Water resources of India

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Water resources of a country constitute one of its vital assets. India receives annual precipitation of about 4000 km^3. The rainfall in India shows very high spatial and temporal variability and paradox of the situation is that Mousinram near Cherrapunji, which receives the highest rainfall in the world, also suffers from a shortage of water during the non-rainy season, almost every year. The total average annual flow per year for the Indian rivers is estimated as 1953 km^3. The total annual replenishable groundwater resources are assessed as 432 km^3. The annual utilizable surface water and groundwater resources of India are estimated as 690 km^3 and 396 km^3 per year, respectively. With rapid growing population and improving living standards the pressure on our water resources is increasing and per capita availability of water resources is reducing day by day. Due to spatial and temporal variability in precipitation the country faces the problem of flood and drought syndrome. Overexploitation of groundwater is leading to reduction of low flows in the rivers, declining of the groundwater resources, and salt water intrusion in aquifers of the coastal areas. Over canal-irrigation in some of the command areas has resulted in waterlogging and salinity. The quality of surface and groundwater resources is also deteriorating because of increasing pollutant loads from point and non-point sources. The climate change is expected to affect precipitation and water availability. So far, the data collection, processing, storage and dissemination have not received adequate attention. The efforts initiated under the Hydrology Project Phase-I and the development of the Decision Support System proposed under Hydrology Project Phase-II are expected to bridge some of the gaps between the developed advanced technologies of water resources planning, designing and management and their field applications. The paper presents availability and demands of water resources in India as well as describes the various issues and strategies for developing a holistic approach for sustainable development and management of the water resources of the country. It also highlights integration of the blue and green flows and concepts of virtual water transfer for sustainable management of the water resources for meeting the demands of the present, without compromising the needs of future generations.

Keywords: Rainwater harvesting, surface water, water resources, water requirements, water transfer.

OF all the planet's renewable resources, water has a unique place. It is essential for sustaining all forms of life, food production, economic development, and for general well being. It is impossible to substitute for most of its uses, difficult to de-pollute, expensive to transport, and it is truly a unique gift to mankind from nature. Water is also one of the most manageable of the natural resources as it is capable of diversion, transport, storage, and recycling. All these properties impart to water its great utility for human beings. The surface water and groundwater resources of the country play a major role in agriculture, hydropower generation, livestock production, industrial activities, forestry, fisheries, navigation, recreational activities, etc. According to National Water Policy[1] in the planning and operation of systems, water allocation priorities should be broadly as: (i) drinking water, (ii) irrigation, (iii) hydropower, (iv) ecology, (v) agro-industries and non-agricultural industries, and (vi) navigation.

India receives annual precipitation of about 4000 km^3, including snowfall. Out of this, monsoon rainfall is of the order of 3000 km^3. Rainfall in India is dependent on the south-west and north-east monsoons, on shallow cyclonic depressions and disturbances and on local storms. Most of it takes place under the influence of south-west monsoon between June and September except in Tamil Nadu, where it is under the influence of north-east monsoon during October and November. India is gifted with a river system comprising more than 20 major rivers with several tributaries. Many of these rivers are perennial and some of these are seasonal. The rivers like Ganges, Brahmaputra and Indus originate from the Himalayas and carry water throughout the year. The snow and ice melt of the Himalayas and the base flow contribute the flows during the lean season. Lal[2] mentioned that more than 50% of water resources of India are located in various tributaries of these river systems. Average water yield per unit area of the Himalayan rivers is almost double that of the south peninsular rivers system, indicating the importance of snow and glacier melt contribution from the high mountains. Apart from the water available in the various rivers of the country, the groundwater is also an important source of water for drinking, irrigation, industrial uses, etc. It accounts for about 80% of domestic water requirement and more than 45% of the total irrigation in the country. As per the international norms, if per-capita water availability is less than 1700 m^3 per year then the country is categorized as water stressed and if it is less than 1000 m^3 per capita per year

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then the country is classified as water scarce. In India per capita surface water availability in the years 1991 and 2001 were 2309 and 1902 m^3 and these are projected to reduce to 1401 and 1191 m^3 by the years 2025 and 2050 respectively. Hence, there is a need for proper planning, development and management of the greatest assets of the country, viz. water and land resources for raising the standards of living of the millions of people, particularly in the rural areas.

Man's influence on hydrological cycle

The hydrological cycle is being modified quantitatively and qualitatively in most of the river basins of our country as a result of the developmental activities such as construction of dams and reservoirs, land use change, irrigation, etc. Such human activities affecting the hydrological regime can be classified into four major groups: (i) activities which affect river runoff by diverting water from rivers, lakes, and reservoirs or by groundwater extraction, (ii) activities modifying the river channels, e.g. construction of reservoirs and ponds, levees and river training, channel dredging, etc. (iii) activities due to which runoff and other water balance components are modified due to impacts of basin surface e.g. agricultural practices, drainage of swamps, afforestation or deforestation, urbanization, etc. and (iv) activities which may induce climate changes at regional or global scale, e.g. modifying the composition of atmosphere by increasing the 'greenhouse' gases or by increased evaporation caused by large scale water projects. For understanding the effects appropriately, hydrological modelling approaches have to be adopted[3] .

