. The major urban centres dumping domestic waste into Yamuna River are Panipat, Sonepat, Delhi, Ghaziabad, Mathura-Vrindavan, Agra, Etawah and Allahabad. The impact of domestic pollution on river depends on the efficiency of wastewater collection systems, and type and length of waste transportation systems. If wastewater gets more retention time within urban premises before reaching receiving water bodies, the pollution load will reduce due to biodegradation and settling. The organic matters and microorganisms are the main constituents of domestic waste. Further, total salts, chlorides, nutrients, detergents, oil and grease, etc. are also contributed by the domestic sources. There are numerous unauthorized colonies existing in various urban centres. Due to the non-availability of sewerage system in these colonies, the night soil is collected, transported and dumped either in drains, tributaries or directly into river without any treatment. During the last few years because of proliferation of Jhuggi Jhompri settlement this activity has increased significantly and has now become a major non-point source of river water pollution.

#### 9.1.1.2 Industrial Pollution

After independence, rapid industrialization occurred in the Yamuna River basin. There are large clusters of industries established in Kota, Gwalior, Indore, Nagda, Khetri, Yamuna Nagar, Panipat, Sonepat, Delhi, Baghpat, Ghaziabad, Gautam Budha Nagar, Faridabad, Mathura and other places. The categories of industries discharging wastewater into Yamuna River includes pulp and paper, sugar, distilleries, textiles, leather, chemical, pharmaceuticals, oil refineries, thermal power plants, food, etc. In order to comply with environment laws, it is compulsory for these industries to treat the effluent to achieve prescribed standards before discharging into the environment.

### *9.1.2 Non Point or Diffused Sources of Pollution*

Just opposite to the point sources the diffused sources are unspecified; numerous in numbers and contribution of each is of less significance, though, in combination the resulting contribution is significant. This pollution is original in the catchment area of the river and transported regularly or occasionally by leaching, drainage and surface water runoff during monsoon. The pollutants originated from diffused sources are topsoil, organic matter, plant residues, nutrients, organic chemicals, toxicants, microorganisms etc. The important diffused pollution sources contributing to Yamuna River are: (i) agricultural pollution sources; (ii) dumping of garbage and dead bodies; (iii) immersion of idols; (iv) pollution due to in-stream uses of water.

#### 9.1.2.1 Agricultural Pollution

There are four major sources that contribute agricultural pollution in the river: (i) agricultural residues; (ii) fertilizer and pesticides; (iii) animal husbandry; and (iv) excess salts from applied irrigation water.

The various types of agricultural residues generated in the river basin are degraded naturally as they are part of saprophytic food chain and thus not contributing much to the river pollution. In the Yamuna basin the application rate of fertilizer is still low, moreover, due to marginal irrigation in the basin there is little chance of leftover nutrients from fertilizer application to leach, drain or wash away except during monsoon. The nutrients and pesticides are generally adsorbed by the sediment particles and reach the river along with run off sediments particularly during early floods. These chemicals geo-accumulate in riverbeds, which are not stable due to the sandy nature of river bottom. Hence, with the flushing of riverbed by water current these chemicals mix slowly with the supernatant river water.

The solid waste generated from animal husbandry is generally collected dry and rarely washed. A major part of this solid waste is used as organic manure. In rural areas the animal husbandry solid waste particularly animal dung is formed into cakes and dried for burning as dung cakes. Because of this, there is no significant water pollution caused from animal husbandry. However, with the change in cooking style with more and more use of cooking gas, urbanization of rural areas, modernized cattle farming, illegal and unorganized dairy farming in urban centers, etc. increase the organic pollution from these sources.

Plants consume water only through transpiration and the salts present in the applied irrigation water accumulate in the soil and ultimately leach or are washed off to adjoining water bodies. As a result, the build-up of salinity is frequently observed in parts of Haryana.

In almost the entire stretch of Yamuna River that lies in the plain area, the riverbed is extensively used for farming during the lean period when the river stream shrinks to minimum. The riverbed farming, which mainly includes vegetables, melons, and cucumbers, starts after the monsoon season and continues till the end of summer season. During farming, there is frequent use of pesticide, washing of vegetables, disposal of farming residues, etc., which provides a direct impact on river water quality.

### *9.1.3 Dumping of Garbage and Dead Bodies*

A large portion of solid waste generated by unauthorized inhabitants all along the banks of Yamuna River or its tributaries finds its way into the river. The waste includes domestic waste, waste from dairies, unauthorized slaughtering, flowers and other material used during worships carcasses of animals, etc. The dumping of human and animal dead bodies are also sometimes observed in the Yamuna River. Disposal of infant dead bodies in the river water is practiced in the entire Yamuna stretch. Floating of human dead bodies partially eaten by animals and in rotten state are generally observed in the lower part of the river. Such disposal of dead bodies increases the risk of pathogenic contamination besides other negative impact.

### *9.1.4 Immersion of Idols*

Immersion of idols, especially during Durga Puja, and Ganesh Puja, takes place all along the banks of rivers. Flowers, Straw, Bamboo, Clay/Plaster of Paris, harmful chemicals used for paints, and plastic bags finds their way into the river. As the Durga Puja festival is also getting popularity in Northern India the rate of idols immersion is also increasing every year.

### *9.1.5 Pollution Due to In-Stream Use of Water*

The various sources of pollution caused by the stream use of water are: bathing and clothe washing; cattle wading; and open defecation. Because of spiritual faith, the bathing in Yamuna River is very common. Bathing, especially mass bathing, significantly contributes disease causing pathogens in the river water and enhance the bacterial load. The religious activities, e.g., offering flowers, milk, sweets, etc. into the river water further increase organic loading in the river, since the food items are not consumed by aquatic animals due to their limited availability. The other activities associated with bathing are cloth washing. This activity contributes inorganic, organic and biological contaminants in the river water besides detergents. Excessive presence of detergents causes significant foaming at the sites of turbulence. Foaming not only hampers the oxygen diffusion rate in the river water, essential for self-purification but also affects various biological activities.

The Yamuna basin is one of the densely populated river basins in the country. In the basin, due to the non-existence of sanitary facilities in rural areas and urban areas, especially in slum clusters, a large section of population uses either the catchment area or directly the river for open defecation. The activity contributes organic pollution and pathogens in the river water.

## 9.2 Water Quality Issues in Yamuna River

Most of the rivers, including Yamuna River, are spiritually regarded as mother. People from all over the country visit various stretches of this river especially at Yamunotri, Paonta Sahib, Mathura-Vrindavan and Bateshwar to take holy dip in river water to purge away their sins. Thus, the river portrays Indian culture and traditions. Deteriorating water quality and decreasing quantity of Yamuna River water hurt the sentiments of Indian masses besides having several adverse impacts on life processes in the river. The issues related with water quality of Yamuna River are described in what follows (CPCB, 1978; CPCB, 1981; CPCB, 1982–1983; CPCB, 1984–2008; CPCB, 1986; CPCB, 1994; CPCB, 2006; CPCB, 2009):

### *9.2.1 High Organic Contents*

Yamuna River receives significantly high amounts of organic matter, which generally originate from domestic sources. For biodegradation, this organic waste requires oxygen, causing a significant depletion of dissolved oxygen in the river water. The oxygen depletion not only affects biotic community of the river but also affects its self-purification capacity. This problem is critical in the river stretch between Delhi and its confluence with Chambal River. In the Delhi stretch, the load of organic matter is so high that it consumes the entire dissolved oxygen available in river water.

### *9.2.2 High Nutrients*

The organic matter after biodegradation releases nutrients in the water. High nutrient concentration leads to eutrophication, a condition characterized by significant diurnal variation in dissolved oxygen concentration and excessive algal growth.

### 9.2.3 Excessive Presence of Pathogens

Continuous flow of sewage waste, dumping of animal dead bodies, etc. and instream uses of water like bathing, cattle wading, etc. contribute significant load of pathogens in the river water, making it unsuitable for drinking and bathing purposes.

### 9.2.4 Accumulation of Pollutants in the Catchment Area

Organic, inorganic and toxic pollutants generated from agricultural and industrial sources are accumulated near the source during dry seasons and get mixed with river water, threatening aquatic life during monsoon or percolated to ground water and making water unfit for human consumption.

### 9.2.5 Aesthetic Value

Yamuna River loses its aesthetic value and glory due to severe odour that releases to the surrounding environment from the anaerobic activities occurring in the river strata and the ugly surface look contributed by blackish water, floating of garbage, plastic bags, dead bodies of animals. The religious activities and tourism are greatly affected because these adversely transform the characteristics of river water.

### 9.2.6 Deforestation in the Catchment Area

Forest cover in the catchment area of the Yamuna is vanishing rapidly. This leads to soil erosion with rainfall, and results in mixing of high amounts of silt, mud etc. in the river water, which in turn increases the turbidity. The turbidity of river water is also increased due to the direct influx of domestic and industrial wastewater. Increased turbidity has an impact on the productivity of water body besides affecting biotic life of aquatic system.

### 9.2.7 Reduction in the Quantity of Water

The fresh water of Yamuna River is over exploited for irrigation use, drinking and industrial uses resulting in very little or sometimes no water in the river at certain locations during summer season. The water scarce condition is so severe that to avoid percolation and evaporation losses, the Delhi's share of Yamuna water transported through WJC is added back into the river through Drain No. 2. All this leads to the stagnation of water and formation of dry zones in the drainage area of the river. The non-availability of fresh water hampers the purification capacity of the river and causes an increase in the concentration of pollutants in the river water.

### 9.2.8 Discharges from Sewage Treatment Plants

Sewage treatment plants (STP's) have been constructed at various urban centers to conserve the water quality of Yamuna River. The treated, untreated or partially treated sewage from these STPs are generally discharged directly or through carrier drain into the river. Prior to installation of STPs the sewage of urban centers was discharged and got mixed with river water at various locations in the wide stretch of river through long and slow transportation system. After installation of STPs along with swift collection and transport systems, the sewage from urban centers concentrated at a few places, where STP's are located. The connection of STP with the river sometimes poses great threat to water quality during non-operation of STP due to unavoidable reasons, e.g., power failure, mechanical problems or maintenance of plants. In such cases the collected sewage is generally bypassed and eventually discharged into the river at a few locations without any treatment. Such problem is very significant in those stretches of river where the STPs are located upstream of the river e.g. Mathura-Vrindavan and Agra. The discharges from these STP's located upstream from the water abstraction point have an impact on the water quality making it unsuitable for various human activities occurring downstream of these STP's.

### 9.2.9 Role of Barrages

Presently there are six barrages in the Yamuna River and some others are in planning stage. The barrages have an impact on the characteristics of Yamuna River:

- Discontinue the river flow.
- Less demand for irrigation water or rainfall in the catchment area leads to intermittent release of water from the barrages and thus affects the river water quality.
- Sludge containing inorganic, organic, and toxic matters are generally deposited upstream of barrages. This settled material flushes downstream along with a sudden release of water from the barrages. Thus, pollutants mix further with the river water at downstream, deteriorating its quality.
- The water is generally released from the barrages during monsoon after a gap of 6–9 months. The water releases from the barrage after a considerable gap, significant amounts of deposited sludge in the reaches downstream, which is dominantly organic in nature also flushes with it and flow in the river downstream. This sludge, after mixing with the water downstream, consumes the available dissolved oxygen rapidly resulting into fish mortality and killing of other fauna of the river.
- Besides the negative impact of barrages on river characteristics, barrages also have one positive impact. Barrage forms a sort of reservoir upstream. This reservoir acts as oxidation pond to treat the river water.

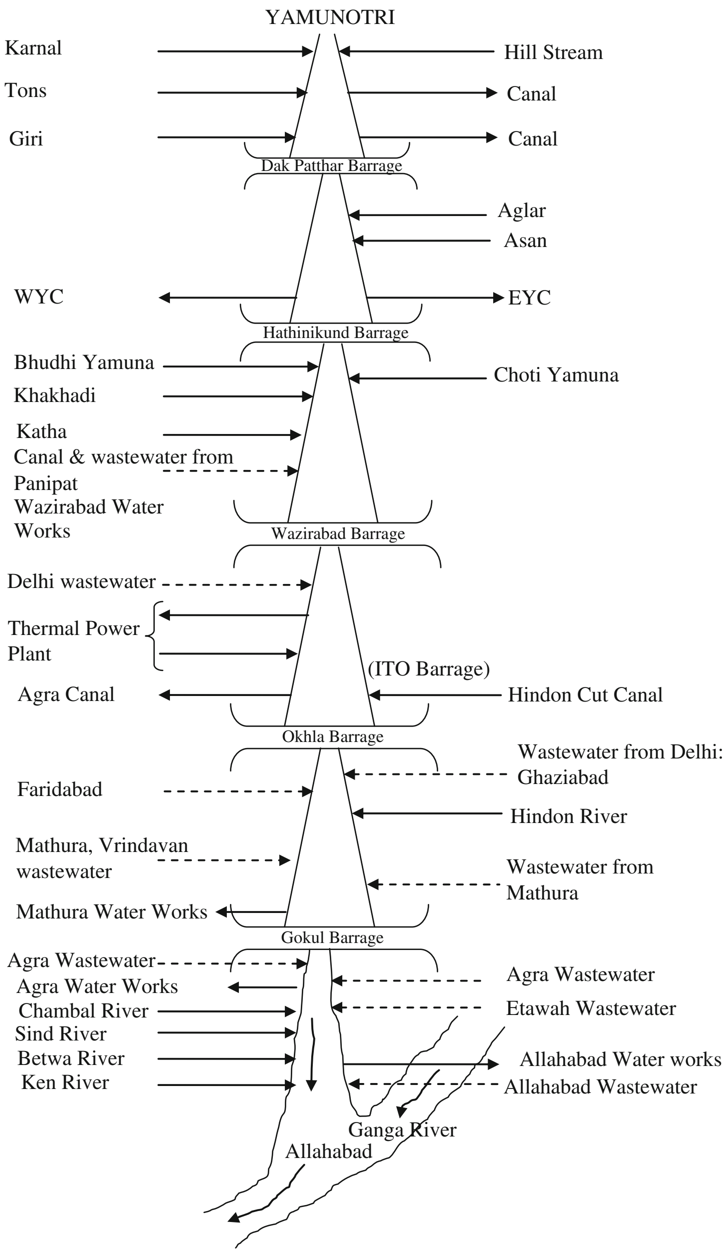


**Fig. 9.1** Segmentation of the Yamuna River system

The water pollution in the river varies with the reaches. Due to the water quality status in the river and changes in flow regime due to human intervention, during the lean period, the Yamuna River is divided into four independent segments (Fig. 9.1). The characteristics of these segments are now discussed.

## 9.3 River Segmentation

The four independent segments are as follows (CPCB, 1994):

Segment I: This segment (length 172 km) is identified from Yamunotri and terminates at Hathnikund/Tajewala barrage. The major source of water in this segment is the melting of glaciers. The water flow in this segment terminates into Western Yamuna canal (WJC) and Eastern Yamuna Canal (EJC) for irrigation and drinking water purposes in command areas.

Segment II: This segment (about 224 km) lies between Hathnikund barrage and Wazirabad barrage. The main source of water in this segment is ground water accrual. A few small tributaries also contribute water in this segment. The water is diverted in this segment from WJC through drain No. 2 to fulfil the raw water demand for drinking water supply to Delhi. The water segment is terminated into Wazirabad reservoir formed due to stagnation of water at Wazirabad barrage. The reservoir water is pumped to the various water works as raw water for treatment to meet the drinking water demand of the capital city. No or very little water is allowed to flow downstream of the Wazirabad barrage during lean seasons.

Segment III: This 22 km segment of Yamuna River is located between the Wazirabad barrage and Okhla barrage. This segment receives water from seventeen sewage drains of Delhi and also from WJC and Upper Ganga Canal via Najafgarh drain and Hindon cut canal, respectively.

Little contribution of water is also made in this segment by Surghat, where the Ganga and Yamuna water are provided for bathing purposes. This river segment terminates into Agra Canal, which is used to augment its flow for irrigation in the states of Haryana and Uttar Pradesh.

Segment IV: This Segment of Yamuna River is about 958 km long initiate immediately downstream of the Okhla barrage and extends up to the confluence with Ganga River at Allahabad. The source of water in this segment are ground water accrual, its tributaries like Hindon, Chambal, Sind, Ken, Betwa, etc. and waste water carrying drains of Delhi, Mathura-Vrindavan, Agra and Etawah. The water of this segment is used for drinking and industrial uses in Mathura and Agra.

In Mathura, recently the Gokul barrage has been constructed to trap the Yamuna River water for drinking purposes. Due to low drinking water demand, only part of water is pumped out and the rest flows downstream. As the water demand will increase in future. It is likely that no water will be allowed to flow downstream like the Wazirabad and Okhla barrages. This may create further segmentation of segment IV into two segments of 154 and 804 km. With the construction of another barrage near Sikandara in Agra the river would be further segmented.

## 9.4 Water Quality Monitoring

Water quality is one of the fundamental constraints important for drinking, bathing and irrigation and is regularly monitored by the Central and State Government Agencies for major river systems and tributaries of major rivers, respectively. The importance of the water quality parameters and their standards has been summarized in the next sections. The responsible departments are: Central Pollution Control Board (CPCB), State Pollution Control Boards, Central Water Commission, etc having different objectives. For example, CPCB is responsible for disseminating information in respect of matters relating to water and air pollution and their prevention and control, whereas CWC collect, maintain and publish the data relating to water resources and its utilization, including the quality of water throughout India and to act as the Central Bureau of Information relating to water resources. However, the ground water quality is being monitored by the combined efforts of Central Ground Water Board (CGWB), State Ground Water Departments (SGWDs), etc. The major responsible water quality agencies are summarized in Table 9.1.

Data collection primarily falls under the Ministry of Environment and Forests in the Central Pollution Control Board and the various State Pollution Control Boards, though the Central Ground Water Board collects some groundwater data as well. The data collection program is under the National Water Quality Monitoring program and within that the sites are divided into three subsets: Global Environmental Monitoring Program, Monitoring of Indian National Aquatic Resources, and the various river action plans. The majority of data is stored on the Environmental Data Bank maintained by the CPCB. The Global Environmental Monitoring System (GEMS), WISDOM, and (Environmental Information System) ENVIS databases also provide some water quality data. Water quality data is collected primarily, and in many places solely by governmental organizations, through central and state pollution control boards, under the umbrella of the Ministry of Environment & Forests and various departments belonging to the Ministry of Water Resources. The water quality monitoring locations of CPCB and CWC for the Yamuna River System from its origin to the confluence with Ganga River are depicted in Fig. 8.1.

The important and frequent water quality monitoring parameters are: temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate ($NO_3^-$), nitrite ($NO_2^-$), total coliform (TC), feacal coliform (FC), etc.

Other measured physio-chemical parameters include Calcium, Magnesium, Sodium, Potassium, Chloride, Sulphate, Boron, Fluoride, Sodium Percent, Total Alkalinity, Hardness, Phosphate, Turbidity, Total Kjeldahl-N, Total Dissolved Solids, and Total Solids. Other biological parameters include S.A.R, Saprobity Index and Diversity Index etc. he type of monitoring station along with the frequency and parameters are given in Table 9.2.

**Table 9.1** Water quality monitoring agencies

| Data base | Objectives | Type of data | Supporting sources | Frequency of monitoring | SW/GW/ Both | Purpose |
|---|---|---|---|---|---|---|
| CPCB | Prevention and control of pollution | Water quality | SPCBs | Monthly, quarterly, yearly | Both | Baseline, trend and flux stations |
| EDB | To facilitate quick and easy retrieval of data base | Air, Water, urban pollution, industrial pollution, hazardous waste | CPCB, SPCBs, etc. | Derived data (annual min., max., mean) | Both | Baseline indicator for environment |
| ENVIS | Disseminating information speedily to the user, to gear up the modern technologies of acquisition, processing, storage, retrieval, and dissemination of information of environmental nature. | Air, Water, Noise | CPCB | Regular updating of website (Derived data) | Both | Baseline information |
| GEMS (UNEP) | State and trends of regional and global water quality; global water quality assessment, prevention and control and strategic planning | Water quality and hydro-meteorological data | UNEP monitoring stations (peninsular states); CPCB | Annual, monthly and diurnal | Both | Baseline, trend and flux stations |
| WISDOM | Collection, storage, analysis, publication | Water quality and hydro-meteorological data | CWC, CGWB | Derived data | Both | Baseline data |
| GEMS and GWIS | Data storage in HIS system | GW quality | CGWB | Primary and derived data | Geospatial GW data | Baseline and Trend |

**Table 9.2** Type of station, frequency of observations and parameters used in water quality monitoring

| Type of station | Frequency | Parameter |
|---|---|---|
| Baseline | Perennial rivers and Lakes:<br>Four times a year<br>Seasonal rivers:<br>3–4 times (at equal spacing) during flow period.<br>Lake:<br>4 times a year | (A) Pre-monsoon: Once a year<br>Analyse 25 parameters as listed below:<br>(a) General: Colour, odour, temp, pH, EC, DO, turbidity, TDS<br>(b) Nutrients: $NH_3$-N, $NO_2 + NO_3$, Total P<br>(c) Organic Matter: BOD, COD<br>(d) Major ions: K, Na, Ca, Mg, $CO_3$, $HCO_3$, Cl, $SO_4$,<br>(e) Other inorganic: F, B and other location- specific parameter, if any<br>(f) Microbiological: Total and Faecal Coliforms<br>(B) Rest of the year (after the pre-monsoon sampling) at every three months' interval: Analyse 10 parameters: Colour, Odour, Temp., pH, EC, DO, $NO_2 + NO_3$, BOD, Total and Faecal Coliforms. |
| Trend | Once every month starting April-May (pre-monsoon), i.e. 12 times a year | (A) Pre-monsoon: Analyse 25 parameters as listed for baseline monitoring<br>(B) Other months: Analyse 15 parameters as listed below<br>(a) General: Colour, Odour, Temp, pH, EC, DO and Turbidity<br>(b) Nutrients: $NH_3$-N, $NO_2 + NO_3$, Total P<br>(c) Organic Matter: BOD, COD<br>(d) Major ions: Cl<br>(e) Microbiological: Total and Faecal coliforms<br>(C) Micropollutant: Once in a year in monsoon season<br>(i) Pesticides-Alpha BHC, Beta BHC, Gama BHC (Lindane), OP-DDT, PP-DDT, Alpha Endosulphan, Beta Endosulphan, Aldrin, Dieldrin, 2,4-D, Carboryl (Carbamate), Malathian, Methyl Parathian, Anilophos, Chloropyriphos<br>(ii) Toxic Metals-As,Cd,Hg,Zn,Cr,Pb,Ni,Fe (Pesticides and Toxic metals may be analysed once a year) |

## 9.5 Physico-Chemical Characteristics of Water Quality Parameters

A basic understanding of the parameters described above is important not only for creating the awareness of water use, but also in protecting the environment. A description of each parameter is given in Table 9.3.

**Table 9.3** Importance of water quality parameters

| S. No. | Parameter | Feature |
|---|---|---|
| 1 | Temperature | The temperature of water body varies with seasons. Temperature of the water body has an impact on the biota and its habitat. Fish and most aquatic organisms are cold-blooded. Consequently, their metabolism increases as the water warms and decreases as it cools. Each species of aquatic organism has its own optimum water temperature. If the water temperature shifts too far from the optimum, the organism suffers. |
| 2 | pH | Potentia hydrogeni is negative logarithm of H+ions. It is measured in scale of 0–14. As the pH goes on increasing from 1 to 6.9, the hydrogen ion concentration goes on decreasing and the solution is acidic. pH 7 represents the neutral condition and beyond 7 is alkaline. Most fish can tolerate pH values of about 5.5–9.0, but serious anglers look for waters between pH 6.5 and 8.2. |
| 3 | Electrical Conductance | EC is the ability of an aqueous solution to conduct the electric current. In water it is the property caused by the presence of various ionic species. Conductivity therefore measures the concentration of substance in solution and does not indicate the nature of these substances. The rock composition determines the chemistry of the watershed soil and ultimately the water body. For example, limestone leads to higher EC because of the dissolution of carbonate minerals in the basin. |
| 4 | Turbidity | When light is passed through a sample having suspended turbidity, some of the light is scattered by the particles. The scattering of light is generally proportional to turbidity. Pollution tends to reduce water clarity. Watershed development and poor land use practices cause increase in erosion, organic matter, and nutrients, all of which cause increases in suspended particulates and algae growth. High concentrations of particulate matter can modify light penetration, cause shallow lakes and bays to fill in faster, and repress benthic habitats impacting both organisms and eggs.<br><br>Fine particulate material can clog or damage sensitive gill structures, prevent proper egg and larval development, and potentially interfere with particle feeding activities. Very high levels of turbidity for a short period of time may not be significant and may even be less of a problem than a lower level that persists longer. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 5 | Total Dissolved Solids | Total dissolved solids (TDS) denote mainly dissolved solids such as minerals present in the water. TDS comprises inorganic salts and small amounts of organic matter that are dissolved in water. The principal constituents are usually the cations calcium, magnesium, sodium and potassium and the anions carbonate, bicarbonate, chloride, sulphate and, particularly in groundwater, nitrate from agricultural use.<br><br>The presence of dissolved solids in water may affect its taste. Water with extremely low TDS concentrations may also be unacceptable because of insipid taste. In addition to palatability, certain components of TDS, such as chlorides, sulphates, magnesium, calcium and carbonates also affect corrosion or encrustation in water distribution systems. |
| 6 | Total suspended solids | Total suspended solids (TSS) denote the suspended impurities present in the water. In most of the cases they are of organic nature and pose severe problems of water pollution. Also, TSS is a parameter that directly relates to land uses in the watershed and is a key parameter used for modelling efforts and for assessing the success of mitigation and restoration efforts.<br><br>High TSS can block light from reaching submerged vegetation. As the amount of light passing through the water is reduced, photosynthesis slows down. Reduced rates of photosynthesis causes less dissolved oxygen to be released into the water by plants. If light is completely blocked from bottom dwelling plants, the plants will stop producing oxygen and will die. As the plants are decomposed, bacteria will use up even more oxygen from the water. Low dissolved oxygen can lead to fish kills.<br><br>High TSS can also cause an increase in surface water temperature, because the suspended particles absorb heat from sunlight. This can cause dissolved oxygen levels to fall even further because warmer waters can hold less dissolved oxygen, and can harm aquatic life in many other ways. |
| 7 | Hardness | Hardness is generally imparted by the calcium and magnesium ions present in water. Polyvalent ions of some other metals like strontium, iron, aluminium, zinc and manganese etc. are also capable of precipitating the soap; concentration of these ions is very low in natural waters.<br><br>Therefore, hardness is generally measured as concentration of calcium and magnesium which are far higher in quantities over other hardness producing ions. Hardness can be a nuisance due to the mineral buildup on plumbing fixtures and poor soap and detergent performance. It often causes aesthetic problems, such as an alkali taste to the water that makes coffee taste bitter; build-up of scale on pipes and fixtures than can lead to lower water pressure; build-up of deposits on dishes, utensils and laundry basins; difficulty in getting soap and detergent to foam; and lowered efficiency of electric water heaters. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 8 | Alkalinity | It is the measure of a solution's capacity to react with a strong acid (usually sulfuric acid $H_2SO_4$) to a predetermined pH. The alkalinity of a solution is usually made up of carbonate, bicarbonate, and hydroxides. Alkalinity is exhibited in solution by alkalies such as sodium hydroxide and by alkaline salts such as sodium carbonate. Soap and soap-based products are alkaline, since soap is a moderately alkaline salt and performs well only in an alkaline medium.<br><br>For protection of aquatic life the buffering capacity should be at least 20 mg/l. Alkalinity is important for fish and aquatic life because it protects rapid pH changes. |
| 9 | Dissolved Oxygen (DO) | The presence of dissolved oxygen (DO) is essential to maintain the higher forms of biological life and to keep proper balance of various populations thus making the water bodies healthy. The chemical and biochemical processes undergoing in a water body are largely dependent upon the presence of oxygen. The main sources of dissolved oxygen are from the atmosphere and the photosynthetic processes of the green plants. Estimation of dissolved oxygen is a key test in water pollution and waste treatment process control. The solubility of oxygen in water depends upon the partial pressure of oxygen in air, temperature of water and mineral content of water.<br><br>Oxygen is produced during photosynthesis and consumed during respiration and decomposition. Because it requires light, photosynthesis occurs only during daylight hours. Respiration and decomposition, on the other hand, occur 24 h a day. This difference alone can account for large daily variations in DO concentrations.<br><br>Other sources of oxygen include the air and inflowing streams. Oxygen concentrations are much higher in air, which is about 21% oxygen, than in water, which is a tiny fraction of 1% oxygen. Where the air and water meet, this tremendous difference in concentration causes oxygen molecules in the air to dissolve into the water. More oxygen dissolves into water when wind stirs the water; as the waves create more surface area, more diffusion can occur.<br><br>Another physical process that affects DO concentrations is the relationship between water temperature and gas saturation. Cold water can hold more oxygen, than warmer water. Warmer water becomes "saturated" more easily with oxygen. As water becomes warmer it can hold DO. So, during the summer months in the warmer top portion of a water body, the total amount of oxygen present may be limited by temperature. If the water becomes too warm, even if 100% saturated, $O_2$ levels may be suboptimal for many species. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 10 | Biochemical Oxygen Demand (BOD) | Biochemical oxygen demand (BOD) is the oxygen required by the microorganisms in depleting the organic matter. Microorganisms' breakdown the carbohydrate and use the energy thus released, but the aquatic system is depleted in oxygen in the process.<br>An estimate of the oxygen consumed in the unit volume of water over a period of time is called BOD.<br><br>The BOD values are very useful in process design, treatment plant efficiency, and stream pollution control management and in evaluating the self purification capacities. BOD5 determination is the measurement of dissolved oxygen content of the sample before and after 5 day incubation. |
| 11 | Chemical Oxygen Demand (COD) | Chemical oxygen demand (COD) is a measure of oxygen consumed during the oxidation of the oxidizable organic matter by a strong oxidizing agent. The determination of COD value is of great importance where BOD values cannot be determined accurately due to the presence of toxins and other unfavourable conditions for growth of microorganisms. The COD gives no indication of whether or not the waste is degradable biologically and nor does it indicates the rate at which biological oxygen would proceed and hence the rate at which the oxygen would be required in a biological system.<br><br>Despite all the limitations, the COD test continues to remain a very important parameter in management and design of treatment plants because of its rapidity in determination. |
| 12 | Total organic carbon (TOC) | Total organic carbon (TOC) provides a speedy and convenient way of determining the degree of organic contamination. Domestic and industrial wastewaters mainly contribute organic contaminants in fresh water bodies. A high organic content means an increase in the growth of micro-organisms which contribute to the depletion of oxygen supplies. |
| 13 | Ammonia | Ammonium of mineral origin is rare in natural waters. The most important source of ammonia is the ammonification of organic matter. Sewage has large quantities of nitrogenous matter, thus its disposal tends to increase the ammonia content of the water. Occurrence of ammonia in water can be accepted as the chemical evidence or organic pollution. If only ammonia is present, pollution by sewage must be very recent. Occurrence of nitrite with ammonia indicates a long time has been passed after nitrogenous matter has been oxidized. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 14 | Nitrate | Most surface water is deficient in nitrate. The most important source of nitrate is biological oxidation of organic nitrogenous substances which come in sewage and industrial wastes. Domestic waste water contains very high amount of nitrogenous compounds. Runoff from agricultural fields is also high in nitrate, which is the highest oxidized form of nitrogen. Atmospheric nitrogen fixed into nitrates by the nitrogen fixing organisms is also a significant contributor to nitrates in the waters.<br><br>It is essential nutrient for photosynthetic autotrophs and in some cases has been identified as the growth limiting nutrient. Nitrates cause reactions with haemoglobin in blood, causing the oxygen carrying capacity of the blood to decrease. |
| 15 | Phosphate | Phosphorus is the eleventh most abundant element on the surface of the earth and is most commonly found as phosphate. It plays an important role in biochemical processes and is a key factor in the eutrophication of surface water. Increased phosphate concentrations are linked with increasing rates of plant growth.<br><br>Phosphorus is necessary for plant and animal growth. Nearly all fertilizers contain phosphates (chemical compounds containing the element, phosphorous). When it rains, varying amounts of phosphates wash from farm soils into nearby waterways. Phosphates stimulate the growth of plankton and water plants that provide food for fish. This may increase the fish population and improve the waterway's quality of life. If too much phosphate is present, algae and water weeds grow wildly, choke the waterway, and use up large amounts of oxygen. |
| 16 | Chloride | Chloride as free ions is one of the major inorganic anions in water and wastewater. The salty taste produced in potable water is due to the presence of chloride ions. High amount of chloride increases corrosive nature.<br><br>Chlorine has been used as an effective disinfectant in drinking water supplies for nearly 100 years. Chlorine is considered necessary to destroy many of the bacteria in your drinking water. Health officials are concerned with the chlorinating by-products, also known as "chlorinated hydrocarbons" or trihalomethanes. Most trihalomethanes are formed in drinking water when chlorine reacts with naturally occurring substances such as decomposing plant and animal materials. Risks for certain types of cancer are now being correlated to the consumption of chlorinated drinking water. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 17 | Sulphate | Sulphate occurs in water naturally as result of leaching from gypsum and other common minerals. In addition sulphate may be added to water system, such as in municipal water supply sulphate content increases during clarification of alum. Sulphate content also increases corrosive nature.<br>The damaging effects of sulfur with animals are mostly brain damage, through malfunctioning of the hypothalamus, and damage to the nervous system. Laboratory tests with test animals have indicated that sulfur can cause serious vascular damage in veins of the brains, the heart and the kidneys. These tests have also indicated that certain forms of sulfur can cause foetal damage and congenital effects. Mothers can even carry sulfur poisoning over to their children through mother milk. It can damage the internal enzyme systems of animals. |
| 18 | Calcium | Calcium is one of the most abundant substances in natural water. It is present in higher quantities in the rocks, from where it is leached to contaminate water. Sewage and industrial wastes are also important source of calcium. Concentration of calcium is reduced at higher pH due to its precipitation as $CaCO_3$. It is one of the important nutrients required by the organisms.<br>High concentration of calcium in water suppresses the formation of lather with soap. It coagulates with soap and makes dirty layers on sinks and tubes etc.<br>Calcium may have beneficial effects when ingested. It may block the absorption of heavy metals in the body and is thought to increase bone mass and prevent certain types of cancer. Very high concentrations of calcium may adversely affect the absorption of other essential minerals in the body. |
| 19 | Magnesium | Magnesium is common constituent of natural water and occurs with calcium. Its concentration is lower than calcium. Magnesium salts breakdown when heated, forming scale in boilers.<br>Magnesium may contribute undesirable tastes to drinking water.<br>Sensitive people may find the taste unpleasant at 100 mg/l. The average person finds the taste unpleasant at about 500 mg/l. These levels are well above the magnesium concentrations found in most water. Magnesium in drinking water may have a laxative effect, particularly with magnesium sulphate concentrations above 700 mg/l. However, the human body tends to adapt to this laxative effect with time. |
| 20 | Carbonate and bicarbonate | These are responsible for hardness and also an important parameter for drinking and irrigation water. Bicarbonate and carbonate ions combined with calcium and magnesium precipitate as calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) respectively when the soil solution concentrates in drying conditions. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 21 | Fluoride | Fluoride contamination in water has geogenic as well as anthropogenic origin. It is consideredas the main contaminant for drinking water as it causes deformity in bones.<br><br>Fluoride is commonly added to the water supply in developing countries because at certain concentrations it can have dental hygiene benefits. However, naturally-occurring Fluoride in the groundwater is sometimes present at very high concentrations and this can cause dental and skeletal problems. |
| 22 | Oil and Grease | The determination of oil and grease includes all the substances that are extractable by the specified solvent. Generally, the substances extractable are oils, fats and waxes. The result obtained indicates only the non volatile fraction of these materials. Oil and grease has the natural tendency to float on the water surface under quiescent conditions, as the density of oil and grease is usually less than one. Not all the oil and grease is in liquid or solid form. Appreciable amounts remain in a finely divided emulsified form.<br><br>The high oil and grease concentration observed in effluent receiving water bodies is responsible for the depletion of fish and other aquatic life. The petroleum films flow on the surface of the water cutting out sunlight for aquatic photosynthesis and reducing oxygen concentration for aquatic life in the water, thereby negatively affecting these aquatic life forms. Some marine animals and reptiles such as turtles are predominantly vulnerable to adverse effects from oil contamination because of their need to breath from the water surface. Petrochemicals such as benzene can cause cancer even at low exposure levels. |
| 23 | Total coli and faecal coli | Total coliforms include bacteria that are found in the soil, in water that has been influenced by surface water, and in human or animal waste. These are indicator parameters for detecting microbiological quality of water. Fecal coliforms are the group of the total coliforms that are considered to be present specifically in the gut and feces of warm-blooded animals. The coliform group comprises all aerobic and facultative anaerobic gram negative, non sporulating, rod shaped bacteria that ferment lactose with gas formation within 48 h at 35°C. Coliform includes bacteria of most common intestinal organism Klebsiella pneumonia and of organism rare association in intestine Enterobactor aerogenes. Other common organisms included in this class are Salmonella shigella, Streptococci, Aeromonas etc. Coliform densities can be determined by multiple tube fermentation technique. This technique provides the most probable number (MPN). |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 24 | Chlorophyll | Surface waters that have high chlorophyll conditions are typically high in nutrients, generally phosphorus and nitrogen. These nutrients cause the algae to grow or bloom. High levels of nitrogen and phosphorus can be indicators of pollution from man-made sources, such as septic system leakage, poorly functioning wastewater treatment plants, or fertilizer runoff. Thus, chlorophyll measurement can be utilized as an indirect indicator of nutrient levels. Chlorophyll a is most common and predominant in all oxygen-evolving photosynthetic organisms such as higher plants, red and green algae.<br><br>Chlorophyll b differs from chlorophyll a only in one of the functional groups bonded to the porphyrin (a -CHO group in place of a -$CH_3$ group). Chlorophyll b is an accessory pigment and acts indirectly in photosynthesis by transferring the light it absorbs to chlorophyll a. Chlorophyll c occurs only in algae, specifically the diatoms, dinoflagellates and brown algae. Its role is to pass on the light excitation to chlorophyll a. |
| 25 | Primary Productivity | Primary production in water body can be determined by light and dark bottle oxygen method. By increasing the production of phytoplankton, fertilization may increase fish production considerably, though much remains to be learned about the optimum amount and frequency of fertilization. Primary production determinations can be used to evaluate the effect of different fertilizer treatments on organic production.<br><br>Net primary productivity (NPP) is the rate at which all the plants in an ecosystem produce net useful chemical energy; it is equal to the difference between the rate at which the plants in an ecosystem produce useful chemical energy and the rate at which they use some of that energy during respiration. The total energy fixed by plants in a community through photosynthesis is referred to as gross primary productivity (GPP). |
| 26 | Heavy metals: in general | Heavy metals are natural components of the earth's crust. To a small extent they enter our bodies via food, drinking water and air. As trace elements, some heavy metals (e.g. copper, selenium, zinc) are essential to maintain the metabolism of the human body. However, at higher concentrations they can lead to poisoning. Heavy metal poisoning could result, for instance, from drinking-water contamination (e.g. lead pipes), high ambient air concentrations near emission sources.<br><br>Heavy metals are dangerous because they tend to bioaccumulate. Bioaccumulation means an increase in the concentration of a chemical in a biological organism over time, compared to the chemical's concentration in the environment.<br><br>Heavy metals can enter a water supply by industrial and consumer waste, or even from acidic rain breaking down soils and releasing heavy metals into streams, lakes, rivers, and groundwater. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 27 | Zinc | Zinc is a very common substance that occurs naturally. Many foodstuffs contain certain concentrations of zinc. Drinking water also contains certain amounts of zinc, which may be higher when it is stored in metal tanks. Industrial sources or toxic waste sites may cause the zinc amounts in drinking water to reach levels that can cause health problems. Most zinc is added during industrial activities, such as mining, coal and waste combustion and steel processing. Some soils are heavily contaminated with zinc, and these are to be found in areas where zinc has to be mined or refined, or were sewage sludge from industrial areas has been used as fertilizer. |
| | | Zinc is the 23rd most abundant element in the Earth's crust. Water is polluted with zinc, due to the presence of large quantities of zinc in the wastewater of industrial plants. Some fish can accumulate zinc in their bodies, when they live in zinc-contaminated waterways. When zinc enters the bodies of these fish it is able to bio magnify up the food chain. |
| 28 | Manganese | Manganese compounds may be present in the atmosphere as suspended particulates resulting from industrial emissions, soil erosion, volcanic emissions and the burning of Methylcyclopentadienyl manganese tricarbonyl (MMT) containing petrol. In surface waters, manganese occurs in both dissolved and suspended forms, depending on such factors as pH, anions present and oxidation–reduction potential. It can bioaccumulate in lower organisms (e.g., phytoplankton, algae, molluscs and some fish) but not in higher organisms; biomagnifications in food chains is not expected to be very significant. |
| 29 | Iron | Iron in an essential element in both plant and animal metabolism. Iron can cause the water to look cloudy, taste poor, and can stain laundry or discolour rice. The drinking water quality standard for Iron is 0.3 mg/l based on aesthetic effects, but this is often exceeded in ground waters. Contamination sources are mainly mining, auto body rust, engine parts etc. |
| 30 | Lead | Major sources of lead contamination are waste from industrial, vehicular emissions, paints and burning of plastics, papers, etc. Lead has impact on blood lead levels below 10 $\mu$g/dl of blood. Its chronic exposure effects impairment of neurological development, suppression of the hematological system and kidney failure. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 31 | Mercury | Mercury is a compound that can be found naturally in the environment. It can be found in metal form, as mercury salts or as organic mercury compounds.<br><br>Mining, electronics and plastic waste, pesticides, pharmaceutical and dental waste are major source of mercury pollution. It causes gastro-intestinal disorders, respiratory tract irritation, renal failure and neurotoxicity.<br><br>Mercury also causes damage to the brain and the central nervous system. Mercury enters the environment as a result of normal breakdown of minerals in rocks and soil through exposure to wind and water. Most of the mercury released from human activities is released into air, through fossil fuel combustion, mining, smelting and solid waste combustion. Some forms of human activity release mercury directly into soil or water, for instance the application of agricultural fertilizers and industrial wastewater disposal. All mercury that is released in the environment will eventually end up in soils or surface waters. |
| 32 | Nickel | Nickel contamination is mainly due to diesel fuel and gasoline, lubricating oil, brake emissions. High nickel concentrations on sandy soils can clearly damage plants and high nickel concentrations in surface waters can diminish the growth rates of algae. Microrganisms can also suffer from growth decline due to the presence of nickel, but they usually develop resistance to nickel after a while.<br><br>For animals nickel is an essential foodstuff in small amounts. But nickel is not only favourable as an essential element; it can also be dangerous when the maximum tolerable amounts are exceeded. This can cause various kinds of cancer on different sites within the bodies of animals, mainly of those that live near refineries. |
| 33 | Cadmium | Sources of cadmium contamination are mainly electronics, plastics, batteries and contaminated water.<br><br>Cadmium causes irritation of the lungs and gastrointestinal tract, kidney damage, abnormalities of the skeletal system and cancer of the lungs and prostate. Cadmium in humans, long-term exposure is associated with renal disfunction. High exposure can lead to obstructive lung disease and has been linked to lung cancer, and damage to human's respiratory systems. |
| 34 | Chromium | Chromium is used in metal alloys and pigments for paints, cement, paper, rubber, and other materials. Low-level exposure can irritate the skin and cause ulceration. Long-term exposure can cause kidney and liver damage, and damage to circulatory and nerve tissue. Chromium often accumulates in aquatic life, adding to the danger of eating fish that may have been exposed to high levels of chromium. |

**Table 9.3** (continued)

| S. No. | Parameter | Feature |
|---|---|---|
| 35 | Copper | Copper is an essential substance to human life, but in high doses it can cause anaemia, liver and kidney damage, and stomach and intestinal irritation. |
| | | In surface water copper can travel great distances, either suspended on sludge particles or as free ions. Copper does not break down in the environment and because of that it can accumulate in plants and animals when it is found in soils. On copper-rich soils only a limited number of plants have a chance of survival. That is why there is not much plant diversity near copper-disposing factories. Due to the effects upon plants copper is a serious threat to the productions of farmlands. Copper can seriously influence the proceedings of certain farmlands, depending upon the acidity of the soil and the presence of organic matter. Copper can interrupt the activity in soils, as it negatively influences the activity of microorganisms and earthworms. The decomposition of organic matter may seriously slow down because of this. |
| | | When the soils of farmland are polluted with copper, animals will absorb concentrations that are damaging to their health. Mainly, sheep and goat suffer great from copper poisoning, because the effects of copper are manifest at fairly low concentrations. |
| 36 | Flow velocity | Velocity depends on the physical characteristics of streams, such as slope, roughness and cross section. Flow of streams affects everything from temperature of the water and concentration of various substances in the water to the distribution of habitats and organisms. It has impact on physico-chemical characteristics of water. Stream flow, acting together with the gradient, and the geology of the bottom substrate, determines the types of habitats present, the shape of the channel, and the composition of the stream bottom. |
| | | Low flow periods in summer allow the stream to heat up rapidly in warm weather while in the fall and winter temperatures may fall rapidly when flow is low. Flow directly affects the amount of oxygen dissolved in the water. |
| 37 | Flow rate | The flow rate of the water body is a primary factor in TSS concentrations. Fast running water can carry more particles and larger-sized sediment. Heavy rains can pick up sand, silt, clay, and organic particles such as leaves, soil, sheared particles from the land and carry it to surface water. A change in flow rate can also affect TSS; if the speed or direction of the water current increases, particulate matter from bottom sediments may be suspended. |

## 9.6 Water Quality Standards

The Bureau of Indian Standard (BIS) has developed standards for drinking water quality. The CPCB has provided best use criteria for surface water bodies. River Action Plans led by Ministry of Environment & Forests are for reviving the river water up to B-class i.e. bathing category. In the Tables 9.4, 9.5, and 9.6 standards of water quality for drinking (BIS, 1991), CPCB classification of designated use, and effluent disposal limits are presented, respectively.

**Table 9.4** Bureau of Indian standard/specification for drinking water (BIS: 10,500, 1991): maximum limit

| Parameter | Requirement desirable limit | Undesirable effect outside the desirable | Permissible limit in the absence of alternate source | Remarks |
|---|---|---|---|---|
| *Essential characteristic* | | | | |
| Colour Hazen Units | 5 | Above 5, consumer acceptance decreases | 25 | Extended to 25 only if toxic substance are not suspect in absence of alternate sources |
| Odour | Un-objectionable | – | – | Test cold and when heated test are several dilutions |
| Taste | Agreeable | – | – | Test to be conducted only after safely has been established |
| Turbidity (NTU) | 5 | Above 5, consumer acceptance decreases | 10 | – |
| pH | 6.5–8.5 | Beyond this range the water will affect the mucous membrane and/or water supply system | No relaxation | – |
| Total Hardness, $CaCO_3$ (mg/l) | 300 | Encrustation in water supply structure and adverse effects on domestic use | 600 | – |

**Table 9.4** (continued)

| Parameter | Requirement desirable limit | Undesirable effect outside the desirable | Permissible limit in the absence of alternate source | Remarks |
|---|---|---|---|---|
| Iron, Fe (mg/l) | 0.3 | Beyond this limit taste/appearance are affected; has adverse effects on domestic uses and water supply structure and promotes iron bacteria | 1.0 | – |
| Chlorides, Cl (mg/l) | 250 | Beyond effects outside the desirable limit | 1,000 | – |
| Residual free Chlorine (mg/l) | 0.2 | – | – | To be applicable only when water is chlorinated. Tested at customer end. When protection against viral infection is required, it should be min. 0.5 mg/l. |
| *Desirable characteristics* | | | | |
| Dissolved solids (mg/l) | 500 | Beyond this, palatability decreases and may cause gastrointestinal irritation. | 2,000 | – |
| Calcium, Ca (mg/l) | 75 | Encrustation in water supply structure and adverse effects on domestic use. | 200 | – |
| Magnesium, Mg (mg/l) | 30 | Encrustation in water supply structure and adverse effects on domestic use. | 100 | – |
| Copper, Cu (mg/l) | 0.05 | Astringent taste dis-coloration and corrosion of pipes fittings and utensils will be caused beyond this. | 1.5 | – |

**Table 9.4** (continued)

| Parameter | Requirement desirable limit | Undesirable effect outside the desirable | Permissible limit in the absence of alternate source | Remarks |
|---|---|---|---|---|
| Manganese, Mn (mg/l) | 0.1 | Beyond this limit taste/appearance are affected, has adverse effect on domestic use and water supply structure | 0.3 | – |
| Sulphate, $SO_4$ (mg/l) | 200 | Beyond this causes gastro intestinal irritation when magnesium or sodium are present | 400 | May be extended upto 400 provided magnesium, Mg does not exceed 30 |
| Nitrate, $NO_3$ (mg/l) | 45 | Beyond this methaemoglobine-mia takes place. | 100 | – |
| Fluoride, F (mg/l) | 1.0 | Fluoride may be kept as low as possible. High fluoride may cause fluorosis. | 1.5 | – |
| Phenolic Compounds, $C_6H_5OH$ (mg/l) | 0.001 | Beyond this, it may cause objectionable taste and odour | 0.002 | – |
| Mercury, Hg (mg/l) | 0.001 | Beyond this the water becomes toxic | No Relaxation | To be tested when pollution is suspected |
| Cadmium, Cd (mg/l) | 0.01 | Beyond this the water becomes toxic | No Relaxation | To be tested when pollution is suspected |
| Selenium, Se (mg/l) | 0.01 | Beyond this the water becomes toxic. | No Relaxation | To be tested when pollution is suspected |
| Arsenic, As (mg/l) | 0.05 | Beyond this the water becomes toxic | No Relaxation | To be tested when pollution is suspected |
| Cyanide, CN (mg/l) | 0.05 | Beyond this the water becomes toxic | No Relaxation | To be tested when pollution is suspected |

**Table 9.4** (continued)

| Parameter | Requirement desirable limit | Undesirable effect outside the desirable | Permissible limit in the absence of alternate source | Remarks |
|---|---|---|---|---|
| Lead, Pb (mg/l) | 0.05 | Beyond this the water becomes toxic | No Relaxation | To be tested when pollution is suspected |
| Zinc, Zn (mg/l) | 5 | Beyond this limit it can cause astringent taste and an opalescence in water | 15 | To be tested when pollution is suspected |
| Anionic detergents, MBAS (mg/l) | 0.2 | Beyond this limit it can cause a light froth in water | 1.0 | To be tested when pollution is suspected |
| Chromium, Cr+6 (mg/l) | 0.05 | May be carcinogenic above this limit | – | – |
| Poly-nuclear Aromatic Hydrocarbons, PAH (mg/l) | – | May be carcinogenic | – | – |
| Mineral oil (mg/l) | 0.01 | Beyond this limit, undesirable taste and odour after chlorination takes place | 0.03 | To be tested when pollution is suspected |
| Pesticides (mg/l) | Absent | Toxic | 0.001 | – |
| Alpha emitters (Bq/l) | – | – | 0.1 | – |
| Beta emitters (Pci/l) | – | – | 1.0 | – |
| Alkalinity (mg/l) | 200 | Beyond this limit, taste becomes unpleasant | 600 | – |
| Aluminium, Al (mg/l) | 0.03 | Cumulative effect is reported to cause dementia | 0.2 | |
| Boron, B (mg/l) | 1.0 | – | 5.0 | – |

**Table 9.5** Water quality criteria for best designated use (CPCB)

| Designated-best-use | Class of water | Criteria |
|---|---|---|
| Drinking Water source without conventional treatment but after disinfection | A | T. Coli: ≤ 50 MPN/100 ml<br>pH: 6.5–8.5<br>DO: ≥ 6 mg/l<br>5 days BOD at 20°C: ≤ 2 mg/l |
| Outdoor bathing (Organized) | B | T. Coli: ≤ 500 MPN/100 ml<br>pH: 6.5–8.5<br>DO: ≥ 5 mg/l<br>5 days BOD at 20°C: ≤ 3 mg/l |
| Drinking water source after conventional treatment and disinfection | C | T. Coli: ≤ 5,000 MPN/100 ml<br>pH: 6.0–9.0<br>DO: ≥ 4 mg/l<br>5 days BOD at 20°C: ≤ 3 mg/l |
| Propagation of Wild life and Fisheries | D | pH: 6.5–8.5<br>DO: ≥ 4 mg/l<br>Free Ammonia, N: ≤ 1.2 mg/l |
| Irrigation, Industrial Cooling, Controlled Waste disposal | E | pH: 6.0–8.5<br>EC at 25°C: ≤ 2,250 micro mhos/cm<br>Sodium absorption Ratio Max. 26<br>Boron: ≤ 2 mg/l |
| No use | Below-E | Not Meeting A, B, C, D and E Criteria |

**Table 9.6** General standards for industrial effluents (maximum limit)

| Parameter | Inland surface water | Public sewers | Land for irrigation | Marine/coastal areas |
|---|---|---|---|---|
| Suspended solids (mg/l) | 100 | 600 | 200 | (a) For process waste water<br>(b) For cooling water effluent 10% above total suspended matter of influent. |
| Particle size of suspended solids | ≤850 micron IS Sieve | – | – | (a) Floatable solids, solids maximum 3 mm<br>(b) Settleable solids, maximum 856 microns |
| pH value | 5.5 – 9.0 | 5.5 – 9.0 | 5.5 – 9.0 | 5.5 – 9.0 |
| Temperature above the receiving water | ≤5°C | – | – | ≤5°C |
| Oil and grease (mg/l) | 10 | 20 | 10 | 20 |
| Total residual chlorine (mg/l) | 1.0 | – | – | 1.0 |
| Ammoniacal Nitrogen, N (mg/l) | 50 | 50 | – | 50 |
| Total Kjeldahl Nitrogen, N (mg/l) | 100 | – | – | 100 |
| Free Ammonia, $NH_3$ (mg/l) | 5.0 | – | – | 5.0 |
| 3 days BOD at 27°C (mg/l) | 30 | 350 | 100 | 100 |
| COD (mg/l) | 250 | – | – | 250 |
| Arsenic, As (mg/l) | 0.2 | 0.2 | 0.2 | 0.2 |
| Mercury, Hg (mg/l) | 0.01 | 0.01 | – | 0.01 |
| Lead, Pb (mg/l) | 0.1 | 1.0 | – | 2.0 |
| Cadmium, Cd (mg/l) | 2.0 | 1.0 | – | 2.0 |
| Hexavalent Chromium, Cr+6 (mg/l) | 0.1 | 2.0 | – | 1.0 |
| Total chromium, Cr (mg/l) | 2.0 | 2.0 | – | 2.0 |

**Table 9.6** (continued)

| Parameter | Inland surface water | Public sewers | Land for irrigation | Marine/coastal areas |
|---|---|---|---|---|
| Copper, Cu (mg/l) | 3.0 | 3.0 | – | 3.0 |
| Zinc, Zn (mg/l) | 5.0 | 15 | – | 15 |
| Selenium, Se (mg/l) | 0.05 | 0.05 | – | 0.05 |
| Nickel, Ni (mg/l) | 3.0 | 3.0 | – | 5.0 |
| Cyanide, CN (mg/l) | 0.2 | 2.0 | 0.2 | 0.2 |
| Fluoride, F (mg/l) | 2.0 | 15 | – | 15 |
| Dissolved phosphates, P (mg/l) | 5.0 | – | – | – |
| Sulphide, S (mg/l) | 2.0 | – | – | 5.0 |
| Phenolic compounds, $C_6H_5OH$ (mg/l) | 1.0 | 5.0 | – | 5.0 |
| Radioactive materials: Alpha emitter's micro curie | 10–7 | 10–7 | 10–8 | 10–7 |
| Beta emitters micro curie | 10–6 | 10–6 | 10–7 | 10–6 |
| Bio-assay test | 90% survival of fish after 96 hours in 100% effluent | 90% survival of fish after 96 h in 100% effluent | 90% survival of fish after 96 h in 100% effluent | 90% survival of fish after 96 h in 100% effluent |
| Manganese (mg/l) | 2.0 | 2.0 | – | 2.0 |
| Iron, Fe (mg/l) | 3.0 | 3.0 | – | 3.0 |
| Vanadium, V (mg/l) | 0.2 | 0.2 | – | 0.2 |
| Nitrate nitrogen (mg/l) | 10.0 | – | – | 20.0 |

These standards shall be applicable for industries, operations or processes other than those industries, operations or process for which standards have been specified in Schedule of the Environment Protection Rules (MoEF, 1989). CPCB has separate effluent disposal standard for individual industries.

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# Chapter 10
# Wastewater Generation and Treatment

**Abstract** The chapter deals with wastewater generation and treatment, including the inventory of wastewater treatment mechanisms in the Yamuna River basin and available gaps in the treatment infrastructure and generation. The trend analysis is also performed to determine the future impact of wastewater generation on the river health. Detailed analysis of city-wise and state-wise wastewater generation are also included in the chapter for determining the critical issues of water quality management of the Yamuna River.

In the Yamuna basin there are two important sources of wastewater, i.e., domestic sewage from urban centres and industrial effluents from different categories of industries. As per the studies carried out by the Central Pollution Control Board (CPCB, 1982–1983, 1994), the domestic wastewater is the predominant source of pollution of the Yamuna River.

Urbanization in the sense of more and more people living in urban areas is by far the most important social change that has taken place in India in recent times. From a modest base of 25.8 million persons in 1901, the number of urban dwellers has risen to 285 million in 2001, signalling a phenomenal eleven-fold increase in urban population over a period of 100 years. During the past three decades of 1971–1901 itself, India's urban population has grown almost three fold, increasing from 109 million to 285 million. The proportion of population living in urban areas (level of urbanization) increased from 17.3% in 1951 to 28.5% in 2001 and the number of urban centres (town and urban agglomerations) swelled from 2843 in 1951 to 5162 in 2001. The earlier trend of migration from rural areas to urban areas gained further momentum due to fast economic growth in urban areas creating large employment opportunities and declining resources availability per capita and shrinking economic opportunities in rural areas (Chapter 7). A large number of rural-urban migrants get absorbed in the informal sector, and several among them took shelter in the slums, with the result that today nearly one half of India's urban employment sector is informal and unorganized. Thus rapid urbanisation places enormous strain on authorities to provide infrastructure necessary to support the population. This is also posing serious environmental problems related to water supply and waste water generation and their disposal.

The annual rate of growth of urban population in India (3.09%) is distinctly higher than that of the high-income industrial market economies (1.4%) and also of the East European economies (1.8%). The latter groups of countries, with around

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two thirds of their population living in urban places, are already highly urbanised. The low-income economies, as a group with a 4.4% growth rate and the middle-income economies with 4.1%, have an edge over India in this regard. As many as sixty, out of a total of ninety-four countries, belonging to low and middle income categories outrank India in urban growth rate. The annual urban growth rate is 4.2% in Mexico, 4.8% in Nigeria and 6.5% in Bangladesh. The corresponding rate in high-income, oil-exporting countries is still higher, being about 8.2%.

In the Indian context, urban population is usually presented in as a six-part classification in Indian censuses. While the first size-class comprises cities i.e., urban places having 100 thousand and more population, the last category consists of the tiny towns, i.e., places having population less than 5,000. In order to provide a meaningful analysis of the changes in size-class composition of urban population, the last three categories namely towns having a population 10,000–19,999; 5,000–9,999; and less than 5,000 are grouped together and termed as small towns. Medium towns are defined to have a population between 20,000 and 49,999; and large towns constitute a population in the range of 50,000–99,999. The places having more than 100 thousand population are named as Class-I cities. On the other hand, cities having population 1 million and more are termed as million plus cities or Metro-cities (Census, 2001).

The importance of different size classes of cities in total urban population has shifted in favour of large cities. In 1,901, 26% of urban inhabitants lived in settlements with over 1,00,000 population. By 2001 this percentage has risen to 60.3% heralding what would seem to be one of the most significant changes in the pattern of habitation in the country. With this change, India is no longer a country that lives in villages and small towns; rather it has acquired a complexion of a country that has an extensive network of large urban settlements. Population growth does have a significant impact on the environment and resources and will heighten demand for food, energy, water, health care, sanitation and housing.

Rapid urbanization and economic growth has led to a steep increase in waste generation. Unregulated growth of urban areas, particularly over the last two decades, without infrastructural services for proper collection, transportation, treatment and disposal of domestic waste water led to increased pollution and health hazards. The municipalities and such other civic authorities who are responsible for management of wastes have not been able to cope with this massive task. This could be attributed to various reasons, including the lack of resources, inability to raise revenues, erosion of authority and inadequate managerial capabilities.

## 10.1 Urbanization in the Yamuna Basin

As per the Census of India, 2001, the total population of the Yamuna River basin is about 130 million. There are 6 metro-cities (population of about 20 million), 61 Class-I cities (Population 11.4 mllion), 61 Class-II towns (Population 4.27 million), 201 Class-III towns (Population 5.94 million), 452 Class-IV towns (Population

**Table 10.1** State-wise urban and rural population in the Yamuna basin

| States | Population in Yamuna basin | | | |
|---|---|---|---|---|
| | Urban | Rural | Total | No. of villages |
| Himachal Pradesh | 149,738 | 715,698 | 865,436 | 2,284 |
| Uttarakhand | 168,269 | 247,804 | 416,073 | 619 |
| Haryana | 4,723,131 | 9,317,117 | 14,040,248 | 4,210 |
| Uttar Pradesh | 9,233,115 | 25,032,382 | 34,265,497 | 18,639 |
| Delhi | 12,819,761 | 963,215 | 13,782,976 | 158 |
| Madhya Pradesh | 10,906,554 | 19,448,621 | 30,355,175 | 22,889 |
| Rajasthan | 8,479,742 | 28,303,047 | 36,782,789 | 26,003 |
| Total | 46,480,310 | 84,027,884 | 130,508,194 | 74,802 |

3.63 million) 148 Class-V towns (Population 1.09 million) and 74,802 villages (Population 84 million). It is observed that urbanization in the Yamuna basin is 35.6%, which is higher than the national average of 28.5% (Census, 2001). Table 10.1 depicts state-wise summary of urban and rural population in the Yamuna basin.

As clear from Table 10.1, Delhi has the highest urban population followed by Madhya Pradesh, Uttar Pradesh and Rajasthan. The State of Himachal Pradesh and Uttarakhand are not very significant from the population point of view as their population put together is less than 1% of the total population in the basin. In the Yamuna basin, the population share under different categories of urban centers is summarized in Table 10.2.

## 10.2 Water Supply and Wastewater Generation

Wastewater generation is a function of water supply. In India piped water supply is largely restricted to urban areas. Rural population and smaller towns still depend on community wells, hand-pumps or even rivers/springs/ponds for their drinking water requirements. As per the CPCB study the water supply facilities are more advanced and effective in large urban centers than smaller ones (CPCB, 2009). The per capita water supply is also higher in larger cities than smaller ones. In the Yamuna basin, it is observed that the per capita water supply varies from 82 lpcd in Rajasthan to 352 lpcd in New Delhi. In smaller towns and rural areas the water supply is just around 45 lpcd. This results in meager wastewater generation from smaller urban centers or rural areas. As per the CPCB's study the Class-I cities in the country generate about 90% of the wastewater, whereas the Class-II towns only 10%. However, in the Yamuna basin, the share of sewage generation from class-I and II cities are 94 and 6%, respectively. If we go further down to Class-III or lower categories of urban centers or villages, practically insignificant or no wastewater is generated there. Hence, in the present study, the wastewater estimation is restricted to only Class-I cities and Class-II towns. The total water supply in the class-I cities and Class-II towns in

**Table 10.2** Distribution of urban population in different categories of urban centers in the Yamuna basin

| State | Class-I | | Class-II | | Class-III | | Class-IV | | Class-V | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No | Pop | No | Pop | No | Pop | No | Pop | No | Pop | No | Pop |
| Uttarakhand | 0 | 0 | 0 | 0 | 2 | 50,956 | 0 | 0 | 2 | 6,747 | 4 | 57,707 |
| Himachal Pradesh | 0 | 0 | 0 | 0 | 3 | 82,763 | 1 | 19,087 | 7 | 29,648 | 11 | 131,509 |
| Uttar Pradesh | 15 | 5,295,761 | 20 | 1,357,105 | 42 | 1,233,719 | 170 | 1,004,874 | 44 | 341,658 | 291 | 9,233,393 |
| Haryana | 14 | 3,328,821 | 5 | 299,861 | 18 | 555,291 | 29 | 422,121 | 15 | 117,037 | 81 | 4,723,198 |
| Delhi | 10 | 11,256,671 | 9 | 635,925 | 20 | 698,194 | 12 | 156,547 | 11 | 72,424 | 62 | 12,819,813 |
| Madhya Pradesh | 16 | 6,248,127 | 16 | 1,153,375 | 60 | 1,709,801 | 200 | 1,400,124 | 51 | 395,127 | 343 | 10,906,881 |
| Rajasthan | 12 | 5,300,518 | 11 | 821,819 | 56 | 1,605,840 | 40 | 626,329 | 18 | 125,236 | 137 | 8,479,867 |
| Total | 67 | 31,429,898 | 61 | 4,268,085 | 201 | 5,936,564 | 452 | 3,629,082 | 148 | 1,087,877 | 929 | 46,352,368 |

the Yamuna basin is about 11,555 MLD. It is also observed that due to the lack of proper collection facilities in most of the cities and towns the wastewater either flows in storm water drains often unlined or accumulates in the vacant plots, low-lying areas, percolates into the ground and pollutes groundwater. The wastewater, which flows in storm water drains ultimately leads to receiving water bodies and pollutes them. Thus, surface and groundwater in and around urban centres especially large urban centres is seriously affected by the discharge of untreated urban wastewater. However, the state-wise expected urban wastewater generation in the Yamuna basin is shown in Fig. 10.1, and it appears that Delhi has the highest wastewater generation followed by Uttar Pradesh, Madhya Pradesh and Rajasthan. Beside this, the city-wise wastewater generation is given in Tables 10.3, 10.4, 10.5, 10.6, and 10.7.

It is also important to consider that those cities/towns located on the banks of a river are most important from pollution point of view. Contribution of pollution from those located away from a river is generally less due to percolation, evaporation losses and lifting by farmers for irrigation en-route. Thus, all those towns, which are located along different rivers in the basin, are very important from a pollution control point of view.

It is observed that a total of 8,444 MLD of wastewater is generated from all the Class-I cities and Class-II towns in the basin out of which the treatment capacity is available for only 3,447 MLD. Thus, there is a large gap of about 5,000 MLD between generation and treatment of wastewater (Table 10.8).

It is also estimated by CPCB (2006) that out of 8,444 MLD of wastewater generated in the basin, about 4,458 MLD is discharged directly into the Yamuna River and about 1,200 MLD is discharged into its tributaries, the remaining 2,786 MLD is either disposed of on land or used for irrigation. Delhi alone generates about 3,743 MLD of wastewater, which is 44% of the entire sewage generated in the basin and 84% of the sewage being discharged into the Yamuna along its entire course. Uttar Pradesh, Madhya Pradesh and Rajasthan share almost equal magnitudes of sewage

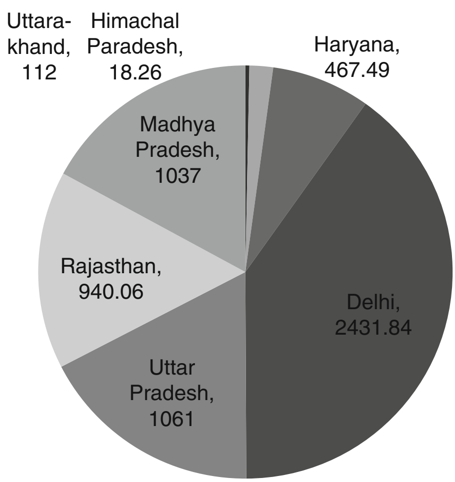



**Fig. 10.1** State-wise wastewater generation (in MLD) in the Yamuna basin

**Table 10.3** Wastewater generation in the cities of Haryana

| City | Population | Water supply rate (lpcd) | Water supply (mld) | Wastewater generation (mld) |
|---|---|---|---|---|
| Faridabad | 1,054,981 | 140 | 148 | 118 |
| Rohtak | 286,773 | 123 | 35 | 28 |
| Panipat | 261,665 | 128 | 33 | 27 |
| Hisar | 256,810 | 123 | 32 | 25 |
| Sonipat | 216,213 | 123 | 27 | 21 |
| Karnal | 210,476 | 170 | 36 | 29 |
| Yamunanagar | 189,587 | 180 | 34 | 27 |
| Gurgaon | 173,542 | 240 | 42 | 33 |
| Sirsa | 160,129 | 130 | 21 | 17 |
| Kurukshetra | 120,072 | 123 | 15 | 12 |
| Jhajjar | 119,839 | 123 | 15 | 12 |
| Kaithal | 117,226 | 123 | 14 | 12 |
| Yamunanagar | 101,300 | 123 | 12 | 10 |
| Rewari | 100,946 | 123 | 12 | 10 |
| Faridabad | 100,528 | 123 | 12 | 10 |
| Hisar | 75,730 | 123 | 9 | 7 |
| Mahendragarh | 62,091 | 90 | 6 | 4 |
| Sirsa | 53,812 | 90 | 5 | 4 |
| Jind | 50,659 | 90 | 5 | 4 |
| Sonipat | 48,518 | 90 | 4 | 3 |
| Jhajjar | 39,004 | 90 | 4 | 3 |
| Faridabad | 38,306 | 90 | 3 | 3 |
| Kurukshetra | 37,130 | 90 | 3 | 3 |
| Panipat | 35,150 | 90 | 3 | 3 |
| Kurukshetra | 33,547 | 90 | 3 | 2 |
| Hisar | 33,130 | 90 | 3 | 2 |
| Sirsa | 32,786 | 90 | 3 | 2 |

generation in this basin. On the sewage treatment front Delhi has the highest sewage treatment capacity of 2,330 MLD which is about 68% of the total sewage treatment capacity in the basin (Table 10.8). However, there is still a large gap between generation and treatment in Delhi itself.

## 10.3 Trends in Sewage Generation and Treatment

The CPCB (2006, 2009) has been regularly updating information on Class-I cities and Class-II towns in the country for water supply and wastewater generation, treatment and disposal. As per the available information the water supply and wastewater generation have increased much faster than population growth in these urban centres, which is clearly depicted in Fig. 10.2. This figure also includes trends in the number of cities, population, water supply, wastewater generation and treatment capacity. However, the treatment capacity has been almost stagnant for one and half decades.

**Table 10.4** Wastewater generations in Delhi

| City | Population | Water supply rate (lpcd) | Water supply (mld) | Wastewater generation (mld) |
|---|---|---|---|---|
| In all 9 districts | 9,817,439 | 270 | 2,651 | 2,121 |
| New Delhi, Central, South West and South | 294,783 | 352 | 104 | 83 |
| North West | 163,716 | 140 | 23 | 18 |
| North West | 153,874 | 140 | 22 | 17 |
| North West | 151,427 | 140 | 21 | 17 |
| West | 150,371 | 140 | 21 | 17 |
| North East | 148,549 | 140 | 21 | 17 |
| East | 132,628 | 120 | 16 | 13 |
| South West | 124,452 | 130 | 16 | 13 |
| South | 119,432 | 140 | 17 | 13 |
| North East | 90,564 | 120 | 11 | 9 |
| North East | 89,117 | 120 | 11 | 9 |
| West | 85,848 | 120 | 10 | 8 |
| North | 69,182 | 120 | 8 | 7 |
| East | 68,978 | 120 | 8 | 7 |
| East | 65,969 | 120 | 8 | 6 |
| South | 58,220 | 130 | 8 | 6 |
| North East | 57,460 | 120 | 7 | 6 |
| North West | 50,587 | 120 | 6 | 5 |
| North East | 48,028 | 120 | 6 | 5 |
| South | 47,336 | 120 | 6 | 5 |
| North East | 45,090 | 120 | 5 | 4 |
| South | 44,895 | 120 | 5 | 4 |
| West | 43,898 | 120 | 5 | 4 |
| North East | 43,364 | 120 | 5 | 4 |
| North East | 42,564 | 120 | 5 | 4 |
| South | 41,243 | 120 | 5 | 4 |
| South | 39,267 | 120 | 5 | 4 |
| South West | 38,580 | 120 | 5 | 4 |

**Table 10.5** Wastewater generations in Uttar Pradesh

| City | Population | Water supply rate (lpcd) | Water supply (mld) | Wastewater generation (mld) |
|---|---|---|---|---|
| Agra | 634,622 | 170 | 108 | 86 |
| Jhansi | 198,135 | 44 | 9 | 7 |
| Mathura | 140,150 | 80 | 11 | 9 |
| Firozabad | 130,863 | 71 | 9 | 7 |
| Muzaffarnagar | 114,783 | 68 | 8 | 6 |
| Saharanpur | 225,396 | 84 | 19 | 15 |
| Ghaziabad | 118,836 | 213 | 25 | 20 |
| Allahabad | 990,298 | 158 | 156 | 125 |

**Table 10.6** Wastewater generations in Rajasthan

| City | Population | Water supply rate (lpcd) | Water supply (mld) | Wastewater generation (mld) |
|---|---|---|---|---|
| Jaipur | 636,768 | 156 | 99 | 79 |
| Ajmer | 264,291 | 78 | 21 | 16 |
| Kota | 212,991 | 149 | 32 | 25 |
| Udaipur | 161,278 | 125 | 20 | 16 |
| Alwar | 100,378 | 77 | 8 | 6 |

**Table 10.7** Wastewater generations in Madhya Pradesh

| City | Population | Water supply rate (lpcd) | Water supply (mld) | Wastewater generation (mld) |
|---|---|---|---|---|
| Indore | 560,936 | 149 | 84 | 67 |
| Gwalior | 406,140 | 93 | 38 | 30 |
| Bhopal | 284,859 | 180 | 51 | 41 |
| Sagar | 154,785 | 55 | 9 | 7 |
| Ratlam | 119,247 | 50 | 6 | 5 |
| Ujjain | 208,561 | 95 | 20 | 16 |

**Table 10.8** Water supply and wastewater generation and treatment in the class-I and II cities/towns in the Yamuna basin

| | Class-I cities | | | Class-II towns | | |
|---|---|---|---|---|---|---|
| States | Water supply (MLD) | WW gen (MLD) | WW treat (MLD) | Water supply (MLD) | WW gen (MLD) | WW Treat (MLD) |
| Himachal Pradesh | 0 | 0 | 0 | 0 | 0 | 0 |
| Uttarakhand | 0 | 0 | 0 | 0 | 0 | 0 |
| Haryana | 819 | 655 | 333 | 70.4 | 56.3 | 3.5 |
| Delhi | 4,679 | 3,743 | 2,330 | 100.0 | 80.0 | 0 |
| Uttar Pradesh | 1,349 | 1,079 | 393.5 | 251.2 | 201.0 | 4.5 |
| Madhya Pradesh | 1,519 | 1,215 | 319 | 151.9 | 121.5 | 9 |
| Rajasthan | 1,537 | 1,230 | 54 | 78.3 | 62.6 | 0 |
| Total | 9,903 | 7,922 | 3,430 | 651.9 | 521.5 | 17 |

## 10.4 Inventory of Water Treatment and Sewage Treatment Plants

Sewage treatment plants (STPs) play an important role in keeping rivers clean. Though several STPs have been installed along the river course with a designed capacity of the order of 2,332.25 MLD for Delhi, 327 MLD for Haryana, and 403.25

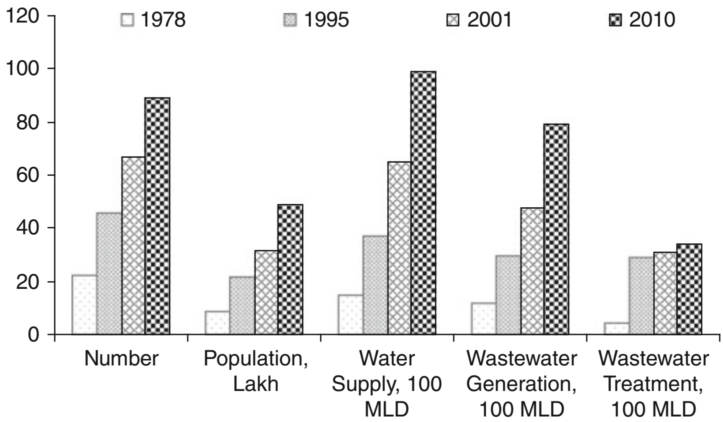



**Fig. 10.2** Change in number, population, water supply, WW generation and treatment in class-I cities of the Yamuna basin

MLD for Uttar Pradesh (CPCB, 1978; CPCB, 2006; CPCB, 2009). However, the river water quality has not been improved significantly. Detailed state-wise inventory of the STPs and common effluent treatment plant (CETPs) in the basin are summarized in Tables 10.9, 10.10, 10.11, and 10.12. These tables also include the designed capacity and running status of the STPs along with influent and effluent BOD values. The main cause of the river quality not yet improved may be: (i) STPs are in general practically not meeting their compliance, (ii) under running of most of the STPs due to lack of sewer connection, (iii) improper drainage system, etc. The density of STPs in Delhi is the highest and is mostly based on the activated sludge process (ASP). However, on the other part, type belongs to either Oxidation Pond (OP) or Up-flow Anaerobic Sludge Blanket (UASB) type. A descriptive map showing the location and type of STPs in the basin and NCT Delhi are depicted in Figs. 10.3 and 10.4, respectively.

