Sustainable Development of Water Resources in India

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ABSTRACT / India has a territory of 328 million hectares, which receives an average annual rainfall of 120 cm; this is among the highest for a comparable geographical area in the world. Despite India's vast water resources, droughts and famines are a common occurrence in many parts of country. This paper briefly surveys India's river-basin systems, drought-prone areas, hydrogeological systems, groundwater potential and utilization in light of water-quality constraints, and environmental pollution in India. This paper concludes by clarifying the main actions required to ensure a sustainable development of water resources in India.

India is the seventh largest country in the world and Asia's second largest country, with an area of 3,287,590 km^2. The Indian mainland stretches from 8°4′ to 37°6′N latitude and 68°7′ to 97°25′E longitude (Figure 1). It has a land frontier of some 15,200 km and a coastline of 7516 km. India's northern frontiers are with Xizang (Tibet) in the Peoples Republic of China, Nepal, and Bhutan. In the northwest, India borders Pakistan; in the northeast, China and Burma; and in the east Burma. The southern peninsula extends into tropical waters of the Indian Ocean with the Bay of Bengal lying to the southeast and the Arabian Sea to the southwest. For administrative purposes India is divided into 24 states and seven union territories. Most of the Indian land mass is in the semiarid tropical belt characterized by seasonal rainfall lasting over a period of three to four months. Agriculture contributes about 46% of the gross national product (Harbans, Singh 1983) and is also the main occupation of the people and the preoccupation of the government having the responsibility to provide adequate food for a population that makes up about 16% of the world (Nanda 1991) and holds a potential agricultural which only 14% of the world's total (Sinha and Swaminathan 1989). It has been estimated that the absolute maximum possible food production in India is 4572 million tons, which is much higher than the current production of 170 million tons. They have considered only one constraint—total potential agricultural land is limited to 143 million hectors—and assumed optimal conditions in all other aspects to arrive at the maximum food supply potential of soils of different grades. Four crops a year, adequate irrigation and nutrient availability, suitable ambient temperature, along with protection against weeds, pests, and pathogens are assumed. It is unlikely, therefore, that the theoretical potential of 4572 million tons will never be reached. Water supply for irrigation would be a major constraint (Ghosh 1987).

The total population of India was approximately 843 million in 1991 (Nanda 1991). The decadal percentage growth rate for the decade was 23.5%. The corresponding figures for census year 1981, were 685 million and 24.8%. The doubling time for the Indian population was considered as 27 years (Ehrlich and Ehrlich 1974). Srinivasan (1988) has estimated the population of India by 2050 AD for three different scenarios. Assuming a rapid fertility decline without any change in the mortality rate, the estimated population would be 1300 million; the figure for rapid decline of both fertility and mortality is 1400 million, while the standard projection (current trend) gives the population as about 1500 million. As per one estimate (Johnson 1988), the annual growth rate is expected to decline from 2.15% for 1979–1980 to 0.58 in 2020–2025 AD. The population of less developed regions is expected to stabilize by 2050–2060 AD (Condie 1984). The total production of rice, wheat, and cereals in 1989 was 173 million tonnes (Dhingra 1990). The amount of food required to feed the stabilized Indian population in 2050 is estimated as 400 million tons (Verma 1989).

The water resources of India are enormous but they

KEY WORDS: India; Water resources; Groundwater; Surface water; Surface water pollution; Groundwater pollution; Sustainable development

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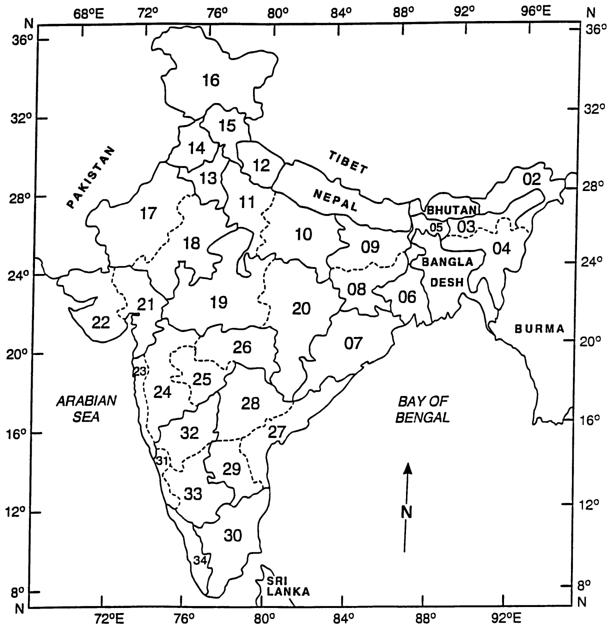

Figure 1. Meterological regions of India with provinces (scale: 1 cm = 200 km). Modified from Mooley and Parthasarathy (1984). 2 = Arunachal Pradesh; 3 = North Assam; 4 = South Assam; 5 and 6 = West Bengal; 7 = Orissa; 8 and 9 = Bihar; 10, 11, and 12 = Uttar Pradesh; 13 = Haryana; 14 = Punjab; 15 = Himachal Pradesh; 16 = Jammu and Kashmir; 17 and 18 = Rajasthan; 19 and 20 = Madhya Pradesh; 21 = Gujarat; 22 = Saurashtra and Kutch; 23 = Konkan; 24, 25, and 26 = Maharastra; 27 = Coastal Andhra Pradesh; 28 = Telangana; 29 = Rayalaseema; 30 = Tamilnadu; 31 = Coastal Karnataka; 32 and 33 = Karnataka; 34 = Kerala.

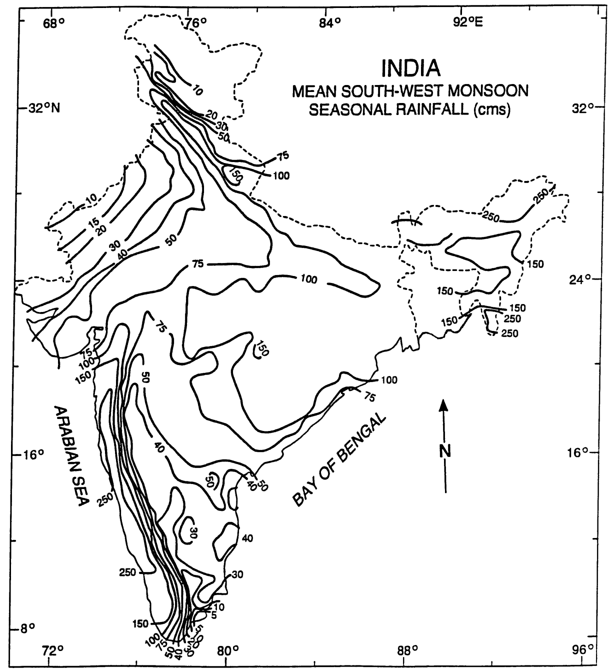

Figure 2. Mean southwest monsoon rainfall (scale: 1 cm = 180 km). Modified from Subrahmanyam (1988).

are unevenly distributed in several terms: seasonally, regionally, basinwide, cultivator class-wise, and crop-wise. Due to the lack of national water resource budgeting and planning, famine in the vast tracts of the western and southern peninsula plateau region and floods in northern and eastern India ravage the lives of millions of Indian farmers and result in crop losses running into several tens of millions of dollars (US$1 = 35 rupees; 1995 rate) year after year. Famine, especially scarcity of drinking water, is causing havoc in Rajasthan (Katchwana 1981), Gujarat, Maharashtra, Andhra Pradesh, Karnataka, and Tamil Nadu (Figure 1).

An overview of India's total water resources reveals that it is much below the natural capacity and technical feasibility. Barely 25%–30% of the moisture that monsoon clouds carry actually precipitates. An average rainfall of 120 cm for the country's 328 million hectares is the highest in the world for a comparable geographical area. As an example, the bulk of precipitation in central and southern India occurs during the southwest monsoon season (June–September) (Figure 2) and the average annual rainfall ranges from 95 to 120 cm.

A perusal of the past 100 years of meteorological data does not show any marked variation. Of course, all rainfall does not become a water resource. After immediate evaporation and transpiration by vegetation, water percolates into the soil and flows as surface water that constitutes the basic water resources. The cycle of water begins with rainfall and ends in evaporation and involves flows going back to the sea. The key to harnessing and harvesting the maximum quantum of water available from rain is to delay the flow of water towards the sea or into the atmosphere. Thus, catching the water when it is on land and controlling it by organizational skill and technological advances is the crux of water planning.

The character of the hydrological cycle determines the crop pattern and productivity, for which precise data on precipitation, river, and stream flows are needed. Groundwater is essential for planning and development of water resources as well as its optimum social productivity. The chief characteristic feature of Indian hydrology is the concentration of rain in major parts of the country in some months during the monsoon season. During the nonrainy months, the river flows dwindle and many of them dry up. There is a need to impound water in reservoirs for subsequent controlled releases. The quantity of average annual flows of major river basins and the possibility of impounding it through reservoirs in the hills and dams in the plains, with groundwater potential and its recharge, decides the extent of irrigation. The main objective of this paper is to study the sustainable development of water resources in India for future generations.

Climate

In India, accurate climate data are available only for the past 100 years (Prasad and Gadgil 1986). Several studies of climate variability on both short and long time scales have been carried out (Thapliyal and Kulshrestha 1991, Jagannathan 1963, Jagannathan and Parthasarathy 1972, Hingane and others 1985, Pramanik and Jagannathan 1954, 1955, Rao and Jagannathan 1963).

The mean annual temperature over India during the period 1901–1982 is shown in Figure 3 (Hingane and others 1985). The trend line indicates about 0.4°C warming during the last 80 years. This warming is mainly caused by the postmonsoon and winter seasons and is found to be pronounced for the west coast, the interior peninsula, and the north-central and northeast regions of the country. The steady increase in the mean annual temperature for India is in contrast to the post-1940 cooling observed for the northern hemisphere. Although the results cannot be expressed in terms of cause-and-effect, a significant increase in the consumption of fossil fuel, deforestation, and land use during the period can be noted (Sinha and Swaminathan 1989).

The major impacts of climate change in India would be on the surface and groundwater hydrology and agriculture of the country. Climate variability and climate change assume great importance for the Indian subcontinent because its economic performance and social progress are dependent on rainfall, and climate change is likely to affect rainfall. India possesses a great variety and diversity of climate, varying from extremely hot to extremely cold, from extremely arid regions to extremely humid regions, from drought-prone areas to flood-prone areas. Climatic conditions govern to a great extent the operation of water resources in the country. The Himalayan rivers of India are ice-fed rivers and thus are very vulnerable to climate change. Rainfall is governed by the southwest and northeast monsoons. The distribution of Indian rainfall shows great temporal and spatial variations. About 80% of the total rainfall occurs during four monsoonal months (June–September) and is not spread uniformly over the country, creating pockets of scarcity in some regions. Thus, large water storage facilities are required to meet the demand during the lean periods.

Agriculture is the dominant sector in the economics of a developing country like India and is the major source of employment, income, and sustenance for the majority of the population of the country. Of the 342×10^6 ha of land area in India, 142×10^6 ha are cultivated, and of that, 31.4% is irrigated. Two main crop seasons, ‘‘kharif’’ or monsoon (July–October) and ‘‘rabi’’ or postmonsoon (November–March), provide almost all food grain production. The intraregional variability in climatic change induced by greenhouse warming, together with the interregional heterogeneities due to differences in spatial factors (soils, topography, length of crop growing season, major rained crops in a given area, runoff harvesting possibilities, groundwater potential) might make the picture more complicated. When considering the increasing demand for water for various activities, it also becomes essential to know with sufficient accuracy the future availability of water, considering the probable effects of climate change, so as to plan and manage the resources and requirements.

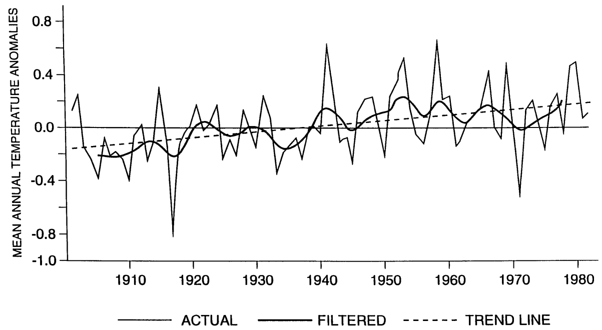

Figure 3. Mean annual temperature anomalies of India during the period 1901–1982. Modified from Hingane and others (1985).

There is an urgent need to view the various projected climate change scenarios in a balanced way. An accurate appraisal of the water resources of India is therefore of the utmost importance for the planning, development, and utilization of water. A focused and careful examination of the different components of the prevailing agricultural systems in different regions should be done in order to provide potential options for adapting to climatic changes.