Monsoon and its forecasting

The word monsoon is derived from 'mausim', an Arabic word, which means season and the word is applied to winds whose direction is reversed completely from one season to the next season. The largest precipitation accumulations for periods greater than 24 h are associated with the Asian monsoon. Normal duration of monsoon in India is about 100 to 120 days beginning from first June. In India, the two monsoon seasons (the southwest monsoon in June to September and the northeast monsoon in November–December) bring forth rains. An important feature affecting the rainfall in India is the change in the direction of wind currents that occurs in different months. In May when the weather is very hot, the south-east trade winds from the south Indian Ocean cross the equator and after deflecting, due to rotation of the earth, extend rapidly into the north Indian ocean, viz. the Bay of Bengal in early May and afterwards get established over both the sea areas. This westerly current, which extends from the Arabic coast to the China sea across India is known as the southwest monsoon. In winter season, the wind currents over India blow from north to south. The winds over the country are mostly of continental origin and are dry during this season. This period is known as the winter in north-east monsoon. The weather disturbances moving from the west result in snowfall as well as rainfall over the Himalayas and rainfall over north India. The north-east monsoon picks up moisture over the Bay of Bengal and produces rain over Tamil Nadu. Scientists of India Meteorological Department (IMD), New Delhi, have developed a new monsoon forecast model that is claimed to be more accurate than the earlier one. The model uses eight land, ocean and wind parameters to predict the extent of the monsoon. It replaces an earlier 16-parameter model, developed in 1988. The new model enables a forecast to be made 40 days earlier than previously, and allows scientists to update their predictions halfway through the June–September monsoon season, a time that is crucial for Indian summer crops. In this model there is scope for correction, as by mid-July, the nature of advance of the monsoon becomes known, and any disturbing trends in El Niño (which can adversely influence the Indian monsoon performance) become apparent. The new model has retained six of the parameters used in the previous model, which had a relatively stable link with the monsoon, and two additional parameters believed to influence the Indian monsoon: temperatures in northwest Europe in January and in the southern Indian Ocean in March. It was devised using 38 years of data up to 1995, and has been verified for the seven-year period from 1996 to 2002. The new model is claimed to be 95% accurate[4]. Its true test lies ahead, but it is expected that India now has a more realistic and more statistically stable model for forecasting monsoons.

Precipitation variability

The long-term average annual rainfall for the country is 1160 mm, which is the highest anywhere in the world for a country of comparable size[2]. The annual rainfall in India however fluctuates widely. The highest rainfall in India of about 11,690 mm is recorded at Mousinram near Cherrapunji in Meghalaya in the northeast[5]. In this region rainfall as much as 1040 mm is recorded in a day. At the other extreme are places like Jaisalmer, in the west, which receives barely 150 mm of rain. Though the average rainfall is adequate, nearly three-quarters of the rain pours down in less than 120 days, from June to September. As much as 21% of the area of the country receives less than 750 mm of rain annually while 15% receives rainfall in excess of 1500 mm. Precipitation generally exceeds 1000 mm in areas to the east of Longitude 78°E. It reaches nearly to 2500 mm along almost the entire west coast and over most of Assam and sub-Himalayan West Bengal. Large areas of peninsular India receive rainfall less than 600 mm. Annual rainfall of less than 500 mm is experienced in western Rajasthan and adjoining parts of Gujarat, Haryana and Punjab. Rainfall is equally low in the interior of the Deccan plateau, east of the Sahyadris. A third area of low precipitation is around Leh in Kashmir.