The overall inventory of water treatment plants (WTPs) in the Yamuna River basin and Delhi is shown in Figs. 10.5 and 10.6, respectively, and the capacities of these WTPs have been summarized in Table 10.13.

## 10.5 Industrial Wastewater Generation, Treatment and Disposal

The Indian economy has never been in such a good shape as it is now with the liberalization measures initiated in 1991 becoming effective. The continued impressive performance of the agricultural sector and a significant improvement in the industrial production since September 1993 have enabled the rate of growth of the Gross Domestic Product (GDP) to rise from 0.8% in 1991–1992 to 6–8% in 2008–2009. This has resulted in rapid industrialization in the Yamuna basin also. There are large clusters of industries established in Kota, Gwalior, Indore, Nagda, Khetri, Yamuna Nagar, Panipat, Sonepat, Delhi, Baghpat, Ghaziabad, Gautam

**Table 10.9** Sewage treatment plants in Delhi

| S. No | Name of the STP's | Design capacity (MLD) | Type of STP | Running Status | Under YAP | *BOD Influent/ effluent |
|---|---|---|---|---|---|---|
| 1 | Coronation Pillar | 181.84 | Activated sludge process (ASP) and Ttrickling filter | Under utilized | | 170/26 |
| 2 | Delhi Gate | 10.00 | High Rate Biofilters (HBR) Densadeg technology | Running on designed capacity | Yes | 140/22 |
| 3 | Ghitorni | 22.73 | ASP | Not in operation | | |
| 4 | Keshopur | 327.31 | ASP | Under utilized | | 216/34 |
| 5 | Kondli | 204.57 | ASP | Under utilized | | 110/28 |
| 6 | Mehrauli | 22.73 | Extended aeration | Under utilized | | 226/22 |
| 7 | Najafgarh | 22.73 | ASP | Under utilized | | 208/28 |
| 8 | Nilothi | 181.84 | ASP | Under utilized | | 264/64 |
| 9 | Narela | 45.46 | ASP | Under utilized | | 160/42 |
| 10 | Okhla | 636.43 | ASP | Under utilized | | 242/24 |
| 11 | Papankalan | 90.92 | ASP | Under utilized | | 168/24 |
| 12 | Rithala | 363.68 | ASP and HBR | Under utilized | | 218/20 |
| 13 | Rohini | 68.19 | Activated sludge process | Not in operation | | |
| 14 | Sen N.H. | 10.0 | HBR | Running on designed capacity | Yes | 155/12 |
| | | 2 | Ultra-violet radiation | | | |
| 15 | Timarpur | 27.27 | Oxidation ponds (OP) | Under utilized | | 106/4 |
| 16 | Yamuna Vihar | 90.92 | ASP | Under utilized | | 256/32 |
| 17 | Vasant Kunj | 23.63 | ASP and Extended aeration | Under utilized | | 260/30 |
| Total STP = 30 | | 2,332.25 | | | | |

Buddha Nagar, Faridabad, Mathura and other places. The categories of industries discharging wastewater into Yamuna River includes pulp and paper, sugar, distilleries, textiles, leather, chemical, pharmaceuticals, oil refineries, thermal power plants, food processing, etc. In order to comply with environment laws, it is compulsory for these industries to treat their effluents to achieve prescribed standards before discharging effluent into the environment.

The rapid industrialization has exerted extra pressure on infrastructure facilities of human settlements manifesting in environmental problems, in terms of increased incidences of air, water, noise pollution and land degradation. It is unfortunate

**Table 10.10** Sewage treatment plants in Haryana

| S. No. | Name of the STP's | | Design capacity (MLD) | Type of STP | Running status | Constructed under YAP | BOD influent/effluent[a] |
|---|---|---|---|---|---|---|---|
| 1 | Yamuna Nagar | STP-I | 10 | UASB | Under utilized | Yes | 188/38 |
| | Jagadhari | STP-II | 25 | UASB | Over the capacity | Yes | 144/26 |
| | Chhchhrauli | STP | 1 | OP | Under utilized | Yes | |
| 2 | Karnal | STP-I | 40 | UASB | Full capacity | Yes | 166/30 |
| | | | 1 | Down flow hanging sponge (DHS-Bio tower) | Full capacity | | 154/29 |
| | | STP-II | 8 | OP | Under utilized | Yes | |
| 3 | Panipat | STP-I | 10 | UASB | Under utilized | Yes | 176/54 |
| | | STP-II | 35 | UASB | Under utilized | Yes | 168/28 |
| 4 | Sonepat | STP-I | 30 | UASB | Under utilized | Yes | 166/29 |
| 5 | Gurgaon | STP-I | 30 | UASB | Full capacity | Yes | |
| 6 | Faridabad | STP-I | 20 | UASB | Under utilized | Yes | 77/39 |
| | | | 2 | Ultra-violet radiation | | | |
| | | | 2 | Solar radiation | | | |
| | | STP-II | 45 | UASB | Under utilized | Yes | 81/33 |
| | | STP-III | 50 | UASB | Under utilized | Yes | |
| 7 | Gharaunda | STP | 3 | OP | Under utilized | Yes | |
| 8 | Gohana | STP | 3.5 | OP | Under utilized | Yes | |
| 9 | Indri | STP | 1.5 | OP | Under utilized | Yes | |
| 10 | Palwaal | STP | 9 | OP | Under utilized | Yes | |
| 11 | Radaur | STP | 1 | OP | Under utilized | Yes | |
| | Total STP = 17 | | **327** | | | | |

[a] Limit for disposal of effluent in natural streams <30 mg/l

**Table 10.11** Sewage treatment plants in Uttar Pradesh

| S. No | Name of the STP's | | Design capacity (MLD) | Type of STP | Running status | Under YAP | BOD influent/effluent[a] |
|---|---|---|---|---|---|---|---|
| 1 | Sharanpur | STP | 38 | UASB | Full capacity | Yes | 67/8 |
| 2 | Muzaffar Nagar | STP | 32.5 | OP | Over the capacity | Yes | 156/32.8 |
| 3 | Ghaziabad | STP-I | 70 | UASB | Full capacity | Yes | 209/50 |
| | | | 3 | karnal technology (KT) | Full capacity | Yes | |
| | | STP-II | 56 | UASB | Full capacity | Yes | 140/37 |
| 4 | Noida | STP-I | 34 | UASB | Full capacity | Yes | 92/35 |
| | | STP-II | 27 | UASB | Full capacity | Yes | 139/30 |
| | | | 2 | Chlorination | | | |
| | | STP-III | 9 | OP | Full capacity | Yes | 161/39 |
| 5 | Vrindavan | STP-I | 4 | OP | Under utilized | Yes | |
| | | STP-II | 0.5 | OP | Under utilized | Yes | 118/57 |
| 6 | Mathura | STP-I | 14.5 | OP | Under utilized | Yes | 176/37 |
| | | STP-II | 12.5 | OP | Under utilized | Yes | |
| 7 | Agra | STP-I | 78 | UASB | Under utilized | Yes | NA/21 |
| | | STP-II | 10 | OP | Under utilized | Yes | 79/23 |
| | | STP-III | 2.25 | OP | Under utilized | Yes | 94/47 |
| 8 | Etawah | STP | 10 | OP | Under utilized | Yes | 135/20 |
| Total STP = 15 | | | **403.25** | | | | |

[a] Limit for disposal of effluent in natural streams <30 mg/l

that environmental considerations tend to get a back seat in economic planning, especially while planning for industrial development. The industrial development inevitably results in the deterioration of environment. Unchecked industrialization processes have disturbed the environmental balance in the Yamuna basin. Most of the urban centres are not only facing problems of domestic pollution loads generated from the urban population but also from pollution loads from large numbers of industries in the residential areas in these urban centres. With the fast growth

**Table 10.12** Common effluent treatment plants in Delhi

| S. No. | Name of the CETP | Design capacity (MLD) | Type | Running Status | Under YAP | BOD influent/effluent[a] |
|---|---|---|---|---|---|---|
| 1 | Badli CETP | 12 | ASP | Under utilized | | 185/24 |
| 2 | GTK CETP | 6 | ASP | Under utilized | | 160/29 |
| 3 | Jhilmil CETP | 16.8 | ASP | Under utilized | | 170/27 |
| 4 | Lawrence Road CETP | 12 | ASP | – | | |
| 5 | Mangolpuri CETP | 2.4 | ASP | Full capacity | | 150/21 |
| 6 | Nangloi CETP | 12 | ASP | Under utilized | | 190/27 |
| 7 | Narela CETP | 4 | ASP | Full capacity | | 210/34 |
| 8 | Okhla CETP | 12 | ASP | Under utilized | | 180/36 |
| 9 | Okhla CETP | 24 | ASP | Under utilized | | 95/27 |
| 10 | SMA CETP | 12 | ASP | Under utilized | | 140/28 |
| 11 | Wazirpur CETP | 24 | ASP | Under utilized | | 130/25 |

[a] Limit for disposal of effluent in natural streams <30 mg/l

of industries a large number of environmental problems arise. A most important environmental problem associated with industrialization is disposal of their wastes. A large number of industrial activities generate solid, liquid or gaseous wastes. Many of these wastes, when released into the environment, cause serious problems of pollution. Normally, control of pollution is "un-economical" and therefore the industries are reluctant to invest their resources on this aspect. Thus, the industrialization has resulted in serious environmental problems in many parts of India.

For rational planning of pollution control strategies it is important to have a complete knowledge of the nature and magnitude of pollution loads generated from different categories of industries. The Central Pollution Control Board has been assessing pollution loads generated from different sources. However, due to the lack of reliable data, the industrial pollution quantification cannot be done by the CPCB. Since the information on the quantification of industrial pollution is of crucial importance, it is decided by CPCB to quantify the pollution load from the industrial production data. The industrial production data are fairly well documented by Central Statistical Organisation, Ministry of Planning, Government of India, and are being regularly updated. The pollution load generated in terms of important pollutants per unit production is also fairly well established by the CPCB under its elaborate studies called "Comprehensive Industries Document Series" on different categories of industries in India. Taking the help of this existing information an attempt is made to estimate the pollution load that is being generated in terms of important pollutants in the Yamuna basin.

As per the information available from different SPCBs there are about 400 large and medium industries belonging to 13 categories of highly polluting industries in the Yamuna basin. The state-wise distribution of these industries is given in

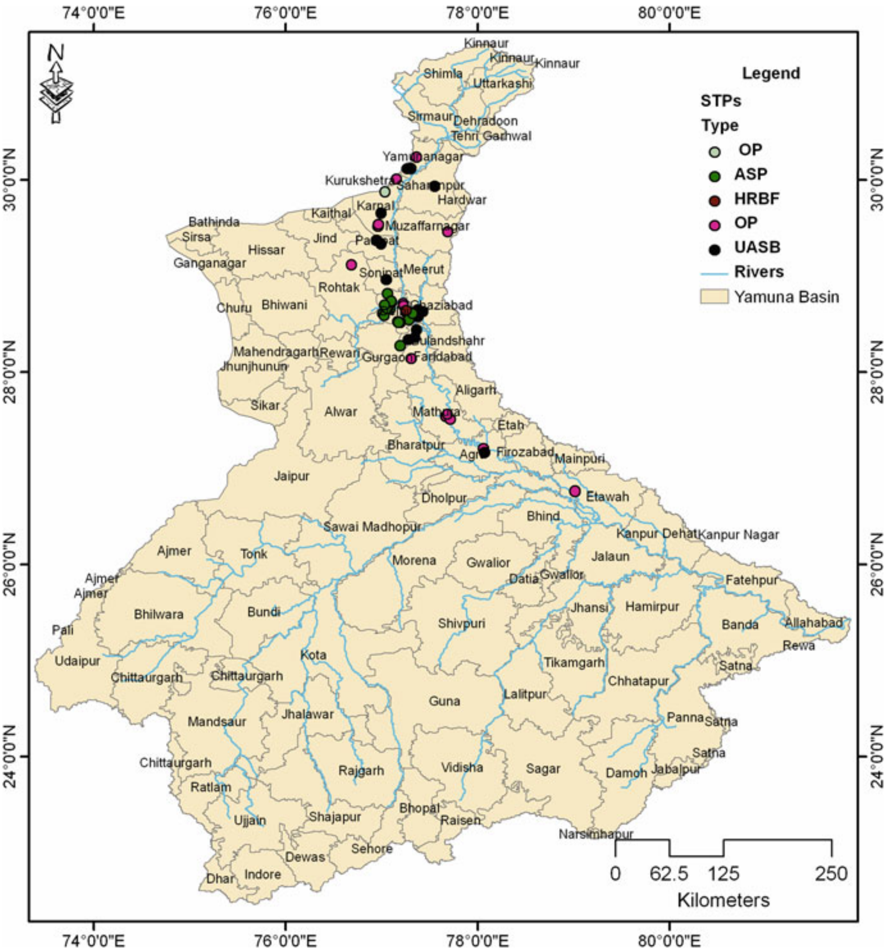



**Fig. 10.3** Sewage treatment plants in the basin

Table 10.14. From this table, it is clear that Uttar Pradesh have the highest number of large and medium industries in the basin followed by Haryana, Rajasthan and Madhya Pradesh. Among different categories, paper mills has highest number followed by pharmaceutical industries, cement, sugar and distilleries, fertilizer plants, thermal power plants and tanneries.

## 10.6 Pollution Load Generation from Industrial Sources

Information on industry-wise pollution load generation is either not available or not reliable due to various reasons. Thus, an approach adopted to estimate pollution contribution from industrial sources is based on industrial production. The

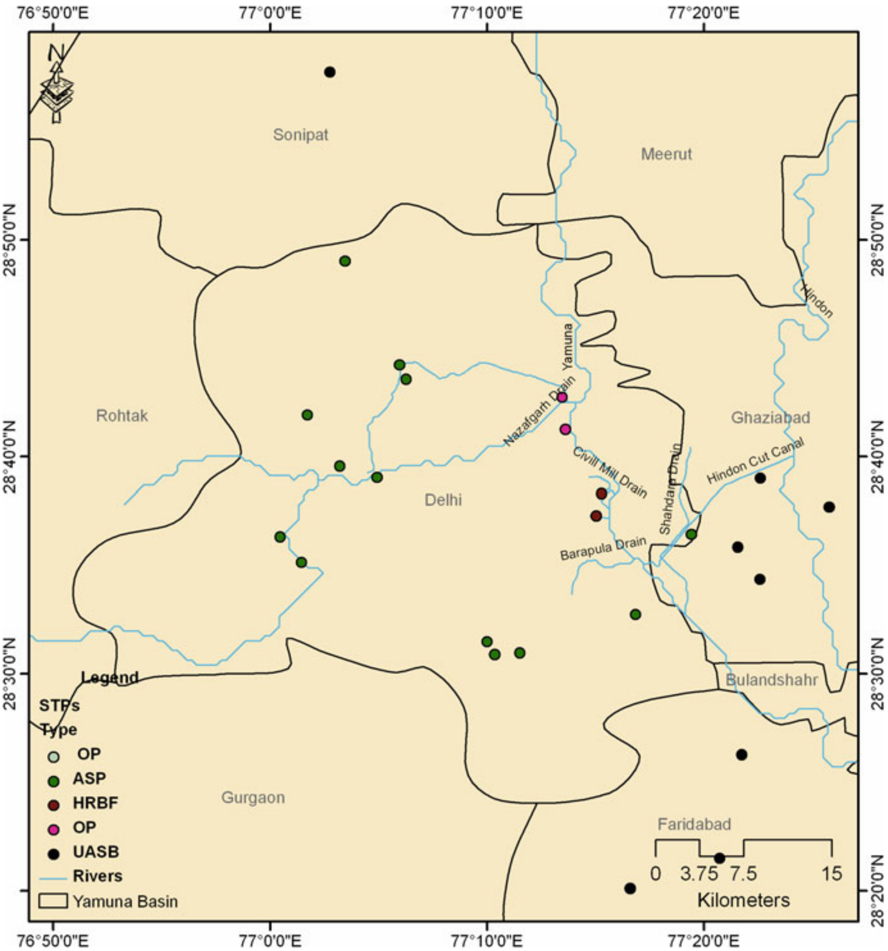



**Fig. 10.4** Sewage treatment plants in NCT Delhi

pollution load in terms of volume of wastewater and BOD load state-wise and industrial category-wise is presented in Figs. 10.7, 10.8, 10.9, 10.10, 10.11, and 10.12.

As revealed from Figs. 10.7, 10.8, 10.9, 10.10, 10.11, and 10.12, UP contributes about 55% of the industrial effluents by volume, followed by Delhi 18%, MP 14%, Haryana 7%, Rajasthan 4% and Himachal Pradesh 2%. From the BOD load generation point of view Uttar Pradesh is contributing 64% of BOD in the basin (Fig. 10.7), followed by Madhya Pradesh, Haryana, Rajasthan, Delhi and Himachal Pradesh. Their contributions are 15%, 10%, 6%, 3% and 2%, respectively. Similarly, a look into the category-wise generation of the volume of wastewater reveals that paper mills contributes the highest volume of wastewater in the basin i.e. 52% followed by sugar industries 15%, textiles 6%, distilleries 3% and others 24%. From the BOD

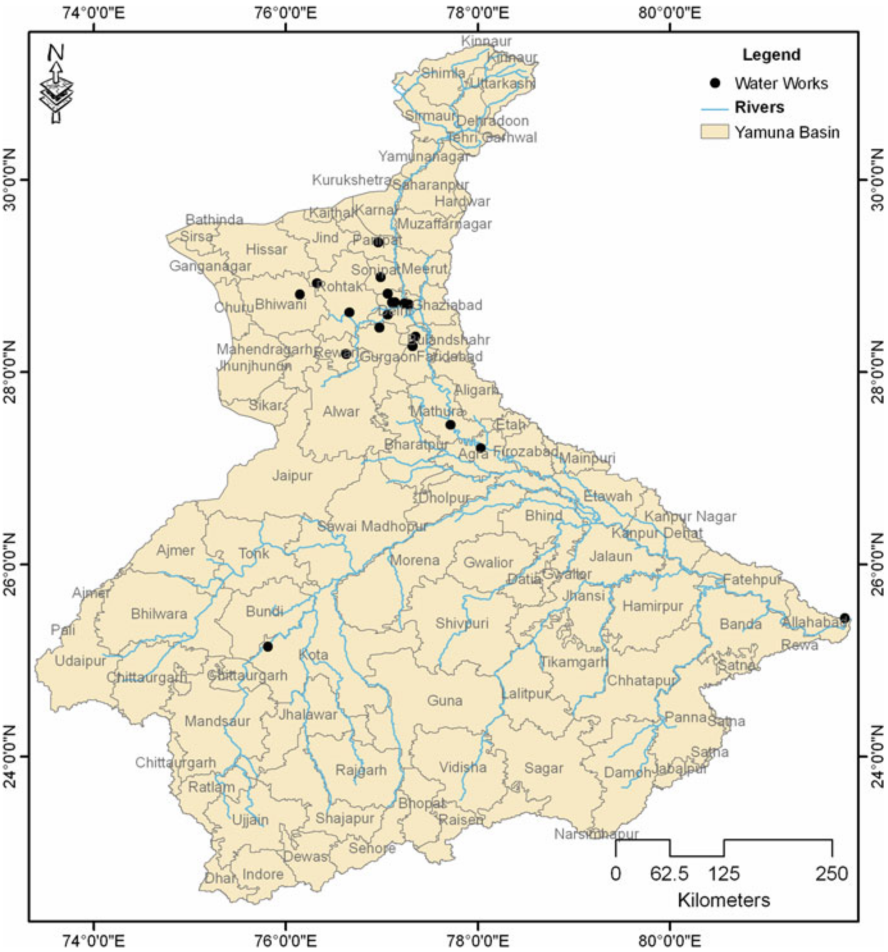



**Fig. 10.5** Location map of water treatment plants in Yamuna basin

load generation point of view it is the distilleries dominates the whole industrial pollution load scenario in the basin, which is 60% (Fig. 6.8) followed by paper mills 27%, sugar 8% and others 5%. The BOD load contributed after treatment into the environment is the highest from paper mills, i.e., 72% (Fig. 10.11) followed by distilleries 22%, sugar 2%, tanneries 3% and others 1%. State-wise estimation of the BOD load contribution into the environment revealed that Uttar Pradesh contributes 70% of the pollution load into the environment (Fig. 10.12) followed by Madhya Pradesh 12%, Haryana 7%, Delhi 5%, Himachal Pradesh and Rajasthan 3% each.

Since Uttar Pradesh dominates in generation and contribution of industrial pollution load, it is important to look into the disposal points. The pollution contribution from Uttar Pradesh is mostly either directly into the Yamuna River or in the Krishni,

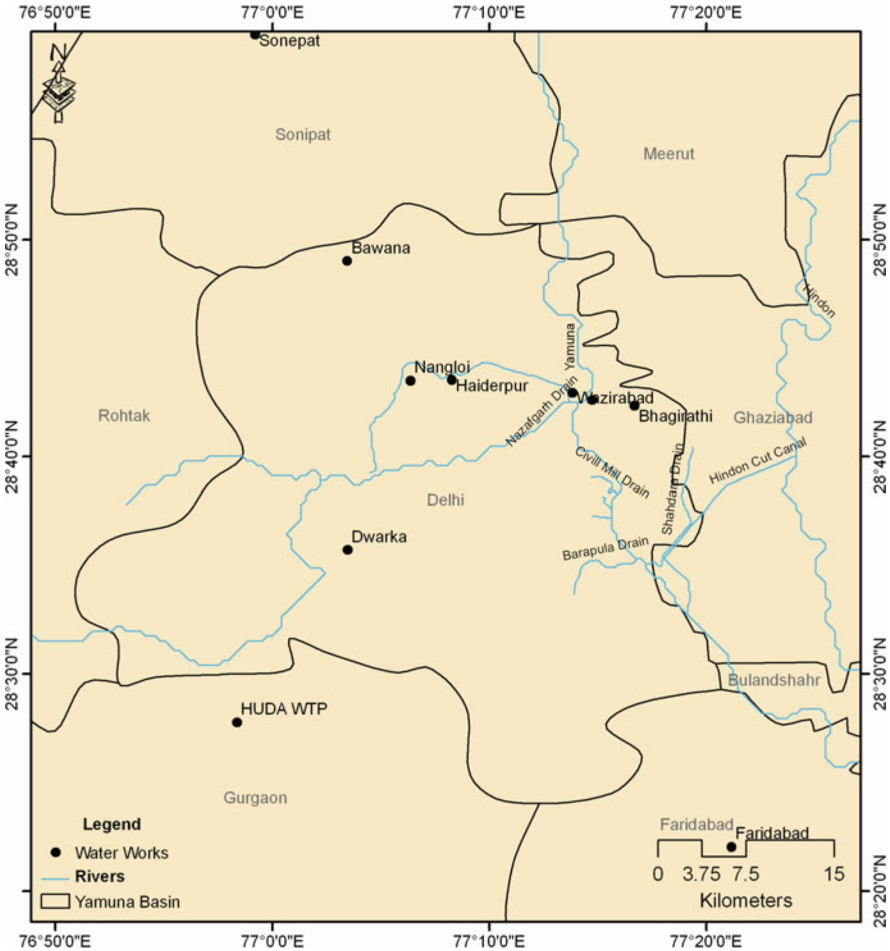



**Fig. 10.6** Location map of water treatment plants in Delhi

the Kali and the Hindon. Most of the industries contributing pollution are agro-based and hence, it is the organic pollution which is most important. The other important state is Haryana, which contributes its industrial pollution either directly into the Yamuna River through, drains No. 2, 6 and 8. These drains are carrying the effluent from the towns located along the river. There is one very important industrial town located on the Western Yamuna Canal (WYC) which discharges its effluent episodically in the WYC, affecting the drinking water quality of Delhi very often. In MP the pollution loads are contributed mostly in Chambal River, Kshipra, Khan, Betwa, Kalisindh, Parwati and Ken rivers. Since these rivers are not perennial and flow for 3–4 months in a year, their contribution of pollution to the Yamuna is not very significant. Similarly, the industrial pollution load contribution from Rajasthan is mostly received by the Chambal and the Banas, which are again not perennial

**Table 10.13** Inventory of water treatment plants

| S. No. | Name/location | Capacity |
|---|---|---|
| **Delhi** | | |
| 1 | Wazirabad WTP | 120 MGD |
| 2 | Bhagirathi WTP | 100 MGD |
| 3 | Sonia Vihar WTP | 140 MGD |
| 4 | Hyderpur WTP | 200 MGD |
| 5 | Nangloi WTP | 40 MGD |
| 6 | Chandrawal WTP | 90 MGD |
| 7 | Bawana | 20 MGD |
| 8 | Dwarka | 40 MGD |
| 9 | Okhla | – |
| 10 | Okhla Ranny Well | 100 MGD |
| 11 | Palla and GW | ≈30 MGD |
| **Uttar Pradesh** | | |
| 1 | Agra Waterworks WTP | 410 MLD |
| 2 | Agra Jeevanimandi WTP | |
| 3 | Mathura | 25 MLD |
| 4 | Allahabad | |
| **Haryana** | | |
| 1 | Jind – Kaithal Canal based water works | |
| 2 | Jind – Narwana Canal based water works | |
| 3 | Panipat Canal based water works | |
| 4 | Palwal Canal based water works | |
| 5 | Jhajjar Canal based water works | |
| 6 | Sonepat Canal based water works | |
| 7 | Gurgaon Canal based water works | |
| 8 | Faridabad Canal based water works | |
| **Kota** | | |
| 1 | Kota | 64 MLD |
| 2 | Jodhpur | 60 MLD |
| 3 | Udaipur (2) | 36.7 MLD |
| 4 | Nagaur | UC |
| 5 | Jaipur | |
| 6 | Sawai Madhopur | |
| 7 | Karauli | UC |

and hence the pollution load is either assimilated in those rivers or percolates in the ground and may pollute the groundwater.

## 10.7 Wastewater Discharged into the Yamuna

As stated above, about 8,444 MLD of wastewater is generated from all the Class-I cities and Class-II towns in the basin out of which about 5,000 MLD is directly discharged into the Yamuna River from 16 cities/towns located on its banks, out of which the treatment capacity exists for about 3,100 MLD. The growth of urban centres exerts pressure on water resources in two ways. The increasing need for

**Table 10.14** State-wise and category-wise number of large and medium industries under 13 categories of polluting industries

| State | Distilleries | Cement | Chloralkalis | Dyes and Dye Int. | Fertilizer | Pharmaceuticals | Paper mills | Rayon | Sugar | TPP | Tanneries | Engineering | Misc. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Madhya Pradesh | 9 | 8 | 1 | 2 | 5 | 17 | 1 | 1 | 5 | 1 | 0 | 0 | 0 | **50** |
| Uttar Pradesh | 6 | 0 | 0 | 5 | 0 | 5 | 47 | 0 | 14 | 3 | 10 | 18 | 69 | **177** |
| Rajasthan | 3 | 28 | 2 | 2 | 14 | 10 | 1 | 1 | 2 | 8 | 0 | 3 | 4 | **78** |
| Delhi | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | **8** |
| Haryana | 7 | 10 | 0 | 2 | 4 | 18 | 8 | 0 | 15 | 3 | 7 | 13 | 3 | **90** |
| Himachal Pradesh | 3 | 2 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **6** |
| Total | **28** | **51** | **3** | **11** | **23** | **51** | **57** | **2** | **36** | **20** | **17** | **34** | **76** | **409** |

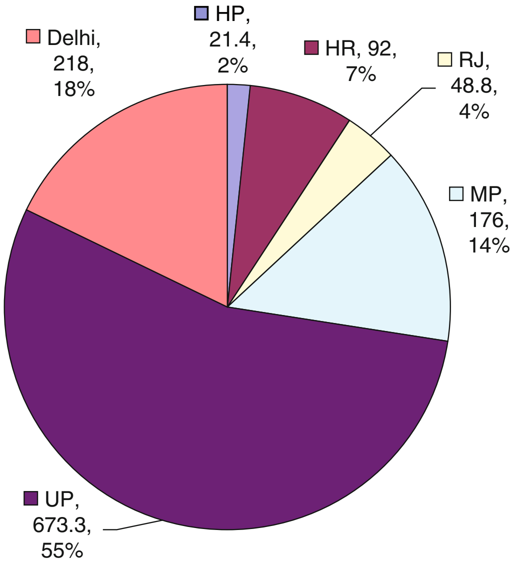



**Fig. 10.7** State-wise industrial effluent generation in the Yamuna basin

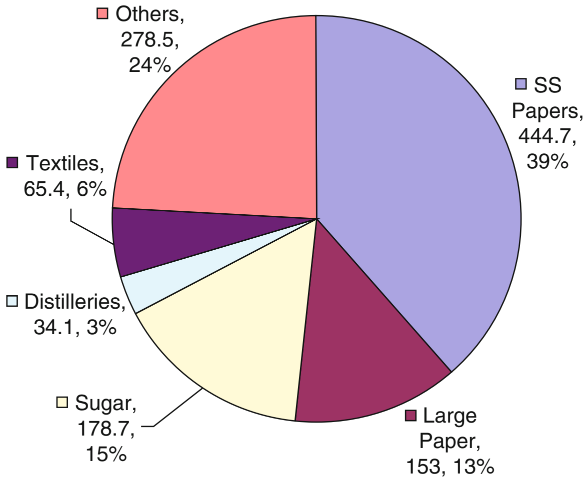



**Fig. 10.8** Category-wise volume of wastewater generated, MLD

water to meet the domestic requirement and the impact of resultant waste water discharge on the receiving waters has the cumulative effect of deteriorating the quality of receiving waters. All the 16 cities along its banks have grown steeply in the past 2–3 decades. The wastewater added from these urban centres has increased manifold and the fresh water availability in many stretches of the river has gone down to zero. This has resulted in the Yamuna to become the main sewer in the Delhi, Mathura and Agra stretches. Delhi, being the capital of India and large business and

**Fig. 10.9** State-wise industrial BOD load generation in the Yamuna basin, t/d

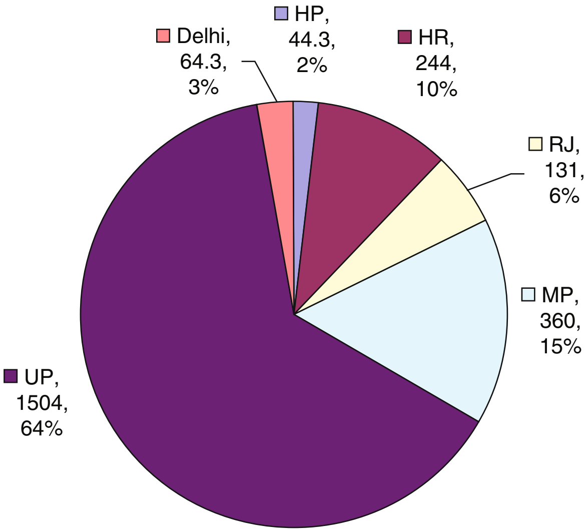
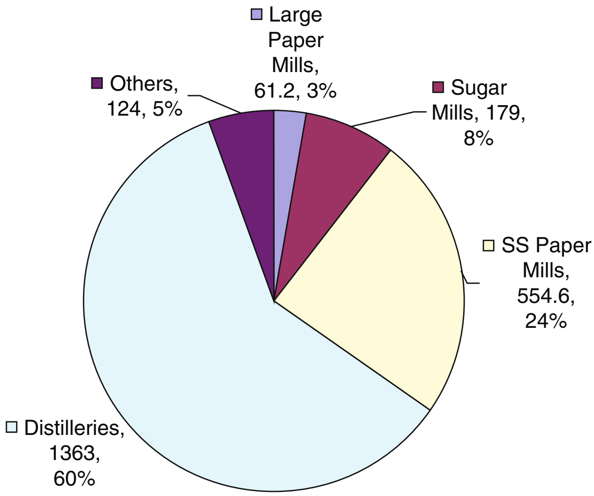



**Fig. 10.10** Category-wise industrial BOD load generation in the Yamuna basin, t/d




commercial centre in North India, provides good employment opportunities. This has resulted in the migration of large population from all over the country to settle in this city and around, leading to heavy pressure on the Yamuna.

The pollution loads estimated in the towns along the river by CPCB are presented in Table 10.15 and in Fig. 10.13.

It is revealed that out of the 16 towns along the river, 10 including Delhi and downstream towns discharge their wastewater directly into the river. Three towns upstream of Delhi in Haryana, i.e., Karnal, Panipat and Sonepat discharge

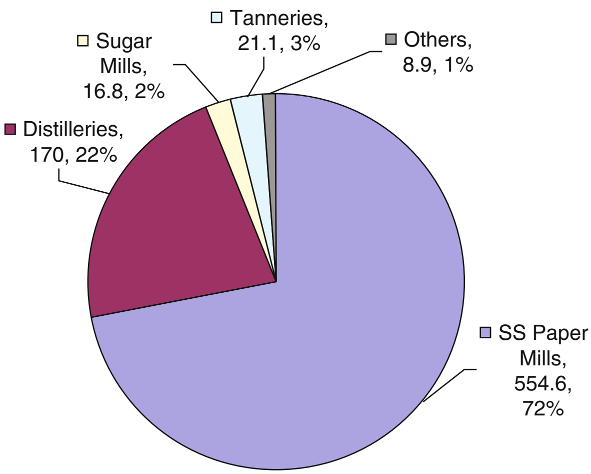



**Fig. 10.11** Category-wise industrial BOD load discharged, t/d

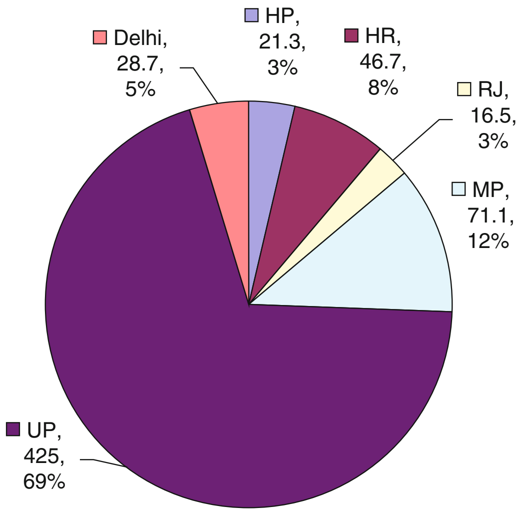



**Fig. 10.12** State-wise Industrial BOD load discharged, t/d

their wastewater into drains leading to the Yamuna after traversing a distance of 20–45 km, resulting in most of the wastewater being either used-up by the farmers for irrigation, evaporated or percolated and not reaching the river in dry season. Yamunanagar discharges its wastewater into the misused Western Yamuna Canal. The two towns in U.P. upstream of Delhi, i.e., Saharanpur and Muzaffarnagar discharge their wastewater into Hindon and Kali Rivers respectively. Delhi contributes highest load into the river. It generates about discharges about 80% of its wastewater into the Yamuna River and about 20% into the Agra Canal. Out of the 80% wastewater discharged into the Yamuna nearly 25% is discharged downstream

**Table 10.15** Major polluting sources of Yamuna River

| Cities/towns | Bank | Volume of WW, MLD | Treatment capacity MLD |
|---|---|---|---|
| Yamunanagar | R | 45 | 35 |
| Saharanpur | L | 45 | 38 |
| Muzaffarnagar | L | 40 | 32.5 |
| Karnal | R | 60 | 48 |
| Panipat | R | 60 | 45 |
| Sonepat | R | 45 | 30 |
| Delhi | R/L | 3, 800 | 2,330 |
| Gurgaon | R | 45 | 30 |
| Faridabad | R | 140 | 115 |
| Ghaziabad | L | 150 | 126 |
| Noida | L | 90 | 70 |
| Vrindavan | R | 5 | 4.5 |
| Mathura | R | 35 | 28 |
| Agra | R | 190 | 90 |
| Etawah | R | 13 | 10 |
| Allahabad | L | 223 | 89 |
| Total | | 4, 986 | 3,121 |

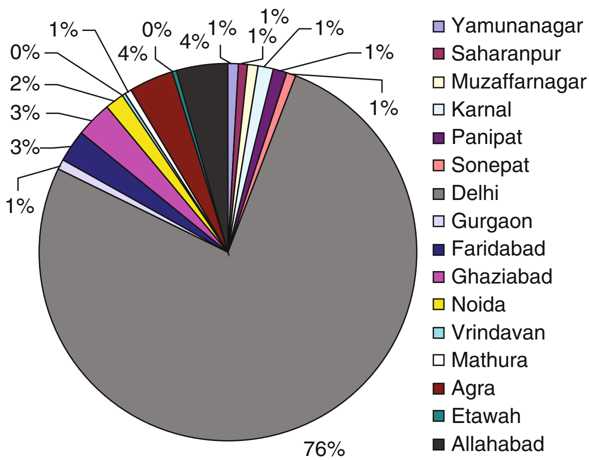



**Fig. 10.13** Town share of wastewater generation along the Yamuna River

of the Okhla Barrage. The wastewater from Faridabad is partly (about 30%) discharged into the Agra Canal and partly discharged into the Yamuna River through a drain being used by farmers for irrigation and partly into the Gaunchi Drain (about 30%) leading to the Yamuna after traversing a distance of about 70 km. During the course of 70 km there is biodegradation and lifting by farmers for irrigation and hence contribution in the river through this drain is almost insignificant.

### *10.7.1 Wastewater Discharged from Delhi*

Yamuna River, which is the main source of water supply for Delhi, plays a crucial role in its growth. The perennial increase in the population and urban activity in Delhi is placing exigent pressures and demands upon this natural resource. As a result, today, there is a heavy pressure on the civic amenities, water supply, and sanitation in particular, leading to a severe impact on the river water quality. Therefore, in order to assess the water quality status of Yamuna River, it becomes imperative to study the growth of the Union Territory (UT) of Delhi in detail.

To understand the city growth the spatial growth trend of Delhi is studied over the years. For this, all the settlements falling within the confines of Union Territory of Delhi are taken and their expansion is noticed in the time series (1901–2001). In order to ascertain the real picture of growth, the decadal growth has been studied. Table 10.16 shows the decadal population growth rate from 1901 to 2001.

The urban area of Delhi has been growing continuously since 1901. As evident from Table 10.16, from 1921 to 1931, there was an enormous rise of 288%, mainly due to the developments coming up after the transfer of the Imperial Capital from Calcutta to Delhi. After the completion of construction of New Delhi in 1931, the expansion became almost stagnant. Therefore, the significant change in the urban area has been experienced only in the post-colonial period. After independence, Delhi has been growing more or less steadily with the urban area expanding to 918.7 km$^2$ during 2001 census, which is as much as 62.5% of the total area of UT of Delhi.

Population has been an integral part of the urban sprawl. The ever increasing population of the country manifests itself by way of the metropolitan cities becoming increasingly congested. This is reflected in the change in population of Delhi since 1901–2001, as shown in Table 10.17.

From Tables 10.16 and 10.17, it can be inferred that Delhi as well as its urban component have followed an upward trend all through this century. However, the

**Table 10.16** Growth of urban area in Delhi

| Year | Area km$^2$ | Net addition km$^2$ | Percentage change |
|---|---|---|---|
| 1901 | 43.3 | – | – |
| 1911 | 43.3 | 0 | 0 |
| 1921 | 168.1 | 124.8 | 288.22 |
| 1931 | 169.6 | 1.5 | 0.89 |
| 1941 | 170.1 | 0.5 | 0.29 |
| 1951 | 195.8 | 25.7 | 15.11 |
| 1961 | 326.3 | 130.5 | 66.65 |
| 1971 | 451.4 | 125.1 | 38.34 |
| 1981 | 591.9 | 140.5 | 31.13 |
| 1991 | 685.3 | 93.4 | 15.78 |
| 2001 | 918.7 | 233.4 | 74.59 |

*Source*: Directorate of Census Operations, Delhi

**Table 10.17** Population growth of Delhi during 1901–2001

| Year | Total population | Percentage increase | Urban population | Percentage to total | Percentage increase |
|---|---|---|---|---|---|
| 1901 | 405,809 | – | 214,112 | 51 | – |
| 1911 | 413,851 | 2 | 237,944 | 56 | 11 |
| 1921 | 488,452 | 18 | 304,420 | 62 | 28 |
| 1931 | 636,246 | 30 | 447,442 | 70 | 47 |
| 1941 | 917,939 | 44 | 695,686 | 76 | 55 |
| 1951 | 1,744,072 | 90 | 1,437,134 | 82 | 107 |
| 1961 | 2,658,612 | 52 | 2,359,408 | 88 | 64 |
| 1971 | 4,065,698 | 53 | 3,647,023 | 90 | 55 |
| 1981 | 6,220,406 | 53 | 5,768,200 | 93 | 58 |
| 1991 | 9,370,475 | 51 | 8,427,083 | 90 | 46 |
| 2001 | 13,782,976 | 47 | 12,819,761 | 93 | 52 |
| 2010 | 20,498,805 | 52 | 19,316,842 | 94 | 51 (Projected) |

*Source*: Directorate of Census Operations, Delhi

biggest jump was witnessed in the decade 1941–1951, when the number really doubled following the influx of refugees from Pakistan. During the last four decades, the growth rate is more or less constant at about 50% per decade.

The density of population in the UT of Delhi in 1981 was 4,231 persons per sq km. This increased to 6,374 persons per sq. km in 1991, registering an increase of as much as 51% in the decade 1981–1991. During the year 2001 the population density has increased to 9,376 persons per km$^2$, which is a further increase of 47% in the decade 1991–2001.

The rate of growth of urban population of Delhi is the highest in the country. The urban population has increased to about 60 times in 100 years. Since the Delhi Master Plan 1962 came into being, DDA has developed more than 20,000 ha of land for various uses. In spite of such huge developmental activities in Delhi, about 70% of population of Delhi still lives in sub-standard areas with a break up of 1.0 million in *jhuggi* clusters, 1.2 million in unauthorised colonies and unauthorised regularised colonies, 1.4 million in slum designated areas, 0.5 million in urban villages, 0.5 million in rural villages and 1.2 million in resettlement colonies.

#### 10.7.1.1 Pollution Load Generation from Domestic Sources in Delhi

Every human activity results in the generation of waste though the nature and quantities of such wastes may vary in a wide range from activity to activity. Rural and urban areas are very much distinct from each other in terms of activities as well as the provision of infrastructure, particularly water supply and sanitation.

The Delhi Jal Board (DJB) suggests that an average of about 240 lpcd of domestic sewage is generated in the sewered areas of Delhi. The entire sewered areas of Delhi can be divided into five sewerage zones, namely, Okhla, Keshopur, Rithala, Coronation Pillar and Shahdra. These sewerage zones accommodate populations of

**Table 10.18** Sewerage zone wise generation of domestic pollution loads

| Sewerage zone | Population | Sewage Generated (MLD) |
|---|---|---|
| 1. Okhla | 3,981,035 | 955.4 |
| 2. Keshopur | 2,044,928 | 490.8 |
| 3. Rithala | 2,461,719 | 590.8 |
| 4. Coronation Pillar | 579,238 | 139.0 |
| 5. Shahdara | 2,384,520 | 572.3 |
| Total | 11,451,442 | 2,748.3 |

varying densities. As a result, the distribution of population in these zones is not uniform. In order to ascertain the total population in each sewerage zone, an intersection of boundaries of sewerage zones and planning zones is obtained. The areas of resulting sub zones are then multiplied with the corresponding Planning Zone densities to find the population of each sub zone. The total population of all the sub zones belonging to one particular sewerage zone is finally obtained. From the total population, total volume of domestic sewage generated can be calculated. Table 10.18 gives the particulars regarding the generation of domestic pollution loads in various sewerage zones.

#### 10.7.1.2 Pollution Load Generation from Industrial Sources

Industries, unlike other human activity, can generate water pollution loads that are highly concentrated in terms of space and time, highly varied in nature (some being refractory and very difficult to either destroy or remove once they have entered a stream), and being highly toxic, pose much more serious hazards, thereby, deserving a much more careful consideration.

It is not possible here to go into the specifics of the wide variety of polluting chemicals generated and discharged by industries. For illustration, only BOD is discussed to indicate the severity of the problem.

There are a large number of large, medium and small scale industries in the U.T. of Delhi. A major fraction of these industrial units are located within the 28 major industrial areas and thus, act as another source of concentrated generation of pollutants. Most of the large and many small and medium scale industries have their own effluent treatment systems, but in the absence of relevant information regarding the extent of treatment provided by the industries, it is difficult to consider pollution reduction due to treatment. The name of industrial areas with their respective sewerage zone is provided in Table 10.19. There are 15 common effluent treatment plants planned for the 28 industrial areas as shown in Table 10.20. Some of them are installed and working. However, the performance of these treatment plants is not satisfactory due to various reasons, including the nature of wastes, non-existence of pre-treatment needed in many industries, etc.

**Table 10.19** Sewerage zone-wise generation of industrial pollution loads

| Sewerage zone | Industrial area | Industrial discharge (MLD) |
|---|---|---|
| 1. Okhla | Okhla Industrial Area | 12.0 |
| | Okhla Industrial Estate | 10.0 |
| | Okhla Flatted Factories | 7.5 |
| | Friends Colony Industrial Estate | 3.0 |
| | Mohan Co-operative Industrial Estate | 13.8 |
| | **Sub Total** | **46.3** |
| 2. Keshopur | Rohtak Road | 14.00 |
| | Karampura Industrial Estate | 9.09 |
| | Mayapuri Industrial Estate | 12.0 |
| | Najafgarh Road Industrial Estate (60%) | 7.20 |
| | Kirti Nagar Industrial Estate | 8.0 |
| | Tilak Nagar Industrial Estate | 8.0 |
| | Naraina Industrial Estate | 10.56 |
| | Mangolpuri Industrial Estate (40%) | 1.5 |
| | **Sub Total** | **70.35** |
| 3. Rithala | Mangolpuri Industrial Estate (60%) | 2.4 |
| | Najafgarh Road Industrial Estate (40%) | 4.80 |
| | Anand Parbat Industrial Estate | 8.0 |
| | Lawrence Road Estate | 2.0 |
| | Badli Indusrial Area | 1.53 |
| | Udyognagar Industrial Estate | 3.21 |
| | Rajasthan Udyognagar Industrial Estate | 10.0 |
| | SMA Industrial Area | 12.0 |
| | Narela Industrial Estate (90%) | 10.0 |
| | Wazirpur Industrial Estate | 20.0 |
| | GT Karnal Road Industrial Estate | 4.0 |
| | SSI Indusrial Area | 3.5 |
| | DSIDC Nangloi Industrial Area | 4.0 |
| | **Sub Total** | **85.44** |
| 4. Coronation Pillar | Azadpur Industrial Estate | 1.94 |
| | Narela Industrial Estate (10%) | 0.54 |
| | **Sub Total** | **2.48** |
| 5. Shahdara | Jhilmil Industrial Estate | 7.0 |
| | Patparganj Industrial Estate | 3.0 |
| | Shahdara Industrial Estate | 3.5 |
| | **Sub Total** | **13.5** |
| | **Grand Total** | **218.07** |

*Note*: Narela (30%) lies outside the Sewerage Zones
*Source*: Central Pollution Control Board, Delhi

#### 10.7.1.3 Pollution Loads Contributed to Yamuna and Agra Canal Through Drains

About 60% of the Delhi population is covered under sewerage facilities; a large part of sewage generated from unsewered areas and also sewered areas where sewer line is defunct due to chocking, silting or sinking the sewage flows in storm water

**Table 10.20** Common effluent treatment plants with design capacity in Delhi

| S. No. | Name of CETP | Capacity (MLD) |
|---|---|---|
| 1 | Anand Parbat Industrial Estate | 24.0 |
| 2 | Badli Industrial Estate | 12.0 |
| 3 | Nangloi Industrial Area | 12.0 |
| 4 | G.T. Karnal Road | 6.0 |
| 5 | Jhilmil Industrial Estate | 16.8 |
| 6 | Lawrence Road Industrial Estate | 12.0 |
| 7 | Mangolpur Industrial Estate | 2.4 |
| 8 | Mayapuri Industrial Estate | 12.0 |
| 9 | Mohan Co-operative Industrial Estate | 16.8 |
| 10 | Najafgarh Road Industrial Estate | 7.2 |
| 11 | Naraina Industrial Estate | 24.0 |
| 12 | Okhla Industrial Area | 24.0 |
| 13 | Okhla Industrial Estate | 12.0 |
| 14 | S.M.A. Industrial Area | 12.0 |
| 15 | Wazirpur Industrial Estate | 24.0 |
| Total | | **218.2** |

**Table 10.21** Discharge and BOD loads in different drains of Delhi

| Drains | BOD Load (T/d) | Discharge ($m^3/s$) | Ultimate disposal |
|---|---|---|---|
| Najafgarh Drain | 79.68 | 24.14 | Yamuna u/s Okhla Barrage |
| Shahdara Drain | 50.53 | 7.65 | Yamuna d/s Okhla Barrage |
| Drain Near Sarita Vihar Bridge | 22.85 | 6.24 | Agra Canal |
| Sen Nursing Home Drain | 17.61 | 1.24 | Yamuna u/s Okhla Barrage |
| Power House Drain | 15.09 | 0.63 | Yamuna u/s Okhla Barrage |
| Maharani Bagh Drain | 9.28 | 0.48 | Yamuna u/s Okhla Barrage |
| Civil Mill Drain | 8.78 | 0.40 | Yamuna u/s Okhla Barrage |
| Sarita Vihar Drain | 8.39 | 0.41 | Yamuna d/s Okhla Barrage |
| Barapulla Drain | 4.18 | 0.75 | Yamuna u/s Okhla Barrage |
| Drain At LPG Bottling Plant | 4.05 | 0.74 | Agra Canal |
| ISBT Drain | 3.77 | 0.41 | Yamuna u/s Okhla Barrage |
| Tuglakabad Drain | 3.35 | 0.34 | Agra Canal |
| Tehkhand Drain | 2.97 | 0.26 | Agra Canal |
| Magazine Road Drain | 1.42 | 0.05 | Yamuna u/s Okhla Barrage |
| Sweeper Colony Drain | 1.08 | 0.09 | Yamuna u/s Okhla Barrage |
| Tonga Stand Drain | 0.76 | 0.05 | Yamuna u/s Okhla Barrage |
| Metcalf house Drain | 0.32 | 0.07 | Yamuna u/s Okhla Barrage |
| Drain No.14 | 0.21 | 0.13 | Yamuna u/s Okhla Barrage |
| Kalkaji Drain | 0.15 | 0.03 | Yamuna u/s Okhla Barrage |
| Khyber Pass Drain | 0.05 | 0.09 | Yamuna u/s Okhla Barrage |
| Total | 234.52 | 44.2 | |

drains. The CPCB has been regularly monitoring the drains in Delhi. The average values of monitoring results of drains are presented in Table 10.21. It is clear from the table that the Najafgarh Drain along with the supplementary drain, carries maximum pollution load to the Yamuna River followed by the Shahdara drain. The two drains together contribute about 55% by load and 72% by volume of waste water.

## 10.8 Concluding Remarks

Based on the discussions and data, the following is concluded:

- It is estimated that out of 8,444 MLD of wastewater generated in the basin, about 4,458 MLD is discharged directly into the Yamuna River.
- About 1,200 MLD is discharged into tributaries of Yamuna River.
- Approximately 2,786 MLD is either disposed of on land or used for irrigation.
- Delhi generates about 3,743 MLD of wastewater, which is 44% of the entire sewage generated in the basin and 84% of the sewage being discharged into the Yamuna along its entire course.
- Uttar Pradesh, Madhya Pradesh and Rajasthan share almost equal amounts of sewage generation in this basin.
- Delhi has the highest sewage treatment capacity of 2,330 MLD which is about 68% of the total sewage treatment capacity in the basin. However, there is still a large gap of 1,413 MLD between generation and treatment capacity.
- Though several STPs have been installed along the river course with a designed capacity of the order of 2,332.25 MLD for Delhi, 327 MLD for Haryana, and 403.25 MLD for Uttar Pradesh, but the river water quality is still the worst. The main causes of the inefficient functioning of STPs are (i) STPs are in general practically not meeting their compliance, (ii) under running of most of the STPs due to the lack of connection, (iii) improper drainage system, (iv) excess BOD concentration coming to the plant due to inadequate water supply, etc.
- The density of STPs in Delhi is the highest and is mostly based on the Activated Sludge Process (ASP). However, on the other part, the type belongs to either Oxidation Pond (OP) or Up-flow Anaerobic Sludge Blanket (UASB) type.

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# Chapter 11
# Water Quality Index and Status

**Abstract** This chapter includes a methodology for determining the water quality status of a river. The water quality of the Yamuna River is described using indirect and direct methods. The indirect method is based on various water quality indices (WQI), whereas the direct method uses water quality data at various locations on the river. Detailed mathematical formulations of the various WQIs, such as National Sanitation Foundation (NSF), Nonlinear NSF, Canadian Council method, Nasirian (2007) method, Universal method, and European Classification Scheme, are presented. Besides the WQI-based approach, a detailed analysis of water quality data is presented in order to determine water quality trends, profile, and monthly variations in the river. The bio-mapping technique is also used to detect the gradual change in the water quality status of the Yamuna River.

## 11.1 Water Quality Index

Continuous assessment of physical, chemical and biological parameters of water is an essential part of water quality control programmes. These efforts lead to the accumulation of considerable information which cannot usually produce direct qualitative determination of water quality. Various methods of data manipulations have been used to condense these records into a more suitable form, and promote effective communication to all concerned. Moreover, these methods can produce a proper means for classification and comparison of different water bodies. The water quality index (WQI) system is a well-known method of expressing water quality that offers a simple, stable and reproducible unit of measure which responds to changes in the principal characteristics of water (Brown et al., 1972).

WQI can be defined as a single numerical expression which reflects the composite influence of significant physical, chemical and microbiological parameters of water quality. A number of indices have been developed to summarize water quality data in an easily expressible and easily understood format (Couillard and Lefebvre, 1985). Since Horton (1965) proposed the first WQI, a great deal of consideration has been given to the development of index methods. The basic differences among these indices are the way their sub-indices were developed. Walski and Parker (1974) used an exponential function to represents the sub indices of various quality variables. Landwehr (1979) suggested the Pearson type 3-distribution function to represent the sub-indices of all quality variables. Bhargava (1987) modified the

R.K. Rai et al., *The Yamuna River Basin*, Water Science and Technology Library 66,
DOI 10.1007/978-94-007-2001-5_11, 

exponential formula; Dinius (1987) used a power function for the majority of sub indices. Various modifications have also been done in the recent years (Nives, 1999; Swamee and Tyagi, 2000; Harrison et al., 2000; Faisal et al., 2003; Ahmad et al., 2004; Shiow-Mey et al., 2004; etc.). However, Nasirian (2007) compared various WQI systems currently in use and showed that none of them describes quality of water from mining effluent because most of sub-indices in current WQIs are not relevant to indicating changes in water quality brought about by mining activities. Looking into the importance of WQI, this chapter addresses the application and comparison of different WQIs. The WQI techniques described herein are: (i) National Sanitation Foundation's WQI (NSF-WQI) (1970); (ii) Multiplicative NSF-WQI technique (1974); (iii) CCME WQI (2001); (iv) WQI (Nasirian, 2007); and (v) Universal Water Quality Index based on the European classification scheme (Boyacioglu, 2007).

### *11.1.1 National Sanitation Foundation's WQI (NSF-WQI)*

During the year 1970, a Water Quality Index (WQI) was developed at the National Sanitation Foundation (NSF). It appears to be the most comprehensive form of WQI (Brown et al., 1972; Landwehr and Deininger, 1976; Sharifi, 1990; etc.). While formulating, the NSF adopted opinions from more than 140 selected water quality experts. On the basis of questionnaire, the NSF was able to draw up a list of valid parameters which had been rated on a scale of importance. They also established the relation of water quality to values in the form of rating curves. In developing rating curves the experts were asked to attribute values for variation in the level of water quality caused by different levels of each of the selected parameters.

WQI is a 100 point scale that summarizes results from a total of nine different parameters. The selected water quality parameters and their weights are given in Table 11.1. The WQI can be mathematically expressed as follows:

$$\text{WQI} = \sum_{i=1}^{n} W_i Q_i \tag{11.1}$$

**Table 11.1** Water quality parameters and their weight (NSF-WQI)

| S. No. | Parameters | Unit | Weight |
|---|---|---|---|
| 1 | Dissolved Oxygen (DO) | % Saturation | 0.17 |
| 2 | Fecal Coliform (FC) | Count/100 ml | 0.16 |
| 3 | pH | Standard unit | 0.11 |
| 4 | Biological Oxygen Demand (BOD) | mg/l | 0.11 |
| 5 | Temperature change | (°C) | 0.10 |
| 6 | Total Phosphate (TP) | mg/l | 0.10 |
| 7 | Nitrate (TN) | mg/l | 0.10 |
| 8 | Turbidity | NTU | 0.08 |
| 9 | Total Suspended Solids (TSS) | mg/l | 0.07 |
| Total Weight | | | 1.00 |

where WQI is the index number between 0 and 100; $Q_i$ is the water quality score for $i$th parameter (number between 0 and 100); $W_i$ is the weight of the $i$th parameter; and $n$ is the number of parameters ($n = 9$).

The water quality score of each parameter is obtained from the related rating curve or equation. The rating curve rapidly transforms the concentration or quotient of a parameter into a quality score. For all the nine parameters, the rating curve can be developed, which is discussed as follows.

#### 11.1.1.1 Rating Curve for Fecal Coliform

Water quality rating curve for the fecal coliform (FC) established by NSF (Fig. 11.1) has been fitted for computational ease.

$$Q_{FC} = -12.12\ \ln(FC) + 99.231;\ \text{if FC} \le 500\,(R^2 = 0.9996) \tag{11.2}$$

$$Q_{FC} = 224.55\ (FC)^{-0.343};\ \text{if } 500 < \text{FC} \le 45{,}000\,(R^2 = 0.995) \tag{11.3}$$

$$Q_{FC} = -3.233\ \ln(FC) + 40.585;\ \text{if } 45{,}000 < \text{FC} < 100{,}000\,(R^2 = 0.994) \tag{11.4}$$

$$Q_{FC} = 2.0;\ \text{if FC} > 100{,}000 \tag{11.5}$$

#### 11.1.1.2 Rating Curve for Total Solids

The fitted rating curve (Fig. 11.2) can be expressed through the following set of numerical expressions:

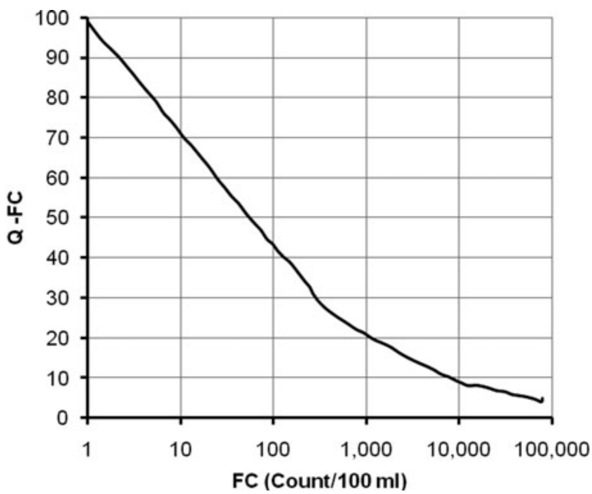


**Fig. 11.1** Rating curve for fecal coliform

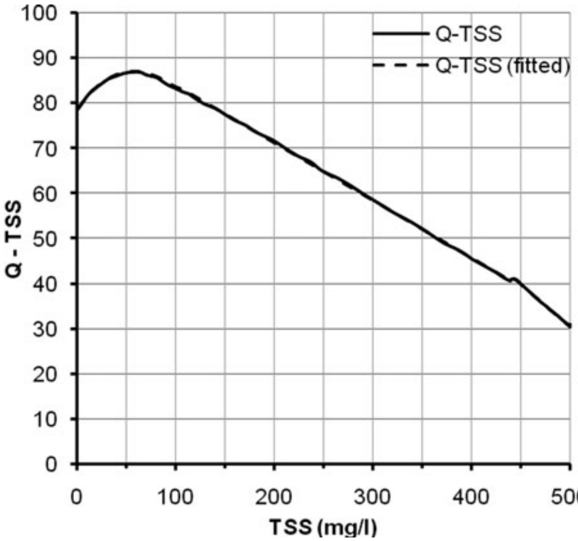


**Fig. 11.2** Rating curve for TSS

$$Q_{\mathrm{TSS}} = 0.000007(\mathrm{TSS})^3 - 0.0034(\mathrm{TSS})^2 + 0.3209(\mathrm{TS}) + 78.557;\ \text{if } 0 < \mathrm{TSS} \le 100\,(R^2 = 0.996) \quad (11.6)$$

$$Q_{\mathrm{TSS}} = -0.1277(\mathrm{TSS}) + 96.866;\ \text{if } 100 < \mathrm{TSS} \le 440\,(R^2 = 0.998) \quad (11.7)$$

$$Q_{\mathrm{TSS}} = -0.1889(\mathrm{TSS}) + 124.92;\ \text{if } 440 < \mathrm{TSS} \le 500\,(R^2 = 0.999) \quad (11.8)$$

$$Q_{\mathrm{TSS}} = 20;\ \text{if } \mathrm{TSS} > 500 \quad (11.9)$$

#### 11.1.1.3 Rating Curve for Dissolved Oxygen

The dissolved oxygen is expressed in terms of the percentage saturation. The $DO_{sat}$ can be estimated from the following relationship:

$$\%\,\mathrm{DO_{sat}} = \frac{\mathrm{DO}}{\mathrm{DO_{sat}}} \times 100 \quad (11.10)$$

where $DO_{sat}$ is the saturated DO at $T$°C for water. The $DO_{sat}$ is estimated using the following relationship:

$$\mathrm{DO_{sat}} = \frac{1}{(0.001639\,T + 0.06282)} - 1.279 \quad (11.11)$$

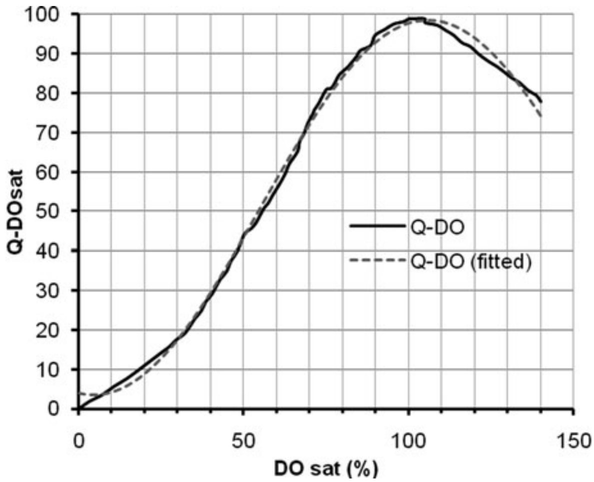


**Fig. 11.3** Rating curve for DO

where $T$ is the water temperature (°C). The rating curve based on Fig. 11.3 can numerically be expressed as:

$$Q_{\mathrm{DO}} = 0.0;\ \text{if } \%\mathrm{DO}_{\mathrm{sat}} \le 0.0 \tag{11.12}$$

$$\begin{aligned} Q_{\mathrm{DO}} = {} & 47.54 \cos[0.03103(\%\mathrm{DO}_{\mathrm{sat}}) - 3.282] + 50.96; \\ & \text{if } 0 < \%\mathrm{DO}_{\mathrm{sat}} \le 140 \end{aligned} \tag{11.13}$$

$$Q_{\mathrm{DO}} = 50.0;\ \text{if } \%\mathrm{DO}_{\mathrm{sat}} > 140 \tag{11.14}$$

#### 11.1.1.4 Rating Curve for Turbidity

Turbidity is measured in terms of NTU. The rating curve developed by NSF is shown in Fig. 11.4. For computational ease the rating curve has been best fitted with appropriate techniques and is shown in Fig. 11.4.

The established fitted rating curve is expressed with the following set of equations.

$$\begin{aligned} Q_{\mathrm{Turb}} = {} & \left[8424 + 18.88 \times (\mathrm{Turb} + 8.527)^2\right]^{0.5} \\ & -4.628\,\mathrm{Turb};\ \text{if } 0 < \mathrm{Turb} \le 100\,\mathrm{NTU} \end{aligned} \tag{11.15}$$

$$Q_{\mathrm{Turb}} = 5;\ \text{if } \mathrm{Turb} > 100\,\mathrm{NTU} \tag{11.16}$$

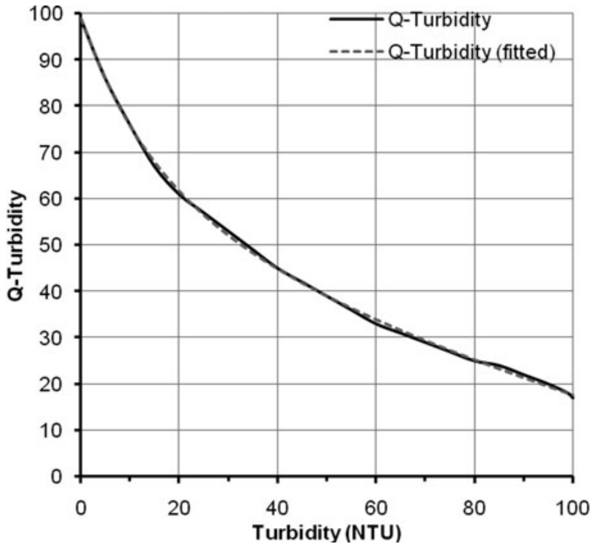


**Fig. 11.4** Rating curve for turbidity

#### 11.1.1.5 Rating Curve for pH

The rating curve developed by NSF was fitted and the comparison is shown in Fig. 11.5. The rating curve can be mathematically expressed as follows:

$$Q_{\text{pH}} = 0;\ \text{if pH} < 2 \tag{11.17}$$

$$\begin{aligned} Q_{\text{pH}} = &-0.0799\,\text{pH}^5 + 1.3838\,\text{pH}^4 - 8.115\,\text{pH}^3 + 21.389\,\text{pH}^2 \\ &- 23.761\,\text{pH} + 9.209;\ \text{if } 2 \le \text{pH} < 7.5\,(R^2 = 0.9997) \end{aligned} \tag{11.18}$$

$$\begin{aligned} Q_{\text{pH}} = &-0.9647\,\text{pH}^4 + 38.69838\,\text{pH}^3 - 572.38\,\text{pH}^2 \\ &+ 3676.2\,\text{pH} - 8555.0;\ \text{if } 7.5 \le \text{pH} \le 12.0\,(R^2 = 0.9999) \end{aligned} \tag{11.19}$$

$$Q_{\text{pH}} = 0;\ \text{if pH} > 12 \tag{11.20}$$

#### 11.1.1.6 Rating Curve for BOD

The fitted rating curve developed from NSF for biological oxygen demand (BOD) is shown in Fig. 11.6. A list of mathematical expressions for computing the parameter score is:

$$\begin{aligned} Q_{\text{BOD}} = &-0.2311\,\text{BOD}^4 + 3.0227\,\text{BOD}^3 - 11.754\,\text{BOD}^2 \\ &+ 3.3994\,\text{BOD} + 100;\ \text{if BOD} < 5\,(R^2 = 0.996) \end{aligned} \tag{11.21}$$

$$\begin{aligned} Q_{\text{BOD}} = &-0.0027\,\text{BOD}^3 + 0.236\,\text{BOD}^2 - 7.4486\,\text{BOD} + 87.674; \\ &\text{if } 5 \le \text{BOD} < 30\,(R^2 = 0.9996) \end{aligned} \tag{11.22}$$

$$Q_{\text{BOD}} = 2;\ \text{if BOD} \ge 30 \tag{11.23}$$

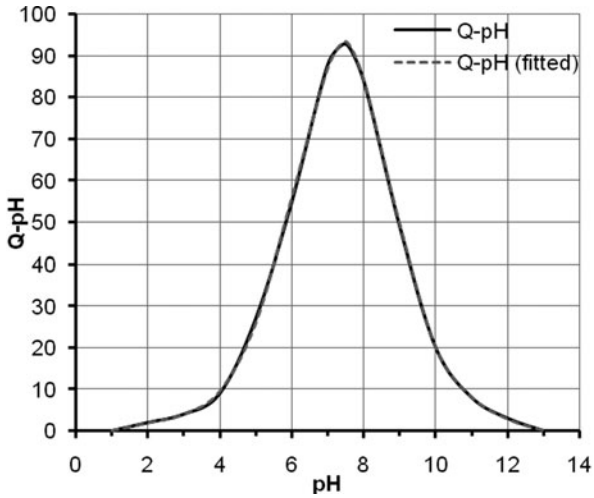


**Fig. 11.5** Rating curve for pH

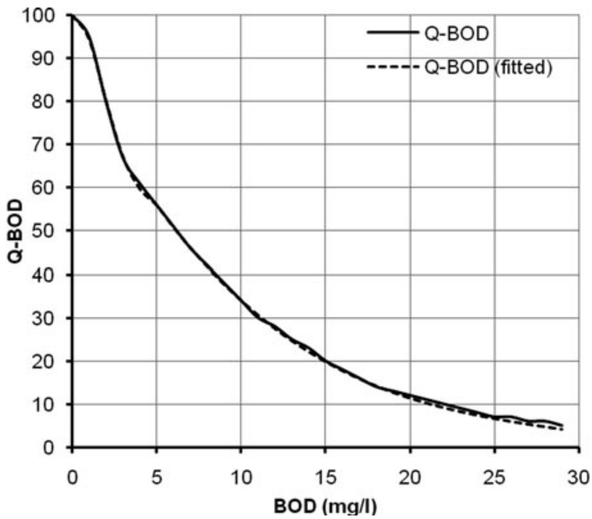


**Fig. 11.6** Rating curve for BOD

#### 11.1.1.7 Rating Curve for Nitrate

The rating curve of nitrate was exponentially fitted (Fig. 11.7) and expressed as follows:

$$Q_{NO_3} = 28.0\ \exp[-0.270(NO_3)] + 72.0\exp[-0.035(NO_3)]\,; \quad \text{if } 0 \le NO_3 \le 100 \tag{11.24}$$

$$Q_{NO_3} = 1.0;\ \text{if } NO_3 > 100 \tag{11.25}$$

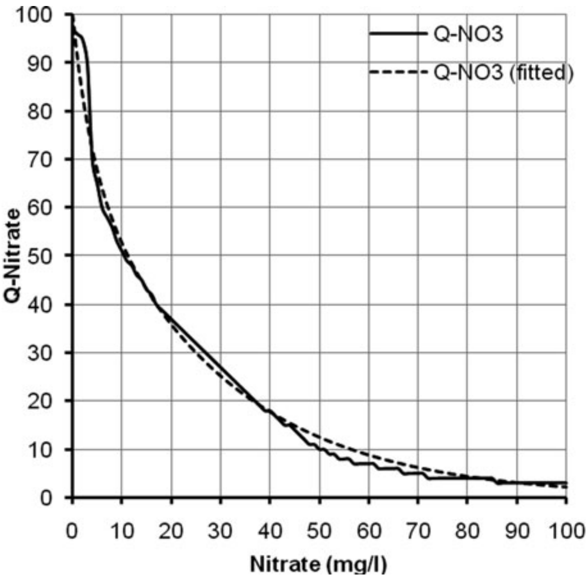


**Fig. 11.7** Rating curve for nitrate

#### 11.1.1.8 Rating Curve for Phosphate

The rating curve of phosphate is suitably fitted (Fig. 11.8) and expressed as follows:

$$Q_{\mathrm{TP}} = 98.37 - 316.5\,\mathrm{TP}^2 + \frac{0.01637}{\mathrm{TP}}; \quad \text{if } 0.01 < \mathrm{TP} \le 0.09 \tag{11.26}$$

$$Q_{\mathrm{TP}} = 35.22\ \exp\left\{\frac{0.3312}{\mathrm{TP}} - 0.2135\,\mathrm{TP}\right\}; \quad \text{if } 1.0 \le \mathrm{TP} \le 7.5 \tag{11.27}$$

$$Q_{\mathrm{TP}} = 7;\ \text{if } 7.5 < \mathrm{TP} \le 10.0 \tag{11.28}$$

$$Q_{\mathrm{TP}} = 2;\ \text{if } \mathrm{TP} > 10.0 \tag{11.29}$$

#### 11.1.1.9 Rating Curve for Temperature Change

Temperature is a critical water quality and environmental parameter because it governs the kinds and types of aquatic life, regulates the maximum dissolved oxygen concentration of the water, and influences the rate of chemical and biological reactions. The organisms within the ecosystem have preferred temperature regimes

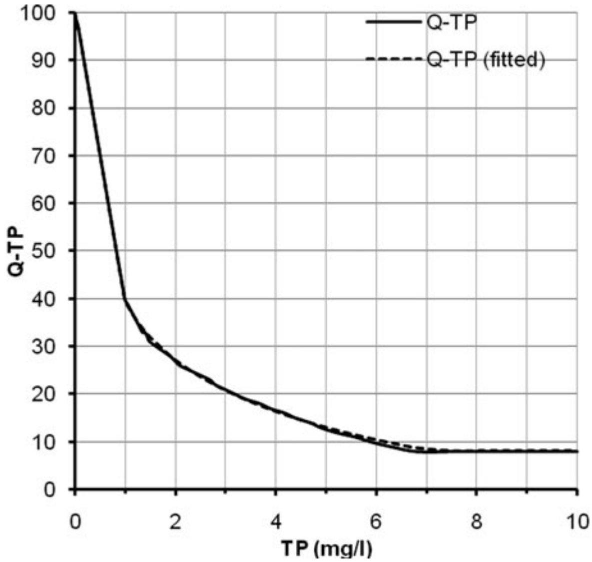


**Fig. 11.8** Rating curve for total phosphate

that change as a function of season, organism age or life stage, and other environmental factors. With respect to chemical and biological reactions, the higher the water temperature the higher the rate of chemical and metabolic reactions.

Seasonal variations in stream temperature may be caused by changing air temperature, solar angle, meteorological events, and a number of physical aspects related to the stream and watershed. These physical features include stream origin, velocity, vegetation types and coverage, stream configuration, land-use, and percentage of impervious area. For example, a narrow, deep well-shaded shoreline reduces the impact of warming by the sun; whereas, a wide shallow stream would be more impacted by solar heating.

The change in temperature ($\Delta T$) refers to the change in temperature between upstream and downstream control points. The rating curve of temperature change developed by NSF is suitably fitted for quick computational purposes (Fig. 11.9) and is expressed with following set of equations.

$$Q_{\Delta T} = 3.8\,\Delta T + 93;\ \text{if}\ -10 \leq \Delta T \leq 0 \tag{11.30}$$

$$Q_{\Delta T} = -5.6\,\Delta T + 101;\ \text{if}\ 0 < \Delta T \leq 10 \tag{11.31}$$

$$Q_{\Delta T} = -2.8\,\Delta T + 73;\ \text{if}\ 10 < \Delta T \leq 15 \tag{11.32}$$

$$Q_{\Delta T} = -1.8\,\Delta T + 58;\ \text{if}\ 15 < \Delta T \leq 20 \tag{11.33}$$

$$Q_{\Delta T} = -1.2\,\Delta T + 46;\ \text{if}\ 20 < \Delta T \leq 30 \tag{11.34}$$

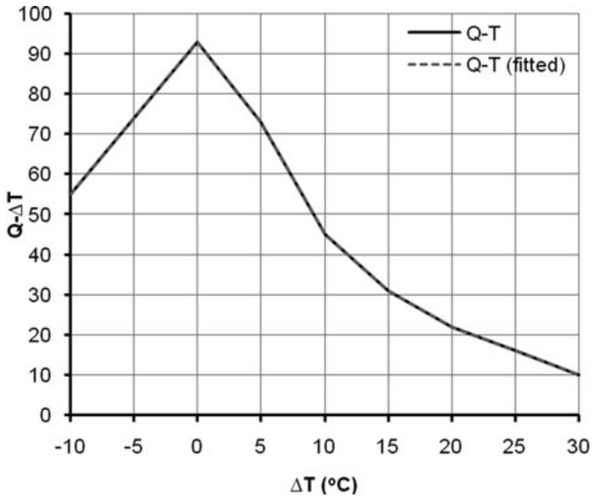


**Fig. 11.9** Rating curve for temperature change

**Table 11.2** Water class based on NSF-WQI

| WQI | Water Class |
|---|---|
| 91–100 | Excellent |
| 71–90 | Good |
| 51–70 | Medium to average |
| 26–50 | Fair |
| 0–25 | Poor |

Once the quality score of the water quality parameters is estimated using the rating curves, the WQI can be estimated using eq. (11.1). Based on the WQI, the water quality can be classified as in Table 11.2.

The computational step for using the NSF-WQI is shown in Example 11.1.

### *11.1.2 Multiplicative NSF-WQI*

Despite the apparent responsiveness of WQI to changes in water quality conditions, analysis of data from the various field studies suggests that the additive WQI (eq. (11.1)) lacks sensitivity in adequately reflecting the effect of a single low value parameter on the overall water quality. O'Connor (1971) noted that the additive model is a good choice when all the parameters are within a reasonable range, but a multiplicative form is more sensitive to discontinuities in the overall quality which may result in zero or poor quality in any parametric dimension. WQI (M) is significantly more sensitive to the effect of a single bad parameter. As a result, a multiplicative form of WQI (WQI-M) can be numerically expressed as follows:

$$\text{WQI}(M) = \prod_{i=1}^{n} Q_i^{w_i} \tag{11.35}$$

where WQI($M$) is the multiplicative water quality index, a number between 0 and 100; $Q_i$ is the score of the $i$th parameter, a number between 0 and 100; $w_i$ is the unit weight of the parameter; and $n$ is the number of parameter considered.