Monsoon Seasons

The precipitation patterns over India have been intensively studied over the years beginning from 1886 (Blanford 1886) with the studies mainly centered on prediction of monsoon rainfall. Agrawal (1952) and Pramanik and Jagannathan (1953) analyzed 40–100 years of rainfall data from different Indian stations and concluded that there was no major climate change in the rainfall series. Further detailed analysis of rainfall

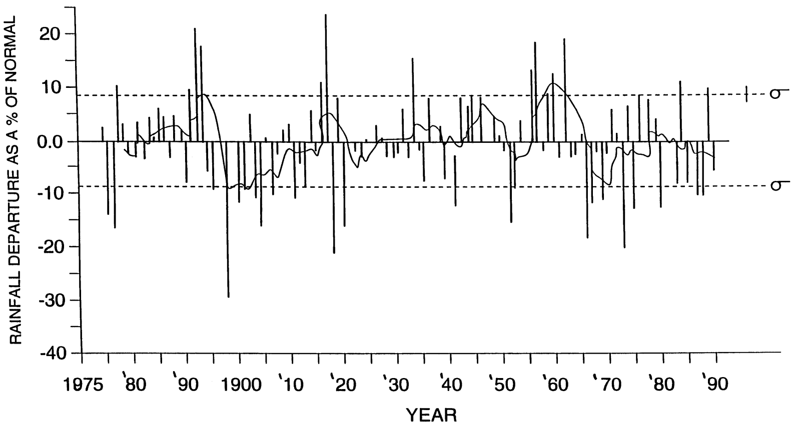

Figure 4. Annual rainfall in India for the period 1875–1989. The curves shows the five-year running mean, the dotted lines indicate the upper and lower limits ± 1 SD. Modified from Thapliyal and Kulshrestha (1991).

data has been done by several investigators (Parthasarathy and Dhar 1974, Parthasarathy 1984) in different regions or subdivisions of India and no long-term trend in the rainfall data was detected. Mooley and Parthasarathy (1984) and recently Thapliyal and Kulshreshtha (1991) have analyzed detailed examinations of the series to determine the trend in annual rainfall over India (Figure 4). They all found that the five-year running mean has fluctuated from the normal rainfall within ±1 SD. They did not find any long-term climate change and trend.

The above studies mainly concentrated on the long-term analysis of temperature and rainfall data. In recent decades, pressure and rainfall have not shown any systematic trend. However, temperature has shown a slight increase over India. Work on the expected climate change in India due to enhanced greenhouse effects, as revealed by global climate models, started recently with studies by Lal and Bhaskaran (1993).

The monsoon seasons of India are two clear-cut rainy seasons having enormous amounts of rainfall followed by one prolonged or two short dry seasons in which there is either sparse or no rainfall. Insofar as the Indian subcontinent is concerned, there are two monsoons. The southwest, or summer monsoon (Mooly and Parthasarathy 1984, Hartmann and Michelsen 1989) (Figure 2), has warm winds blowing from the ocean over almost the entire country and causing copious amounts of rainfall from June to September (Figure 2). The northeast or winter monsoon (Figure 5) is characterized by a dry continental airmass blowing from the vast Siberian high pressure area from December to March. Except for a coastal strip in the southeastern portion of south India and in the extreme northern portion over Kashmir, the rest of the country during this season receives practically no rainfall. Figure 6 shows the average rainfall from the southern tip of India to northern India. Figure 7 shows the rainfall on west coast

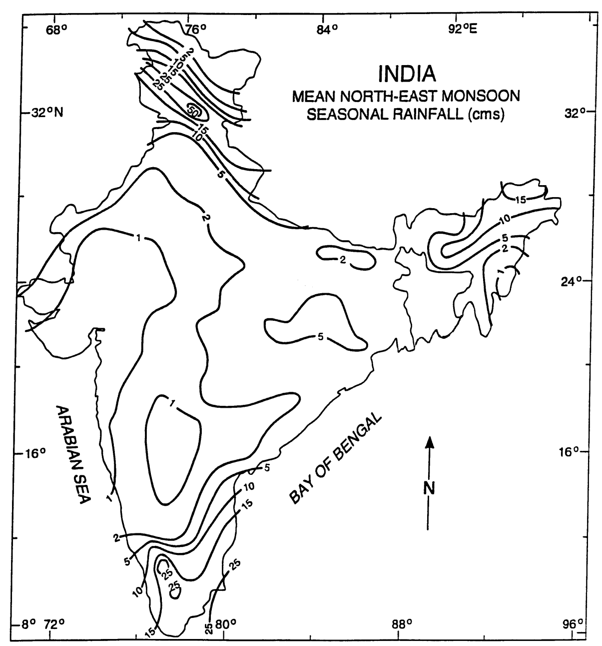

Figure 5. Mean northeast monsoon rainfall (scale: 1 cm = 180 km). Modified from Subrahmanyam (1988).

(Figure 7a), southern tip to north (Figure 7b), and east coast (Figure 7c) of India. The west coast is affected by the southwest monsoon but the east coast is affected by two monsoons. Figure 8 shows rainfall across the south, center, and north of India from west coast to east. The west coast of India gets more rainfall than the east coast. Typically, northwestern India gets less rainfall than eastern coast. A clear understanding of these situations is available from Figures 2, 5, and 6, which show the mean annual rainfall distribution, rainfall distribution during the southwest monsoon, and rainfall distribution during the northeast monsoon seasons, respectively, over India.

Climatically, therefore, the southwest monsoon season (Figure 2) is one of countrywide inundation and river floods while the northeast monsoon season (Figure 5) is characterized by general dryness and even occasional droughts. From the point of view of severe floods and droughts, however, the two transitional periods—October and November (between the southwest and northeast monsoon seasons) and April and May (between the northeast and the southwest monsoon seasons) are critical and apprehension causing. During October and November there is intense cyclonic activity in the Bay of Bengal and the Arabian Sea on account of which there are prolonged and heavy spells of rainfall (Figure 7c) leading to large-scale inundation and floods especially in the eastern and the western coastal sections of peninsular India. In the other transition season (April and May), except for an occasional bay cyclone, there is not only intense dryness but even enormous heat, which together devastate the entire country with shortages of water even for drinking purposes. As if these disparities were not enough, monsoon air circulations are highly erratic. The outcome is such that the onset and withdrawal of the systems are unduly advanced or delayed, and create a variety of water problems in the form of regional floods or droughts.

India has innumerable rivers (Figure 9) that provide water for homes and agriculture (Rao 1979), yet they can also cause wide-spread destruction and devastation through floods and inundation. With other factors remaining the same, floods are mainly due to heavy rainfall and, since the monsoon season is associated with intense and widespread rainfall, it is but natural that the southwest monsoon season happens also to be flood season in most parts of India. Heavy rainfall of fairly long duration conducive to flood production in India is normally associated with the following meteorological situations: (1) movement of depressions/cyclones in the interior of the country, (2) passage of a number of weather disturbances in quick succession following almost the same track, and (3) a "break monsoon" situation or shifting of the monsoon trough from its normal position over the Indo-Gangetic Plain to the foothills of the Himalayas.

Geographically, the northern and eastern parts of India suffer from floods more frequently and on a much larger scale than the southern and the western parts. To the north of the Vindhyan mountains is a low-lying plain from Punjab to West Bengal created by the alluvial soil deposited by large rivers like the Indus and the Ganga and their tributaries. In Assam there is a narrow stretch of vulnerable land through which the mighty river Brahmaputra and its tributaries flow. All these rivers have their sources in the high Himalayas, which

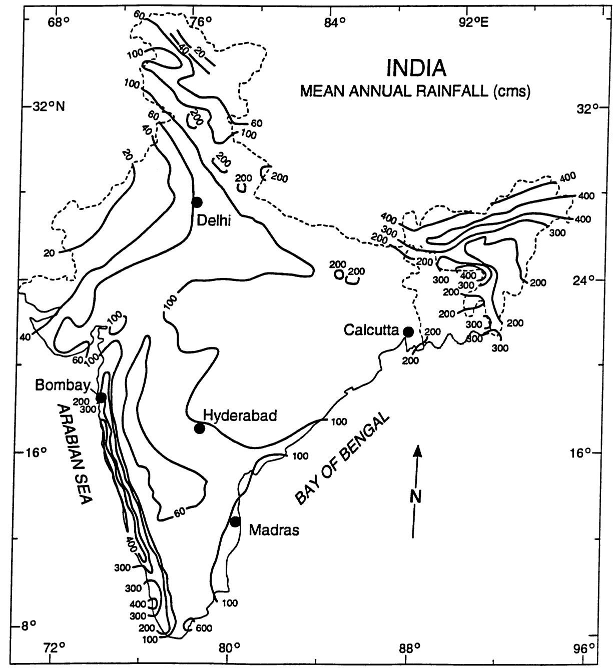

Figure 6. Mean annual rainfall (scale: 1 cm = 180 km). Modified from Subrahmanyam (1988).

nourish them with inexhaustible waters from both rainfall and snow and glacier melt. Below the Vindhyan and Satpura mountains the situation is different; the western ghats from which most of the southern rivers originate are not as high as the Himalayas. Moreover, the region through which these rivers flow is a tableland (the Deccan Plateau) formed by hard volcanic rocks (the Deccan traps), which have withstood the rigors of sun and rain for ages.

From the distributions of annual and seasonal rainfall (Figures 2, 6, and 7), it is evident that heavy rainfall is confined largely to the southwestern, eastern, and the northeastern portions of the country. The central region and the Gangetic Plain lie in the zone of moderate rainfall, while the north Deccan and adjoining areas receive heavy rainfall towards the end of the monsoon season. Thus, heavy rain in the Himalayas occurs at the peak of the southwest monsoon season. The eastern districts of Andhra Pradesh and Tamil Nadu receive most of their rainfall from October to December (Figure 7c) due to severe cyclonic storms that form in the central and the southern Bay of Bengal and move west or northwest across the peninsula. They then enter the Arabian Sea and change their course northward, causing heavy to very heavy rainfall along the western coastal areas, but since the rivers in this region are short and wide, the floods produced by such rains last for no more than one to two days, pose little threat, and do not cause much damage.

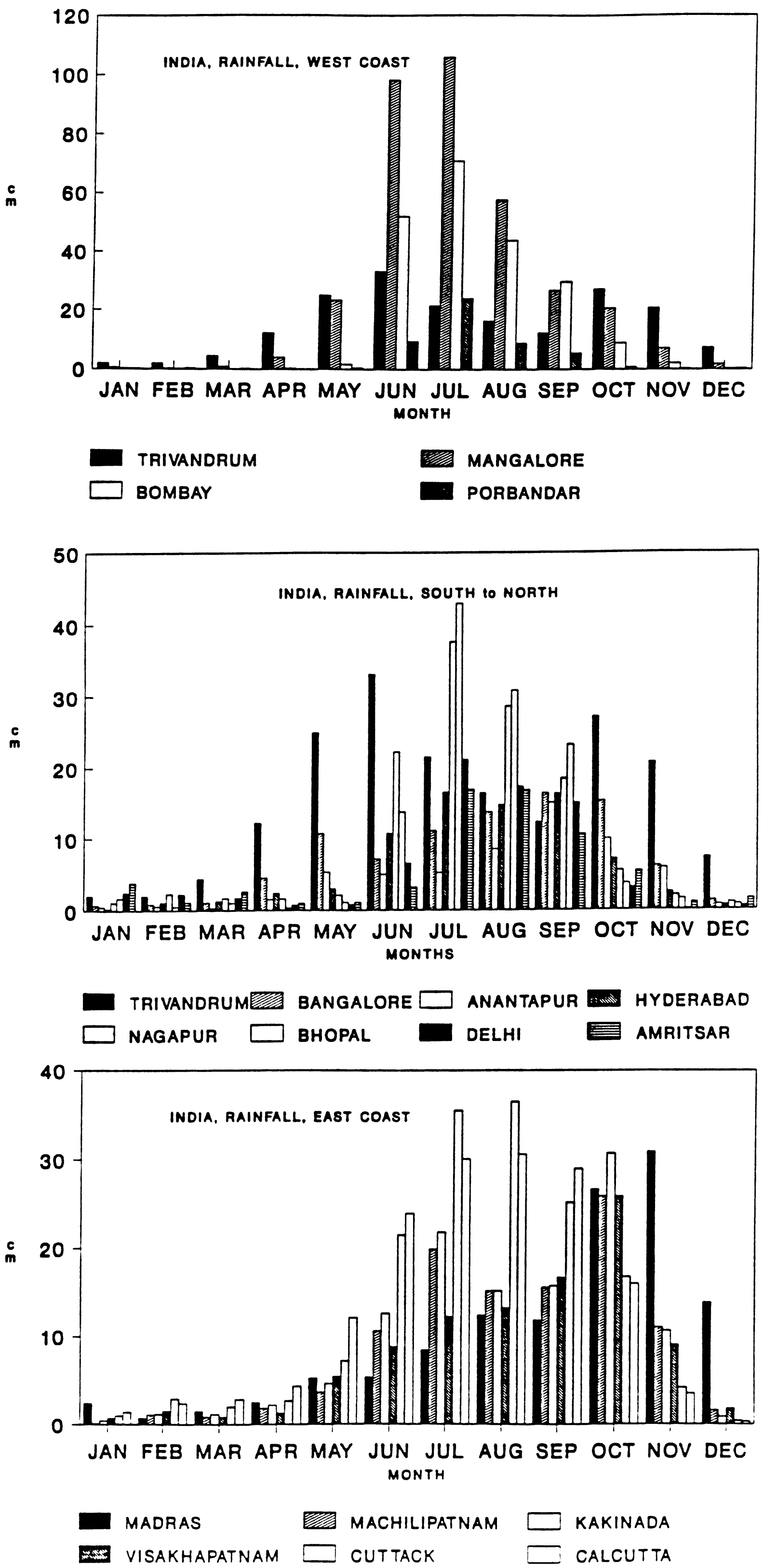

Figure 7. Distribution of rainfall in west coast, south to north, and east coast of India.