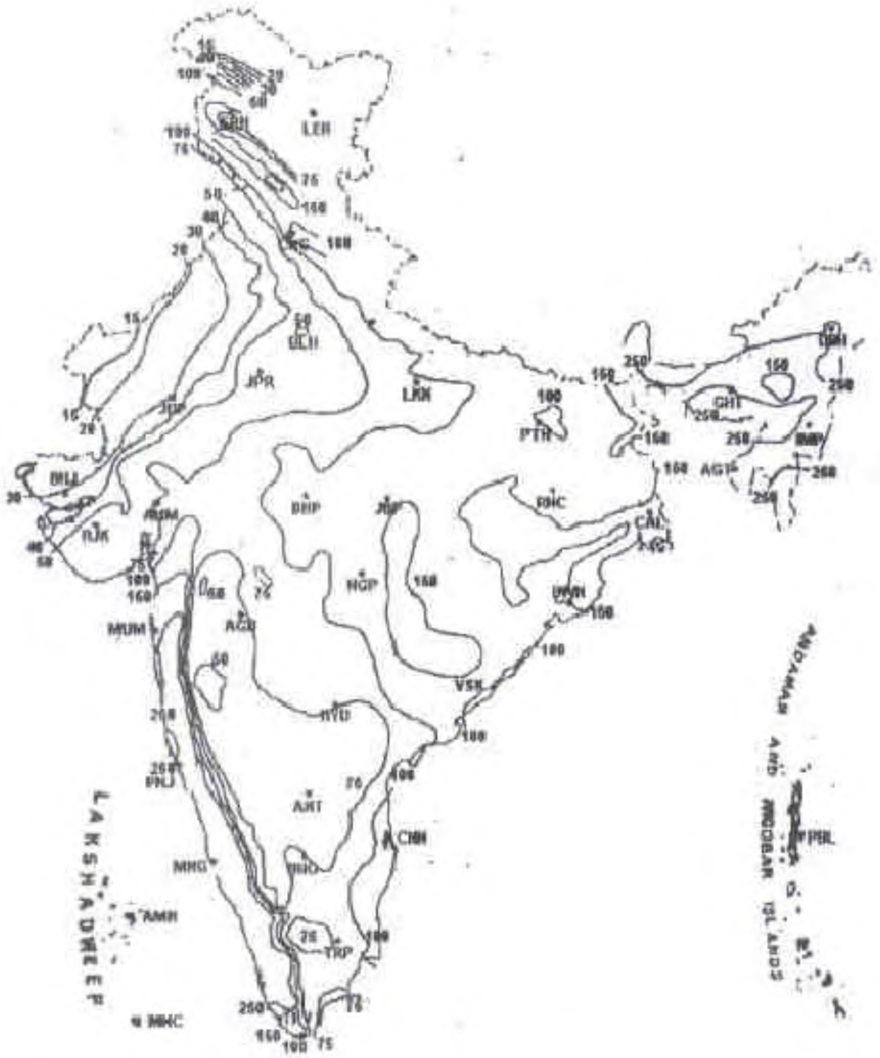

Figure 1. Distribution of normal annual rainfall in India (IMD, 2004).

The rest of the country receives moderate rainfall. Snowfall is restricted to the Himalayan region. Figure 1 shows the distribution of normal annual rainfall in India[6].

Water resources of India

Although India occupies only 3.29 million km^2 geographical area, which forms 2.4% of the world's land area, it supports over 15% of the world's population. The population of India as on 1 March 2001 stood at 1,027,015,247 persons. Thus, India supports about 1/6th of world population, 1/50th of world's land and 1/25th of world's water resources[7]. India also has a livestock population of 500 million, which is about 20% of the world's total livestock population. More than half of these are cattle, forming the backbone of Indian agriculture. The total utilizable water resources of the country are assessed as 1086 km^3. A brief description of surface and groundwater water resources of India is given below.

Surface water resources

In the past, several organizations and individuals have estimated water availability for the nation. Recently, the National Commission for Integrated Water Resources Development[8] estimated the basin-wise average annual flow in Indian river systems as 1953 km^3. The details are given in Table 1.

Utilizable water resource is the quantum of withdrawable water from its place of natural occurrence. Within the limitations of physiographic conditions and socio-political environment, legal and constitutional constraints and the technology of development available at present, utilizable quantity of water from the surface flow has been assessed by various authorities differently. The utilizable annual surface water of the country is 690 km^3 (Table 1)[9]. There is considerable scope for increasing the utilization of water in the Ganga–Brahmaputra basins by construction of storages at suitable locations in neighbouring countries.

Table 1. Basinwise average flow and utilizable water[9] (in km^3/year)

Sl. no	River basin	Average annual flow	Utilizable flow
1	Indus	73.31	46
2	Ganga–Brahmaputra–Meghna Basin		
	2a Ganga	525.02	250
	2b Brahmaputra sub-basin	629.05	24
	2c Meghna (Barak) sub-basin	48.36	
3	Subarnarekha	12.37	6.81
4	Brahmni–Baitarani	28.48	18.3
5	Mahanadi	66.88	49.99
6	Godavari	110.54	76.3
7	Krishna	69.81	58
8	Pennar	6.32	6.86
9	Cauvery	21.36	19
10	Tapi	14.88	14.5
11	Narmada	45.64	34.5
12	Mahi	11.02	3.1
13	Sabarmati	3.81	1.93
14	West-flowing rivers of Kachchh and Saurashtra including Luni	15.1	14.98
15	West flowing rivers south of Tapi	200.94	36.21
16	East-flowing rivers between Mahanadi and Godavari	17.08	
17	East-flowing rivers between Godavari and Krishna	1.81	13.11
18	East-flowing rivers between Krishna and Pennar	3.63	
19	East-flowing rivers between Pennar and Cauvery	9.98	16.73
20	East-flowing rivers south of Cauvery	6.48	
21	Area of North Ladakh not draining into Indus	0	NA
22	Rivers draining into Bangladesh	8.57	NA
23	Rivers draining into Myanmar	22.43	NA
24	Drainage areas of Andman, Nicobar and Lakshadweep Islands	0	NA
	Total (rounded)	1953	690