In the determination of WQI($M$), $Q_i$, $W_i$, and $n$ are similar to the NSF-WQI. When all the parameters are not measured (i.e. only 5 parameters out of 9) then the weights are adjusted, instead of WQI, as follows:

$$w_i^{\text{new}} = w_i + w_i \times \left( \frac{1 - \sum_i w_i}{\sum_i w_i} \right) \tag{11.35a}$$

The calculation procedure of WQI (M) is given in Example 11.2.

**Example 11.1** During January, 2008 the water quality parameters measured at Palla site (i.e. upstream to the Wazirabad barrage) in Yamuna River are: Temperature at Sonepat (*d*/*s*) = 13°C, Temperature at Palla = 12°C, pH = 7.67, DO = 10.5, BOD = 2.0, FC = 1700. Calculate the WQI and water quality class using NSF WQI technique for Palla.

| S. No. | Parameters | Measured value | Unit | Weight | Sub-index | Weight used | WQI (A) |
|---|---|---|---|---|---|---|---|
| (a) | DO | 10.5 | mg/l | | | | |
| (b) | $DO_{sat}$ | 10.84 | mg/l | | | | |
| (c) | *T* (u/s) | 13 | °C | | | | |
| (d) | *T* (site) | 12 | °C | | | | |
| 1 | $\%DO_{sat}$ | 96.83 | % | 0.17 | 96.68 | 0.17 | 16.44 |
| 2 | FC | 1,700.0 | count/100 ml | 0.16 | 17.51 | 0.16 | 2.80 |
| 3 | pH | 7.67 | std unit | 0.11 | 91.69 | 0.11 | 10.09 |
| 4 | BOD | 2 | mg/l | 0.11 | 80.27 | 0.11 | 8.83 |
| 5 | Delta *T* | 1 | °C | 0.10 | 95.40 | 0.10 | 9.54 |
| 6 | TP | * | mg/l | 0.10 | 2.00 | 0.00 | 0 |
| 7 | TN | * | mg/l | 0.10 | 1.00 | 0.00 | 0 |
| 8 | Turbidity | * | NTU | 0.08 | 5.00 | 0.00 | 0 |
| 9 | TSS | * | mg/l | 0.07 | 20.00 | 0.00 | 0 |
| Total | | | | **1.00** | | **0.65** | **47.69** |

* represents the values which were not measured

When all the nine parameters are not measured then WQI will be adjusted as: $\text{WQI}_{\text{adjusted}} = \frac{\text{WQI}_{\text{calculated}}}{\sum_{i=1}^{n} w_i}$

The water quality index is calculated as: WQI = 47.69/0.65 = 73.37; and the water class can be categorized as "GOOD".

**Example 11.2** During January, 2008 the water quality parameters measured at Palla site (i.e. upstream to the Wazirabad barrage) in Yamuna River are: Temperature at Sonepat (d/s) = 13°C, Temperature at Palla = 12°C, pH = 7.67, DO = 10.5, BOD = 2.0, FC = 1,700. Calculate the WQI and water quality class using WQI (M) technique for Palla.

| S. No. | Parameters | Measured value | Unit | Weight | Sub index | Weight used | Adjusted weight | WQI (M) |
|---|---|---|---|---|---|---|---|---|
| (a) | DO | 10.5 | mg/l | | | | | |
| (b) | $DO_{sat}$ | 10.84 | mg/l | | | | | |
| (c) | T (u/s) | 13 | °C | | | | | |
| (d) | T (site) | 12 | °C | | | | | |
| 1 | $\%DO_{sat}$ | 96.83 | % | 0.17 | 96.68 | 0.17 | 0.26 | 3.31 |
| 2 | FC | 1,700 | Counts/100 ml | 0.16 | 17.51 | 0.16 | 0.25 | 2.02 |
| 3 | pH | 7.67 | Std unit | 0.11 | 91.69 | 0.11 | 0.17 | 2.15 |
| 4 | BOD | 2 | mg/l | 0.11 | 80.27 | 0.11 | 0.17 | 2.10 |
| 5 | Delta T | 1 | °C | 0.10 | 95.40 | 0.10 | 0.15 | 2.02 |
| 6 | TP | * | mg/l | 0.10 | 2.00 | 0.00 | 0.00 | 1.00 |
| 7 | TN | * | mg/l | 0.10 | 1.00 | 0.00 | 0.00 | 1.00 |
| 8 | Turbidity | * | NTU | 0.08 | 5.00 | 0.00 | 0.00 | 1.00 |
| 9 | TSS | * | mg/l | 0.07 | 20.00 | 0.00 | 0.00 | 1.00 |
| Total | | | | **1.00** | | **0.65** | **1.00** | **60.84** |

* represents the values which were not measured

Therefore the Multiplicative WQI [WQI(*M*)] is 60.84 and the corresponding water class can be categorized as “MEDIUM to AVERAGE”. The lesser value as compared to the WQI(*A*) shows the importance of monitored parameter.

### *11.1.3 CCME WQI*

The Water Quality Index (WQI) of the Canadian Council of Ministers of the Environment (CCME) is based on a formula developed by the British Columbia Ministry of Environment, Lands and Parks and modified by Alberta Environment. The index incorporates three elements: (a) *scope*: the number of variables not meeting water quality objectives; (b) *frequency*: the number of times these objectives are not met; and (c) *amplitude*: the amount by which the objectives are not met. The index produces a number between 0 (worst water quality) and 100 (best water quality). These numbers are divided into five descriptive categories to simplify presentation.

#### 11.1.3.1 Data Requirement

The time period chosen will depend on the amount of data available and the reporting requirements of the user. A minimum period of one year is often used because data are usually collected to reflect this period (monthly or quarterly monitoring data). Data from different years may also be clubbed, especially when monitoring in certain years is incomplete, but as with combining stations some degree of variability will be lost.

The calculation of CCME-WQI requires at least four variables, sampled a minimum of four times, be used. However, a maximum number of variables or samples are not specified. The selection of appropriate water quality variables for a particular region is necessary for the index to yield meaningful results. Clearly, choosing a small number of variables for which the objectives are not met will provide a different picture than if a large number of variables are considered, only some of which do not meet objectives.

#### 11.1.3.2 Calculation of Index

The CCME WQI can be expressed through the three elements as follows:

$$\text{CCME : WQI} = 100 - \left( \frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{11.36}$$

The divisor 1.732 normalizes the resultant values within the range between 0 and 100.

$F_1$ (Scope) represents the percentage of variables that do not meet their objectives a least once during the time period under consideration ("failed variables"), relative to that number of variables measured:

$$F_1 = \left( \frac{\text{Number of failed variables}}{\text{Total number of variables}} \right) \times 100 \tag{11.37}$$

$F_2$ (Frequency) represents the percentage of individual tests that do not meet the objectives ("failed test").

$$F_2 = \left( \frac{\text{Number of failed tests}}{\text{Total number of tests}} \right) \times 100 \tag{11.38}$$

$F_3$ (Amplitude) represents the amount by which failed test values do not meet their objectives. $F_3$ is calculated using the following three steps:

(a) The number of times by which an individual concentration is greater than (or less than, when the objective is a minimum) the objective is termed an "excursion" and is expressed as follows. When the test value must not exceed the objective (for example, BOD):

$$\text{Excursion}_i = \left( \frac{\text{Failed test value}_i}{\text{Objective}_i} \right) - 1 \tag{11.39}$$

For the cases in which the test value must not fall below the objectives (for example DO):

$$\text{Excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed test value}_i}\right) - 1 \quad (11.40)$$

(b) The collective amount by which individual tests are out of compliance is calculated by summing the excursions of individual tests from their objectives and dividing by the total number of tests (both those meeting objectives and those not meeting objectives). This variable, referred to as the normalized sum of excursions, or *nse*, is calculated as:

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{Excursion}_i}{\text{Number of tests}} \quad (11.41)$$

$F_3$ is then calculated by an asymptotic function that scales the normalized sum of the excursions from objectives (*nse*) to yield a range between 0 and 100.

$$F_3 = \frac{\text{nse}}{0.01 \times \text{nse} + 0.01} \quad (11.42)$$

Once the factors have been obtained, the CCME WQI can be calculated using eq. (11.36). Based on the CCME WQI value, water quality is ranked by relating it to a descriptive category as follows (Table 11.3):

Application of the CCME-WQI is presented in Example 11.3.

**Example 11.3** Estimate the CCME-WQI from the monthly data collected from the Palla site of Yamuna River. The water quality parameters measured by CPCB along with objectives are listed in the following Table 11.4.

**Table 11.3** Water class based on CCME-WQI

| Category | CCME WQI | Characteristics |
|---|---|---|
| Excellent | 95–100 | Water quality is protected with a virtual absence of threat or impairment; conditions very close to natural or pristine levels. |
| Good | 80–94 | Water quality is protected with only a minor degree of threat or impairment; conditions rarely depart from natural or desirable levels. |
| Fair | 65–79 | Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels. |
| Marginal | 45–64 | Water quality is frequently threatened or impaired; conditions often depart from natural or desirable levels. |
| Poor | 0–44 | Water quality is almost always threatened or impaired; conditions usually depart from natural or desirable levels. |

**Table 11.4** Monthly water quality data of Palla site in Yamuna River for the year of 2005

| Date | DO | pH | AMM. | TKN | BOD | EC | TC | FC |
|---|---|---|---|---|---|---|---|---|
| Jan, 05 | 8.4 | 8.08 | **1.36** | | 1 | 475 | **8,000** | **900** |
| Feb, 05 | 8.1 | 8.11 | 0.69 | 1.65 | 2 | 574 | **20,000** | **600** |
| Mar, 05 | 8.8 | 8.15 | 0.48 | 1.95 | 4 | 446 | **15,000** | **470** |
| Apr, 05 | 8.8 | 8.61 | 0.41 | 1.12 | 2 | 518 | **18,200** | **1,650** |
| May, 05 | 7.2 | 7.75 | BDL | 0.56 | 1 | 465 | **42,000** | **1,950** |
| Jun, 05 | 7.9 | 7.09 | BDL | BDL | 1 | 496 | **24,000** | **7,400** |
| Jul, 05 | 6.3 | 8.33 | **1.63** | 4.43 | 2 | 398 | **79,000** | 380 |
| Aug, 05 | 7.3 | 7.25 | 0.31 | 0.84 | 1 | 190 | **61,000** | 300 |
| Sep, 05 | 10.9 | 7.26 | BDL | | 3 | 485 | **17,900** | 310 |
| Oct, 05 | 6.1 | 7.3 | 0.14 | | 2 | 265 | **26,000** | **12,100** |
| Nov, 05 | 11.2 | 7.41 | 0.7 | | 2 | **850** | **49,000** | **2,500** |
| Dec, 05 | 9.5 | 7.42 | 0.81 | | 2 | 662 | **130,000** | **6,600** |
| Objective | **>4** | **6.5–8.5** | **<1.2** | **<10** | **<3** | **<700** | **<5,000** | **<4,500** |

## Calculation:

Case I: When all the listed parameters are considered for the analysis

| Date | DO | pH | AMM. | TKN | BOD | EC | TC | FC | |
|---|---|---|---|---|---|---|---|---|---|
| Jan, 05 | 8.4 | 8.08 | **1.36** | | 1 | 475 | **8,000** | 900 | |
| Feb, 05 | 8.1 | 8.11 | 0.69 | 1.65 | 2 | 574 | **20,000** | 600 | |
| Mar, 05 | 8.8 | 8.15 | 0.48 | 1.95 | **4** | 446 | **15,000** | 470 | |
| Apr, 05 | 8.8 | **8.61** | 0.41 | 1.12 | 2 | 518 | **18,200** | 1,650 | |
| May, 05 | 7.2 | 7.75 | BDL | 0.56 | 1 | 465 | **42,000** | 1,950 | |
| Jun, 05 | 7.9 | 7.09 | BDL | BDL | 1 | 496 | **24,000** | **7,400** | |
| Jul, 05 | 6.3 | 8.33 | **1.63** | 4.43 | 2 | 398 | **79,000** | 380 | |
| Aug, 05 | 7.3 | 7.25 | 0.31 | 0.84 | 1 | 190 | **61,000** | 300 | |
| Sep, 05 | 10.9 | 7.26 | BDL | | 3 | 485 | **17,900** | 310 | |
| Oct, 05 | 6.1 | 7.3 | 0.14 | | 2 | 265 | **26,000** | **12,100** | |
| Nov, 05 | 11.2 | 7.41 | 0.7 | | 2 | **850** | **49,000** | 2,500 | |
| Dec, 05 | 9.5 | 7.42 | 0.81 | | 2 | 662 | **130,000** | **6,600** | |
| Objective | **>4** | **6.5–8.5** | **<1.2** | **<10** | **<3** | **<700** | **<5,000** | **<4,500** | **Total** |
| Number of failed tests | 0 | 1 | 2 | 0 | 1 | 1 | 12 | 3 | **20** |
| Number of failed variables | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | **6** |

No. of Variables = 8

No. of Tested Samples = 91

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right) \times 100 = 100 \times 6/8 = 75.00$$

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right) \times 100 = 100 \times 20/91 = 21.98$$

Estimation of Excursions:

| Date | DO | Excursion | pH | Excursion | AMM. | Excursion | TKN | Excursion | BOD | Excursion | EC | Excursion | TC | Excursion | FC | Excursion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan, 05 | 8.4 | 0 | 8.08 | 0.000 | 1.36 | 0.13 | | 0.00 | 1 | 0.00 | 475 | 0.00 | 8,000 | 0.60 | 900 | 0.00 |
| Feb, 05 | 8.1 | 0 | 8.11 | 0.000 | 0.69 | 0.00 | 1.65 | 0.00 | 2 | 0.00 | 574 | 0.00 | 20,000 | 3.00 | 600 | 0.00 |
| Mar, 05 | 8.8 | 0 | 8.15 | 0.000 | 0.48 | 0.00 | 1.95 | 0.00 | 4 | 0.33 | 446 | 0.00 | 15,000 | 2.00 | 470 | 0.00 |
| Apr, 05 | 8.8 | 0 | 8.61 | 0.013 | 0.41 | 0.00 | 1.12 | 0.00 | 2 | 0.00 | 518 | 0.00 | 18,200 | 2.64 | 1,650 | 0.00 |
| May, 05 | 7.2 | 0 | 7.75 | 0.000 | 0.00 | 0.00 | 0.56 | 0.00 | 1 | 0.00 | 465 | 0.00 | 42,000 | 7.40 | 1,950 | 0.00 |
| Jun, 05 | 7.9 | 0 | 7.09 | 0.000 | 0 | 0.00 | 0 | 0.00 | 1 | 0.00 | 496 | 0.00 | 24,000 | 3.80 | 7,400 | 0.64 |
| Jul, 05 | 6.3 | 0 | 8.33 | 0.000 | 1.63 | 0.36 | 4.43 | 0.00 | 2 | 0.00 | 398 | 0.00 | 79,000 | 14.80 | 380 | 0.00 |
| Aug, 05 | 7.3 | 0 | 7.25 | 0.000 | 0.31 | 0.00 | 0.84 | 0.00 | 1 | 0.00 | 190 | 0.00 | 61,000 | 11.20 | 300 | 0.00 |
| Sep, 05 | 10.9 | 0 | 7.26 | 0.000 | 0 | 0.00 | | 0.00 | 3 | 0.00 | 485 | 0.00 | 17,900 | 2.58 | 310 | 0.00 |
| Oct, 05 | 6.1 | 0 | 7.3 | 0.000 | 0.14 | 0.00 | | 0.00 | 2 | 0.00 | 265 | 0.00 | 26,000 | 4.20 | 12,100 | 1.69 |
| Nov, 05 | 11.2 | 0 | 7.41 | 0.000 | 0.7 | 0.00 | | 0.00 | 2 | 0.00 | 850 | 0.21 | 49,000 | 8.80 | 2,500 | 0.00 |
| Dec, 05 | 9.5 | 0 | 7.42 | 0.000 | 0.81 | 0.00 | | 0.00 | 2 | 0.00 | 662 | 0.00 | 130,000 | 25.00 | 6,600 | 0.47 |
| Objective | >4 | 0 | 6.5–8.5 | 0.013 | <1.2 | 0.49 | <10 | 0.00 | <3 | 0.33 | <700 | 0.21 | <5,000 | 86.02 | <4,500 | **2.80** |

The total excursion is computed using the following equations:

$$\text{Excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_i}\right) - 1;$$
$$\text{Excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed test value}_i}\right) - 1$$

$$\sum_{i=1}^{n} \text{Excursion}_i = 89.87$$

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{Excursion}_i}{\text{Number of tests}} = 89.87/91 = 0.99$$
$$F_3 = \frac{\text{nse}}{0.01 \times \text{nse} + 0.01} = \frac{0.99}{0.01 \times 0.99 + 0.01} = 49.68$$

The WQI using CCME approach is:

$$\text{CCME : WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$

$$= 100 - \left(\frac{\sqrt{75.0_1^2 + 21.98^2 + 49.68^2}}{1.732}\right) = 46.52$$

Based on the CCME WQI, the water quality class can be categorized as "MARGINAL", i.e., the conditions often depart from natural or desirable levels.

Case II: When TC and FC is not considered (i.e. for aquatic lives)

| Date | DO | pH | AMM. | TKN | BOD | EC | |
|---|---|---|---|---|---|---|---|
| Jan, 05 | 8.4 | 8.08 | **1.36** | | 1 | 475 | |
| Feb, 05 | 8.1 | 8.11 | 0.69 | 1.65 | 2 | 574 | |
| Mar, 05 | 8.8 | 8.15 | 0.48 | 1.95 | 4 | 446 | |
| Apr, 05 | 8.8 | 8.61 | 0.41 | 1.12 | 2 | 518 | |
| May, 05 | 7.2 | 7.75 | BDL | 0.56 | 1 | 465 | |
| Jun, 05 | 7.9 | 7.09 | BDL | BDL | 1 | 496 | |
| Jul, 05 | 6.3 | 8.33 | **1.63** | 4.43 | 2 | 398 | |
| Aug, 05 | 7.3 | 7.25 | 0.31 | 0.84 | 1 | 190 | |
| Sep, 05 | 10.9 | 7.26 | BDL | | 3 | 485 | |
| Oct, 05 | 6.1 | 7.3 | 0.14 | | 2 | 265 | |
| Nov, 05 | 11.2 | 7.41 | 0.7 | | 2 | **850** | |
| Dec, 05 | 9.5 | 7.42 | 0.81 | | 2 | 662 | |
| Objective | **>4** | **6.5–8.5** | **<1.2** | **<10** | **<3** | **<700** | **Total** |
| Number of failed tests | 0 | 1 | 2 | 0 | 1 | 1 | 5 |
| Number of failed variables | 0 | 1 | 1 | 0 | 1 | 1 | 4 |

Estimation of Excursions:

| Date | DO | Excursion | pH | Excursion | AMM. | Excursion | TKN | Excursion | BOD | Excursion | EC | Excursion |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan, 05 | 8.4 | 0 | 8.08 | 0.000 | **1.36** | 0.13 | | 0.00 | 1 | 0.00 | 475 | 0.00 |
| Feb, 05 | 8.1 | 0 | 8.11 | 0.000 | 0.69 | 0.00 | 1.65 | 0.00 | 2 | 0.00 | 574 | 0.00 |
| Mar, 05 | 8.8 | 0 | 8.15 | 0.000 | 0.48 | 0.00 | 1.95 | 0.00 | 4 | 0.33 | 446 | 0.00 |
| Apr, 05 | 8.8 | 0 | 8.61 | 0.013 | 0.41 | 0.00 | 1.12 | 0.00 | 2 | 0.00 | 518 | 0.00 |
| May, 05 | 7.2 | 0 | 7.75 | 0.000 | 0.00 | 0.00 | 0.56 | 0.00 | 1 | 0.00 | 465 | 0.00 |
| Jun, 05 | 7.9 | 0 | 7.09 | 0.000 | 0 | 0.00 | 0 | 0.00 | 1 | 0.00 | 496 | 0.00 |
| Jul, 05 | 6.3 | 0 | 8.33 | 0.000 | **1.63** | 0.36 | 4.43 | 0.00 | 2 | 0.00 | 398 | 0.00 |
| Aug, 05 | 7.3 | 0 | 7.25 | 0.000 | 0.31 | 0.00 | 0.84 | 0.00 | 1 | 0.00 | 190 | 0.00 |
| Sep, 05 | 10.9 | 0 | 7.26 | 0.000 | 0 | 0.00 | | 0.00 | 3 | 0.00 | 485 | 0.00 |
| Oct, 05 | 6.1 | 0 | 7.3 | 0.000 | 0.14 | 0.00 | | 0.00 | 2 | 0.00 | 265 | 0.00 |
| Nov, 05 | 11.2 | 0 | 7.41 | 0.000 | 0.7 | 0.00 | | 0.00 | 2 | 0.00 | **850** | 0.21 |
| Dec, 05 | 9.5 | 0 | 7.42 | 0.000 | 0.81 | 0.00 | | 0.00 | 2 | 0.00 | 662 | 0.00 |
| Objective | **>4** | **0** | **6.5–8.5** | **0.013** | **<1.2** | **0.49** | **<10** | **0.00** | **<3** | **0.33** | **<700** | **0.21** |

No. of Variables = 6
No. of Tested Samples = 67

$$F_1 = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right) \times 100 = 100 \times 4/6 = 66.67$$

$$F_2 = \left(\frac{\text{Number of failed tests}}{\text{Total number of tests}}\right) \times 100 = 100 \times 5/67 = 7.46$$

The total Excursion is computed by using the following equations:

$$\text{Excursion}_i = \left(\frac{\text{Failed test value}_i}{\text{Objective}_i}\right) - 1;$$
$$\text{Excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed test value}_i}\right) - 1$$

$$\sum_{i=1}^{n} \text{Excursion}_i = 1.05$$

$$\text{nse} = \frac{\sum_{i=1}^{n} \text{Excursion}_i}{\text{Number of tests}} = 1.05/67 = 0.02$$
$$F_3 = \frac{\text{nse}}{0.01 \times \text{nse} + 0.01} = \frac{0.02}{0.01 \times 0.02 + 0.01} = 1.546$$

The WQI using CCME approach is:

$$\text{CCME : WQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$
$$= 100 - \left(\frac{\sqrt{66.67_1^2 + 7.46^2 + 1.546^2}}{1.732}\right) = 61.3$$

Based on CCME WQI, the water quality class can be categorized as "MARGINAL BUT TENDS TO FAIR", i.e., water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels.

### *11.1.4 WQI*

WQI discussed are either highly specialized or very simple in terms of the number of variables considered. None seem to be geared to the protection of multiple water uses or to encompass the variety of measurements of water quality. Nasirian (2007) introduced the new WQI that provides an indication of the quality of water influenced by domestic and some general industrial effluents along with the water impacted by mining. The parameters included in the estimation of WQI are pH, $NO_3$, radionuclides, dissolved oxygen, $PO_4$, heavy metals, electrical conductivity (EC), $SO_4$, and suspended solid. A WQI should be made up sub-indices of parameters that can explain water quality comprehensively. The survey showed that both total dissolved solids (TDS) and electrical conductivity (EC) were selected in the top 10 preferred parameters.

#### 11.1.4.1 Formulation of WQI

The new WQI (Nasirian, 2007) proposed is in accordance with Nives (1999). The WQI was calculated by summing up individual quality rating ($q_i$) and weighting factor ($w_i$) as follows:

$$\text{WQI} = \sum_{i=1}^{n} w_i q_i \quad (11.43)$$

where $q_i$ is the water quality score of the $i$th parameter, $w_i$ is the weighting factor for the $i$th parameter, and n is the number of parameters. Parameters and their weights are listed in Table 11.5. The water quality standards are given Table 11.6.

**Table 11.5** Parameters and weights for Nasirian's WQI

| S. No. | Parameters | Unit | Weight |
|---|---|---|---|
| 1 | pH | Standard Unit | 0.18 |
| 2 | Nitrate $(NO_3^-)$ | mg/l | 0.13 |
| 3 | Radionuclides ($^{238}U$, $^{232}Th$) | Bq/l | 0.12 |
| 4 | Dissolved Oxygen (DO) | mg/l | 0.11 |
| 5 | Phosphate $(PO_4^-)$ | mg/l | 0.11 |
| 6 | Heavy Metals (Cd, Pb, As, Ni, Mn, Fe, Hg) | mg/l | 0.11 |
| 7 | Electrical Conductivity (EC) | µs/cm | 0.08 |
| 8 | Sulphate $(SO_4^-)$ | mg/l | 0.08 |
| 9 | Suspended Solids (SS) | mg/l | 0.08 |

**Table 11.6** List of water quality standard

| Parameters | DL[a] (USEPA) | MPL[b] (USEPA) | Canadian quality | BIS[c] for drinking water |
|---|---|---|---|---|
| pH | 6.5–8.5 | | | 6.5–8.5 |
| TDS (mg/l) | | | | 500 (DL)<br>2,000 (MPL) |
| $PO_4$ (mg/l) | 0.1 | | | |
| Turbidity (NTU) | | | | |
| DO (mg/l) | 5 | 3 | | 3–5 |
| BOD (mg/l) | | | | 3 |
| $NO_3$ (mg/l) | | | | 45 (DL)<br>100 (MPL) |
| Cl (mg/l) | | | | 250 (DL)<br>1,000 (MPL) |
| F (mg/l) | | | | 1.0 (DL)<br>1.5 (MPL) |
| Fecal Coliform (count/100 ml) | | | | 0 (DL) |
| Total Coliform (count/100 ml) | | | | 10 (DL) |

**Table 11.6** (continued)

| Parameters | DL[a] (USEPA) | MPL[b] (USEPA) | Canadian quality | BIS[c] for drinking water |
|---|---|---|---|---|
| Cd (mg/l) | 0.005 | 0.005 | 0.005: Drinking<br>0.00002: Aquatic<br>0.005: Agriculture | 0.01 (DL)<br>No relaxation (MPL) |
| Cr (mg/l) | | | | 0.05 (DL)<br>No relaxation (MPL) |
| Cu (mg/l) | | | | 0.05 (DL)<br>1.5 (MPL) |
| Cyanide (mg/l) | | | | 0.05 (DL)<br>No relaxation (MPL) |
| Zn (mg/l) | | | | 5 (DL)<br>15 (MPL) |
| Pb (mg/l) | 0 | 0.015 | 0.01: Drinking<br>0.001: Aquatic<br>0.2: Agriculture | 0.05 (DL)<br>No relaxation (MPL) |
| As (mg/l) | 0 | 0.010 | 0.025: Drinking<br>0.005: Aquatic<br>0.1: Agriculture | 0.05 (DL)<br>No relaxation (MPL) |
| Hg (mg/l) | 0.002 | 0.002 | 0.0001: Drinking<br>0.0001: Aquatic<br>0.003: Agriculture | 0.001 (DL)<br>No relaxation (MPL) |
| Ni (mg/l) | – | 0.100 | 0.2: Drinking<br>0.025: Aquatic<br>0.02: Agriculture | |
| Mn (mg/l) | – | 0.050 | 0.05: Drinking<br>0.1: Aquatic<br>0.2: Agriculture | 0.10 (DL)<br>0.30 (MPL) |
| Total Fe (mg/l) | – | 0.300 | 0.3: Drinking<br>0.3: Aquatic<br>5.0: Agriculture | |
| $SO_4^{2-}$ (mg/l) | | | 500: Drinking<br>NA: Aquatic<br>1000: Agriculture | 200 (DL)<br>400 (MPL) |
| Suspended Solids (mg/l) | | | | |
| EC (μ mhos/cm) | | | NA: Drinking<br>NA: Aquatic<br>700: Agriculture | 300 (DL)<br>700 (MPL) |
| $^{238}U$ (Bq/l) | 0 | 0.37 | – | |
| $^{232}Th$ (Bq/l) | 0 | 3.40 | – | |

*USEPA* US Environmental Protection Agency
[a] *DL* Desirable limit – The level of contamination in drinking water below which there is no known or expected risk to health.
[b] *MPL* Maximum Permissible Limit – The highest level of a contaminant that is allowed in drinking water.
[c] *BIS* Bureau of Indian Standards

#### 11.1.4.2 Water Quality Rating Curve

The rating curve developed by the National Sanitation Foundation (NSF) for pH, nitrate ($NO_3$), dissolved oxygen (DO) and phosphate ($PO_4$) is used. For other parameter viz., radionuclides, heavy metals, electrical conductivity (EC), sulphate ($SO_4^{2-}$), and suspended solids (SS), the rating curve proposed by Nasirian (2007) is adequate to use.

#### 11.1.4.3 Rating Curve for Radionuclides

The water quality score for radionuclides parameters ($^{238}$U, $^{232}$Th) is estimated from the following rating curve formulae:

$$Q_{\text{radio}} = -100 \times \bar{r} + 100;\ \text{if}\ \bar{r} < 1 \tag{11.44}$$

$$Q_{\text{radio}} = 0;\ \text{if}\ \bar{r} \geq 1 \tag{11.45}$$

in which $\bar{r}$ is estimated from following equation:

$$\bar{r} = \frac{1}{n}\sum_{i=1}^{n} r_i \tag{11.46}$$

where, $r_i$ is the activity concentration quotient of radionuclides $i$ (eq. (11.47)), while $n$ is number of radionuclides considered.

$$r_i = C_i/C_{\text{s}} \tag{11.47}$$

In eq. (11.47), $C_i$ is the concentration of the $i$th radionuclide, and $C_{\text{s}}$ is the maximum permissible activity concentration of radionuclide. The maximum permissible activity concentration is given in Table 11.6. Due to the toxicity of radionuclides, a limit for $r_i$ is introduced. The water quality score ($Q_{\text{radio}}$) becomes zero if anyone of the radionuclide quotient is greater or equal to one ($r_i \geq 1$).

#### 11.1.4.4 Rating Curve for Heavy Metals

Similar to the procedure of radionuclides, the water quality score for the heavy metal can be estimated through the rating curve proposed by Nasirian (2007):

$$Q_{\text{heavy metal}} = -100 \times \bar{h} + 100;\ \text{if}\ \bar{h} < 1 \tag{11.48}$$

$$Q_{\text{heavy metal}} = 0;\ \text{if}\ \bar{h} \geq 1 \tag{11.49}$$

in which $\bar{h}$ can be estimated from following equation:

$$\bar{h} = \frac{1}{n}\sum_{i=1}^{n} h_i \tag{11.50}$$

where, $h_i$ is the activity concentration quotient of heavy metals $i$ (eq. (11.47)), while $n$ is number of heavy metal parameters considered:

$$h_i = C_i/C_s \tag{11.51}$$

In eq. (11.51), $C_i$ is the concentration of the $i$th heavy metal element, and $C_s$ is the maximum permissible concentration of element (Table 11.6). Due to the toxicity of heavy metal presence, a limit for $h_i$ is introduced. The water quality score ($Q_{\text{heavy metal}}$) becomes zero if anyone of the element quotients is greater than or equal to one ($h_i \geq 1$) [i.e. $C_i \geq C_s$].

#### 11.1.4.5 Rating Curve for EC

The best fit equation developed by Nasirian (2007) for electrical conductivity to compute the water quality score from measured data (μS/cm = μ mhos/cm) are as follows:

$$Q_{\text{EC}} = -0.0714 \times \text{EC} + 100;\ \text{if EC} \leq 700\,\mu\text{S/cm} \tag{11.52}$$

$$Q_{\text{EC}} = -0.00943 \times \text{EC} + 56.60;\ \text{if } 700 < \text{EC} \leq 6000\,\mu\text{S/cm} \tag{11.53}$$

$$Q_{\text{EC}} = 0;\ \text{if EC} > 6000\,\mu\text{S/cm} \tag{11.54}$$

[Note: Unit conversion: 1 dS/m = 1 mmho/cm = 1,000 μS/cm; 1,000 m mho/cm = 1 μ mho/cm].

#### 11.1.4.6 Rating Curve for $SO_4$

The best fit equation developed for sulphate to compute the water quality score from measured data is:

$$Q_{SO_4} = -0.1 \times (SO_4) + 100;\ \text{if } SO_4 < 1000\,\text{mg/l} \tag{11.55}$$

$$Q_{SO_4} = 0;\ \text{if } SO_4 \geq 1000\,\text{mg/l} \tag{11.56}$$

#### 11.1.4.7 Rating Curve for Suspended Solids (SS)

The best fit equation developed for suspended solids to compute the water quality score from measured data is:

$$Q_{\text{SS}} = 100;\ \text{if SS} < 20\,\text{mg/l} \tag{11.57}$$

$$Q_{\text{SS}} = -0.77 \times \text{SS} + 115.3;\ \text{if } 20 \leq \text{SS} \leq 150\,\text{mg/l} \tag{11.58}$$

$$Q_{\text{SS}} = 0;\ \text{if SS} > 150\,\text{mg/l} \tag{11.59}$$

#### 11.1.4.8 Water Quality Classification

Based on the new WQI proposed by Nasirian (2007) water quality can be classified as follows (Table 11.7):

The application of the methodology is presented in example 11.4.

**Example 11.4** Estimate the water quality index and class of Nizamuddin Bridge site (Quarter stream) of Yamuna River using the CPCB data. The average water quality parameter measured during the year 2003 by CPCB is given in Table 11.8.

**Table 11.7** Water class based on Nasirian's WQI

| Quality | WQI range | Class |
|---|---|---|
| Clean | 80–100 | 90–100: Class I |
| | | 80–90: Class II |
| Slightly polluted | 60–80 | 50–80: Class III |
| Very polluted | 0–60 | 40–50: Class IV |
| | | 0–40: Class V |

**Table 11.8** Water quality parameters of Nizamuddin Bridge site of Yamuna River and computational step for Nasirian's WQI

| Parameters | Unit | Perm. limit | Measured | Quotient ($r_i$) | $\bar{r}$ | WQ score | Weights | Weight used | WQI |
|---|---|---|---|---|---|---|---|---|---|
| Temp | °C | | 26 | | | | | | |
| $DO_{sat}$ | mg/l | | 8.21 | | | | | | |
| DO | mg/l | 5 | 0.9 | | | | | | |
| pH | Std unit | 6.5–8.5 | 7 | | | 87.12 | 0.18 | 0.18 | 15.68 |
| Nitrate | mg/l | 100 | 18.6 | | | 37.73 | 0.13 | 0.13 | 4.91 |
| Phosphate | mg/l | 0.1 | NM | | | 2.00 | 0.11 | 0 | 0.00 |
| $\%DO_{sat}$ | % | | 10.97 | | | 4.37 | 0.11 | 0.11 | 0.48 |
| Sulphate | mg/l | 400 | NM | | | 0.00 | 0.08 | 0 | 0.00 |
| SS | mg/l | | NM | | | 0.00 | 0.08 | 0 | 0.00 |
| EC | μS/cm | 700 | 894 | | | 48.2 | 0.08 | 0.08 | 3.85 |
| $^{238}U$ | Bq/l | 0.37 | NM | 0.00 | | | | | |
| $^{232}Th$ | Bq/l | 3.4 | NM | 0.00 | 0.0 | 100. | 0.12 | 0 | 0.00 |
| Cd | mg/l | 0.01 | NM | | | | | | |
| Pb | mg/l | 0.05 | NM | | | | | | |
| As | mg/l | 0.05 | NM | | | | | | |
| Ni | mg/l | 0.025 | 0.02 | 0.80 | | | | | |
| Mn | mg/l | 0.3 | NM | | | | | | |
| Fe | mg/l | 0.3 | 5.05 | 16.83 | | | | | |
| Hg | mg/l | 0.001 | NM | | | | | | |
| Cu | mg/l | 1.5 | 0.02 | 0.01 | | | | | |
| Zn | mg/l | 15 | 0.08 | 0.01 | 4.4 | 0.00 | 0.11 | 0.11 | 0.00 |
| Total | | | | | | | | **0.61** | **24.9** |

*NM* refers to the parameters not measured; μS/cm = micro mhos/cm; Bq/l = Becquerel/litre

In the Yamuna River, radionuclides are not reported so far, therefore, the activity concentration is assumed zero. For heavy metals, four parameters, viz., Ni, Fe, Cu, and Zn are considered.

The WQI is estimated as:

$$\mathrm{WQI}_{\mathrm{adjusted}} = \frac{\mathrm{WQI}}{\mathrm{Weight\ used}} = \frac{26.62}{0.61} = 40.58$$

Based on the classification, the water is “VERY POLLUTED” and class is very close to “CLASS-V”

### *11.1.5 Universal WQI Based on European Classification Scheme (UWQI)*

The Universal Water Quality Index (UWQI) was developed to provide a simpler method for describing the quality of surface water used for drinking water supply. UWQI has an advantage over pre-existing indices by reflecting appropriateness of water for specific use, particularly for drinking water supply rather than general supply and has been developed by studying the super-national standard. The UWQI was developed on the basis of the following water quality standards (Boyacioglu, 2007): (a) The quality required of surface water intended for the abstraction of drinking water in the Member States 75/440/EEC set by the Council of the European Communities (EC, 1991); (b) The classification of inland waters according to quality – Turkish water pollution control regulation – WPCR (Official Gazette, 1988); and (c) other reported scientific information. Water quality standard for drinking water supply for the development of UWQI is given in Table 11.9.

According to the EC legislation (75/440/EEC), water quality of surface waters intended for the abstraction of drinking water is classified into three groups. For each class the treatment level required to transform surface water into drinking water is different and can be summarized as follows:

- Class I: Simple physical treatment and disinfection, e.g., rapid filtration and disinfection
- Class II: Normal physical treatment, chemical treatment and disinfection, e.g., pre-chlorination, coagulation, flocculation, decantation, filtration, disinfection (final chlorination)
- Class III: Intensive physical and chemical treatment, extended treatment and disinfection, e.g., chlorination to break-point, coagulation, flocculation, decantation, filtration, adsorption (activated carbon), disinfection (ozone, final chlorination) (EC, 1991).

**Table 11.9** Classification of water quality for the development of UWQI

| Parameter | Unit | Class I (excellent) | Class II (acceptable) | Class III (polluted) | Remarks |
|---|---|---|---|---|---|
| Total coliform | Count/ 100 ml | 50 | 5,000 | 50,000 | It is used to indicate whether other potentially harmful bacteria may be present |
| Cadmium | mg/l | 0.003 | 0.005 | 0.010 | Chemicals from industrial and domestic discharges |
| Cyanide | mg/l | 0.010 | 0.050 | 0.100 | |
| Mercury | mg/l | 0.0001 | 0.0005 | 0.002 | |
| Selenium | mg/l | 0.010 | 0.010 | 0.020 | Naturally occurring chemicals |
| Arsenic | mg/l | 0.020 | 0.050 | 0.100 | |
| Fluoride | mg/l | 1 | 1.5 | 2 | |
| Nitrate-nitrogen | mg/l | 5 | 10 | 20 | Chemicals from agricultural activities |
| DO | mg/l | 8 | 6 | 3 | Operational monitoring parameters |
| pH | | 6.5–8.5 | 5.5–6.4<br>8.6–9.0 | <5.5<br>>9.0 | |
| BOD | mg/l | <3 | <5 | <7 | Indicator of organic pollution |
| Total phosphorous-$PO_4$-P | mg/l | 0.02 | 0.16 | 0.65 | It is included to satisfy the ecological requirement of certain types of environment |

#### 11.1.5.1 Aggregation Function of UWQI

The aggregation function of Universal Water Quality Index (NWQI) is defined as follows:

$$\text{UWQI} = \sum_{i=1}^{n} w_i q_i \tag{11.60}$$

where UWQI is the universal water quality index, $w_i$ is the weight of the $i$th parameter, and $q_i$ is the sub-index for $i$th parameter (Table 11.10).

The weights of the parameters, $w_i$ corresponding to the rating is given in Table 11.11. Based on the value of UWQI, the water quality can be categorized using the Table 11.12.

**Example 11.5** Pumping station at Wazirabad for Delhi water supply receives water from Palla via drain no 8. The water quality parameters published by CPCB for the year 2005 is shown in the table below. Calculated the suitability of water for drinking using the Universal Water Quality Index (UWQI).

**Table 11.10** Mathematical equations formulated for UWQI

| Variable | Range | Sub-index function |
|---|---|---|
| BOD | $BOD < 3$ | $q_{BOD} = 100$ |
| | $3 \leq BOD < 6$ | $q_{BOD} = -25 \times BOD + 175$ |
| | $6 \leq BOD < 7$ | $q_{BOD} = -22.5 \times BOD + 162.5$ |
| | $BOD \geq 7$ | $q_{BOD} = 0$ |
| Nitrate | $NO_3 \leq 5$ | $q_{NO_3} = 100$ |
| | $5 < NO_3 \leq 10$ | $q_{NO_3} = -10 \times NO_3 + 150$ |
| | $10 < NO_3 \leq 20$ | $q_{NO_3} = -4.5 \times NO_3 + 95$ |
| | $NO_3 > 20$ | $q_{NO_3} = 0$ |
| Arsenic | $As \leq 0.02$ | $q_{As} = 100$ |
| | $0.02 < As \leq 0.05$ | $q_{As} = -1666.7 \times As + 133.33$ |
| | $0.05 < As \leq 0.1$ | $q_{As} = -900 \times As + 95$ |
| | $As > 0.1$ | $q_{As} = 0$ |
| DO | $DO \geq 8$ | $q_{DO} = 100$ |
| | $8 < DO \leq 6$ | $q_{DO} = 25 \times DO - 100$ |
| | $6 < DO \leq 3$ | $q_{DO} = 15 \times DO - 40$ |
| | $DO < 3$ | $q_{DO} = 0$ |
| Fluoride | $F \leq 1$ | $q_F = 100$ |
| | $1 < F \leq 2$ | $q_F = -95 \times F + 194.17$ |
| | $F > 2$ | $q_F = 0$ |
| Total phosphorous | $TP \leq 0.02$ | $q_{TP} = 100$ |
| | $0.02 < TP \leq 0.16$ | $q_{TP} = -357.14 \times TP + 107.14$ |
| | $0.16 < TP \leq 0.65$ | $q_{TP} = -91.83 \times TP + 64.694$ |
| | $TP > 0.65$ | $q_{TP} = 0$ |
| Mercury | $Hg \leq 0.0001$ | $q_{Hg} = 100$ |
| | $0.0001 < Hg \leq 0.0005$ | $q_{Hg} = -125000 \times Hg + 112.5$ |
| | $0.0005 < Hg \leq 0.002$ | $q_{Hg} = -30000 \times Hg + 65$ |
| | $Hg > 0.002$ | $q_{Hg} = 0$ |
| Selenium | $Se \leq 0.01$ | $q_{Se} = 100$ |
| | $0.01 < Se \leq 0.02$ | $q_{Se} = 4500 \times Se + 95$ |
| | $Se > 0.02$ | $q_{Se} = 0$ |
| Cyanide | $CN \leq 0.01$ | $q_{CN} = 100$ |
| | $0.01 < CN \leq 0.05$ | $q_{CN} = -1250 \times CN + 112.5$ |
| | $0.05 < CN \leq 0.10$ | $q_{CN} = -900 \times CN + 95$ |
| | $CN > 0.10$ | $q_{CN} = 0$ |
| Cadmium | $Cd \leq 0.003$ | $q_{Cd} = 100$ |
| | $0.003 < Cd \leq 0.005$ | $q_{Cd} = -25000 \times Cd + 175$ |
| | $0.005 < Cd \leq 0.010$ | $q_{Cd} = -9000 \times Cd + 95$ |
| | $Cd > 0.010$ | $q_{Cd} = 0$ |
| Total coliform | $TC \leq 50$ | $q_{TC} = 100$ |
| | $50 < TC \leq 5000$ | $q_{TC} = -10.857 \ln(TC) + 142.47$ |
| | $5000 < TC \leq 50000$ | $q_{TC} = -21.715 \ln(TC) + 284.95$ |
| | $TC > 50000$ | $q_{TC} = 0$ |
| pH | $6.5 \leq pH \leq 8.5$ | $q_{pH} = 100$ |
| | $5.5 \leq pH \leq 6.4$ and $8.6 \leq pH \leq 9.0$ | $q_{pH} = 50$ |
| | $pH < 5.5$ and $pH > 9.0$ | $q_{pH} = 0$ |

**Table 11.11** Significance ratings and weights for UWQI

| Category | Variable | Rating | Weight factor |
|---|---|---|---|
| Health hazard | Total coliform | 4 | 0.114 |
| | Cadmium | 3 | 0.086 |
| | Cyanide | 3 | 0.086 |
| | Mercury | 3 | 0.086 |
| | Selenium | 3 | 0.086 |
| | Arsenic | 4 | 0.113 |
| | Fluoride | 3 | 0.086 |
| | Nitrate-nitrogen | 3 | 0.086 |
| Operational monitoring | DO | 4 | 0.114 |
| | pH | 1 | 0.029 |
| Oxygen depletion | BOD | 2 | 0.057 |
| | Total phosphorous | 2 | 0.057 |

**Table 11.12** Ranking of water quality based on UWQI

| Rank | UWQI | Rank | UWQI |
|---|---|---|---|
| Excellent | 95–100 | Marginal | 25–49 |
| Good | 75–94 | Poor | 0–24 |
| Fair | 50–74 | | |

## Calculation:

| Category | Parameter | Unit | Weight | Measured | Sub-index | Weight used | WQI |
|---|---|---|---|---|---|---|---|
| Health hazard | TC | count/ 100 ml | 0.114 | 40,842 | 54.39 | 0.114 | 6.20 |
| | Cd | mg/l | 0.086 | NM | 0.00 | 0.000 | 0.00 |
| | CN | mg/l | 0.086 | NM | 0.00 | 0.000 | 0.00 |
| | Hg | mg/l | 0.086 | NM | 0.00 | 0.000 | 0.00 |
| | Se | mg/l | 0.086 | NM | 0.00 | 0.000 | 0.00 |
| | As | mg/l | 0.113 | NM | 0.00 | 0.000 | 0.00 |
| | F | mg/l | 0.086 | NM | 0.00 | 0.000 | 0.00 |
| | Nitrate | mg/l | 0.086 | 1.51 | 100.0 | 0.086 | 8.60 |
| Operational monitoring | DO | mg/l | 0.114 | 7 | 75.00 | 0.114 | 8.55 |
| | pH | | 0.029 | 7.7 | 100.0 | 0.029 | 2.90 |
| Oxygen depletion | BOD | mg/l | 0.057 | 2 | 100.0 | 0.057 | 5.70 |
| | TP | mg/l | 0.057 | NM | 0.00 | 0.000 | 0.00 |
| Total | | | | | | **0.400** | **31.95** |

*NM* refers to the parameters not measured

$$\text{WQI}_{\text{adjusted}} = \frac{\text{WQI}_{\text{calculated}}}{\text{Weight used}} = \frac{31.95}{0.40} = 79.88$$

Therefore the water quality can be ranked "GOOD". However, for drinking purposes all the health hazard parameters need to be collected for better decision making.

## *11.1.6 Concluding Remarks on Water Quality Index*

In this section the estimation of water quality class based on the numeric system (i.e. water quality index) has been presented in detail. Various techniques have been discussed with their advantages and disadvantages. To understand the applicability of these techniques, suitable examples are also presented with the case of the Yamuna River system using the data of CPCB. It has been observed that Indian Water Quality Monitoring System does not satisfy the requirements of the parameters used in the discussed WQIs.

Therefore, finally the Water Quality Index (WQI) proposed by the National Sanitation Foundation (NSF) is applied to determine the water quality status of the Yamuna River based on the water quality parameters reported by CPCB for the year 2005. The analysis is presented in Example 11.6. From the analysis, it can be revealed that the water quality is steeply polluted within the Palla to the Nizamuddin Bridge stretch, whereas the water quality has gradually improved from Mazawali to Allahabad near the confluence with Ganga River, though the quality is still in the category of medium to average (i.e., NSF-WQI = 70) (Fig. 11.10).

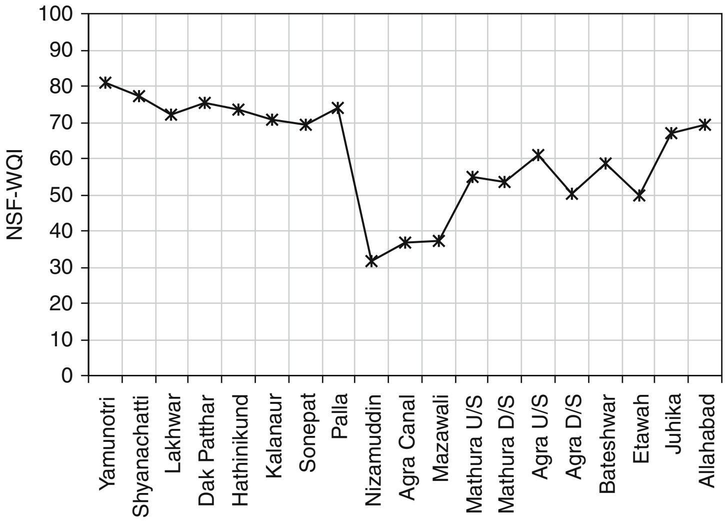


**Fig. 11.10** NSF-WQI profile of the Yamuna River for the year 2005

**Table 11.13** Average value of water quality parameters of CPCB sites of Yamuna River for the year of 2005

| Location/Site | pH | COD (mg/l) | BOD (mg/l) | AMM (mg/l) | TKN (mg/l) | DO (mg/l) | WT (°C) | TC (count/100 ml) | FC (count/100 ml) |
|---|---|---|---|---|---|---|---|---|---|
| Yamunotri | | 1 | 1 | 0.57 | 0.84 | 8.4 | 6.0 | 80 | 18 |
| Shyanachatti | | 2 | 1 | 0.66 | 0.84 | 10.2 | 9.5 | 1,650 | 360 |
| Lakhwar | | 2 | 1 | 0.63 | 1.12 | 8.5 | 16.5 | 88,500 | 1,584 |
| Dak Patthar | | 2 | 1 | 0.71 | 1.40 | 9.3 | 19.3 | 108,393 | 2,023 |
| Hathinikund | 7.7 | 8 | 2 | 0.29 | 1.46 | 9.2 | 19.7 | 569,617 | 8,379 |
| Kalanaur | 7.8 | 10 | 2 | 0.41 | 1.49 | 8.1 | 22.5 | 616,125 | 12,881 |
| Sonepat | 7.7 | 16 | 3 | 0.67 | 1.87 | 7.5 | 23.2 | 910,783 | 14,309 |
| Palla | 7.7 | 11 | 2 | 0.55 | 1.51 | 8.4 | 24.1 | 40,842 | 2,930 |
| Nizamuddin Bridge | 7.4 | 67 | 23 | 17.42 | 24.24 | 0.5 | 25.7 | 37,010,000 | 2,952,100 |
| Agra Canal | 7.4 | 47 | 15 | 9.78 | 13.94 | 0.8 | 25.0 | 13,500,000 | 981,333 |
| Mazawali | 7.6 | 57 | 17 | 19.62 | 26.33 | 2.4 | 24.6 | 4,512,727 | 755,727 |
| Mathura U/S | 7.7 | 37 | 10 | 10.65 | 15.22 | 6.3 | 26.4 | 1,700,250 | 57,708 |
| Mathura D/S | 7.7 | 32 | 8 | 10.89 | 16.66 | 5.6 | 27.0 | 3,152,500 | 328,850 |
| Agra U/S | 7.9 | 32 | 9 | 5.49 | 10.18 | 8.3 | 26.3 | 5,421,333 | 229,083 |
| Agra D/S | 7.7 | 46 | 13 | 7.44 | 12.34 | 5.1 | 26.8 | 35,317,500 | 1,728,333 |
| Bateshwar | 8.0 | 44 | 11 | 4.19 | 6.95 | 10.2 | 27.5 | 16,838,333 | 23,858 |
| Etawah | 8.2 | 46 | 14 | 2.49 | 4.91 | 11.6 | 27.0 | 14,492,750 | 17,983 |
| Juhika | 8.1 | 25 | 5 | 1.04 | 3.62 | 8.31 | 25.75 | 2,36,500 | 9,206 |
| Allahabad | 8.0 | 7 | 2 | 0.64 | 2.96 | 7.3 | 25.1 | 1,021,000 | 31,350 |

**Example 11.6** Calculate the NSF-WQI and assess the average water class for the entire monitoring sites of Yamuna River located by CPCB for the year 2005 (Table 11.13).

**Calculation:**
Results can be summarized as follows:

| Location/Site | WQI | Class | Location/Site | WQI | Class |
|---|---|---|---|---|---|
| Yamunotri | 81.13 | Good | Mazawali | 36.98 | Fair |
| Shyanachatti | 76.98 | Good | Mathura U/S | 55.05 | Average |
| Lakhwar | 72.32 | Good | Mathura D/S | 53.62 | Average |
| Dak Patthar | 75.58 | Good | Agra U/S | 60.88 | Average |
| Hathinikund | 73.28 | Good | Agra D/S | 50.12 | Average |
| Kalanaur | 70.76 | Average to Good | Bateshwar | 58.47 | Average |
| Sonepat | 69.22 | Average | Etawah | 49.93 | Fair[a] |
| Palla | 73.86 | Good | Juhika | 66.86 | Average |
| Nizamuddin Bridge | 31.72 | Fair | Allahabad | 69.49 | Average |
| Agra Canal | 36.79 | Fair | | | |

[a] Average BOD and DO reported by CPCB for the year 2005 are 14 and 11.6 mg/l with average temperature of 27°C, respectively. The saturated DO at 27°C can be estimated to be 8.06 mg/l, resulting in the percentage DO saturation of nearly 144%, which reduced the overall WQI number.

The water quality status of the Yamuna River based on NSF-WQI is shown in Fig. 11.10, which reflects that the stretch between Palla to Agra D/S is critical and need to be protected.

## 11.2 Water Quality Status Based on the Data

The water quality of the river is highly dependent on the availability of freshwater in the river, which is greatly varied in time and space. Precipitation is confined to only three months in a year and varies greatly. Most of the water flows in the Yamuna (nearly 80%) in the monsoon period (July, August and September) only. Whatever water flows during the non-monsoon period (October to June) is extensively used for irrigation and drinking leaving very little or no water in the river to flow.

It is observed that about 500 km long stretch of the river is in bad shape, having poor water quality most of the time, which is below the desired limit (i.e. designated best use). In the dry season four distinct gradients of pollution load can be distinguished in the river stretch between Wazirabad and Etawah. The stretch between Wazirabad and Okhla is the most heavily polluted one, carrying the massive input of wastewater from Delhi (CPCB, 2006). This input sets off a progressive series of chemical and biological events in the downstream water. This stretch is characterized by high bacterial population, cloudy appearance, high BOD and strong disagreeable odour – all indicating general depletion of oxygen. Masses of gaseous sludge rising from the bottom are often noticed floating near the surface of the water. During monsoon, due to flood the sludge deposited in this stretch is flushed and stays in suspension which causes a rise in the oxygen uptake downstream. This causes heavy fish mortality every year during the first flushing after the onset of monsoon. Even in this short stretch, remarkable purification takes place due to high temperature and long retention time due to the two barrages one at Okhla and the other at ITO (nearly 10 km upstream of the Okhla Barrage). The ITO Barrage is used to divert the Yamuna water for cooling of the two Thermal Power Plants located near ITO. In the stretch between Okhla and Agra (225 km) the same status of water quality can be observed, which is due to the wastewater inflow from the Okhla barrage, and several wastewater lateral drains between downstream of Okhla up to Agra. After a few kilometers the repeated additions of sewage are mainly noticeable by a higher state of eutrophication leading to the formation of algal mats in the river. Excessive algal cause problems associated with the oxygen balance in the water (daytime super saturation and night-time oxygen depletion). The water quality from DO, BOD, and bacterial points of view is not fit for designated best uses in this stretch. The Agra Water Works is drawing its raw water from this only. The next 210 km long stretch from Agra to the confluence with the Chambal River at Etawah is characterized by self- purification processes of the Agra effluents. The confluence with relatively clean Chambal River is of great value in diluting the pollution load of Yamuna River before it joins the Ganga at Allahabad. During the monsoon period due to great discharge in the river, most of the barrages are opened, which makes the river as continuous system. However, during this period (i.e. monsoon) entire waste deposits in the river comes in suspension and flowed downstream, which leads extensive damage to the river's ecosystem. More or less, the Yamuna River hardly fulfil the criteria of designated best uses (CPCB, 1978; CPCB, 1981; CPCB, 1982–1983; CPCB, 1984–2008; CPCB, 1994).

### *11.2.1 Water Quality Trends in the Yamuna*

The water quality data acquired by National River Conservation Directorate (NRCD) during the past 10 years were compiled for all monitoring locations. For all the locations, temporal variations in DO, BOD, total coliform and fecal coliform have been analysed and depicted in Fig. 11.11. It is clear from Fig. 11.11 that the water quality of the river has gradually shown similar trends of deterioration throughout the 10 years period. The year 2006 was worst for the river in terms of water quality. This can be attributed to the drought in the catchment of the river resulting in low flow conditions. In general, water quality is gradually deteriorating due to the decrease in the discharge.

### *11.2.2 Water Quality Profile of the Yamuna*

The water quality of the Yamuna River in terms of organic pollution and coliform count has been satisfactory from origin till Palla as evident from Figs. 11.12, 11.13, 11.14, and 11.15.

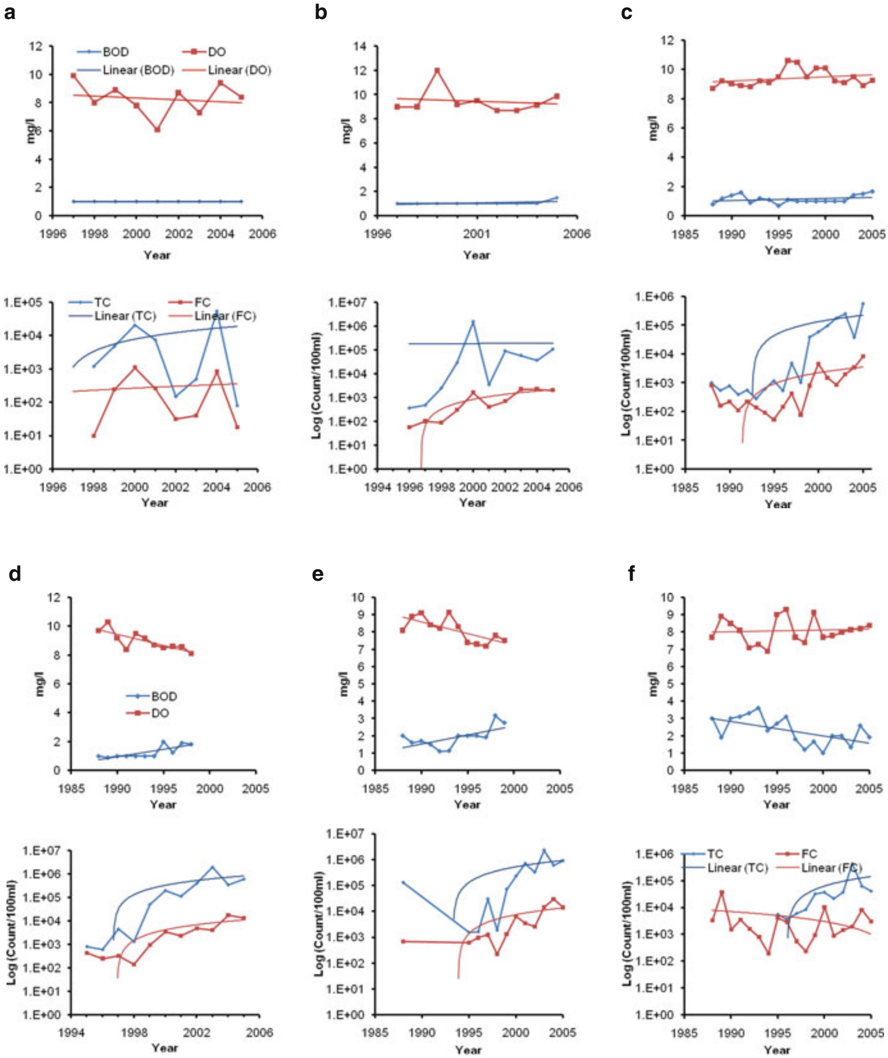


**Fig. 11.11** Water quality trend at different locations in the Yamuna River (**a**) Water quality trends at Yamunotri site; (**b**) Water quality trends at Dak Patthar site; (**c**) Water quality trends at Hathinikund site; (**d**) Water quality trends at Kalanaur site; (**e**) Water quality trends at Sonepat site; (**f**) Water quality trends at Palla (U/S Wazirabad) site; (**g**) Water quality trends at Nizamuddin Bridge site; (**h**) Water quality trends at Agra canal site; (**i**) Water quality trends at Mazawali site; (**j**) Water quality trends at Mathura U/S site; (**k**) Water quality trends at Mathura D/S site; (**l**) Water quality trends at Agra U/S site; (**m**) Water quality trends at Agra D/S site; (**n**) Water quality trends at Bateshwar site; (**o**) Water quality trends at Etawah site; (**p**) Water quality trends at Juhika site; (**q**) Water quality trends at Allahabad site

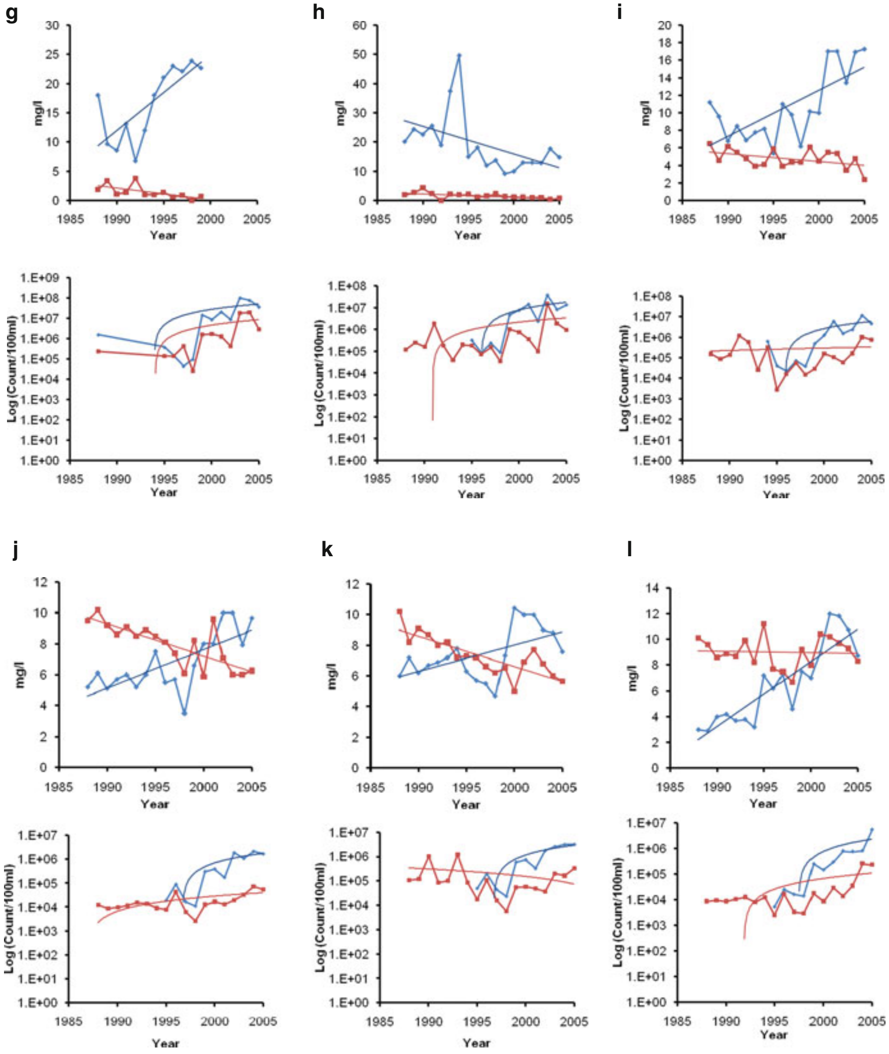


**Fig. 11.11** (continued)

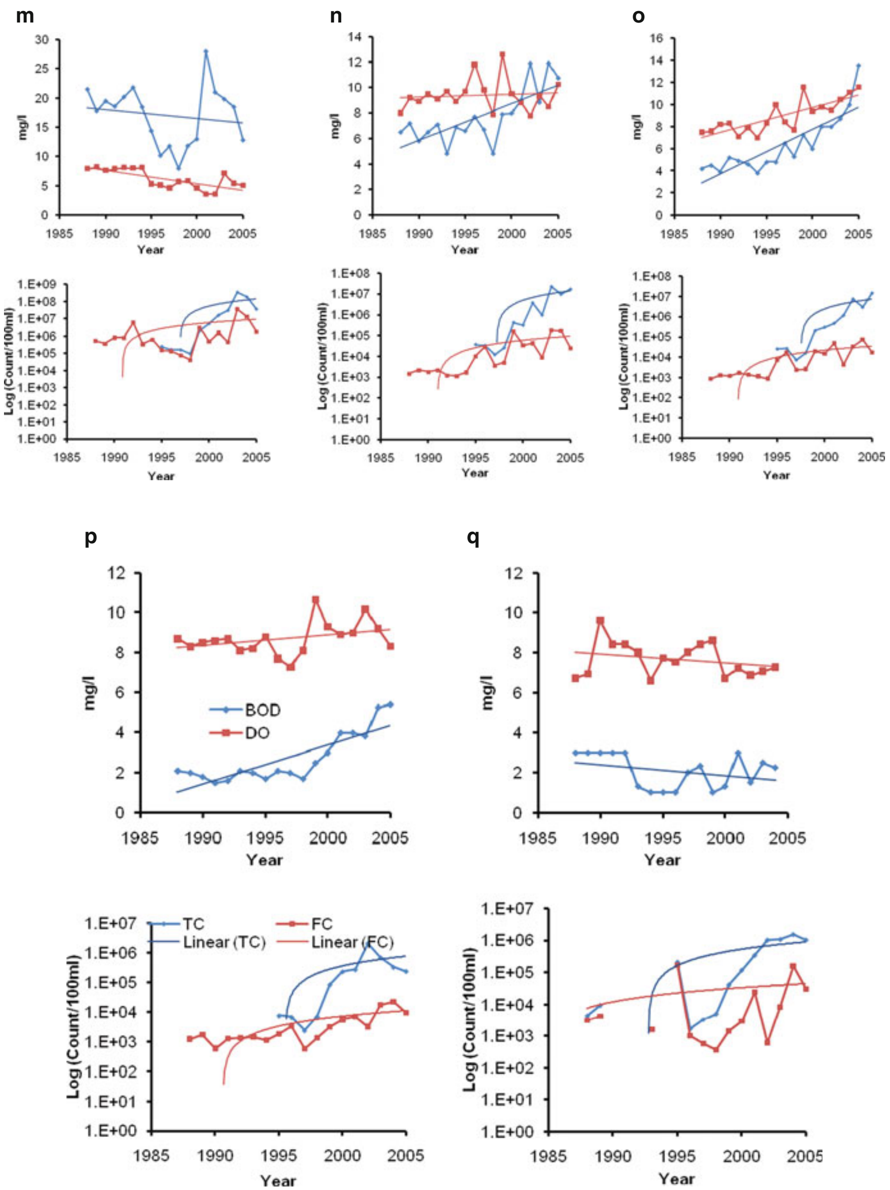


**Fig. 11.11** (continued)

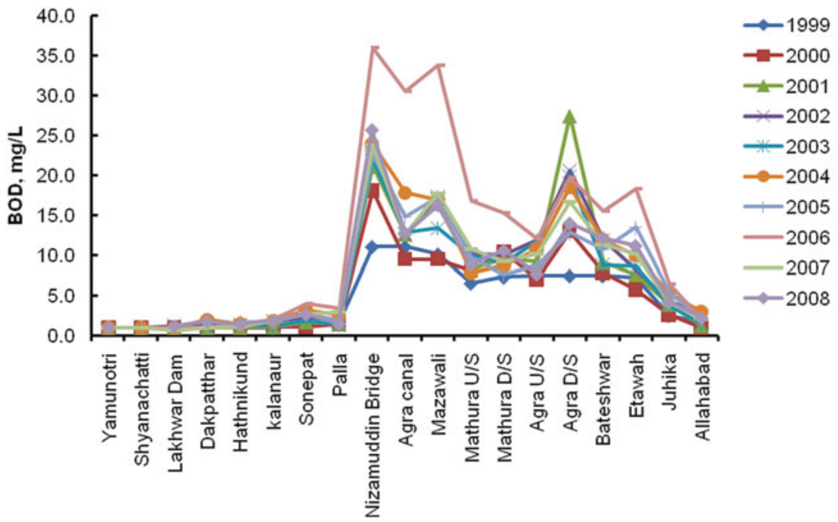


**Fig. 11.12** Ten year water quality profile of Yamuna River – BOD

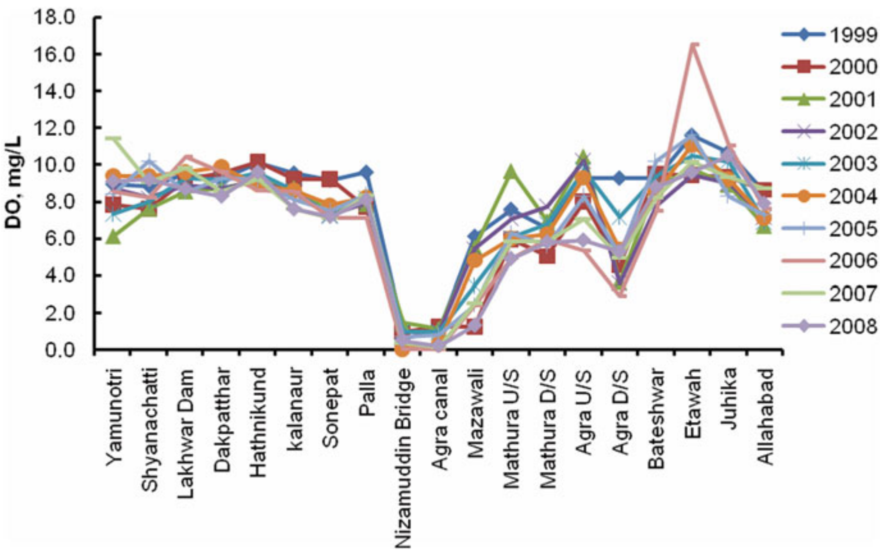


**Fig. 11.13** Ten year water quality profile of Yamuna River – DO

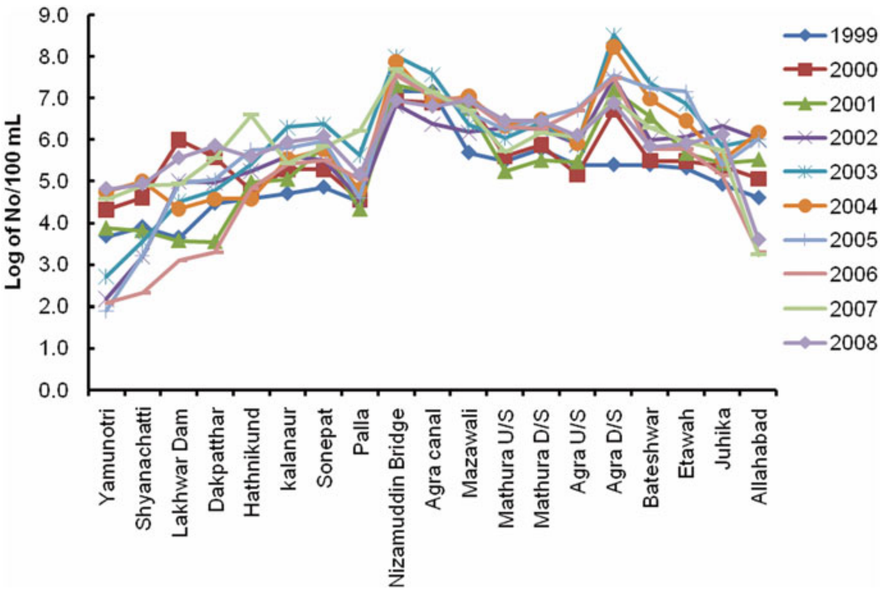


**Fig. 11.14** Ten year water quality profile of Yamuna River – Total Coliform

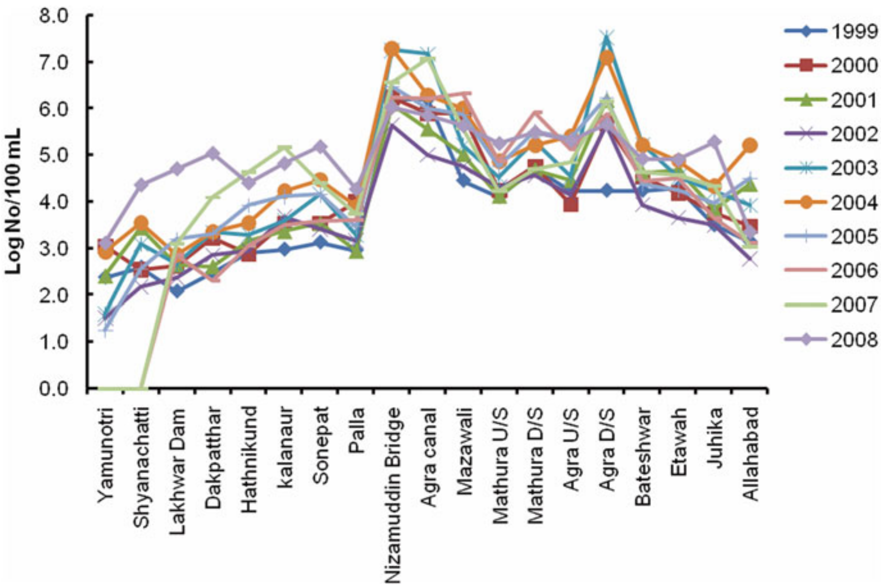


**Fig. 11.15** Ten year water quality profile of Yamuna River – Fecal Coliform

Though there has been a gradual increase in BOD from origin to the upstream of Delhi. However, the average BOD values have been well below the designated best use criteria in this stretch. The BOD level has increased significantly after the Wazirabad barrage. This is mainly due to the discharge of partially treated wastewater through several drains in Delhi. The average BOD values are not confirming the desired water quality criteria till the confluence of Chambal River. In the Delhi stretch (Wazirabad barrage to Okhla barrage), several bathing Ghats (i.e. place of spiritual bathing along the river banks) are located though the water quality is not up to the bathing standards.

#### 11.2.2.1 Bio-mapping of the Yamuna River

Bio-mapping is a good tool for water quality analysis of the river, and is commonly used to visualize the gradual changes in the river. Here, dissolved oxygen (DO) has been used as an indicator for the analysis of water quality status, and therefore, the DO-maps have been prepared for various years for comparison. Using the average DO values at various locations in the river Yamuna for the years 2003, 2008 and 2009, the DO map of the river has been prepared for the entire length. The DO maps for these years are depicted in Figs. 11.16, 11.17, and 11.18. Comparison of the DO levels (Figs. 11.16, 11.17, and 11.18) reveals that the water quality of the river is continuously degrading. It can be seen from these figures that the stretch of the red colour (DO < 4 mg/l) is elongating and the stretch presented by green colour (DO > 6 mg/l) has been significantly decreased, showing further deterioration of water quality of the river.

For detailed water quality analysis of the river Yamuna, samples at various locations in the river and wastewater drains have been collected in the year 2009; and simultaneously the photographs were taken. The water colour can be easily seen in the photographs (Plate 11.1) which themselves describe the water quality. Along with photographs the water quality parameters are also listed for visual correlation.

### *11.2.3 Monthly Variation in Water Quality Parameters*

Monthly variation in the water quality parameter is important for management of the river system. Based on the data collected from CPCB during the period 1999–2008, the monthly average has been estimated for important sites, and is shown in Figs. 11.19, 11.20, 11.21, 11.22, 11.23, 11.24, 11.25, and 11.26. It is clear from the figures that in general, DO is reducing and BOD is increasing during monsoon. This is due to the inflow of sediment-laden runoff into the river. However, for the Delhi segment, monthly variation is almost reverse as compared to other stretches. In this stretch, during monsoon, water quality is significantly improving because of high discharges. After monsoon period, water quality of the river gradually deteriorated due to wastewater influence.