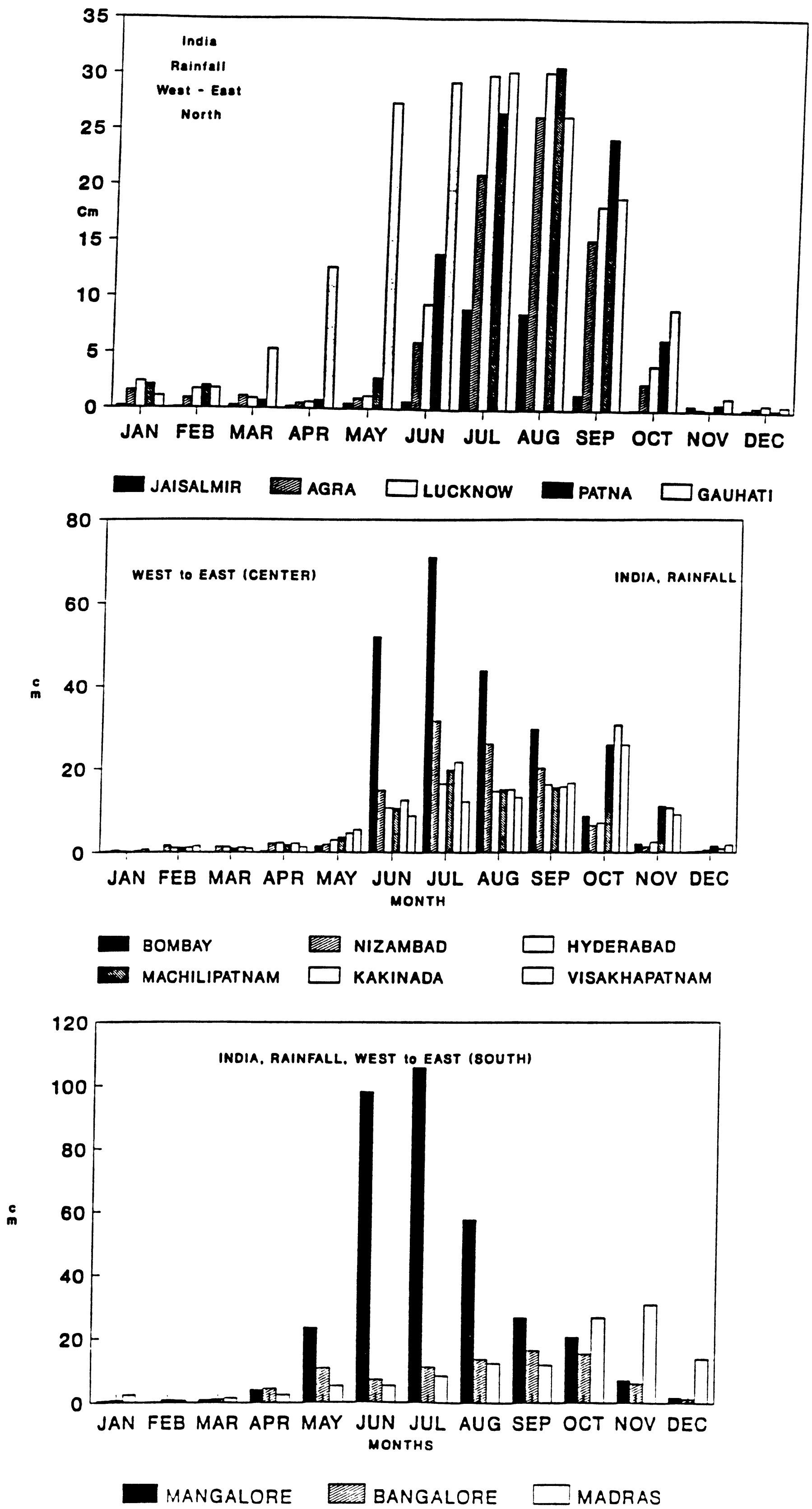

Figure 8. Distribution of rainfall profiles across India; northern India (west–east), central India (west–east), and southern India (west–east).

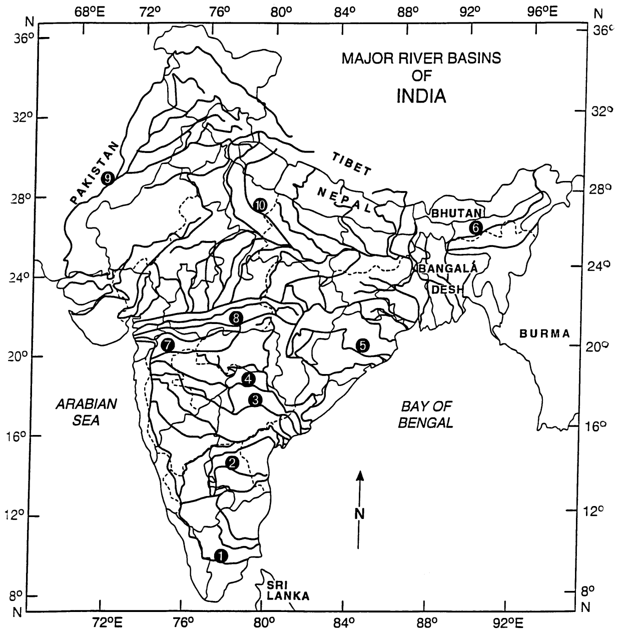

Figure 9. Major river basins in India (scale: 1 cm = 170 km). Modified from Rao (1979). 1 = Cauvery river; 2 = Pennar River; 3 = Krishna River; 4 = Godavari River; 5 = Mahanadi River; 6 = Brahamputra River; 7 = Tapati River; 8 = Narmada River; 9 = Indus River; 10 = Ganga River.

Moisture Zones

The essentials and elements of climatic classification, as applied to India, have been reported by Subrahmanyam (1988) and are therefore omitted here. Figure 10 shows the climate types for India and neighboring countries. These moist climates are separated from the extensive semiarid zone of the Deccan by a narrow fringe of subhumid climate; thus, while the transition of moisture zones from wet to dry is from east to west in north India, it is in the opposite direction in the south, closely following the rainfall patterns in both sections of the country. Small patches of humid climate exist at high elevations in the Aravallis and on the western and eastern ghats in south India.

A special feature of Figure 10, which has not been brought out by the other schemes of classification, is the unambiguous existence of absolutely arid climates in the central Deccan, right in the middle of the Krishna basin, strongly reiminscent of the desertic zone of the Indus basin. These sections of the India are a striking illustration of the evolution of climates due to the interplay between general atmospheric circulation and physical relief.

The east coast in the southeastern section of south India experiences subhumid climate on account of some moisture relief provided by the winter monsoon; in the absence of the latter, this region too would have been a semiarid strip continuous with the vast semiarid tract of the peninsula.

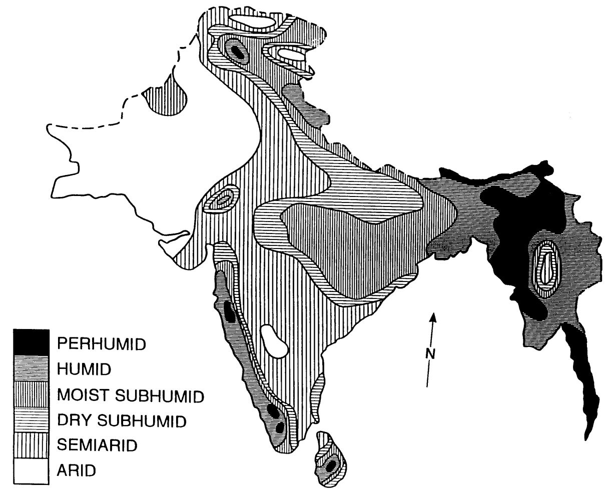

Figure 10. Climatic types of India and neighboring countries based on the moisture distribution (scale: 1 cm = 200 km). Modified from Subrahmanyam and Murty (1968).

Table 1. Hydrological characteristics of major river basins in India

River	Discharge (m^3/s)	Runoff (m^3/yr)	Drainage area (km^2)	Mean basin elevation (m)	Mean river length (km)
Brahmputra	16,186	510,450	690,000	5000	2900
Ganges	14,556	459,040	970,000	3900	6315
Indus	6,589	207,800	1,165,000	2500	2900
Godavari	3,330	105,000	290,000	400	1500
Krishna	2,146	67,675	260,000	420	1300
Mahanadi	2,113	66,640	132,090	500	885
Narmada	1,291	40,705	90,000	760	1300
Cauvery	664	20,950	72,000	630	765
Tapti	570	17,982	62,000	740	700
Minor rivers	3,000	104,736	240,000		

Source: Rao (1979).

River Systems

India is endowed with a network of 2.89 million km^2 of river basin systems (Table 1), with an average annual discharge of 1900 billion m^3 of water. Indian river basin systems (Figure 9) can be classified into four categories: (1) major rivers: with catchment areas of more than 20,000 km^2; (2) medium rivers: with catchment areas of 2000 to 20,000 km^2; (3) minor rivers: with catchment areas of less than 2000 km^2; and (4) desert rivers: with flow for some distance, which disappear into desert of

Rajasthan. There are 14 major rivers in India, covering 2.35 million km^2 of basin area with an annual discharge of 1406 billion m^3 of water. Of this huge quantity of water, only 1.5 million km^2 of cultivable area can be irrigated due to the lack of technical and financial resources.

In the first category of 14 major rivers, three river systems lie to the north of the Tropic of Cancer (23.5° latitude), which passes just north of Bhopal, seven systems are between the Tropic of Cancer and 20° latitude, passing through Bhubaneshwar, and four are in Peninsular India (Rao 1979).

The second category is medium rivers, of which there are 44, with catchment areas between 2000 and 20,000 km^2, covering a cumulative basin area of 0.24 million km^2. The annual average discharge is 112 billion m^3 of water, which irrigates 0.08 million km^2 of cultivated land. Of these 44 medium rivers, 19 flow west, 21 flow east, and the remaining flow into other countries.

The third category is minor river basins having a drainage area of less than 2000 km^2 each. They are numerous and are essentially small streams flowing from the western and eastern ghats into the sea. Their total catchment area is 0.2 million km^2. They are characterized by steep gradients, much silt, and the uncertain nature of their flow. They cause damage by heavy floods that occur at intervals of years. However, they play a significant role in extending irrigation to the coastal areas, particularly in Kerala and Tamil Nadu. Minor rivers flowing east contain only a quarter of the total estimated flow of minor rivers of 120 billion m^3, with the larger amount of water flowing down the minor rivers flowing west (Rao 1979).

The fourth category is rivers that flow for some distance and disappear in the desert of Rajasthan. Their waters are used for irrigation but their flow is uncertain in magnitude and time due to the highly erratic pattern of rainfall. The total basin area of desert rivers is about 100,000 km^2 and their annual average flow is 10 billion m^3.

The total annual volume of water discharged by all the river systems in India is 1645 billion m^3. Of this, the major river systems contribute 85%, while the medium and minor, including desert, rivers contribute 7% and 8%, respectively. More water is carried in the minor rivers than the medium rivers. The total flow in all the rivers of the world is estimated as 27,137 billion m^3, of which two thirds enters the sea and the rest enters lakes and swamps. The total flow of all the rivers in India is 6% of the flow of all rivers in the world (Rao 1979).

Atmospheric Change Effects on Water Resources

Recently, atmospheric change and its impacts has received considerable attention globally, and some work in this direction has also been recently initiated in India. Groisman and Kovyneva (1989) assessed the impacts of atmospheric change on water resources by using a set of statistical estimates for the parameters describing the relationship between changes in global climatic variables and those in local atmospheric characteristics for different seasons of the year. They used annual mean surface air temperature averaged over the extratropical zone of the northern hemisphere as a global variable. They observed that an increase in mean annual surface air temperature has resulted in increasing precipitation totals over the whole of India, especially along the western coast of the subcontinent.

By applying high general circulation models (GCM), the IPCC (1990) reports for the Indian continent state the warming varies from 1 to 2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5–15% in summer. Summer soil moisture increases by 5–10%.

Lal and Chandar (1993) examined the impact of atmospheric change due to the increase of atmospheric change of the Indian subcontinent. Their model results obtained from the atmospheric warming experiment suggested an increase of over 2°K over the monsoon region in the next 100 years. The model computed an increase in total seasonal precipitation (Figure 11). However, any significant precipitation change could only be isolated over some areas. Lal and Chandar (1993) did not find any evidence for a significant change in the mean monsoon onset date or in its interannual variability in a warmer world. Lal and Chander (1993) have evaluated that an enhanced warming over the Indian subcontinent by the end of the next century would result in more runoff in the northeast and central plains during the monsoon, with no substantial change during the winter season (Figure 12).

Lal and Bhaskaran (1993) evaluated the possible changes in the climate of the Thar Desert due to atmospheric change. The results pointed to a pronounced warming and associated enhancement in the evaporation rate without any significant change in the precipitation over the region over the next 100 years. This may lead to an enhanced aridity over the Thar Desert and could have major implications for the hydrology and water resources in this region.