Table 2. Groundwater resources of India (in km^3/year)

1	Total replenishable groundwater resource	432
2	Provision for domestic, industrial and other uses	71
3	Available groundwater resource for irrigation	361
4	Utilizable groundwater resource for irrigation (90% of the sl. no. 3)	325
5	Total utilizable groundwater resource (Sum of sl. nos 2 and 4)	396

Groundwater resources

The annual potential natural groundwater recharge from rainfall in India is about 342.43 km^3, which is 8.56% of total annual rainfall of the country. The annual potential groundwater recharge augmentation from canal irrigation system is about 89.46 km^3. Thus, total replenishable groundwater resource of the country is assessed as 431.89%. After allotting 15% of this quantity for drinking, and 6 km^3 for industrial purposes, the remaining can be utilized for irrigation purposes. Thus, the available groundwater resource for irrigation is 361 km^3, of which utilizable quantity (90%) is 325 km^3. The estimates by the Central Groundwater Board (CGWB) of total replenishable groundwater resource, provision for domestic, industrial and irrigation uses and utilizable groundwater resources for future use are given in Table 2. The basinwise per capita water availability varies between 13,393 m^3 per annum for the Brahmaputra–Barak basin to about 300 m^3 per annum for the Sabarmati basin. The state-wise estimates of dynamic groundwater (fresh) resource made by the CGWB[10] are given in Table 3. The basin-wise groundwater potential of the country is given in Table 4.

Water requirements of India

Traditionally, India has been an agriculture-based economy. Hence, development of irrigation to increase agricultural production for making the country self-sustained and for poverty alleviation has been of crucial importance for the planners. Accordingly, the irrigation sector was assigned a very high priority in the 5-year plans. Giant schemes like the Bhakra Nangal, Hirakud, Damodar Valley, Nagarjunasagar, Rajasthan Canal project, etc. were taken up to increase irrigation potential and maximize agricultural production.

Long-term planning has to account for the growth of population. According to National Water Policy[1], the production of food grains has increased from around 50 million tonnes in the fifties to about 203 million tonnes in the year 1999–2000. A number of individuals and agencies have estimated the likely population of India by the year 2025 and 2050. According to the estimates adopted by NCIWRD[9], by the year 2025, the population is expected to be 1333

Table 3. State-wise dynamic fresh groundwater resource of India (in km^3/year)

Sl. No.	State	Replenishable groundwater resource from normal natural recharge	Replenishment due to recharge augmentation from canal irrigation	Total replenishable groundwater resource	Percentage contribution of recharge augmentation to total GW resource
1	Andhra Pradesh	20.03	15.26	35.29	43
2	Arunachal Pradesh	1.44	0.00	1.44	0
3	Assam	24.23	0.49	24.72	2
4	Bihar	28.31	5.21	33.52	16
5	Goa	0.18	0.03	0.21	14
6	Gujarat	16.38	4.00	20.38	20
7	Haryana	4.73	3.80	8.53	45
8	Himachal Pradesh	0.29	0.08	0.37	22
9	Jammu & Kashmir	2.43	2.00	4.43	45
10	Karnataka	14.18	2.01	16.19	12
11	Kerala	6.63	1.27	7.90	16
12	Madhya Pradesh	45.29	5.60	50.89	11
13	Maharashtra	33.40	4.47	37.87	12
14	Manipur	3.15	0.00	3.15	0
15	Meghalaya	0.54	0.00	0.54	0
16	Mizoram	Not assessed			
17	Nagaland	0.72	0.00	0.72	0
18	Orissa	16.49	3.52	20.01	18
19	Punjab	9.47	9.19	18.66	49
20	Rajasthan	10.98	1.72	12.70	14
21	Sikkim	Not assessed			
22	Tamil Nadu	18.91	7.48	26.39	28
23	Tripura	0.57	0.10	0.67	15
24	Uttar Pradesh	63.43	20.39	83.82	24
25	West Bengal	20.30	2.79	23.09	12
26	Union territories	0.35	0.05	0.40	13
	Total	342.43	89.46	431.89	21

Table 4. Groundwater potential in river basins of India[11] (pro-rata basis) (in km^3/year)

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

million in high-growth scenario and 1286 million in low growth scenario. For the year 2050, high rate of population growth is likely to result in about 1581 million people while the low growth projections place the number at nearly 1346 million. Keeping in view the level of consumption, losses in storage and transport, seed requirement, and buffer stock, the projected food-grain and feed demand for 2025 would be 320 million tonnes (high-demand scenario) and 308

Table 5. Per capita per year availability and utilizable surface water in India (in m^3)