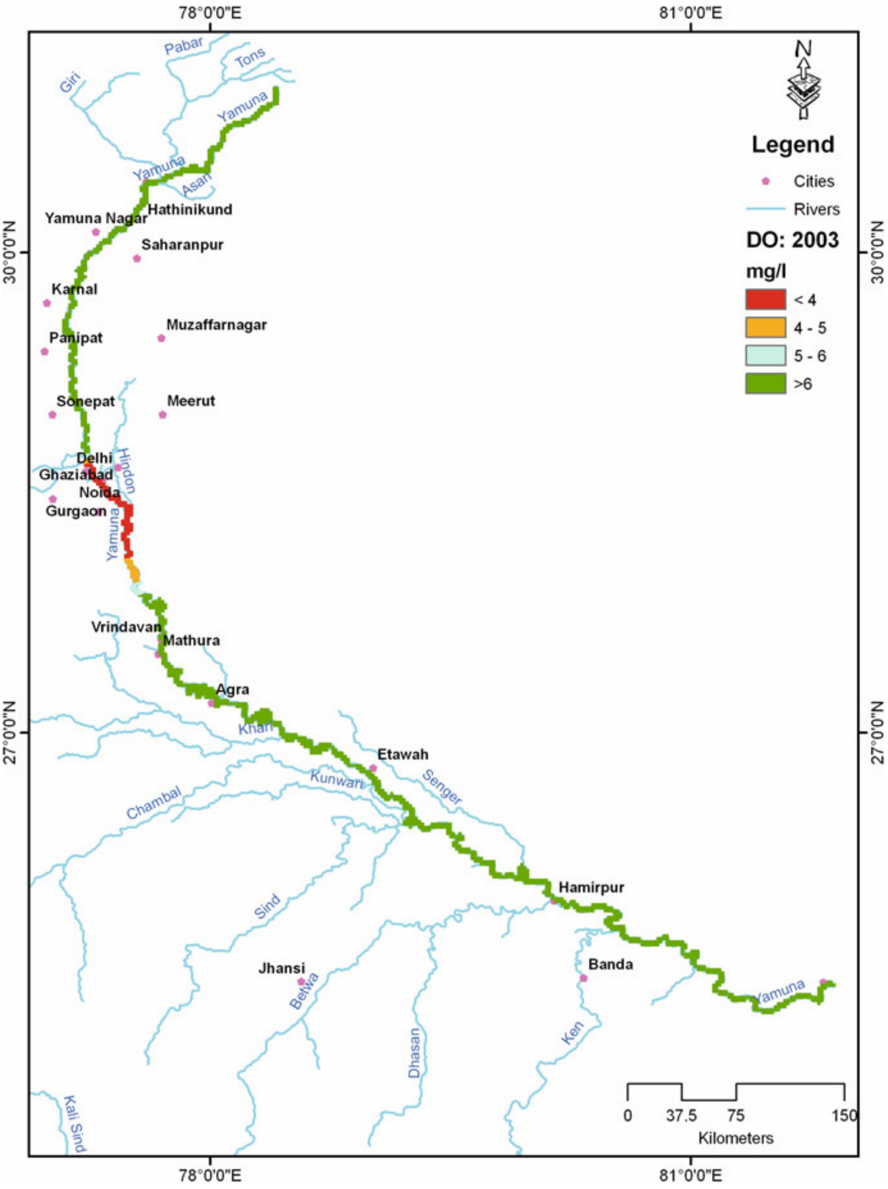


**Fig 11.16** Water quality status using the DO mapping for the year 2003

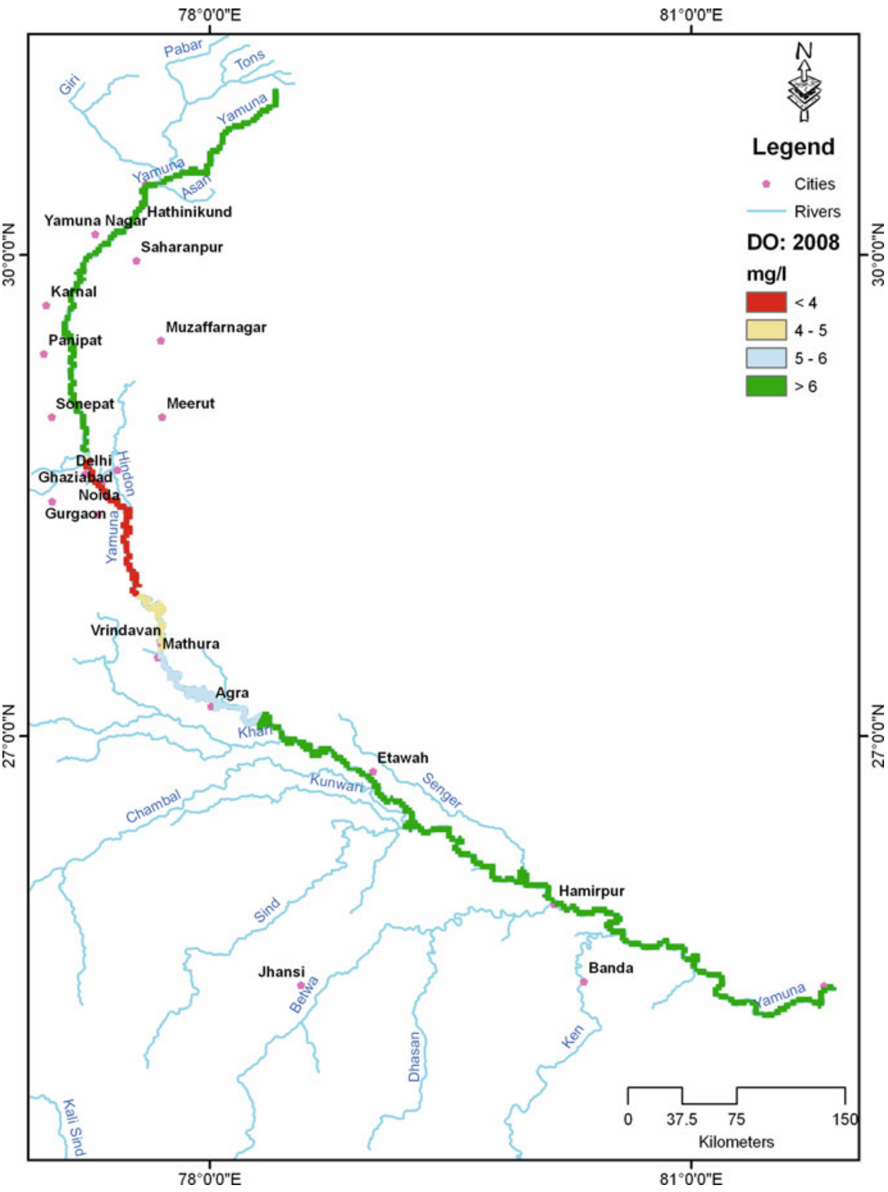


**Fig 11.17** Water quality status using the DO mapping for the year 2008

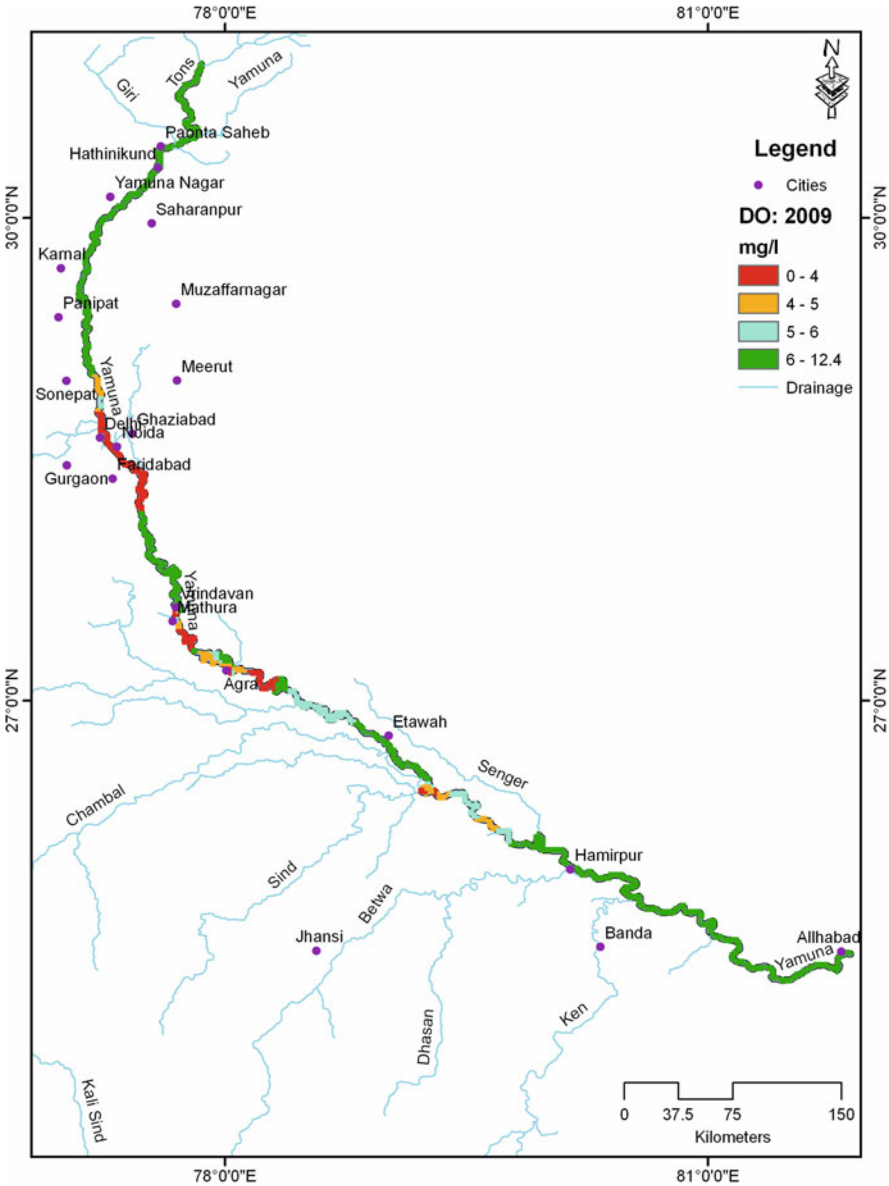


**Fig 11.18** Water quality status using the DO mapping for the year 2009

*Drain No. 8: Wazirabad barrage gets water through Storm Water Drain (No. 8) via Palla* [pH = 7.49, EC = 201μmhos/cm, TDS = 120.6 mg/l, Turbidity = 8.5 NTU, $NH_4$ = 0 mg/l, BOD = 2.0 mg/l, TC = 500 MPN/100ml, FC = 450, DO = 8.3 mg/l]

*Yamuna at Palla* [pH = 7.47, EC = 255.4, TDS = 153, Turbidity = 77, $NH_4$ =0.13, BOD = 4.77, TC = 67,066, FC = 7,033, DO = 5.5, *Q* = 11 cumec]

*Yamuna at Nigambodh Ghat* [pH = 7.4, EC = 1,449, TDS = 886, Turbidity = 40.8, $NH_4$ = 3.47, BOD = 43.46, TC = 3,100,080, FC = 21,00,031, DO = 0.0, *Q* = 13.72]

*Yamuna at Nizamuddin Bridge* [pH = 7.37, EC = 1,364, TDS = 823, Turbidity = 20, $NH_4$ = 8.24, BOD = 25.4, TC = 412,042, FC = 247,624, DO = 0.49, *Q* = 21.93]

*Yamuna at Okhla Barrage* [pH = 6.91, EC = 11,02.5, TDS = 673, Turbidity = 17.5, $NH_4$ = 3.85, BOD = 19.35, TC = 262,775, FC = 262,537, DO = 2.28]

*Yamuna at Kosi Shergarh* [pH = 7.76, EC = 1,805, TDS = 1119, Turbidity = 11.5, $NH_4$ = 8, BOD = 10.7, TC = 310, FC = 260, DO = 12.4, *Q* = 10]

**Plates 11.1(a)** Photographs showing the status of Yamuna River and its water quality parameters

*Yamuna at Vrindavan* [pH = 7.76, EC = 1,367, TDS = 844, Turbidity = 10.5, $NH_4$ = 21.4, BOD = 25.9, TC = 755, FC = 419, DO = 9.3, *Q* = 13]

*Yamuna near Taj Mahal* [pH = 7.04, EC = 1,309, TDS = 779, Turbidity = 20.5, $NH_4$ = 6.3, BOD = 15.75, TC = 170,000, FC = 6,000, DO = 7.55, *Q* = 11.44]

*Yamuna at Bateshwar* [pH = 7.81, EC = 1,383, TDS = 826, Turbidity = 30, $NH_4$ = 5.7, BOD = 16, TC = 900,000, FC = 20,000, DO = 5.7]

*Yamuna near Etawah* [pH = 7.91, EC = 1,434, TDS = 857, Turbidity = 38, $NH_4$ = 4.6, BOD = 49, TC = 24,000, FC = 200,00, DO = 6.9]

*Yamuna at Hamirpur* [pH = 8.7, EC = 1,110, TDS = 710, Turbidity = 29, $NH_4$= 0.0, BOD = 41.6, TC = 460, FC = 21, DO = 6.7, *Q* = 45.15]

*Yamuna at Allahabad* [pH = 8.46, EC = 790, TDS = 505, Turbidity = 20, $NH_4$ = 0.44, BOD = 31.4, TC = 75, FC = 20, DO = 8.3, *Q*=62.7 cumec]

**Plates 11.1(a)** (continued)

*Chambal River at Kondal* [pH = 8.14, EC = 618, TDS = 367, Turbidity = 27, $NH_4$ = 2.1, BOD = 12, TC = 300, FC = 300, DO = 12, *Q* = 8.4 cumec]

*Sind River* [pH = 7.86, EC = 568, TDS = 343, Turbidity = 97, $NH_4$ = 4.5, BOD = 21.1, TC = 160,000, FC = 160,00, DO = 3.6, *Q* = 4.97 cumec]

*Betwa River* [pH = 8.63, EC = 480, TDS = 307, Turbidity = 32, BOD = 0.0, TC = 150, FC = 21, DO = 8.8, *Q* = 4.02 cumec]

*Ken River* [pH = 8.53, EC = 540, TDS = 345, Turbidity = 35, $NH_4$ = 0.44, BOD = 0.0, TC = 23, FC = 4, DO = 7.2, *Q* = 2.78 cumec]

**Plates 11.1(a)** (continued)

*Nazafgarh outfall*: [pH = 7.21, EC = 1,517, TDS = 922, Turbidity = 53, $NH_4$ = 61, BOD = 61, COD = 176, *Q* = 13.03 cumec]

*Barapulla Drain* [pH = 8.4, EC = 1,421, TDS = 909, Turbidity = 78, BOD = 62.4, COD = 187, *Q* = 0.5 cumec]

**Plates 11.1(b)** Photographs showing the status of drains polluting the Yamuna River

*Power House Drain* [pH = 7.16, EC = 1,239, TDS = 768, Turbidity = 76.2, $NH_4$ = 8.8, BOD = 54.6, COD = 249, $Q$ = 0.623 cumec]

*Sen Nursing Home drain* [pH = 7.21, EC = 1553, TDS = 955, Turbidity = 66, $NH_4$ = 6.84, BOD = 77, COD = 216, $Q$ = 0.516 cumec]

*Mantola Drain, Agra* [pH = 7.69, EC = 2,687, TDS = 1,657, Turbidity = 71, $NH_4$ = 7.55, BOD = 77.7, COD = 217.4 (Flow measurement was not performed due to deep sludge)]

**Plates 11.1(b)** (continued)

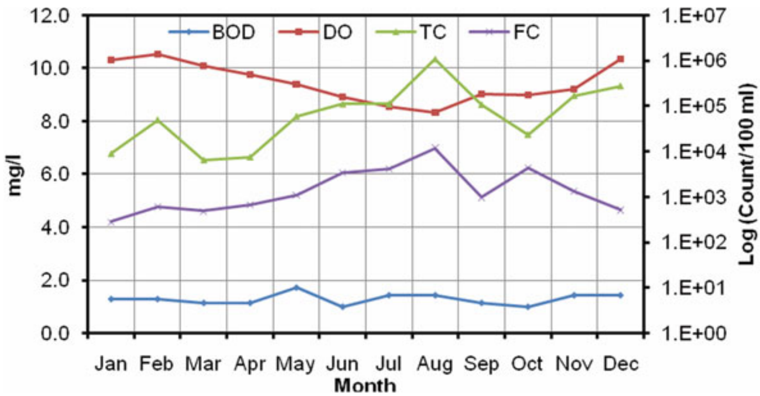


**Fig. 11.19** Monthly variation in water quality at Hathinikund

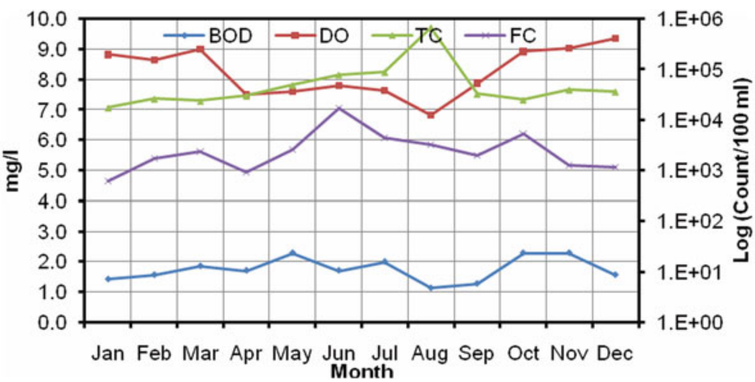


**Fig. 11.20** Monthly variation in water quality at Palla

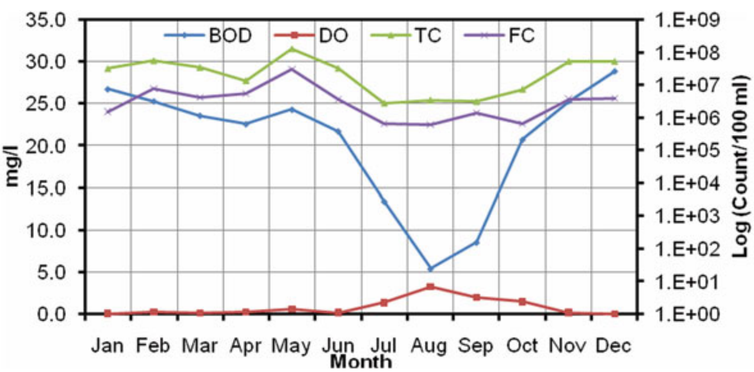


**Fig. 11.21** Monthly variation in water quality at Nizamuddin Bridge

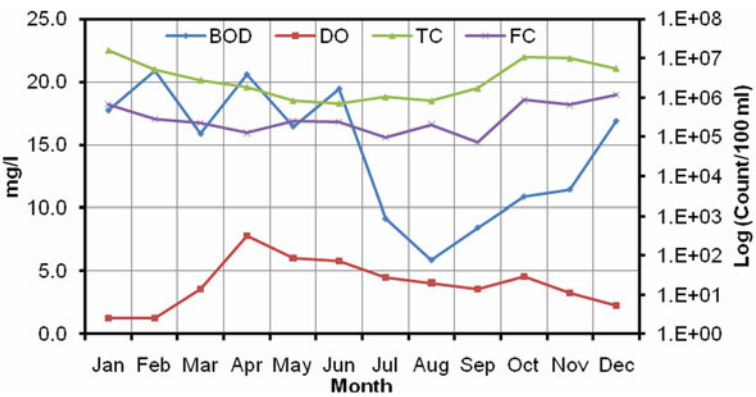


**Fig. 11.22** Monthly variation in water quality at Mazawali

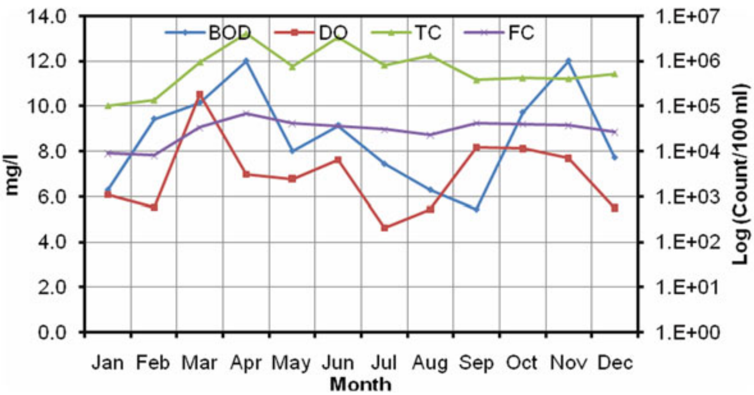


**Fig. 11.23** Monthly variation in water quality at Mathura U/S

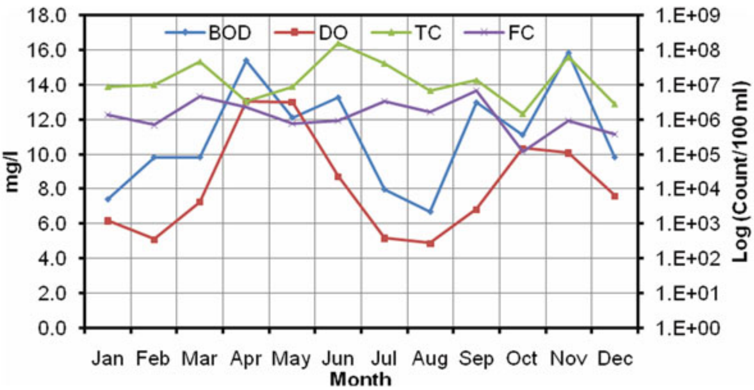


**Fig. 11.24** Monthly variation in water quality at Agra D/S

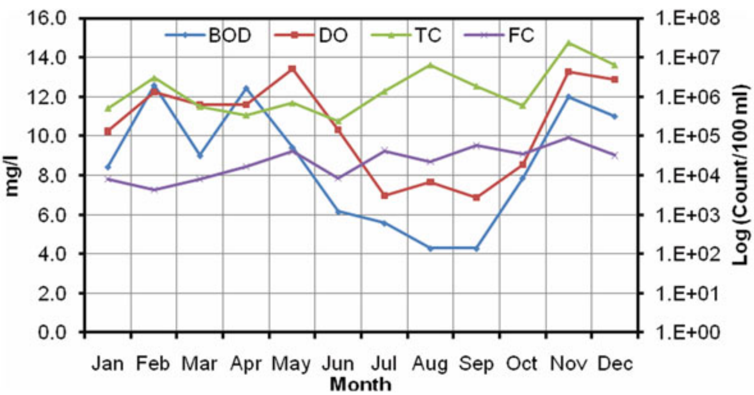


**Fig. 11.25** Monthly variation in water quality at Etawah

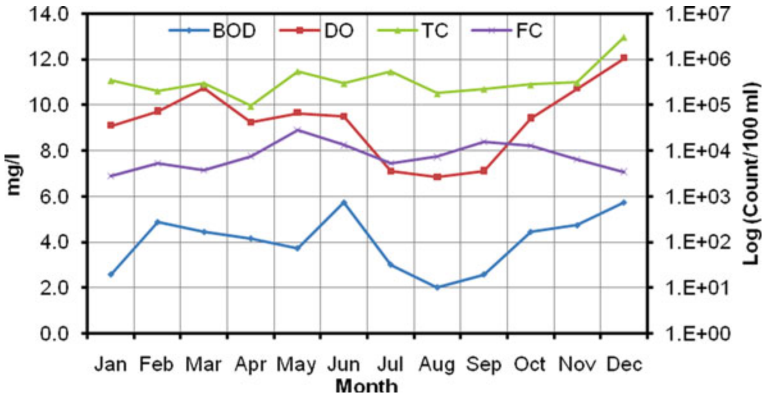


**Fig. 11.26** Monthly variation in water quality at Juhika

## 11.3 Concluding Remarks

Yamuna River maintains reasonable good quality upstream of Delhi and thus it satisfies the designated best use criteria most of the times except sometimes in summer season. Addition of huge amounts of untreated domestic sewage in Delhi and non-availability of dilution water results in degradation of water quality downstream stretch of the river. The river in its 500 km stretch from Delhi to the Chambal confluence is not fit for its designated best use even in the monsoon season when sufficient dilution is available. The pollution is predominantly organic in nature. Therefore, the depletion of oxygen is the major impact on the polluted stretch of the river which disturbs the river ecosystem to a large extent. The biodegradation of this organic pollution results in the release of nutrients which in turn promotes the growth of algae and other aquatic plants in the river. This excessive growth of unwanted plants results in the situation of eutrophication. Due to eutrophic conditions in this segment of the river, the dissolved oxygen during nights is depleted to a large extent resulting in mass killing of fishes and other aquatic life. The conditions are worsened by the addition of untreated domestic sewage from Mathura and Agra. Thus in this entire stretch of 500 km, the oxygen is the key factor which determines the health of the river and distribution of aquatic life in it.

The microbial pollution is prevailing over the entire Yamuna River due to the contribution of human wastes. The Yamuna River is used for almost all the uses identified under the designated best use classification of CPCB. Considering its holy nature people from all over the country gather at several places along the river to take a holy dip in it, especially in places like Vrindavan, Mathura, Bateshwar and Allahabad where lakhs of people gather on some auspicious occasions to take a holy dip. The results of CPCB monitoring indicate that the river is not meeting the designated best use criteria for outdoor bathing. At present there is no study to establish the health impact of taking bath in the river.

Results of micro-pollutant analysis in water and sediment indicate that some of these pollutants especially pesticides like DDT and BHC are presented in quite significant amounts. Other micro-pollutants are generally found either below the detection limit or in low concentration. The micro-pollutants are generally discharged along with huge amounts of organic matter and thus they are adsorbed on the surface of organic particles and settle down in the sediment in the bottom of drains and river bed. This deposited sludge is annually flushed during floods in the monsoon season. Thus, the river and drains are being annually cleaned and are not allowed to build up micro-pollutants in their beds year after year.

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# Chapter 12
# Environmental Flows

**Abstract** This chapter presents techniques for the estimation of environmental flows for a river, including the advantages and disadvantages of various methodologies for environmental flow estimation for a river. A component based technique for environmental flows is presented for the river, which are highly intercepted and used for pollutant transport. The technique describes the various water demands of the river, such as water requirements for aquatic habitat (i.e., ecological requirement), water requirements for groundwater conservation (i.e., seepage loss), water requirements for evaporation (i.e., evaporation loss), and water requirements for assimilation of river pollution (i.e., dilution water demand). Comparison between various hydrology-based techniques, such as Tennant method, modified Tennant method, and environmental management class based environmental flow estimator, is also included in the chapter.

Water resources and catchment development activities often intercept natural flows in rivers and streams. The interception leads to the impairment of various day to day water-based activities and ecosystem functions. In order to satisfy environmental flow requirements, a minimum continuous water supply to the streams must be maintained, which helps in the sustenance of aquatic life and ecosystems, without being a burden to the development. Environmental flows also make a critical contribution to the river health, economic development and poverty alleviation. Such flows even facilitate groundwater recharge and ensure the continued availability of the many benefits that healthy river and groundwater systems bring to society (O'Keefe, 2000; Tharme and King, 1998; Tharme, 2003; Smakhtin et al., 2006). Environmental flow, besides being a lifeline of aquatic habitat, also helps in the reduction of water footprint, which is defined as the total volume of freshwater used by any individual or community to produce goods and services consumed by the individual or the community. Multiple services rendered by the environmental flow decline the water footprint through the enhancement of virtual water consumption.

## 12.1 Definition

The term environmental flows (EFs) are also termed with different names, such as "Environmental Water Requirement"; "Environmental Water Demand"; etc. On the other hand, EF should not be confused with some similar terminologies

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like “In-stream Flow Requirement (IFR)”, which mostly refers to the flow for fish; “Drought IFR”, which is a reduced flow in dry years to maintain aquatic species without assuring their reproduction; and “Minimum Flow” that merely limits the abstraction of flow in the dry season. However, the “Maintenance IFR” although not synonymous to environmental flow, is similar. It refers to the flow regime required for maintaining all river ecosystem functions. But unlike EF, the maintenance IFR does not assure socio-economic or hydrological benefits.

The terminology “Ecological Demand of Water”, too sometimes creates confusion. Being consistent with term Ecology, the primary focus of ecological demand most frequently remains the water requirement for ecosystem services only, and overlooks other important roles of water, like aquifer recharging, soil moisture maintenance, prevention of salinization in the estuary, the drift of silt material, evapotranspiration requirement, and more (Iyer, 2005).

Based on this discussion, the environmental flow, in general, should at least include the water required for the assimilation of pollutants, evaporation, groundwater conservation, and aquatic-habitat conservation.

## 12.2 Methods for Assessment of Environmental Flows

Ecologists agree that the major criteria for determining environmental flows should include the maintenance of both spatial and temporal patterns of river flow, i.e., the flow variability which affects the structural and functional diversity of rivers and their flood plains and which in turn influences the species diversity of the river (Richter et al., 1997; Poff et al., 1997; Dyson et al., 2003; Gordon et al., 2004; Ward and Tockner, 2001; Ward et al., 2001; Knights, 2002; Nature Conservancy, 2006). Bunn and Arthington (2002) have formulated four basic principles that emphasize the role of flow regime in structuring aquatic life and show the link between flow and ecosystem changes: (i) Flow is a major determinant of physical habitat in rivers and in turn is the major determinant of biotic composition. Therefore, river flow modifications eventually lead to changes in the composition and diversity of aquatic communities. (ii) Aquatic species have evolved life history strategies primarily in response to natural flow regimes. Therefore, flow regime alterations can lead to the loss of biodiversity of native species. (iii) Maintenance of natural patterns of longitudinal and lateral connectivity in river floodplains determines the ability of many aquatic species to move between the river and flood plain or between the main river and its tributaries. The loss of longitudinal and lateral connectivity can lead to local extinction of species. (iv) The invasion of exotic and introduced species in rivers is facilitated by the alteration of flow regimes. Inter-basin water transfer may represent a significant mechanism for the spread of exotic species.

For the estimation of environmental flows, several methodologies have been developed and used in different rivers. Depending on data requirements for calculation, these methodologies can be categorized into four major groups (Palau, 1994; Jowett, 1997; Alcaźar et al., 2008): (i) Hydrology-based methods: These are based on the study of historical flow regime records (Tennant, 1976; Richter et al., 1997; Hughes and Münster, 2000; Hughes and Hannart, 2003; Smakhtin and Anputhas, 2006; and Kashaigili et al., 2007). (ii) Hydraulic methods: These methods are based on the study of the hydraulic geometry of stream channels (Collings, 1972). (iii) Habitat methods: These are based on the simulation of physical habitats, such as the Instream Flow Incremental Methodology (Bovee, 1982). (iv) A fourth group of methodologies labeled "holistic" have appeared more recently as a response to a changing conception of water resources management arising from a more global vision of the riverine ecosystem (e.g., King and Louw, 1998). A brief description of these methodologies is summarized in Table 12.1.

**Table 12.1** Various approaches for estimating environmental flows

| S. No. | Methods | Description |
|---|---|---|
| 1. | Look-up tables | Using the thumb rule on simple indices given in the look-up tables. This method is used when few or no local ecological data are available. In this method $Q_{95}$ (i.e. the flow equaled or exceeded 95% of time) is considered as environmental flow. This method is purely based on river hydrology. |
| 2. | Tennant method | This method was based on the index developed by calibrating the data from hundreds of rivers in the United States of America (USA).<br>Percentages of mean annual flow (MAF) are specified that provide different quality habitats for fish; e.g.<br>(i) 10% of MAF: poor quality (survival),<br>(ii) 30% of MAF: moderate habitats (Satisfactory),<br>(iii) 60% of MAF: excellent habitats. |
| 3. | Range of variability approach | It is a desktop method, which identifies the components of a natural flow regime, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events) and duration (indexed by moving average minima and maxima). |
| 4. | Hydraulic rating method | It is also a desktop method, which uses changes in hydraulic variable such as those in the wetted perimeter, and the area of riverbed submerged, to define environmental flows. These provide simple indices of available habitat in a river at a given discharge.<br>This method provides simple indices of available habitat in a river at a given discharge and perimeter. More appropriate to support scenario based decision-making and water allocation negotiations. |
| 5. | Building block method | It is based on the functional analysis of the system. The basic premise is that riverine species are dependent on basic elements (building blocks) of the flow regime, including low flows and floods that maintain the sediment dynamics and geomorphologic structure of the river. This method is flexible, robust, more focused on the whole ecosystem. |
| 6. | Habitat analysis | This method is replicable and predictive; however, it is expensive to collect hydraulic and ecological data. |

Despite wide applications of the hydrology-based methods for estimating environmental flows, such as Tennant method (Tennant, 1976), desktop reserve model (Hughes and Münster, 2000; Kashaigili et al., 2007), range of variability approach (Richter et al, 1997), and environmental management class (EMC) based environmental flow estimation (Smakhtin and Anputhas, 2006; Smakhtin and Eriyagama, 2008), do not account for the different components of environmental flows, and therefore the applicability of these methodologies has become limited when a river is highly intercepted, receives wastewater discharge, and has a lack of historical records. On the other hand, in the fourth category, a few studies have been undertaken (King and Louw, 1998, Yang et al., 2009). In the study by Yang et al. (2009), environmental flows for Yellow River were estimated, based on the classification and regionalization of ecosystems, multiple ecological management objectives, and spatial variability. This approach considered natural water consumption, such as water losses for evaporation and infiltration in the area above the section that fulfills environmental flow requirements of the terrestrial ecosystems. However, the water requirement for assimilating pollutants was not considered, which the major concern is when the river is used for pollutant transport also.

This chapter describes the application of two hydrology-based methods, such as the Tennant method (Tennant, 1976) and Environment Management Class based approach developed by Smakhtin and Anputhas (2006) and Smakhtin and Eriyagama (2008). Looking into the limitations of these methods for Indian River conditions, a comprehensive method has been developed and is presented here.

## 12.3 The Tennant Method

The Tennant method bases its stream flow requirements on the observation that aquatic-habitat conditions are similar in streams carrying the same proportion of the Mean Annual Flow (MAF). The method establishes stream flow requirements on the basis of a predetermined percentage of MAF (Tennant, 1976), and associates aquatic-habitat conditions with different percentages of MAF (Table 12.2). The Tennant method is less sensitive to summer water withdrawals than methods that use low flow statistics to determine stream flow requirements because the Tennant stream flow requirements are derived from the mean annual flow statistics, which is largely determined by high flows.

Minimum stream flows for small streams during summer were established by the Tennant method as 40, 30, and 10% of MAF, which represent good, fair, and poor habitat conditions, respectively. At the 30% MAF, most of the stream substrate is submerged, but at 10% MAF half or more of the stream substrate can be exposed (Tennant, 1976). The 10% MAF value is often used to determine minimum stream flow requirements in summer. To account for seasonal variability, Tennant (1976) established different stream flow requirements for summer and winter seasons. In the mountainous Western United States, where the tenant method was developed, precipitation patterns and snowmelt runoff typically result in low

**Table 12.2** Relations between aquatic-habitat conditions and mean annual flow described by the Tennant method for small streams

| Aquatic-habitat condition for small streams | % MAF (April–Sept) [for India: monsoon season (June–Sept)] | % MAF (Oct–March) [for India: non-monsoon season (Oct–May)] |
|---|---|---|
| Flushing flows | 200 | 200 |
| Optimum range | 60–100 | 60–100 |
| Outstanding | 60 | 40 |
| Excellent | 50 | 30 |
| Good | 40 | 20 |
| Fair | 30 | 10 |
| Poor | 10 | 10 |
| Severe degradation | <10 | <10 |

stream flows in fall and early winter, and high stream flows in spring and summer. Therefore, the Tennant stream flow recommendations are higher in summer than in winter. Similar criteria can also be evaluated for Indian streams, where during the Monsoon (June to September) high flows occur and for the rest of the year low flow condition is achieved. This condition is almost similar to the mountainous Western United States and therefore can be adopted for Indian rivers. Considering river flow variability, the Tennant method was modified for Indian rivers by distributing the estimated environmental flow throughout the year considering similar monthly flow distribution patterns. For Indian conditions, the monthly distribution of 25% MAF may be considered as the ecological flows except for the highly polluted river conditions like the Wazirabad to Okhla barrage reach of the Yamuna River.

### *12.3.1 The Modified Tennant Method*

Looking into the importance of the flow variability in the river system, the constant allowance for environmental flow based on the mean annual flow (MAF) will be not adequate for the Indian River system which has a large variation in the flow during the monsoon and non-monsoon periods. It leads to the revision in the methodology, in which the allowable estimated environmental flows should be temporally distributed considering the temporal variation of the stream flows.

### *12.3.2 Application of Modified Tennant Method*

Using the Tennant method, environmental flows for different reaches of the Yamuna River have been estimated. The reaches considered for the estimation of environmental flows are:

(i) Origin to the Hathinikund barrage (Paonta),
(ii) Hathinikund barrage to the Wazirabad barrage (Kalanaur site),
(iii) Wazirabad barrage to Okhla barrage (Delhi Railway Bridge site, DRB),
(iv) Okhla barrage to the Agra discharge site (Agra discharge site), and
(v) Agra to the Allahabad at the confluence of Ganga River (Pratappur discharge site).

In the analysis, 10-daily discharge data for the period of 1989–2007 have been used. The first step of this methodology is to estimate the mean annual flow (MAF) of the respective reaches, and is given in Table 12.3 which also includes the allocation of environmental flow volume with respect to the different aquatic-habitat conditions. The second important step for applying the modified Tennant method is to derive the monthly flow distribution of MAF for the reach. This step is carried out by analyzing the monthly discharge data followed by the estimation of mean monthly flow. The estimated monthly distribution of MAF is presented in Table 12.4.

Using the appropriate monthly distribution (Table 12.4) with respect to the site, monthly volume of environmental flows at different aquatic-habitat conditions (using Table 12.3) can be obtained, and is given in Tables 12.5, 12.6, 12.7, 12.8, and 12.9. These tables also give the mean monthly e-flow requirements.

Since the Yamuna River water is highly regulated due to the upstream uses and Delhi water supply from the Wazirabad barrage, therefore the flow is no more virgin. Under such circumstances the first two condition (i.e., poor and fair classes cannot be considered). Therefore, to maintain the environmental flows in the Delhi Stretch (i.e. Wazirabad to Okhla reach), it is highly recommended to use the "Good Class (i.e., 40% MAF)" aquatic-habitat condition. The temporal flow volumes and mean discharges are shown in Figs. 12.1 and 12.2. However, in this computation the assimilation requirement for dilution of pollutants has been

**Table 12.3** Estimated environmental flow allocation for different sites of Yamuna River using Tennant method

| | | | | Aquatic-habitat condition | | | |
|---|---|---|---|---|---|---|---|
| S. No. | Reach | Site name | MAF (MCM) | Poor: 10% MAF | Fair: 25% MAF | Fair: 30% MAF | Good: 40% MAF |
| 1 | Origin to Hathinikund | Paonta | 4,818.0 | 481.2 | 1,203.0 | 1,443.6 | 1,924.8 |
| 2 | Hathinikund to Wazirabad | Kalanaur | 4,167.0 | 416.7 | 1,041.7 | 1,250.1 | 1,666.8 |
| 3 | Wazirabad to Okhla | DRB | 4,547.0 | 454.7 | 1,136.7 | 1,364.1 | 1,818.8 |
| 4 | Okhla to Agra | Agra | 4,225.0 | 422.5 | 1,056.2 | 1,267.5 | 1,690.0 |
| 5 | Agra to Allahabad | Pratappur | 51,556.0 | 5,156.1 | 12,890.2 | 15,468.3 | 20,624.4 |

**Table 12.4** Monthly percent distribution of MAF for different sites/reaches of the Yamuna River

| | Discharge sites of Yamuna | | | | |
|---|---|---|---|---|---|
| Months | Paonta | Kalanaur | DRB | Agra | Pratappur |
| June | 4.57 | 2.23 | 2.16 | 1.66 | 1.79 |
| July | 16.83 | 18.50 | 14.63 | 9.96 | 12.61 |
| August | 33.15 | 38.88 | 37.17 | 32.07 | 34.33 |
| September | 21.51 | 24.24 | 25.84 | 30.96 | 31.33 |
| October | 5.82 | 5.76 | 5.50 | 9.96 | 6.06 |
| November | 2.87 | 3.24 | 3.30 | 4.97 | 2.86 |
| December | 2.27 | 0.77 | 2.11 | 2.77 | 2.42 |
| January | 2.27 | 0.77 | 2.02 | 1.89 | 1.90 |
| February | 2.83 | 0.60 | 1.78 | 1.66 | 1.84 |
| March | 3.99 | 2.81 | 1.65 | 1.33 | 1.79 |
| April | 1.66 | 1.10 | 2.42 | 1.66 | 1.79 |
| May | 2.24 | 1.10 | 1.43 | 1.11 | 1.26 |

**Table 12.5** E-flows using modified Tennant method for the origin to the Hathinikund reach

| | | Poor: 10%MAF | | Fair: 25%MAF | | Fair: 30%MAF | | Good: 40%MAF | |
|---|---|---|---|---|---|---|---|---|---|
| Month | %Dist | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 4.57 | 22.00 | 8.49 | 55.00 | 21.22 | 66.00 | 25.46 | 88.00 | 33.95 |
| Jul | 16.83 | 81.00 | 30.24 | 202.50 | 75.60 | 243.00 | 90.73 | 324.00 | 120.97 |
| Aug | 33.15 | 159.50 | 59.55 | 398.75 | 148.88 | 478.50 | 178.65 | 638.00 | 238.20 |
| Sep | 21.51 | 103.50 | 39.93 | 258.75 | 99.83 | 310.50 | 119.79 | 414.00 | 159.72 |
| Oct | 5.82 | 28.00 | 10.45 | 70.00 | 26.14 | 84.00 | 31.36 | 112.00 | 41.82 |
| Nov | 2.87 | 13.80 | 5.32 | 34.50 | 13.31 | 41.40 | 15.97 | 55.20 | 21.30 |
| Dec | 2.27 | 10.90 | 4.07 | 27.25 | 10.17 | 32.70 | 12.21 | 43.60 | 16.28 |
| Jan | 2.27 | 10.90 | 4.07 | 27.25 | 10.17 | 32.70 | 12.21 | 43.60 | 16.28 |
| Feb | 2.83 | 13.60 | 5.62 | 34.00 | 14.05 | 40.80 | 16.87 | 54.40 | 22.49 |
| Mar | 3.99 | 19.20 | 7.17 | 48.00 | 17.92 | 57.60 | 21.51 | 76.80 | 28.67 |
| Apr | 1.66 | 8.00 | 3.09 | 20.00 | 7.72 | 24.00 | 9.26 | 32.00 | 12.35 |
| May | 2.24 | 10.80 | 4.03 | 27.00 | 10.08 | 32.40 | 12.10 | 43.20 | 16.13 |
| Total | 100.0 | 481.2 | | 1,203.0 | | 1,443.6 | | 1,924.8 | |

not considered as this component is not in the scope of this method. The E-flow requirements for other reaches are graphically shown in Figs. 12.2, 12.3, 12.4, and 12.5.

## 12.4 EMC Based Environmental Flow Calculator

The estimation of environmental flows, based on the Smakhtin and Anputhas (2006) and Smakhtin and Eriyagama (2008), requires establishing the environmental management classes followed by the derivation of environmental flow duration

**Table 12.6** E-flows using modified Tennant method for the Hathinikund to Wazirabad reach

| | | Poor: 10%MAF | | Fair: 25%MAF | | Fair: 30%MAF | | Good: 40%MAF | |
|---|---|---|---|---|---|---|---|---|---|
| Month | %Dist | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 2.23 | 9.30 | 3.59 | 23.25 | 8.97 | 27.90 | 10.76 | 37.20 | 14.35 |
| Jul | 18.50 | 77.10 | 28.79 | 192.75 | 71.96 | 231.30 | 86.36 | 308.40 | 115.14 |
| Aug | 38.88 | 162.00 | 60.48 | 405.00 | 151.21 | 486.00 | 181.45 | 648.00 | 241.94 |
| Sep | 24.24 | 101.00 | 38.97 | 252.50 | 97.42 | 303.00 | 116.90 | 404.00 | 155.86 |
| Oct | 5.76 | 24.00 | 8.96 | 60.00 | 22.40 | 72.00 | 26.88 | 96.00 | 35.84 |
| Nov | 3.24 | 13.50 | 5.21 | 33.75 | 13.02 | 40.50 | 15.63 | 54.00 | 20.83 |
| Dec | 0.77 | 3.20 | 1.19 | 8.00 | 2.99 | 9.60 | 3.58 | 12.80 | 4.78 |
| Jan | 0.77 | 3.20 | 1.19 | 8.00 | 2.99 | 9.60 | 3.58 | 12.80 | 4.78 |
| Feb | 0.60 | 2.50 | 1.03 | 6.25 | 2.58 | 7.50 | 3.10 | 10.00 | 4.13 |
| Mar | 2.81 | 11.70 | 4.37 | 29.25 | 10.92 | 35.10 | 13.10 | 46.80 | 17.47 |
| Apr | 1.10 | 4.60 | 1.77 | 11.50 | 4.44 | 13.80 | 5.32 | 18.40 | 7.10 |
| May | 1.10 | 4.60 | 1.72 | 11.50 | 4.29 | 13.80 | 5.15 | 18.40 | 6.87 |
| Total | 100.0 | 416.7 | | 1,041.7 | | 1,250.1 | | 1,666.8 | |

**Table 12.7** E-flows using modified Tennant method for the Wazirabad to the Okhla reach

| | | Poor: 10%MAF | | Fair: 30%MAF | | Fair: 25%MAF | | Good: 40%MAF | |
|---|---|---|---|---|---|---|---|---|---|
| Month | %Dist | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 2.16 | 9.80 | 3.78 | 29.40 | 11.34 | 24.50 | 9.45 | 39.20 | 15.12 |
| Jul | 14.63 | 66.50 | 24.83 | 199.50 | 74.48 | 166.25 | 62.07 | 266.00 | 99.31 |
| Aug | 37.17 | 169.00 | 63.10 | 507.00 | 189.29 | 422.50 | 157.74 | 676.00 | 252.39 |
| Sep | 25.84 | 117.50 | 45.33 | 352.50 | 136.00 | 293.75 | 113.33 | 470.00 | 181.33 |
| Oct | 5.50 | 25.00 | 9.33 | 75.00 | 28.00 | 62.50 | 23.33 | 100.00 | 37.34 |
| Nov | 3.30 | 15.00 | 5.79 | 45.00 | 17.36 | 37.50 | 14.47 | 60.00 | 23.15 |
| Dec | 2.11 | 9.60 | 3.58 | 28.80 | 10.75 | 24.00 | 8.96 | 38.40 | 14.34 |
| Jan | 2.02 | 9.20 | 3.43 | 27.60 | 10.30 | 23.00 | 8.59 | 36.80 | 13.74 |
| Feb | 1.78 | 8.10 | 3.35 | 24.30 | 10.04 | 20.25 | 8.37 | 32.40 | 13.39 |
| Mar | 1.65 | 7.50 | 2.80 | 22.50 | 8.40 | 18.75 | 7.00 | 30.00 | 11.20 |
| Apr | 2.42 | 11.00 | 4.24 | 33.00 | 12.73 | 27.50 | 10.61 | 44.00 | 16.98 |
| May | 1.43 | 6.50 | 2.43 | 19.50 | 7.28 | 16.25 | 6.07 | 26.00 | 9.71 |
| Total | 100 | 454.7 | | 1,364.1 | | 1,136.75 | | 1,818.8 | |

curves (EFDC) and finally the environmental flow time series. Environmental flows aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition, which is also referred to as "desired future state", "environmental management class (EMC)", "ecological management category" or level of environmental protection (DWAF, 1997; Aceman and Dunbar, 2004). The higher the EMC, the more water will need to be allocated for the ecosystem maintenance or conservation and more flow variability will need to be preserved.

**Table 12.8** E-flows using modified Tennant method for the Okhla to the Agra site reach

| | | Poor: 10%MAF | | Fair: 25%MAF | | Fair: 30%MAF | | Good: 40%MAF | |
|---|---|---|---|---|---|---|---|---|---|
| Month | %Dist | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 1.66 | 7.01 | 2.70 | 17.53 | 6.76 | 21.03 | 8.11 | 28.04 | 10.82 |
| Jul | 9.96 | 42.10 | 15.72 | 105.25 | 39.30 | 126.30 | 47.16 | 168.40 | 62.87 |
| Aug | 32.07 | 135.50 | 50.59 | 338.75 | 126.47 | 406.50 | 151.77 | 542.00 | 202.36 |
| Sep | 30.96 | 130.80 | 50.46 | 327.00 | 126.16 | 392.40 | 151.39 | 523.20 | 201.85 |
| Oct | 9.96 | 42.10 | 15.72 | 105.25 | 39.30 | 126.30 | 47.16 | 168.40 | 62.87 |
| Nov | 4.97 | 21.00 | 8.10 | 52.50 | 20.25 | 63.00 | 24.31 | 84.00 | 32.41 |
| Dec | 2.77 | 11.70 | 4.37 | 29.25 | 10.92 | 35.10 | 13.10 | 46.80 | 17.47 |
| Jan | 1.89 | 8.00 | 2.99 | 20.00 | 7.47 | 24.00 | 8.96 | 32.00 | 11.95 |
| Feb | 1.66 | 7.01 | 2.90 | 17.53 | 7.24 | 21.03 | 8.69 | 28.04 | 11.59 |
| Mar | 1.33 | 5.60 | 2.09 | 14.00 | 5.23 | 16.80 | 6.27 | 22.40 | 8.36 |
| Apr | 1.66 | 7.01 | 2.70 | 17.53 | 6.76 | 21.03 | 8.11 | 28.04 | 10.82 |
| May | 1.11 | 4.67 | 1.74 | 11.68 | 4.36 | 14.01 | 5.23 | 18.68 | 6.97 |
| Total | 100.0 | 4,222.5 | | 1,056.2 | | 1,267.5 | | 1,690.0 | |

Ideally, these classes should be based on empirical relationships between flow and ecological status/conditions associated with clearly identifiable thresholds. However, at present the evidence for such thresholds is not sufficient and these categories are simply a management concept, which has been developed and used in the world because of the need to make decisions under conditions of limited knowledge. Placing a river into certain EMC is often accomplished by expert judgment using the scoring system (DWAF, 1997; Environmental Agency, 2001). Alternatively, EMCs may be seen as default "scenarios" of environmental protection and the corresponding EF as "scenarios" of environmental water demand.

Smakhtin and Anputhas (2006) defined six EMCs corresponding to the default levels of environmental flows (Table 12.10). A river which falls into classes C to F would normally be present in densely populated areas with multiple men induced impacts. Poor ecosystem conditions (Class E and F) are sometimes not considered acceptable from the management perspective and the management intention is always to "move" such rivers up to the least acceptable class D through rehabilitation measures. It can be noted that the ecosystems in class F are likely to be those which have been modified beyond rehabilitation to anything resembling a natural condition.

In this approach, the environmental flow duration curve is derived for different EMC classes from the reference flow duration curve, and finally the monthly time series spatial interpolation technique is used (Smakhtin and Anputhas, 2006; and Hughes and Smakhtin, 1996). In this manner, the general pattern of flow variability is preserved, although with every shift, part of the variability is lost. The procedure of deriving the environmental flow duration curve followed by the monthly time series of e-flows is presented in the following section.

**Table 12.9** E-flows using modified Tennant method for the Agra to the Allahabad reach

| | | Poor: 10%MAF | | Fair: 25%MAF | | Fair: 30%MAF | | Good: 40%MAF | |
|---|---|---|---|---|---|---|---|---|---|
| Month | % Dist | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 1.79 | 92.51 | 35.69 | 231.27 | 89.23 | 277.53 | 107.07 | 370.04 | 142.76 |
| Jul | 12.61 | 650.06 | 242.71 | 1,625.16 | 606.76 | 1,950.19 | 728.12 | 2,600.25 | 970.82 |
| Aug | 34.33 | 1,770.17 | 660.91 | 4,425.43 | 1,652.27 | 5,310.51 | 1,982.72 | 7,080.69 | 2,643.63 |
| Sep | 31.33 | 1,615.16 | 623.13 | 4,037.89 | 1,557.83 | 4,845.47 | 1,869.39 | 6,460.63 | 2,492.53 |
| Oct | 6.06 | 312.53 | 116.69 | 781.33 | 291.71 | 937.59 | 350.06 | 1,250.12 | 466.74 |
| Nov | 2.86 | 147.51 | 56.91 | 368.79 | 142.28 | 442.54 | 170.73 | 590.06 | 227.65 |
| Dec | 2.42 | 125.01 | 46.67 | 312.53 | 116.69 | 375.04 | 140.02 | 500.05 | 186.70 |
| Jan | 1.90 | 98.11 | 36.63 | 245.27 | 91.57 | 294.33 | 109.89 | 392.44 | 146.52 |
| Feb | 1.84 | 95.01 | 39.27 | 237.52 | 98.18 | 285.03 | 117.82 | 380.04 | 157.09 |
| Mar | 1.79 | 92.51 | 34.54 | 231.27 | 86.35 | 277.53 | 103.62 | 370.04 | 138.16 |
| Apr | 1.79 | 92.51 | 35.69 | 231.27 | 89.23 | 277.53 | 107.07 | 370.04 | 142.76 |
| May | 1.26 | 65.01 | 24.27 | 162.52 | 60.68 | 195.02 | 72.81 | 260.03 | 97.08 |
| Total | 100.0 | 5,156.1 | | 12,890.2 | | 15,468.3 | | 20,624.4 | |

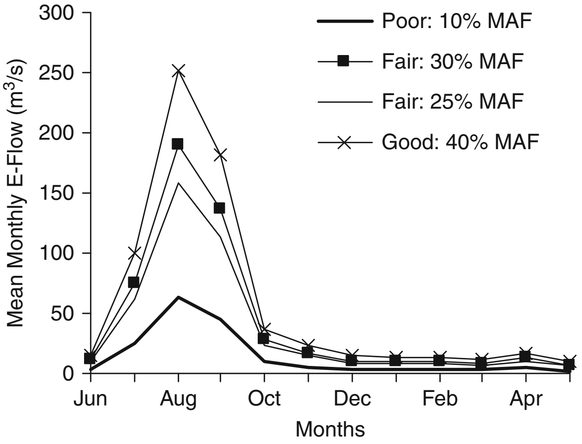


**Fig. 12.1** Mean monthly e-flow rates for the Wazirabad-Okhla reach

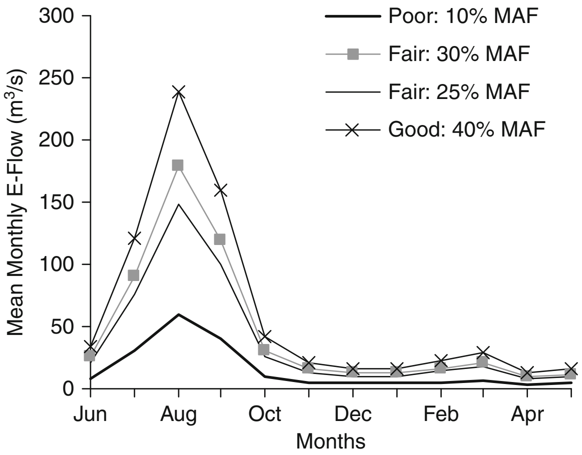


**Fig. 12.2** Mean monthly e-flow rates for the Origin-Hathinikund reach

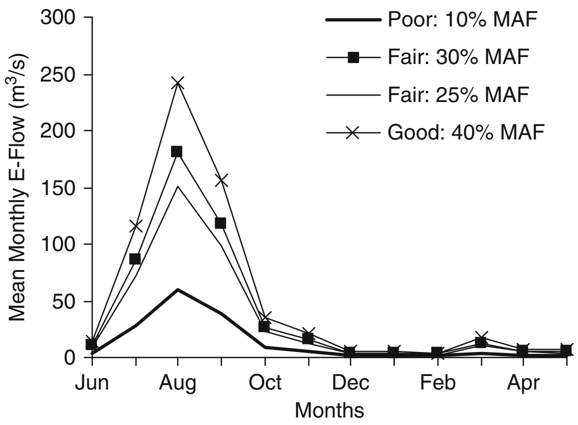


**Fig. 12.3** Mean monthly e-flow rates for the Hathinikund-Wazirabad reach

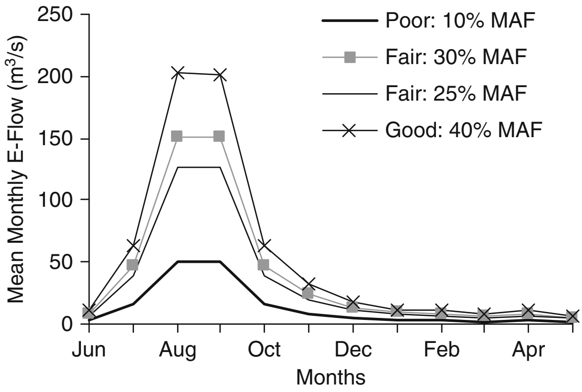


**Fig. 12.4** Mean monthly e-flow rates for the Okhla-Agra reach

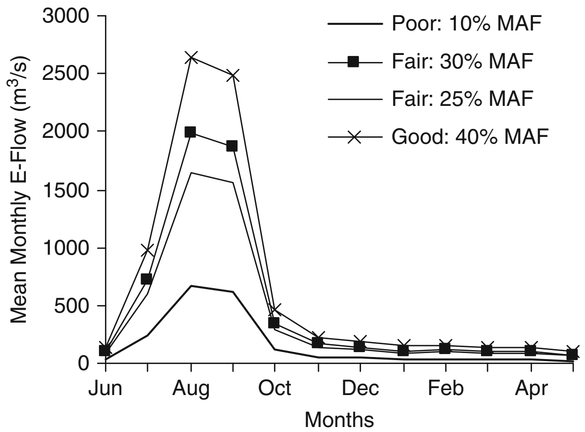


**Fig. 12.5** Mean monthly e-flow rates for the Agra-Pratappur reach

## *12.4.1 Establishing Environmental Flow Duration Curve*

A simple approach has been proposed by Smakhtin and Anputhas (2006) to determine the default FDC representing the summary of EF for each EMC. In this approach, the original reference FDC is represented by table of flow values covering the entire range of probabilities of occurrence. For representing the FDC, 17 fixed percentage points: 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9, and 99.99% are considered. These points adequately cover the entire range of flow regime. These percentage points are used to determine the environmental flow duration curve (E-FDC) corresponding to the EMC by lateral shifting of the original reference FDC to the left along the probability axis.

An FDC shift by one step means that a flow which is exceeded 99.99% of the time in the original FDC will now be exceeded 99.9% of the time; the flow at 99.9% becomes the flow at 99%; the flow at 99% becomes the flow at 95%; etc. The procedure for deriving the E-FDC in graphical and tabular is shown in Fig. 12.6 and Table 12.11, respectively.

**Table 12.10** Environmental Management Classes (EMCs)

| EMC | Status | Ecological description | Management perspective | Default FDC shift limit |
|---|---|---|---|---|
| **A** | Natural | Pristine condition or minor modification of in-stream and riparian habitat | • Protected river and basins.<br>• Reserves and national parks.<br>• No new water projects (dam, diversions, etc.) allowed | Lateral shift of reference FDC one percentage point to the left along the time axis from the original FDC position |
| **B** | Slightly modified | Largely intact biodiversity and habitats despite water resources development and/or basin modifications | Water supply schemes or irrigation development present and/or allowed | Lateral shift of reference FDC one percentage point to the left along the time axis from the position of the FDC for A class |
| **C** | Moderately modified | The habitat and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present. | Multiple disturbances associated with the need for socio-economic development, e.g., dams, diversion, habitat modification and reduced water supply | Lateral shift of reference FDC one more percentage point to the left along the time axis from the position of the FDC for B class |
| **D** | Largely modified | • Large changes in natural habitat, biota and basic ecosystem functions have occurred.<br>• A clearly lower than expected species richness.<br>• Much lowered presence of intolerant species.<br>• Alien species prevail | Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation | Lateral shift of reference FDC one more percentage point to the left along the time axis from the position of the FDC for C class |

**Table 12.10** (continued)

| EMC | Status | Ecological description | Management perspective | Default FDC shift limit |
|---|---|---|---|---|
| **E** | Seriously modified | • Habitat diversity and availability have declined.<br>• A strikingly lower than expected species richness.<br>• Only tolerant species remain.<br>• Indigenous species can no longer breed.<br>• Alien species. | High human population density and extensive water resources exploitation | Lateral shift of reference FDC one more percentage point to the left along the time axis from the position of the FDC for D class |
| **F** | Critically modified | • Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota.<br>• In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible. | This status is not acceptable from the management perspective.<br>Management interventions are necessary to restore flow pattern, river habitats, etc. (if still possible/feasible) – to "move" a river to a higher management category. | Lateral shift of reference FDC one more percentage point to the left along the time axis from the position of the FDC for E class |

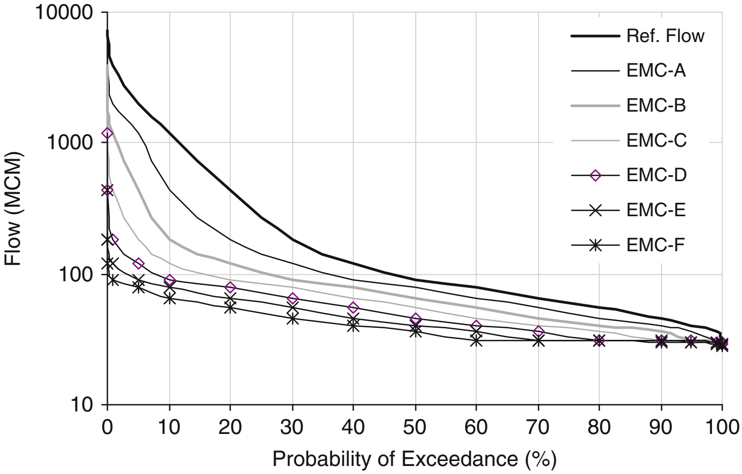


**Fig. 12.6** An example E-FDCs for Delhi Railway Bridge site of Yamuna River

**Table 12.11** Computational procedure of environmental FDC (E-FDC)

| % | Reference FDC | EMC-A | EMC-B | EMC-C | EMC-D | EMC-E | EMC-F |
|---|---|---|---|---|---|---|---|
| 0.01 | 7,148 | 7,148 | 3,910 | 2,018 | 1,204 | 431 | 180 |
| 0.1 | 7,148 | 3,910 | 2,018 | 1,204 | 431 | 180 | 120 |
| 1 | 3,910 | 2,018 | 1,204 | 431 | 180 | 120 | 89.9 |
| 5 | 2,018 | 1,204 | 431 | 180 | 120 | 89.9 | 77.9 |
| 10 | 1,204 | 431 | 180 | 120 | 89.9 | 77.9 | 64.6 |
| 20 | 431 | 180 | 120 | 89.9 | 77.9 | 64.6 | 55.5 |
| 30 | 180 | 120 | 89.9 | 77.9 | 64.6 | 55.5 | 45.7 |
| 40 | 120 | 89.9 | 77.9 | 64.6 | 55.5 | 45.7 | 40.1 |
| 50 | 89.9 | 77.9 | 64.6 | 55.5 | 45.7 | 40.1 | 36.2 |
| 60 | 77.9 | 64.6 | 55.5 | 45.7 | 40.1 | 36.2 | 31.4 |
| 70 | 64.6 | 55.5 | 45.7 | 40.1 | 36.2 | 31.4 | 31 |
| 80 | 55.5 | 45.7 | 40.1 | 36.2 | 31.4 | 31 | 30.5 |
| 90 | 45.7 | 40.1 | 36.2 | 31.4 | 31 | 30.5 | 30 |
| 95 | 40.1 | 36.2 | 31.4 | 31 | 30.5 | 30 | 29.6 |
| 99 | 36.2 | 31.4 | 31 | 30.5 | 30 | 29.6 | 29.1 |
| 99.9 | 31.4 | 31 | 30.5 | 30 | 29.6 | 29.1 | 28.7 |
| 99.99 | 31 | 30.5 | 30 | 29.6 | 29.1 | 28.7 | 28.3 |

### *12.4.2 Simulating Continuous Monthly Time Series of Environmental Flows*

An environmental FDC, discussed above, for any EMC gives only a summary of the EF regime acceptable for this EMC. However, one such curve is determined; it is also possible to convert it into actual environmental monthly flow time series.

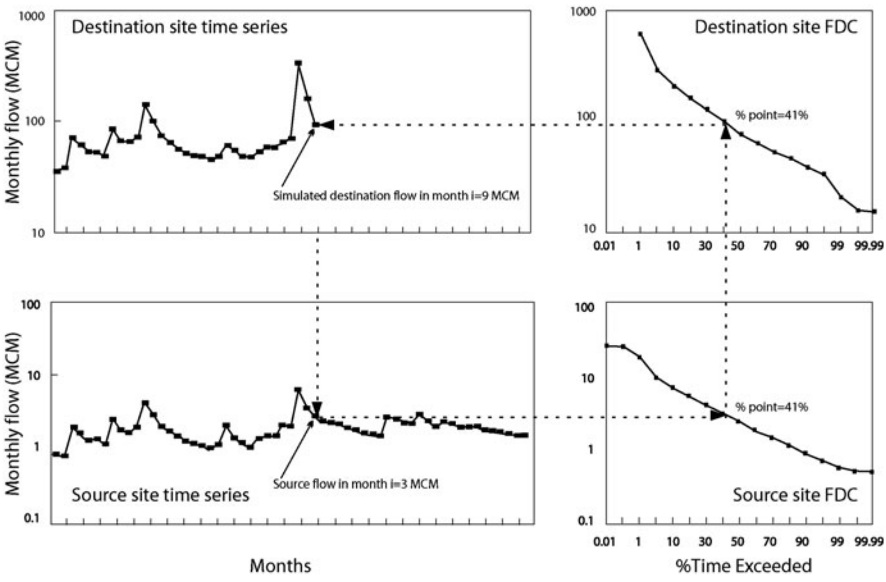


**Fig. 12.7** Spatial interpolation technique (Hughes and Smakhtin, 1996)

To accomplish this, a spatial interpolation technique proposed by Hughes and Smakhtin (1996) can be used. The underlying principle in this technique is that flows occurring simultaneously at sites in reasonable close proximity to each other correspond to similar percentage points on their respective FDCs. The site at which stream flow time series is generated is referred as destination site. The site with available time series, which is used for the generation, is called a "source site". In essence, the procedure is to transfer the streamflow time series from the location where the data are available to the destination site. The destination FDC is the one representing the EF sequence to be generated, while the source FDC and time series are those representing the reference natural flow regime at the same site. The procedure is therefore, to generate the modified time series (environmental flow time series) based on the linear transformation through two sets of FDCs (i.e. reference and E-FDC) corresponding to the reference time series. The procedure can be further elaborated through the following steps (Fig. 12.7):

(i) Identify the percentage point position on the reference FDC corresponding to the natural stream flow.
(ii) Using the identified percentage point, estimate the stream flow volume from the environmental FDC using the linear transformation.
(iii) Convert the stream flow volume as monthly stream flow discharge.
(iv) The final discharge value calculated, in the above steps, will be the monthly discharge corresponding to the time of natural stream flow time series. This results in the monthly time series of the environmental flow at particular EMC.

The generated environmental flow time series can be suitably interpreted by different specialists, like aquatic ecologist, hydrologist, etc., for making decisions.

### *12.4.3 Application of the Methodology*

To implement the technique, 10-daily data from various sites at Yamuna River for the period of 1989–2007 are first converted into the monthly flow data, and used to calculate the flow duration curve followed by the environmental flow duration curve and the monthly environmental flow time series. The sample calculation of the E-FDC for the Paonta Saheb is given in Table 12.12. The derived monthly flow time series, so derived following the aforesaid procedure, is analyzed to derive the allocation rule for monthly environmental flows.

Using the discharge data of different sites, the environmental flows is estimated for all the considered reaches of the Yamuna River. Site wise results are summarized in Tables 12.12, 12.13, 12.14, 12.15, 12.16, and 12.17) as well as in the graphical form through Figs. 12.8 through 12.22 for various stretches of the Yamuna River (i.e. Sections 12.4.3.1, 12.4.3.2, 12.4.3.3, 12.4.3.4 and 12.4.3.5).