Divya and Jain (1993) studied a sensitivity analysis of the response of a catchment situated in central India to expected climatic changes using several scenarios of

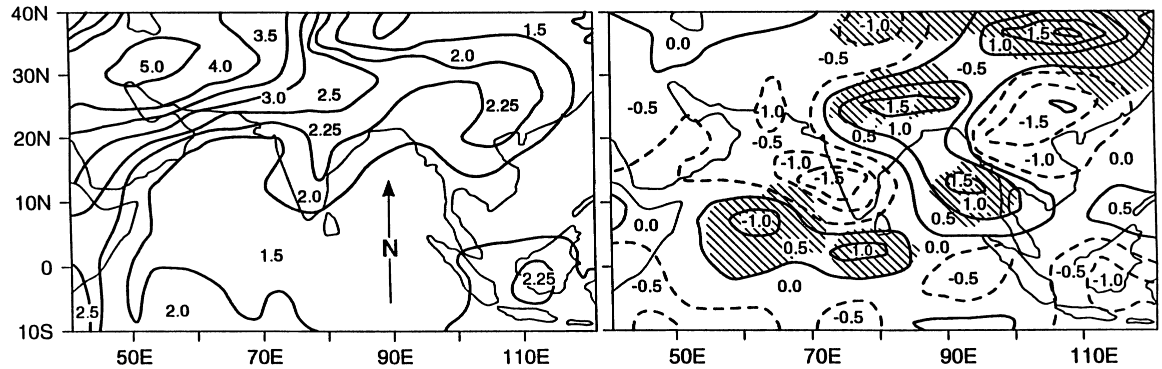

Figure 11. Spatial distribution of change in (left) temperature; and (right) rainfall for the Indian subcontinent as simulated by the Hamburg coupled climate model. The hatched area represents significant changes at the 90% level. Modified from Lal and Bhaskaran (1993).

atmospheric change and a regional model. The changes in runoff were more dramatic for the months when the runoff was already very small.

The regional effects of climate change due to atmospheric warming on various components of the hydrological cycle were examined (surface runoff, soil moisture, and evapotranspiration) using a conceptual model on a monthly basis and hypothetical scenarios of precipitation and temperature changes for three drainage basins in different locations in central India. A sensitivity analysis indicated that basins located in comparatively drier regions are more sensitive to atmospheric changes. Basin characteristics such as soil type, moisture holding capacity, and runoff coefficient also play an important role in deciding the basin response. To study the effect of atmospheric variations on the design and operation of water resources projects, the response of the hypothetical reservoirs of two drainage basins of India to atmospheric variations was studied (Mehrotra and Divya 1994). Series of stream flows under different atmospheric variations were derived and used in modeling the influences of these variation on reservoir storage. The results of the study indicated a high probability of significant effects of atmospheric change on reservoir storage.

Drought-Prone Areas

The regional distribution of rainfall over the Indian subcontinent is highly uneven and shows wide variations (Figure 13) (Hartmann and Michelsen 1989). Thus, at one end of the scale we have the two zones of excessive rainfall comprising the western ghats and the outer slopes of the Himalayas, nearly the whole of Assam and the eastern fringe of the Gangetic delta—the annual rainfall in these areas varies from 180 cm to 500 cm. Next in order of annual rainfall but larger in area is the belt with the annual rainfall varying between 80 and 180 cm. Parts of eastern India not included in the zone of excessive rainfall—Orissa and the Gangetic Plain as far as Kanpur and beyond this belt varying in width from 50 to 100 m skirting the base of the Himalayas up to the further extremity of Punjab—are included in this zone. It also includes the whole of Madhya Pradesh, the plateau of Bundelkhand and Malwa, the eastern half of Hyderabad, the eastern ghats and the coastal plains of Karnataka with a narrow belt on the summits of the western ghats (Raghavendra 1980). The third zone is the rest of peninsula having less than 75 cm of rainfall per year, and in certain limited tracts even as little as only 25 cm. The tract where famines are likely is where annual rainfall averages between 40 and 75 cm and where the variability of annual rainfall is more than 30% (Figure 13). Failure of rains is less common in those areas that have an annual average rainfall of 75–150 cm because of lower precipitation variability (10%–20%), but when they occur at all, they prove very destructive because the population in these regions is dense, the holdings are small, and the lower classes of agricultural population are generally very poor. These two types of areas in the past have been the seats of the most disastrous famines.

Drought in a semiarid area today is due to low rainfall and low irrigation in dry regions. Some 19 talukas (subregional municipalities) in nine districts (regional municipalities) of Rajastan, 50 talukas in 11 districts of Gujarat, and 87 talukas in 12 districts of Maharashtra, covering one third of the state's cultivated area, and 88 talukas in Karnataka, spreading to two thirds of the state's cultivated area, classified as drought-prone, are today the hotbed of drinking water and fodder shortages (Desarda 1987).

Creating and utilizing irrigation potential is the major policy issue from the point of view of the highest

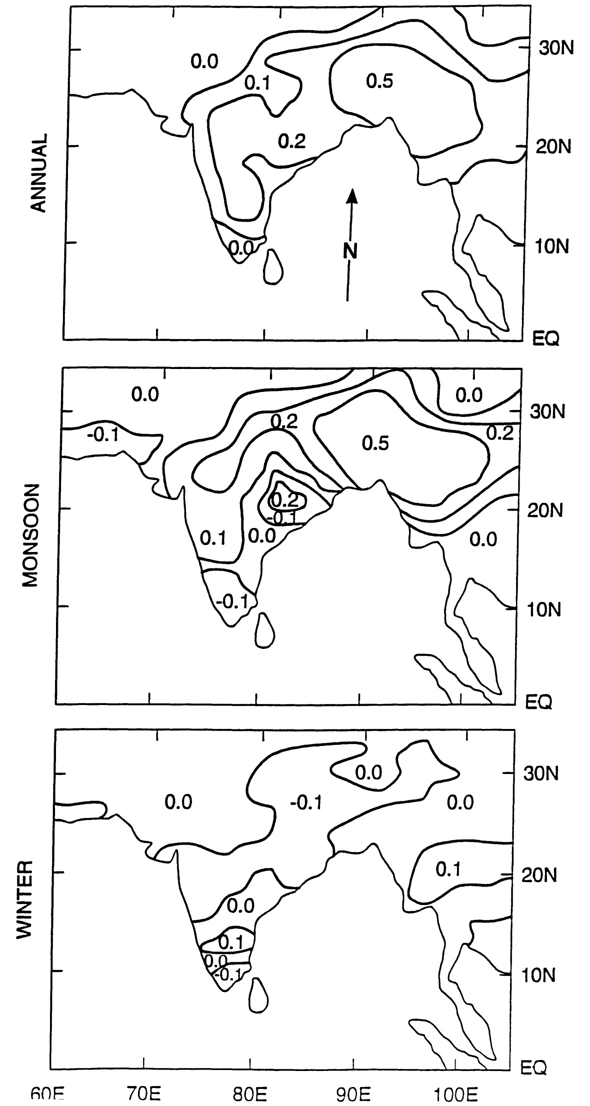

Figure 12. Annual and seasonal changes in surface runoff due to global warming for the Indian subcontinent as simulated by the ECHM3T-42 model. Modified from Lal and Chandar (1993).

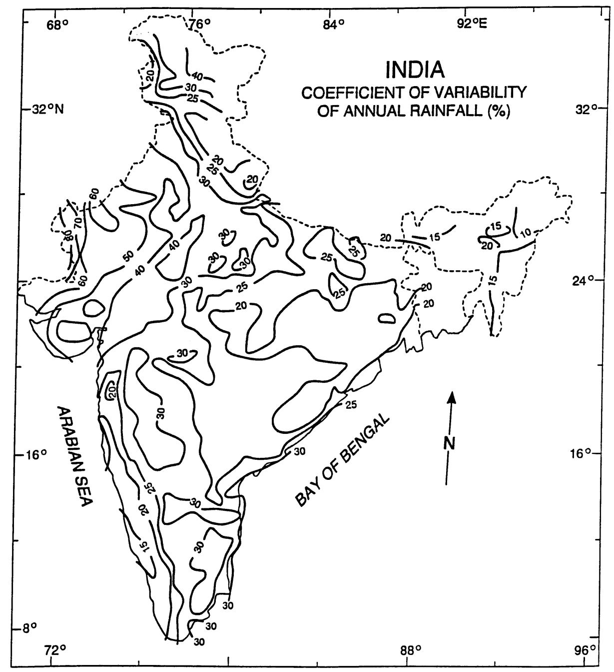

Figure 13. Coefficient of variability of annual rainfall (%) in India (scale: 1 cm = 180 km). Modified from Subrahmanyam (1988).

possible exploitation, maximum utilization, and salvaging of drought areas from crop damage and depletion of cattle. Of the basic water resources of 185 million (mn) ha/m, 105 are usable; after meeting the domestic and industrial demands, what is left for irrigation is 77 mn ha/m or just 20% of the water yields from rain. Viewed in terms of the irrigable land area, it is 113.5 mn ha/m or nearly 60% of the gross cropped area. However, there is a regionwide difference in the ultimate potential. The percentage of the gross cropped area that can be ultimately irrigated varies from 17% in Himachal Pradesh to 85% in Punjab.

The ultimate potential of the four states of the dry region from surface sources in not more than 35%. We also note variations among the states with respect to the percentage of the potential tapped so far. In the case of Karnataka, Maharashtra, and Andhra Pradesh, half of the potential remains untapped (Chatterjee 1967). In the face of the famine under which large parts of Andhra Pradesh, Maharashtra, Karnataka and Gujarat are reeling currently, the importance of developing protective irrigation cannot be overemphasized. Indeed, it is a vital necessity.

One significant feature of the northwestern states like Punjab and Haryana as compared to the western dry region is that they could get enough water for irrigation from the perennial rivers flowing through their plains or across their boundaries, e.g., the Punjab river system. For the southern and western drought-prone region, there is no such possibility without a large-scale interbasin transfer. Therefore, the current option is to use and spread the available water in such a way that it covers the largest possible cropped area. In such a situation the irrigation system should be designed to afford life-saving watering, which is termed 'protective.'

Applying the fourfold criteria of nature, the extent of rainfall, irrigation availability revenue remission, and incidence of crop failure results in the drought-prone area designation of Figure 14. Broadly, there are 90

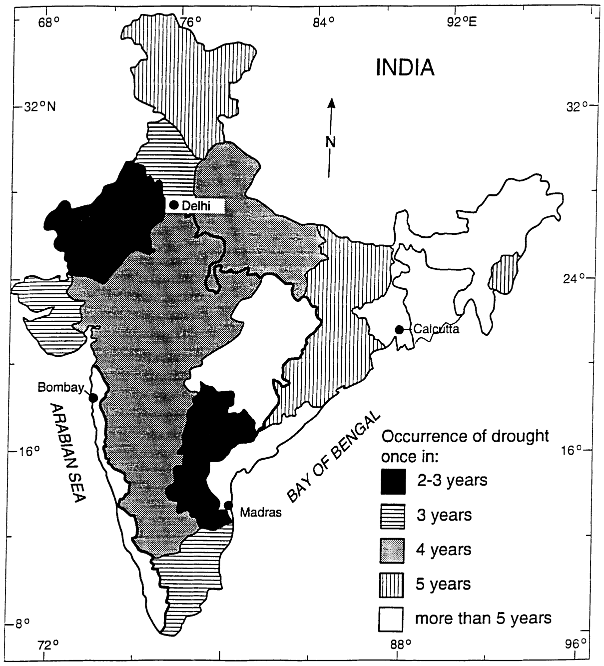

Figure 14. Likelihood of drought occurrence in India (scale: 1 cm = 150 km).

Table 2. Estimated present utilization and future requirement of water by 2025 AD, unit mn ha/m (Bandyopadhyay 1989)

	Utilization (1985)			Future requirement (2025 AD)		
Water use	Surface water	Ground water	Total	Surface water	Ground water	Total
Irrigation	33.14	17.34	50.48	61.17	24.37	85.54
Domestic	0.22	0.06	0.28	1.21	0.43	1.64
Industrial	0.14		0.14	0.82		0.82
Power supply	0.43		0.43	1.50		1.50
Pisciculture				2.79		2.79
Forestry				2.21		2.21
Livestock	0.49		0.49	1.18		1.18
Navigation						
Pollution						
Recreation						
Total demand	34.42	17.40	51.82	70.88	24.80	95.68
Total utilizable	68.41	35.58	103.99	68.41	35.58	103.99
Percentage	50.30	48.90	49.80	103.60	69.70	92.00

Source: Bandyopadhyay (1989).

districts in 12 states. Among many districts few talukas may be free of famine hazards. Drought-prone areas account for 53% of the cultivated land. Their locations are: 15 in the Ganga basin, 15 in western Rajastan, 15 in Gujarat and Madhya Pradesh, and 45 in peninsular India south of the Narmada (Desarda 1987).

The main problem in 60 districts in peninsular India and 15 in the northwest is that they do not have enough water for drinking and farming. The national water balance in 1985 and 2025 given in Table 2 clearly indicates that even under normal rainfall conditions an absolute scarcity of water is going to overtake the country in three or four decades (Bandyopadhyay 1989). There are three avenues to consider: (1) an augmentation of the water resources within the area and the basin by comprehensive soil, water, and forest conservation measures; (2) effect interbasin transfers; and (3) groundwater exploration.

Major rivers must be interlinked and form a national water grid (Murthy 1989). The Ganga–Cauvery project is vital in this link (Rao 1979). Earlier arguments of the 1950s and 1960s stated that, in view of a long gestation period and heavy energy requirement to lift water, the project was beyond the nation's capacity. These views have become secondary to the sizable stock of food grains and capital goods like steel, cement, and energy generating capacity.