Sl. no.	Year	Population (in million)	Per-capita surface water availability	Per-capita utilizable surface water
1	1951	361	5410	1911
2	1955	395	4944	1746
3	1991	846	2309	816
4	2001	1027	1902	672
5	2025 (Projected)	a. 1286 (low growth)	1519	495
		b. 1333 (high growth)	1465	
6	2050 (Projected)	a. 1346 (low growth)	1451	421
		b. 1581 (high growth)	1235	

million tonnes (low-demand scenario). The requirement of food grains for the year 2050 would be 494 million tonnes (high-demand scenario) and 420 million tonnes (low-demand scenario). Table 5 provides details of the population of India and per capita water availability as well as utilizable surface water for some of the years from 1951 to 2050 (projected). The availability of water in India shows wide spatial and temporal variations. Also, there are very large inter annual variations. Hence, the general situation of availability of per capita availability is much more alarming than what is depicted by the average figures.

Domestic use

Community water supply is the most important requirement and it is about 5% of the total water use. About 7 km^3 of surface water and 18 km^3 of groundwater are being used for community water supply in urban and rural areas. Along with the increase in population, another important change from the point of view of water supply is higher rate of urbanization. According to the projections, the higher is the economic growth, the higher would be urbanization. It is expected that nearly 61% of the population will be living in urban areas by the year 2050 in high-growth scenario as against 48% in low growth scenario.

Different organizations and individuals have given different norms for water supply in cities and rural areas. The figure adopted by the NCIWRD[9] was 220 litre per capita per day (lpcd) for class I cities. For the cities other than class I, the norms are 165 for the year 2025 and 220 lpcd for the year 2050. For rural areas, 70 lpcd and 150 lpcd have been recommended for the years 2025 and 2050. Based on these norms and projection of population, it is estimated that by 2050, water requirements per year for domestic use will be 90 km^3 for low demand scenario and 111 km^3 for high demand scenario. It is expected that about 70% of urban water requirement and 30% of rural water requirement will be met by surface water sources and the remaining from groundwater.

Irrigation

The irrigated area in the country was only 22.6 million hectare (Mha) in 1950–51. Since the food production was much below the requirement of the country, due attention was paid for expansion of irrigation. The ultimate irrigation potential of India has been estimated as 140 Mha. Out of this, 76 Mha would come from surface water and 64 Mha from groundwater sources. The quantum of water used for irrigation by the last century was of the order of 300 km^3 of surface water and 128 km^3 of groundwater, total 428 km^3. The estimates indicate that by the year 2025, the water requirement for irrigation would be 561 km^3 for low-demand scenario and 611 km^3 for high-demand scenario. These requirements are likely to further increase to 628 km^3 for low-demand scenario and 807 km^3 for high-demand scenario by 2050.

Hydroelectric power

The hydropower potential of India has been estimated at 84,044 MW at 60% load factor. At the time of independence, the installed capacity of hydropower projects was 508 MW. By the end of 1998, the installed hydropower capacity was about 22,000 MW. The status of hydropower development in major basins is highly uneven. According to an estimate, India has plans to develop 60,000 MW additional hydropower by the twelfth five-year plan. It includes 14,393 MW during the tenth five-year plan (2002–2007); 20,000 MW during eleventh (2007–2012) and 26,000 MW during the twelfth (2012–2017) five-year plans. A potential of the order of 10,000 MW is available for development of small hydropower projects in the Himalayan and sub-Himalayan regions of the country. Therefore, it is not only desirable but also a pressing need of time to draw a master plan for development of small, medium and large hydro-schemes for power generation.

Industrial water requirement

Rough estimates indicate that the present water use in the industrial sector is of the order of 15 km^3. The water use by thermal and nuclear power plants with installed capacities of 40,000 MW and 1500 MW (1990 figures) respectively, is estimated to be about 19 km^3. In view of shortage of water, the industries are expected to switch over to water-efficient technologies. If the present rate of water use con-

Table 6. Annual water requirement for different uses[9] (in km^3)

Use	Year 1997–98	Year 2010			Year 2025			Year 2050		
		Low	High	%	Low	High	%	Low	High	%
Surface water										
Irrigation	318	330	339	48	325	366	43	375	463	39
Domestic	17	23	24	3	30	36	5	48	65	6
Industries	21	26	26	4	47	47	6	57	57	5
Power	7	14	15	2	25	26	3	50	56	5
Inland navigation		7	7	1	10	10	1	15	15	1
Environment – Ecology		5	5	1	10	10	1	20	20	2
Evaporation losses	36	42	42	6	50	50	6	76	76	6
Total	399	447	458	65	497	545	65	641	752	64
Groundwater										
Irrigation	206	213	218	31	236	245	29	253	344	29
Domestic	13	19	19	2	25	26	3	42	46	4
Industries	9	11	11	1	20	20	2	24	24	2
Power	2	4	4	1	6	7	1	13	14	1
Total	230	247	252	35	287	298	35	332	428	36
Grand total	629	694	710	100	784	843	100	973	1180	100
Total water use										
Irrigation	524	543	557	78	561	611	72	628	807	68
Domestic	30	42	43	6	55	62	7	90	111	9
Industries	30	37	37	5	67	67	8	81	81	7
Power	9	18	19	3	31	33	4	63	70	6
Inland navigation	0	7	7	1	10	10	1	15	15	1
Environment – Ecology	0	5	5	1	10	10	1	20	20	2
Evaporation losses	36	42	42	6	50	50	6	76	76	7
Total	629	694	710	100	784	843	100	973	1180	100