**Table 12.12** Reference and environmental FDCs for different environment management classes (EMCs) for Paonta Saheb

| % | Ref Flow | EMC-A | EMC-B | EMC-C | EMC-D | EMC-E | EMC-F |
|---|---|---|---|---|---|---|---|
| 0.01 | 2,859 | 2,859 | 2,418 | 1,662 | 1,308 | 677 | 387 |
| 0.1 | 2,859 | 2,418 | 1,662 | 1,308 | 677 | 387 | 224 |
| 1 | 2,418 | 1,662 | 1,308 | 677 | 387 | 224 | 144 |
| 5 | 1,662 | 1,308 | 677 | 387 | 224 | 144 | 94.2 |
| 10 | 1,308 | 677 | 387 | 224 | 144 | 94.2 | 61.8 |
| 20 | 677 | 387 | 224 | 144 | 94.2 | 61.8 | 44.1 |
| 30 | 387 | 224 | 144 | 94.2 | 61.8 | 44.1 | 33.1 |
| 40 | 224 | 144 | 94.2 | 61.8 | 44.1 | 33.1 | 28.6 |
| 50 | 144 | 94.2 | 61.8 | 44.1 | 33.1 | 28.6 | 23.7 |
| 60 | 94.2 | 61.8 | 44.1 | 33.1 | 28.6 | 23.7 | 19.6 |
| 70 | 61.8 | 44.1 | 33.1 | 28.6 | 23.7 | 19.6 | 19.2 |
| 80 | 44.1 | 33.1 | 28.6 | 23.7 | 19.6 | 19.2 | 18.8 |
| 90 | 33.1 | 28.6 | 23.7 | 19.6 | 19.2 | 18.8 | 18.4 |
| 95 | 28.6 | 23.7 | 19.6 | 19.2 | 18.8 | 18.4 | 18 |
| 99 | 23.7 | 19.6 | 19.2 | 18.8 | 18.4 | 18 | 17.6 |
| 99.9 | 19.6 | 19.2 | 18.8 | 18.4 | 18 | 17.6 | 17.3 |
| 99.99 | 19.2 | 18.8 | 18.4 | 18 | 17.6 | 17.3 | 16.9 |

**Table 12.13** Monthly distribution of environmental flows for Paonta site of the Yamuna

| | Mean Flow | | EMC-A | | EMC-B | | EMC-C | | EMC-D | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 220.0 | 84.9 | 142.0 | 54.8 | 82.0 | 31.6 | 48.0 | 18.5 | 42.0 | 16.2 |
| Jul | 810.0 | 302.4 | 505.0 | 188.5 | 278.0 | 103.8 | 179.0 | 66.8 | 112.0 | 41.8 |
| Aug | 1,595.0 | 595.5 | 1,100.0 | 410.7 | 685.0 | 255.7 | 398.0 | 148.6 | 230.0 | 85.9 |
| Sep | 1,035.0 | 399.3 | 631.0 | 243.4 | 392.0 | 151.2 | 235.0 | 90.7 | 140.0 | 54.0 |
| Oct | 280.0 | 104.5 | 160.0 | 59.7 | 97.0 | 36.2 | 71.0 | 26.5 | 50.0 | 18.7 |
| Nov | 138.0 | 53.2 | 93.0 | 35.9 | 71.0 | 27.4 | 41.0 | 15.8 | 33.0 | 12.7 |
| Dec | 109.0 | 40.7 | 71.0 | 26.5 | 56.0 | 20.9 | 41.0 | 15.3 | 28.0 | 10.4 |
| Jan | 109.0 | 40.7 | 71.0 | 26.5 | 56.0 | 20.9 | 41.0 | 15.3 | 28.0 | 10.4 |
| Feb | 136.0 | 56.2 | 93.0 | 38.4 | 71.0 | 29.3 | 41.0 | 16.9 | 33.0 | 13.6 |
| Mar | 192.0 | 71.7 | 117.0 | 43.7 | 83.0 | 30.9 | 56.0 | 20.9 | 36.0 | 13.4 |
| Apr | 80.0 | 30.8 | 71.0 | 27.4 | 41.0 | 15.8 | 28.0 | 10.8 | 28.0 | 10.8 |
| May | 108.0 | 40.3 | 71.0 | 26.5 | 41.0 | 15.3 | 28.0 | 10.4 | 28.0 | 10.4 |

**Table 12.14** Monthly distributions of e-flows for the Hathinikund barrage to Wazirabad barrage reach

| | Mean flow | | EMC-A | | EMC-B | | EMC-C | | EMC-D | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 93 | 35.88 | 56.00 | 21.60 | 31.00 | 11.96 | 19.00 | 7.33 | 13.00 | 5.02 |
| Jul | 771 | 287.86 | 411.00 | 153.45 | 161.00 | 60.11 | 75.00 | 28.00 | 39.00 | 14.56 |
| Aug | 1,620 | 604.84 | 1,028.00 | 383.81 | 537.00 | 200.49 | 238.00 | 88.86 | 96.00 | 35.84 |
| Sep | 1,010 | 389.66 | 501.00 | 193.29 | 225.00 | 86.81 | 95.00 | 36.65 | 48.00 | 18.52 |
| Oct | 240 | 89.61 | 150.00 | 56.00 | 102.00 | 38.08 | 49.00 | 18.29 | 27.00 | 10.08 |
| Nov | 135 | 52.08 | 57.00 | 21.99 | 32.00 | 12.35 | 20.00 | 7.72 | 16.00 | 6.17 |
| Dec | 32 | 11.95 | 18.00 | 6.72 | 16.00 | 5.97 | 12.00 | 4.48 | 11.00 | 4.11 |
| Jan | 32 | 11.95 | 18.00 | 6.72 | 16.00 | 5.97 | 12.00 | 4.48 | 11.00 | 4.11 |
| Feb | 25 | 10.33 | 18.00 | 7.44 | 16.00 | 6.61 | 12.00 | 4.96 | 15.00 | 6.20 |
| Mar | 117 | 43.68 | 56.00 | 20.91 | 38.00 | 14.19 | 22.00 | 8.21 | 15.00 | 5.60 |
| Apr | 46 | 17.75 | 37.00 | 14.27 | 18.00 | 6.94 | 12.00 | 4.63 | 11.00 | 4.24 |
| May | 46 | 17.17 | 37.00 | 13.81 | 18.00 | 6.72 | 12.00 | 4.48 | 11.00 | 4.11 |

**Table 12.15** Monthly distribution of environmental flows for DRB site of the Yamuna

| | Mean Flow | | EMC-A | | EMC-B | | EMC-C | | EMC-D | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s |
| Jun | 98 | 37.81 | 65 | 25.08 | 56 | 21.60 | 42 | 16.20 | 42 | 16.20 |
| Jul | 665 | 248.28 | 316 | 117.98 | 131 | 48.91 | 92 | 34.35 | 68 | 25.39 |
| Aug | 1,690 | 630.97 | 976 | 364.40 | 486 | 181.45 | 210 | 78.41 | 118 | 44.06 |
| Sep | 1,175 | 453.32 | 560 | 216.05 | 299 | 115.35 | 160 | 61.73 | 100 | 38.58 |
| Oct | 250 | 93.34 | 140 | 52.27 | 112 | 41.82 | 75 | 28.00 | 62 | 23.15 |
| Nov | 150 | 57.87 | 125 | 48.23 | 56 | 21.60 | 50 | 19.29 | 46 | 17.75 |
| Dec | 96 | 35.84 | 65 | 24.27 | 56 | 20.91 | 50 | 18.67 | 41 | 15.31 |
| Jan | 92 | 34.35 | 65 | 24.27 | 48 | 17.92 | 42 | 15.68 | 39 | 14.56 |
| Feb | 81 | 33.48 | 65 | 26.87 | 47 | 19.43 | 41 | 16.95 | 38 | 15.71 |
| Mar | 75 | 28.00 | 63 | 23.52 | 56 | 20.91 | 54 | 20.16 | 49 | 18.29 |
| Apr | 110 | 42.44 | 91 | 35.11 | 68 | 26.23 | 52 | 20.06 | 42 | 16.20 |
| May | 65 | 24.27 | 62 | 23.15 | 52 | 19.41 | 50 | 18.67 | 42 | 15.68 |

**Table 12.16** Monthly distribution of environmental flows for the Okhla to Agra reach of the Yamuna

| | Mean flow | | EMC-A | | EMC-B | | EMC-C | | EMC-D | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s | MCM | m$^3$/s |
| Jun | 70.10 | 27.04 | 42.1 | 16.24 | 25.2 | 9.72 | 15.8 | 6.10 | 15.0 | 5.79 |
| Jul | 421.00 | 157.18 | 196.0 | 73.18 | 109.0 | 40.70 | 65.0 | 24.27 | 48.0 | 17.92 |
| Aug | 1,355.00 | 505.90 | 799.0 | 298.31 | 404.0 | 150.84 | 200.0 | 74.67 | 112.0 | 41.82 |
| Sep | 1,308.00 | 504.63 | 743.0 | 286.65 | 379.0 | 146.22 | 190.0 | 73.30 | 110.0 | 42.44 |
| Oct | 421.00 | 157.18 | 238.0 | 88.86 | 135.0 | 50.40 | 82.0 | 30.62 | 58.0 | 21.65 |
| Nov | 210.00 | 81.02 | 126.0 | 48.61 | 75.7 | 29.21 | 50.5 | 19.48 | 35.0 | 13.50 |
| Dec | 117.00 | 43.68 | 70.0 | 26.14 | 50.5 | 18.85 | 40.0 | 14.93 | 26.0 | 9.71 |
| Jan | 80.00 | 29.87 | 69.0 | 25.76 | 43.1 | 16.09 | 32.0 | 11.95 | 24.0 | 8.96 |
| Feb | 70.10 | 28.98 | 56.0 | 23.15 | 42.1 | 17.40 | 31.0 | 12.81 | 22.0 | 9.09 |
| Mar | 56.00 | 20.91 | 46.0 | 17.17 | 36.0 | 13.44 | 30.0 | 11.20 | 20.0 | 7.47 |
| Apr | 70.10 | 27.04 | 40.0 | 15.43 | 33.4 | 12.89 | 24.0 | 9.26 | 16.0 | 6.17 |
| May | 46.70 | 17.44 | 24.0 | 8.96 | 24.0 | 8.96 | 16.8 | 6.27 | 11.0 | 4.11 |

**Table 12.17** Monthly distributions of environmental flows for the Agra to Allahabad reach of the Yamuna

| | Mean flow | | EMC-A | | EMC-B | | EMC-C | | EMC-D | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ | MCM | $m^3/s$ |
| Jun | 925 | 356.87 | 561 | 216.44 | 502 | 193.67 | 421 | 162.42 | 421 | 162.42 |
| Jul | 6,500 | 2,426.82 | 3,095 | 1,155.54 | 1,499 | 559.66 | 1,121 | 418.53 | 883 | 329.67 |
| Aug | 17,700 | 6,608.42 | 10,374 | 3,873.21 | 5,060 | 1,889.19 | 2,243 | 837.44 | 1,346 | 502.54 |
| Sep | 16,150 | 6,230.71 | 9,857 | 3,802.85 | 5,020 | 1,936.73 | 2,523 | 973.38 | 1,388 | 535.49 |
| Oct | 3,125 | 1,166.74 | 1,710 | 638.44 | 1,121 | 418.53 | 981 | 366.26 | 715 | 266.95 |
| Nov | 1,475 | 569.06 | 1,121 | 432.48 | 940 | 362.65 | 694 | 267.75 | 648 | 250.00 |
| Dec | 1,250 | 466.70 | 841 | 313.99 | 748 | 279.27 | 561 | 209.45 | 470 | 175.48 |
| Jan | 981 | 366.26 | 841 | 313.99 | 748 | 279.27 | 561 | 209.45 | 463 | 172.86 |
| Feb | 950 | 392.69 | 561 | 231.89 | 561 | 231.89 | 561 | 231.89 | 421 | 174.02 |
| Mar | 925 | 345.36 | 561 | 209.45 | 561 | 209.45 | 421 | 157.18 | 421 | 157.18 |
| Apr | 925 | 356.87 | 561 | 216.44 | 561 | 216.44 | 421 | 162.42 | 411 | 158.56 |
| May | 650 | 242.68 | 561 | 209.45 | 460 | 171.74 | 379 | 141.50 | 379 | 141.50 |

#### 12.4.3.1 Paonta Saheb (Origin to Hathinikund reach)

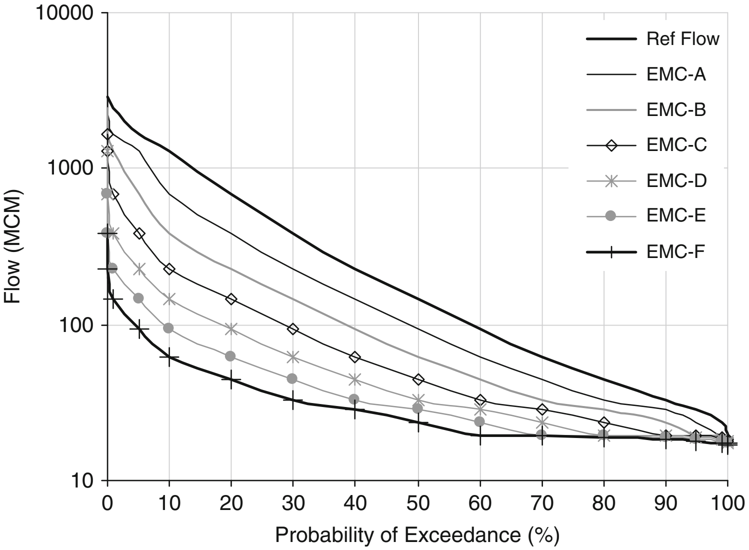


**Fig. 12.8** Reference and environmental FDCs for Paonta site at the Yamuna

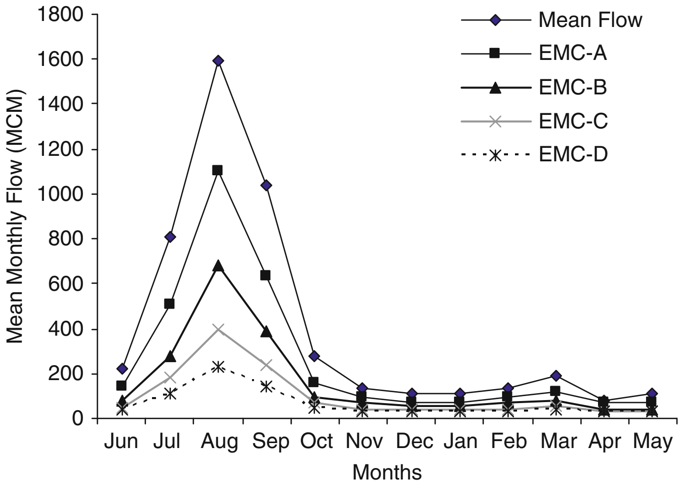


**Fig. 12.9** Mean monthly allocation of e-flow volume for different management classes for the origin to Hathinikund barrage reach

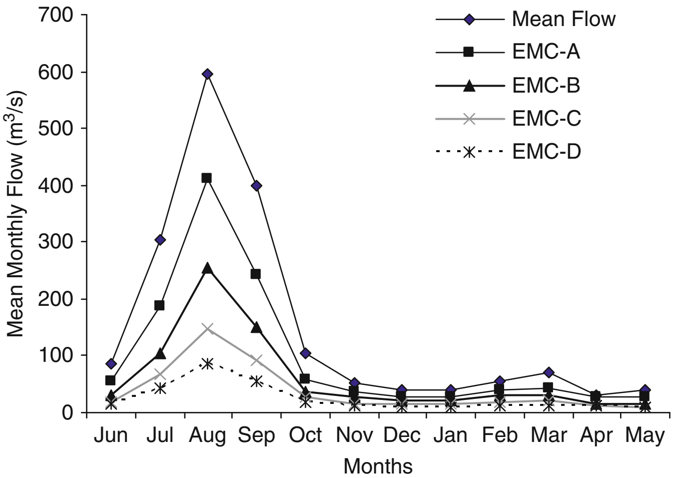


**Fig. 12.10** Mean monthly environmental flows for different management classes for the origin to Hathinikund barrage reach

#### 12.4.3.2 Kalanaur Site (Hathinikund Barrage to Wazirabad Barrage Reach)

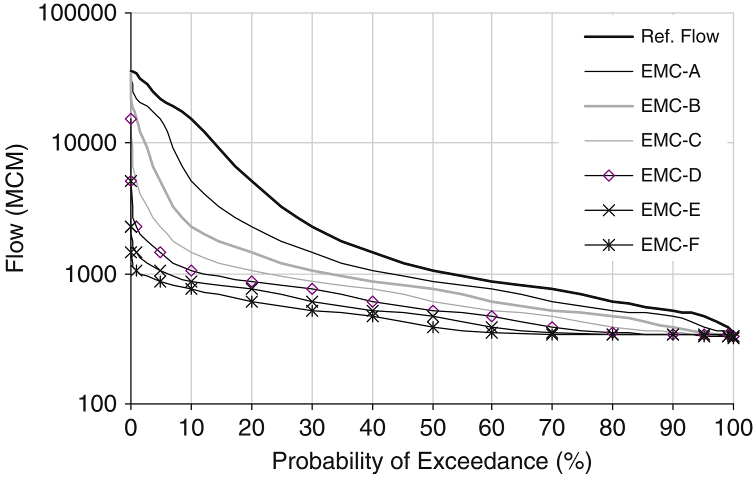


**Fig. 12.11** Reference and environmental FDCs for Kalanaur site at the Yamuna

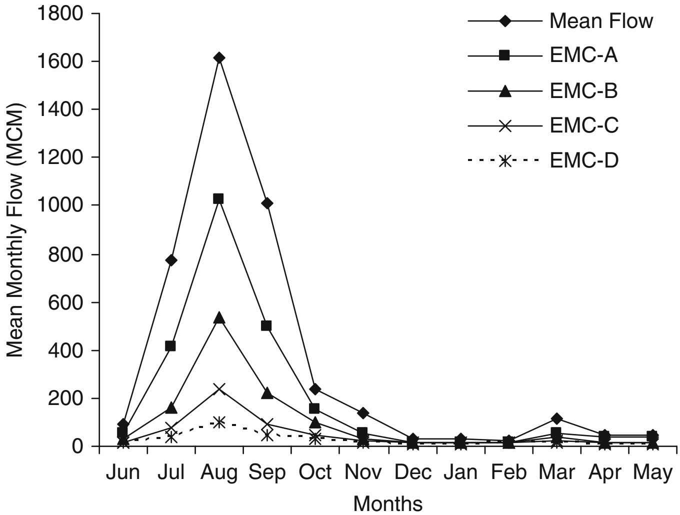


**Fig. 12.12** Mean monthly allocation of environmental flow volume for different management classes for the Hathinikund barrage to Wazirabad barrage reach

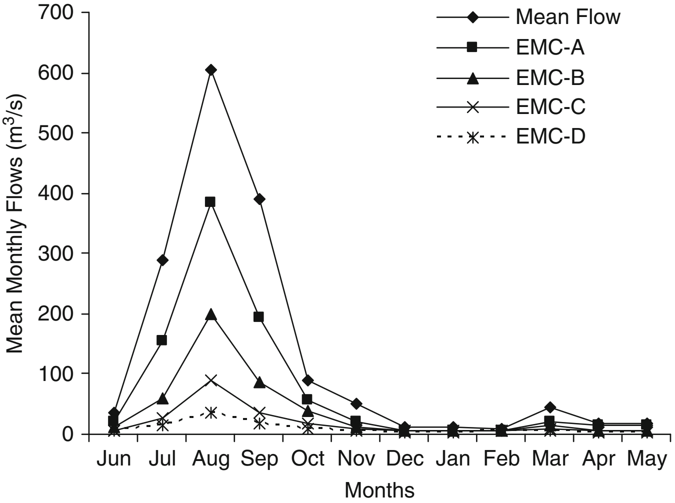


**Fig. 12.13** Mean monthly environmental flows for different management classes for the Hathinikund barrage to Wazirabad barrage reach

#### 12.4.3.3 Delhi Railway Bridge, DRB (Wazirabad to Okhla Reach)

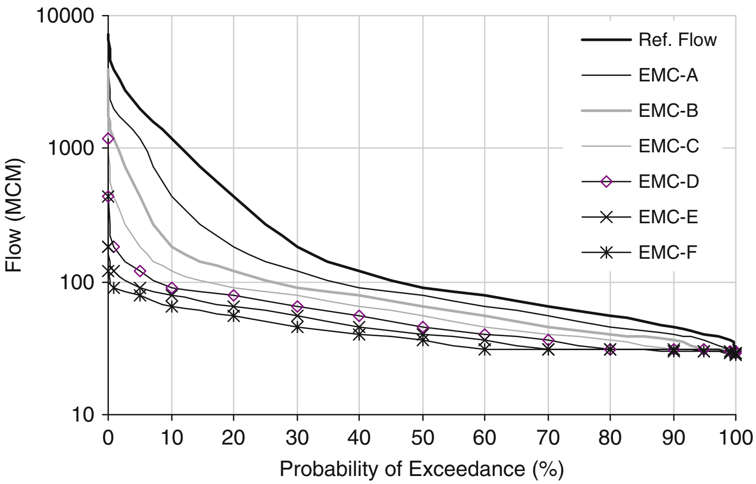


**Fig. 12.14** Reference and Environmental FDCs for DRB site of Yamuna

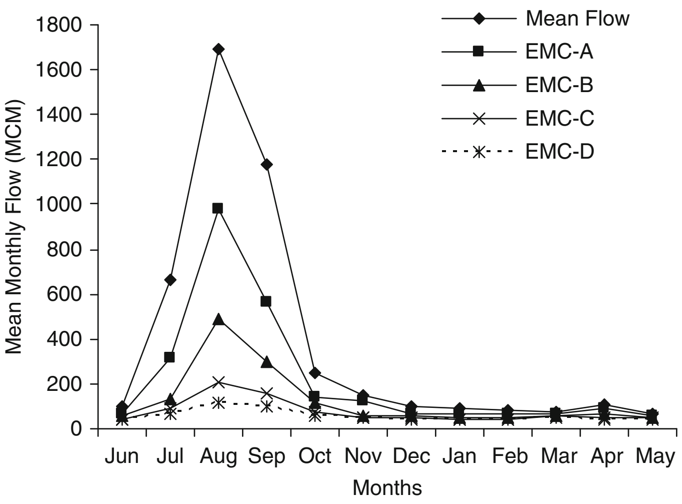


**Fig. 12.15** Mean monthly allocation of environmental flow volume for different management classes for the Wazirabad to Okhla reach

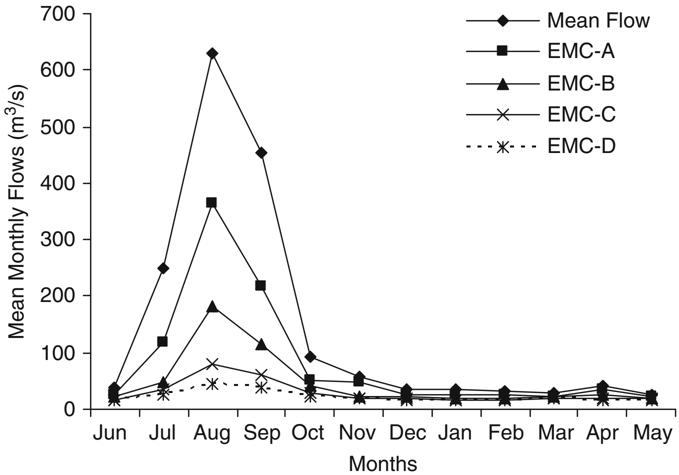


**Fig. 12.16** Mean monthly environmental flows for different management classes for the Wazirabad to Okhla reach

#### 12.4.3.4 Agra site (Okhla to Agra Reach)

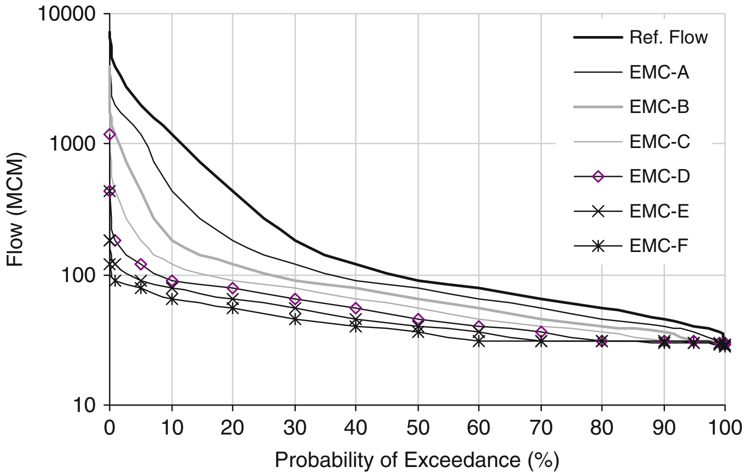


**Fig. 12.17** Reference and Environmental FDCs for Agra site at the Yamuna

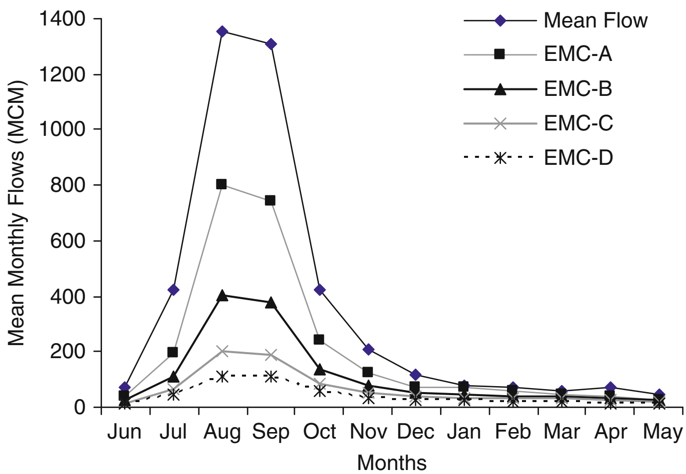


**Fig. 12.18** Mean monthly allocation of environmental flow volume for different management classes for the Okhla to Agra reach

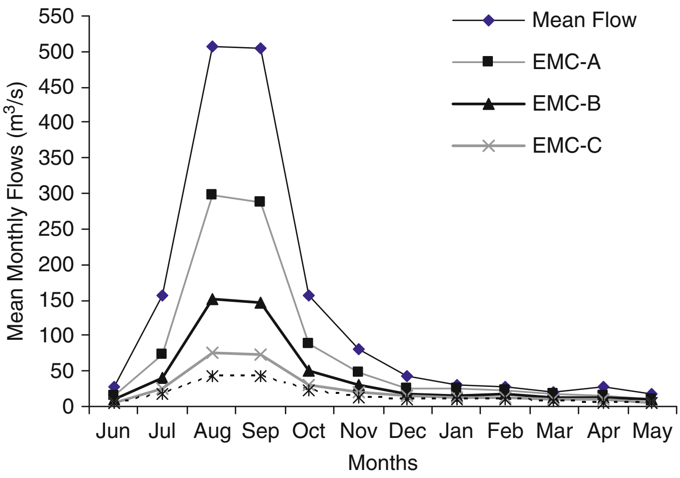


**Fig. 12.19** Mean monthly environmental flows for different management classes for the Okhla to Agra reach

#### 12.4.3.5 Pratappur Site (Agra to Allahabad Reach)

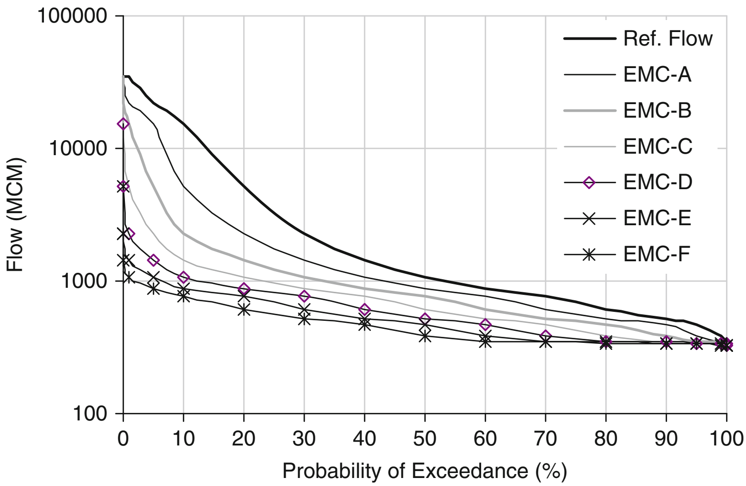


**Fig. 12.20** Reference and Environmental FDCs for Pratappur site at the Yamuna

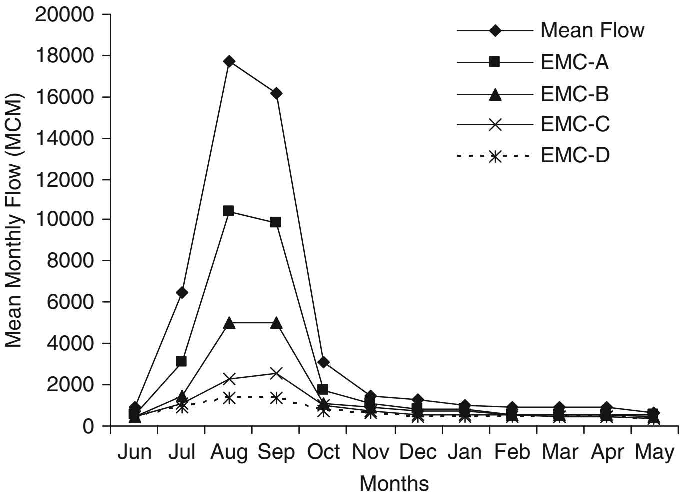


**Fig. 12.21** Mean monthly allocation of environmental flow volume for different management classes for the Agra to Allahabad reach

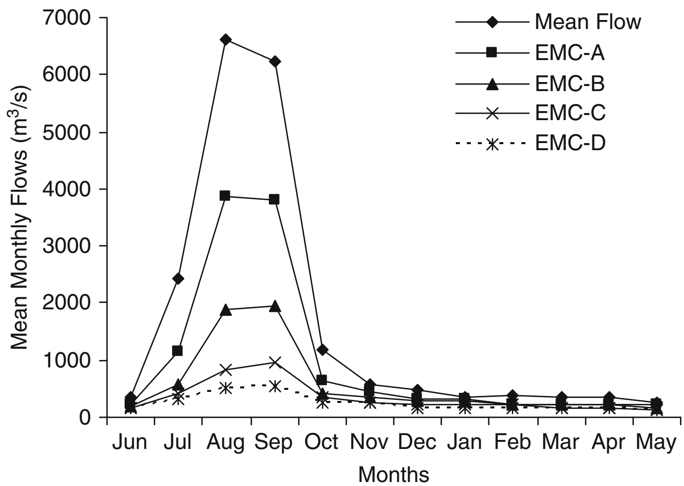


**Fig. 12.22** Mean monthly environmental flows for different management classes for the Agra to Allahabad reach

The above two methods has the limitation that they are completely based on the hydrology, and do not consider the pollution, interception of the river, groundwater conservation, etc. Looking into these limitations a comprehensive method has been developed for the Indian Rivers which are highly intercepted and being used for pollution transport. The following section gives the detailed investigation of the methodology.

## 12.5 Development of Component Based Environmental Flow Estimator

Incorporating water demands for the assimilation of polluted river water, evaporation, conservation of groundwater, and ecological requirements, the proposed technique requires component-wise development and analysis for the river system. The component-wise methodology is now described.

### *12.5.1 Water Requirement for Assimilation of Polluted River Water*

The assimilation capacity of a river is defined as its capacity to digest pollutants by means of biological activity and physical purification, both of which depend on the use of the water body and the quality standards adopted by the management agency (Lee and Wen, 1996). Calculation of the quantity of water needed for assimilation of polluted river water requires calculation of the inverse of assimilative capacity; that is, it represents the minimum quantity of water needed to permit self-purification and dilution of pollutants. A mathematical expression for the quantity of water needed for the assimilation of polluted water in a river can be derived as follows.

Let $Q_0^*$ be the flow rate from the upstream (m$^3$/s), $C_0$ be the concentration of pollutants from the upstream (mg/l), $q_1$ be the flow rate from pollutant sources (m$^3$/s), $C_1$ be the concentration of pollutants from pollutant sources (mg/l), $Q_1$ be the flow rate released from the environmental reservoir (m$^3$/s), $C$ be the concentration of pollutants from the environmental reservoir (mg/l), $C_N$ be the standard for water quality (mg/l), $k$ be the degradation coefficient (1/day), $x_1$ be the length of river stretch, and $u$ be the average velocity of flow (m/s) (Fig. 12.23).

The intermixing concentration of pollutants, $L_0$, can be calculated as:

$$L_0 = \left( \frac{q_1 C_1 + Q_0^* C_0}{q_1 + Q_0^*} \right) \tag{12.1}$$

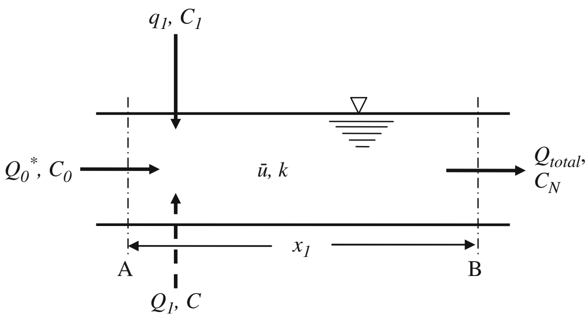


**Fig. 12.23** Components of continuity equation in a river stretch under control volume

If $k$ is the degradation coefficient of the pollutant, then the pollutant concentration of environmental reservoir flow and the weighted concentration of intermixed pollutants after time $t$ can be expressed as:

$$C_t = C\exp(-kt) \tag{12.2}$$

and

$$L_t = L_0\exp(-kt) \tag{12.3}$$

where

$$t = x_1/\bar{u} \tag{12.4}$$

The mass conservation equation after time $t$ and distance $x_1$ can be expressed as:

$$Q_1 C_t + L_t\left(q_1 + Q_0^*\right) = Q_{\text{total}} C_N \tag{12.5}$$

where

$$Q_{\text{total}} = Q_1 + q_1 + Q_0^* \tag{12.6}$$

Using eqs. (12.2) through (12.6), eq. (12.5) can be recast as:

$$\begin{aligned} Q_1 C\exp(-kt) + \left(\frac{q_1 C_1 + Q_0^* C_0}{q_1 + Q_0^*}\right)\left(q_1 + Q_0^*\right)\exp(-kt) \\ = \left(Q_1 + q_1 + Q_0^*\right) C_N \end{aligned} \tag{12.7}$$

Simplification of eq. (12.7) yields

$$Q_1 = \frac{\left(q_1 C_1 + Q_0^* C_0\right)\exp(-kt) - \left(q_1 + Q_0^*\right)C_N}{C_N - C\exp(-kt)} \tag{12.8}$$

Substituting eq. (12.4) into eq. (12.8) yields

$$Q_1 = \frac{\left(q_1 C_1 + Q_0^* C_0\right)\exp(-k \cdot x_1/\bar{u}) - \left(q_1 + Q_0^*\right)C_N}{C_N - C\exp(-kt)} \tag{12.9}$$

Equation (12.9) gives the water required for assimilation of pollutants in the river stretch.

### 12.5.2 *Water Required for Evaporation*

Evaporation losses are an important part of a river's environmental water demand, especially during summer. Evaporation decreases the quantity of river water without greatly affecting the quantity of pollutants in the river. The evaporative loss of the river can be estimated using the following formula:

$$Q_2 = \begin{cases} 10^{-3}\, T \cdot L_C \cdot (E - P), & E > P \\ 0, & E \le P \end{cases} \tag{12.10}$$

where $Q_2$ = the water demand created by evaporation ($m^3$), $T$ = the average top width of river, which depends upon the depth of flow (m), $L_C$ = the length of river stretch (m), $P$ = the monthly rainfall (mm), and $E$ = the monthly evaporation (mm). Evaporation from the water surface can be estimated using the Penman (1948) method, whereas the monthly normal values are used for monthly rainfall.

#### 12.5.2.1 Estimation of Evaporation

The Penman method (Penman, 1948), a well-known combination equation (i.e., combination of an energy balance and an aerodynamic formula) can be expressed as:

$$\lambda E = \frac{\{\Delta(R_n - G)\} + (\gamma E_a)}{(\Delta + \gamma)} \tag{12.11}$$

where $\lambda E$ = the evaporative latent heat flux (MJ $m^{-2}d^{-1}$), $\lambda$ = the latent heat of vaporization (MJ $kg^{-1}$) = 2.45 MJ $kg^{-1}$, $\Delta$ = the slope of the saturated vapor pressure curve (i.e. $\partial e_s/\partial T$) (kPa °$C^{-1}$), $e_s$ = the saturated vapor pressure (kPa), $T$ = the temperature (°$C^{-1}$), $R_n$ = the net radiation flux (MJ $m^{-2}d^{-1}$), $G$ = the sensible heat flux into soil (MJ $m^{-2}d^{-1}$), $\gamma$ = the psychometric constant (kPa °$C^{-1}$) = 0.059 kPa °$C^{-1}$, $E_a$ = the vapor transport flux (MJ $m^{-2}d^{-1}$) $= f\{u_2, (e_s - e_a)\}$, $u_2$ = the wind speed (m $s^{-1}$), and $e_a$ = the actual vapor pressure (kPa). Variables used in eq. (12.11) can be estimated from various relationships summarized in Table 12.18.

### *12.5.3 Water Required for Groundwater Conservation*

The amount of water infiltrated from a channel can be expressed as a function of the hydraulic conductivity of channel surroundings and geometric dimensions of the channel. For stream channels, where the depth of water table is large relative to the water depth in the stream, the seepage loss can be mathematically described as (Harr, 1962).

$$q_3 = K(B + \beta h) \tag{12.12}$$

where $q_3$ is the unit seepage flow rate ($m^3$ $s^{-1}$ per m of channel length), $K$ is the hydraulic conductivity (m $s^{-1}$), $B$ is the channel width (m) $= f(h)$, $h$ is the depth of water (m), and $\beta$ is the coefficient $= f$ (channel geometry). Equation (12.12) can be modified for the total seepage loss in the stretch as:

$$Q_3 = KP_w L_C \tag{12.13}$$

**Table 12.18** Auxiliary equations used for the Penman method

| Parameter | Relationships |
|---|---|
| Relative humidity, RH (%) | $\mathrm{RH} = \dfrac{e_a}{e^0(T)} \times 100\%$<br>$e^0(T)$ is the saturation vapor pressure at the same temperature (kPa), $T$ is temperature (°C), and $e_a$ is the actual vapor pressure (kPa) |
| Saturation vapor pressure, $e_s$ (k Pa) | $e^0(T) = 0.6108\ \exp\left\{\dfrac{17.27\,T}{T + 237.3}\right\}$<br>$e_s = 0.5\left[e^0(T_{max}) + e^0(T_{min})\right]$<br>$T_{max}$ and $T_{min}$ are the daily maximum and minimum temperatures (°C) |
| Actual vapor pressure, $e_a$ (kPa) | $e_a = e^0(T_{dew}) = 0.6108\ \exp\left\{\dfrac{17.27\,T_{dew}}{T_{dew} + 237.3}\right\}$<br>$e_a = e_s \times (\mathrm{RH}/100)$ |
| Slope if the saturation vapor pressure, $\Delta$ (kPa °C$^{-1}$) | $\Delta = \dfrac{4098\left[0.6108\ \exp\left(\dfrac{17.27\,T}{T + 237.3}\right)\right]}{(T + 237.3)^2}$ |
| Extraterrestrial radiation, $R_a$ (MJ m$^{-2}$d$^{-1}$) | $R_a = \dfrac{24\,(60)}{\pi} G_{sc} d_r\,[\omega_s\ \sin(\varphi) \cdot \sin(\delta) + \cos(\varphi) \cdot \cos(\delta) \cdot \sin(\omega_s)]$<br>$G_{sc}$ = solar constant (0.0820 MJ m$^{-2}$ min$^{-1}$)<br>$d_r = 1 + 0.033\ \cos(2\pi J/365)$<br>$J$ = number of the day in the year between 1 (1st January) and 365 or 366 (31st December)<br>$\omega_s = \arccos[-\tan(\varphi) \cdot \tan(\delta)]$<br>$\varphi$ = latitude (radian) [radian = $\pi$ (decimal degree)/180]<br>$\delta = 0.409\ \sin\left[\dfrac{2\pi J}{365} - 1.39\right]$ |
| Solar radiation, $R_s$ (MJ m$^{-2}$d$^{-1}$)<br>When $n = N$, the solar radiation will becomes the clear sky solar radiation. | $R_s = \left(a_s + b_s \dfrac{n}{N}\right) \cdot R_a$<br>$n$ = actual duration of sunshine hours (hours);<br>$N$ = maximum possible daylight hours (hours);<br>$n/N$ = relative sunshine hour (dimensionless);<br>$a_s = 0.25$, and $b_s = 0.50$<br>$N = 24\,\omega_s/\pi$ |
| Net shortwave radiation, $R_{ns}$ (MJ m$^{-2}$d$^{-1}$) | $R_{ns} = (1 - \alpha) \cdot R_s$<br>$\alpha$ = albedo or reflection coefficient.<br>For hypothetical grass reference, $\alpha = 0.23$<br>For deep water $\alpha$ = 0.04–0.09<br>For shallow water, $\alpha$ = 0.09–0.12 |

**Table 12.18** (continued)

| Parameter | Relationships |
|---|---|
| Net longwave radiation, $R_{nl}$ (MJ $m^{-2}d^{-1}$) | $R_{nl} = \sigma \left[ \frac{T_{max,K^4} + T_{min,K^4}}{2} \right] \cdot \left(0.34 - 0.14\sqrt{e_a}\right) \times \left(1.35\frac{R_s}{R_{so}} - 0.35\right)$<br>$\sigma$ = Stefan-Boltzman constant (= $4.903 \times 10^{-9}$ MJ $K^{-4}$ $m^{-2}$ $day^{-1}$)<br>$T_{max,K}$ =daily maximum temperature (K) [$K$ = °C + 273.16];<br>$T_{min,K}$ =daily minimum temperature (K);<br>$R_s/R_{so}$ =relative shortwave radiation ($\leq$1.0). |
| Net radiation, $R_n$ (MJ $m^{-2}d^{-1}$) | $R_n = R_{ns} - R_{nl}$ |
| Soil heat flux, $G$ (MJ $m^{-2}d^{-1}$) | For water surface, $G = 0$ |

where $P_w$ is the wetted perimeter (m), $L_C$ is the channel length (m), and $Q_3$ is the seepage loss ($m^3s^{-1}$). For a wide open channel (i.e., B >> 2 h), eq. (12.13) can be simplified as:

$$Q_3 = KBL_C \tag{12.14}$$

Using the wetted perimeter, the length of river stretch and hydraulic conductivity, the water required for groundwater conservation can be estimated using the formula given through eq. (12.13). However, most of the Indian rivers carry sediments with different magnitudes, depending upon the seasonal flow variation. Due to sedimentation processes, sediments get deposited during the low flow season. Deposition of finer particle causes clogging of the porous medium resulting in a 50–75% reduction of hydraulic conductivity. Therefore, in the study, instead of using the hydraulic conductivity, an effective hydraulic conductivity of the river bed was used. Accordingly, eq. (12.13) was modified as:

$$Q_3 = K_{eff}P_wL_C \tag{12.15}$$

where $K_{eff}$ is the effective hydraulic conductivity of the porous material (m/s).

#### 12.5.3.1 Estimation of Wetted Perimeter

For a particular discharge, the wetted perimeter of the stream can be estimated using appropriate Manning's roughness, longitudinal slope and river cross-section (Fig. 12.24). The following steps can be considered for estimating the wetted perimeter based on the discharge value:

Step 1: Derive the rating curve (i.e., stage vs discharge relationship using the cross-section data in the form of $x$–$z$) based on estimated water area, wetted perimeter, hydraulic radius, longitudinal slope, and Manning's roughness. For

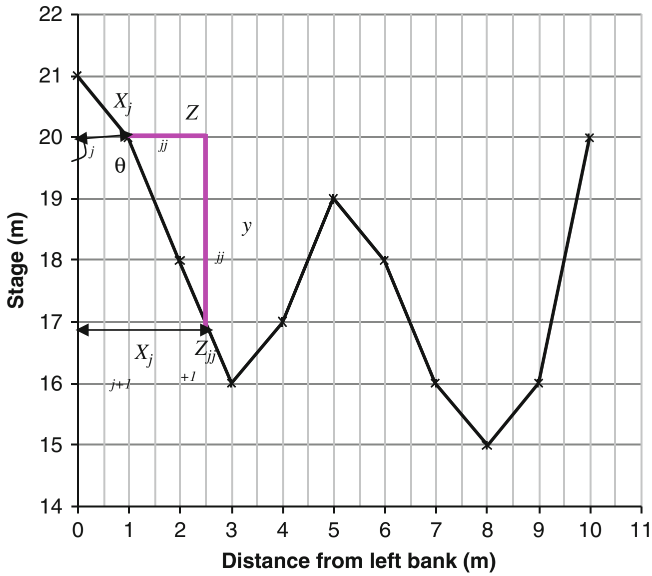


**Fig. 12.24** Typical diagram of river cross-section

discharge estimation, Manning's formula is used:

$$Q = A_{\mathrm{w}} R^{2/3} S^{1/2} / n \tag{12.16}$$

where $Q$ is the discharge (m$^3$/s), $n$ is the Manning roughness [L$^{-1/3}$T], and $S$ is the longitudinal slope (m/m). Once the discharge is estimated corresponding to the depth of flow, a rating curve can be developed.

Step 1a: Estimate the water area with respect to depth, using the cross-section ($x$–$z$) data, with the trapezoidal rule, which is:

$$\int_{x_0}^{x_0+nh} f(x)\,\mathrm{d}x = \frac{h}{2}(y_0 + y_n) + h(y_1 + y_2 + y_3 + \cdots + y_{n-1}) \tag{12.17}$$

Step 1b: Estimate the wetted perimeter using the following formula:

$$p_{\mathrm{w}\,jj} = \left(x_{jj+1} - x_{jj}\right) / \cos\left[\tan^{-1}\left\{\left(z_{jj} - z_{jj+1}\right) / \left(x_{jj+1} - x_{jj}\right)\right\}\right] \tag{12.18}$$

where $p_{\mathrm{w}}$ is the wetted perimeter.

Step 1c: Estimate the hydraulic radius at each depth using the following relationship:

$$R = A_{\mathrm{w}} / p_{\mathrm{w}} \tag{12.19}$$

where $R$ is the hydraulic radius (m), $A_w$ is the water area ($m^2$), and $p_w$ is the wetted perimeter (m).

Step 2: Based on the desired discharge value, stage, water area and wetted perimeter can be estimated using a linear interpolation technique. The discharge value was considered corresponding to the 25% MAF (Tennant, 1976), so that ecological flow can be maintained.

### *12.5.4 Water Required for Aquatic-Habitat Conservation*

The ecological flow for the river is considered to maintain the aquatic diversity in the river. Based on the methodology presented by Tennant (1976), 25% of the mean annual flow (MAF) can be considered appropriate for the ecological maintenance. He found that rivers with more stable flow regimes had relatively higher flow requirements than rivers with more variable flow regimes. This is because in highly variable flow regimes the biota would have adjusted to the relative scarcity of water, while in more reliably flowing rivers the biota are more sensitive to the reduction in flow (Hughes and Hannart, 2003). Considering this aspect, for Indian conditions and required flow variability, the modified Tennant method at 25% MAF is found more appropriate than the uniform flow allocation.

### *12.5.5 Application of Methodology*

The proposed methodology is applied to estimate environmental flows for different stretches of Yamuna River, a major tributary of Ganga River. Due to large abstractions at the Hathinikund barrage, the downstream part of the river is almost dry, though the 4.5 cumec water is allocated for the downstream release during December to June. However, after traversing a few kilometers, this water disappears and the river becomes dry up to the Palla. After the Wazirabad barrage near Delhi, there is no release during the dry period (i.e., December to June). The water available in the Wazirabad barrage to the Okhla barrage stretch is due to wastewater outfalls of more than 30 cumecs with recorded BOD of more than 30 mg/l. After the Okhla barrage, a similar situation persists and the river has little water all the way up to Etawah where the Chambal River joins. However, due to base flow, the river does not get dry. After Etawah, the river quality gets improved and up to the confluence with Ganga River, it becomes environmentally good. Considering these aspects, Yamuna River is of major interest for the estimation of environmental flow. The stretch-wise important parameters are given in Table 12.19.

#### 12.5.5.1 Data Preparation and Analysis

The data and sources used for different environmental flow components are listed in Table 12.20 which also includes the steps required for deriving data. Using the

**Table 12.19** Important parameters for different stretches of the Yamuna River

| S. No. | Stretch | Length, $L_c$ (km) | Avg. slope (m/m) | Manning's $n$ | Latitude at centroid (°) | Avg. waste water discharge ($m^3/s$) | Avg. BOD (mg/l)[a] | Degradation rate coeff., $k$ (per day) |
|---|---|---|---|---|---|---|---|---|
| 1 | Hathinikund to Palla | 254.0 | 0.00055 | 0.035 | 29.5249 | 5.0 | 20.0 | 0.40 |
| 2 | Wazirabad to Okhla | 22.0 | 0.000327 | 0.040 | 28.6510 | 30.0 | 30.0 | 0.25 |
| 3 | Okhla to Agra | 310.0 | 0.000139 | 0.035 | 27.4571 | 10.0 | 30.0 | 0.38 |
| 4 | Agra to Etawah | 305.0 | 0.000136 | 0.035 | 26.9548 | 4.0 | 30.0 | 0.40 |
| 5 | Etawah to Pratappur (Allahabad) | 465.0 | 0.000055 | 0.035 | 25.6785 | 4.0 | 30.0 | 0.42 |

[a] BOD level after treatment; BOD concentration of dilution water was assumed 2 mg/l

dataset and river characteristics (Table 12.19), the seepage loss component of environmental flow is estimated using eqs. (12.15) through (12.19). The water required to assimilate pollutants in the river is estimated using eq. (12.9). The river evaporation loss is estimated using eq. (12.10) with auxiliary equations. The water requirement for the conservation of aquatic-habitat was considered as monthly distribution of 25% MAF.

**Table 12.20** List of data required for computation using component based method

| Components | Data required | Source/procedure |
|---|---|---|
| 1. Water requirement for assimilating the pollutants in the river | • the flow rate from upstream ($m^3/s$),<br>• the concentration of pollutants from upstream (mg/l),<br>• the flow rate from the pollutant sources ($m^3/s$),<br>• the concentration of pollutants from the pollutant sources (mg/l),<br>• the concentration of pollutants in the environmental reservoir (mg/l),<br>• the standard for water quality (mg/l),<br>• the degradation coefficient (1/day),<br>• the length of river stretch, and<br>• the average velocity of flow (m/s) | • Central Pollution Control Board<br>• Primary measurements |

**Table 12.20** (continued)

| Components | Data required | Source/procedure |
|---|---|---|
| 2. Water requirement for groundwater conservation | • The effective hydraulic conductivity (m/s)<br>• Manning's roughness<br>• Mean monthly flows at 25% MAF ($m^3$/s)<br>• River cross section<br>  ◦ Wetted perimeter (m)<br>  ◦ Water area ($m^2$)<br>  ◦ Rating curve<br>• Length of stretch (m) | • Based on the river bed texture, hydraulic conductivity is fixed from literature and adjusted for effective hydraulic conductivity.<br>• Based on the river condition Manning's roughness is fixed using the available literatures.<br>• Long term mean monthly flows were derived from the available 10-daily discharge data of different cites of Yamuna River. The data were collected from the Central Water Commission.<br>• Using the mean monthly flows and estimated mean monthly flow (MAF) at the site, percentage distribution of MAF is derived.<br>• At 25% of MAF, the corresponding monthly distribution is estimated<br>• Survey was conducted for river cross-section |
| 3. Water requirement for evaporation loss | • Top width of river water (m) derived from cross-section<br>• Length of stretch (m)<br>• Monthly normal rainfall (mm)<br>• Monthly Evaporation (mm) from Penman method<br>  ◦ Maximum, minimum, and mean temperature (°C)<br>  ◦ Dew point temperature (°C)<br>  ◦ Latitude (degree decimal)<br>  ◦ Albedo | • Cross-section and the mean monthly flows is used for deriving the depth of flows. Corresponding to the depth of flow top width of river is computed.<br>• Monthly rainfall normals were collected from the India Meteorological Department.<br>• Data required for the estimation of the evaporation is collected from India Meteorological Department, and National Climatic Data Center (freely available). |
| 4. Water requirement for aquatic-habitat conservation | • Discharge data ($m^3$/s)<br>  ◦ Mean annual flow (MCM)<br>  ◦ Monthly distribution of mean annual flow (%) | • In component 2, it is covered. |

The methodology is individually applied to each stretch, namely, the Hathinikund barrage to Palla, Wazirabad barrage to Okhla barrage, Okhla barrage to Etawah, and Etawah to Pratappur near the confluence with Ganga River. For all these stretches, results are obtained; for economy of space, different components of environmental flow for the Hathinikund to Palla stretch only are presented in Fig. 12.25. Tabular results for all the stretches are given in Tables 12.21, 12.22, 12.23, 12.24, 12.25,

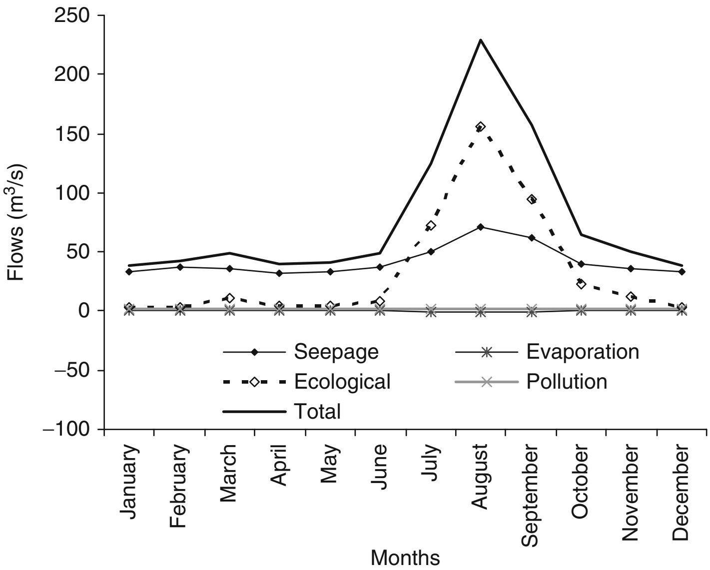


**Fig. 12.25** Components of environmental flows for the Hathinikund-Palla stretch

and 12.26. It is observed that the water requirement for groundwater conservation is quite high, followed by dilution water requirement. The dilution component is another important component when the river is being utilized for pollutant transport. It is also observed that the environmental water demand is high during the period of June to October, but is not a major concern for the Indian rivers, because the Monsoon is active during these months. During the rest of the year, attention needs to be paid.

For the Wazirabad to Okhla stretch which is a short stretch, the water required to assimilate pollutants is very high, as compared to other demands (Table 12.22). For this stretch, dilution is not effectively modified by the river water. Therefore, the assimilation water demand is further estimated under different influent conditions (Table 12.23). In Table 12.23, dilution water was estimated for combinations of treatment quality and effluent discharge. The estimated dilution water is very high as compared to the availability. Under such a condition, without diverting the waste discharge for other uses after treatment, it is not possible to maintain the environmental flow in the river for this stretch. Similarly, the stretch from Okhla barrage to Agra is also critical and needs to be taken care of.

The total environmental flow requirement along with the available flow was compared, as shown in Figs. 12.26, 12.27, 12.28, 12.29, and 12.30. These figures reveal that during the non-monsoon period, the water available in the river does not satisfy environmental flows for all the stretches except for the Etawah to Pratappur stretch.

**Table 12.21** Environmental flow components for the Hathinikund to Palla stretch of Yamuna River

| Month | Mean monthly water requirement (MCM) | | | | | Mean monthly discharge required ($m^3/s$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution ($5\ m^3/s$ + 30 BOD) | Total EF | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution ($5\ m^3/s$ + 30 BOD) | Total EF |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) |
| January | 90.06 | 0.54 | 8.00 | 5.68 | 104.28 | 33.62 | 0.20 | 2.99 | 2.12 | 38.93 |
| February | 90.72 | 0.91 | 6.25 | 5.13 | 103.01 | 37.50 | 0.38 | 2.58 | 2.12 | 42.58 |
| March | 95.24 | 2.00 | 29.25 | 5.68 | 132.17 | 35.56 | 0.75 | 10.92 | 2.12 | 49.35 |
| April | 82.13 | 2.30 | 11.50 | 5.50 | 101.43 | 31.69 | 0.89 | 4.44 | 2.12 | 39.13 |
| May | 90.63 | 2.92 | 11.50 | 5.68 | 110.73 | 33.84 | 1.09 | 4.29 | 2.12 | 41.34 |
| June | 95.10 | 1.86 | 23.25 | 5.50 | 125.71 | 36.69 | 0.72 | 8.97 | 2.12 | 48.50 |
| July | 134.65 | −0.96 | 192.75 | 5.68 | 332.12 | 50.27 | −0.36 | 71.96 | 2.12 | 124.00 |
| August | 185.63 | −1.77 | 405.00 | 5.50 | 594.36 | 71.62 | −0.68 | 156.25 | 2.12 | 229.30 |
| September | 164.80 | −0.53 | 252.50 | 5.68 | 422.45 | 61.53 | −0.20 | 94.27 | 2.12 | 157.72 |
| October | 102.07 | 1.34 | 60.00 | 5.50 | 168.91 | 39.38 | 0.52 | 23.15 | 2.12 | 65.16 |
| November | 95.16 | 1.03 | 33.75 | 5.68 | 135.62 | 35.53 | 0.38 | 12.60 | 2.12 | 50.63 |
| December | 90.05 | 0.69 | 8.00 | 5.68 | 104.42 | 33.62 | 0.26 | 2.99 | 2.12 | 38.99 |

**Table 12.22** Environmental flow components for the Wazirabad to Okhla stretch of Yamuna River

| Month | Mean monthly water requirement (MCM) | | | | | Mean monthly discharge required ($m^3/s$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (30 $m^3/s$ + 30 BOD) | Total EF | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (30 $m^3/s$ + 30 BOD) | Total EF |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) |
| January | 15.76 | 0.084 | 23.00 | 321.78 | 360.62 | 5.88 | 0.03 | 8.59 | 120.14 | 134.64 |
| February | 15.52 | 0.116 | 20.00 | 290.64 | 326.28 | 6.42 | 0.05 | 8.27 | 120.14 | 134.87 |
| March | 14.05 | 0.197 | 18.70 | 321.78 | 354.73 | 5.25 | 0.07 | 6.98 | 120.14 | 132.44 |
| April | 17.93 | 0.312 | 27.50 | 311.40 | 357.14 | 6.92 | 0.12 | 10.61 | 120.14 | 137.79 |
| May | 13.06 | 0.263 | 16.25 | 321.78 | 351.35 | 4.88 | 0.10 | 6.07 | 120.14 | 131.18 |
| June | 16.71 | 0.240 | 24.50 | 311.40 | 352.85 | 6.45 | 0.09 | 9.45 | 120.14 | 136.13 |
| July | 56.73 | 0.125 | 166.25 | 321.78 | 544.89 | 21.18 | 0.05 | 62.07 | 120.14 | 203.44 |
| August | 67.31 | 0.079 | 422.50 | 311.40 | 801.29 | 25.97 | 0.03 | 163.00 | 120.14 | 309.14 |
| September | 140.59 | 0.787 | 293.70 | 321.78 | 756.86 | 52.49 | 0.29 | 109.66 | 120.14 | 282.58 |
| October | 31.73 | 0.282 | 62.50 | 311.40 | 405.91 | 12.24 | 0.11 | 24.11 | 120.14 | 156.60 |
| November | 22.32 | 0.158 | 37.50 | 321.78 | 381.76 | 8.33 | 0.06 | 14.00 | 120.14 | 142.53 |
| December | 16.16 | 0.090 | 24.00 | 321.78 | 362.03 | 6.03 | 0.03 | 8.96 | 120.14 | 135.17 |

**Table 12.23** Environmental flow requirement for the Wazirabad to Okhla stretch of Yamuna River under different effluent flow conditions

| | | | | Water required to assimilate the pollution | | | | Total EF ($m^3/s$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Seepage ($m^3/s$) | Evapo. ($m^3/s$) | Ecolog. (25%MAF) ($m^3/s$) | 30 $m^3/s$ + 10 mg/l BOD | 30 $m^3/s$ + 5 mg/l BOD | 5 $m^3/s$ + 10 mg/l BOD | 5 $m^3/s$ + 5 mg/l BOD | 30 $m^3/s$ + 10 mg/l BOD | 30 $m^3/s$ + 5 mg/l BOD | 5 $m^3/s$ + 10 mg/l BOD | 5 $m^3/s$ + 5 mg/l BOD |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) | (xii) |
| January | 5.88 | 0.03 | 8.59 | 120.14 | 26.29 | 25.46 | 6.36 | 134.64 | 40.79 | 39.96 | 20.86 |
| February | 6.42 | 0.05 | 8.27 | 120.14 | 26.29 | 25.46 | 6.36 | 134.87 | 41.02 | 40.19 | 21.09 |
| March | 5.25 | 0.07 | 6.98 | 120.14 | 26.29 | 25.46 | 6.36 | 132.44 | 38.59 | 37.76 | 18.66 |
| April | 6.92 | 0.12 | 10.61 | 120.14 | 26.29 | 25.46 | 6.36 | 137.79 | 43.94 | 43.11 | 24.01 |
| May | 4.88 | 0.10 | 6.07 | 120.14 | 26.29 | 25.46 | 6.36 | 131.18 | 37.33 | 36.50 | 17.40 |
| June | 6.45 | 0.09 | 9.45 | 120.14 | 26.29 | 25.46 | 6.36 | 136.13 | 42.28 | 41.45 | 22.35 |
| July | 21.18 | 0.05 | 62.07 | 120.14 | 26.29 | 25.46 | 6.36 | 203.44 | 109.59 | 108.76 | 89.66 |
| August | 25.97 | 0.03 | 163.00 | 120.14 | 26.29 | 25.46 | 6.36 | 309.14 | 215.29 | 214.46 | 195.36 |
| September | 52.49 | 0.29 | 109.66 | 120.14 | 26.29 | 25.46 | 6.36 | 282.58 | 188.73 | 187.90 | 168.80 |
| October | 12.24 | 0.11 | 24.11 | 120.14 | 26.29 | 25.46 | 6.36 | 156.60 | 62.75 | 61.92 | 42.82 |
| November | 8.33 | 0.06 | 14.00 | 120.14 | 26.29 | 25.46 | 6.36 | 142.53 | 48.68 | 47.85 | 28.75 |
| December | 6.03 | 0.03 | 8.96 | 120.14 | 26.29 | 25.46 | 6.36 | 135.17 | 41.32 | 40.49 | 21.39 |

**Table 12.24** Environmental flow components for the Okhla to Agra stretch of Yamuna River

| | Mean monthly water requirement (MCM) | | | | | Mean monthly discharge required ($m^3/s$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (10 $m^3/s$ + 30 BOD) | Total EF | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (10 $m^3/s$ + 30 BOD) | Total EF |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) |
| January | 92.63 | 0.98 | 20.00 | 26.09 | 139.70 | 34.58 | 0.37 | 7.47 | 9.74 | 52.16 |
| February | 91.35 | 1.29 | 17.53 | 23.56 | 133.73 | 37.76 | 0.53 | 7.25 | 9.74 | 55.28 |
| March | 82.43 | 1.96 | 14.00 | 26.09 | 124.48 | 30.78 | 0.73 | 5.23 | 9.74 | 46.47 |
| April | 104.82 | 3.04 | 17.53 | 25.25 | 150.64 | 40.44 | 1.17 | 6.76 | 9.74 | 58.12 |
| May | 76.57 | 2.53 | 11.68 | 26.09 | 116.87 | 28.59 | 0.94 | 4.36 | 9.74 | 43.63 |
| June | 97.80 | 2.68 | 17.53 | 25.25 | 143.26 | 37.73 | 1.03 | 6.76 | 9.74 | 55.27 |
| July | 207.85 | 1.13 | 105.25 | 26.09 | 340.32 | 77.60 | 0.42 | 39.30 | 9.74 | 127.06 |
| August | 234.33 | 0.04 | 338.75 | 25.25 | 598.37 | 90.41 | 0.02 | 130.69 | 9.74 | 230.85 |
| September | 233.10 | 1.09 | 327.00 | 26.09 | 587.28 | 87.03 | 0.41 | 122.09 | 9.74 | 219.26 |
| October | 190.91 | 2.84 | 105.25 | 25.25 | 324.25 | 73.65 | 1.10 | 40.61 | 9.74 | 125.09 |
| November | 131.95 | 1.61 | 52.50 | 26.09 | 212.15 | 49.26 | 0.60 | 19.60 | 9.74 | 79.21 |
| December | 95.81 | 0.98 | 29.25 | 26.09 | 152.13 | 35.77 | 0.37 | 10.92 | 9.74 | 56.80 |

**Table 12.25** Environmental flow components for the Agra to Etawah stretch of Yamuna River

| | Mean monthly water requirement (MCM) | | | | | Mean monthly discharge required ($m^3/s$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | Seepage | Evapo. | Ecolog. (250%MAF) | Pollution (4 $m^3/s$ + 30 BOD) | Total EF | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (4 $m^3/s$ + 30 BOD) | Total EF |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) |
| January | 121.55 | 1.32 | 48.00 | 15.88 | 186.75 | 45.38 | 0.49 | 17.92 | 5.93 | 69.73 |
| February | 120.26 | 1.73 | 42.00 | 14.35 | 178.34 | 49.71 | 0.72 | 17.36 | 5.93 | 73.72 |
| March | 111.36 | 2.68 | 33.00 | 15.88 | 162.92 | 41.58 | 1.00 | 12.32 | 5.93 | 60.83 |
| April | 134.67 | 3.91 | 42.06 | 15.37 | 196.01 | 51.96 | 1.51 | 16.23 | 5.93 | 75.62 |
| May | 105.38 | 3.50 | 28.02 | 15.88 | 152.78 | 39.34 | 1.31 | 10.46 | 5.93 | 57.04 |
| June | 127.23 | 3.40 | 42.06 | 15.37 | 188.06 | 49.09 | 1.31 | 16.23 | 5.93 | 72.55 |
| July | 273.90 | 0.54 | 252.60 | 15.88 | 542.92 | 102.26 | 0.20 | 94.31 | 5.93 | 202.70 |
| August | 317.08 | −1.47 | 813.00 | 15.37 | 1,143.98 | 122.33 | −0.57 | 313.66 | 5.93 | 441.35 |
| September | 309.90 | 0.90 | 784.80 | 15.88 | 1,111.48 | 115.70 | 0.34 | 293.01 | 5.93 | 414.98 |
| October | 217.02 | 3.24 | 252.60 | 15.37 | 488.23 | 83.73 | 1.25 | 97.45 | 5.93 | 188.36 |
| November | 159.72 | 1.96 | 126.00 | 15.88 | 303.56 | 59.63 | 0.73 | 47.04 | 5.93 | 113.34 |
| December | 123.97 | 1.30 | 70.20 | 15.88 | 211.35 | 46.29 | 0.49 | 26.21 | 5.93 | 78.91 |

**Table 12.26** Environmental flow components for the Etawah to Pratappur (Allahabad) stretch of Yamuna River

| | Mean monthly water requirement (MCM) | | | | | Mean monthly discharge required ($m^3/s$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (4 $m^3/s$ + 30 BOD) | Total EF | Seepage | Evapo. | Ecolog. (25%MAF) | Pollution (4 $m^3/s$ + 30 BOD) | Total EF |
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) | (ix) | (x) | (xi) |
| January | 536.27 | 6.02 | 245.27 | 3.27 | 790.83 | 200.22 | 2.25 | 91.57 | 1.22 | 295.26 |
| February | 539.62 | 7.70 | 237.52 | 2.95 | 787.79 | 223.06 | 3.18 | 98.18 | 1.22 | 325.64 |
| March | 522.69 | 12.65 | 231.27 | 3.27 | 769.88 | 195.15 | 4.72 | 86.35 | 1.22 | 287.44 |
| April | 535.49 | 15.65 | 231.27 | 3.16 | 785.57 | 206.59 | 6.04 | 89.22 | 1.22 | 303.08 |
| May | 434.41 | 14.38 | 162.52 | 3.27 | 614.58 | 162.19 | 5.37 | 60.68 | 1.22 | 229.46 |
| June | 534.52 | 12.91 | 231.27 | 3.16 | 781.86 | 206.22 | 4.98 | 89.22 | 1.22 | 301.64 |
| July | 911.06 | −7.55 | 1,625.16 | 3.27 | 2,531.94 | 340.15 | −2.82 | 606.77 | 1.22 | 945.32 |
| August | 1,401.81 | −19.23 | 4,425.43 | 3.16 | 5,811.17 | 540.82 | −7.42 | 1,707.34 | 1.22 | 2,241.96 |
| September | 1,389.56 | −0.91 | 4,037.89 | 3.27 | 5,429.81 | 518.80 | −0.34 | 1,507.58 | 1.22 | 2,027.26 |
| October | 956.71 | 8.91 | 781.33 | 3.16 | 1,750.11 | 369.10 | 3.44 | 301.44 | 1.22 | 675.20 |
| November | 567.92 | 7.04 | 368.79 | 3.27 | 947.02 | 212.04 | 2.63 | 137.69 | 1.22 | 353.58 |
| December | 549.82 | 6.05 | 312.53 | 3.27 | 871.67 | 205.28 | 2.26 | 116.69 | 1.22 | 325.44 |

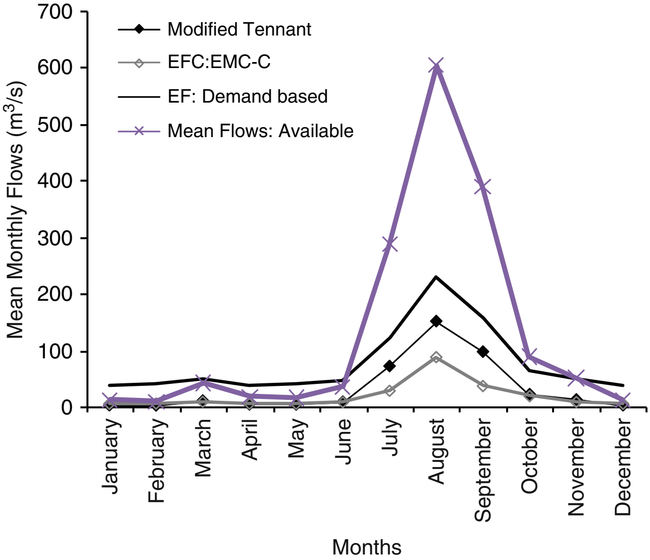


**Fig. 12.26** Comparison of different methods of EF estimation for the Hathinikund-Palla stretch ($L_c = 254.0$ km, $Q_{waste} = 5$ m$^3$/s, BOD = 30 mg/l)

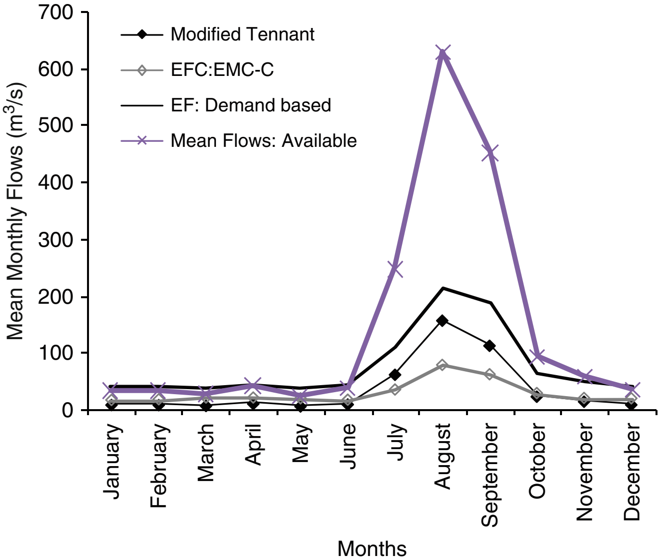


**Fig. 12.27** Comparison of different methods of EF estimation for the Wazirabad-Okhla stretch ($L_c = 22.0$ km, $Q_{waste} = 5$ m$^3$/s, BOD = 10 mg/l)

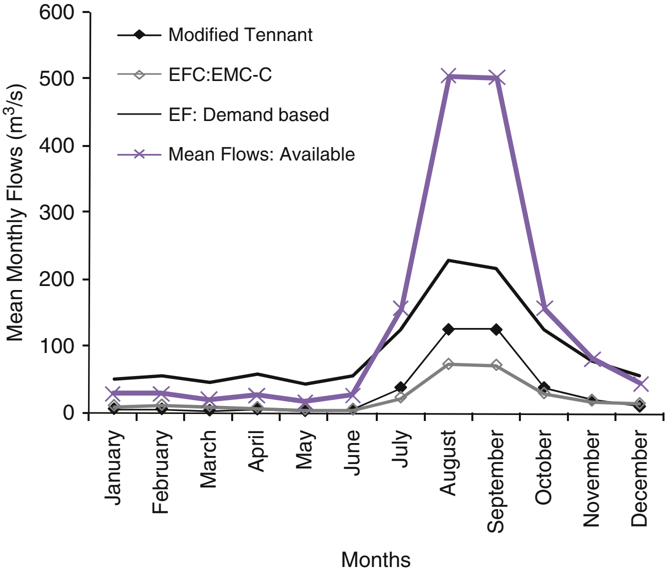


**Fig. 12.28** Comparison of different methods of EF estimation for the Okhla-Agra stretch ($L_c$ = 310.0 km, $Q_{waste}$ = 10 $m^3$/s, BOD = 30 mg/l)

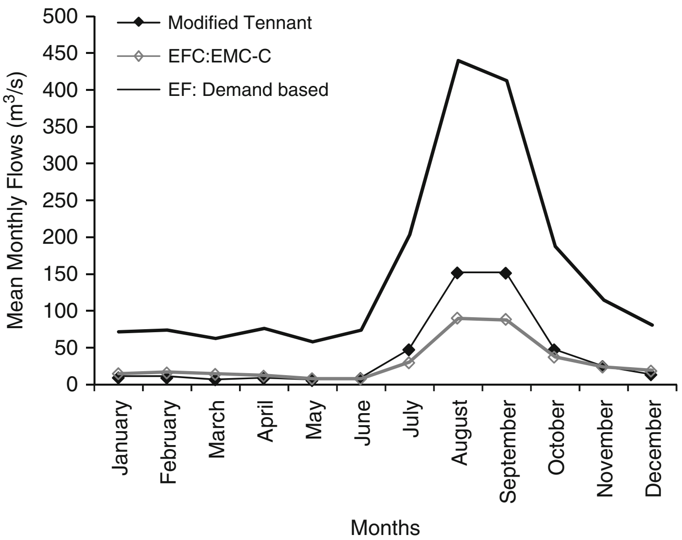


**Fig. 12.29** Comparison of different methods of EF estimation for the Agra-Etawah stretch ($L_c$ = 305.0 km, $Q_{waste}$ = 4 $m^3$/s, BOD = 30 mg/l)

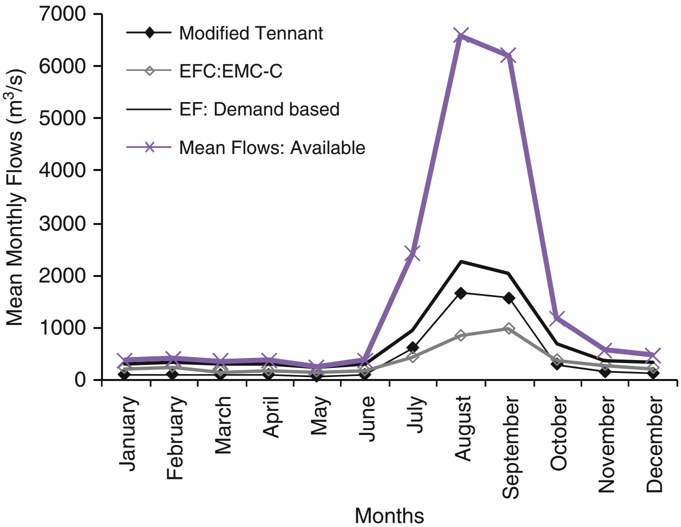


**Fig. 12.30** Comparison of different methods of EF estimation for the Etawah-Pratappur stretch ($L_c = 465.0$ km, $Q_{waste} = 4$ m$^3$/s, BOD = 30 mg/l)

## 12.6 Comparison of the Approaches

The proposed approach is compared with two hydrology-based approaches: the Tennant method and EMC based environmental flow calculator. A description of these methods has already been presented in earlier sections.

Results obtained from all the methods for all the stretches are shown in Figs. 12.26, 12.27, 12.28, 12.29, and 12.30, sequentially for the Hathinikund-Palla, Wazirabad-Okhla, Okhla-Agra, Agra-Etawah, and Etawah-Pratappur stretches. Comparison of results shows that the proposed method gives higher values than the other two methods, and seems practical when the river morphology is considered. The most important component of environmental flows is seepage and is very large in the alluvial rivers as the average width of the river is 650 m with the range of 350–1,800 m.

The method "Component based Environmental flow calculator" is comprehensive when river is highly intercepted and being used for the disposal of pollutants either treated/partially treated/untreated than the other methods. The hydrology-based methods, on the other hand, require good historical discharges and hydrologic regime. The length of record should include the entire alteration made in the river. A hydrology-based method has a major disadvantage in that it is a black box method whose accuracy largely depends on the length of record. Further, the hydrology-based method does not account for the water requirement for assimilating pollutants in the river. This means that if the river is highly intercepted and used for pollutant transport then hydrology-based methods do not yield realistic estimates of environmental flows.

**Table 12.27** Summary of the environmental flow components for Yamuna River

| S. No. | Segment | Length (km) | Ecological (MCM) | Seepage (MCM) | Evaporation (MCM) | Pollution (MCM) | Total E-flows (MCM) |
|---|---|---|---|---|---|---|---|
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) | (viii) |
| 1 | Hathinikund to Pall | 254.0 | 1,041.75 (42.78) | 1,316.24 (54.05) | 10.33 (0.42) | 66.86 (2.75) | 2,435.00 |
| 2 | Wazirabad to Okhla (Delhi Segment) | 22.0 | 1,136.40 (21.22) | 427.87 (7.99) | 2.73 (0.05) | 3,788.70 (70.74) | 5,355.71 |
| 3 | Okhla to Agra | 310.0 | 1,056.27 (39.94) | 1,639.50 (54.23) | 20.17 (0.67) | 307.16 (10.16) | 3,023.15 |
| 4 | Agra to Etawah | 305.0 | 2,534.30 (52.08) | 2,122.00 (43.61) | 23.01 (0.47) | 187.01 (3.84) | 4,866.40 |
| 5 | Etawah to Pratappur (Allahabad) | 465.0 | 12,890.25 (58.93) | 8,879.88 (40.60) | 63.6 (0.29) | 38.47 (0.18) | 21,872.20 |

Values in the parenthesis are percent demand of total environmental flows

The proposed method does not consider the water required for the sediment transport. It is assumed that if it is considered once in a year then it is automatically possible during the wet season (i.e., August and September).

For aquatic-habitat conservation (i.e., ecological flow) in the river, monthly distribution of 25% MAF is sufficient (Tennant, 1976). However, the question is "how to maintain this ecological flow in the river?". The importance of each component for the river can be seen from Table 12.27 which shows that seepage and dilution components are important. If only ecological component estimated by Tennant (1976) (i.e., 25% MAF criteria) is allocated for the river; all the flow will disappear due to the seepage loss. More clearly, to maintain the ecological demand throughout the river stretch, it is required to satisfy other demands quantitatively, such as seepage and evaporation. Further, if river is receiving pollutants, water quality will become inadequate for aquatic conservation, and therefore additional water needs to be added to assimilate the pollutants within the stretch. This means that if there are no losses and effluent flow is considered then environmental flow estimated by the Tennant method will be appropriate, although it is not practically possible. This is the basic reason for overestimating the environmental flow demand by the proposed method as compared to other methods.

## 12.7 Concluding Remarks

For environmental flow estimation various hydrology-based techniques are commonly used. These techniques either estimate the ecological flow or environmental flow without considering the pollution and manmade alterations. In this chapter, four important components, i.e., ecological, seepage, evaporation, and dilution of pollutant assimilation are considered for a comprehensive assessment of environmental flows in the river. Of course, the ecological flow is most important for proper ecosystem functioning of the river, but it cannot be maintained if other three components (i.e., seepage, evaporation and dilution) are not satisfied.

It may be affirmed that the seepage component is important for the Yamuna River that largely affects the allocation of ecological flow (Table 12.27). Besides the seepage component, the dilution component is another essential component for maintaining water quality for the survival of aquatic habitat as most of the rivers in India are getting wastewater effluent (Table 12.27).

The water availability in the Yamuna River is not enough to meet environmental demands during the months of December to June except for the Etawah to Allahabad stretch. This stretch has no major industrial and domestic influence. Also, this stretch receives good quality water from four major tributaries, such as Chambal, Sind, Betwa and Ken.

The Delhi stretch is of high concern to the Ministry of Environment and Forests, Government of India, as this stretch receives pollutants from 23 wastewater drains and there is no release of water from the Wazirabad barrage. Therefore, for this stretch, the water demand for assimilating pollutants becomes very high as compared to the available water. Under such circumstances, there is only one solution for Delhi: "Do not use the river for pollutant transport." To be more precise, all the wastewater either treated or untreated should be diverted for other uses, such as irrigation, construction, etc., and should not be discharged into the river.

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# Chapter 13
# Cropping Plan for Water Resources Management

**Abstract** In India, nearly 75% of utilizable water resources are used for irrigation. Due to intensive agriculture and changes in climatic patterns, water scarcities are becoming frequent for agriculture, industry, energy and households. Therefore, it is imperative to implement cropping patterns that can lead to reduced agricultural water demand, while preserving farmers' economic returns. Looking into this scenario, the chapter determines economically feasible intercropping patterns for the Yamuna River basin.

In India, approximately 70% of the population depends on agriculture and the agricultural sector is a major part of the Indian economy. For sustained agriculture, water and climate are vital, for they govern agricultural productivity, market value, employment, and the living standard. The other governing factors for agricultural operation, selection of crops, cultivation methods, and irrigation methods are topography and soil. Agriculture, including crop planning, crop diversity, consumptive use of crops, and spatio-temporal availability of water resources for irrigation are highly sensitive to global warming or climate change.

In India, three distinct crop seasons can be identified: *kharif* (July to October), *rabi* (October to March) and *Zaid* (April to June), and agricultural water demands are met by three sources: rainfall, canal irrigation, and groundwater pumping. However, most of the *kharif* crop planning is dependent upon the onset of monsoons whose patterns seem to have changed due to climate change. Rai et al. (2010) reported that in the Yamuna River basin the date of onset of effective monsoons has positively shifted and the number of rainy days has reduced. These two changes are critical for water resources management, because most of the rainfall becomes confined to a shorter duration, resulting in increased flooding and declining aquifer recharge. Declining recharge induces crop water deficit for *rabi* crops and supplementary irrigation stress for *kharif* crops. Under such water deficit conditions, crop water management seems to be the only way for sustainable agriculture. Therefore, the objective of this study is to discuss the suitability of cropping patterns for sustainable agriculture from the perspective of both water demand and economy. Specific objectives include: (i) identification of crops based on climate, soil, and landscapes; (ii) identification of cropping patterns; (iii) estimation of crop water requirements; (iv) identification of cropping patterns based on minimum water use; and (v) economic evaluation of cropping patterns and net savings of irrigation water.

Yamuna River (Fig. 13.1), a holy river and a major tributary of the Ganga River which originates from the Shivalik range of Lesser Himalayas and after traversing

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DOI 10.1007/978-94-007-2001-5_13, 

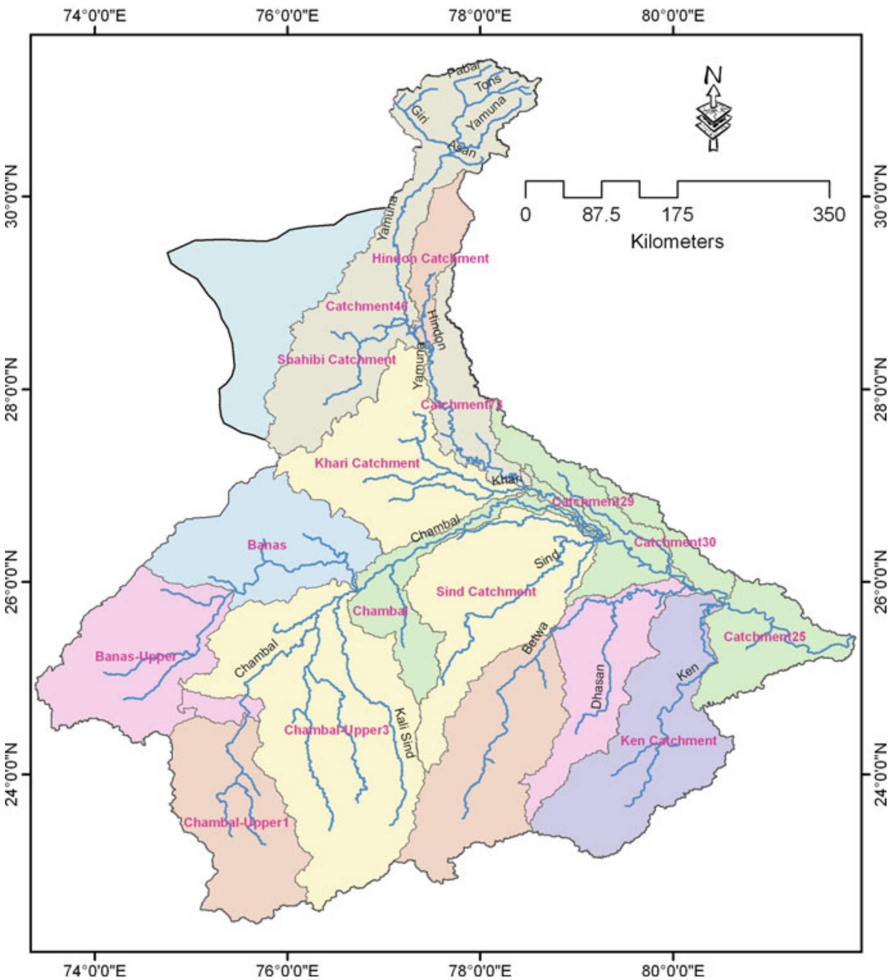


**Fig. 13.1** Sub catchments of Yamuna River basin

approximately 1,350 km it joins the Ganga at the right bank near Allahabad (called "Sangam"). The detailed description of Yamuna river basin such as climate, soil, landuse, water resources etc. has been presented in previous chapters. As stated in previous chapter that many tributaries are joining the river Yamuna after Okhla barrage. Most of these tributaries are highly intercepted by various irrigation and multi-purpose projects resulting in little discharge before their confluence. Because of high utilization, the Yamuna River carries very little discharge during the lean season.