From the point of view of expeditious tackling of the drought problem:

1. In the case of 15 districts of Ganga basin, water availability is not at all a problem. Obstacles to eradicating drought there are institutional, viz., land reforms and reorganization of credit cooperatives, etc.

2. To solve the problem for those in peninsular India north of the Narmada, the Narmada project is key.

3. The problem of 45 peninsular districts south of the Narmada is serious and few measurements are initiated. This requires the development of protective irrigation through land and water conservation programs and linkage to employment guarantees and drought eradication programs. The other source of water is groundwater. Groundwater depends on geology and other hydrogeological conditions.

Geology

India can be best described as a stable continent of Precambrian formations, which in its northward movement compressed the Tethys Sea where 15,000 m of sediments have accumulated since the Palaeozoic. In this geocollision, the maximal compression on the plastic sediment occurred in the area of contact of the Indian craton and Laurasia: this corresponds to the present Great Himalayas with its immense folds and impressive thrusts. At either end, where the compression of the Indian block ceased, the chains bent anticlockwise in Kashmir and clockwise in Assam (Krishnan 1975, Rogers and Callahan 1987). Moreover, the present Indo-Gangetic plain with its thick alluvial filling is a trough created by the warping down of the Indian Continent under the Asian mass (Tibet). It is also a 300 km-long drainage system where three powerful rivers, the Indus, the Ganges, and the Brahmaputra, carry annually an amount of water equal to the yearly discharge of the equatorial Zaire.

Physiographically, India has the following three distinct features (Figure 15): (1) the mountainous region of the Himalayas—the extra peninsula; (2) the great Indus–Ganga–Brahmaputra plains; and (3) the triangular plateau of the peninsula.

The extrapeninsular region, the zone of Himalayan folding forms and arc-shaped belts with Naga-Lushai folding, and the entire northern part is occupied by the great effusives and intrusives (Figure 15). The Himalayan foredeep, occupied by Indus–Ganga–Brahmaputra alluvium, is believed to be constituted by posttectonic molasse sediments. The peninsular shield is essentially made up of an Archean basement complex of gneiss, granitoids, charnockities, etc., metasedimentary and metabasic rocks of the Dharwar system, followed by rocks of the Cuddapah and Vindhyan systems. The west-central part of this shield is occupied by Deccan traps of large thickness. The Gondwana rocks occupy the rift systems in the peninsular shield.

The extrapeninsular and the peninsular regions are unlike each other in every respect. The latter has more or less remained, from the dawn of the geological history, a solid mass with no marine sedimentation during the Cambrian. The former had continuous marine sedimentation almost throughout its history from the Cambrian period (Krishnan 1975). Relic mountains and flat and shallow valleys characterize the peninsular region in contrast to the lofty mountains, deep valleys, and torrential rivers marking the extrapeninsular region. The Indus–Ganga–Brahmaputra rivers brought down rich, thick sediments to form the extensive alluvial plain between the extrapeninsular and peninsular regions, beginning with the last phase of the Himalayan upheavals and continuing through the Pleistocene up to recent times. The present shape of the country was achieved in the Pleistocene period. The rivers of the peninsula are of great antiquity, compared to the youthful rivers of the extrapeninsular area, and their river channels have reached the base level of erosion. The Godavari, the Krishna, and the Cauvery and their tributaries have developed the rich and fertile deltas with the sediments brought to the east coast.

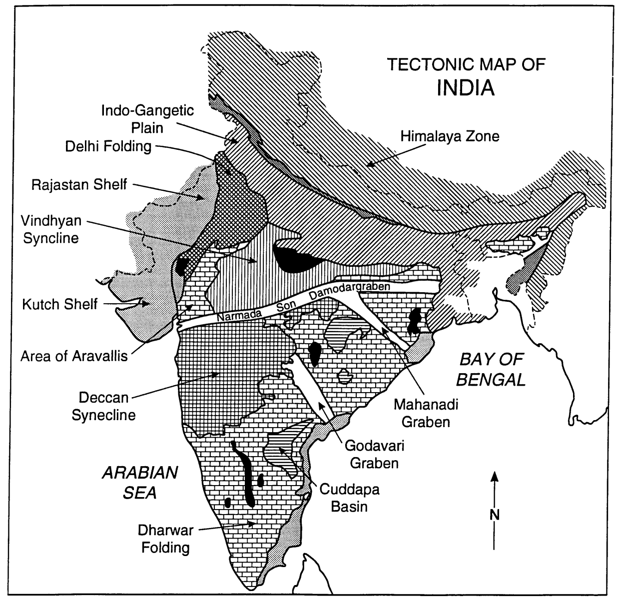

Figure 15. Geological map of India (scale: 1 cm = 170 km). Modified from Rogers and Callahan (1987).

Hydrogeological Framework

In India, groundwater has also been exploited substantially during the past few decades for irrigation. Most of the groundwater utilization in India is from shallow aquifer zones at depths less than 100 m. Based on studies of the mode of occurrences and availability, groundwater is mainly governed by geological formations, the nature and extent of aquifer bodies, and hydrogeological properties in relation to groundwater flow characteristics; thus, the hydrogeological (Chaturvedi 1982, Ranganath 1982) framework of India has been divided into three major categories (Figure 16): (1) the areas underlain by unconsolidated formations; (2) the areas underlain by semiconsolidated formations; and (3) the areas underlain by consolidated formations.

Areas Underlain by Unconsolidated Formations

The Indo-Gangetic plains, coastal plains, Brahmputra Valley, Bengal basin, and the foredeep region of the Himalayan geosynclinal belt from the western to eastern Himalayas are occupied by this group of rocks. The intermountain valleys in Kashmir and Himachal Pradesh, Kalka of Haryana, Doon of Uttar Pradesh, and the inter-Cratonic basins like the Narmada–Tapati–Purna basins are also occupied by these sediments. Thus, the aeolian sediments of Rajasthan and Gujarat arid tracts are also included in this category. These sediments consist mainly of clays, silts, sands, gravels, pebbles, cobbles, boulders, ferruginous nodules, and calcareous

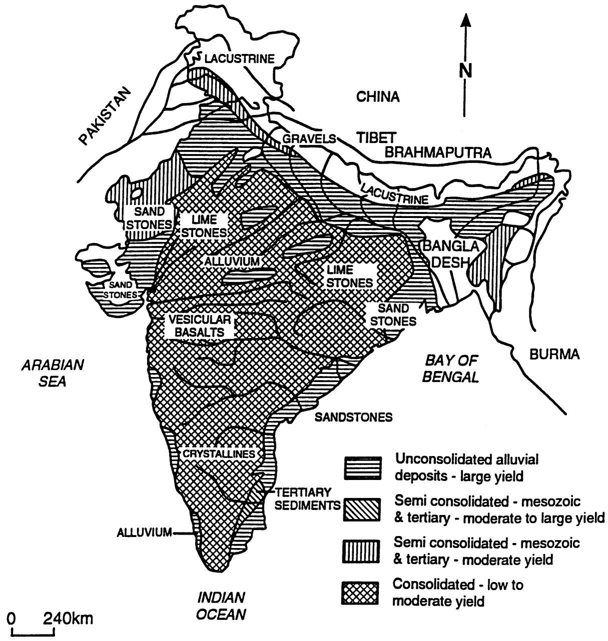

Figure 16. Hydrogeological map of India. Modified from Ranganath (1982).

concentrations, etc. They are Quaternary rocks and are broadly classified as recent alluvium, older alluvium, and coastal alluvium formations.

Fairly thick and regularly extensive confined/unconfined aquifers extend up to 300 m in the recent alluvium, clay, silt, sand, gravel, and calcareous concentrations, etc., with prospects of large yield above 150 m^3/h. The older alluvium and laterite, silt, and ferruginous concentrations, lithomargic clay, gravel, etc., are also good with respect to yield, above 150 m^3/h, but they are discontinuous confined/unconfined aquifers down to 300 m.

Areas Underlain by Semiconsolidated Formations

Assam; Sikkim; Uttar Pradesh; Punjab; Jammu; Kashmir, Andaman, and Nicobar islands; Tripura; Arunachal; Cambay Basin in Gujarat; east coastal areas; and west Rajasthan contain these formations, while the terrestrial freshwater deposits belonging to Gondawana system of the Peninsular shield also fall in this category. These formations belong to Palaeozoic, Mesozoic, and Cenozoic groups of rocks, particularly from Carboniferous to Mio-Pliocene periods. These formations are composed of shales, sandstones, limestones, flysch, and molasse beds. Moderately thick but regionally extensive confined/unconfined aquifers, they extend down to 150 m in some areas with moderate yield of 50–150 m^3/h, while in other parts, they are discontinuous with similar yield. Their yield goes below 5 m^3/h in west Bengal, Uttar Pradesh, west Rajasthan, Bihar, Madhya Pradesh, and Andhra Pradesh.

Areas Underlain by Consolidated Formations

While the unconsolidated and semiconsolidated formations are porous formations, the consolidated formations are characterized as fissured (Narasimhan 1990). Almost the entire peninsular region is occupied by these consolidated formations ranging in age from Archean to Tertiary. The Archeans generally include the schistose formations of the Dharwar system, gneiss, charnockites, etc., while the Precambrians include the Cuddapaths and the Vindhyans. The Deccan traps range in age from Upper Mesozoic to Lower Tertiary and are well jointed, fissured, vesicular, and massive. The sedimentaries and metasedimentaries belong to Cenozoic, Mesozoic and Upper Precambrian systems and are composed of sandstones, limestones, shales, slates, quartzites, etc.

Two water-bearing zones can generally identified in hard rock areas (Narasimhan 1990, Briz-Kishore 1993, Ranganath 1982): the composed or weathered zone and water-bearing joints and fractures. In the weathered and decomposed part of the bedrock, the groundwater occupies the intergranular spaces of the formation material. The yielding capacity of this zone is often limited and is seasonal in character. The groundwater flow systems are of local type, where each local system has its recharge area at a topographic high and its discharge area at a topographic low, which are adjacent to each other. The intermediate and regional groundwater flow systems do not exist because of negligible hydraulic conductivity with depth.

The crystalline rocks generally do not possess original or primary openings, and fresh crystalline rocks have less than 1% porosity and negligible hydraulic conductivity. The ability of crystalline rocks to store and transmit water is dependent on the development of secondary openings, which were formed by fracturing and weathering. The weathered part of these crystalline rocks is of particular importance both as a storage zone for groundwater and as aquifer for open wells and shallow tube wells. The hydrogeology and groundwater resource in Deccan Traps is explained by many hydrogeologists (Deolankar 1990, Uhl and Joshi 1986). In general, this zone does not contribute appreciably to tube well yield, and the contained water can be tapped only by constructing large-diameter wells. In most cases, this zone is entirely shut off by the lining in a tube well.

The saturated fractures and joints found in the relatively unweathered bedrock at greater depths are capable of yielding a substantial quantity of water. The

Table 3. Groundwater potential in states (1980)

State	Gross recharge	Recoverable recharge	Existing net extraction (mn ha/m)	Groundwater balance	Stage of groundwater development
Andhar Pradesh	4.61	3.22	0.72	2.50	22
Assam	1.36	0.95	0.95	0.94	9
Bihar	2.91	2.03	0.74	1.29	36
Gujarat	1.63	1.14	0.48	0.66	42
Haryana	0.77	0.59	0.62(−)	0.03	105
Jammu and Kashmir	0.25	0.17	0.01	0.16	6
Karnataka	1.37	1.11	0.15	0.96	14
Kerala	1.05	0.73	0.03	0.70	4
Madhya Pradesh	8.20	5.74	0.42	5.32	7
Maharashtra	4.93	3.45	0.67	2.78	19
Punjab	1.40	0.98	0.89	0.09	91
Orissa	1.95	1.36	0.098	1.26	7
Rajasthan	1.43	1.00	0.37	0.63	37
Tamil Nadu	2.60	1.83	1.35	0.47	74
Uttar Pradesh	9.58	6.71	2.53	4.18	38
West Bengal	2.15	1.50	0.43	1.07	29
Total	46.00	32.20	9.54	22.66	

Source: ARDC (1979).

fractures and joints are mostly horizontal in nature and interconnected with a network of joints and fissures. The yield from these zones is not readily affected by seasonal changes. In the granite and gneiss of south India, such saturated zones are normally encountered at depths ranging from 10 to 50 m. In tectonically disturbed areas, they may even occur at greater depths of 100 m or more. These zones are usually weathered and have a small vertical extent of a few tens of centimeters. The normal yield of a tube well tapping such zones is around 5.5 m^3/h. Very low yields of about 450–900 liters/h are frequent, whereas quite large yields up to 90,000 liters/h have been reported from a few isolated tube wells.

In the consolidated or fissured formations, the occurrence of groundwater is restricted to weathered residue and fracture zones having secondary porosity, and the yield is above 20 m^3/h in the mesozoic and Palaeozoic formations, while it goes down to 5–20 m^3/h and even below 5 m^3/h in the Precambrian and Archean formations. This is true of the peninsular region and parts of Gujarat and northeast India.