tinues, the water requirement for industries in 2050 would be 103 km^3; this is likely to be nearly 81 km^3 if water-saving technologies are adopted on a large scale.

Total water requirements

Total annual requirement of water for various sectors has been estimated and its break up is given Table 6.

With the increasing population as well as all round development in the country, the utilization of water has also been increasing at a fast pace. In 1951, the actual utilization of surface water was about 20% and 10% in the case of groundwater. The utilizable water in river basins is highly uneven. For example in the Brahmaputra basin, which contributes 629 billion m^3 of surface water of the country's total flow, only 24 billion m^3 is utilizable.

Water resources management in India

In view of the existing status of water resources and increasing demands of water for meeting the requirements of the rapidly growing population of the country as well as the problems that are likely to arise in future, a holistic, well-planned long-term strategy is needed for sustainable water resources management in India. The water resources management practices may be based on increasing the water supply and managing the water demand under the stressed water availability conditions. Data monitoring, processing, storage, retrieval and dissemination constitute the very important aspects of the water resources management. These data may be utilized not only for management but also for the planning and design of the water resources structures. In addition to these, now a days decision support systems are being developed for providing the necessary inputs to the decision makers for water resources management. Also, knowledge sharing, people's participation, mass communication and capacity building are essential for effective water resources management. Some important aspects of such strategies are described as follows.

Flood management

Among all natural disasters, floods are the most frequent to be faced in India. Floods in the eastern part of India, viz. Orissa, West Bengal, Bihar and Andhra Pradesh in the recent past, are striking examples. According to the information published by different government agencies, the tangible and intangible losses due to floods in India are increasing at alarming rate. As reported by the Central Water Commission (CWC) under the Ministry of Water Resources, Government of India, the annual average area affected by floods is 7.563 Mha. This observation is based on the data for the period 1953–2000 published in IWRS[12], with variability ranging from 1.26 Mha in 1965 to 1.75 Mha in 1978. On an average floods have affected about 33 million persons during 1953 to 2000. There is every possibility that this figure may increase due to rapid growth of population and increased encroachments of the flood plains for habitation, cultivation and other activities.

The main causes of floods in India are inadequate capacity within river banks to contain high flows, river bank erosion and silting of river beds. The additional factors are as land slides leading to obstruction of flow and change of the river course, retardation of flow due to tidal and backwater effects, poor natural drainage in the flood-prone area, cyclone and associated heavy rain storms or cloud bursts, snowmelt and glacial outbursts and dam break flows.

After the disastrous floods of 1954 a national programme of flood management was launched. The Government of India has taken a number of steps for flood management. As stated by Mohapatra and Singh[13], some of the important policies on flood management include: policy statement (1954), high level committee on flood (1957), policy statement (1958), ministerial committee on flood control (1964), ministers committee on flood and flood relief (1972); working groups on flood control for five-year plans; Rashtriya Barh Ayog[14], National Water Policy (1987), National Commission for Integrated Water Resource Development (1996), Regional Task Force (1996), and National Water Policy[1]. The committees and commissions constituted by the government have given valuable recommendations on different issues of flood management. Various types of structural and non-structural measures have been taken up to reduce the damages in the flood plains. The structural measures, such as the construction of embankments, levees, spurs, etc. have been implemented in some of the states. The total length of constructed embankments is 16,800 km and drainage channels are of 32,500 km. A total of 1040 towns and 4760 villages are currently protected against flood. Barring occasional breaches in embankments, these have provided reasonable protection to an area of about 15.07 Mha. A large number of reservoirs have been constructed and these reservoirs have resulted in reduction of intensity of floods.

The non-structural measures such as flood forecasting and warning are also being adopted. The flood forecasting and flood warning in India commenced in 1958, for the Yamuna river in Delhi. It has evolved to cover most of the flood-prone interstate river basins in India. The CWC has established a flood forecasting system covering 62 major rivers with more than 157 stations for issuing flood forecasts covering almost all the flood-prone states. The response of state governments towards enactment of flood plain zoning bill is not encouraging. Though some of the states (e.g. Rajasthan and Manipur) have enacted the flood plain zoning legislation, the major flood-affected states (e.g. Assam, Himachal, Goa and Sikkim) have not considered such legislation. A working group of National Natural Resources Management System[15] standing committee on water resources for flood risk zoning of major flood-prone rivers considering remote sensing input was constituted by the Ministry of Water Resources in 1999. The working group recommended flood risk zoning using satellite-based remote sensing with a view to giving thrust towards implementation of flood plain zoning measures[15].