A water balance study of Yamuna River basin is presented in Chapter 8, which showed that all the sub-catchments of the Yamuna, excepting the Upper Himalayan and Ken sub-catchments, were under water deficit (see Table 13.1). Under such

**Table 13.1** Summary of basin water balance

| S. No | Catchments | Area ($km^2$) | DWR (MCM) | CWR (MCM) | IWR (MCM) | GWR (MCM) | SMS (MCM) | NGW (MCM) | SWR (MCM) | TWR (MCM) | S/D (MCM) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (i) | (ii) | (iii) | (iv) | (v) | (vi) | (vii) = (iv) + (v) + (vi) | (viii) | (ix) | (x) | (xi) = (viii) + (ix) + (x) | (xii) = (xi)−(vii) |
| 1 | Himalayan | 11,058 | 54.3 | 1,332 | 10.8 | 1,397.1 | 1,935 | 457 | 3,605 | 5,997 | 4,599 |
| 2 | Chambal | 134,967 | 721 | 62,771 | 144.2 | 63,636.2 | 23,619 | 93,82.9 | 26,736 | 59,739 | −3,897 |
| 3 | Sind | 27,940 | 166.8 | 13,786 | 33.3 | 13,986.1 | 4,890 | 3,441.7 | 1,888 | 10,220 | −3,766 |
| 4 | Betwa | 43,836 | 287.5 | 26,456 | 57.5 | 26,801 | 7,671 | 5,701 | 11,803 | 25,175 | −1,626 |
| 5 | Ken | 28,806 | 137.2 | 12,808 | 27.4 | 12,972.6 | 5,041 | 3,113 | 8,089 | 16,244 | 3,271 |
| 6 | Yamuna | 365,870 | 3,713 | 200,761 | 742.6 | 205,216.6 | 64,027 | 45,428.8 | 61,219 | 170,675 | −34,541 |

*DWR* Domestic water requirement, *IWR* Industrial water requirement, *CWR* Crop water requirement, *GWR* Gross water requirement, *SMS* Soil moisture storage, *NGW* Net groundwater availability, *SWR* Surface water resources, *TWR* Total water resources, *S/D* Surplus/deficit circumstances, it becomes essential to manage the water resources of the Yamuna basin so that long term equity and economy can be maintained. It is seen from Table 13.1 that agricultural demand is much higher than domestic and industrial demands; therefore, attention needs to be paid to the sustainability of the agricultural sector and in turn the sustainability of the economy of India.

## 13.1 Landuse and Agriculture

Major land uses in the basin are typified by agriculture, forests, non-agriculture, barren land, permanent pasture, cultivable wasteland, and cultivated fallow. Of the total basin area (i.e., 342,541 $km^2$), more than 50% of the area (i.e., net sown area is 187,908.6 $km^2$) is under agriculture. Catchment wise net sown area and irrigation facility are summarized in Table 13.2 which also includes cropping intensity, net irrigated area and sources of irrigation. It is apparent from the table that only 56% of the net sown area is irrigated for which groundwater resource the major water resource is used for irrigation. Approximately 67% of the net irrigated area is being irrigated by ground water. The rest of the net irrigated area uses canal (27%) and other sources (6%). The rest of the net sown area (i.e., 44%) is completely rainfed. To analyze Table 13.2, it is observed that the catchments belonging to the left bank of the Yamuna (i.e., Hindon, Karwan and Senger) are highly irrigated (percent net irrigated area is 89%) due to the Ganga canal network. These catchments fall within the Ganga-Yamuna *Duab*. These catchments not only have canal networks, but the ground water table is relatively high to support supplementary irrigation.

A majority of agricultural lands is sown more than once in a single crop-calendar year. The average cropping intensity in the basin varies between 105 and 212%, depending upon the water availability and topography with an average of 140%. Combinations of cropping patterns largely depend on the crop diversity which is a good indicator of sustainable agriculture. Higher the crop diversity lesser will be the risk involved. There are various crops that can be cultivated in a year in the basin, depending on climate, soil, and water. Based on the physical environment, the suitability of crops is listed in Table 13.3. Major climatic factors affecting crops are temperature, annual rainfall, wind speed and sunshine hours. Crops grown in different climatic zones have different water demands.

Sub-basin wise cultivated crops during *kharif* and *rabi* are summarized in Tables 13.4 and 13.5, respectively. Based on Table 13.4, the area under soybean is the largest in the basin, followed by paddy, cotton, arhar and maize; however, a small value of the coefficient of spatial variation for paddy (i.e., CV = 0.48) shows its dominance as a most common food crop. In spite of the largest area being sown under soybean, its dominance is reduced due to the large value of the coefficient of spatial variation (CV = 2.0). Similarly among *rabi* crops grown (Table 13.5), wheat, mustard, barley and potato are the major crops; however, a less value of the coefficient of spatial variation for wheat (i.e., 0.65) indicates its dominance as a major food crop in the Yamuna basin.

**Table 13.2** Agriculture and irrigation sources in the Yamuna basin

| Catchments | Net sown area ($km^2$) | Area sown more than once ($km^2$) | Grass area ($km^2$) | Cropping intensity (%) | Net irrigated area, NIA ($km^2$) | NIA by canal (%) | NIA by tube well (%) | NIA by other sources (%) |
|---|---|---|---|---|---|---|---|---|
| Sahibi | 10,914.3 | 6,257.3 | 17,171.6 | 164 | 7,685.4 | 21.28 | 78.66 | 0.05 |
| Hindon | 5,052.2 | 2,687.9 | 7,740.1 | 153 | 4,519.3 | *18.45* | *79.88* | 1.67 |
| Khri | 13,395.2 | 6,316.0 | 19,711.2 | 148 | 10,270.6 | 9.98 | 89.39 | 0.63 |
| Chambal | 62,349.2 | 14,239.6 | 76,588.7 | 125 | 27,753.7 | 15.24 | 76.15 | 8.61 |
| Sind | 14,918.3 | 3,283.4 | 18,201.7 | 123 | 7,335.3 | 33.92 | 57.41 | 8.66 |
| Betwa | 26,853.1 | 6,304.5 | 33,157.6 | 126 | 12,129.2 | 22.65 | 60.57 | 16.78 |
| Ken | 15,834.4 | 4,043.9 | 19,878.2 | 127 | 6,640.1 | 15.14 | 67.00 | 17.86 |
| Karwan | 3,503.4 | 2,000.5 | 5,503.9 | 157 | 3,160.8 | *18.37* | *80.10* | 1.53 |
| Sengar | 4,136.4 | 2,399.0 | 65,35.4 | 158 | 3,607.2 | *25.94* | *73.85* | 0.21 |
| *Yamuna* | *187,908.6* | *66,094.7* | *254,003.3* | *141* | *105,178.3* | *27.16* | *66.93* | *5.90* |

**Table 13.3** Suitability of crops under different physical environments

| | Climatic factors | | | | | |
|---|---|---|---|---|---|---|
| Crop | Annual rainfall (mm) | Germination temperature (°C) | Optimum temperature (°C) | Maximum temperature (°C) | Climate zone | Non-climatic factor: soil |
| Paddy | >800 | 10 | 20–35 | 40 | Tropical and Sub tropical. Need hot, humid climate and prolong sunshine | Alluvial soil, red soil and black soil are very good for rice cultivation. The pH of soil ranges from 5 to 8. |
| Sorghum (Jowar) | 500–600 | 12 | 20–25 | 32 | Semi arid tropical | Light to medium deep black soil |
| Maize | 700–1,000 | 12 | >12 (no frost) | 35 | Tropical, Sub tropical and temperate | Sandy to heavy clay (pH of soil between 7.5 and 8.5) |
| Pearl Millet (Bajra) | 500–600 | 10 | 23–28 | 30 | Semi arid tropical | Wide range of soil from very light soil to red loam soil |
| Arhar (Pigeon pea) | 800–1,000 | 20 | 25–30 | 45 | Tropical and sub tropical | Sandy to heavy clay loam |
| Soybean | 700–1,000 | 20 | 30 | 35 | Sub humid to humid | Sandy loam to clay soil with pH of 7.0 |
| Cotton | >500 | 15 | 21–27 | 40 | Tropical and sub tropical | Well drained deep alluvial soil to black clayey soil |
| Wheat | 300–700 | 20 | 22–23 | 28 | Semi arid to humid | Well drained clay loam and loam |
| Barley | 300–700 | 20 | 23–25 | 30 | Temperate climate having cold dry winter with low rainfall: Semi arid to sub humid | Well drained fertile loam or light clay soil |
| Gram | 800–2,000 | 20 | 25–35 | 35 | Tropical | Sandy, heavy loam, well drained loam soil |
| Potato | 150–200 | 18–20 | 20 (no frost) | 30 | Temperate and cool climate | Well drained sandy loam and fertile loam soils are most suitable for potato cultivation |
| Groundnut | 500–1,250 | 20 | 30 | 35 | Tropical region and extends to sub tropical | Sandy loam, loamy soil and in black soil with drainage |
| Mustard | 250–400 | 20 | 22–23 | 28 | Tropical as well as temperate zone | Light to heavy loam soil. pH around 7.0 |

**Table 13.4** Common cropping systems for *kharif* season in the Yamuna basin (in $km^2$)

| Catchments | Paddy | Jowar | Maize | Bajra | Arhar | Soybean | Cotton |
|---|---|---|---|---|---|---|---|
| Sahibi | 1,283.6 | 122.0 | 16.8 | 788.8 | 72.6 | 0.07 | 556.8 |
| Hindon | 800.4 | 34.6 | 285.5 | 80.5 | 74.0 | 0.04 | 2.6 |
| Khri | 429.7 | 60.5 | 47.4 | 475.9 | 86.9 | 3.6 | 152.8 |
| Chambal | 671.3 | 5.0 | 350.9 | 277.7 | 601.3 | 18,530.0 | 1,143.0 |
| Sind | 584.9 | 0.8 | 51.7 | 2.6 | 591.6 | 1,654.51 | 0.01 |
| Betwa | 233.4 | 0.5 | 21.2 | 3.1 | 1,454.7 | 5,388.5 | 0.7 |
| Ken | 643.6 | 0.1 | 0.2 | 0.0 | 533.8 | 1,674.1 | 0.01 |
| Karwan | 371.3 | 2.6 | 336.5 | 65.5 | 70.8 | 0.0 | 6.8 |
| Sengar | 634.2 | 2.5 | 246.3 | 30.7 | 115.5 | 0.25 | 6.0 |
| *Yamuna* | *13,526.8* | *1,014.6* | *1,901.7* | *24,66.2* | *35,12.3* | *25,790.4* | *6,117.44* |
| ***CV*** | **0.48** | 1.65 | 0.99 | 1.44 | 1.15 | 2.01 | 1.91 |

**Table 13.5** Common cropping systems for *rabi* season in the Yamuna basin (in $km^2$)

| Catchments | Wheat | Barley | Gram | Potato | Groundnut | Mustard | Sugarcane |
|---|---|---|---|---|---|---|---|
| Sahibi | 4,067.0 | 294.3 | 336.9 | 4.4 | 252.4 | 3,174.8 | 140.0 |
| Hindon | 2,472.3 | 62.4 | 3.0 | 68.3 | 16.4 | 79.7 | 1,900.8 |
| Khri | 5,089.4 | 482.3 | 112.9 | 324.7 | 278.3 | 5,441.1 | 75.4 |
| Chambal | 12,252.9 | 667.6 | 3,044.7 | 404.9 | 1,248.6 | 10,347.1 | 105.5 |
| Sind | 4,407.9 | 104.7 | 866.9 | 67.7 | 426.4 | 2,052.7 | 65.9 |
| Betwa | 6,923.9 | 190.0 | 2,712.0 | 48.2 | 676.9 | 771.0 | 93.2 |
| Ken | 3,571.7 | 51.6 | 1,904.4 | 54.0 | 75.9 | 199.9 | 177.7 |
| Karwan | 2,167.5 | 164.9 | 19.2 | 142.7 | 1.2 | 379.5 | 270.6 |
| Sengar | 25,54.87 | 188.4 | 32.8 | 231.5 | 2.2 | 515.9 | 67.5 |
| *Yamuna* | *560,10.4* | *3,967.8* | *8,691.3* | *1,566.6* | *2,394.8* | *25,938.4* | *5,756.6* |
| ***CV*** | **0.65** | 0.84 | 1.22 | 0.93 | 1.25 | 1.34 | 1.85 |

## 13.2 Parameters of Cropping Pattern

The parameters, most influential in choosing an optimum cropping pattern, are: crop water requirement, crop suitability based on the physical environment, cropping system, productivity, water utilization under different conditions, and economic value to the farmer. Among these parameters, the net crop return is perhaps the most important parameter used in the adoption of a particular pattern. The procedure of crop water requirement is now described.

### *13.2.1 Estimation of Crop Water Requirement*

The crop water requirement for a specific crop is estimated using the FAO 56 procedure (Allen et al., 1998), in which the crop coefficient is multiplied with the reference evapotranspiration using:

$$ET_c = K_c \times ET_0 \tag{13.1}$$

where $ET_c$ is the crop water requirement (mm), $K_c$ is the crop coefficient, and $ET_0$ is the reference evapotranspiration (mm). The value of daily $ET_0$ depends on the climatic factor and location of the area, and can be estimated using the Penman-Montieth formula as:

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,u_2\,\left(e_z^0 - e_z\right)}{\Delta + \gamma\,(1 + 0.34\,u_2)} \tag{13.2}$$

In eq. (13.2) $ET_0 =$ the grass reference ET (mm/d), $R_n =$ the net radiation (MJ m$^{-2}$ d$^{-1}$), $G =$ the sensible heat exchange from the surface to the soil or water (MJ m$^{-2}$ d$^{-1}$), $T =$ the mean daily temperature (°C), $\Delta =$ the slope of the saturation vapor pressure versus temperature (kPa °C$^{-1}$), $\gamma =$ the psychometric constant (= 0.0642 kPa °C$^{-1}$), $u_2 =$ the mean 24-h wind speed at 2 m above the ground (ms$^{-1}$), $e_z^0 =$ the saturation vapor pressure based on measurements at 1.5–2.0 m (kPa), and $e_z =$ the actual vapor pressure (kPa).

When wind speed is measured at a height other than 2 m above the ground surface then the adjusted value of wind speed can be computed as (Jensen et al., 1990):

$$u_2 = u_1 \left[\ln\{(z_2 - d)/z_{om}\} / \ln\{(z_1 - d)/z_{om}\}\right] \tag{13.3}$$

The wind level adjustments are relatively insensitive to the value of $z_{om}$, and for water a value of $d$ is generally considered to be zero. Therefore, eq. (13.3) takes on the following reduced form:

$$u_2 = u_1\,\left[\ln(z_2)/\ln(z_1)\right] \tag{13.4}$$

where $z_1 =$ the wind measurement height (m), and $z_1 = 2$ m.

The saturation vapor pressure for daily or longer time step can be computed as (Allen et al., 1989; Jensen et al., 1990):

$$e_z^0 = \left[e^0\,(T_{max}) + e^0\,(T_{min})\right]/2 \tag{13.5}$$

where $T_{max}$ and $T_{min}$ are the daily maximum and minimum temperature (°C), respectively; and $e^0$ (in kPa) can be computed using the relationship proposed by Tetens (1930) and Murray (1967):

$$e^0 = \exp\left[\frac{16.78\,T - 116.9}{T + 237.3}\right] \tag{13.6}$$

where $T$ is the daily temperature (°C). Equation (13.6) calculates within 0.1% of values in the Smithsonian Meteorological Tables for temperatures in the range of 0–50°C (Allen et al., 1989).

The slope of the saturation vapor pressure curve $\Delta$ (in kPa °C$^{-1}$) can be computed using the expression given by Allen et al. (1989):

$$\Delta = \frac{4098\, e^0}{(T + 237.3)^2} \tag{13.7}$$

where $T$ is in °C. The actual vapor pressure $e$ (kPa) is computed as:

$$e = \frac{\text{RH}}{100} \times e^0 \tag{13.8}$$

where RH is the mean relative humidity (%).

The net radiation flux $R_n$ can be measured directly using hemispherical net radiometers or estimated from the net short-wave and net long-wave components as:

$$R_n = (1 - \alpha)\, R_s^{\downarrow} - R_b^{\uparrow} \tag{13.9}$$

where $R_s$ is the short-wave radiation received by a water, soil or vegetated surface; $\alpha$ is the short-wave reflectance or albedo; and $R_b$ is the net back, or net outgoing, long-wave radiation.

For vegetated surfaces the value of $\alpha$ can be taken as 0.23 within a range of 0.20–0.25. The short-wave radiation $R_s$ (in MJ m$^{-2}$ d$^{-1}$) can be estimated as (Doorenbos and Pruitt, 1977):

$$R_s = \left(0.25 + 0.50\,\frac{n}{N}\right) \cdot R_A \tag{13.10}$$

where $R_A$ is the extra-terrestrial radiation (MJ m$^{-2}$ d$^{-1}$), $n/N$ is the ratio between actual measured bright sunshine hour and maximum possible sunshine hours. The value of $R_A$ can be computed for a location as a function of latitude and day of the year using the following set of mathematical equations given by Duffie and Beckman (1991):

$$R_A = \frac{24\,(60)}{\pi} \cdot G_{sc} \cdot d_r \cdot [\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\sin(\omega_s)] \tag{13.11}$$

where $R_A$ = the daily extra-terrestrial radiation (MJ m$^{-2}$ d$^{-1}$), and $\phi$ = the latitude of the station (radians) (negative for southern latitudes). The declination $\delta$ (in radians) can be estimated as:

$$\delta = 0.4093\ \sin\left[2\pi\,\frac{(284 + J)}{365}\right] \tag{13.12}$$

where $J$ is the day of the year (January 1st = 1). The term $d_r$ in eq. (13.11), the relative distance of the earth from the sun, was computed as:

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi}{365}J\right) \quad (13.13)$$

The sunset hour angle $\omega_s$ (in radians) can be estimated as:

$$\omega_s = \arccos\left[-\tan(\phi)\tan(\delta)\right] \quad (13.14)$$

$$\omega_s = \frac{\pi}{2} - \arctan\left[\frac{-\tan(\phi)\tan(\delta)}{\left[1-\tan^2(\phi)\tan^2(\delta)\right]^{1/2}}\right] \quad (13.15)$$

$G_{sc}$ in eq. (13.11) is the solar constant (= 0.0820 MJ m$^{-2}$ min$^{-1}$) as recommended by the International Association of Meteorology and Atmospheric Physics (London and Fröhlich, 1982). The value of maximum possible sunshine hours $N$ was approximately computed as:

$$N = \omega_s (24/\pi) \quad (13.16)$$

For the Yamuna basin the stage wise $ET_c$ was calculated for different crops for different sub-basins. The estimated values of crop coefficients ($K_c$) corresponding to the stage development, suggested by FAO 56, were used for the estimation of crop water requirements as given in Table 13.6. The estimated average consumptive use of different crops and reported values by ICAR (Indian Council of Agricultural Research) are given in Table 13.7.

The crop water requirement varies with the stage of growth. When water supply is limited, it is necessary to take into account the critical stages of crop growth with respect to moisture. The term critical stage is commonly used to define the growth when plants are most sensitive to the shortage of water causing a drastic reduction in yield. The critical stages of different crops are summarized in Table 13.8.

## *13.2.2 Suitability of Crops Based on Physical Environment*

The physical environment for crops includes climate (i.e., germination temperature, optimum temperature, maximum temperature, rainfall, and climate), soil, and topography. Based on these factors suitable crops for the Yamuna basin is listed in Table 13.3.

### 13.2.2.1 Cropping Systems

A study of cropping systems is not only useful to understand the overall sustainability of agriculture but also in generating parameters that are useful in the assessment of water resources availability. Cropping systems of a region are also determined by soil and climatic parameters which determine the overall agro-ecological setting for nourishment and of a crop or set of crops for cultivation. The important cropping systems are: (i) sole cropping (monoculture) referring to a single crop grown

**Table 13.6** Approximate date of sowing, growth stage and crop coefficients for important crops of the Yamuna basin

| Crop | Sowing date (Approx) | Growth stage: Initial | Development | Middle | Late | Total duration |
|---|---|---|---|---|---|---|
| Wheat | 1st November | 20 | 60 | 20 | 50 | 150 |
| *Kc* | | *0.40* | *1.00* | *1.20* | *0.60* | |
| Barley | 1st November | 15 | 25 | 50 | 30 | 120 |
| *Kc* | | *0.20* | *1.00* | *1.15* | *0.25* | |
| Gram | 20th October | 20 | 30 | 30 | 20 | 100 |
| *Kc* | | *0.35* | *0.75* | *1.05* | *0.50* | |
| Potato | 25th October | 25 | 30 | 30 | 30 | 115 |
| *Kc* | | *0.52* | *0.81* | *1.10* | *0.70* | |
| Mustard | 1st November | 25 | 35 | 35 | 40 | 135 |
| *Kc* | | *0.38* | *0.38* | *1.00* | *0.56* | |
| Bajra | 10th June | 20 | 35 | 25 | 30 | 110 |
| *Kc* | | *0.41* | *1.00* | *1.20* | *0.40* | |
| Paddy | 20th June | 30 | 30 | 60 | 30 | 150 |
| *Kc* | | *1.05* | *1.20* | *1.20* | *0.75* | |
| Jowar | 20th June | 20 | 40 | 45 | 20 | 125 |
| *Kc* | | *0.42* | *1.00* | *1.20* | *0.40* | |
| Maize | 15th May | 20 | 35 | 40 | 30 | 125 |
| *Kc* | | *0.42* | *0.95* | *1.00* | *0.50* | |
| Arhar | 15th June | 20 | 35 | 40 | 30 | 125 |
| *Kc* | | *0.63* | *0.63* | *0.63* | *0.63* | |
| Soybean | 15th May | 20 | 35 | 60 | 25 | 140 |
| *Kc* | | *0.40* | *1.00* | *1.15* | *0.50* | |
| Groundnut | 15th May | 35 | 45 | 35 | 25 | 140 |
| *Kc* | | *0.52* | *0.85* | *1.00* | *0.55* | |
| Cotton | 10th April | 30 | 50 | 60 | 55 | 195 |
| *Kc* | | *0.43* | *1.00* | *1.15* | *0.60* | |
| Sugarcane | 15th November | 30 | 50 | 180 | 60 | 320 |
| *Kc* | | *0.47* | *1.00* | *1.25* | *0.70* | |

in a season; (ii) rotational cropping wherein cropping is done in a defined sequence; (iii) mixed cropping referring to a process of growing two or more crops together on the same piece of land, mixed cropping is widely practiced in India, particularly during the kharif season; and (iv) intensive cropping wherein the process of growing a number of crops on the same piece of land during a given period of time. The aim is to increase the income per unit area within a specified period of time. Intensive cropping can be either multiple or intercropping. In multiple cropping systems, two or more crops are grown in succession within a year, for example, “paddy-potato-sunflower” followed by “paddy-wheat-gram”; whereas, in an intercropping system more than one crop is grown in the same field during a growing season.

The existing cropping pattern sub-catchment-wise during *Kharif* and *Rabi* for the Yamuna basin is given in Tables 13.9, 13.10, 13.11, 13.12, 13.13, 13.14, 13.15, and 13.16. Among the *kharif* crops, soybean, arhar and cotton account for the highest share of the total *kharif* cropped area for Chambal, Sind and Betwa catchments; and

**Table 13.7** Estimated crop water requirements

| Kharif season | | | Rabi season | | |
|---|---|---|---|---|---|
| Crop | $ET_c$ (FAO 56) [mm] | $ET_c$ (ICAR) [mm] | Crop | $ET_c$ (FAO 56) [mm] | $ET_c$ (ICAR) [mm] |
| Paddy | 530–834 (784.4, 34.8) | 900–1,500 | Wheat | 207–527 (427.3, 46.5) | 450–650 |
| Sorghum (Jowar) | 337–522 (487, 23.5) | 450–650 | Groundnut | 370–559 (526, 26.3) | 500–700 |
| Maize | 422–631 (584, 35.4) | 500–800 | Potato | 140–364 (291, 32.2) | 300–700 |
| Cotton | 544–940 (891, 56.3) | 700–1,300 | Mustard | 166–432 (347, 39.0) | 300–450 |
| Soybean | 445–668 (627, 32.4) | 450–700 | Gram | 102–295 (213, 25.0) | 100–250 |
| Arhar | 273–417 (391, 19.2) | 350–450 | Sugarcane | 1,647–1,822 (1,708, 53.4) | 1,500–2,500 |
| Bajra | 301–447 (414, 23.7) | 400–650 | Barley | 140–375 (296, 35.0) | 250–350 |

**Table 13.8** Critical stages of different crops

| Crops | Critical satges |
|---|---|
| Paddy | Transplanting, Panicle initiation, flowering. |
| Sorghum (Jowar) | Booting, Blooming, milky and dough stage |
| Maize | Teaseling, silking stages to early grain formation |
| Bajra | Panicle initiation, flowering |
| Cotton | Flowering and boll development |
| Soybean | Blooming and seed formation |
| Wheat | Crown root initiation, shooting, earing |
| Groundnut | Flowering, Peg penetration, Seed development |
| Pulses | Flowering and pod formation |
| Potato | Tuber initiation to tuber maturity |

for other catchments paddy is the most dominating crop, followed by maize and arhar. Wheat is grown in almost every district occupying the maximum share of the total *rabi* cropped area. Most of the irrigation water is shared among these major crops.

Tables 13.9, 13.10, 13.11, 13.12, 13.13, 13.14, 13.15, and 13.16 also include the sub-catchment and district-wise net sown area along with the area under major *kharif* and *rabi* crops and their percentage distribution. These numbers were further used for the estimation of crop-wise water demand and to finally determine suitable crop combinations based on water use and gross return.

The final selection of cropping patterns and their implementation largely depend on crop yield, productivity, and gross return. For all crops, the Ministry of Agriculture, Government of India (GoI), in concert with the State Governments, fixes the minimum support price for farmers. These prices are fixed on the basis

**Table 13.9** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha)[a] | Rabi (ha)[a] | Kharif Crops | | | | | | | Rabi Crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: Chambal Upper 1** | | | | | | | | | | | | | | | | |
| Chittaurgarh | 26,751 | 10,460 | 16,479 | 0.10 | 0.00 | 5.80 | 0.00 | 2.00 | 89.80 | 2.30 | 39.00 | 2.00 | 3.40 | 0.00 | 18.90 | 36.30 |
| Mandsaur | 426,899 | 279,192 | 99,041 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 99.40 | 0.20 | 31.50 | 0.10 | 8.20 | 0.00 | 2.00 | 58.20 |
| Jhalawar | 32,111 | 20,166 | 11,528 | 0.30 | 0.00 | 0.20 | 0.00 | 2.00 | 97.50 | 0.00 | 33.40 | 0.10 | 4.20 | 0.10 | 2.00 | 60.20 |
| Shajapur | 44,779 | 32,599 | 12,672 | 0.00 | 0.00 | 0.00 | 0.00 | 1.60 | 98.40 | 0.00 | 40.40 | 0.10 | 52.00 | 3.30 | 1.40 | 2.40 |
| Ratlam | 192,940 | 125,604 | 39,553 | 0.00 | 0.00 | 0.50 | 0.00 | 0.80 | 84.30 | 14.40 | 62.20 | 0.00 | 19.70 | 0.40 | 0.60 | 17.10 |
| Ujjain | 449,192 | 374,177 | 123,079 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 99.90 | 0.00 | 51.20 | 0.00 | 35.90 | 1.70 | 0.40 | 10.60 |
| Dewas | 53,026 | 43,375 | 18,294 | 0.00 | 0.00 | 0.00 | 0.00 | 0.80 | 88.70 | 10.60 | 57.30 | 0.00 | 37.10 | 4.20 | 0.50 | 0.00 |
| Dhar | 96,289 | 66,632 | 19,739 | 0.00 | 0.00 | 0.60 | 0.00 | 0.20 | 68.30 | 31.00 | 85.30 | 0.00 | 8.00 | 0.70 | 4.50 | 0.30 |
| Indore | 187,346 | 166,551 | 61,637 | 0.00 | 0.00 | 0.00 | 0.00 | 0.10 | 99.80 | 0.00 | 68.10 | 0.00 | 15.10 | 15.40 | 0.50 | 0.90 |
| **Catchment: Chambal Upper 2** | | | | | | | | | | | | | | | | |
| Chittaurgarh | 27,646 | 10,810 | 17,030 | 0.10 | 0.00 | 5.80 | 0.00 | 2.00 | 89.80 | 2.30 | 39.00 | 2.00 | 3.40 | 0.00 | 18.90 | 36.30 |
| Mandsaur | 93,347 | 61,049 | 21,657 | 0.00 | 0.00 | 0.00 | 0.00 | 0.30 | 99.40 | 0.20 | 31.50 | 0.10 | 8.20 | 0.00 | 2.00 | 58.20 |
| **Catchment: Banas** | | | | | | | | | | | | | | | | |
| Sikar | 14 | 1 | 6 | 0.00 | 0.00 | 0.03 | 91.05 | 6.48 | 0.00 | 2.44 | 36.45 | 10.11 | 14.49 | 0.00 | 12.30 | 26.63 |
| Jaipur | 3,597 | 370 | 2,575 | 0.00 | 0.45 | 3.71 | 79.03 | 15.46 | 0.04 | 1.31 | 33.31 | 11.12 | 2.46 | 0.00 | 13.13 | 39.97 |
| Sawai Madhopur | 2,487 | 20 | 2,487 | 5.07 | 0.93 | 1.91 | 53.35 | 2.79 | 35.94 | 0.00 | 16.68 | 0.29 | 0.36 | 0.00 | 2.11 | 80.54 |
| Ajmer | 16,041 | 670 | 2,951 | 0.00 | 0.52 | 14.17 | 1.97 | 2.17 | 0.00 | 81.18 | 32.41 | 12.83 | 1.39 | 0.00 | 3.56 | 49.76 |
| Tonk | 11,213 | 66 | 9,094 | 0.17 | 1.41 | 42.11 | 15.49 | 20.97 | 1.66 | 18.19 | 15.28 | 1.25 | 0.77 | 0.00 | 3.63 | 79.05 |
| Bhilwara | 123,916 | 11,301 | 53,904 | 0.92 | 0.07 | 51.33 | 0.00 | 10.55 | 4.74 | 32.38 | 38.04 | 7.66 | 2.06 | 0.04 | 10.61 | 41.49 |
| Bundi | 88 | 21 | 88 | 15.41 | 0.01 | 7.07 | 0.36 | 6.16 | 70.89 | 0.09 | 37.94 | 0.28 | 0.53 | 0.04 | 0.13 | 59.77 |
| Udaipur | 46,830 | 1,686 | 21,307 | 0.00 | 0.00 | 11.85 | 0.00 | 60.73 | 24.65 | 2.77 | 63.41 | 8.81 | 4.06 | 0.00 | 5.75 | 17.73 |
| Chittaurgarh | 122,205 | 47,782 | 75,278 | 0.06 | 0.00 | 5.84 | 0.00 | 1.97 | 89.81 | 2.31 | 38.97 | 1.97 | 3.38 | 0.02 | 18.91 | 36.26 |
| Mandsaur | 10,289 | 6,729 | 2,387 | 0.00 | 0.00 | 0.00 | 0.00 | 0.35 | 99.44 | 0.21 | 31.48 | 0.14 | 8.18 | 0.03 | 1.99 | 58.18 |

[a] Area under major crops *Padd* paddy, *Jowa* Jowar, *Maiz* Maize, *Arha* Arhar, *Soyb* Soybean, *Cott* Cotton, *Whea* Wheat, *Barl* Barley; *Pota* Potato, *Gron* Groundnut, *Must* Mustard

**Table 13.10** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: Chambal Upper 3** | | | | | | | | | | | | | | | | |
| Sawai Madhopur | 688,173 | 5,505 | 688,173 | 5.07 | 0.93 | 1.91 | 53.35 | 2.79 | 35.94 | 0.00 | 16.68 | 0.29 | 0.36 | 0.00 | 2.11 | 80.54 |
| Morena | 185,102 | 814 | 168,813 | 46.60 | 0.00 | 0.09 | 0.00 | 35.92 | 17.39 | 0.00 | 29.01 | 0.67 | 2.20 | 0.17 | 0.07 | 67.32 |
| Tonk | 27,051 | 160 | 21,938 | 0.17 | 1.41 | 42.11 | 15.49 | 20.97 | 1.66 | 18.19 | 15.28 | 1.25 | 0.77 | 0.00 | 3.63 | 79.05 |
| Bhilwara | 32,686 | 2,981 | 14,219 | 0.92 | 0.07 | 51.33 | 0.01 | 10.55 | 4.74 | 32.38 | 38.04 | 7.66 | 2.06 | 0.04 | 10.61 | 41.49 |
| Shivpuri | 1,913 | 543 | 1,248 | 3.30 | 0.00 | 0.00 | 0.00 | 7.92 | 88.77 | 0.00 | 38.42 | 0.48 | 11.77 | 0.15 | 25.02 | 23.57 |
| Bundi | 216,220 | 52,325 | 216,220 | 15.41 | 0.01 | 7.07 | 0.36 | 6.16 | 70.89 | 0.09 | 37.94 | 0.28 | 0.53 | 0.04 | 0.13 | 59.77 |
| Kota | 656,579 | 328,290 | 535,112 | 5.29 | 0.00 | 0.16 | 0.00 | 0.15 | 94.39 | 0.00 | 31.64 | 0.15 | 0.57 | 0.09 | 0.16 | 67.38 |
| Chittaurgarh | 15,550 | 6,080 | 9,579 | 0.06 | 0.00 | 5.84 | 0.00 | 1.97 | 89.81 | 2.31 | 38.97 | 1.97 | 3.38 | 0.02 | 18.91 | 36.26 |
| Guna | 307,946 | 69,596 | 46,808 | 0.18 | 0.00 | 0.00 | 0.00 | 0.71 | 99.12 | 0.00 | 58.19 | 0.05 | 30.43 | 0.09 | 0.11 | 10.39 |
| Mandsaur | 96,744 | 63,270 | 22,445 | 0.00 | 0.00 | 0.00 | 0.00 | 0.35 | 99.44 | 0.21 | 31.48 | 0.14 | 8.18 | 0.03 | 1.99 | 58.18 |
| Jhalawar | 274,571 | 172,431 | 98,571 | 0.35 | 0.00 | 0.16 | 0.00 | 1.95 | 97.53 | 0.01 | 33.39 | 0.14 | 4.21 | 0.09 | 1.97 | 60.17 |
| Vidisha | 24,019 | 7,374 | 9,656 | 0.00 | 0.00 | 0.01 | 0.00 | 17.60 | 82.39 | 0.00 | 51.79 | 0.05 | 47.12 | 0.06 | 0.44 | 0.42 |
| Shajapur | 402,798 | 293,237 | 113,992 | 0.00 | 0.00 | 0.00 | 0.00 | 1.56 | 98.43 | 0.00 | 40.43 | 0.08 | 52.01 | 3.26 | 1.45 | 2.44 |
| Rajgarh | 426,801 | 275,287 | 99,445 | 0.00 | 0.00 | 0.00 | 0.00 | 2.01 | 97.98 | 0.01 | 44.57 | 0.12 | 52.33 | 0.79 | 1.22 | 0.88 |
| Bhopal | 28,471 | 17,396 | 15,090 | 0.00 | 0.00 | 0.00 | 0.00 | 1.94 | 98.05 | 0.01 | 73.96 | 0.00 | 24.76 | 0.09 | 0.52 | 0.21 |
| Ujjain | 30,392 | 25,316 | 8,327 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 99.91 | 0.04 | 51.16 | 0.03 | 35.95 | 1.72 | 0.38 | 10.63 |
| Sehore | 167,442 | 126,084 | 87,237 | 0.00 | 0.01 | 0.00 | 0.00 | 1.53 | 98.41 | 0.04 | 68.47 | 0.01 | 30.03 | 0.06 | 0.22 | 0.03 |
| Dewas | 108,343 | 88,625 | 37,378 | 0.00 | 0.00 | 0.00 | 0.00 | 0.80 | 88.65 | 10.55 | 57.33 | 0.03 | 37.12 | 4.16 | 0.46 | 0.03 |
| Agra | 43,497 | 405 | 41,105 | 34.76 | 6.75 | 4.54 | 0.41 | 44.54 | 0.00 | 9.00 | 50.71 | 3.83 | 1.08 | 11.65 | 0.00 | 32.50 |
| Etawah | 24,455 | 9,953 | 19,687 | 81.52 | 0.15 | 10.64 | 0.53 | 7.15 | 0.00 | 0.00 | 75.68 | 3.02 | 0.93 | 5.15 | 0.11 | 14.08 |

**Table 13.11** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: Sind** | | | | | | | | | | | | | | | | |
| Etawah | 12,551 | 5,108 | 10,104 | 81.50 | 0.20 | 10.60 | 0.50 | 7.10 | 0.00 | 0.00 | 75.70 | 3.00 | 0.90 | 5.10 | 0.10 | 14.10 |
| Morena | 108,548 | 478 | 98,996 | 46.60 | 0.00 | 0.10 | 0.00 | 35.90 | 17.40 | 0.00 | 29.00 | 0.70 | 2.20 | 0.20 | 0.10 | 67.30 |
| Bhind | 307,811 | 9,696 | 220,085 | 39.90 | 0.10 | 0.00 | 0.00 | 58.20 | 1.80 | 0.00 | 33.40 | 1.80 | 0.90 | 0.30 | 0.00 | 63.50 |
| Jalaun | 47,775 | 2,771 | 18,871 | 4.60 | 0.00 | 0.00 | 0.00 | 90.60 | 4.80 | 0.00 | 84.20 | 3.90 | 3.20 | 0.20 | 0.10 | 6.90 |
| Gwalior | 153,562 | 153,562 | 91,523 | 88.30 | 0.00 | 0.00 | 0.00 | 11.70 | 0.00 | 0.00 | 89.20 | 0.50 | 6.10 | 1.00 | 0.00 | 0.00 |
| Datia | 180,424 | 32,296 | 114,028 | 3.20 | 0.00 | 0.00 | 0.00 | 94.50 | 2.30 | 0.00 | 64.10 | 2.00 | 11.60 | 0.20 | 8.10 | 10.10 |
| Jhansi | 74,498 | 8,865 | 371,75 | 2.00 | 0.00 | 0.00 | 0.00 | 94.30 | 3.70 | 0.00 | 69.00 | 1.60 | 9.50 | 0.20 | 15.50 | 4.10 |
| Shivpuri | 321,525 | 91,313 | 209,634 | 3.30 | 0.00 | 0.00 | 0.00 | 7.90 | 88.80 | 0.00 | 38.40 | 0.50 | 11.80 | 0.20 | 25.00 | 23.60 |
| Guna | 141,106 | 31,890 | 21,448 | 0.20 | 0.00 | 0.00 | 0.00 | 0.70 | 99.10 | 0.00 | 58.20 | 0.00 | 30.40 | 0.10 | 0.10 | 10.40 |
| Vidisha | 39,290 | 12,062 | 15,795 | 0.00 | 0.00 | 0.00 | 0.00 | 17.60 | 82.40 | 0.00 | 51.80 | 0.00 | 47.10 | 0.10 | 0.40 | 0.40 |
| **Catchment: Ken** | | | | | | | | | | | | | | | | |
| Fatehpur | 744 | 231 | 440 | 97.10 | 0.00 | 0.10 | 0.00 | 2.80 | 0.00 | 0.00 | 82.90 | 0.10 | 0.10 | 3.40 | 0.20 | 7.80 |
| Hamirpur | 404,992 | 239,755 | 80,593 | 0.20 | 0.00 | 0.00 | 0.00 | 99.10 | 0.70 | 0.00 | 64.30 | 0.60 | 13.90 | 0.20 | 7.70 | 9.30 |
| Banda | 43,013 | 7,699 | 7,355 | 99.70 | 0.00 | 0.00 | 0.00 | 0.10 | 0.20 | 0.00 | 92.80 | 0.10 | 1.40 | 0.20 | 1.30 | 3.00 |
| Chhatapur | 2,764 | 406 | 1,440 | 0.00 | 0.00 | 0.00 | 0.00 | 58.50 | 41.50 | 0.00 | 58.40 | 4.40 | 26.10 | 0.60 | 3.50 | 6.80 |
| Satna | 12,230 | 673 | 4,623 | 7.80 | 0.00 | 0.00 | 0.00 | 8.20 | 84.10 | 0.00 | 65.60 | 1.50 | 29.40 | 1.30 | 0.00 | 2.00 |
| Panna | 233,270 | 7,931 | 76,513 | 33.40 | 0.00 | 0.00 | 0.00 | 57.80 | 8.80 | 0.00 | 48.20 | 1.20 | 45.50 | 0.80 | 0.20 | 3.80 |
| Sagar | 285,030 | 120,283 | 112,017 | 0.00 | 0.00 | 0.00 | 0.00 | 11.70 | 88.30 | 0.00 | 52.50 | 0.20 | 44.80 | 0.90 | 0.80 | 0.40 |
| Damoh | 412,228 | 68,018 | 147,165 | 5.80 | 0.00 | 0.00 | 0.00 | 4.30 | 90.00 | 0.00 | 42.70 | 0.00 | 55.60 | 0.60 | 0.50 | 0.60 |
| Jabalpur | 25,359 | 837 | 9,459 | 10.40 | 0.10 | 0.10 | 0.00 | 81.00 | 8.40 | 0.00 | 60.90 | 0.00 | 34.00 | 0.30 | 0.10 | 3.80 |
| Raisen | 16,673 | 3,168 | 7,386 | 1.60 | 0.00 | 0.00 | 0.00 | 2.90 | 95.50 | 0.00 | 61.60 | 0.00 | 37.20 | 0.10 | 0.10 | 0.10 |
| Narsimhapur | 8,981 | 2,173 | 4,787 | 0.10 | 0.00 | 0.00 | 0.00 | 16.50 | 83.40 | 0.00 | 33.80 | 0.00 | 49.60 | 0.40 | 0.00 | 0.20 |

**Table 13.12** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: Betwa Upper** | | | | | | | | | | | | | | | | |
| Jhansi | 893 | 106 | 446 | 2.00 | 0.00 | 0.00 | 0.00 | 94.30 | 3.70 | 0.00 | 69.00 | 1.60 | 9.50 | 0.20 | 15.50 | 4.10 |
| Shivpuri | 641,67 | 18,223 | 41,837 | 3.30 | 0.00 | 0.00 | 0.00 | 7.90 | 88.80 | 0.00 | 38.40 | 0.50 | 11.80 | 0.20 | 25.00 | 23.60 |
| Tikamgarh | 18 | 4 | 11 | 0.00 | 0.00 | 0.00 | 0.00 | 40.40 | 59.50 | 0.00 | 58.00 | 6.30 | 15.10 | 0.90 | 10.80 | 8.60 |
| Lalitpur | 508,587 | 127,147 | 254,294 | 0.00 | 0.00 | 0.00 | 0.00 | 90.60 | 9.40 | 0.00 | 65.30 | 4.20 | 22.40 | 0.30 | 5.40 | 2.30 |
| Guna | 242,493 | 54,803 | 36,859 | 0.20 | 0.00 | 0.00 | 0.00 | 0.70 | 99.10 | 0.00 | 58.20 | 0.00 | 30.40 | 0.10 | 0.10 | 10.40 |
| Sagar | 195,916 | 82,677 | 76,995 | 0.00 | 0.00 | 0.00 | 0.00 | 11.70 | 88.30 | 0.00 | 52.50 | 0.20 | 44.80 | 0.90 | 0.80 | 0.40 |
| Vidisha | 113,474 | 34,837 | 45,617 | 0.00 | 0.00 | 0.00 | 0.00 | 17.60 | 82.40 | 0.00 | 51.80 | 0.00 | 47.10 | 0.10 | 0.40 | 0.40 |
| Bhopal | 30,731 | 18,777 | 16,287 | 0.00 | 0.00 | 0.00 | 0.00 | 1.90 | 98.00 | 0.00 | 74.00 | 0.00 | 24.80 | 0.10 | 0.50 | 0.20 |
| Raisen | 161,344 | 30,655 | 71,475 | 1.60 | 0.00 | 0.00 | 0.00 | 2.90 | 95.50 | 0.00 | 61.60 | 0.00 | 37.20 | 0.10 | 0.10 | 0.10 |
| Sehore | 4,299 | 3,237 | 2,240 | 0.00 | 0.00 | 0.00 | 0.00 | 1.50 | 98.40 | 0.00 | 68.50 | 0.00 | 30.00 | 0.10 | 0.20 | 0.00 |
| **Catchment: Betwa Lower** | | | | | | | | | | | | | | | | |
| Kanpur Dehat | 40,957 | 9,297 | 26,049 | 77.20 | 0.10 | 8.20 | 1.20 | 13.00 | 0.20 | 0.00 | 75.10 | 2.30 | 1.50 | 2.00 | 0.00 | 16.50 |
| Jalaun | 62,683 | 3,636 | 24,760 | 4.60 | 0.00 | 0.00 | 0.00 | 90.60 | 4.80 | 0.00 | 84.20 | 3.90 | 3.20 | 0.20 | 0.10 | 6.90 |
| Fatehpur | 96,153 | 29,807 | 56,923 | 97.10 | 0.00 | 0.10 | 0.00 | 2.80 | 0.00 | 0.00 | 82.90 | 0.10 | 0.10 | 3.40 | 0.20 | 7.80 |
| Hamirpur | 225,502 | 133,497 | 44,875 | 0.20 | 0.00 | 0.00 | 0.00 | 99.10 | 0.70 | 0.00 | 64.30 | 0.60 | 13.90 | 0.20 | 7.70 | 9.30 |
| Jhansi | 204,732 | 24,363 | 102,161 | 2.00 | 0.00 | 0.00 | 0.00 | 94.30 | 3.70 | 0.00 | 69.00 | 1.60 | 9.50 | 0.20 | 15.50 | 4.10 |
| Tikamgarh | 180,308 | 367,83 | 115,037 | 0.00 | 0.00 | 0.00 | 0.00 | 40.40 | 59.50 | 0.00 | 58.00 | 6.30 | 15.10 | 0.90 | 10.80 | 8.60 |
| Chhatapur | 481,599 | 70,795 | 250,913 | 0.00 | 0.00 | 0.00 | 0.00 | 58.50 | 41.50 | 0.00 | 58.40 | 4.40 | 26.10 | 0.60 | 3.50 | 6.80 |
| Lalitpur | 142,820 | 35,705 | 71,410 | 0.00 | 0.00 | 0.00 | 0.00 | 90.60 | 9.40 | 0.00 | 65.30 | 4.20 | 22.40 | 0.30 | 5.40 | 2.30 |
| Sagar | 190,453 | 80,371 | 74,848 | 0.00 | 0.00 | 0.00 | 0.00 | 11.70 | 88.30 | 0.00 | 52.50 | 0.20 | 44.80 | 0.90 | 0.80 | 0.40 |
| Raisen | 8,894 | 1,690 | 3,940 | 1.60 | 0.00 | 0.00 | 0.00 | 2.90 | 95.50 | 0.00 | 61.60 | 0.00 | 37.20 | 0.10 | 0.10 | 0.10 |

**Table 13.13** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: 73** | | | | | | | | | | | | | | | | |
| Muzaffarnagar | 3,444 | 510 | 3,444 | 85.30 | 0.00 | 1.70 | 0.10 | 12.70 | 0.00 | 0.20 | 38.00 | 0.40 | 0.10 | 0.70 | 0.00 | 1.00 |
| Meerut | 41,081 | 5,587 | 41,081 | 77.40 | 0.10 | 12.10 | 0.30 | 10.00 | 0.00 | 0.20 | 39.70 | 0.10 | 0.10 | 2.80 | 0.00 | 1.70 |
| Ghaziabad | 51,786 | 12,480 | 41,481 | 54.30 | 0.50 | 24.70 | 17.60 | 2.90 | 0.00 | 0.00 | 65.40 | 2.70 | 0.00 | 2.50 | 0.00 | 1.50 |
| Bulandshahr | 113,074 | 59,477 | 100,410 | 34.10 | 0.30 | 55.00 | 6.70 | 3.70 | 0.00 | 0.30 | 71.50 | 4.60 | 0.20 | 2.80 | 0.00 | 3.30 |
| Faridabad | 32,838 | 8,801 | 23,873 | 61.50 | 16.70 | 0.10 | 13.40 | 7.80 | 0.00 | 0.50 | 89.80 | 1.00 | 0.00 | 0.20 | 0.00 | 4.50 |
| Aligarh | | | | 38.60 | 0.00 | 44.20 | 5.10 | 10.70 | 0.00 | 1.40 | 76.00 | 8.50 | 0.40 | 3.10 | 0.00 | 8.90 |
| Etah | 1,518 | 427 | 1,169 | 31.80 | 0.00 | 41.70 | 7.60 | 18.80 | 0.00 | 0.10 | 78.20 | 6.50 | 1.90 | 3.90 | 0.20 | 6.30 |
| Mathura | 204,706 | 31,934 | 204,706 | 91.50 | 1.00 | 1.30 | 0.90 | 1.90 | 0.00 | 3.50 | 71.60 | 5.00 | 0.10 | 2.90 | 0.00 | 16.80 |
| Firozabad | 33,398 | 4,743 | 31,795 | 63.90 | 0.10 | 19.00 | 0.80 | 16.20 | 0.00 | 0.00 | 63.40 | 8.90 | 1.10 | 17.20 | 0.00 | 9.20 |
| Agra | 79,426 | 739 | 75,058 | 34.80 | 6.70 | 4.50 | 0.40 | 44.50 | 0.00 | 9.00 | 50.70 | 3.80 | 1.10 | 11.60 | 0.00 | 32.50 |
| **Catchment: 46** | | | | | | | | | | | | | | | | |
| Kinnaur | 47 | 10 | 10 | 0.00 | 0.00 | 15.30 | 0.00 | 84.70 | 0.00 | 0.00 | 8.10 | 76.00 | 0.00 | 15.90 | 0.00 | 0.00 |
| Shimla | 51,568 | 1,753 | 5,286 | 65.70 | 0.00 | 30.30 | 0.00 | 3.90 | 0.00 | 0.00 | 16.10 | 3.90 | 0.00 | 80.00 | 0.00 | 0.00 |
| Uttarkashi | 9,948 | 1,622 | 2,139 | 95.10 | 0.00 | 0.00 | 0.00 | 3.00 | 1.90 | 0.00 | 52.60 | 1.20 | 0.00 | 31.50 | 0.00 | 14.60 |
| Dehradun | 30,337 | 6,401 | 10,921 | 99.00 | 0.00 | 0.40 | 0.00 | 0.60 | 0.10 | 0.00 | 64.30 | 0.20 | 0.00 | 3.70 | 1.30 | 6.80 |
| Sirmaur | 44,399 | 12,299 | 12,920 | 38.40 | 0.00 | 51.90 | 0.00 | 9.70 | 0.00 | 0.00 | 75.30 | 4.70 | 0.40 | 12.00 | 0.00 | 0.00 |
| Tehri Garhwal | 4,281 | 608 | 702 | 92.40 | 0.00 | 0.00 | 0.00 | 0.50 | 7.10 | 0.00 | 72.00 | 0.70 | 0.00 | 13.90 | 0.00 | 13.40 |
| Yamunanagar | 69,649 | 33,780 | 62,336 | 96.80 | 0.00 | 2.00 | 0.00 | 1.20 | 0.00 | 0.00 | 61.90 | 0.00 | 0.00 | 1.10 | 0.10 | 1.90 |
| Saharanpur | 124,812 | 34,823 | 108,961 | 93.00 | 0.00 | 0.30 | 0.00 | 6.60 | 0.00 | 0.10 | 46.90 | 0.00 | 0.00 | 0.30 | 1.70 | 0.70 |
| Hardwar | 172 | 25 | 156 | 96.40 | 0.00 | 0.60 | 0.00 | 2.90 | 0.00 | 0.10 | 35.20 | 0.00 | 0.00 | 0.40 | 1.20 | 0.70 |
| Kurukshetra | 17,152 | 12,864 | 14,734 | 98.80 | 0.00 | 0.20 | 0.10 | 1.00 | 0.00 | 0.00 | 85.00 | 0.00 | 0.10 | 3.80 | 0.00 | 0.50 |
| Karnal | 100,152 | 90,537 | 98,550 | 98.80 | 0.00 | 0.20 | 0.70 | 0.30 | 0.00 | 0.00 | 92.60 | 0.10 | 0.10 | 0.50 | 0.00 | 0.40 |
| Jind | 4,312 | 2,949 | 3,820 | 56.50 | 0.10 | 0.00 | 14.20 | 0.00 | 0.00 | 29.20 | 92.30 | 0.30 | 0.10 | 0.00 | 0.00 | 5.70 |

**Table 13.14** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: 46 (Continued...)** | | | | | | | | | | | | | | | | |
| Muzaffarnagar | 50,833 | 7,523 | 50,833 | 85.30 | 0.00 | 1.70 | 0.10 | 12.70 | 0.00 | 0.20 | 38.00 | 0.40 | 0.10 | 0.70 | 0.00 | 1.00 |
| Panipat | 81,037 | 62,885 | 79,416 | 98.90 | 0.00 | 0.10 | 0.90 | 0.10 | 0.00 | 0.10 | 91.80 | 0.00 | 0.10 | 0.20 | 0.00 | 0.80 |
| Meerut | 37,100 | 5,046 | 37,100 | 77.40 | 0.10 | 12.10 | 0.30 | 10.00 | 0.00 | 0.20 | 39.70 | 0.10 | 0.10 | 2.80 | 0.00 | 1.70 |
| Rohtak | 362,119 | 166,937 | 327,356 | 27.60 | 30.50 | 0.10 | 8.10 | 13.60 | 0.00 | 20.00 | 68.80 | 0.60 | 0.30 | 0.00 | 0.00 | 21.10 |
| Sonipat | 100,451 | 50,125 | 92,515 | 76.00 | 15.10 | 0.50 | 5.80 | 0.40 | 0.00 | 2.20 | 88.10 | 0.40 | 0.00 | 0.20 | 0.00 | 3.40 |
| Bhiwani | 111,159 | 31,569 | 89,038 | 11.00 | 2.10 | 0.10 | 21.60 | 1.00 | 0.00 | 64.30 | 37.00 | 1.50 | 3.90 | 0.00 | 0.00 | 57.10 |
| Ghaziabad | 10,928 | 2,634 | 8,753 | 54.30 | 0.50 | 24.70 | 17.60 | 2.90 | 0.00 | 0.00 | 65.40 | 2.70 | 0.00 | 2.50 | 0.00 | 1.50 |
| Delhi | 31,352 | 10,346 | 16,836 | 66.80 | 32.50 | 0.30 | 0.30 | 0.10 | 0.00 | 0.00 | 99.70 | 0.20 | 0.10 | 0.00 | 0.00 | 0.00 |
| Bulandshahr | 2,361 | 1,242 | 2,097 | 34.10 | 0.30 | 55.00 | 6.70 | 3.70 | 0.00 | 0.30 | 71.50 | 4.60 | 0.20 | 2.80 | 0.00 | 3.30 |
| Gurgaon | 75,735 | 6,968 | 45,517 | 12.60 | 5.30 | 0.00 | 80.60 | 0.40 | 0.00 | 1.10 | 42.10 | 1.60 | 0.00 | 0.00 | 0.30 | 56.00 |
| Jhunjhunun | 42,361 | 3,516 | 24,019 | 0.00 | 0.00 | 0.00 | 91.50 | 4.60 | 0.00 | 3.90 | 28.80 | 3.50 | 19.90 | 0.00 | 0.70 | 47.10 |
| Faridabad | 10,208 | 2,736 | 7,421 | 61.50 | 16.70 | 0.10 | 13.40 | 7.80 | 0.00 | 0.50 | 89.80 | 1.00 | 0.00 | 0.20 | 0.00 | 4.50 |
| Mahendragarh | 147,890 | 28,691 | 137,833 | 0.00 | 0.10 | 0.00 | 53.40 | 0.30 | 0.00 | 46.30 | 27.00 | 0.40 | 2.50 | 0.00 | 0.30 | 69.80 |
| Rewari | 109,986 | 30,136 | 101,627 | 1.80 | 3.70 | 0.00 | 71.30 | 0.00 | 0.00 | 23.10 | 36.10 | 0.70 | 0.10 | 0.00 | 0.30 | 62.90 |
| Alwar | 202,952 | 27,804 | 188,542 | 0.20 | 0.60 | 3.80 | 52.90 | 0.10 | 0.00 | 42.30 | 33.70 | 2.80 | 1.60 | 0.00 | 0.20 | 61.70 |
| Sikar | 64,141 | 5,644 | 29,120 | 0.00 | 0.00 | 0.00 | 91.10 | 6.50 | 0.00 | 2.40 | 36.40 | 10.10 | 14.50 | 0.00 | 12.30 | 26.60 |
| Jaipur | 636,48 | 6,556 | 45,572 | 0.00 | 0.40 | 3.70 | 79.00 | 15.50 | 0.00 | 1.30 | 33.30 | 11.10 | 2.50 | 0.00 | 13.10 | 40.00 |

**Table 13.15** Sub-catchment wise crops sown

| District | NSA (ha) | Krf (ha) | Rabi (ha) | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: Kali-Hindon** | | | | | | | | | | | | | | | | |
| Saharanpur | 46,696 | 13,028 | 40,766 | 93.00 | 0.00 | 0.30 | 0.00 | 6.60 | 0.00 | 0.10 | 46.90 | 0.00 | 0.00 | 0.30 | 1.70 | 0.70 |
| Hardwar | 15,869 | 2,269 | 14,425 | 96.40 | 0.00 | 0.60 | 0.00 | 2.90 | 0.00 | 0.10 | 35.20 | 0.00 | 0.00 | 0.40 | 1.20 | 0.70 |
| Muzaffarnagar | 61,823 | 9,150 | 61,823 | 85.30 | 0.00 | 1.70 | 0.10 | 12.70 | 0.00 | 0.20 | 38.00 | 0.40 | 0.10 | 0.70 | 0.00 | 1.00 |
| Meerut | 2,671 | 363 | 2,671 | 77.40 | 0.10 | 12.10 | 0.30 | 10.00 | 0.00 | 0.20 | 39.70 | 0.10 | 0.10 | 2.80 | 0.00 | 1.70 |
| **Catchment: Hindon Lower** | | | | | | | | | | | | | | | | |
| Saharanpur | 18,574 | 5,182 | 16,215 | 93.00 | 0.00 | 0.30 | 0.00 | 6.60 | 0.00 | 0.10 | 46.90 | 0.00 | 0.00 | 0.30 | 1.70 | 0.70 |
| Muzaffarnagar | 57,634 | 8,530 | 57,634 | 85.30 | 0.00 | 1.70 | 0.10 | 12.70 | 0.00 | 0.20 | 38.00 | 0.40 | 0.10 | 0.70 | 0.00 | 1.00 |
| Meerut | 77,738 | 10,572 | 35,837 | 77.40 | 0.10 | 12.10 | 0.30 | 10.00 | 0.00 | 0.20 | 39.70 | 0.10 | 0.10 | 2.80 | 0.00 | 1.70 |
| Ghaziabad | 57,736 | 13,914 | 46,247 | 54.30 | 0.50 | 24.70 | 17.60 | 2.90 | 0.00 | 0.00 | 65.40 | 2.70 | 0.00 | 2.50 | 0.00 | 1.50 |
| Delhi | 525 | 173 | 282 | 66.80 | 32.50 | 0.30 | 0.30 | 0.10 | 0.00 | 0.00 | 99.70 | 0.20 | 0.10 | 0.00 | 0.00 | 0.00 |
| Bulandshahr | 52,35 | 2,754 | 4,649 | 34.10 | 0.30 | 55.00 | 6.70 | 3.70 | 0.00 | 0.30 | 71.50 | 4.60 | 0.20 | 2.80 | 0.00 | 3.30 |
| Faridabad | 70 | 19 | 51 | 61.50 | 16.70 | 0.10 | 13.40 | 7.80 | 0.00 | 0.50 | 89.80 | 1.00 | 0.00 | 0.20 | 0.00 | 4.50 |
| **Catchment: 29** | | | | | | | | | | | | | | | | |
| Aligarh | 47,547 | 13,931 | 43,933 | 38.60 | 0.00 | 44.20 | 5.10 | 10.70 | 0.00 | 1.40 | 76.00 | 8.50 | 0.40 | 3.10 | 0.00 | 8.90 |
| Etah | 49,776 | 13,987 | 38,328 | 31.80 | 0.00 | 41.70 | 7.60 | 18.80 | 0.00 | 0.10 | 78.20 | 6.50 | 1.90 | 3.90 | 0.20 | 6.30 |
| Mathura | 154 | 24 | 154 | 91.50 | 1.00 | 1.30 | 0.90 | 1.90 | 0.00 | 3.50 | 71.60 | 5.00 | 0.10 | 2.90 | 0.00 | 16.80 |
| Firozabad | 93,055 | 13,214 | 88,588 | 63.90 | 0.10 | 19.00 | 0.80 | 16.20 | 0.00 | 0.00 | 63.40 | 8.90 | 1.10 | 17.20 | 0.00 | 9.20 |
| Mainpuri | 92,365 | 47,568 | 75,832 | 63.20 | 0.30 | 24.20 | 2.10 | 10.10 | 0.00 | 0.00 | 83.40 | 2.50 | 0.80 | 7.90 | 0.10 | 5.00 |
| Agra | 7,213 | 67 | 6,816 | 34.80 | 6.70 | 4.50 | 0.40 | 44.50 | 0.00 | 9.00 | 50.70 | 3.80 | 1.10 | 11.60 | 0.00 | 32.50 |
| Etawah | 290,743 | 118,332 | 234,048 | 81.50 | 0.20 | 10.60 | 0.50 | 7.10 | 0.00 | 0.00 | 75.70 | 3.00 | 0.90 | 5.10 | 0.10 | 14.10 |
| Kanpur Dehat | 83,836 | 19,031 | 53,320 | 77.20 | 0.10 | 8.20 | 1.20 | 13.00 | 0.20 | 0.00 | 75.10 | 2.30 | 1.50 | 2.00 | 0.00 | 16.50 |
| Jalaun | 256,284 | 14,864 | 101,232 | 4.60 | 0.00 | 0.00 | 0.00 | 90.60 | 4.80 | 0.00 | 84.20 | 3.90 | 3.20 | 0.20 | 0.10 | 6.90 |
| Fatehpur | 19 | 6 | 11 | 97.10 | 0.00 | 0.10 | 0.00 | 2.80 | 0.00 | 0.00 | 82.90 | 0.10 | 0.10 | 3.40 | 0.20 | 7.80 |
| Hamirpur | 13,227 | 7,830 | 2,632 | 0.20 | 0.00 | 0.00 | 0.00 | 99.10 | 0.70 | 0.00 | 64.30 | 0.60 | 13.90 | 0.20 | 7.70 | 9.30 |
| Jhansi | 14,321 | 1,704 | 7,146 | 2.00 | 0.00 | 0.00 | 0.00 | 94.30 | 3.70 | 0.00 | 69.00 | 1.60 | 9.50 | 0.20 | 15.50 | 4.10 |

**Table 13.16** Sub-catchment wise crops sown

| | | | | Kharif crops | | | | | | | Rabi crops | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| District | NSA (ha) | Krf (ha) | Rabi (ha) | Padd | Jowa | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must |
| **Catchment: 25** | | | | | | | | | | | | | | | | |
| Fatehpur | 184,573 | 57,218 | 109,267 | 97.10 | 0.00 | 0.10 | 0.00 | 2.80 | 0.00 | 0.00 | 82.90 | 0.10 | 0.10 | 3.40 | 0.20 | 7.80 |
| Banda | 474,949 | 85,016 | 81,216 | 99.70 | 0.00 | 0.00 | 0.00 | 0.10 | 0.20 | 0.00 | 92.80 | 0.10 | 1.40 | 0.20 | 1.30 | 3.00 |
| Chhatapur | 254 | 37 | 132 | 0.00 | 0.00 | 0.00 | 0.00 | 58.50 | 41.50 | 0.00 | 58.40 | 4.40 | 26.10 | 0.60 | 3.50 | 6.80 |
| Satna | 43,334 | 2,383 | 16,380 | 7.80 | 0.00 | 0.00 | 0.00 | 8.20 | 84.10 | 0.00 | 65.60 | 1.50 | 29.40 | 1.30 | 0.00 | 2.00 |
| Panna | 31,590 | 1,074 | 10,362 | 33.40 | 0.00 | 0.00 | 0.00 | 57.80 | 8.80 | 0.00 | 48.20 | 1.20 | 45.50 | 0.80 | 0.20 | 3.80 |
| **Catchment: 30** | | | | | | | | | | | | | | | | |
| Mainpuri | 20,191 | 10,398 | 16,577 | 63.20 | 0.30 | 24.20 | 2.10 | 10.10 | 0.00 | 0.00 | 83.40 | 2.50 | 0.80 | 7.90 | 0.10 | 5.00 |
| Etawah | 101,061 | 41,132 | 81,354 | 81.50 | 0.20 | 10.60 | 0.50 | 7.10 | 0.00 | 0.00 | 75.70 | 3.00 | 0.90 | 5.10 | 0.10 | 14.10 |
| Kanpur Dehat | 82,913 | 18,821 | 52,733 | 77.20 | 0.10 | 8.20 | 1.20 | 13.00 | 0.20 | 0.00 | 75.10 | 2.30 | 1.50 | 2.00 | 0.00 | 16.50 |
| Fatehpur | 72,225 | 22,390 | 42,757 | 97.10 | 0.00 | 0.10 | 0.00 | 2.80 | 0.00 | 0.00 | 82.90 | 0.10 | 0.10 | 3.40 | 0.20 | 7.80 |
| Hamirpur | 2,517 | 1,490 | 501 | 0.20 | 0.00 | 0.00 | 0.00 | 99.10 | 0.70 | 0.00 | 64.30 | 0.60 | 13.90 | 0.20 | 7.70 | 9.30 |
| Banda | 3,548 | 635 | 607 | 99.70 | 0.00 | 0.00 | 0.00 | 0.10 | 0.20 | 0.00 | 92.80 | 0.10 | 1.40 | 0.20 | 1.30 | 3.00 |
| **Catchment: 41** | | | | | | | | | | | | | | | | |
| Firozabad | 34,524 | 4,902 | 32,867 | 63.90 | 0.10 | 19.00 | 0.80 | 16.20 | 0.00 | 0.00 | 63.40 | 8.90 | 1.10 | 17.20 | 0.00 | 9.20 |
| Agra | 24,054 | 224 | 10,824 | 34.80 | 6.70 | 4.50 | 0.40 | 44.50 | 0.00 | 9.00 | 50.70 | 3.80 | 1.10 | 11.60 | 0.00 | 32.50 |
| Etawah | 80,527 | 32,774 | 64,824 | 81.50 | 0.20 | 10.60 | 0.50 | 7.10 | 0.00 | 0.00 | 75.70 | 3.00 | 0.90 | 5.10 | 0.10 | 14.10 |
| Bhind | 350 | 11 | 250 | 39.90 | 0.10 | 0.00 | 0.00 | 58.20 | 1.80 | 0.00 | 33.40 | 1.80 | 0.90 | 0.30 | 0.00 | 63.50 |

of probable crop production and estimated cultivation cost. The probable crop production is estimated based on the climatic support to crops. Catchment-wise estimated average yield, and minimum support price by GoI are summarized in Table 13.17. However, while estimating the actual production, district-wise crop yield is used. Considering water requirement, minimum support price, and average yield (Table 13.17), it is found that during the *kharif* season cultivation of jowar, soybean, bajra and arhar are more economic than the cultivation of other crops; whereas during the rabi season, mustard, wheat, potato lead to good economic returns with less water requirement and high yield. Barley and gram are of equally good economic value and can be taken as *rabi* crop.

## 13.3 Identification of Suitable Crop Rotation

Rotational cropping is one of the major and widely used agricultural practices in India. A well-planned rotation not only reduces diseases, pests and weeds but also offers other advantages, such as increasing the soil fertility and utilization of cropping land. Based on the physical environment, soil, historical crop rotation, and minimum support price, twelve combinations of crop rotations are identified: (i) cotton-wheat, (ii) paddy-potato, (iii) paddy-barley, (iv) paddy-barley-maize, (v) paddy-barley-bajra, (vi) paddy-wheat, (vii) groundnut-jowar, (viii) groundnut-barley, (ix) soybean-wheat-maize, (x) arhar-wheat, (xi) paddy-gram, and (xii) paddy-mustard. From the estimated reference evapotranspiration and crop coefficients, theoretical crop water demands are estimated for each district in the sub-catchments. The total crop water demand and gross income for each combination and each sub-catchment are summarized in Tables 13.18 and 13.19, respectively. From Table 13.18 it is observed that the rotational combination of crops “soybean-wheat-maize”, “paddy-wheat”, and “arhar-wheat” are the major crop rotations used for income. Based on gross returns (Table 13.19), different crop rotations for catchments are marked in “bold.”

From Tables 13.9, 13.10, 13.11, 13.12, 13.13, 13.14, 13.15, 13.16, 13.18, and 13.19, it can be remarked that the arhar-wheat rotation can be practiced in all the districts in the Yamuna basin, as it can be grown in the prevailing climatic conditions and the water consumption for this combination is less as compared to others.

In the Chambal basin, most frequently practiced crop rotations are cotton-wheat, soybean-wheat, arhar-wheat, and groundnut-barley. In the Sind and Ken catchments, paddy is the most dominating crop among all the cereals; that is why all the rotations followed by paddy are practiced throughout. Sorghum and millets must take over a good proportion of the kharif land as water requirements (Tables 13.7 and 13.18) for these crops are less than for paddy (for example, paddy-wheat practice can be shifted to sorghum-wheat and paddy-gram can be shifted to bajra-gram to save water).

In the Betwa catchment, the cultivated area under paddy is almost negligible (Table 13.12), except for Kanpur Dehat and Fatehpur that fall within the Ganga-Yamuna *Duab*. Most of the seasonal practice for *kharif-rabi* combination can be possible with only *kharif* crops like Arhar or soyabean. *Kharif*

**Table 13.17** Catchment wise estimated average crop yields and minimum support prices

| | Kharif season | | | | | | | Rabi season | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Catchment/Crops | Padd | Jow | Maiz | Bajr | Arha | Soyb | Cott | Whea | Barl | Gram | Pota | Grou | Must | Suga |
| MSP: 2008–2009 (Rs/qt) | 850 | 840 | 840 | 840 | 2,000 | 1,350 | 2,500 | 1,080 | **680** | **1,730** | **500** | 2,100 | **1,830** | 89 |
| MSP: 2009–1010 (Rs/qt) | 950 | **840** | 840 | **840** | **2,300** | **1,350** | 2,500 | **1,080** | | | | | | 139 |
| $ET_c$ (mm): Average | 784 | **487** | 584 | **414** | **391** | **627** | 891 | **427** | **296** | **213** | **291** | 526 | **347** | 1,708 |
| $ET_c$ (mm): Range (lo) | 530 | 337 | 422 | 301 | 273 | 445 | 544 | 207 | 140 | 102 | 140 | 370 | 166 | 1,647 |
| $ET_c$ (mm): Range (up) | 834 | 522 | 631 | 447 | 417 | 668 | 940 | 527 | 375 | 295 | 364 | 559 | 432 | 1,822 |
| ***Sub-catchment wise average yield (qt/ha)*** | | | | | | | | | | | | | | |
| Chambal up 1 | 5.7 | 1.0 | 3.3 | 7.8 | – | 20.7 | 11.2 | 24.1 | 18.2 | 6.1 | 1,333.2 | 11.3 | 157.7 | 201.9 |
| Chambal up 2 | 11.5 | 0.0 | 4.1 | 6.8 | – | 22.4 | 9.6 | 27.0 | 22.3 | 5.4 | 3,987.5 | 10.6 | 150.0 | 250.0 |
| Chambal up 3 | 9.5 | 3.5 | 9.1 | 9.0 | 7.9 | 18.5 | 11.5 | 22.2 | 16.9 | 6.1 | 2,277.4 | 11.1 | 138.3 | 306.3 |
| Banas | 1.3 | 0.0 | 7.5 | 7.2 | 7.2 | 18.4 | 9.6 | 25.0 | 22.5 | 13.4 | – | 10.6 | – | – |
| Sind | 8.4 | 14.8 | 9.3 | 11.7 | 9.9 | 18.2 | 9.2 | 24.2 | 20.9 | 9.5 | 21,053.9 | 11.4 | 148.6 | 268.8 |
| Ken | – | 9.2 | 3.9 | 9.4 | 5.8 | – | 9.2 | 17.2 | 13.2 | 9.3 | 1,997.3 | 10.1 | 140.2 | 316.8 |
| Betwa Upper | – | 6.7 | 2.2 | 10.2 | 7.3 | – | 11.0 | 18.5 | 17.7 | 7.3 | 17,737.1 | 10.8 | 155.3 | 296.7 |
| Betwa Lower | 0.8 | 10.3 | 2.5 | 11.5 | 7.6 | 11.3 | 8.1 | 21.9 | 17.4 | 10.8 | 42,305.0 | 10.5 | 167.4 | 163.6 |
| Catch 73 | 12.8 | 22.0 | 7.1 | 11.9 | 11.5 | 14.1 | 5.2 | 34.6 | 27.4 | 9.6 | 68,077.6 | 4.0 | 205.8 | 35.0 |
| Catch-46 | 15.5 | 21.5 | 3.1 | 7.6 | 12.4 | 11.8 | 4.6 | 32.7 | 21.7 | 11.0 | 13,145.4 | 0.9 | 162.7 | 45.0 |
| Kali-Hindon | 14.3 | 23.0 | 2.9 | 10.5 | 9.5 | 12.3 | 5.7 | 33.8 | 24.5 | 6.9 | 1,398.6 | 3.3 | 186.1 | 55.0 |
| Hindon Lower | 14.1 | 23.8 | 4.7 | 10.3 | 10.5 | 12.4 | 5.4 | 35.3 | 26.7 | 8.3 | 6,441.9 | 2.0 | 177.6 | 55.0 |
| Catch 29 | 8.5 | 17.6 | 7.1 | 13.2 | 10.7 | 14.5 | 6.3 | 29.7 | 23.6 | 12.4 | 66,990.0 | 4.7 | 193.2 | 50.0 |
| Catch 25 | 10.0 | 8.8 | 2.7 | 9.4 | 5.3 | 11.9 | 5.7 | 17.0 | 11.7 | 9.3 | 1,135.7 | 6.3 | 115.1 | 55.0 |
| Catch 30 | 7.8 | 17.1 | 10.1 | 13.6 | 9.5 | 15.0 | 6.6 | 26.2 | 19.8 | 15.4 | 17,095.9 | 5.4 | 148.3 | 50.0 |
| Catch 41 | 10.6 | 21.5 | 10.4 | 13.9 | 12.5 | 18.5 | 8.4 | 28.8 | 26.6 | 12.1 | 38,998.4 | 2.9 | 148.9 | 45.0 |
| **Average Yield (qt/ha)** | 10.5 | **18.4** | 5.6 | **11.3** | **9.9** | **13.5** | 6.2 | **28.9** | ***22.2*** | ***10.6*** | **28,398.7** | 4.4 | **167.2** | 61.5 |

**Table 13.18** Catchment-wise water requirements under different crop rotations

| | Crop-Rotation Combination and Estimated Water Requirement (ha m) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cotton-wheat | Paddy-potato | Paddy-barley | Paddy-barley-maize | Paddy-barley-bajra | Paddy-wheat | Groundnut-jowar | Groundnut-barley | Soyabean-wheat-maize | Arhar-wheat | Paddy-gram | Paddy-mustard |
| Catchment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Chambal up 1 | 140,251 | 120 | 177 | 873 | 110 | 16,972 | 2,121 | 3,775 | 535,456 | 103,388 | 2,218 | 7,693 |
| Chambal up 2 | 3,649 | 6 | 114 | 464 | 114 | 110 | 1,612 | 1,947 | 6,228 | 3,484 | 138 | 2,318 |
| Chambal up 3 | 174,233 | 21,609 | 23,160 | 26,843 | 9,252 | 237,824 | 10,815 | 15,741 | 1,198,192 | 324,005 | 279,53 | 472,126 |
| **Chambal** | **318,133** | **21,735** | **23,450** | **28,179** | **9,477** | **254,906** | **14,547** | **21,463** | **1,739,876** | **430,877** | **30,308** | **482,137** |
| Banas | 34,164 | 115 | 1,897 | 6,726 | 1,907 | 23,292 | 10,422 | 13,546 | 60,267 | 31,392 | 955 | 21,605 |
| Sind | 5,743 | 115,159 | 120,671 | 8,769 | 7,923 | 291,041 | 17 | 38,466 | 162,658 | 206,965 | 130,273 | 105,558 |
| Ken | 250,99 | 12,354 | 12,037 | 240 | 0 | 117,597 | 6 | 4,849 | 2,866 | 208,894 | 53,811 | 16,030 |
| Betwa Upper | 37,968 | 1,444 | 4,386 | 539 | 0 | 133,384 | 3 | 16,489 | *45,487* | *200,931* | 31,225 | 8,224 |
| Betwa Lower | 13,923 | 30,849 | 33,728 | 32,928 | 6,437 | 181,638 | 80 | 31,308 | *113,604* | *318,661* | 48,383 | 40,417 |
| **Betwa** | **51,891** | **32,293** | **38,114** | **33,467** | **6,437** | **315,022** | **82** | **47,797** | **159,091** | **519,592** | **79,608** | **48,641** |
| Kali-Hindon | 18,001 | 18,040 | 17,928 | 18,087 | 16,192 | 35,831 | 0 | 550 | 10,689 | 16,929 | 16,133 | 16,399 |
| Hindon Lower | 29,164 | 23,661 | 23,500 | 27,407 | 24,650 | 52,270 | 5 | 271 | 8,216 | 30,425 | 23,062 | 23,699 |
| **Hindon** | **47,165** | **41,701** | **41,428** | **45,494** | **40,842** | **88,101** | **5** | **821** | **18,906** | **47,354** | **39,195** | **40,097** |
| Catch 29 | 51,252 | 58,923 | 133,990 | 157,117 | 135,526 | 335,068 | 449 | 9,164 | 155,100 | 227,294 | 127,879 | 149,674 |
| Catch 25 | 0 | 111,294 | 110,229 | 43,995 | 0 | 189,660 | 139 | 894 | 39,553 | 80,630 | 111,295 | 114,183 |
| Catch 30 | 0 | 35,818 | 61,711 | 58,937 | 38,801 | 114,263 | 148 | 1,182 | 61,785 | 62,043 | 60,891 | 68,948 |
| Catch 41 | 10,940 | 4,571 | 24,716 | 27,023 | 24,808 | 54,960 | 76 | 1,555 | 22,529 | 33,082 | 23,424 | 28,586 |
| Catch 73 | 138,610 | 63,326 | 62,386 | 85,698 | 65,721 | 193,638 | 852 | 2,946 | 975 | 139,602 | 56,634 | 78,646 |
| Catch-46 | 399,831 | 239,007 | 287,991 | 293,569 | 310,904 | 592,449 | 7,461 | 12,240 | 21,051 | 340,380 | 252,952 | 385,205 |
| **Total (ha-m)** | **1,082,828** | **736,295** | **918,618** | **789,215** | **642,345** | **2,569,997** | **34,205** | **154,923** | **2,444,655** | **2,328,105** | **967,227** | **1,539,309** |

**Table 13.19** Catchment-wise gross-returns under different crop rotations

| | Gross return (million Rs) | | | | | | |
|---|---|---|---|---|---|---|---|
| Catchment | Cott-whet | Pad-Pot | Pad-Barl | Pad-Barl-Maiz | Pad-Barl-Pl Mlt | Pad-Wht | Gn-Jowr |
| Chambal Up 1 | **6,409** | 632 | 8 | 40 | 8 | 4,970 | 87 |
| Chambal Up 2 | **393** | | | | 0 | 391 | 8 |
| Chambal Up 3 | **19,233** | 639 | 276 | 394 | 323 | **19,154** | 97 |
| Banas | **1,422** | | | | | **1,422** | 1 |
| Sind | **10,658** | 3,164 | 3,179 | 3,188 | 3,179 | **13,693** | 1,471 |
| Ken | **3,368** | 204 | 111 | 111 | | **3,464** | 33 |
| Betwa up | **6,241** | 90 | 131 | 131 | | **6,252** | 533 |
| Betwa lower | **10,989** | 823 | 873 | 878 | 873 | **11,574** | 639 |
| Catch-73 | 0 | 3,045 | 1,732 | 2,342 | 1,776 | **14,033** | 7 |
| Catch-46 | **31,858** | 6,355 | 6,235 | 6,467 | 7,558 | **33,799** | 153 |
| Kali-Hindon | 0 | 419 | 388 | 391 | 388 | **1,906** | 12 |
| Hindon Lwr | 0 | 720 | 602 | 695 | 632 | **3,495** | 6 |
| Catch 29 | 0 | 4,672 | 3,449 | 4,033 | 3,476 | **19,757** | 26 |
| Catch 25 | 0 | 1,907 | 1,711 | 1,712 | 1,711 | **5,952** | 11 |
| Catch 30 | 0 | 1,596 | 1,428 | 1,551 | 1,433 | **6,525** | 4 |
| Catch 41 | 0 | 1,056 | 691 | 764 | 693 | **3,146** | 2 |
| **Total Dr Rtn (Rs)** | 90,571 | 25,321 | 20,817 | 22,697 | 22,050 | **149,535** | 3,090 |
| **Total (ha-m)** | 1,082,828 | 736,295 | 918,618 | 789,215 | 642,345 | **2,569,997** | 34,205 |

**Table 13.19** (continued)

| | Gross return (million Rs) | | | | |
|---|---|---|---|---|---|
| Catchment | Gn-Barl | Soy-Wht-Maiz | Arhr-Wht | Pad-Gram | Pad-Must |
| Chambal Up 1 | 95 | **20,385** | **5,009** | 1,145 | |
| Chambal Up 2 | 14 | **1,267** | **396** | | |
| Chambal Up 3 | 201 | **33,341** | **19,312** | 3,368 | 577 |
| Banas | 29 | **1,649** | **1,442** | | |
| Sind | 1,614 | **12,330** | **11,392** | 4,328 | 6,123 |
| Ken | 48 | **5,725** | **3,591** | 2,567 | 199 |
| Betwa up | 654 | **9,419** | **9,119** | 2,658 | 96 |
| Betwa lower | 927 | **12,720** | **13,077** | 3,309 | 1,008 |
| Catch-73 | 417 | **13,327** | **12,826** | 1,351 | 2,979 |
| Catch-46 | 302 | **28,055** | **28,520** | 6,270 | 14,414 |
| Kali-Hindon | 16 | **1,524** | **1,547** | 385 | 401 |
| Hindon Lwr | 36 | **3,015** | **2,967** | 574 | 607 |
| Catch 29 | 570 | **17,450** | **17,827** | 3,116 | 4,452 |
| Catch 25 | 15 | **4,263** | **4,323** | 1,825 | 1,832 |
| Catch 30 | 73 | **5,292** | **5,377** | 1,399 | 1,905 |
| Catch 41 | 108 | **2,634** | **2,651** | 612 | 955 |
| **Total Dr Rtn (Rs)** | 5,116 | **172,396** | **139,377** | 32,907 | 35,549 |
| **Total (ha-m)** | 154,923 | **2,444,655** | **2,328,105** | 967,227 | 1,539,309 |

intercropping can be suggested as the best solution for the sustainable use of the net sown area and also improving the productivity. In catchment 73, all the districts have an average area of more than 50% used for paddy cultivation during *kharif*. Based on the estimated water demand (Tables 13.7 and 13.18), the combination with paddy would be the appropriate rotation. The water requirement in the paddy-gram and paddy-barley rotation is quite less than paddy-wheat. In the Kali-Hindon catchment, paddy cultivation area in the *kharif* season is more than 80% (Table 13.15). Sequentially the rotation with paddy is advisable with gram, mustard, barley and potato, according to the estimated water requirement.