Groundwater Potential

From time to time, estimates of groundwater potential of India have been made by various agencies. The assessment by Raghava Rao (1969) and colleagues placed it at 267,000 million m^3 (Raghava Rao 1969), while others estimated it at 255,000 million m^3 (Rao 1979). The Central Working Group on Groundwater, Ministry of Food and Agriculture estimated the net annual recharge at 265,000 million m^3, while the overexploitation committee put the annual recharge at 46-mn ha/m (ARDC 1979). Most of the state groundwater organizations computed groundwater potentials on the basis of new norms recommended by Agricultural Refinance and Development Corporation (ARDC 1979). The recoverable recharge is taken as 70% of gross recharge (Table 3).

Table 4. Irrigation potential (groundwater) in million hectare cumulative levels

	1950–1951	1960–1961	1968–1969	1973–1974	1977–1978	1979–1980
Groundwater	6.50	8.30	12.50	16.50	19.80	22.00

Source: ARDC (1979).

Groundwater Utilization

Groundwater as a source of water supply has been utilized in India from time immemorial, mainly for domestic needs and also partly for irrigation. The pattern of its utilization changed in recent times, nearly 90% being used for irrigation purposes, so much so that groundwater potential is exposed more often in terms of irrigation potential. The progressive increase of groundwater potential in India can be seen from Table 4.

The tempo of exploration of groundwater resources picked up in the late 1960s, mainly due to the drought in Bihar. Now the rate of construction of groundwater

Table 5. Ultimate groundwater potential in states

State	Ground-water potential (ha)	Dug wells (N)	Private tube wells (N)	Public tube wells (N)
Andhra Pradesh	2,200,000	1,500,000	75,000	1,500,000
Assam	700,000		150,000	1,000,000
Bihar	4,000,000	600,000	800,000	10,000,000
Gujarat	1,500,000	750,000	5,000	4,000,000
Haryana	1,500,000	5,000	300,000	2,000,000
Himachal	50,000		1,000	500,000
Jammu and Kashmir	150,000	10,000	12,000	200,000
Karnataka	1,200,000	800,000		
Kerala	300,000	700,000	10,000	
Madhya Pradesh	3,000,000	2,000,000	30,000	500,000
Maharashtra	2,000,000	1,300,000	3,000	
Manipur	5,000			100,000
Meghalaya	15,000		2,000	
Nagaland	5,000			50,000
Orissa	1,500,000	550,000	30,000	5,000,000
Punjab	3,500,000	10,000	600,000	2,000,000
Rajasthan	2,000,000	900,000	20,000	70,000
Sikkim	2,000			
Tamil Nadu	1,500,000	1,500,000	100,000	
Tripura	15,000		15,000	100,000
Uttar Pradesh	12,000,000	1,500,000	1,400,000	27,000,000
West Bengal	2,500,000	50,000	500,000	5,000,000
Union Territories	120,000	25,000	25,000	300,000
Total	39,762,000	12,200,000	4,076,000	59,320,000

Source: CGWB (1976).

Table 6. Groundwater development by states

State	Groundwater potential (ha)	Cumulative 1980–1981 estimated[a]	Utilization (%)	Balance[a]
Andhra Pradesh	2,200,000	1080	49.09	1120
Assam	700,000	48	6.8	652
Bihar	4,000,000	1535	38.37	2465
Gujarat	1,500,000	1351	87.66	149
Haryana	1,500,000	1262	84.13	238
Himachal	50,000	6.5	13.00	43.5
Jammu and Kashmir	150,000	5	3.00	145
Karnataka	1,200,000	455	37.91	745
Kerala	300,000	27	9.00	273
Madhya Pradesh	3,000,000	1052	35.06	1948
Maharashtra	2,000,000	1119	55.95	881
Manipur	5,000	0.1	2.00	4.9
Meghalaya	15,000	6.1	40.66	8.9
Nagaland	5,000			5
Orissa	1,500,000	350	23.33	1150
Punjab	3,500,000	2925	83.57	575
Rajasthan	2,000,000	1515	75.75	485
Sikkim	2,000			2
Tamil Nadu	1,500,000	1117	74.46	383
Tripura	15,000	5.5	36.66	9.5
Uttar Pradesh	12,000,000	8824	73.53	7624
West Bengal	2,500,000	550	22.00	1950
Union Territories	120,000	57	47.50	63
Total	39,762,000	23,300		16,462

Source: ARDC (1979).

[a]Multiply columns 3 and 5 (10^3).

structures is on the order of 200,000 dug wells, 240,000 private wells, and 3600 public tube wells annually. Along with this, the annual rate of installation of electric pump sets is of the order of 410,000 and diesel pump sets during the 1980–1985 period. Utilization of groundwater resources from irrigation touched the 23 million hectare mark in 1980–1981, which is a 57% utilization of the ultimate potential. The ultimate groundwater potential and groundwater utilization vary from state to state as shown in Tables 5 and 6 (ARDC 1979).

Exploitation of groundwater has exceeded the 80% mark in Gujarat, Haryana, and Punjab; 70% in Rajasthan, Tamil Nadu, and Uttar Pradesh; while in Andhra Pradesh and Maharashtra it is 49% and 55%, respectively, and in the remaining states it is below 40%, touching a low mark of 2% in Manipur. Calculations by the ARDC overexploitation committee gave an upward revision of the groundwater resource availability, but also revealed that in Haryana and Punjab the recoverable recharge component has been exceeded by withdrawals. These states have to give serious consideration to the problem before effecting further withdrawals.

Groundwater Quality

Groundwater quality is affected by many factors, the most important being: (1) physiochemical characteristics of the rocks through which the water is circulating; (2) geology of the location; (3) climate of the area, including intensity, duration, and frequency of rainfall, intensity and duration of solar radiation, wind velocity, temperature, etc., as these affect the quantity and frequency of recharge, evapotranspiration losses, etc.; (4) role of microorganisms, which includes oxidative and reductive biodegradation of organic matter, fixation of atmospheric nitrogen, mineralization and immobilization of nitrogen species, denitrification, oxidation–reduction of sulfur species and transition elements, etc.; (5) chemical, physical, and mineralogical characteristics of the soils through which rainwater percolates underground; (6) topography of the area, which affects the depth to groundwater, slope of the area, and the time of contact, etc.; (7) vegetation cover, which affects evapotranspiration losses, CO_2 contents of soil, air, etc.; (8) mixing of connate waters; (9) intrusion of saline waters, as in coastal areas; and (10) role of human intrusion affecting the hydrological cycle at a microscale by abstracting groundwater, construction of storage reservoirs and canals, etc., and in bringing about degradation in water quality through utilization of water for domestic, irrigation and industrial uses and through unscientific disposal of waste disposal, city disposal, etc.

Based on physiographic and hydrogeological considerations, attempts have been made during the last 40 to 50 years decades to delineate different groundwater provinces in India (Auden 1940, Taylor 1959, Chatterjee 1967, Mithal 1969, Handa 1964, 1975, 1984). It must, however, be pointed out that quality of groundwater in the phreatic zone is not constant but varies considerably from time to time. Furthermore, in any one area, groundwaters of different quality may occur due to local differences in geology, etc., but it is dominant types that are described here.

Hydrogeological Exploration

The key to successful groundwater exploration lies in obtaining essential information on the geology and hydrology of a basin. Knowledge of hydrology is needed to determine the sources of recharge and discharge of groundwater. Precipitation may infiltrate directly to the subsurface or it may go as runoff and stream flow which infiltrates inpart. Excess water, supplied to the land for irrigation purposes, could sink partly underground and contribute significantly to the groundwater reservoir. Quantitative evaluation of all these items is essential for proper understanding of groundwater occurrence and availability. The second essential item is precise information on the geological formation such as sedimentation framework, structural framework, thickness of various geological units acting as aquifers, and permeability and storage characteristics.

The hydrological and geological features when combined would lead to understanding the hydrological system or unit. It could be a major unit or a microunit. Each of the basins or subbasins would have surface hydrological boundaries and a subsurface system with a certain degree of transmissivity and storage (Uhl and Joshi 1986, Versey and Singh 1982). One must analyze these boundaries and parameters as accurately as possible before any system is subjected to development programs and management practices by modelling (Bobba and Singh 1995, Radhakrishna 1990).

A rapid inexpensive reconnaissance survey over a region could be conducted in unexplored regions through quick field traverses and noting all relevant geological and hydrological features. Interpretations of satellite and aerial photographs combined with field checks should become a part of these studies (Bobba and others 1992). All available hydrological, data such as water levels, spring discharges, yield characters of well structures, and water quality parameters, when properly evaluated over a geological terrain, would facilitate preparation of a preliminary hydrological map.

The above studies could be further intensified to map the terrain in detail and estimate the microlevel changes in flow patterns, velocity potentials, yield characters, and chemical quality variations. These detailed studies could be done over a period of time, say, one hydrological cycle or two hydrological cycles depending upon the logistics. Detailed hydrological and hydrochemical maps could then be prepared and serve as potential tools for development of groundwater either for drinking or for irrigation. The above studies would, in general, help evolve the following hydrological information: (1) the primary and secondary porosity and permeability characteristics of the materials; (2) aquifer boundaries; (3) depth of water table and probable saturated thickness of aquifers; (4) relationship between topography, geology, and hydrology; (5) identification of recharge and discharge areas; (6) relationships between surface and groundwaters; (7) estimates of productive areas for groundwater development and design of well fields; and (8) and estimates of groundwater quality, fresh or saline.

Hydrogeochemical Zones

On the basis of chemical composition, the groundwater quality in India can be classified as follows: (1) bicarbonate-type water; (2) bicarbonate–chloride-type groundwater; (3) chloride–bicarbonate-type groundwater; (4) sulfate–chloride-type groundwater (5) chloride–sulfate-type groundwater; and (6) chloride-type groundwater. The characteristics and distribution of the various types of groundwaters are briefly outlined below:

Bicarbonate Groundwater

The groundwater in this group is characterized by relatively high bicarbonate contents, which in terms of milliequivalents/liter exceed 50% of the total anions present. The chloride and sulfate ion concentrations are normally below 2.0 and 1.0 me/liter respectively: the $Cl:SO_4$ mole ratio being normally more than 1, although exceptions do occur, e.g., in Doon valley (UP). Among the cations, the alkaline earths form over 50% of the total cations and the Ca:Mg mole ratio varies from less than unity to over 4. The electrical conductivity (EC) values for these waters are normally below 1000 μS / cm.

In northeastern India, these waters are generally undersaturated with respect to calcite but in other places they are either in equilibrium or even supersaturated with respect to the mineral. Saturation with respect to dolomite is, however, more common, particularly in the basaltic area of Madhya Pradesh (Das and Kidwai 1981). They are all undersaturated with respect to strontianite. All groundwater in this category was found to be undersaturated with respect to gypsum ($CaSO_4 \cdot 2H_2O$), celestite ($SrSO_4$), and fluorite (CaF_2). Furthermore, they normally plot in the kaolinite stability field.

This type of groundwater is confined mainly to the humid and subhumid areas in India. In the northeast this includes Assam, Meghalaya, Arunachal, Nagaland, Mizorum, Manipur, and Tripura; in the east, West Bengal (excluding Calcutta and the costal zone), Bihar, Orissa (excluding the costal zone); in the north, Jammu and Kashmir, Himachal Pradesh, northern Punjab; in the northeast, Haryana, Utter Pradesh (excluding some parts of southern and southwestern UP), and parts of Rajasthan and Gujarat (excluding coastal zone). In south, it includes Kerala (excluding the coastal zone), parts of Maharashtra, Andhra Pradesh (excluding the coastal zone); Tamil Nadu (excluding coastal zone).

Bicarbonate–Chloride Water

In this type of groundwater, the dominance of bicarbonate ions is less compared to the bicarbonate-type groundwater, the bicarbonate ions being normally 30%–50% of the total anions present. The concentration of chloride is quite significant and the same is true for sodium. The EC of these waters is normally below 2500 μS / cm, although in a few cases groundwaters with EC values up to 5000 μS / cm are found (Subbarao and Satyanarayana 1988).

These waters are normally in equilibrium or supersaturated with respect to calcite ($CaCO_3$) and dolomite ($CaCO_3$, $MgCO_3$), but undersaturated with respect to strontianite, gypsum, celestite and fluorite. However, in a few areas, e.g., in Bhatinda and Sangrur (Punjab) and Gurgaon (Haryana), these waters may be in equilibrium or even supersaturated with respect to fluoride. They normally plot in the kaolinite stability field, but fluoride-saturated waters tend to plot in the montmorillonite stability field, as do the HCO_3–Cl–Na groundwaters.

Chloride–Bicarbonate Water

The groundwater in this classification has chloride ions as the dominant anion, followed by bicarbonate. Among the cations, sodium is normally dominant, followed by Mg and Ca ions. The EC of these waters is normally above 5000 μS / cm, although in some cases EC may be less than 5000 μS / cm.

The groundwater in this category is normally supersaturated with respect to calcite and dolomite but undersaturated with respect to strontianite, gypsum, and celesite (Subba Rao and Vachaspati 1978). Most of these waters are in equilibrium or even supersaturated with respect to fluoride e.g., in Bankapatti (Sirohi district), eastern parts of Nagapur and Jodhpur (West Rajasthan), Hazurabad in Karimnagar, Koilsager in the Mahabubnagar district (Raju and Goud 1990, Naram 1981), Nandigam in the Krishna district, and Nalgonda (all in Andhra Pradesh), where fluoride concentration may be 8 mg / liter or even more. A good proportion of these waters plots in the stability field of montomorillonite, although a few also plot in the kaolinite stability field.