## 13.4 Identification of Suitable Cropping Patterns

Increasing crop productivity and saving irrigation water are two interrelated issues raising a lot of concern these days in India. Legume or cereal intercropping pattern is generally more productive than the sole crop and can be a way of saving irrigation water. Considering the land use pattern and major crops grown during *kharif* and *rabi*, intercropping for the Yamuna basin is categorized into two groups. The possible intercropping patterns taken for this study area are given in Table 13.20.

During the kharif season, paddy, arhar and soybean are the major crops (see Tables 13.9, 13.10, 13.11, 13.12, 13.13, 13.14, 13.15, and 13.16). Specific intercropping patterns (the row spacing for the particular type crop combination) considered for the study are chosen from various documents (ICAR, 2006). Then, district-wise water requirements for intercropping patterns are estimated for all the sub-catchments. The sub-catchment wise water and gross-income summary are given in Tables 13.21, 13.22, 13.23, and 13.24. From Table 13.20, it may be

**Table 13.20** Possible intercropping combinations for the Yamuna basin

| Crop Season | Combination | Area ratio |
|---|---|---|
| Kharif | Soybean+Paddy | 1:2 |
| | Soybean+Cotton | 1:1 |
| | Soybean+Arhar | 1:1 |
| | Soybean+Arhar | 4:2 |
| | Soybean+Jowar | 2:2 |
| | Bajra+Soyabean | 4:2 |
| | Bajra+Soyabean | 1:1 |
| | Arhar+ Sorghum | 1:2 |
| | Arhar+ Bajra | 1:2 |
| | Arhar+Maize | 1:2 |
| | Arhar+ Paddy | 1:3 |
| Rabi | Groundnut +Wheat | 3:1 |
| | Wheat+Gram | 4:2 |
| | Mustard+Potato | 1:3 |
| | Mustard+Wheat | 1:9 |
| | Mustard+Gram | 1:2 |

**Table 13.21** Sub-catchment wise estimated water requirements for inter cropping patterns for Rabi

| | Rabi | | | | |
|---|---|---|---|---|---|
| | Grout +Whet | Wht+Gram | Must+Pot | Must+Wht | Must+Gram |
| Catchment | 12 | 13 | 14 | 15 | 16 |
| Chambal up 1 | 200,869 | 132,213 | 143,772 | 195,503 | 120,172 |
| Chambal up 2 | 19,081 | 12,015 | 13,033 | 17,685 | 10,920 |
| Chambal up 3 | 684,125 | 678,140 | 733,759 | 1,001,204 | 615,040 |
| ***Chambal*** | ***904,075*** | ***822,368*** | ***890,564*** | ***1,214,393*** | ***746,132*** |
| Banas | 83,751 | 51,305 | 52,054 | 75,087 | 46,645 |
| Sind | 426,760 | 240,167 | 256,858 | 357,375 | 217,145 |
| Ken | 221,382 | 136,368 | 147,658 | 202,820 | 123,554 |
| Betwa Upper | 270,068 | 165,998 | 179,915 | 247,148 | 150,423 |
| Betwa Lower | 385,724 | 227,361 | 245,622 | 338,181 | 205,763 |
| ***Betwa*** | ***655,793*** | ***393,359*** | ***425,537*** | ***585,329*** | ***356,186*** |
| Kali-Hindon | 60,113 | 27,524 | 30,511 | 42,864 | 23,320 |
| Hindon Lower | 80,687 | 39,990 | 43,081 | 59,223 | 36,158 |
| ***Hindon*** | ***140,800*** | ***67,514*** | ***73,592*** | ***102,087*** | ***59,478*** |
| Catch 73 | 266,305 | 138,066 | 148,526 | 204,864 | 124,730 |
| Catch-46 | 812,720 | 402,713 | 437,071 | 602,399 | 358,280 |
| Catch 29 | 336,415 | 181,341 | 144,684 | 269,887 | 163,680 |
| Catch 25 | 109,480 | 75,067 | 75,323 | 96,534 | 79,030 |
| Catch 30 | 100,185 | 54,960 | 41,610 | 81,744 | 49,616 |
| Catch 41 | 56,300 | 30,139 | 18,479 | 44,841 | 27,203 |
| **Total (ha m)** | **4,113,966** | **2,593,367** | **2,711,955** | **3,837,359** | **2,351,680** |

remarked that the estimated water requirement for the soybean intercropping is less than for paddy. Among the combinations, the soybean-arhar combination requires less water than others. The soybean-sorghum intercropping not only requires less water but also provides better crop rotation with millets. It is apparent from Tables 13.21 and 13.22 that bajra (millets) with soybean and arhar can save a lot of water. The arhar-paddy intercropping consumes less water than soybean with paddy or cotton intercropping.

It is observed from Table 13.23 that among the various cropping patterns suitable for the Yamuna River basin, four inter-cropping patterns for the Kharif season are identified based on economic returns and water requirements. These inter-crops are maize-arhar (1:1), soybean-arhar (1:2), soybean-arhar (1:1), and paddy-arhar (1:1).

Catchment-wise inter-cropping patterns can be identified from Tables 13.17 and 13.18. Among the various patterns for the rabi season, it is observed from Table 13.24 that the mustard-potato (1:1) combination is the most economic and water conservative, followed by the wheat-gram (1:1) and mustard-wheat (1:1) combinations. However, catchment-wise rabi inter-crops can be selected based on Tables 13.21 and 13.24.

**Table 13.22** Sub-catchment wise estimated water requirements for inter cropping patterns for Kharif

| | Kharif | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Soy+Padd (1:2) | Soy+Cott (1:1) | Soy+Arhr (1:1) | Soy+Arhr (4:2) | Soy+Jowr (2:2) | Bajr+Soy (4:2) | Bajr+Soy (1:1) | Arhr+Jowr (1:2) | Arhr+Bajr | Arhr+Maiz | Arhr+Padd |
| Catchment | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Chambal up 1 | 797,281 | 816,460 | 542,491 | 583,154 | 596,582 | 511,972 | 550,099 | 492,625 | 430,647 | 552,976 | 752,888 |
| Chambal up 2 | 51,239 | 52,616 | 35,034 | 37,672 | 38,479 | 33,101 | 35,563 | 31,713 | 27,825 | 35,720 | 48,318 |
| Chambal up 3 | 1,108,944 | 1,143,573 | 760,291 | 817,886 | 833,793 | 718,394 | 772,064 | 685,509 | 603,205 | 775,258 | 1,044,536 |
| **Chambal** | **1,957,464** | **2,012,648** | **1,337,816** | **1,438,712** | **1,468,854** | **1,263,467** | **1,357,726** | **1,209,847** | **1,061,676** | **1,363,955** | **1,845,741** |
| Banas | 48,902 | 50,112 | 33,461 | 35,975 | 36,770 | 31,662 | 33,997 | 30,331 | 26,634 | 34,123 | 46,118 |
| Sind | 142,332 | 266,577 | 177,922 | 191,638 | 194,493 | 169,150 | 181,630 | 158,869 | 141,719 | 182,109 | 240,274 |
| Ken | 323,802 | 337,548 | 223,981 | 241,272 | 244,943 | 212,272 | 228,167 | 200,057 | 177,689 | 229,689 | 303,858 |
| Betwa Upper | 261,907 | 272,074 | 180,414 | 194,225 | 197,348 | 170,433 | 183,287 | 161,558 | 142,811 | 184,562 | 246,198 |
| Betwa Lower | 307,846 | 321,050 | 213,240 | 229,723 | 233,097 | 202,228 | 217,343 | 190,265 | 169,261 | 218,743 | 288,765 |
| **Betwa** | **569,754** | **593,124** | **393,654** | **423,948** | **430,445** | **372,661** | **400,630** | **351,824** | **312,071** | **403,305** | **534,963** |
| Kali-Hindon | 18,613 | 19,502 | 12,658 | 13,852 | 14,348 | 12,642 | 13,541 | 11,331 | 10,254 | 13,247 | 17,119 |
| Hindon Lower | 30,786 | 32,132 | 21,636 | 23,333 | 23,661 | 20,802 | 22,283 | 19,246 | 17,409 | 22,312 | 28,749 |
| **Hindon** | **49,399** | **51,634** | **34,294** | **37,184** | **38,009** | **33,444** | **35,824** | **30,576** | **27,663** | **35,559** | **45,868** |
| Catch 73 | 87,056 | 97,917 | 65,859 | 70,984 | 71,996 | 63,125 | 67,652 | 58,667 | 52,876 | 67,796 | 87,938 |
| Catch-46 | 489,772 | 510,738 | 342,461 | 369,957 | 376,460 | 330,827 | 354,357 | 305,306 | 275,835 | 353,640 | 456,632 |
| Catch 29 | 186,138 | 194,218 | 132,199 | 142,393 | 144,315 | 126,106 | 135,274 | 117,773 | 105,719 | 126,708 | 173,767 |
| Catch 25 | 103,818 | 111,126 | 89,006 | 93,668 | 80,694 | 70,247 | 74,646 | 75,121 | 68,837 | 86,015 | 107,048 |
| Catch 30 | 61,224 | 70,901 | 49,700 | 53,540 | 54,262 | 47,382 | 50,841 | 21,424 | 39,703 | 47,902 | 65,494 |
| Catch 41 | 27,857 | 30,041 | 20,083 | 21,619 | 21,913 | 19,166 | 20,548 | 18,472 | 16,093 | 18,097 | 25,948 |
| **Total (ha m)** | **4,047,518** | **4,326,583** | **2,900,437** | **3,120,890** | **3,163,152** | **2,739,508** | **2,941,293** | **2,578,267** | **2,306,516** | **2,948,899** | **3,933,650** |

**Table 13.23** Sub-catchment wise estimated gross returns for inter cropping patterns for Kharif

| Catchment | Soya+Pad (1:2) | Soya+Cot (1:1) | Soy+Arhr (1:1) | Soy+Arhr (1:2) | Soy+Jowr (1:1) | Bajr+Soy (4:2) | Bajr+Soy (1:1) | Jowr+Arhr (1:1) | Bajr+Arhr (1:1) | Maiz+Arhr (1:1) | Pad+Arhr (1:1) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Chambal Up 1 | 5, 892 | 16, 233 | 13, 449 | 12,548 | 9,111 | 5,451 | 8,126 | 4,962 | 3,649 | 16,782 | **3,258** |
| Chambal Up 2 | 290 | 912 | 799 | 775 | 453 | 359 | 487 | 268 | 312 | 1,175 | **182** |
| Chambal Up 3 | 5,426 | 15,829 | 15,882 | 16,290 | 10,054 | 5,387 | 7,705 | 9,332 | 6,201 | 22,092 | **4,882** |
| Banas | 32 | 101 | 405 | 509 | 163 | 415 | 335 | 391 | 621 | 1,009 | **179** |
| Sind | 5,882 | 3,857 | 5,597 | 5,157 | 5,009 | 4,061 | 4,775 | 3,493 | 3,181 | 6,600 | **5,093** |
| Ken | 3,118 | 1,402 | 2,158 | 1,970 | 1,367 | 908 | 1,362 | 538 | 531 | 4,078 | **2,885** |
| Betwa Up | 3,017 | 3,622 | 5,175 | 5,198 | 2,580 | 1,702 | 2,554 | 1,784 | 1,748 | 3,590 | **2,789** |
| Betwa lwr | 3,348 | 1,774 | 4,307 | 4,574 | 1,933 | 1,178 | 1,760 | 1,942 | 1,712 | 4,146 | **3,728** |
| Catch 73 | 1,593 | 6 | 1,109 | 1,475 | 436 | 468 | 354 | 1,308 | 1,199 | 1,916 | **2,339** |
| Catch 46 | 6,562 | 6,695 | 6,311 | 8,380 | 469 | 6,173 | 4,655 | 4,731 | 10,313 | 5,644 | **10,474** |
| Kali-Hindon | 328 | 62 | 198 | 223 | 63 | 44 | 64 | 93 | 94 | 238 | **392** |
| Hindon Lwr | 582 | 58 | 375 | 462 | 155 | 234 | 205 | 342 | 408 | 551 | **770** |
| Catch 29 | 3,062 | 352 | 3,464 | 4,384 | 1,228 | 1,391 | 1,219 | 3,243 | 3,231 | 4,546 | **4,737** |
| Catch 25 | 1,181 | 15 | 1,286 | 1,705 | 272 | 331 | 256 | 1,190 | 1,169 | 1,836 | **1,953** |
| Catch 30 | 1,199 | 136 | 1,628 | 2,080 | 524 | 587 | 508 | 1,513 | 1,491 | 1,820 | **1,993** |
| Catch 41 | 492 | 0 | 549 | 732 | 144 | 188 | 141 | 558 | 554 | 785 | **828** |
| Total Rtn (M Rs) | 42,003 | 51,053 | **62,694** | **66,462** | 33,962 | 28,878 | 34,506 | 35,688 | 36,413 | **76,808** | **46,481** |
| Total WR (ha m) | 4,047,518 | 4,326,583 | **2,900,437** | **3,120,890** | 3,163,152 | 2,739,508 | 2,941,293 | 2,578,267 | 2,306,516 | **2,948,899** | **3,933,650** |

**Table 13.24** Sub-catchment wise estimated gross returns for inter cropping patterns for Rabi

| Catchment | Gn+Wht (3:1) | Wht+Gram (1:1) | Must+Pot (1:1) | Must+Wht (1:1) | Gram +Must (1:1) |
|---|---|---|---|---|---|
| Chambal Up 1 | 9,230 | 6,682 | 13,760 | 8,816 | 3,417 |
| Chambal Up 2 | 605 | 664 | 731 | 999 | 294 |
| Chambal Up 3 | 25,617 | 46,441 | 14,153 | 53,472 | 27,275 |
| Banas | 1,008 | 2,546 | 81 | 3,498 | 1,250 |
| Sind | 16,971 | 18,970 | 29,580 | 19,839 | 14,371 |
| Ken | 6,640 | 5,573 | 14,062 | 5,996 | 3,779 |
| Betwa Up | 11,109 | 9,686 | 20,376 | 9,751 | 7,525 |
| Betwa lwr | 11,193 | 15,257 | 22,994 | 15,736 | 11,676 |
| Catch 73 | 6,774 | 14,069 | 27,414 | 18,559 | 11,479 |
| Catch 46 | 18,000 | 29,333 | 24,098 | 47,344 | 22,331 |
| Kali-Hindon | 2,295 | 2,512 | 4,631 | 3,521 | 1,914 |
| Hindon Lwr | 2,576 | 4,476 | 7,067 | 5,734 | 3,354 |
| Catch 29 | 13,227 | 17,665 | 24,170 | 21,363 | 14,854 |
| Catch 25 | 2,967 | 3,441 | 5,307 | 4,743 | 2,482 |
| Catch 30 | 4,097 | 5,277 | 6,195 | 6,412 | 4,415 |
| Catch 41 | 2,295 | 3,011 | 2,872 | 3,573 | 2,606 |
| **Total Rtn (M Rs)** | 134,603 | **185,602** | **217,491** | **229,356** | 133,023 |
| **Total WR (ha m)** | 4,113,966 | **2,593,367** | **2,711,955** | **3,837,359** | 2,351,680 |

## 13.5 Water Conservation Under Different Cropping Patterns

Analyzing the gross income and water requirements for inter-cropping patterns for all the catchments (Tables 13.21, 13.22, 13.23, and 13.24), the best inter-cropping patterns are identified, as given in Table 13.25 which also includes theoretical water requirements for combinations of crop in *kharif* and *rabi* seasons. Based on dual crop seasons, the total water requirements are estimated on an annual basis, considering the major crop area only.

When analyzing cropping patterns there is the possibility of skipping a few more crops and their cultivated areas. Therefore, the estimated theoretical crop water demands are projected considering the *kharif* ratio and *rabi* Ratio to cover the entire Net Sown Area (NSA) of the catchments (Table 13.26). The estimated crop water requirements under different combinations are further compared with the crop water requirements reported in the baseline (Table 13.1) and water saving statistics are computed, as shown in Table 13.27. From these comparative statistics, it is apparent that the best inter-cropping pattern can save significant amounts of water.

The range of water saving for the Chambal, Sind, Betwa, and Ken are 2.5–10.1, 16.5–30.0, 4.4–11.4, and 5.7–8.5%, respectively. However, the annual combinations, II+I, II+II, and III+I for the Ken catchment are not appropriate,

**Table 13.25** Catchment-wise inter-cropping patterns and water requirements considering the Kharif and Rabi areas under major crops

| | Kharif | | | Rabi | | Total CWR (MCM) with combinations | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Catchment | I | II | III | I | II | I + I | I + II | II + I | II + II | III + I |
| **Chambal** | Maiz+Arhr (1:1) | Soy+Arhr (1:1) | Soy+Arhr (1:2) | Wht+Grm (1:1) | Grm+Must (1:1) | | | | | |
| CWR (MCM) | 13,981 | 13,713 | 14,747 | 8,737 | 7,928 | 22,718 | 21,909 | 22,449 | 21,641 | 23,484 |
| **Sind** | Soyb+Pad (1:1) | Maiz+Arhr (1:1) | Soyb+Arhr (1:1) | Must+Pot (1:1) | Wht+Grm (1:1) | | | | | |
| CWR (MCM) | 1,423 | 1,821 | 1,779 | 2,569 | 2,402 | 3,992 | 3,825 | 4,390 | 4,223 | 4,348 |
| **Betwa** | Soyb+Arhr (1:1) | Soy+Arhr (1:2) | Maiz+Arhr (1:1) | Must+Pot (1:1) | Wht+Grm (1:1) | | | | | |
| CWR (MCM) | 3,937 | 4,240 | 4,033 | 4,255 | 3,934 | 8,192 | 7,870 | 8,495 | 8,173 | 8,288 |
| **Ken** | Maiz+Arhr (1:1) | Pad+Arhr (1:1) | Soyb+Pad (1:1) | Must+Pot (1:1) | Wht+Grm (1:1) | | | | | |
| CWR (MCM) | 2,297 | 3,038 | 3,238 | 1,477 | 1,364 | 3,774 | 3,661 | 4,515 | 4,402 | 4,715 |
| **Yamuna** | Maiz+Arhr (1:1) | Soy+Arhr (1:2) | Soy+Arhr (1:1) | Must+Pot (1:1) | Wht+Grm (1:1) | | | | | |
| CWR (MCM) | 29,489 | 31,209 | 29,004 | 27,120 | 25,934 | 56,609 | 55,423 | 58,328 | 57,143 | 56,124 |

**Table 13.26** Catchment-wise inter-cropping patterns and water requirements considering the reported Kharif and Rabi areas and their projection up to the Net Sown Area (NSA)

| | | | Kharif | | | Rabi | | Total CWR (MCM) with combinations | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Catchment | Kharif ratio | Rabi ratio | I | II | III | I | II | I + I | I + II | II + I | II + II | III + I |
| **Chambal** | 2.59 | 2.63 | 13,981 | 13,713 | 14,747 | 8,737 | 7,928 | 59,237 | 57,108 | 58,542 | 56,413 | 61,223 |
| **Sind** | 3.99 | 1.66 | 1,423 | 1,821 | 1,779 | 2,569 | 2,402 | 9,926 | 9,649 | 11,511 | 11,235 | 11,344 |
| **Betwa** | 3.71 | 2.24 | 3,937 | 4,240 | 4,033 | 4,255 | 3,934 | 24,162 | 23,440 | 25,287 | 24,565 | 24,520 |
| **Ken** | 3.20 | 3.20 | 2,297 | 3,038 | 3,238 | 1,477 | 1,364 | 12,082 | 11,720 | 14,456 | 14,094 | 15,096 |
| **Yamuna** | 2.86 | 1.82 | 29,489 | 31,209 | 29,004 | 27,120 | 25,934 | 133,670 | 131,511 | 138,586 | 136,426 | 132,285 |

Kharif Ratio = NSA/Kharif Area Under Major Crops; Rabi Ratio = NSA/Rabi Area Under Major Crops

**Table 13.27** Catchment-wise water savings under different combinations of inter-cropping patterns

| Catch | CWR: baseline (Table 13.1) | Total CWR (MCM) with combinations | | | | | % Water savings | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | I + I | I + II | II + I | II + II | III + I | I + I | I + II | II + I | II + II | III + I |
| **Chambal** | 62,771 | 59,237 | 57,108 | 58,542 | 56,413 | 61,223 | 5.6 | 9.0 | 6.7 | 10.1 | 2.5 |
| **Sind** | 13,786 | 9,926 | 9,649 | 11,511 | 11,235 | 11,344 | 28.0 | 30.0 | 16.5 | 18.5 | 17.7 |
| **Betwa** | 26,456 | 24,162 | 23,440 | 25,287 | 24,565 | 24,520 | 8.7 | 11.4 | 4.4 | 7.1 | 7.3 |
| **Ken** | 12,808 | 12,082 | 11,720 | 14,456 | 14,094 | 15,096 | 5.7 | 8.5 | 12.9 | 10.0 | −17.9 |
| **Yamuna** | 200,761 | 133,670 | 131,511 | 138,586 | 136,426 | 132,285 | 33.4 | 34.5 | 31.0 | 32.0 | 34.1 |

as more water is required under these combinations. Beside this, for the entire Yamuna River basin 31.0–34.5% water can be saved by using these combinations.

## 13.6 Impact of Change in Cropping Patterns on Water Allocation

The above 34.5% saving in irrigation water does not only satisfy the deficit in the Yamuna basin but can also create additional water of approximately 34.7 BCM at Pratappur near the confluence of River Ganga. The monthly additional water availability in the basin at Pratappur is shown in Fig. 13.2, whereas the additional water in the river in terms of flow is given in Fig. 13.3. The distribution of the flow is based on the actual long term monthly distribution of annual flows in the river at different sites. Similarly, additional water availability and flows for the Agra and Delhi Railway Bridge (DRB) sites are shown in Figs. 13.4, 13.5, 13.6, and 13.7, respectively.

Further, the enhanced flow condition in the river at the Delhi Railway Bridge site is compared with environmental flows (Rai et al., 2010) for the Wazirbad-Okhla stretch, as shown in Fig. 13.8. If crop planning is achieved up to 75% in the catchment corresponding to the Delhi Railway Bridge site (i.e., 30,793 $km^2$), environmental flows in the river can be achieved if the pollution discharge is regulated up to 10 mg/l BOD with 5 cumecs.

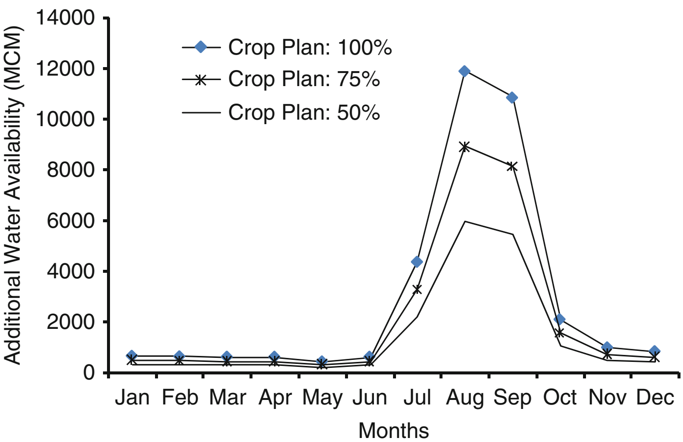


**Fig. 13.2** Additional water availability in the Yamuna basin at Pratappur when crop planning is considered

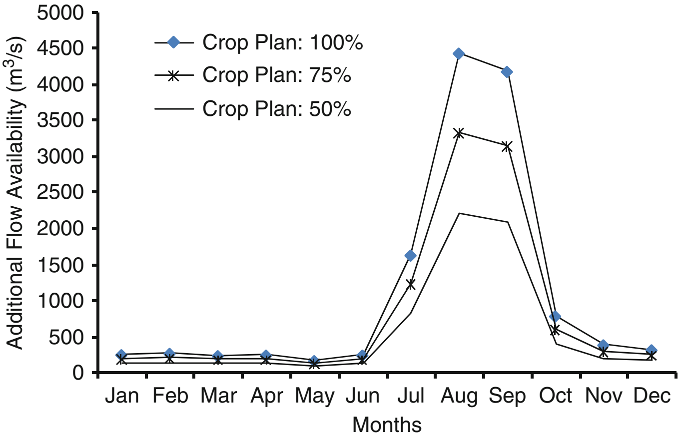


**Fig. 13.3** Additional flow availability in the Yamuna basin at Pratappur when crop planning is considered

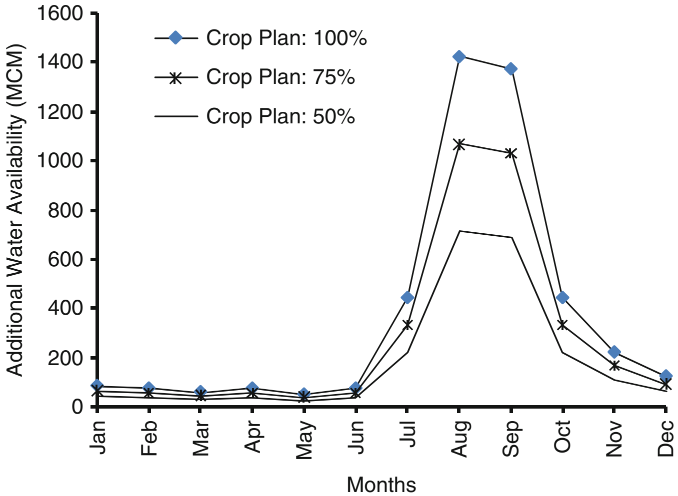


**Fig. 13.4** Additional water availability in the Yamuna basin at Agra when crop plan is considered

## 13.7 Concluding Remarks

The following conclusions can be drawn from this study:

(i) Considering water requirements, minimum support price, and average yield, it is found that during the *kharif* season cultivation of jowar, soybean, bajra and arhar crops are more economic than other crops; whereas during the *rabi* season, mustard, wheat, and potato produce high yields and good economic

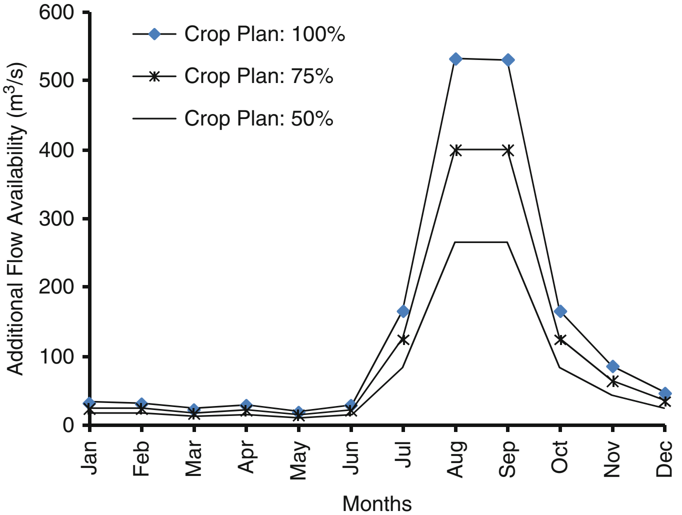


**Fig. 13.5** Additional flow availability in the Yamuna basin at Agra when crop planning is considered

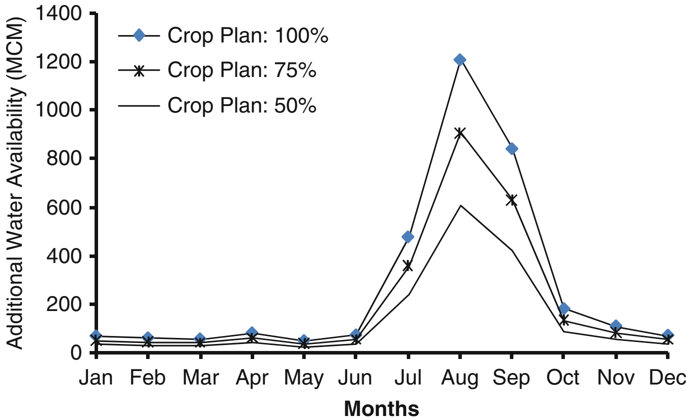


**Fig. 13.6** Additional water availability in the Yamuna basin at DRB when crop planning is considered

returns and require less water. Barley and gram are of equally good economic value and can be implemented as *rabi* crops.

(ii) Based on water requirements and gross income, major rotational combinations of crops in the basin are soybean-wheat-maize, paddy-wheat, and arhar-wheat.

(iii) For paddy growing areas, the sequential rotation with gram, mustard, barley and potato is advisable, according to the estimated water requirement.

(iv) Amongst all identified combinations, the soybean-arhar combination requires less water than others. The soybean-jowar intercropping not only requires less

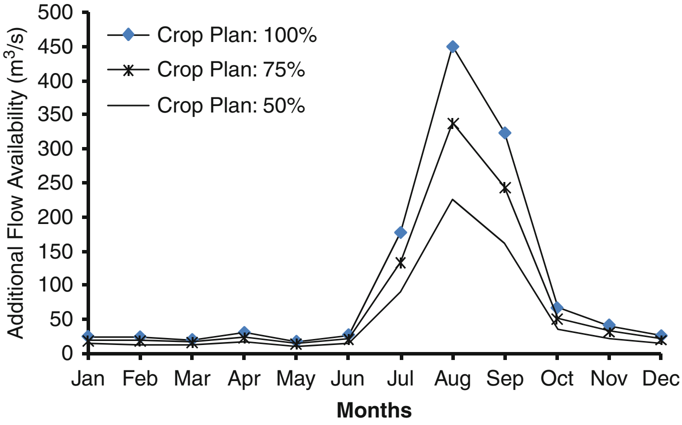


**Fig. 13.7** Additional flow availability in the Yamuna basin at DRB when crop planning is considered

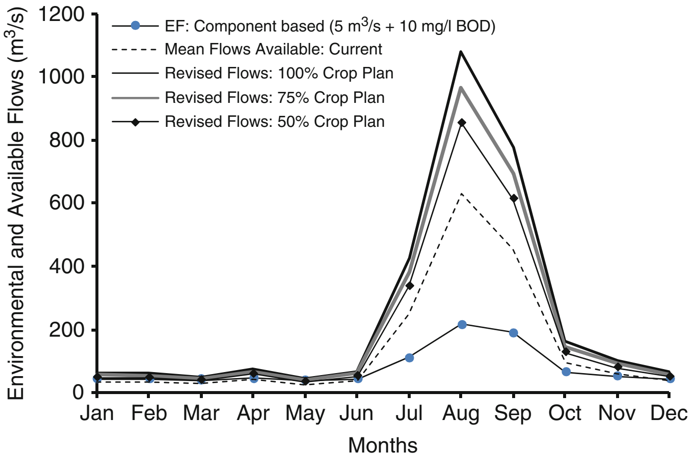


**Fig. 13.8** Environmental flows and available flows with crop planning for the Wazirabad to Okhla stretch

water but also provides better crop rotation with bajra. It is also found that bajra (millets) with soybean and arhar can save significant amounts of water. The arhar-paddy intercropping consumes less water than the soybean-paddy or cotton intercropping.

(v) Amongst the various cropping patterns suitable for the Yamuna basin, four inter-cropping patterns for the kharif season are identified based on economic returns and water requirements. These patterns include: maize-arhar (1:1), soybean-arhar (1:2), soybean-arhar (1:1), and paddy-arhar (1:1). Similarly for the *rabi* season the mustard-potato (1:1) pattern is found most economic and water conservative, followed by wheat-gram (1:1) and mustard-wheat (1:1) combinations.

(vi) Using the best inter-cropping pattern, 31.0–34.5% irrigation water can be saved in the entire Yamuna basin, which helps reduce ground water exploitation.

(vii) If crop planning is achieved up to 75% of the catchment corresponding to the Delhi Railway Bridge site (i.e., 30,793 $km^2$), environmental flows for the Wazirabad-Okhla stretch can be achieved, with the proviso that the pollution discharge is regulated up to 10 mg/l BOD with 5 $m^3$/s.

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# Appendix A
# Salient Feature of Dams in the Yamuna Basin

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DOI 10.1007/978-94-007-2001-5, © Springer Science+Business Media B.V. 2012