Sulfate–Chloride Water

The groundwater falling in this classification has sulfate and chloride as the dominant ions among the anions, and sodium dominant among the cations, followed by Ca and sometimes also by magnesium. The EC of these waters normally exceeds 5000 μS / cm. The groundwaters in this category occur in the Tiruchinapalli district, Tamil Nadu, and in some parts of south and southwest Haryana and west of Rajasthan (Katchawana 1981, Kapoor and others 1985).

Chloride–Sulfate Waters

This type of groundwater is characterized by chloride as the predominant anion followed by sulfate. Among the cations, sodium is dominant. The EC values of such waters are normally above 5000 μS / cm. The groundwaters are in equilibrium or supersaturated with respect to calcite and dolomite and are in many cases in ‘‘near equilibrium’’ with respect to strontianite (in coastal areas). However, with respect to gypsum, celestite, and fluoride, they are normally undersaturated. They plot mostly in the montmorillonite stability field. The groundwaters falling in this classification are located in the coastal areas (Subba Rao and Vachaspati 1973, Somasundaram and others 1993) and in the arid and semiarid parts of India Rajastan, etc. (Katchawana 1981).

Chloride–Sodium Water

The groundwaters belonging to this category are normally in equilibrium or supersaturated with respect to calcite, dolomite, and in coastal areas (Subba Rao and Vachaspati 1973, Subbarao and Satyanaryana 1988, Somasundaram and others 1993) also with respect to strontianite. These waters are, however, undersaturated with respect to gypsum, celestite, and fluoride and plot mostly in the montmorillonite stability field. These types of groundwaters are characterized by the dominance of the chloride and sodium ions and have EC values above 15,000 μS/cm. In many cases these saline waters are being used for the manufacture of common salt. It may also be noted here that in northeastern India, the saline waters occur in the form of springs, with varying discharges.

Water Pollution in India

Groundwater Pollution

High iron waters. In northeast India, West Bengal (Handa 1975) and in some other parts of India, groundwaters with relatively high iron concentrations have been observed. In northeast India, for example, groundwaters having as much as 20 mg/liter Fe have been observed. High iron groundwaters containing up to 2–3 mg/liter Fe are also found in some parts of UP, Pondicherry, etc. The occurrence of high iron groundwaters is associated with a humid climate, occurrence of pisolitic nodules containing iron (e.g., in West Bengal), and lowering of redox potential due to anaerobic conditions.

High fluoride waters. In many parts of the semiarid to arid parts of India (Handa 1975), e.g., in the western parts of Sirohi district, eastern Nagaur, southwestern Ganganagar, northwest and east of Jodhpur (all in Rajasthan), Prakasam (Raman and Rao 1983), Nalgonda, Anantapur, Chittor, Medak, Nandigama taluk in the Krishna district, Vishakhapatnam (Sarma and Swamy 1981, 1983, Prakash and others 1989), Hazurabad taluk in Karimnagar (all in AP) and in some parts of Haryana, Tamil Nadu, Karnataka, and Punjab, groundwaters with high concentrations of fluoride are found. The highest values for fluoride were recorded in Bankapatti, where concentrations up to 17–20 mg/liter have been found.

High manganese waters. In Unnao district (UP) and in some other parts of India (Handa 1984), groundwater with relatively high concentrations of manganese is encountered. Apparently these waters owe their origin to the occurrence of anaerobic conditions that resulted in the mobilization of manganese present in the strata through which the groundwater was circulating.

High nitrate and potassium waters. In many parts of India, waters with high K and/or high NO_3 content occur, with K and/or nitrate ions exceeding 1000 mg/liter. It has been suggested that this phenomenon is due to contamination from nutrient-enriched return irrigation flows (Jacks and Sharma 1983, Pawar and Shaikh 1995). In some cases anomalous values of phosphates have also been found.

Table 7. Average concentration (mg/liter) of river waters of India

River	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3	SO_4	Cl^{-}	SiO_2	TDS
Ga	7.3	16.9	12.8	18.4	5.9	170.0	17.2	14.0	26.4	281
Br	7.1	17.1	8.0	6.3	2.9	94.2	9.6	5.6	8.5	152
In	7.7	26.8	0.7	1.3	2.1	64.0	15.0	9.2	5.3	124
Go	8.1	22.0	5.0	12.0	3.0	105.0	16.0	17.0	8.0	232
Kr	7.7	29.0	8.1	30.0	2.4	178.0	24.0	38.0	15.6	281
Ma	7.5	20.0	4.3	3.4	2.4	66.0	20.5	11.7	9.1	155
Na	8.2	17.0	12.4	9.0	6.6	108.0	21.4	30.0	19.9	224
Ta	8.3	28.5	13.2	28.5	3.2	173.0	31.0	20.3	23.6	294
Ca	7.8	15.4	16.0	30.0	2.6	53.3	39.0	18.0	39.0	326

Source: Ramesh and Subramanian (1988).

[a]Ga = Ganges, Br = Brahmaputra, In = Indus, Go = Godavari, Kr = Krishna, Ma = Mahanadi, Na = Narmada, Ta = Tapti, Ca = Cauvery.

Streamwater Chemistry

The average water chemistry for various rivers are summarized in Table 7 (Ramesh and Subramanian 1993, Subramanian 1979). In general, the alkalinity increases downstream for all rivers, independent of basin characteristics. The HCO_3^- and Ca^{2+} contents differ significantly for the two average river waters, suggesting that chemical weathering is intense in the Indian subcontinent (Biksham and Subramanian 1988). The Ganges accounts for about 36% of the dissolved materials transported by rivers, and more than 60% of the Ganges basin lies in the Kankar carbonate-rich alluvial terrain. Hence, HCO_3^- and Ca^{2+} appear to be higher in rivers. However, the proportion of HCO_3^- and Ca^{2+} to the total contribution is about the same for both averages. Major parts of the Mahanadi, Godavari, and Krishna basins lie in the Deccan trap country, where as most of the Cauvary, Narmada, and Tapti basins lie in hard rocks, such as Archean gneiss or Vindhyan systems. The Ganges and Brahamputra basins have complex geology, but the Ganges lies mainly in recent alluvium. In spite of the diverse geology, the water chemistry appears to be relatively uniform. However, the extent of chemical weathering influencing the streamwater chemistry can be evaluated properly only when individual rivers are studied.

River water pollution. There is no systematic study available to provide a comprehensive picture of the magnitude and spatial dimension of water pollution in India. However, studies carried on by India's Central Public Health Engineering Institute at Nagapur and the Central Inland Fisheries Research Institute at Calcutta, Allahabad, highlight the seriousness of the water pollution problem. The average chemical composition of

Table 8. Average sewage composition of some cities in India

Parameter (mg/liter)	Lucknow	Kanpur	Madras	Nagpur	Delhi Najafgarh	Delhi Rajghat
Total solids	800	1500	1700	1200	650	525
Susp. solids	300	600	500	200		
Diss. solids	500	900	1200	1000		
BOD_5	113	250	350	350		
COD						
Total N	55	50	60	60	14.2	30.3
pH	8.30	7.00	7.30	7.28	7.22	7.44

Source: Dakshini and Soni (1979).

Table 9. Estimated annual animal wastes produced in India in terms of N, P, and K

Source	Quantity (million tons)	P_2O_5	K_2O	N
Cattle dung	1225	0.79	1.35	2.98
Buffalo dung	437	0.28	0.49	0.75
Goat and sheep dung	20	0.06	0.02	0.21
City refuse	15	0.08	0.09	0.12
Urine	274.1	0.004	0.01	0.30
Other animals	22.7	0.16	0.12	0.20

Source: Vimal and Talashilkar (1983).

sewage in some major cities of India is given in Table 8 (Mishra 1979, Dakshni and Soni 1979, Bharati and others 1979, NEERI '94 1994).

With the increase in human and livestock populations, the wastes produced in India have increased considerably. Table 9 gives the estimated annual waste production from these sources in India (Vimal and Talashilkar 1983). Since most of the cities situated along the banks of the streams do not have any sewage-treatment facilities, the release of sewage into rivers can pollute the water. Even in Delhi, which has a sewage treatment plant, over 100 million gallons of untreated sewage is discharged into the Yamuna river (Dakshini and Soni 1979, Sarin and Krisnaswami 1984). In fact, according to the latest health statistics (1982) around 11 million people in India suffered from various water-borne diseases and 11,234 died. The diseases include typhoid, infectious hepatitis, dysentery, and gastroenteritis.

Apart from pollution from animal wastes, referred to above, industries also release waste effluents either directly into streams or into drains/channels that eventually join the streams, resulting in degradation of water quality (Table 10). Table 11 gives the status of some major industries with effluent treatment plants in different cities. Only 42% of the major industries in India have effluent treatment plants. In addition to these, there are numerous small industries that discharge their untreated wastes into the streams and lakes.

Stream pollution. It is estimated that 70% of India's inland waters are of "doubtful quality." Unsatisfactory methods for disposal and treatment of sewage and industrial wastes are among the major causes of water pollution. Waste materials are commonly discharged without treatment into inland or coastal waters (Table 12). For example, raw sewage is dumped into the Ganga at Varnasi (Table 13), where water is used for drinking purposes by thousands of piligrms each day (Mathur 1979, Tripati and others 1991). In Calcutta, Bombay, and Madras, part of the untreated sewage goes directly to the river or sea (Ghosh 1969, Somasundaran and others 1993). Information collected from officials of 20 major Indian cities on status of sewage disposal revealed that nine cities (Kanpur, Bangalore, Poona, Nagpur, Lucknow, Agra, Varnasi, Madurai, and Allahabad) had no sewage treatment plant; six cities (Amritsar, Hyderabad, Indore, Jaipur, Sholapur, and Patna) had secondary treatment plants; only two cities (Ahmedabad and Delhi) had modern sewage treatment plants. The untreated sewage going into the river or sea at Calcutta, Bombay, and Madras creates serious odor problems in some sections of these cities. In addition, the overburdened sewers of these three metropolitan centers lead into the water mains laid under them, polluting the drinking water supply. In India there are no legal standards of maximum allowable pollution and no data exist on the capacities of receiving streams to absorb pollution loads without adverse environmental impact.

Water pollution resulting from industrial waste disposal into streams or other bodies of water is localized in industrial centers such as Bombay, Calcutta, Delhi (Agrawal and others 1986), Kanpur (Garg and others 1992) and the Damodar Valley (Table 11). Destruction of fish from lack of dissolved oxygen or from the toxic effect of industrial wastes has been reported in rivers such as the Damodar (Gopalkrishnan and others 1966, NEERI '94 1994), Son, Mahanadi, Jamuna, Ganges (Tripathi and others 1991), Cauvary, Krishna, Mahi near Baroda, and Kalu near Bombay. A large fish kill was

Table 10. Hazardous waste generation in Maharashtra state (% distribution)

District	Inorganic chemicals	Textiles and leather	Engineering	Dyes, etc.	Organics and petroleum	Others	Total
Thane	15.36	8.71	7.38	6.52	1.70	1.43	41.1
Bombay	6.0	5.2	1.7	0.3	0.9	30.8	44.9
Raigad	0.11	1.28	<0.1	1.35	1.53	0.92	5.19
Pune	<0.1	0.01	1.41	0.15	0.14	0.49	2.2
Nagpur	<0.1	0.3	2.03	<0.1	0.01	0.16	2.5
Others	0.75	<0.1	2.48	0.08	<0.1	0.80	4.11
Total	22.22	15.5	15.0	8.4	4.28	34.6	100.0

Source: NEERI'94 (1994).

Table 11. Pollution load from major industrial discharges in river Damodar (kg/day)

Source[a]	BOD	COD ($\times 10^3$)	TSS ($\times 10^3$)	TDS ($\times 10^3$)	Fe	Hg	Mn	As	Pb	Cr
2	556	107	490	15.2	1,163	1.6	35	4.7	1.4	3.9
3	34	3.87	5.74	1.12	107	0.02	1.3	0.06	0.29	0.3
4	541	163	140	270	1,192	0.05	16.5	8.3	4.6	10
5	1,942	45	235	830	1,094		50.4	2.7	27	19
6	4	19.4	22.6	0.39	66		1.5	0.02	0.36	0.1
7	5	0.22	0.18	0.17	1.98		0.1		0.03	0.04
8	97	531	382	7.60	483		8.6	0.09	2	1.5
9	50	0.43	1.16	0.94	24	0.05	1			0.2
10	23	0.32	0.39	2.39	13.4		2.84		0.25	0.19
11	2,371	32.2	78.6	44.2	911	0.16	0.41	1.25	9.5	6.6
12	1,096	3.81	1.72	11.6	434	0.03	15.2		2.5	2.3
13	316	25.6	0.44	29.4	402		6.3	0.14	2.1	1.4
14	123	3.80	5.76	12.3	30.8	0.2	6.4	0.14		
15	545	6.29	4.71	3.01	26.2	0.004	1.8			
16	136	2.71	1.31	6.24	96	0.12	5.3	0.2	1.9	1.1
17	3	0.04	28.6	12.4	9	2.1	2.1			
18	574	55.4	59.7	15.7	364	0.06	39.6	0.16	0.12	7.6

Source: NEERI'94 (1994).