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Submergence ('000 $km^2$) | Gross capacity ('000 cu m) | Live capacity ('000 cu m) | Spillway capacity ('000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam ('000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baisly | Kaliasote | Bhopal | MP | Betwa | Betwa | 1988 | 365.2 | 5,295 | 35,887 | 34,410 | 1,355 | TE | 67.08 | 1,080 | – | IRR |
| Balwantpura | Local | Bhopal | MP | Betwa | Betwa | 1994 | 29.53 | 3,560 | 6,130 | 6,100 | 430 | TE | 16.1 | 93 | – | IRR |
| Banchor | Kerwan | Bhopal | MP | Betwa | Betwa | 1976 | 64.5 | 4,824 | 25,026 | 22,600 | 453 | TE | 22.6 | 396.5 | 168 | IRR |
| BandaBedra | Local | Bhopal | MP | Betwa | Betwa | 1986 | 15.54 | 1,904 | 7,179 | 5,415 | 52.29 | TE | 17.14 | 1,954.5 | 200 | IRR |
| Bandha | Ajnal | Bhopal | MP | Betwa | Betwa | 1962 | 36.9 | 3,130 | 16,277 | 15,216 | 133.1 | TE | 17.1 | 1,581 | – | I/Ind |
| Baniganj | Local | Bhopal | MP | Betwa | Betwa | 1984 | 4.14 | 387 | 1,315 | 1,222 | 56.37 | TE | 11.26 | 253.44 | 87 | IRR |
| Baniganj | Ghodp'r | Bhopal | MP | Betwa | Betwa | 1986 | 34.6 | 2,059 | 12,410 | 11,570 | 121.44 | TE | 23.42 | 1,841 | 568 | IRR |
| Bansichikhli | Local | Bhopal | MP | Betwa | Betwa | 1991 | 51.52 | 5,340 | 14,822 | 12,680 | 201 | TE | 14.9 | 2,438.42 | 448 | IRR |
| Barana Bamori | – | Bhopal | MP | Betwa | Betwa | 2002 | – | – | 1,960 | 1,764 | 53.37 | TE | 12.1 | 750 | – | IRR |
| Barbatpur | – | Bhopal | MP | Betwa | Betwa | 2004 | – | – | 2,370 | 2,133 | 63.45 | TE | 18.8 | 1,005 | – | IRR |
| Bardha | | Chhatarpur | MP | Betwa | Betwa | 1963 | 3,496 | 8,666 | 11,250 | 11,006 | 170 | TE | 21.34 | 1,341 | | IRR. |
| Barkheda | | Chhatarpur | MP | Betwa | Betwa | 1966 | 16.88 | 1,741 | 7,950 | 7,470 | 60 | TE | 15.85 | 442 | | IRR. |
| Barkhedi | | Chhatarpur | MP | Betwa | Betwa | 1970 | 2.9 | | 1,054 | 979 | 38 | TE | 11.79 | 1,440 | | IRR. |
| Barkhedi | | Chhatarpur | MP | Betwa | Betwa | 1972 | 4.14 | 523 | 1,105 | 975 | 56 | TE | 10.98 | 178 | | IRR. |
| Barmandal | | Chhatarpur | MP | Betwa | Betwa | 1986 | 7.32 | 613 | 963 | 1,849 | 86 | TE | 20.48 | 386 | 113 | IRR. |
| Barnoo | | Chhatarpur | MP | Betwa | Betwa | 1986 | 5.5 | 319 | 1,529 | 1,435 | 65 | TE | 19.44 | 579 | 92 | IRR. |
| Barod | | Chhatarpur | MP | Betwa | Betwa | 1986 | 3.2 | 477 | 881 | 813 | 47 | TE | 10.56 | 915 | 43 | IRR. |
| Bhuhrla Tank | Kaliasot | Dewas | MP | Betwa | Betwa | 1988 | 365.2 | 5,295 | 35,380 | 34,410 | 1,355 | TE | 67.08 | 1,080 | | IRR |
| BhutiaNallaT. | Local | Dewas | MP | Betwa | Betwa | 1994 | 29.53 | 3,560 | 6,130 | 6,100 | 430 | TE | 16.1 | 93 | | IRR |
| Bila | Kerwan | Dewas | MP | Betwa | Betwa | 1976 | 64.5 | 4,824 | 25,026 | 22,600 | 453 | TE | 22.6 | 396.5 | 168 | IRR |
| Birmawal | Local | Dewas | MP | Betwa | Betwa | 1986 | 15.54 | 1,904 | 7,179 | 5,415 | 52 | TE | 17.14 | 1,954.5 | 200 | IRR |
| Bisonia | Local | Dewas | MP | Betwa | Betwa | 1984 | 4.14 | 387 | 1,316 | 1,222 | 56 | TE | 11.26 | 253.44 | 87 | IRR |
| Bithlee | Ghorap'r | Dewas | MP | Betwa | Betwa | 1986 | 34.6 | 2,059 | 12,410 | 11,570 | 121 | TE | 23.42 | 1,841 | 568 | IRR |
| BodiT1 | Local | Dewas | MP | Betwa | Betwa | 1992 | 11.65 | 1,156 | 3,807 | 3,502 | 43 | TE | 13.71 | 108 | 1,820 | IRR |
| Daroli | Local | Guna | MP | Betwa | Betwa | 1973 | 124.1 | 5,380 | 21,650 | 18,810 | 72,920 | TE | 29.87 | 3,169.93 | | IRR. |
| Datoda | Local | Guna | MP | Betwa | Betwa | 1956 | 46.54 | 2,150 | 13,050 | 11,700 | 396 | TE | 25 | 667.57 | | IRR. |
| Deopur | Local | Guna | MP | Betwa | Betwa | 1917 | 53.41 | 3,000 | 11,270 | 10,660 | 207 | TE | 14.63 | 2,700 | | I/WS |
| Devikheda | Local | Guna | MP | Betwa | Betwa | 1976 | 9 | 1,181 | 1,593 | 1,206 | 97 | TE | 11.8 | 911.35 | | IRR. |
| Dhamdhusar | Local | Guna | MP | Betwa | Betwa | 1916 | 7.15 | 108 | 2,410 | 2,369 | 122 | TE | 10.82 | 1,432 | | IRR. |
| Imlikheda | Arialkha | Raisen | MP | Betwa | Betwa | 1972 | 14.76 | 1,635 | 7,644 | 7,219 | 47 | TE | 19.65 | 310 | 400 | IRR |
| IndiraGandhiT | Local | Raisen | MP | Betwa | Betwa | U/C | 9 | 815 | 4,736 | 4,408 | 62 | TE | 18.1 | 716 | | IRR |
| IndiraGandhiT | Khand | Raisen | MP | Betwa | Betwa | 1997 | 25.9 | 1,760 | 17,082 | 8,316 | 235 | TE | 20.7 | 210 | 216 | IRR |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of comple-tion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IndraDaman | Local | Raisen | MP | Betwa | Betwa | 1978 | 6.21 | 1,466 | 2,650 | 2,480 | 64 | TE | 16.46 | 894 | 38.485 | IRR |
| Jabera | Local | Raisen | MP | Betwa | Betwa | 1936 | 85.45 | 2,130 | 13,872 | 12,796 | 430 | TE | 15.24 | 990 | | IRR |
| Jaglatank | Bhoghvi | Raisen | MP | Betwa | Betwa | 1958 | 52 | 6,040 | 19,364 | 17,665 | 533 | TE | 13.73 | 780 | | IRR |
| Jaguwa | kuhynala | Raisen | MP | Betwa | Betwa | 1958 | 8.68 | 657 | 1,646 | 1,520 | 97 | TE | 11.58 | 445 | | IRR |
| Jaguwa | Local | Raisen | MP | Betwa | Betwa | 1957 | 2.59 | 370 | 1,031 | 963 | 40 | TE | 10.08 | 800 | | IRR |
| Jajone | Charua | Raisen | MP | Betwa | Betwa | 1958 | 8.29 | 1,108 | 2,577 | 2,435 | 82 | TE | 10.05 | 1,100 | | IRR |
| Jalheridhana | Local | Raisen | MP | Betwa | Betwa | 1968 | 2.58 | 273 | 1,000 | 939 | 25 | TE | 10.05 | 296 | 29.2 | IRR |
| Jamakheri | Local | Raisen | MP | Betwa | Betwa | 1998 | 4.76 | 347 | 1,920 | 1,800 | 61.62 | TE | 17.04 | 418 | 143 | IRR |
| Jamakheri | Local | Raisen | MP | Betwa | Betwa | | 2.72 | 513 | 1,353 | 1,286 | 15.55 | TE | 11.65 | 270 | 442 | IRR |
| Jamber | Local | Raisen | MP | Betwa | Betwa | | 2.75 | 265 | 920 | 854 | 30 | TE | 15.41 | 273 | 64.4 | IRR |
| Jamonia | Local | Raisen | MP | Betwa | Betwa | 2000 | 6.48 | 830 | 2,730 | 2,576 | 37 | TE | 11.95 | 927 | 119 | IRR |
| Jamonia | Local | Raisen | MP | Betwa | Betwa | 2000 | 3.5 | 296 | 1,430 | 1,309 | 48 | TE | 11.11 | 619 | 94.647 | IRR |
| JamTalai Tank | Local | Raisen | MP | Betwa | Betwa | | 3.24 | 276 | 942 | 863 | 42 | TE | 12.19 | 720 | 67 | IRR |
| JamTalai Tank | Barna | Raisen | MP | Betwa | Betwa | 1975 | 3.5 | 770 | 5,288 | 4,558 | 6,825 | TE | 16.06 | 286.5 | | IRR |
| JamunBai | Palakmati | Raisen | MP | Betwa | Betwa | | 50.29 | 1,943 | 11,039 | 10,438 | 177 | TE | 22.71 | 210 | 169 | IRR |
| Jhamdhar | Local | Rajgarh | MP | Betwa | Betwa | 1957 | 5.18 | 717 | 2,454 | 2,429 | 77 | TE | 12.2 | 731 | | IRR. |
| Jhandatola | Local | Rajgarh | MP | Betwa | Betwa | 1975 | 7.51 | 607 | 2,094 | 1,921 | 88 | TE | 12.19 | 549 | | IRR. |
| Karjuni | | Sagar | MP | Betwa | Betwa | 1982 | 7.12 | 380 | 3,270 | 3,250 | 35 | TE | 18.68 | 384 | | IRR. |
| Kerwan | | Sagar | MP | Betwa | Betwa | 1984 | 4.2 | 542 | 1,588 | 1,488 | | TE | 15.68 | 762.19 | | IRR. |
| Kuda | Local | Sehore | MP | Betwa | Betwa | 1984 | 1.94 | 232 | 736 | 685 | 29 | TE | 12.5 | 675 | | IRR |
| KumediTank | Local | Sehore | MP | Betwa | Betwa | 1986 | 4.22 | 535 | 1,510 | 1,326 | 15 | TE | 14.96 | 1,215 | | IRR |
| Machhariya | Local | Shivpuri | MP | Betwa | Betwa | 1980 | 83.5 | 343,530 | 18,980 | 15,710 | 551 | TE | 27.6 | 240 | | IRR. |
| Madai | Local | Shivpuri | MP | Betwa | Betwa | 1995 | 56.97 | 2,550 | 13,840 | 126 | 660 | TE | 33.8 | 1,980 | | I/WS |
| Madwajhari | Local | Shivpuri | MP | Betwa | Betwa | 1979 | 6.37 | 1,494 | 9,240 | 49,490 | 58 | TE | 13.51 | 130 | | IRR. |
| Makhani | Local | Shivpuri | MP | Betwa | Betwa | 1981 | 6.87 | 460 | 1,000 | 9,929 | 69 | TE | 12.19 | 732 | | IRR. |
| Mala | Local | Shivpuri | MP | Betwa | Betwa | 1911 | 47.16 | 3,580 | 3,580 | 3,191 | 396 | TE | 10.98 | 210 | | IRR. |
| Malavar | Local | Shivpuri | MP | Betwa | Betwa | 1913 | 37.81 | 1,730 | 3,864 | 3,793 | 312 | TE | 13.5 | 540 | | IRR. |
| Mehgaontola | | Tikamgarh | MP | Betwa | Betwa | 1968 | 29.2 | 2,816 | 10,248 | 6,688 | 96 | TE | 20.73 | 137 | | IRR. |
| Mohari | | Tikamgarh | MP | Betwa | Betwa | 1963 | 11.65 | | 1,911 | 1,341 | 41 | TE | 14.38 | 137 | | IRR. |
| Molipura | | Tikamgarh | MP | Betwa | Betwa | 1969 | 11.52 | 1,074 | 2,666 | 2,398 | 123 | TE | 17.1 | 330 | | IRR. |
| Moliyakhedi | | Tikamgarh | MP | Betwa | Betwa | 1976 | 7.88 | | 2,840 | 2,590 | 28 | TE | 12.5 | 1,189 | | IRR. |
| Momanpura | | Tikamgarh | MP | Betwa | Betwa | | 5.53 | | 1,560 | 410 | 70 | TE | 12.2 | 400 | | IRR. |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Submergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Narayanpura | Naren | Vidisha | MP | Betwa | Betwa | 1981 | 61.44 | 8,217 | 20,550 | 18,328 | 430 | TE | 29.85 | 3,567 | 479 | IRR |
| Narayanpura | Kethan | Vidisha | MP | Betwa | Betwa | 1975 | 64.75 | 3,690 | 19,157 | 17,574 | 226 | TE | 25.36 | 900 | 280 | IRR |
| Narola | Local | Vidisha | MP | Betwa | Betwa | 1968 | 17.35 | – | 6,880 | 6,331 | 108.67 | TE | 18.6 | 480 | 104 | IRR |
| Nawadpura T | Jawari | Vidisha | MP | Betwa | Betwa | 1968 | 2.88 | 357 | 1,160 | 1,159 | 55 | TE | 12 | 450 | 57 | IRR |
| Noonpani | Halali | Vidisha | MP | Betwa | Betwa | 1975 | 699 | 52,590 | 25,270 | 22,700 | 642 | TE | 29.56 | 945 | 678.27 | IRR |
| Pabra | Local | Mungawali | MP | Betwa | Betwa | 1916 | 7.15 | 108 | 2,410 | 2,369 | 122 | TE | 10.82 | 1,432 | | IRR. |
| Panagar | Local | Sehore | MP | Betwa | Betwa | 1984 | 1.94 | 232 | 736 | 685 | 29 | TE | 12.5 | 675 | | IRR |
| Panagar | Local | Sehore | MP | Betwa | Betwa | 1986 | 4.22 | 535 | 1,510 | 1,326 | 15 | TE | 14.96 | 1,215 | | IRR |
| Pillowa | Local | AshokNagar | MP | Betwa | Betwa | 1917 | 53.41 | 3,000 | 11,270 | 10,660 | 207 | TE | 14.63 | 2,700 | | I/WS |
| Raipura | Local | Hoshangabad | MP | Betwa | Betwa | 1984 | 6.48 | 200 | 2,820 | 2,450 | 86 | TE | 11.95 | 1,485 | | IRR |
| Rampurakhurd | Local | Raisen | MP | Betwa | Betwa | 1978 | 6.21 | 1,466 | 2,650 | 2,480 | 64 | TE | 16.46 | 894 | 38 | IRR |
| Ranjeet | kuhynala | Raisen | MP | Betwa | Betwa | 1958 | 8.68 | 6,573 | 1,646 | 1,520 | 97 | TE | 11.58 | 445 | | IRR |
| Rechhai | | | MP | Betwa | Betwa | 1963 | 3,496 | 8,666 | 11,250 | 11,006 | 170 | TE | 21.34 | 1,341 | | IRR. |
| VeerSagar | Local | Pichor | MP | Betwa | Betwa | 1911 | 47.16 | 3,580 | 3,580 | 3,191 | 396 | TE | 10.98 | 210 | | IRR. |
| VindhyaWasini | Local | Pichor | MP | Betwa | Betwa | 1913 | 37.81 | 1,730 | 3,864 | 3,793 | 312 | TE | 13.5 | 540 | | IRR. |
| Barwa Sagar | Barwa Nala | Jhansi | UP | Betwa | Betwa | 1694 | 52 | | 10,200 | 9,180 | 6,877 | TE | 21.03 | 1,067 | | I |
| Magar Pur | Local Drain | Jhansi | UP | Betwa | Betwa | 1694 | 18.13 | | 2,460 | 2,214 | 173 | TE | 10.2 | 739.1 | | I |
| Pachwara Lake | Local | Jhansi | UP | Betwa | Betwa | 1694 | 21.093 | | 6,150 | 5,850 | 41.04 | TE/PG | 13.72 | 208 | | I |
| Parichha | Betwa | Jhansi | UP | Betwa | Betwa | 1886 | 80.2 | | 78,760 | 77,170 | 21,547 | PG | 16.77 | 1,174.59 | | I |
| Dhekwan | Betwa | Jhansi | UP | Betwa | Betwa | 1909 | 194.3 | | 57,800 | 52,020 | 15,177 | PG | 18.97 | 2,970 | | I |
| Pahuj | Pahuj | Jhansi | UP | Betwa | Betwa | 1909 | 402 | | 18,250 | 18,210 | 1,528.2 | PG | 10.67 | 2,040 | 1,824 | I |
| Lachura | Sunhari | Hamirpur | UP | Betwa | Betwa | 1910 | 218.5 | | 20,640 | 10,560 | 14,444 | PG | 14.94 | 542.3 | | I |
| Siori Lake | Lakheri | Hamirpur | UP | Betwa | Betwa | 1911 | 19.9 | | 7,820 | 7,600 | 452.4 | TE | 13.94 | 2,306 | | I |
| Majhgawan | Gunchi nala | Hamirpur | UP | Betwa | Betwa | 1917 | | | 25,460 | 22,914 | 169.8 | TE | 19.43 | 1,402 | 37,800 | I |
| Barwar | Bora | Jhansi | UP | Betwa | Betwa | 1923 | 100.64 | | 33,780 | 31,650 | 2,831.3 | TE | 20.4 | 2,233 | 2,933.8 | I |
| Saprar | Saprar | Jhansi | UP | Betwa | Betwa | 1952 | 200.5 | | 76,200 | 65,700 | 1,143.32 | TE | 16.76 | 3,000 | | I |
| Govind Sagar | Shahjad | Lalit Pur | UP | Betwa | Betwa | 1953 | 247.88 | | 96,884 | 50,110 | 1,445 | TE | 18.29 | 3,606 | 13,406 | I |
| Matatila | Betwa | Jhansi | UP | Betwa | Betwa | 1964 | 138.85 | | 1,132,580 | 1,019,400 | 15,350 | TE | 45.72 | 6,315.15 | 5,012.05 | I/H |
| Keolari | Keolari | Hamirpur | UP | Betwa | Betwa | 1966 | 25.667 | | 7,570 | 7,230 | 254.06 | TE | 11.73 | 23,000 | | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Submergence ('000 $km^2$) | Gross capacity ('000 cu m) | Live capacity ('000 cu m) | Spillway capacity ('000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam ('000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chandrawal | Chandrawal | Hamirpur | UP | Betwa | Betwa | 1973 | 119.2 | | 34,731 | 30,665 | 1,252 | TE | 18.2 | 5,724 | 52,900 | I |
| Jamni | Jamni | Lalit Pur | UP | Betwa | Betwa | 1973 | 247.235 | | 92,490 | 84,020 | 2,521.25 | TE | 26.22 | 5,400 | | I |
| Rohini | Rohini | Lalit Pur | UP | Betwa | Betwa | 1983 | | | 12,110 | 10,899 | 290 | TE | 17.82 | 650 | | I |
| Khaprar | Khaprar | Jhansi | UP | Betwa | Betwa | 1985 | 15 | | 3,500 | 2,980 | 267.3 | TE | 11.2 | 1,100 | | I |
| Dongari | Pahuj | Jhansi | UP | Betwa | Betwa | 1986 | 19.2 | | 9,920 | 8,320 | 618 | TE | 13.72 | 2,760 | | I |
| Sajnam | Sajnam | Jhansi | UP | Betwa | Betwa | 1990 | 237.5 | | 83,500 | 74,250 | 2,000 | TE | 22.34 | 5,147 | | I |
| Shahjad | Shahjad | Lalit Pur | UP | Betwa | Betwa | 1992 | 299.3 | | 130,000 | 96,060 | 4,000 | TE | 29 | 4,160 | 2,624 | I |
| Pathrai | Pathrai | Jhansi | UP | Betwa | Betwa | U/C | 59.4 | | 123,770 | 78,500 | 1,263 | TE | 15.1 | 3,800 | | I |
| Sijar | Sijar | Jhansi | UP | Betwa | Betwa | UC | 22.5 | | 55,850 | 54,800 | 392.62 | TE | 13.8 | 1,900 | | I |
| Rajghat | Betwa | Lalitpur | UP | Betwa | Betwa | | 2,453 | | 2,172,000 | 1,945,000 | 33,893 | TE/ PG | 43.8 | 10,790 | | I/H |
| Pahari | Dhasan | Not known | UP | Dhasan | Betwa | 1912 | 80.3 | | 47,800 | 46,000 | 12,776 | PG | 10 | 580.95 | | I |
| **Storage Capacity of Betwa Sub-basin** | | | | | | | | | **4,922,912** | **4,373,265** | | | | | | |
| Akhajhiri | Local | Dhar | MP | Chambal | Chambal | 1988 | 2.36 | 316 | 416 | 375 | 59 | TE | 22.8 | 265 | | IRR. |
| Amahi | Local | Dhar | MP | Chambal | Chambal | 1976 | 8.18 | 558 | 2,410 | 1,700 | 94 | TE | 14.89 | 450 | | IRR. |
| Amiya Bahadurpur | Local | Dhar | MP | Chambal | Chambal | 1978 | 8 | 630 | 2,480 | 2,120 | 76 | TE | 15.04 | 508 | | IRR. |
| BandiaNalla | Local | Bhopal | MP | Chambal | Chambal | 1985 | 10.1 | 934 | 2,680 | 2,448 | 55 | TE | 11.33 | 900 | 86 | IRR |
| Banskheda | Local | Bhopal | MP | Chambal | Chambal | 1992 | 11.65 | 1,156 | 3,808 | 3,502 | 42.76 | TE | 13.71 | 108 | 1,820 | IRR |
| Barmandal | | Chhatarpur | MP | Chambal | Chambal | 1964 | 10.25 | 400 | 1,070 | 911 | 79 | TE | 10 | 2130 | | IRR. |
| Bishanda | Local | Dewas | MP | Chambal | Chambal | 1985 | 10.1 | 934 | 2,680 | 2,440 | 55 | TE | 11.33 | 900 | 86 | IRR |
| BodiT1 | Local | Dewas | MP | Chambal | Chambal | 1991 | 51.052 | 5,340 | 1,487 | 12,680 | 201 | TE | 14.9 | 2,438.42 | 448 | IRR |
| Borena | Local | Dhar | MP | Chambal | Chambal | 1988 | 2.36 | 316 | 416 | 375 | 59 | TE | 22.8 | 265 | | IRR. |
| Bori | Local | Dhar | MP | Chambal | Chambal | 1976 | 8.18 | 558 | 2,410 | 1,700 | 94 | TE | 14.89 | 450 | | IRR. |
| Chaidipura | Local | Dhar | MP | Chambal | Chambal | 1978 | 8 | 630 | 2,480 | 2,120 | 76 | TE | 15.04 | 508 | | IRR. |
| Chillar | Local | Dhar | MP | Chambal | Chambal | 1980 | 13.96 | 578 | 1,827 | 1,497 | 130 | TE | 11 | 530 | | IRR. |
| Dahod | Local | Guna | MP | Chambal | Chambal | 1985 | 124.3 | 4,870 | 37,500 | 35,151 | 1,556 | TE | 40.85 | 630 | | IRR. |
| Daroli | Local | Guna | MP | Chambal | Chambal | 1985 | 249.12 | 117 | 85,010 | 78,106 | 2,605 | TE | 40.15 | 670 | | WS |
| Datla | Local | Guna | MP | Chambal | Chambal | 1980 | 174.1 | 8,470 | 46,593 | 40,983 | 598 | TE | 30.5 | 825.39 | | IRR. |
| Dedla | Local | Guna | MP | Chambal | Chambal | 1917 | 89.03 | 4,337 | 15,038 | 14,184 | 1,450 | TE | 24.38 | 1,646 | | IRR. |
| DeepSagar | Local | Guna | MP | Chambal | Chambal | 1995 | 36.24 | 3,104 | 14,760 | 13,430 | 406 | TE | 25.55 | 1,285 | | IRR. |
| Deori | Local | Guna | MP | Chambal | Chambal | 1907 | 15.54 | 1,064 | 4,270 | 3,850 | 113 | TE | 14.45 | 720 | | I/WS |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Depalpur | Local | Guna | MP | Chambal | Chambal | 1986 | 6.22 | 554 | 1,557 | 1,481 | 76 | TE | 16.83 | 630 | | IRR. |
| Deri | Local | Guna | MP | Chambal | Chambal | 1992 | 2.95 | 243 | 797 | 760 | 43 | TE | 16.43 | 526 | | IRR. |
| DhablaDewan | Local | Guna | MP | Chambal | Chambal | 1986 | 6.86 | 397 | 1,530 | 1,448 | 81 | TE | 15.93 | 680 | | IRR. |
| DhablaDewan | Local | Guna | MP | Chambal | Chambal | 1984 | 11.35 | 1,034 | 2,582 | 2,422 | 120 | TE | 15.61 | 450 | | IRR. |
| Dhamnod | Local | Guna | MP | Chambal | Chambal | 1915 | 2.59 | 220 | 703 | 635 | 40 | TE | 10.28 | 690 | | IRR. |
| Dhamnod | Local | Guna | MP | Chambal | Chambal | 1917 | 30.02 | 2,140 | 6,090 | 5,476 | 140 | TE | 11.88 | 1,380 | | IRR. |
| Dhandibada | Sukait | Guna | MP | Chambal | Chambal | 2002 | 43.08 | 2,810 | 8,860 | 8,250 | 466,650 | TE | 13.89 | 1,390 | 281 | IRR. |
| Dholka | Koil | Gwalior | MP | Chambal | Chambal | 1953 | 54.37 | 279 | 7,381 | 7,206 | 37 | PG | 11.89 | 780 | | Feeder |
| DongerBodi | Local | Indore | MP | Chambal | Chambal | 1976 | 14 | 1,150 | 2,493 | 2,158 | 117 | TE | 13.3 | 950 | | IRR. |
| Doraha | Local | Indore | MP | Chambal | Chambal | 1980 | 35 | 465 | 567 | 534 | 50 | TE | 12.46 | 1,966.5 | | IRR. |
| Doraha | Local | Indore | MP | Chambal | Chambal | 1975 | 2.51 | 220 | 623 | 583 | 39 | TE | 10.67 | 810 | | IRR. |
| Dunguna | Local | Indore | MP | Chambal | Chambal | 1931 | 103.56 | 8,340 | 22,460 | 13,390 | 624 | TE | 10.05 | 3,240 | | IRR. |
| Gambhir (PHE) | Gambhir | Indore | MP | Chambal | Chambal | 1939 | 485 | 486 | 15,963 | 146 | 707 | TE | 18 | 1,850 | 14,650 | WS |
| Gryaspura | Local | Mandsaur | MP | Chambal | Chambal | 1960 | 23,025 | 60,000 | 73,220 | 67,974 | 21,238 | PG | 62.17 | 514 | | I/Hydl |
| GuradiaRoopchand | Local | Mandsaur | MP | Chambal | Chambal | 1988 | 6.45 | 343 | 1,035 | 880 | 41 | TE | 15.79 | 412.5 | | IRR. |
| GuradiaRoopchand | Local | Mandsaur | MP | Chambal | Chambal | 1988 | 8.83 | 1,164 | 2,963 | 1,812 | 29 | TE | 15.85 | 1,410 | | IRR. |
| Gurari | Local | Mandsaur | MP | Chambal | Chambal | 1956 | 9.32 | 107 | 2,197 | 2,061 | 104 | TE | 19.26 | 751 | | IRR. |
| GwalSagar | Local | Mandsaur | MP | Chambal | Chambal | 1954 | 24.58 | 2,007 | 5,657 | 5,269 | 216 | TE | 18.9 | 792.48 | | IRR. |
| Harridih | Local | Mandsaur | MP | Chambal | Chambal | 1979 | 8.8 | 321 | 1,200 | 1,028 | 99 | TE | 16.55 | 457.32 | | IRR. |
| Harsi | Local | Mandsaur | MP | Chambal | Chambal | 1982 | 14.75 | 891 | 2,660 | 2,300 | 146 | TE | 16.23 | 1,250 | | IRR. |
| Harsi | Local | Mandsaur | MP | Chambal | Chambal | 2000 | 14.75 | 998 | 3,554 | 2,421 | 146 | TE | 12.75 | 960 | | IRR. |
| Hasduamudar | Local | Mandsaur | MP | Chambal | Chambal | 2003 | 9.14 | 418 | 1,580 | 1,350 | 105 | TE | 12.01 | 815 | | IRR. |
| Jamunia | Local | Raisen | MP | Chambal | Chambal | 2002 | 2.98 | 876 | 972 | 900 | 1,555 | TE | 19.63 | 369 | 862 | IRR |
| Jamunia | Chhapi | Rajgarh | MP | Chambal | Chambal | 1972 | 86.8 | 4,825 | 15,740 | 13,540 | 1,305 | TE | 17.08 | 1,829 | | IRR. |
| JamuniyaRao | Dudhi | Rajgarh | MP | Chambal | Chambal | 2001 | 119.41 | 5,700 | 30,770 | 20,810 | 1,310 | TE/CS | 16.25 | 3,570 | | IRR. |
| Jawahargarh | Puchi | Rajgarh | MP | Chambal | Chambal | 1992 | 20.73 | 1,865 | 7,264 | 6,520 | 189 | TE | 16.1 | 915 | | IRR. |
| Jawari | Local | Rajgarh | MP | Chambal | Chambal | 1982 | 1.91 | 277 | 1,226 | 1,179 | 33 | TE | 15.32 | 555 | | IRR. |
| Jhaloni | Local | Rajgarh | MP | Chambal | Chambal | 1991 | 3.11 | 336 | 1,062 | 1,030 | 46 | TE | 13.41 | 604 | | IRR. |
| Jhaloni | Local | Rajgarh | MP | Chambal | Chambal | 1979 | 5.47 | 862 | 2,134 | 2,060 | 80 | TE | 13.8 | 953 | | IRR. |
| Jhalpipli | Local | Rajgarh | MP | Chambal | Chambal | 1975 | 11.65 | 238 | 6,223 | 5,827 | 37 | TE | 12.19 | 2,506 | | IRR. |
| Jhapdi | Local | Rajgarh | MP | Chambal | Chambal | 1975 | 3.37 | 258 | 808 | 730 | 48 | TE | 17.1 | 640 | | IRR. |
| Jhapdi | Local | Rajgarh | MP | Chambal | Chambal | 1968 | 3.18 | 372 | 999 | 932 | 67 | TE | 11.89 | 1,051.56 | | IRR. |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of comple-tion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jhikri | Local | Rajgarh | MP | Chambal | Chambal | 1991 | 8.54 | 855 | 2,301 | 2,108 | 78 | TE | 11.5 | 1,676 | | IRR. |
| Jojharpur | Local | Rajgarh | MP | Chambal | Chambal | 1982 | 2.85 | 290 | 1,081 | 1,006 | 43 | TE | 11.58 | 762 | | IRR. |
| Julwania | Local | Rajgarh | MP | Chambal | Chambal | 1982 | 5.18 | 355 | 1,109 | 986 | 59 | TE | 14.97 | 556 | | IRR. |
| Julwania | Local | Rajgarh | MP | Chambal | Chambal | 1981 | 2.7 | 281 | 920 | 817 | 54 | TE | 15.31 | 603 | | IRR. |
| Jumnera | Local | Rajgarh | MP | Chambal | Chambal | 1972 | 2.72 | 300 | 776 | 749 | 20 | TE | 10.05 | 1,007.28 | | IRR. |
| Jumnera | Local | Rajgarh | MP | Chambal | Chambal | 2001 | 4.35 | 415 | 1,330 | 1,225 | 80 | TE | 13.21 | 845 | | IRR. |
| Junapani | Local | Rajgarh | MP | Chambal | Chambal | 2002 | 2.59 | 260 | 789 | 728 | 57 | TE | 13.21 | 655 | | IRR. |
| Kabadia | Local | Rajgarh | MP | Chambal | Chambal | 2002 | 14.28 | 967 | 3,484 | 3,071 | 176 | TE | 19.75 | 915 | 86 | IRR. |
| KacheriFeeder | Gunjari | Rajgarh | MP | Chambal | Chambal | 2002 | 26.8 | 1,200 | 4,824 | 4,174 | 327 | TE | 20.38 | 975 | 176 | IRR. |
| Kadodia | Local | Rajgarh | MP | Chambal | Chambal | 2002 | 5.9 | 620 | 1,407 | 1,256 | 88 | TE | 18.79 | 718 | 129 | IRR. |
| Kakarhai | Local | Rajgarh | MP | Chambal | Chambal | 2003 | 8.58 | 730 | 3,881 | 3,358 | 275 | TE | 20.3 | 435 | 209 | IRR. |
| Kaketo | Local | Rajgarh | MP | Chambal | Chambal | 2003 | 14.68 | 719 | 2,148 | 1,787 | 208 | TE | 16.4 | 536 | 77 | IRR. |
| Kaketo | Local | Ratlam | MP | Chambal | Chambal | 1984 | 183.88 | 5,972 | 54,268 | 49,916 | 1,473 | TE | 36.86 | 1,360 | | IRR./WS |
| Kalrewa | Local | Ratlam | MP | Chambal | Chambal | 1981 | 7.76 | 490 | 1,520 | 1,341 | 90 | TE | 12.21 | 540 | | IRR. |
| Kalyanpura | Local | Ratlam | MP | Chambal | Chambal | 1997 | 90.88 | 396 | 13,570 | 11,305 | 324 | TE | 18.3 | 820 | 1,900 | IRR. |
| KheriaPunawali | Utawali | Sehore | MP | Chambal | Chambal | 1983 | 49.21 | 4,959 | 18,060 | 15,580 | 386 | TE | 25 | 875 | | IRR |
| Khor | Local | Sehore | MP | Chambal | Chambal | 1938 | 24.59 | 3,770 | 12,496 | 11,327 | 216 | TE | 14.12 | 2,160 | | IRR |
| Khor | Local | Sehore | MP | Chambal | Chambal | 1980 | 6.8 | 1,160 | 3,794 | 3,544 | 36 | TE | 14.1 | 743.9 | | IRR |
| Kohru | Local | Sehore | MP | Chambal | Chambal | 1976 | 4.1 | 347 | 1,250 | 1,158 | 56 | TE | 18.18 | 792.68 | | IRR |
| Koka | Local | Sehore | MP | Chambal | Chambal | 1979 | 7.35 | 788 | 3,164 | 3,114 | 1,645 | TE | 12.8 | 1,127.76 | | IRR |
| Kolwakhedi | Utawali | Sehore | MP | Chambal | Chambal | 1988 | 22.5 | 1,602 | 4,259 | 4,015 | 144 | TE | 12.8 | 2,040 | | IRR |
| Konajhir | Local | Sehore | MP | Chambal | Chambal | 1985 | 9.31 | 233 | 3,070 | 2,830 | 104 | TE | 12.31 | 870 | | IRR |
| KoopTank | Local | Sehore | MP | Chambal | Chambal | 1984 | 5.18 | 631 | 1,725 | 1,608 | 55 | TE | 10.97 | 1,050 | | IRR |
| Kosduna | Local | Sehore | MP | Chambal | Chambal | 1984 | 5.18 | 649 | 1,725 | 1,589 | 67 | TE | 10.94 | 1,127.76 | | IRR |
| Kuari | Local | Sehore | MP | Chambal | Chambal | | 3.5 | 1,140 | 1,035 | 1,005 | 26 | TE | 11.07 | 1,200 | | IRR |
| Kulwa | Local | Sehore | MP | Chambal | Chambal | 1981 | 5.7 | 650 | 2,090 | 1,840 | 32 | TE | 14.47 | 1,890 | | IRR |
| Kumharwara | Local | Sehore | MP | Chambal | Chambal | 1958 | 3.89 | | 1,307 | 1,245 | 38 | TE | 10.3 | 1,415.38 | | IRR |
| Kumharwara | Local | Sehore | MP | Chambal | Chambal | UC | 4.29 | 420 | 1,327 | 1,225 | 47 | TE | 11.43 | 782 | | IRR |
| KundaNala | Local | Sehore | MP | Chambal | Chambal | 2002 | 3.36 | 365 | 1,038 | 950 | 29 | TE | 11.43 | 892 | | IRR |
| KundaNala | Local | Sehore | MP | Chambal | Chambal | 1985 | 124.3 | 4,870 | 37,500 | 35,160 | 1,556 | TE | 40.85 | 630 | – | IRR |
| Kundujeta | Local | Sehore | MP | Chambal | Chambal | 1985 | 249.12 | | 85,010 | 78,106 | 2,605 | TE | 40.15 | 670 | | I/WS |
| Kundujeta | Local | Shajapur | MP | Chambal | Chambal | | 16.18 | 1,705 | 2,550 | 2,311 | 47 | TE | 10.06 | 1,860 | | IRR |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of comple-tion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kusmeli | Local | Shajapur | MP | Chambal | Chambal | 1916 | 33.28 | 1,354 | 3,240 | 3,087 | 116 | TE | 10.02 | 2,148 | 182 | IRR |
| Kusmeli | Local | Shajapur | MP | Chambal | Chambal | 1980 | 2.33 | 300 | 565 | 499 | 34 | TE | 12.25 | 930 | 75 | IRR |
| Kutarinalla | Local | Shajapur | MP | Chambal | Chambal | 1982 | 2.06 | 142 | 441 | 389 | 34 | TE | 16.6 | 175.5 | 33 | IRR |
| Kutdhar | Local | Shajapur | MP | Chambal | Chambal | | 3.89 | 448 | 1,186 | 1,086 | 54 | TE | 10.99 | 507 | | IRR |
| Laduna | Local | Shajapur | MP | Chambal | Chambal | 2000 | 4.92 | 546 | 1,519 | 1,394 | 55 | TE | 11.7 | 1,020 | 77 | IRR |
| Lakhundar | Local | Shajapur | MP | Chambal | Chambal | 1916 | 35 | 2,250 | 4,280 | 3,850 | 280 | TE | 10.87 | 2,225 | 189 | IRR |
| Larpur | Tiller | Shajapur | MP | Chambal | Chambal | 1987 | 174 | 9,752 | 52,197 | 31,120 | 1,430 | TE | 26.54 | 2,220 | 683 | IRR |
| Larpur | Chiller | Shajapur | MP | Chambal | Chambal | 1972 | 98.42 | 8,460 | 34,790 | 31,110 | 687 | TE | 30.48 | 2,866 | 683 | IRR |
| Lasudiakangar | Local | Shajapur | MP | Chambal | Chambal | 1974 | 11.48 | 673 | 2,860 | 2,426 | 127 | TE | 20.72 | 821.6 | 88 | IRR |
| LasurTank | Local | Shajapur | MP | Chambal | Chambal | 2000 | 82.95 | 7,800 | 32,150 | 30,650 | 632 | TE | 23.3 | 2,385 | 830 | IRR |
| Laxmikheda | Local | Shajapur | MP | Chambal | Chambal | 1980 | 45.34 | 2,632 | 11,210 | 10,120 | 340 | TE | 25.87 | 894 | 298 | IRR |
| LilgiBundBela | Local | Shajapur | MP | Chambal | Chambal | 1989 | 21.77 | 1,540 | 4,080 | 3,560 | 198 | TE | 22.29 | 1,230 | 20 | IRR |
| LilgiBundBela | Local | Shajapur | MP | Chambal | Chambal | 1983 | 15.4 | 1,102 | 3,742 | 3,372 | 123 | TE | 21.65 | 1,410 | 18 | IRR |
| LilgiReservoir | Local | Shajapur | MP | Chambal | Chambal | | 11.39 | | 1,473 | 1,473 | 68 | TE | 22.18 | 808 | | IRR |
| Limbi | Local | Shajapur | MP | Chambal | Chambal | 1980 | 5.18 | 277 | 1,017 | 911 | 67 | TE | 17.84 | 289.16 | 4 | IRR |
| LokpalSagar | Local | Shajapur | MP | Chambal | Chambal | 1981 | 6.91 | 506 | 1,370 | 1,212 | 104 | TE | 14.24 | 510 | 40 | IRR |
| LokpalSagar | Local | Shajapur | MP | Chambal | Chambal | 1980 | 7.77 | 1,424 | 1,694 | 1,497 | 72 | TE | 11.4 | 1,425 | 134 | IRR |
| Lolki | Local | Shajapur | MP | Chambal | Chambal | 1992 | 3.88 | 380 | 1,147 | 1,054 | 51 | TE | 15.63 | 703 | 80 | IRR |
| Longerpura | Local | Shajapur | MP | Chambal | Chambal | 1983 | 4.4 | 371 | 1,226 | 1,112 | 59 | TE | 14 | 1,050 | 73 | IRR |
| Longerpura | Local | Shajapur | MP | Chambal | Chambal | 1989 | 3.36 | 350 | 976 | 894 | 49 | TE | 14.59 | 720 | 80 | IRR |
| LowerPalakmati | Local | Shajapur | MP | Chambal | Chambal | 1989 | 6.3 | 817 | 1,900 | 1,740 | 55 | TE | 14.39 | 1,545 | 91 | IRR |
| LowerPalakmati | Local | Shajapur | MP | Chambal | Chambal | 1985 | 6.14 | 564 | 1,350 | 1,186 | 76 | TE | 10.1 | 576 | 66 | IRR |
| Makroda | Local | Shivpuri | MP | Chambal | Chambal | 1982 | 14.98 | 10,290 | 2,330 | 19,730 | 148 | TE | 11.68 | 763 | | IRR. |
| Manikheda | Local | Shivpuri | MP | Chambal | Chambal | 1914 | 11 | 640 | 2,270 | 2,260 | 96 | TE | 10.37 | 640 | | IRR. |
| Manikheda | Local | Shivpuri | MP | Chambal | Chambal | 1911 | 26.92 | 1,880 | 7,440 | 7,193 | 148 | TE | 12.2 | 1,280 | | IRR. |
| MudiaKheri | Local | Tikamgarh | MP | Chambal | Chambal | | | | | | | TE | 12 | 1,210 | | IRR |
| Mundri | Local | Ujjain | MP | Chambal | Chambal | 1978 | 31.07 | 6,854 | 7,547 | 6,862 | 241 | TE | 22.78 | 1,419 | | IRR. |
| Mutwan | Gandhi | Ujjain | MP | Chambal | Chambal | 1980 | 82.65 | 8,146 | 25,230 | 22,350 | 533 | TE | 18.9 | 1,859 | | IRR. |
| Nagdagajora | Local | Ujjain | MP | Chambal | Chambal | 1982 | 34.95 | 1,874 | 6,450 | 5,550 | 130 | TE | 21.33 | 701 | | IRR. |
| Nagdagajora | Kalisindh | Ujjain | MP | Chambal | Chambal | 1979 | 69.4 | 2,510 | 7,560 | 5,110 | 200 | TE | 17.72 | 1,275 | | IRR. |
| NagdaNalla | Local | Ujjain | MP | Chambal | Chambal | 1981 | 60.52 | 3,980 | 12,460 | 10,330 | 200 | TE | 18.6 | 3,450 | | IRR. |
| Nagri | Local | Ujjain | MP | Chambal | Chambal | 1985 | 6.47 | 478 | 1,555 | 1,113 | 56 | TE | 10.44 | 1,320 | | IRR. |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Naharkheda | Local | Ujjain | MP | Chambal | Chambal | 1980 | 20.48 | 951 | 2,675 | 2,360 | 189 | TE | 13.1 | 960 | | IRR. |
| Nakheri | Local | Ujjain | MP | Chambal | Chambal | 1987 | 3.52 | 234 | 830 | 742 | 51 | TE | 12.19 | 570 | | IRR. |
| Naktora | Local | Ujjain | MP | Chambal | Chambal | 1908 | 39.08 | 2,160 | 5,830 | 4,943 | 256 | TE | 11.89 | 1,560 | | IRR. |
| Nalajhiri | Local | Ujjain | MP | Chambal | Chambal | 1984 | 4.76 | 269 | 850 | 776 | 62 | TE | 11.8 | 840 | | IRR. |
| NalTank | Local | Ujjain | MP | Chambal | Chambal | 1957 | 5.7 | 337 | 1,105 | 1,065 | 72 | TE | 10.06 | 840 | | IRR. |
| Nandanwara | Local | Ujjain | MP | Chambal | Chambal | 2001 | 9.25 | 828 | 1,884 | 1,760 | 103 | TE | 12.19 | 870 | | IRR. |
| Nandkho | Local | Ujjain | MP | Chambal | Chambal | 2001 | 20.72 | 1,023 | 3,500 | 2,950 | 189 | TE | 13.88 | 990 | | IRR. |
| Padari | Local | Chachoda | MP | Chambal | Chambal | 1915 | 2.59 | 220 | 703 | 635 | 40 | TE | 10.28 | 690 | | IRR. |
| Padaria | Utawali | Sehore | MP | Chambal | Chambal | 1983 | 49.21 | 4,959 | 18,060 | 15,580 | 386 | TE | 25 | 875 | | IRR |
| Padhar | Local | Sehore | MP | Chambal | Chambal | 1938 | 24.59 | 3,770 | 12,496 | 11,327 | 216 | TE | 14.12 | 2,160 | | IRR |
| Pagara | Local | Sehore | MP | Chambal | Chambal | 1984 | 5.18 | 631 | 1,725 | 1,608 | 55 | TE | 10.97 | 1,050 | | IRR |
| Panpura | Local | Shajapur | MP | Chambal | Chambal | 1980 | 5.18 | 277 | 1,017 | 911 | 67 | TE | 17.84 | 289.16 | 4 | IRR |
| Patharehta | Local | Indore | MP | Chambal | Chambal | 1980 | 35 | 465 | 567 | 534 | 50 | TE | 12.46 | 1,966.5 | | IRR. |
| Patia | Local | Mandsaur | MP | Chambal | Chambal | 1956 | 9.32 | 107 | 2,197 | 2,061 | 104 | TE | 19.26 | 751 | | IRR. |
| Pdamasagar | Local | Mandsaur | MP | Chambal | Chambal | 1982 | 14.75 | 891 | 2,660 | 2,300 | 146 | TE | 16.23 | 1,250 | | IRR. |
| Phugawadi | Local | Shajapur | MP | Chambal | Chambal | | 16.18 | 1,705 | 2,550 | 2,311 | 47 | TE | 10.06 | 1,860 | | IRR |
| Phugawadi | Local | Shajapur | MP | Chambal | Chambal | 1916 | 33.28 | 1,354 | 3,240 | 3,087 | 116 | TE | 10.02 | 2,148 | 182 | IRR |
| PipariyaJagroj | Local | Raghogarh | MP | Chambal | Chambal | 1907 | 15.54 | 1,064 | 4,270 | 3,850 | 113 | TE | 14.45 | 720 | | I/WS |
| Pipliyapada | Local | Sehore | MP | Chambal | Chambal | 1976 | 4.1 | 347 | 1,250 | 1,158 | 56 | TE | 18.18 | 792.68 | | IRR |
| Pipliyapada | Local | Sehore | MP | Chambal | Chambal | 1985 | 9.31 | 233 | 3,070 | 2,830 | 104 | TE | 12.31 | 870 | | IRR |
| Piploda | Local | Sehore | MP | Chambal | Chambal | | 3.5 | 1,140 | 1,035 | 1,005 | 26 | TE | 11.07 | 1,200 | | IRR |
| Piploda | Local | Sehore | MP | Chambal | Chambal | 1958 | 3.89 | | 1,307 | 1,245 | 38 | TE | 10.3 | 1,415.38 | | IRR |
| Piplyakala | Local | Dewas | MP | Chambal | Chambal | 1977 | 8.8 | 836 | 2,476 | 2,343 | 100 | TE | 11.5 | 1,500 | | IRR |
| PipraniNo.2T | Local | Shajapur | MP | Chambal | Chambal | 1992 | 3.88 | 380 | 1,147 | 1,054 | 51 | TE | 15.63 | 703 | 80 | IRR |
| PipraniNo.2T | Local | Shajapur | MP | Chambal | Chambal | 1983 | 4.4 | 371 | 1,226 | 1,112 | 59 | TE | 14 | 1,050 | 73 | IRR |
| Poiadonger | Local | Dhar | MP | Chambal | Chambal | 1983 | 2.32 | | 530 | 482 | | TE | 12.4 | 540 | | IRR. |
| Ramova | Local | Karera | MP | Chambal | Chambal | 1911 | 26.92 | 1,880 | 7,440 | 7,193 | 148 | TE | 12.2 | 1,280 | | IRR. |
| Rampur | Koil | Gwalior | MP | Chambal | Chambal | 1953 | 54.37 | 279 | 7,381 | 7,206 | 37 | PG | 11.89 | 780 | | Feeder |
| Rampur | Local | Shajapur | MP | Chambal | Chambal | 1916 | 35 | 2,250 | 4,280 | 3,850 | 280 | TE | 10.87 | 2,225 | 189 | IRR |
| Rampura | Chhapi | Rajgarh | MP | Chambal | Chambal | 1972 | 86.8 | 4,825 | 15,740 | 13,540 | 1,305 | TE | 17.08 | 1,829 | | IRR. |
| Rampura | Local | Rajgarh | MP | Chambal | Chambal | 1982 | 2.85 | 290 | 1,081 | 1,006 | 43 | TE | 11.58 | 762 | | IRR. |
| Rechhai | Local | Dewas | MP | Chambal | Chambal | 1997 | 10.1 | 532 | 3,180 | 2,911 | 110 | TE | 16.58 | 425 | | IRR |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of comple-tion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Renjhari | | | MP | Chambal | Chambal | 1964 | 10.25 | 400 | 1,070 | 911 | 79 | TE | 10 | 2,130 | | IRR. |
| Rjagarh | | | MP | Chambal | Chambal | 1921 | 19.42 | 1,470 | 4,810 | 4,507 | 53 | TE | 13.26 | 1,368.5 | | IRR. |
| Sendpa | Local | Sheopur | MP | Chambal | Chambal | 1934 | 236 | 8,185 | 55,700 | 40,050 | 1,246 | TE | 16.7 | 1,158 | | IRR. |
| Sidhkhad | Local | Guna | MP | Chambal | Chambal | 1917 | 89.03 | 4,337 | 15,038 | 14,184 | 1,450 | TE | 24.38 | 1,646 | | IRR. |
| Sikuwa | Local | Dewas | MP | Chambal | Chambal | 1916 | 19.2 | 173 | 4,230 | 4,100 | 181 | TE | 11 | 1,470 | | IRR |
| SurajmalJain | Local | Depalpur | MP | Chambal | Chambal | 1931 | 103.56 | 8,340 | 22,460 | 13,390 | 624 | TE | 10.05 | 3,240 | | IRR. |
| Tons Barrage | Local | Sabalgarh | MP | Chambal | Chambal | 1908 | 60.63 | 1,792 | 5,469 | 5,462 | 423 | TE | 13.39 | 2,255 | | IRR. |
| Umariya | Local | Sabalgarh | MP | Chambal | Chambal | 1899 | 106 | 2,183 | 3,823 | 3,433 | 642 | TE/PG | 10.67 | 1,052 | | IRR. |
| Virhana | Local | Dhana | MP | Chambal | Chambal | 1914 | 11 | 640 | 2,270 | 2,260 | 96 | TE | 10.37 | 640 | | IRR. |
| Govindpura | | Katni | MP | Chambal | Chambal | 1917 | 5.18 | 1,000 | 1,393 | 1,236 | 72 | TE | 11.93 | 1,073 | | IRR. |
| Rajsamand | Gomti Banas | Rajsamand | RJ | Banas | Chambal | 1671 | 18.1 | | 107,100 | 98,650 | 1,621 22.351 | TE | 39.2 | 5,585.05 | | I |
| Jai Samand | Gomti | Udaipur | RJ | Banas | Chambal | 1730 | 56 | | 566,000 | 163,000 | 4,706 | TE/PG | 41.1 | 457.4 | | I |
| Swaroop Sagar | Berach | Girwa | RJ | Banas | Chambal | 1795 | 4.18 | | 13,670 | 9,000 | 564 | TE | 22 | 660 | | I |
| Hingonia | Banas | Phagi | RJ | Banas | Chambal | 1862 | | | 7,523 | 6,771 | | TE | 15.5 | – | NA | – |
| Chandrana | Banganga | Dausa | RJ | Khri | Chambal | 1871 | | | 4,930 | 4,437 | 1,203 | TE | 11 | – | 4,810 | I |
| Kharad | Banganga | JPR – Ramgarh | RJ | Khri | Chambal | 1877 | | | 11,805 | 10,625 | | TE | 29.5 | – | – | – |
| Kalakh Sagar | Local nallah | Jaipur | RJ | Banas | Chambal | 1883 | | | 20,000 | 16,500 | | TE | 13 | | | I |
| Madho Sagar | Banganga | Sikrai Ramgarh | RJ | Khri | Chambal | 1887 | | | 22,603 | 20,343 | | TE | 14.63 | 2,440 | NA | – |
| Fateh Sagar | Berach | Girwa | RJ | Banas | Chambal | 1889 | 2.42 | | 12,080 | 6,990 | 135 | TE | 21 | | | I/S |
| Buchra | Sabi | Kot-putali | RJ | Khri | Chambal | 1889 | | | 16,360 | 14,724 | 731 | T | 16.31 | 366 | NA | I |
| Chaparwara | Banas | Dudu | RJ | Banas | Chambal | 1894 | | | 35,000 | 35,000 | 800 | TE | 13 | 200 | NA | I |
| Sainthal Sagar | Banganga | Dausa | RJ | Khri | Chambal | 1898 | | | 13,705 | 12,335 | | TE | 17 | 4,180 | 12,800 | – |
| Sheel Ki Dungri | Banas | Jaipur | RJ | Banas | Chambal | 1900 | | | 4,160 | 3,744 | | TE | 19.8 | 1,981 | – | – |
| Ram Garh | Banqanga | Jamuwa JPR | RJ | Khri | Chambal | 1901 | | | 58,970 | 58,970 | 2,100 | TE | 26 | | | I |
| Mandal | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1903 | 0.214 | | 13,877 | 11,895 | 1,300 | TE | 26 | 1,825 | | I/S |
| Dheel | Morel | Bonli | RJ | Banas | Chambal | 1911 | | | 25,230 | 25,230 | | TE | 27.62 | 655 | | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Submergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bhopal Sagar | Berach | Kapasan | RJ | Banas | Chambal | 1936 | 8.19 | | 18,540 | 18,400 | 645 | TE | 28 | 287 | | I |
| Chittoli | Sabi | Virat Nagar | RJ | Khri | Chambal | 1950 | | | 24,536 | 22,082 | | TE | 19.5 | – | NA | – |
| Govta | Manali | Mandal Garh | RJ | Banas | Chambal | 1955 | | | 6,850 | 6,850 | 894 | TE | 18 | 168 | | I |
| Patan (Deosagar) | Local Nalla | Patan | RJ | Banas | Chambal | 1956 | | | 6,930 | 6,237 | 457.05 | TE | 13.4 | 1,652 | | I |
| Surwal | Gambhir | S.Modhopur | RJ | Chambal | Chambal | 1956 | 9.85 | | 22,880 | 22,280 | 609 | TE | 32 | 183 | | I |
| Bagolia | Berach | Mav1i | RJ | Banas | Chambal | 1956 | 3.5 | | 19,400 | 13,350 | 827 | TE | 12.7 | 3,079 | | I |
| Kalisil | Kalisil Banas | Sapotru | RJ | Banas | Chambal | 1956 | | | 41,700 | 37,250 | 889 | TE | 25 | 2,560 | | I |
| Man Sarowar | Chambal | Khandar | RJ | Chambal | Chambal | 1957 | 4.65 | | 13,650 | 12,260 | 407 | TE | 26 | 378.65 | | I |
| Paibala Pura | Mej River | Nainwa | RJ | Chambal | Chambal | 1957 | 9.4 | | 10,200 | 10,000 | 632 | TE | 14.63 | 3,644.52 | | I |
| Juggar | Juggar Banas | Hindaun | RJ | Khri | Chambal | 1957 | | | 39,460 | 34,850 | 769 | TE | 21 | 239.26 | | I |
| Ora | Khari | Sheoganj | RJ | Banas | Chambal | 1957 | 7.46 | | 22,650 | 22,280 | 836 | TE | 20.12 | 5,618.87 | | I |
| Bundika Gothra | Mej River | Hindoli | RJ | Chambal | Chambal | 1957 | 6.7 | | 28,400 | 28,400 | 857 | TE/PG | 20.14 | 2,613.94 | | I |
| Sareri | Khari | Bhilwara | RJ | Banas | Chambal | 1957 | 52.2 | | 55,800 | 55,010 | 1,604 | TE/PG | 42 | 3,630 | | I |
| Khari | Khari | Asind | RJ | Banas | Chambal | 1957 | 8.84 | | 38,940 | 33,280 | 1,911 | TE/PG | 17.67 | 2,391 | | I |
| Arwar | Khari | Shahpura | RJ | Banas | Chambal | 1957 | 18.8 | | 47,910 | 47,770 | 2,761 | TE/PG | 15.8 | 1,112.6 | | I |
| Pachki Baori | Began | Bundi | RJ | Chambal | Chambal | 1957 | | | 5,600 | 5,600 | | TE | 19 | 954 | | I |
| Kala Bhala | Khari | Deogarh | RJ | Chambal | Chambal | 1958 | | | 4,240 | 3,870 | 351 | TE | 14.06 | 979 | | I |
| Bhimlat | Mangli | Bundi | RJ | Chambal | Chambal | 1958 | | | 10,800 | 10,700 | 442 | TE/PG | 17 | 274 | | I |
| Nandsamand | Banas | Nathwara | RJ | Banas | Chambal | 1958 | 4.4 | | 21,200 | 20,600 | 3,240 | TE | 23 | 1,733.89 | | I |
| Meja | Kothari | Mandal | RJ | Banas | Chambal | 1958 | 26.5 | | 96,220 | 91,720 | 5,781 | TB/PG | 19.2 | 1,270 | | I |
| Gudha | Mejchambal | Hindoli | RJ | Chambal | Chambal | 1958 | | | 95,650 | 93,700 | 5,883 | TE | 25 | 2,760 | | I |
| Matrakundia | Kotharia | Bhilwara | RJ | Banas | Chambal | 1958 | | | 49,986 | 44,987 | 8,240 | TE/PG | 16.67 | | | I |
| Gambhiri | Berach | Nimbahera | RJ | Banas | Chambal | 1958 | 20.57 | | 76,400 | 65,100 | 10,800 | TE | 21 | 611.12 | | I |
| Nagdi | Nagdi | Jahazpur | RJ | Banas | Chambal | 1959 | | | 5,150 | 5,090 | 199 | TE | 15 | 805 | | I |
| Galwa | Galwa | Uniara | RJ | Banas | Chambal | 1960 | | | 52,790 | 52,440 | 3,240 | TE | 16.08 | 6,068 | | I |
| Mashi | Bandi | Newai | RJ | Banas | Chambal | 1960 | 10.62 | | 48,100 | 35,117 | 11,954 | TE | 12.88 | 2,103 | | I |
| Kota Barrage | Chambal | Kota | RJ | Chambal | Chambal | 1960 | 4.84 | | 108,060 | 245,500 | 21,225 | TE | 51.9 | 551.68 | | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence ('000 $km^2$) | Gross capacity ('000 cu m) | Live capacity ('000 cu m) | Spillway capacity ('000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam ('000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atawara | Banas | Gangapur | RJ | Banas | Chambal | 1961 | 0.51 | | 5,235 | 5,094 | 402 | TE | 10.36 | 2,671 | NA | I |
| Banakiya | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1962 | 5.5 | | 9,439 | 9,269 | 849.33 | TE | 12.92 | 2,555 | NA | I |
| Alnia | Alnia Hukud | Ladpura | RJ | Chambal | Chambal | 1962 | 12.8 | | 43,700 | 43,710 | 1,325 | PG | 14 | 1,023.2 | | I |
| Bithan | Banas | Jaswantpur | RJ | Banas | Chambal | 1963 | | | 6,390 | 6,000 | 354 | TE | 14 | 706 | | I |
| Parbati Dam | Chambal | Bacera | RJ | Chambal | Chambal | 1963 | 23 | | 115,200 | 102,800 | 1,763 | TE/PG | 28.11 | 2,318 | | I |
| Kaladeh | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1964 | 0.55 | | 1,711 | 1,550 | 224 | TE | 14.75 | 526 | 151 | I |
| Berach | Berach | Villabhnagar | RJ | Banas | Chambal | 1965 | | | 30,470 | 28,770 | 2,775 | TE | 19 | 5,822 | | I |
| Mandawara | Kundal | Swaroopganj | RJ | Sahibi | Chambal | 1967 | 0.65 | | 2,460 | 2,160 | 170 | TE | 15.25 | 457 | | I |
| Ranapratap Sagar | Chambol | Kota | RJ | Chambal | Chambal | 1970 | 198.29 | | 2,898,690 | 1,566,520 | 18,408 | PG | 53.8 | 1,143 | | I/H/S |
| Badgaon | Banas | Vallabh Nagar | RJ | Banas | Chambal | 1973 | 9.79 | | 31,490 | 30,150 | 2,874 | TE | 21.12 | 457.2 | | I |
| Jawahar Sagar | Chambal | Kota | RJ | Chambal | Chambal | 1973 | | | 52,000 | 13,200 | 21,240 | PG | 36 | 393 | | H |
| Luneri | Local Nalla | Swaroopganj | RJ | Sahibi | Chambal | 1976 | 0.86 | | 2,440 | 2,450 | 174 | TE | 11.4 | 1,493 | | I |
| Panchana | Gambhiri | Karauli | RJ | Khri | Chambal | 1977 | 9.24 | | 59,450 | 52,650 | 5,238.6 | TE | 33.19 | 1,207.8 | | I |
| Morasagar | Banas | Bamenwas | RJ | Banas | Chambal | 1978 | 5.85 | | 12,930 | 12,870 | 59 | TE | 25 | 94.5 | | I |
| Abhaya Pura | Bhimlat | Bundi | RJ | Chmbal | Chambal | 1978 | | | 7,997 | 7,270 | 531 | TE | 15.64 | 1,645 | | I |
| Jetpura | Eru | Mandalgarh | RJ | Chambal | Chambal | 1978 | 4.3 | | 168OO | 16,300 | 1,064 | TE | 21.8 | 585 | | I |
| Gopalpura | Chambal | Kishanganj | RJ | Chambal | Chambal | 1979 | 6.29 | | 32,600 | 31,900 | 1,175 | ER/PG | 14.43 | 4,388.49 | | I |
| Kanyakheri | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1980 | | | 4,300 | 3,870 | 171 | TE | 10.5 | 3,656 | | I |
| Modia Mahadev | Local Nalla | Chittorgarh | RJ | Banas | Chambal | 1980 | | | 3,885 | 3,648 | 595 | TE | 16.53 | 625 | | I |
| Jhadol | Banas | Kotri | RJ | Banas | Chambal | 1980 | | | 10,335 | 9,287 | 21,160 | TE | 15 | 870 | | I |
| Titora | Local nallah | Jahazpur | RJ | Banas | Chambal | 1981 | 0.145 | | 1,358 | 1,231 | 144.89 | TE | 12 | 749 | NA | I |
| Anwasa | Local nallah | Bhilwara | RJ | Banas | Chambal | 1981 | | | 2,820 | 2,538 | 494.2 | TE | 12.2 | | – | I |
| Devliya | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1982 | 2.4 | | 2,380 | 2,380 | 230 | TE | 16.1 | 250 | 40 | I |
| Mandol | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1982 | 0.651 | | 6,800 | 6,263 | 5,720 | TE | 12.65 | – | | I/S |
| Domti Kokra | Moral | Manda1garh | RJ | Banas | Chambal | 1983 | | | 4,720 | 4,160 | 303 | TE | 27 | 61 | | I |
| Saran Kheri | Local Nalla | Jhalra Patan | RJ | Kali Sindh | Chambal | 1983 | | | 1,230 | 1,107 | 330 | TE | 16 | 960 | – | I |
| Panghatiya | Local nallah | Mandalgarh | RJ | Banas | Chambal | 1984 | 1.13 | | 1,274 | 1,133 | 143 | TE | 13.9 | 210 | NA | I |
| Luharia | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1984 | 1.547 | | 2,917 | 2,832 | 299 | TE | 10.2 | 2,973.6 | NA | I |
| Kothari Stage 1 | Banas | Kohri | RJ | Banas | Chambal | 1984 | 7.6 | | 26,000 | 21,500 | 6,005 | TE/PG | 25.4 | 4,326 | | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of comple-tion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Barkheri | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1985 | 0.52044 | | 1,598 | 1,473 | 135.93 | TE | 15.58 | 889 | NA | I |
| Bassi | Corail Berach | Gangrar | RJ | Banas | Chambal | 1985 | 2.8 | | 23,200 | 20,240 | 2,401 | TE | 36 | 1,044 | | I |
| Pachanpura | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1985 | 0.306 | | 9,480 | 9,280 | 3,549 | TE | 14.7 | – | | I |
| Bhimsagar | Kalisindh | Jhalawar | RJ | Kali Sindh | Chambal | 1985 | 18.02 | | 79,750 | 72,500 | | PG | 26 | | | I |
| Sawan Bhado | Ara | Sangod | RJ | Chambal | Chambal | 1986 | 4.4 | | 30,000 | 27,850 | 1,346 | TE | 29.8 | 4,692 | | I |
| Patiyal | Local nallah | Mandalgarh | RJ | Banas | Chambal | 1991 | 0.38 | | 1,708 | 1,529 | 5.3 | TE | 13.9 | 765 | NA | I |
| Sushil Sagar | Local nallah | Mandalgarh | RJ | Banas | Chambal | 1991 | 0.69 | | 2,202 | 1,982 | 216 | TE | 12.84 | 430 | NA | I |
| Wageri-Tank | Local nallah | Rajasmand | RJ | Banas | Chambal | 1992 | | | 2,390 | 2,160 | 5,657 | PG/TE | 22.2 | 430.25 | – | I |
| Shiv-Sagar | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1993 | 0.312 | | 2,094 | 2,050 | 218.28 | TE | 22.7 | 247 | – | I |
| Dorai | Brahmani | Begun | RJ | Banas | Chambal | 1995 | | | 8,500 | 7,650 | 657 | TE | 14.83 | 1,050 | | I |
| Bilas | Bilas | Kishanganj | RJ | Chambal | Chambal | 1996 | 6.5 | | 28,800 | 26,700 | 12,148 | TE | 19.17 | 4,650 | | I |
| Pitha Ka Mund | Local Nalla | Mandalgarh | RJ | Banas | Chambal | 1997 | | | 1,890 | 1,701 | 144.98 | TE | 11.7 | 871 | | I |
| Sanwaria Sarover | Local Nalla | Chittorgarh | RJ | Banas | Chambal | 1997 | 3.024 | | 5,408 | 5,180 | 512 | TE | 11.08 | 380 | | I |
| Jude Ka Naka | Local Nalla | Bhilwara | RJ | Banas | Chambal | 1998 | | | 1,780 | 1,720 | 257.05 | TE | 18.7 | 135 | – | |
| Motipura | Local nallah | Bhilwara | RJ | Banas | Chambal | 1999 | | | 1,170 | 1,053 | 164.82 | PG | 14.65 | 180 | – | I |
| Bari Mansarowar | Local nallah | Chittorgarh | RJ | Banas | Chambal | 1999 | 3.74 | | 9,482 | 8,419 | 661 | TE | 14.75 | 363.25 | NA | I |
| Bisalpur | Banas | Deoli | RJ | Banas | Chambal | 1999 | 218.36 | | 1,095,840 | 1,040,950 | 29,046 | PG | 39.5 | 574 | | I/S |
| Navratan Sagar | Local nallah | Jahazpur | RJ | Banas | Chambal | 2000 | 6.382 | | 2,260 | 2,040 | 389 | TE | 12.2 | 1,200 | NA | I |
| Kantaliya | Nekhadi | Asind | RJ | Banas | Chambal | 2000 | | | 1,020 | 918 | 546.34 | TE | 11.35 | 305 | | I |
| Ruparel | Ruparel | Begun | RJ | Banas | Chambal | 2004 | | | 9,700 | 8,730 | 654 | TE | 16.42 | 955 | | I |
| Chauli | Chauli | Jhalawar | RJ | Kali Sindh | Chambal | 2005 | 12.27 | | 53,500 | 48,220 | 1,284 | TE | 27.65 | 2,225 | | I/S |
| Chhapi | Chhapi | Aklera | RJ | Chambal | Chambal | 2006 | 9.7 | | 7,850C | 59,580 | 4,370 | PG | 34 | 310 | | I |
| Lassaria | Dai | Kekri | RJ | Banas | Chambal | 1981–1982 | 2.64 | | 11,500 | 10,650 | 2,320 | TE | 20.15 | 4,325 | | I |
| Udai Sagar | Berach | Girwa | RJ | Banas | Chambal | S.T | | | 31,130 | 27,590 | 1,419 | PG/TE | 19.35 | 315 | | I |
| Uncha | Local nallah | Chittorgarh | RJ | Banas | Chambal | ST | 1.175 | | 2,605 | 2,515 | 65.03 | TE | 14 | 1,800 | NA | I |
| Mundliya Kheri | Local Nalla | Jhalawar | RJ | Kali Sindh | Chambal | ST | | | 4,420 | 4,370 | 395.26 | TE | 12.5 | 1,890 | – | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence ('000 $km^2$) | Gross capacity ('000 cu m) | Live capacity ('000 cu m) | Spillway capacity ('000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam ('000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jaisamand | Banganga | Alwar | RJ | Khri | Chambal | ST | | | 26,942 | 24,248 | 410 | PG | 10 | 1,671 | NA | – |
| Soniyana | Local nallah | Chittorgarh | RJ | Banas | Chambal | ST | 2.92 | | 6,800 | 6,226 | 725 | TE | 11.7 | 3,060 | 105 | I |
| Nahar Sagar | Khari | Shahpura | RJ | Banas | Chambal | ST | | | 20,000 | 20,000 | 1,414 | TE | 12 | 1,560 | | I |
| Kukas | Local nallah | Jaipur | RJ | Banas | Chambal | ST | | | 1,925 | 1,925 | | TE | 13 | 487 | | I |
| Sankal Khera | Local nallah | Chittorgarh | RJ | Banas | Chambal | U/C | 0.616 | | 3,170 | 3,080 | 315 | TE | 20.9 | 1,700 | NA | I |
| Kalikhar | Kalikhar | Manohar Thana | RJ | Kali Sindh | Chambal | U/C | | | 11,328 | 10,830 | 1,299 | TE | 18 | | | I |
| Lhasi | Lhasi | Baran | RJ | Chambal | Chambal | U/C | | | 30,800 | 28,300 | 1,428 | TE | 17.58 | | | I |
| Piplad | Piplad | Jhalawar | RJ | Kali Sindh | Chambal | U/C | | | 23,078 | | 1,463 | TE | 15.77 | | | I |
| Takli | Takli | Kota | RJ | Chambal | Chambal | U/C | | | 33,740 | 29,900 | 2,294 | TE | 16.68 | | | I/S |
| Gagrin | Ahu | Jhalawar | RJ | Kali Sindh | Chambal | U/C | | | 52,600 | 47,100 | 4,447 | TE | 25.48 | 2,535 | | I |
| Benthali | Benthali | Baran | RJ | Banas | Chambal | U/C | | | | | | TE | 21.6 | | | |
| Chakan | Chakan | Bundi | RJ | Chambal | Chambal | U/C | | | | | | TE | 15 | | | |
| Gararda | Gararda | Bundi | RJ | Chambal | Chambal | U/C | | | | | | TE | 31.76 | | | |
| Gulandi | Gulandi | Jhalawar | RJ | Kali Sindh | Chambal | U/C | | | | | | TE | 17.14 | | | |
| Hindlot | Local nallah | Baran | RJ | Banas | Chambal | U/C | | | | | | TE | 19.7 | | | |
| Bherunda | Moral | S.Madhopur | RJ | Banas | Chambal | | | | 2,100 | 1,900 | 131 | TE | 17 | 36 | | I |
| Deopura | Nahari | S.Madhopur | RJ | Banas | Chambal | | | | 8,180 | 7,600 | 302 | TE | 23 | 1,127 | | I |
| Silibari | Roop Rail | Alwar | RJ | Sahibi | Chambal | | | | 5,600 | 5,400 | 346 | TE | 15 | 99 | | I |
| Reriya | Banganga | Baswa | RJ | Khri | Chambal | | | | 4,580 | 3,840 | 628 | TE | 16 | 100 | | I |
| Baretha Bund | Yamuna | Bayana | RJ | Khri | Chambal | | 13.56 | | 51,510 | 49,530 | 968 | TE | 16.31 | | | I |
| Basundni | Khari | Kekri | RJ | Banas | Chambal | | | | 7,780 | 7,210 | 1,241 | TE | 20 | 427 | | I |
| Gosunda | Banas | Chittaurgerh | RJ | Banas | Chambal | | 23.39 | | 75,470 | 67,050 | 20,643 | TE/PG | 23 | 639.5 | | I |
| Bishan Samand | Gambhir | Todabhim | RJ | Khri | Chambal | | | | 11,550 | 11,550 | | TE | 11.08 | 61 | | I |
| Madhar | Berach | Girwa | RJ | Banas | Chambal | | | | 2,377 | 2,260 | | PG | 22 | | | I |
| Gandhi Sagar | Chambal | Mandasur | MP | Chambal | Chambal | 1960 | 660 | | 7,320,000 | 6,800,000 | 21,238 | PG | 62.17 | 514 | | I/H |
| Bisalpur | Banas | Deoli | RJ | Banas | Chambal | 1999 | 212.3 | | 1,100,000 | 890,000 | 29,046 | PG | 39.5 | 574 | 1,096,000 | I/S |
| Ranapratap Sagar | Chambal | Kota | RJ | Chambal | Chambal | 1969 | 198.29 | | 2,900,000 | 1,570,000 | 18,400 | PG | 53.59 | 1,143 | 567 | I/H/S |
| **Storage Capacity of Chambal Sub-basin** | | | | | | | | | **19,612,066** | **15,581,173** | | | | | | |
| Bardha | Local | Chhatarpur | MP | Ken | Ken | 1995 | | | 1,350 | 1,215 | 0 | TE | 12.05 | 396 | 0 | IRR |
| Bargone | | Chhatarpur | MP | Ken | Ken | 1974 | 76.85 | 7,620 | 27,580 | 26,220 | 244 | TE | 22.3 | 3,000 | 340 | IRR. |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence ('000 $km^2$) | Gross capacity ('000 cu m) | Live capacity ('000 cu m) | Spillway capacity ('000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam ('000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Barkheda | | Chhatarpur | MP | Ken | Ken | 1969 | 47.9 | 4,391 | 10,849 | 10,377 | 179 | TE | 15.85 | 1,410 | 146 | IRR. |
| BarkhediSiloki | | Chhatarpur | MP | Ken | Ken | 1975 | 7.38 | 971 | 2,323 | 2,150 | 56 | TE | 10.82 | 1,220 | | IRR. |
| BarothaTank | | Damoh | MP | Ken | Ken | 1929 | 161.3 | | 19,960 | 16,870 | 887 | TE | 16.76 | 2,518 | | IRR. |
| Barrach | | Damoh | MP | Ken | Ken | 1962 | 37.54 | 171 | 5,160 | 4,900 | 226 | TE | 22.8 | 1,341 | | IRR. |
| Basinkhar | | Damoh | MP | Ken | Ken | 1959 | 16.36 | 1,821 | 4,050 | 3,390 | 148 | TE | 20.03 | 1,587 | | IRR. |
| Basni | | Damoh | MP | Ken | Ken | 1981 | 6.67 | 1,620 | 4,210 | 3,920 | 61 | TE | 14.6 | 1,740 | | IRR. |
| Bhaisawar | | Damoh | MP | Ken | Ken | 1913 | 11.52 | 460 | 2,550 | 2,517 | 132 | TE | 11.95 | 1,575 | | IRR. |
| Bhirata | | Damoh | MP | Ken | Ken | 1994 | 3.38 | 443 | 1,280 | 1,224 | 26 | TE | 16.16 | 568 | | IRR. |
| Hashalpur | | Panna | MP | Ken | Ken | 1977 | 13.83 | 736 | 4,760 | 4,528 | 346 | TE | 17.38 | 540 | | IRR. |
| Hashalpur | | Panna | MP | Ken | Ken | 1961 | | 440 | 1,588 | 1,481 | 152 | TE | 12.8 | 265 | | IRR. |
| Hathaikheda | | Panna | MP | Ken | Ken | 1975 | 5.5 | | 1,163 | 1,073 | 70 | TE | 21.12 | 705 | | IRR. |
| Hathaikheda | | Panna | MP | Ken | Ken | 1989 | 5.12 | | 1,627 | 1,498 | | TE | 12.2 | 630 | | IRR. |
| Karmodia | | Sagar | MP | Ken | Ken | 1985 | 2.59 | 277 | 1,267 | 1,207 | 46 | TE | 18 | 465 | | IRR. |
| Kasturipura | | Sagar | MP | Ken | Ken | 1969 | 1.84 | | 886 | 781 | 30 | TE | 16.46 | 767 | | IRR. |
| Katkiya | | Sagar | MP | Ken | Ken | 1926 | 79.98 | | 6,000 | 5,790 | 225 | TE | 23 | 310 | | IRR. |
| Kazikhedi | | Sagar | MP | Ken | Ken | 1978 | 30.72 | 1,800 | 13,280 | 12,160 | 256 | TE | 24.58 | 945 | | I/W |
| Mongra | | Tikamgarh | MP | Ken | Ken | | 9.32 | | 3,499 | 3,123 | 95 | TE | 10.97 | 854 | | IRR. |
| MotiNalla | | Tikamgarh | MP | Ken | Ken | | 7.8 | | 1,732 | 1,559 | 41 | TE | 12.5 | 681 | | IRR. |
| Naren | Karnari | Vidisha | MP | Ken | Ken | 1956 | 15.54 | 1,041 | 3,580 | 3,481 | 91 | TE | 14.6 | 1,560 | 468 | IRR |
| Narola | Local | Vidisha | MP | Ken | Ken | 1964 | 3.37 | 708 | 1,320 | 1,260 | 40 | TE | 11.2 | 330 | 65 | IRR |
| Panpura | | | MP | Ken | Ken | 1974 | 76.85 | 7,620 | 27,580 | 26,220 | 244 | TE | 22.3 | 3,000 | 340 | IRR. |
| Paronch | | | MP | Ken | Ken | 1926 | 79.98 | | 6,000 | 5,790 | 225 | TE | 23 | 310 | | IRR. |
| Roomal | | | MP | Ken | Ken | 1962 | 37.54 | 171 | 5,160 | 4,900 | 226 | TE | 22.8 | 1,341 | | IRR. |
| S.AshokSagar | | | MP | Ken | Ken | 1913 | 11.52 | 460 | 2,550 | 2,517 | 132 | TE | 11.95 | 1,575 | | IRR. |
| Sagonikala | | | MP | Ken | Ken | 1961 | | 440 | 1,588 | 1,481 | 152 | TE | 12.8 | 265 | | IRR. |
| Siloda | | | MP | Ken | Ken | 1912 | 3 | | 675 | 665 | 44 | | 10.94 | 546 | | IRR |
| SimariyaNo.1 | | | MP | Ken | Ken | 1919 | 7.12 | | 3,482 | 3,134 | 38 | TE | 11.62 | 1,097 | | IRR. |
| Sudra | | | MP | Ken | Ken | 1917 | 5.18 | 1,000 | 1,393 | 1,236 | 72 | TE | 11.93 | 1,073 | | IRR. |
| Ghorapachhar | | Katni | MP | Ken | Ken | 1912 | 14.89 | | 1,250 | 1,052 | | TE | 11.74 | 1,280 | | IRR. |
| Ghorapachhar | | Katni | MP | Ken | Ken | 1966 | 4.27 | | 1,610 | 680 | 39 | TE | 10.66 | 1,037 | | IRR. |
| Gidwasan | | Katni | MP | Ken | Ken | 1912 | 3 | | 675 | 665 | 44 | | 10.94 | 546 | | IRR |
| Gangau | Ken | Chhatar Pur | UP | Ken | Ken | 1915 | 149.9 | | 58,472 | 52,625 | 13,723 | PG | 16.15 | 826 | | I |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Submergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raipura | Arjun nala | Mahoba | UP | Ken | Ken | 1930 | | | 12,453 | 6,289 | 283 | TE | 13 | 3,509 | | I |
| Kabrai | Magaria | Mahoba | UP | Ken | Ken | 1955 | 50.5 | | 14,617 | 11,944 | 387 | TE | 18.24 | 2,440 | 425,000 | I |
| Arjun | Arjun | Mahoba | UP | Ken | Ken | 1957 | 180 | | 69,206 | 63,826 | 678 | TE | 25.88 | 4,206 | 1,823 | I |
| Rangawan | Bannel Nala | Chhatar Pur | UP | Ken | Ken | 1957 | 25.9 | | 164,238 | 155,177 | 2,407.93 | TE | 27.4 | 2,073 | | I |
| Salar Pur | Kardia | Mahoba | UP | Ken | Ken | 1960 | | | 4,020 | 3483 | 158 | TE | 11 | 2,975 | 13,406 | I |
| Urmil | Urmil | Mahoba | UP | Ken | Ken | 1994 | 250.3 | | 116,600 | 60,310 | 5,664 | TE | 25.56 | 4,700 | | I |
| Maudaha | Birma | Mahoba | UP | Ken | Ken | 2003 | 54.39 | | 200,000 | 179,000 | 111,328 | TE | 22 | 3,480 | 1,554 | I |
| Virat Sagar | Dhasan | Mahoba | UP | Ken | Ken | U/C | | | | | | | 180.5 | 1,550 | | |
| **Storage Capacity of Ken Sub-basin** | | | | | | | | | **811,583** | **691,717** | | | | | | |
| Deorikheda | Local | Guna | MP | Sind | Sind | 1915 | 31.03 | 1,870 | 4,530 | 4,361 | 256 | TE | 12.19 | 2,790 | | IRR. |
| Depalpur | Local | Guna | MP | Sind | Sind | 1916 | 12.3 | 932 | 2,070 | 1,816 | 125 | TE | 12.19 | 1,676 | | IRR. |
| DevendraSagar | Local | Guna | MP | Sind | Sind | 1916 | 16.77 | 1,094 | 2,670 | 2,363 | 113 | TE | 12.2 | 1,221 | | IRR. |
| Dhablamata | Local | Guna | MP | Sind | Sind | 1995 | 8.62 | 867 | 1,910 | 1,690 | 119 | TE | 17.68 | 1,800 | | IRR. |
| Dhantoli | Parwati | Gwalior | MP | Sind | Sind | 1917 | 1,960 | 25,230 | 192,670 | 179,020 | 4,758 | TE | 29.28 | 2,138 | | IRR. |
| Dhapora | Sank | Gwalior | MP | Sind | Sind | 1917 | 414.24 | 19,319 | 130,800 | 134,240 | 4,067 | TE/PG | 24.08 | 1,524 | | I/WS |
| Dhapora | Local | Gwalior | MP | Sind | Sind | 1931 | 75.11 | 8,533 | 12,960 | 12,827 | 708 | TE | 21.33 | 384 | | IRR. |
| DharamSagar | Local | Gwalior | MP | Sind | Sind | 1895 | 64.75 | 2,780 | 8,290 | 8,440 | 425 | TE | 16.47 | 975 | | I/WS |
| Dharwara | Local | Gwalior | MP | Sind | Sind | 1976 | 25.9 | 9,710 | 4,308 | 4,150 | 250 | TE | 14.17 | 2,610 | | IRR. |
| Dholawad | Local | Gwalior | MP | Sind | Sind | 1913 | 26 | 744 | 2,384 | 2,146 | 532 | TE | 12.19 | 660 | | IRR. |
| Dhumdhuma | Mower | Gwalior | MP | Sind | Sind | 1984 | 83 | | 44,250 | 16,920 | 292 | TE | 24.05 | 2,150 | | I/WS |
| LowerSakarwara | Sindh | Shivpuri | MP | Sind | Sind | 1989 | 5,944 | 16,243 | 108 | 910 | 265,400 | TE/PG | 35.63 | 2,568.7 | | IRR. |
| LowerSakarwara | | Shivpuri | MP | Sind | Sind | 2003 | 58.28 | | 324 | 292 | 324 | TE | 16.11 | 690 | | IRR |
| MadanSagar | Local | Shivpuri | MP | Sind | Sind | 1913 | 31.06 | 2,030 | 6,234 | 6,154 | 198 | TE | 12.5 | 1,688 | | |
| MadanSagar | Local | Shivpuri | MP | Sind | Sind | 1966 | 30.41 | 1,050 | 4,758 | 4,320 | 253 | TE | 21.03 | 580 | | IRR. |
| MadarkhaBandhi | Local | Shivpuri | MP | Sind | Sind | 1984 | 22.01 | 300 | 2,350 | 1,830 | 184 | TE | 14.08 | 206 | | IRR. |
| MadarkhaBandhi | Local | Shivpuri | MP | Sind | Sind | 1918 | 72.53 | 2,130 | 7,780 | 7,775 | 482 | PG | 13.81 | 2,145 | | I/WS |
| Madhar | Local | Shivpuri | MP | Sind | Sind | 1969 | 9.83 | 1,404 | 5,870 | 5,636 | 147 | TE | 13.71 | 810 | | IRR. |
| Maglipada | Local | Shivpuri | MP | Sind | Sind | 1977 | 8.1 | 940 | 1,630 | 1,427 | 97 | TE | 18.58 | 652 | | IRR. |
| Maglipada | Local | Shivpuri | MP | Sind | Sind | 1996 | 32.68 | | 6,450 | 5,700 | 180 | TE | 11.33 | 1,950 | | IRR. |
| Mahendra Sagar | Local | Shivpuri | MP | Sind | Sind | 1991 | 14.33 | 920 | 2,013 | 1,668 | 144 | TE | 15.51 | 465 | | IRR. |
| Majhgawan | Local | Shivpuri | MP | Sind | Sind | 1907 | 51.2 | | 2,050 | 131 | 13,200 | TE | 12.19 | 3,109 | | IRR. |

| Name of dam | River/ tributary | District | State | Sub-basin | Basin | Year of completion | Catch area ($km^2$) | Sub-mergence (‘000 $km^2$) | Gross capacity (‘000 cu m) | Live capacity (‘000 cu m) | Spillway capacity (‘000 cumec) | Type of dam | HT of dam (m) | Length of dam (m) | Vol of dam (‘000 cu m) | Purpose |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Majhgawan | Local | Shivpuri | MP | Sind | Sind | 1973 | 77.7 | 4,310 | 11,710 | 9,870 | 269 | TE | 15.1 | 2,055 | | IRR. |
| Mala | Local | Shivpuri | MP | Sind | Sind | 1978 | 17.78 | 1,000 | 1,800 | 1,620 | 170 | TE | 10.82 | 1,067 | | IRR. |
| Malavar | Local | Shivpuri | MP | Sind | Sind | 1987 | 7.12 | 656 | 1,450 | 1,276 | 42 | TE | 15.24 | 1,050 | | IRR. |
| Manjikhedi | Parwati | Shivpuri | MP | Sind | Sind | 1934 | 1,035.6 | 8,907 | 80,510 | 79,180 | 1,811 | PG | 37.64 | 1,047 | | IRR. |
| Moorumnalla | | Tikamgarh | MP | Sind | Sind | 1986 | 8.02 | | 1,825 | 1,643 | 50 | TE | 12.42 | 236 | | IRR. |
| Pabra | Local | Guna | MP | Sind | Sind | 1916 | 16.77 | 1,094 | 2,670 | 2,363 | 113 | TE | 12.2 | 1,221 | | IRR. |
| Phaliamao | Local | Shivpuri | MP | Sind | Sind | 1969 | 9.83 | 1,404 | 5,870 | 5,636 | 147 | TE | 13.71 | 810 | | IRR. |
| Piplai | Local | AshokNagar | MP | Sind | Sind | 1915 | 31.03 | 1,870 | 4,530 | 4,361 | 256 | TE | 12.19 | 2,790 | | IRR. |
| Pipliyakumar | Local | AshokNagar | MP | Sind | Sind | 1916 | 12.3 | 932 | 2,070 | 1,816 | 125 | TE | 12.19 | 1,676 | | IRR. |
| Ramova | Local | Shivpuri | MP | Sind | Sind | 1913 | 31.06 | 2,030 | 6,234 | 6,154 | 198 | TE | 12.5 | 1,688 | | |
| ShivgarthBedli | Parwati | Dabra | MP | Sind | Sind | 1934 | 1,035.6 | 8,907 | 80,510 | 79,180 | 1,811 | PG | 37.64 | 1,047 | | IRR. |
| Tonkara | Local | Gohad | MP | Sind | Sind | 1919 | 1,140 | 10,700 | 15,056 | 13,550 | 1,572 | TE | 12.19 | 2,134 | | IRR. |
| Tora | Local | Sabalgarh | MP | Sind | Sind | 1910 | 28.5 | 1,852 | 4,493 | 4,106 | 125 | TE | 12.34 | 914 | | IRR. |
| Udiyapura | Asan | Joura | MP | Sind | Sind | 1927 | 520 | 13,730 | 120,530 | 108,477 | 1,330 | TE/PG | 27 | 1,683 | | IRR. |
| Umariya | Asan | Morena | MP | Sind | Sind | 1914 | 1,036 | 18,390 | 91,550 | 90,382 | 4,918 | TE | 19.98 | 1,158 | | SR |
| Umariya | Sank | Morena | MP | Sind | Sind | 1914 | 251.42 | 6,712 | 16,315 | 9,645 | 1,377 | TE/PG | 13.79 | 658 | | IRR. |
| Upper Chhirpuri | Local | Shivpuri | MP | Sind | Sind | 1918 | 72.53 | 2,130 | 7,780 | 7,775 | 482 | PG | 13.81 | 2,145 | | I/WS |
| Upper Palakmati | Local | Karera | MP | Sind | Sind | 1907 | 51.2 | | 2,050 | 131 | 13,200 | TE | 12.19 | 3,109 | | IRR. |
| Yashvant Sagar | Parwati | Dabra | MP | Sind | Sind | 1917 | 1,960 | 25,230 | 192,670 | 179,020 | 4,758 | TE | 29.28 | 2,138 | | IRR. |
| YashwantNagar | Sank | Gwalior | MP | Sind | Sind | 1917 | 414.24 | 19,319 | 130,800 | 134,240 | 4,067 | TE/PG | 24.08 | 1,524 | | I/WS |
| YashwantNagar | Local | Gwalior | MP | Sind | Sind | 1931 | 75.11 | 8,533 | 12,960 | 12,827 | 708 | TE | 21.33 | 384 | | IRR. |
| ZotKheti | Local | Gwalior | MP | Sind | Sind | 1895 | 64.75 | 2,780 | 8,290 | 8,440 | 425 | TE | 16.47 | 975 | | I/WS |
| **Storage Capacity of Sind Sub-basin** | | | | | | | | | **1,248,082** | **1,165,507** | | | | | | |
| Kishau | Tons | Dehradun | UK | Tons | Yamuna | U/C | 21.7 | | 1,810,000 | 133,000 | 23,019 | PG | 236 | 680 | 9,500 | I/H |
| Lakhwar | Yamuna | Dehradun | UK | Yamuna | Yamuna | U/C | 29.5 | | 580,000 | 330,000 | 8,000 | PG | 204 | 451.78 | 2,800 | I/H |
| Renuka | Giri | Shimla | HP | Giri | Yamuna | U/C | | | | 49,800,000 | | | | | | |
| Vyasi | Yamuna | Dehradun | UK | Yamuna | Yamuna | U/C | 9.65 | | 1,160,000 | 1,044,000 | 8,000 | PG | 88 | 203 | 2,250 | I/H |
| **Storage Capacity of Yamuna Upper Catchment** | | | | | | | | | **3,550,000** | **51,307,000** | | | 148 | 844.5 | | |
| **Storage Capacity of Yamuna Basin** | | | | | | | | | **30,144,643** | **73,118,663** | | | | | | |

# Appendix B
# District-Wise Domestic Water Demand and Groundwater Resources

| S. No. | District | State | Area ($km^2$) | Total population | Urban population | Rural population | Domestic water demand (MCM) | Total recharge (MCM) | GW flow (MCM) | Net GW availability (MCM) | Total draft (MCM) | Stage GW development (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Kinnaur | HP | 72.9 | 874 | 0 | 874 | 0.01 | 1.16 | 0.12 | 1.05 | 0.28 | 26.42 |
| 2 | Shimla | HP | 3,660.4 | 622,266 | 143,121 | 479,145 | 14.05 | 33.25 | 3.33 | 29.93 | 6.71 | 22.42 |
| 3 | Uttarkashi | UK | 2,580.2 | 95,466 | 7,637 | 87,829 | 1.66 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| 4 | Dehradun | UK | 2,135.3 | 886,158 | 469,664 | 416,494 | 29.22 | 373.87 | 18.69 | 355.18 | 20.99 | 5.91 |
| 5 | Sirmaur | HP | 2,375.9 | 484,675 | 48,468 | 436,207 | 8.76 | 81.16 | 8.12 | 73.04 | 12.87 | 17.62 |
| 6 | Tehri Garhwal | UK | 379.2 | 51,948 | 5,195 | 46,753 | 0.94 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| 7 | Yamunanagar | HR | 966.1 | 570,006 | 216,602 | 353,404 | 15.83 | 310.62 | 31.06 | 279.56 | 282.42 | 101.02 |
| 8 | Saharanpur | UP | 3,414.8 | 2,680,579 | 696,951 | 1,983,628 | 63.30 | 1,491.12 | 109.43 | 1,381.69 | 1,265.67 | 91.6 |
| 9 | Hardwar | UK | 329.8 | 202,175 | 62,674 | 139,501 | 5.12 | 136.21 | 13.62 | 122.59 | 118.18 | 96.4 |
| 10 | Kurukshetra | HR | 197.2 | 101,759 | 26,457 | 75,302 | 2.40 | 53.32 | 3.45 | 49.88 | 82.60 | 165.62 |
| 11 | Kaithal | HR | 837.3 | 331,581 | 63,000 | 268,581 | 7.03 | 219.23 | 21.92 | 197.30 | 352.65 | 178.73 |
| 12 | Ganganagar | RJ | 1,331.5 | 114,505 | 85,879 | 28,626 | 4.65 | 22.22 | 2.22 | 19.99 | 9.07 | 45.34 |
| 13 | Sirsa | HR | 1,189.2 | 310,376 | 80,698 | 229,678 | 7.33 | 171.94 | 8.60 | 163.35 | 186.73 | 114.32 |
| 14 | Karnal | HR | 2,091.8 | 1,370,155 | 369,942 | 1,000,213 | 32.83 | 1,005.69 | 60.48 | 945.21 | 1,296.29 | 137.14 |
| 15 | Jind | HR | 2,683.4 | 1,183,366 | 236,673 | 946,693 | 25.48 | 750.22 | 54.26 | 695.96 | 485.20 | 69.72 |
| 16 | Hissar | HR | 5,048.5 | 1,181,347 | 307,150 | 874,197 | 27.90 | 467.98 | 38.47 | 429.51 | 289.97 | 67.51 |
| 17 | Muzaffarnagar | UP | 2,697.3 | 2,384,413 | 619,947 | 1,764,466 | 56.31 | 1,268.43 | 109.39 | 1,159.04 | 952.31 | 82.16 |
| 18 | Panipat | HR | 1,585.4 | 875,135 | 358,805 | 516,330 | 25.22 | 326.57 | 28.82 | 297.75 | 464.88 | 156.13 |
| 19 | Meerut | UP | 2,195.4 | 2,566,376 | 1,231,860 | 1,334,516 | 80.18 | 1,112.90 | 79.71 | 1,033.18 | 670.89 | 64.93 |
| 20 | Rohtak | HR | 4,735.6 | 1,003,954 | 351,384 | 652,570 | 26.84 | 293.75 | 23.82 | 269.93 | 179.04 | 66.33 |
| 21 | Sonipat | HR | 1,221.9 | 1,158,323 | 289,581 | 868,742 | 26.95 | 428.65 | 21.43 | 407.22 | 462.94 | 113.68 |
| 22 | Bhiwani | HR | 4,883.7 | 1,509,070 | 286,723 | 1,222,347 | 31.97 | 656.95 | 44.40 | 612.56 | 636.27 | 103.87 |
| 23 | Churu | RJ | 1,380.8 | 158,790 | 114,329 | 44,461 | 6.28 | 11.73 | 1.12 | 10.61 | 7.95 | 74.89 |
| 24 | Ghaziabad | UP | 1,700.6 | 2,945,491 | 1,472,746 | 1,472,745 | 94.07 | 1,119.37 | 83.03 | 1,036.35 | 664.03 | 61.6 |
| 25 | Delhi | DL | 1,471.0 | 13,844,958 | 12,875,811 | 969,147 | 836.59 | 296.98 | 15.53 | 281.45 | 479.25 | 170.28 |
| 26 | Bulandshahr | UP | 1,555.9 | 1,048,670 | 241,194 | 807,476 | 23.67 | 587.21 | 54.38 | 532.83 | 349.30 | 65.56 |
| 27 | Gurgaon | HR | 2,823.5 | 1,705,388 | 375,185 | 1,330,203 | 37.91 | 489.25 | 46.50 | 442.76 | 641.51 | 144.89 |

| S. No. | District | State | Area (km$^2$) | Total population | Urban population | Rural population | Domestic water demand (MCM) | Total recharge (MCM) | GW flow (MCM) | Net GW availability (MCM) | Total draft (MCM) | Stage GW develop-ment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28 | Jhunjhunun | RJ | 4,254.7 | 1,378,536 | 289,493 | 1,089,043 | 30.16 | 186.66 | 17.31 | 169.35 | 338.77 | 200.04 |
| 29 | Faridabad | HR | 2,013.7 | 1,933,104 | 1,082,538 | 850,566 | 65.76 | 510.70 | 25.54 | 485.16 | 245.02 | 50.5 |
| 30 | Mahendragarh | HR | 1,989.9 | 833,785 | 108,392 | 725,393 | 15.93 | 207.65 | 20.77 | 186.88 | 200.37 | 107.22 |
| 31 | Rewari | HR | 1,347.8 | 665,803 | 119,845 | 545,958 | 13.88 | 245.32 | 18.38 | 226.94 | 273.31 | 120.43 |
| 32 | Alwar | RJ | 8,168.9 | 2,801,946 | 420,292 | 2,381,654 | 55.48 | 811.66 | 71.24 | 740.42 | 1,071.63 | 144.73 |
| 33 | Sikar | RJ | 1,884.0 | 552,003 | 115,921 | 436,082 | 12.08 | 83.45 | 8.27 | 75.19 | 100.56 | 133.75 |
| 34 | Aligarh | UP | 2,923.3 | 2,364,942 | 685,833 | 1,679,109 | 58.31 | 827.82 | 67.15 | 760.67 | 615.00 | 80.85 |
| 35 | Etah | UP | 700.0 | 439,591 | 74,730 | 364,861 | 9.01 | 197.47 | 19.75 | 177.72 | 139.22 | 78.34 |
| 36 | Mathura | UP | 3,803.1 | 2,369,319 | 1,705,910 | 663,409 | 93.74 | 1,236.65 | 123.67 | 1,112.98 | 914.67 | 82.18 |
| 37 | Jaipur | RJ | 11,041.5 | 4,206,812 | 2,061,338 | 2,145,474 | 132.90 | 536.32 | 48.67 | 487.65 | 909.94 | 186.6 |
| 38 | Bharatpur | RJ | 4,777.6 | 1,992,263 | 378,530 | 1,613,733 | 42.21 | 469.31 | 39.65 | 429.66 | 429.21 | 99.89 |
| 39 | Firozabad | UP | 2,093.8 | 1,819,530 | 545,859 | 1,273,671 | 45.49 | 688.86 | 63.59 | 625.27 | 503.27 | 80.49 |
| 40 | Mainpuri | UP | 1,567.1 | 910,503 | 136,575 | 773,928 | 18.03 | 528.91 | 43.18 | 485.73 | 397.44 | 81.82 |
| 41 | Agra | UP | 4,383.0 | 3,940,326 | 1,694,340 | 2,245,986 | 116.28 | 1,166.67 | 116.67 | 1,050.01 | 931.24 | 88.69 |
| 42 | Sawai Madhopur | RJ | 10,651.7 | 1,129,080 | 914,555 | 214,525 | 48.20 | 409.13 | 38.48 | 370.65 | 418.71 | 112.97 |
| 43 | Etawah | UP | 4,240.5 | 4,388,959 | 833,902 | 3,555,057 | 92.99 | 2,729.75 | 223.16 | 2,506.59 | 1,248.21 | 49.8 |
| 44 | Ajmer | RJ | 5,514.8 | 1,417,301 | 566,920 | 850,381 | 40.35 | 229.06 | 21.26 | 207.80 | 255.15 | 122.79 |
| 45 | Dholpur | RJ | 2,879.7 | 941,659 | 169,499 | 772,160 | 19.63 | 236.97 | 21.41 | 215.56 | 229.70 | 106.56 |
| 46 | Kanpur (D) | UP | 3,770.0 | 1,157,375 | 81,016 | 1,076,359 | 19.71 | 710.87 | 52.18 | 658.69 | 325.27 | 49.38 |
| 47 | Morena | MP | 11,428.8 | 1,565,746 | 344,464 | 1,221,282 | 34.80 | 912.83 | 45.64 | 867.19 | 234.30 | 27.02 |
| 48 | Bhind | MP | 4,689.1 | 1,505,185 | 361,244 | 1,143,941 | 34.50 | 830.35 | 41.52 | 788.83 | 197.49 | 25.04 |
| 49 | Kanpur (N) | UP | 186.1 | 745,801 | 499,687 | 246,114 | 28.22 | 180.22 | 14.43 | 165.79 | 111.63 | 67.33 |
| 50 | Tonk | RJ | 7,213.7 | 1,204,695 | 252,986 | 951,709 | 26.36 | 421.73 | 32.48 | 389.25 | 375.20 | 96.39 |
| 51 | Jalaun | UP | 4,761.8 | 1,519,008 | 349,372 | 1,169,636 | 34.29 | 1,006.57 | 82.65 | 923.92 | 300.25 | 32.5 |
| 52 | Gwalior | M | 5,068.6 | 1,561,136 | 936,682 | 624,454 | 55.27 | 662.07 | 33.10 | 628.97 | 184.78 | 29.38 |
| 53 | Datia | MP | 1,896.9 | 618,396 | 136,047 | 482,349 | 13.75 | 433.64 | 21.68 | 411.96 | 182.45 | 44.29 |
| 54 | Fatehpur | UP | 3,642.4 | 2,025,191 | 202,519 | 1,822,672 | 36.59 | 1,218.65 | 83.67 | 1,134.98 | 800.43 | 70.52 |

| S. No. | District | State | Area (km$^2$) | Total population | Urban population | Rural population | Domestic water demand (MCM) | Total recharge (MCM) | GW flow (MCM) | Net GW availability (MCM) | Total draft (MCM) | Stage GW develop-ment (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 55 | Hamirpur | UP | 7,020.7 | 3,004,860 | 570,923 | 2,433,937 | 63.67 | 1,344.57 | 94.78 | 1,249.78 | 716.44 | 57.33 |
| 56 | Udaipur | RJ | 6,997.3 | 1,147,559 | 218,036 | 929,523 | 24.31 | 129.19 | 12.92 | 116.27 | 132.31 | 113.79 |
| 57 | Bhilwara | RJ | 10,451.4 | 2,027,572 | 425,790 | 1,601,782 | 44.37 | 435.98 | 43.55 | 392.43 | 455.27 | 116.01 |
| 58 | Jhansi | UP | 5,364.2 | 1,861,384 | 763,167 | 1,098,217 | 53.64 | 757.16 | 43.68 | 713.48 | 305.55 | 42.83 |
| 59 | Shivpuri | MP | 10,331.8 | 1,673,752 | 284,538 | 1,389,214 | 34.30 | 1,221.22 | 61.06 | 1,160.16 | 791.43 | 68.22 |
| 60 | Banda | UP | 6,996.8 | 1,406,361 | 225,018 | 1,181,343 | 28.34 | 806.58 | 69.51 | 737.06 | 270.57 | 36.71 |
| 61 | Bundi | RJ | 5,482.1 | 910,027 | 172,905 | 737,122 | 19.28 | 318.23 | 72.81 | 245.42 | 266.00 | 108.39 |
| 62 | Pali | RJ | 26.8 | 5,684 | 1,193 | 4,491 | 0.12 | 0.97 | 0.09 | 0.88 | 1.01 | 114.4 |
| 63 | Kota | RJ | 12,513.7 | 1,601,754 | 848,930 | 752,824 | 52.82 | 462.21 | 45.61 | 416.60 | 482.49 | 115.82 |
| 64 | Allahabad | UP | 2,160.8 | 1,469,371 | 352,649 | 1,116,722 | 33.68 | 356.28 | 30.41 | 325.88 | 225.25 | 69.12 |
| 65 | Tikamgarh | MP | 5,076.6 | 1,335,154 | 240,328 | 1,094,826 | 27.83 | 895.01 | 44.75 | 850.26 | 436.96 | 51.39 |
| 66 | Chhatapur | MP | 8,620.6 | 1,474,128 | 324,308 | 1,149,820 | 32.77 | 998.84 | 49.94 | 948.90 | 536.34 | 56.52 |
| 67 | Lalitpur | UP | 5,038.4 | 977,442 | 146,616 | 830,826 | 19.35 | 678.05 | 55.38 | 622.67 | 321.92 | 51.7 |
| 68 | Chittaurgarh | RJ | 8,252.9 | 1,444,261 | 231,082 | 1,213,179 | 29.10 | 349.62 | 34.31 | 315.31 | 449.13 | 142.44 |
| 69 | Rewa | MP | 0.3 | 84 | 13 | 71 | 0.00 | 0.02 | 0.00 | 0.02 | 0.01 | 41.82 |
| 70 | Satna | MP | 1,164.4 | 292,259 | 61,374 | 230,885 | 6.40 | 101.30 | 5.06 | 96.23 | 66.12 | 68.71 |
| 71 | Guna | MP | 11,253.9 | 1,710,593 | 359,225 | 1,351,368 | 37.43 | 662.37 | 33.12 | 629.25 | 342.25 | 54.39 |

| S. No. | District | State | Area (km$^2$) | Total population | Urban population | Rural population | Domestic water demand (MCM) | Total recharge (MCM) | GW flow (MCM) | Net GW availability (MCM) | Total draft (MCM) | Stage GW development (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 72 | Panna | MP | 6,658.1 | 952,104 | 123,774 | 828,330 | 18.19 | 570.21 | 28.51 | 541.70 | 132.46 | 24.45 |
| 73 | Mandsaur | MP | 10,101.6 | 1,333,411 | 253,348 | 1,080,063 | 28.25 | 839.76 | 41.99 | 797.77 | 873.26 | 109.46 |
| 74 | Jhalawar | RJ | 6,271.4 | 1,179,023 | 165,063 | 1,013,960 | 22.94 | 456.28 | 26.83 | 429.44 | 451.57 | 105.15 |
| 75 | Sagar | MP | 9,774.3 | 2,375,157 | 688,796 | 1,686,361 | 58.56 | 1,428.39 | 71.42 | 1,356.97 | 632.93 | 46.64 |
| 76 | Damoh | MP | 7,011.7 | 1,444,408 | 274,438 | 1,169,970 | 30.60 | 588.88 | 29.44 | 559.44 | 292.96 | 52.37 |
| 77 | Vidisha | MP | 7,358.6 | 1,228,881 | 258,065 | 970,816 | 26.89 | 701.28 | 35.06 | 666.22 | 313.07 | 46.99 |
| 78 | Shajapur | MP | 6,222.5 | 1,306,731 | 248,279 | 1,058,452 | 27.69 | 559.34 | 27.97 | 531.38 | 601.88 | 113.27 |
| 79 | Rajgarh | MP | 6,365.4 | 1,311,264 | 222,915 | 1,088,349 | 26.87 | 979.42 | 48.97 | 930.45 | 723.13 | 77.72 |
| 80 | Jabalpur | MP | 840.5 | 194,991 | 111,145 | 83,846 | 6.70 | 48.71 | 2.44 | 46.28 | 19.43 | 41.99 |
| 81 | Ratlam | MP | 2,882.0 | 720,510 | 216,153 | 504,357 | 18.01 | 377.30 | 18.87 | 358.44 | 420.51 | 117.32 |
| 82 | Bhopal | MP | 2,820.4 | 1,923,506 | 1,538,805 | 384,701 | 81.44 | 357.73 | 17.89 | 339.84 | 242.39 | 71.32 |
| 83 | Ujjain | MP | 6,086.2 | 1,716,306 | 669,359 | 1,046,947 | 48.27 | 836.91 | 41.85 | 795.06 | 866.80 | 109.02 |
| 84 | Raisen | MP | 3,598.1 | 546,905 | 98,443 | 448,462 | 11.40 | 674.28 | 33.71 | 640.56 | 220.90 | 34.48 |
| 85 | Sehore | MP | 3,099.3 | 536,181 | 96,513 | 439,668 | 11.17 | 392.58 | 19.63 | 372.95 | 232.82 | 62.43 |
| 86 | Dewas | MP | 2,993.7 | 628,666 | 169,740 | 458,926 | 15.06 | 445.25 | 22.26 | 422.99 | 280.82 | 66.39 |
| 87 | Narsingpur | MP | 135.1 | 28,502 | 4,560 | 23,942 | 0.57 | 36.03 | 1.80 | 34.23 | 21.39 | 62.5 |
| 88 | Dhar | MP | 1,563.8 | 331,530 | 56,360 | 275,170 | 6.79 | 210.24 | 10.51 | 199.73 | 198.99 | 99.63 |
| 89 | Indore | MP | 2,896.7 | 2,047,931 | 1,433,552 | 614,379 | 79.61 | 497.58 | 24.88 | 472.70 | 493.68 | 104.44 |

# Appendix C
# Area to Point Rainfall Ratios (%) for Deriving the Hourly Distribution of Daily Rainfall

| Area | Duration (hours) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (sq miles) | 0.50 | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 9.00 | 12.00 | 15.00 | 18.00 | 21.00 | 24.00 |
| 10.0 | 68.33 | 76.39 | 82.66 | 85.60 | 87.40 | 88.65 | 89.59 | 91.41 | 92.52 | 93.28 | 93.85 | 94.29 | 94.65 |
| 20.0 | 61.89 | 71.23 | 78.67 | 82.21 | 84.40 | 85.92 | 87.06 | 89.31 | 90.67 | 91.61 | 92.31 | 92.86 | 93.31 |
| 30.0 | 57.74 | 67.81 | 75.98 | 79.91 | 82.35 | 84.05 | 85.34 | 87.86 | 89.39 | 90.46 | 91.25 | 91.87 | 92.38 |
| 40.0 | 54.63 | 65.21 | 73.91 | 78.13 | 80.76 | 82.60 | 83.99 | 86.72 | 88.39 | 89.55 | 90.41 | 91.09 | 91.64 |
| 50.0 | 52.14 | 63.10 | 72.21 | 76.65 | 79.43 | 81.39 | 82.86 | 85.77 | 87.55 | 88.79 | 89.71 | 90.44 | 91.03 |
| 60.0 | 50.05 | 61.30 | 70.75 | 75.39 | 78.30 | 80.34 | 81.89 | 84.95 | 86.83 | 88.13 | 89.11 | 89.87 | 90.49 |
| 70.0 | 48.26 | 59.74 | 69.47 | 74.27 | 77.29 | 79.42 | 81.03 | 84.22 | 86.18 | 87.55 | 88.57 | 89.37 | 90.02 |
| 80.0 | 46.69 | 58.36 | 68.33 | 73.27 | 76.39 | 78.59 | 80.26 | 83.57 | 85.60 | 87.02 | 88.08 | 88.91 | 89.59 |
| 90.0 | 45.28 | 57.11 | 67.29 | 72.37 | 75.57 | 77.84 | 79.56 | 82.97 | 85.07 | 86.53 | 87.63 | 88.49 | 89.19 |
| 100.0 | 44.02 | 55.98 | 66.35 | 71.54 | 74.82 | 77.15 | 78.91 | 82.42 | 84.58 | 86.09 | 87.22 | 88.11 | 88.83 |
| 110.0 | 42.87 | 54.94 | 65.47 | 70.77 | 74.12 | 76.50 | 78.31 | 81.90 | 84.12 | 85.67 | 86.83 | 87.75 | 88.49 |
| 120.0 | 41.81 | 53.98 | 64.66 | 70.05 | 73.47 | 75.90 | 77.75 | 81.42 | 83.70 | 85.28 | 86.47 | 87.41 | 88.17 |
| 130.0 | 40.84 | 53.09 | 63.91 | 69.38 | 72.86 | 75.34 | 77.22 | 80.97 | 83.29 | 84.92 | 86.14 | 87.09 | 87.87 |
| 140.0 | 39.94 | 52.25 | 63.19 | 68.75 | 72.29 | 74.81 | 76.72 | 80.55 | 82.91 | 84.57 | 85.81 | 86.76 | 87.59 |
| 150.0 | 39.09 | 51.47 | 62.52 | 68.15 | 71.74 | 74.30 | 76.25 | 80.14 | 82.55 | 84.24 | 85.51 | 86.51 | 87.32 |

| Area (sq miles) | Duration (hours) 0.50 | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 9.00 | 12.00 | 15.00 | 18.00 | 21.00 | 24.00 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 160.0 | 38.30 | 50.73 | 61.89 | 67.58 | 71.23 | 73.82 | 75.80 | 79.76 | 82.21 | 83.93 | 85.22 | 86.24 | 87.06 |
| 170.0 | 37.56 | 50.03 | 61.28 | 67.05 | 70.74 | 73.37 | 75.38 | 79.39 | 81.88 | 83.63 | 84.94 | 85.98 | 86.82 |
| 180.0 | 36.86 | 49.37 | 60.71 | 66.53 | 70.27 | 72.93 | 74.97 | 79.04 | 81.57 | 83.34 | 84.67 | 85.73 | 86.58 |
| 190.0 | 36.19 | 48.74 | 60.16 | 66.04 | 69.82 | 72.52 | 74.57 | 78.70 | 81.27 | 83.07 | 84.42 | 85.49 | 86.36 |
| 200.0 | 35.57 | 48.14 | 59.64 | 65.57 | 69.38 | 72.11 | 74.20 | 78.37 | 80.98 | 82.80 | 84.17 | 85.26 | 86.14 |
| 210.0 | 34.97 | 47.57 | 59.13 | 65.12 | 68.97 | 71.73 | 73.84 | 78.06 | 80.70 | 82.54 | 83.94 | 85.03 | 85.93 |
| 220.0 | 34.40 | 47.02 | 58.65 | 64.68 | 68.57 | 71.36 | 73.49 | 77.76 | 80.43 | 82.30 | 83.71 | 84.82 | 85.72 |
| 230.0 | 33.85 | 46.49 | 58.18 | 64.26 | 68.19 | 71.00 | 73.15 | 77.47 | 80.16 | 82.06 | 83.48 | 84.61 | 85.53 |
| 240.0 | 33.33 | 45.99 | 57.74 | 63.86 | 67.81 | 70.65 | 72.82 | 77.19 | 79.91 | 81.83 | 83.27 | 84.41 | 85.34 |
| 250.0 | 32.84 | 45.50 | 57.30 | 63.47 | 67.45 | 70.32 | 72.51 | 76.91 | 79.67 | 81.60 | 83.06 | 84.21 | 85.15 |
| 260.0 | 32.36 | 45.03 | 56.88 | 63.09 | 67.11 | 69.99 | 82.20 | 76.65 | 79.43 | 81.38 | 82.86 | 84.02 | 84.97 |
| 270.0 | 31.90 | 44.58 | 56.48 | 62.72 | 66.77 | 69.68 | 71.90 | 76.39 | 79.20 | 81.17 | 82.66 | 83.84 | 84.80 |
| 280.0 | 31.46 | 44.14 | 56.09 | 62.37 | 66.44 | 69.37 | 71.62 | 76.14 | 78.97 | 80.97 | 82.47 | 83.66 | 84.63 |
| 290.0 | 31.03 | 43.72 | 55.71 | 62.02 | 66.12 | 69.07 | 71.34 | 75.90 | 78.75 | 80.76 | 82.28 | 83.48 | 84.46 |
| 300.0 | 30.62 | 43.31 | 55.34 | 61.69 | 65.81 | 68.78 | 71.06 | 75.66 | 78.54 | 80.57 | 82.10 | 83.31 | 84.30 |

*Sources*: CWC (1973). Estimation of design flood peak: A method based on unit hydrograph principle, Rep. No. 1/73, Hydrology for Small Catchments Directorate, Central Water Commission, Government of India, New Delhi

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