[a]2: Patratu thermal power station; 3: Chandrapura thermal power station; 4: Santhldih thermal power station; 5: Durgapur thermal power station; 6: Rajarappa coal washery; 7: Kathara coal washery; 8: Sudamdih coal washery; 9: Godo nullah; 10: Jharia nullah; 11: Tamla nullah; 12: Bokaro steel plant; 13: Durgapur steel plant; 14: FCI, Sindri; 15: Bengal paper mills; 16: Phillips Carbon Black Ltd; 17: Nigha colliery; 18: Jamadoba power house #3.

Table 12. Trace metal concentration in sewage samples from different locations in Mumbai (Bombay)

Element	Bhandup	Colaba	Dadar	Ghatkopar	Khar
Cr	293.14	603.7	394.12	81.00	62.68
Fe ($\times 10^3$)	9.9	8.6	1.0	8.0	7.7
Co	7.9	15.59	5.80	6.06	11.65
Sc	1.92	1.32	2.30	1.65	1.56
Ba	208.67	450.94	134.43	144.57	170.20
Ce	7.50	4.71	8.72	5.72	5.26
Eu	0.15	0.092	0.14	0.09	0.098
Zn	347.42	289.95	593.86	335.94	491.88

Source: NEERI'94 (1994).

reported in the Jamuna River near Delhi due to the untreated waste of an insecticide factory located at Najafgarh, north of the city. In March 1970, the plant that filters water from the Jamuna for over half a million residents of South Delhi was shut down for three days because it was clogged with dead fish resulting from industrial waste. During this water crisis municipal tankers distributed water to residents of South Delhi. However, hepatitis due to use of ''contaminated'' water was revealed in a survey conducted by the All-India Institute of Medical Sciences in Kailash, which is located south of Delhi and received drinking water from the plant. The concentrations of total DDT residues ranged from 0.04 to 1.42 µg/liter in the water and from 0.007 to 5.63 mg/kg in bottom sediments were detected at Delhi. The total DDT concentration was higher at the downstream Wazirabad site where there is a mixing of river water with the discharge from the Najafgarh drain, which also carries effluents of a DDT factory along with that of other industries (Agrawal and others 1986).

The Damodar river is perhaps the most polluted

Table 13. Pollution load (kg/day) discharged through city sewage in the river Ganges at Varnasi

Parameter	AG[a]	SG	HG	CG	RPG	RG	Total
BOD	365	665	1,122	1,890	1,980	19,120	25,082
COD	872	1,420	2,502	4,160	3,936	41,280	54,170
Acidity	163	83	179	271	335	2,288	3,919
$CaCO_3$	2,717	1,466	2,056	3,232	4,109	39,024	52,604
Cl	174	138	277	506	498	5,688	7,281
NO_3^-	6.0	3.0	5.4	9.8	13.8	88	214
PO_4^{3-}	11.2	6.4	13.14	19.0	28.2	216.8	295

Source: Tripathi and others (1991).

[a]AG = Assi ghat; SG = Shivala ghat; HG = Harishchandra; CG = Chauki ghat; RPG = Rajendra Prasad ghat; RG = Rajghat.

river (Table 11) in India (Gopalkrishna and others 1966, NEERI '94 1994). It receives wastes from various industries on its banks—steel mills, coke-oven plants, coal-based chemical industries, and fertilizer factory wastes such as alkalis, ammonia, cyanide, and phenols (Table 11). About 160,000 m^3 of waste water having a BOD of over 43,000 kg from industries is discharged daily into the Damodar river.

Untreated wastes from chemical and rayon industries between Bombay and Kalyan flow into the creeks, sewers, or streams which find their way to the Kalu River. As a result of the efforts by the State Water Pollution Investigation Centre in Bombay, the industries are being persuaded to limit their effluents to improve the water quality in the Kalu and Ulhas estuaries. Industrial effluents flowing into the Cauvery River, the major source of drinking water in Tamil Nadu, contain tannery, distillery, and acidic sugar mill wastes with a high alkalinity content and dissolved solids. The fish catch dwindled in the Bhadra River near Bhadravati, Mysore, because of wastes from paper and steel mills. The Godavari in Andhra Pradesh and the Chaliyarin Kerala, the Tapti, and the Chambal in Madhya Pradesh are among the other major Indian rivers contaminated by industrial wastes at various locations.

The Ganga River, with a length of 2500 km, is one of the largest rivers on the Indian subcontinent. There are 48 large cities and 66 small towns situated on its banks, and none of them has sewage treatment plant; the major part of the sewage is discharged into the river. Discharge of untreated industrial waste effluents and animal and human excreta along its banks are the other major sources of pollution. There are several stretches along its course where the river is grossly polluted, viz., near Kannauj, Kanpur, Allahabad, Varnasi (Table 13), Ballia, Patna, and Calcutta. The data of Bharati and others (1979) is given in Table 14 for some constituents present in the Ganga river water at Sarsaiya Ghat in Kanpur.

Table 14. Pollution concentration ranges for some parameters in Ganga river Kanpur

	Conc. range (mg/liter)
Dissolved oxygen	1.48–3.75
BOD_5	4.53–0.62
Total P	0.10–0.12
Cr(VI)	0.11–0.479
Cd	0.107–0.347
Fe	0.901–1.567
Pb	0.042–0.197
Cu	0.123–0.177
Zn	1.134–3.816

Source: Bharati and others (1979).

Sustainable Development of Water Resources

The main actions required to ensure sustainable development of water resources in India are explained below with brief comments being provided in each case.

Water Resources Planning

Water, as a basic factor in economic and social development, should always be taken into consideration in national and regional planning. The water resources planning process should obviously comply with the general methods for economic planning processes, of which detailed reference is not appropriate in this paper. A brief allusion to some aspects that should specifically condition planning for a sustainable development of water resources is, however, justified. These aspects are the following:

1. The interdependence of the different types of water sources and of the different water uses (this makes it necessary to consider the river basin as the basic unit for water resources planning);
2. The irregularity of the annual and interannual occurrence of water resources (this makes it necessary to consider not only the mean values but also

other characteristic values of the distribution, for instance, the extreme values corresponding to floods and droughts);

3. The circumstances that rivers—often the main source of water supply are also the natural collectors of polluted waters (this makes it necessary to bear in mind, jointly, the problems of water quantity and quality);
4. The distinction has to be made between consumptive and nonconsumptive water use, the uses which condition simultaneously quantity and quality of water or only one or the other.
5. The importance of economic, social, and environmental impacts of hydraulic projects has to be assessed.

The relationship between water resources and other natural resources management reinforces the need of assuming both an economic and an environmental perspective in water resources planning. The water resources policies should also be coordinated with other regional and national policies with emphasis on agricultural, forest, industrial, energy, and public health policies. This coordination should take place within the framework of a land-use planning policy and, of course, the general social and economic planning.

Assessment of Water Resources

The water resources planning process requires knowledge of existing and required water resources and how the various parts of water resources systems interact. This assessment must cover water availability, both natural and modified by man's action, and must include both surface waters and groundwater, consider the aspects of quantity and quality, and refer to the present situation and the future. Moreover, as regards international river basins, an effort must always be made to carry out the assessment by joint action of countries sharing river basins.

As regards the assessment of demand, it must not only include projections of water consumption and of pollution discharge, but also a definition of the evolution of water quality goals. Classification of watercourses according to their water quality may form part of this definition.

A reliable assessment of the water resources is an expensive process as it requires the existence of a good hydrological monitoring network relating to the climate and to water quantity and quality and proper data processing, storage, and retrieval systems.

A different approach for assessing water resources is trying to evaluate them in monetary terms. This raises the issue of the usefulness of establishing national systems of natural resources accounts in general, and particularly for water.

Increased Efficiency in Water Use

There is much room for increased efficiency in water resources use. Irrigation is, in this respect, a major issue, as water is often supplied to farmers at a cost well below the cost of supply. If we could significantly improve the equity in water resources use and the reliability of the irrigation projects, food production would greatly benefit. Efficiency should also be increased in industrial water uses, particularly by resorting to clean technologies and recycling practices. Finally, the efficiency of domestic water supply, which deals with highly valued treated water, should also be increased by resorting to conservation measures, water recirculation and, in cases where consumption is excessive, progressive pricing schemes.

Water Quality Control

Water pollution control is crucial for a sustainable development of water resources (Glassberger and van Lelyveld 1985). Persistent efforts should be made to decrease or at least avoid the increase of surface water pollution in many parts of the world. Pollution problems are particularly important in relation to groundwater because of the very slow movement of groundwater in the soil, which is likely to determine long-term pollution effects that are difficult and slow to reverse (Bobba and Singh 1995). The extremely low velocities of groundwater movement can imply that water pollution is only detected after a number of years and, once the aquifers are contaminated, several decades could pass before regeneration could be achieved. Pollution by water-carried sediments with accumulations of toxic chemicals and heavy metals also should be controlled because of possible consequences for water quality.

Impact of Climate Changes

There are a number of possible alternatives for coping with the consequences of climatic change on water resources, including prevention strategies, changes in water resources management and planning, abandonment of certain areas, and compensation for affected water areas. Further research is also needed on the linkages among climate, meteorology, and hydrology, especially by developing better models that simulate the physical reality in river basins and that take into consideration the regional aspects of climatic change.

The current practice of setting some scenarios based on the results of global circulation models but without being able to assign probabilities to these scenarios is somewhat limited. This limitation will only be overcome when it is possible to establish a direct relationship between climatic modeling and hydrologic modeling (Bobba and others 1995). Linking global circulation modeling and regional water-balance modeling is likely to be the best way to obtain new and better information on the impact of global climatic change on regional water resources. In the future, water resources planning should always include the consideration of plausible climatic change scenarios when doing the sensitivity analysis and deriving social, economic, and environmental impacts that are part of the planning process.

Legislation Relative to Water Resources

Sustainable development of water resources requires adequate legal support that may take the form of basic laws and regulations. Examples of aspects that call for regulations are the following: (1) definition of the legal right to ownership and use of the water resources; (2) definition of the possible uses of the various reaches of the watercourses and of the quality goals of their water, according to existing uses and those foreseen in the future; (3) definition of the maximum admissible pollution levels in receiving waters and of the standards for effluent characteristic parameters; and (4) definition of the conditions for licensing water use, establishment of pricing systems for water use, in particular for water withdrawal charges and pollution charges, and of fines and other penalties for disrespecting the standards.

Education and Training

Education in relation to water resources is needed at all levels from the water project designer to the water user. Water resources management is the result of teamwork by a large number of people with different qualifications and levels of education, such as economists, jurists, sociologists, environmentalists, administrators, engineers, hydrologists, hydrogeologists, chemists, biologists, and ecologists. These specialists must have, besides the basic knowledge acquired during their studies, specific training to enable them to play a proper part in the various activities of water resources management. Personnel education and training is indeed one of the most difficult, but important tasks and must be regarded as a priority, because the success of a water resources management policy largely depends on having skilled professionals.

Research and Development

The main aim of water resources research and development is to anticipate future water problems and indicate the best ways of studying them. Systematization, according to research topics of the various water resources problems and coordination of research, is extremely important and helps to ensure rational water resources management by providing solutions for problems as they arise. The various problems may be considered as corresponding to the main research needs in water resources research and development, to be investigated on a regional, national, and international scale. Science and technology is essential to ensure a sustainable development of water resources and can help to clarify many of the relevant technical, economic, and institutional issues, but research and development can only be effective if the necessary steps to implement its results are taken, this being a major difficulty in some countries.

Information Systems and Public Participation

Information systems are essential for public awareness of water resources problems and management principles and procedures, which is a condition for a sustainable development of water resources. Public participation in water resources management is vital to ensure access by decision makers to the points of view of the public and consequently to help in reaching the public. Public participation must be as great as possible, involving all interested groups. It is essential that the decision makers, i.e., the government representatives as well as the representatives of the various financial interests, work at the local level to face public opinion, where it actually exists. The future of water resources should be discussed in regional and local forums and not in the capitals where power is centered.

International Cooperation

The international cooperation in relation to water resources can be ensured through bilateral or multilateral agreements between countries sharing surface or groundwater resources or through international action resulting from political or scientific initiatives. These international initiatives may, in some cases, have a global dimension as with the issues related to climate change. Combining international experience of countries with different levels of development may also be mutually beneficial as the developing countries can learn from the experiences of the more developed countries, taking the lessons of their successes and failures, and the more developed countries have the opportunity to use their skills to help sustainable water resources development in the developing countries.

International cooperation in water resources use should aim to ensure an equitable share of water between nations and regions. In fact, a condition for sustainable develop of water resources could be to manage international water resources as if they belonged to each bordering country, i.e., respecting the water mobility within each river basin and ensuring maximization of benefits provided by water. This objective should be primary, particularly when water is scarce, it being understood that adequate criteria to share the benefits among the different countries in the river basin should be established and applied.

Institutional Problems of Water Resources Management

Considering the interdisciplinary and intersectoral character of water resources problems, it is essential for the achievement of a sustainable development of water resources that adequate institutional frameworks for water resources management are established in each region and each country. There are different types of framework adopted for different conditions, such as conditions of water occurrence, political systems, and stage of development, but the adoption of an adequate water resources framework in each case is essential to deal with the issues previously referred to.

Conclusions

It is concluded that unless an integrated and sustainable approach to utilization of water resources is adapted either at a regional or a national level, problems of water scarcity, droughts, and famines will continue to occur year after year in many parts of India. With a growing population, increasing industrialization, and higher demands for good quality water, these problems will get even more acute in the decades to come. Participation of the private, government, and industrial sectors in addressing the problems is urgently needed.

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