The flood management measures have to be more focused and targeted towards the decided objectives within a stipulated time frame. For flood plain zoning, methods have to be evolved in consultation with the local bodies so that the legislation on flood plain zoning is adopted. As suggested by the Working Group of tenth five-year plan that the possible apprehensions of difficulties in drafting a legislation should not become a bar to the idea of the approach of flood plain zoning itself. Flood forecasting constitutes one of the most important actions of flood disaster preparedness. Technical advancement in a well-planned flood forecasting and warning system can help in providing higher lead time for timely action. It is well recognized that long-term solution of flood problems lies in creating appropriate flood storage in reservoirs. The total live storage capacity of completed projects in India is about 174 km^3. A large flood storage space in reservoirs is required for a successful flood management programme. Flood management also calls for community participation. Farmers, professional bodies, industries and voluntary organizations have to be aware about flood management. People's participation in preparedness, flood fighting and disaster response is required. Media like radio, TV, newspapers can also play an important role in flood management. As India shares river systems with six neighbouring countries, viz. Nepal, China, Bhutan, Pakistan, Bangladesh and Myanmar, bilateral cooperation for flood management is necessary for India and the concerned country. The government of India has taken some initiatives in this regard however, more active participation is required.

Drought management

The drought-prone area assessed in the country is of the order of 51.12 Mha. The planning and management of the effects of drought appear to have a low priority due to associated randomness and uncertainty in defining the start and end of droughts. Further, most of the drought planning and management schemes are generally launched after persisting drought conditions. The traditional system of drought monitoring and estimating losses by crop cutting needs replacement with real time remote sensing, GIS, GPS and modelling techniques for ensuring transparency and quick response. Scope of losses may be extended to groundwater depletion, damage to perennial trees, plantations, orchards and depletion in fertility of livestock. Food, fodder, agricultural inputs and water banks may be established in vulnerable areas instead of their storage in surplus regions to avoid transport bottlenecks during the drought. Robust and rainfall independent off-farm livelihood opportunities may be targeted in the drought mitigation strategy. Conjunctive use of surface and groundwater, aquifer recharge and watershed management with community participation is another important policy paradigm shift to be internalized fully.

After normal rainfall resumes there is a rapid decrease of government and public interest in drought-planning schemes. Most of the time the execution of the drought management scheme is based on the administrative units, while planning of water resources is based on basin scale. Therefore, an integrated basin development approach is required to be developed and implemented for preparing the drought management plan before, during and after the occurrence of the drought. In this regard, there is a need for the development of the decision support systems (DSS) for the monitoring and management of the drought on basin scale utilizing the advanced capabilities of remote sensing, geographical information system and knowledge-based systems. The DSS should also provide support to the decision makers for providing the information at different spatial and temporal scales. It would help them in taking the required management measures in the drought-prone areas for different administrative units. In the drought-prone areas, publication campaign may be launched for water conservation with the help of electronic and print media. Necessary steps may be taken at political, administrative and technical levels to encourage people participation in the drought management for optimum utilization of the available water supply to meet the demands. Strengthening of R&D and capacity building in terms of emerging information technologies and issues of damages is also called upon to bring in resilience in the drought coping strategies.

Groundwater management

To protect the aquifers from overexploitation, an effective groundwater management policy oriented towards promotion of efficiency, equity and sustainability is required. Agricultural holdings in India are highly fragmented and the rural population density is large. The exploitation of groundwater resources should be regulated so as not to exceed the recharging possibilities, as well as to ensure social equity. The detrimental environmental consequences of over-exploitation of groundwater need to be effectively prevented by the Central and State Governments. Overexploitation of groundwater should be avoided, especially near the coasts to prevent ingress of seawater into freshwater aquifers[1]. Clearly, a joint management approach combining government administration with active people participation is a promising solution[16].

In critically overexploited areas, bore-well drilling should be regulated till the water table attains the desired elevation. Artificial recharge measures need to be urgently implemented in these areas. Amongst the various recharge techniques[17], percolation tanks are least expensive in terms of initial construction costs. Many such tanks already exist but a vast majority of these structures have silted up. In such cases, cleaning of the bed of the tank will make them reusable. Promotion of participatory action in rehabilitating tanks for recharging would go a long way in augmenting groundwater supply. Due to declining water table, the cost of extraction of groundwater has been increasing over time and wells often go dry. This poses serious financial burden on farmers. Hence, special programmes need to be designed to support these farmers. Finally, the role of government will have to switch from that of a controller of groundwater development to that of a facilitator of equitable and sustainable development. Shah[18] mentions that three large-scale responses to groundwater depletion in India have emerged in recent years in an uncoordinated manner, and each presents an element of what might be its coherent strategy of resources governance as follows:

Energy–irrigation nexus: Throughout South Asia, the ‘groundwater boom’ was fired during the 1970s and 90s by government support to tubewells and subsidies to electricity supplied by state-owned electricity utilities to farmers. The invidious energy–irrigation nexus that emerged as a result and wrecked the electricity utilities and encouraged waste of groundwater are widely criticized. However, hidden in this nexus is a unique opportunity for groundwater managers to influence the working of the colossal anarchy that is India’s groundwater socio-ecology. Even while subsidizing electricity, many state governments have begun restricting power supply to agriculture to cut their losses. The International Water Management Institute Research has shown that with intelligent management of power supply to agriculture, energy–irrigation nexus can be a powerful tool for groundwater demand management in livelihood supporting socio-ecologies to create tradable poverty rights in groundwater. Mexico finally had to turn to electricity supply management to enforce its groundwater concessions[19].

Inter-basin transfers to recharge unconfined alluvial aquifers: In western India’s unconfined alluvial aquifers, it is being increasingly realized that groundwater depletion can be countered only by importing surface water, Arizona-style. The Jiangsu province in eastern China has implemented its own little inter-basin water transfer from Yangzee to counter groundwater depletion in the Northern part. Similarly, one of the major uses Gujarat has found for water of the Sardar Sarovar Project on Narmada river is to recharge the depleted aquifers of North Gujarat and Kachchh. A key consideration behind India’s proposed mega-scheme to link its northern rivers with peninsular rivers too is to counter groundwater depletion in western and southern India.

Mass-based recharge movement: In many parts of hard-rock India, groundwater depletion has invoked wildfire community-based mass movement for rainwater harvesting and recharge, which interestingly has failed to take off in unconfined alluvial aquifers. It is difficult to assess the social value of this movement partly because 'formal hydrology' and 'popular hydrology' have failed to find a meeting ground. Scientists want check dams sited near recharge zones; villagers want them close to their wells. Scientists recommend recharge tubewells to counter the silt layer impeding recharge; farmers just direct floodwaters into their wells after filtering. Scientists worry about upstream–downstream externalities; farmers say everyone lives downstream. Scientists say the hard-rock aquifers have too little storage to justify the prolific growth in recharge structures; people say a recharge structure is worthwhile if their wells provide even 1000 m^3 of life-saving irrigation/ha in times of delayed rain. Hydrologists keep writing the obituary of the recharge movement; but the movement has spread from eastern Rajasthan to Gujarat, thence to Madhya Pradesh and Andhra Pradesh. Protagonists think that with better planning of recharge structures and larger coverage, decentralized recharge movement can be a major response to India's groundwater depletion because it can ensure that water tables in pockets of intensive use rebound close to pre-development levels at the end of the monsoon season every year they have a good monsoon, which is at least twice in five years. They surmise that this is not impossible because even today, India's total groundwater extraction is barely 5% of its annual precipitation.

Shah[18] mentions the following workable solutions for management of groundwater resources:

- Banning private wells is futile; crowd them out by improving public water supply.
- Regulating final users is impossible; facilitate mediating agencies to emerge, and regulate them.
- Pricing agricultural groundwater use is infeasible; instead, use energy pricing and supply to manage agricultural groundwater draft.
- No alternative to improved supply side management: better rain-water capture and recharge, imported surface water in lieu of groundwater pumping.
- Grow the economy, take pressure off land, and formalize the water sector.

Conjunctive use of surface and groundwater

Large canal infrastructure network for providing irrigation has been the prime goal of the Government of India, since the first five-year plan, which continued up to seventh five-year plan. In some of the irrigation project commands such as Sarda Sahayak in UP, Gandak in Bihar, Chambal in Rajasthan, Nagarjuna Sagar in Andhra Pradesh, Ghataprabha and Malaprabha in Karnataka etc., problems of waterlogging are being faced. The main reason for excessive use of surface water as compared to groundwater is its much lower price for irrigation as compared to the cost incurred in using groundwater. Waterlogging problems could be overcome if conjunctive use of surface and groundwater is made. Groundwater utilization for irrigation in waterlogged areas can help to lower the groundwater table and reclaim the affected soil. Over exploitation of groundwater in areas like Mehsana, in Gujarat; parts of Meeurt and Varanasi districts in Uttar Pradesh, Coimbatore in Tamil Nadu and Karnal district in Haryana etc. have resulted in mining of groundwater[20]. Many research workers have focused the causes of waterlogging[21]. Several groundwater flow modelling studies have focused on assessing the waterlogged areas and measures to control problems of waterlogging and salinization[22,23]. It is desirable that the irrigation needs for fulfilling crop water requirements should be satisfied by judicious utilization of available canal water in conjunction with groundwater so as to keep the water table within the acceptable range. Thus, the optimal conjunctive use of the region's surface and groundwater resources would help in minimizing the problems of waterlogging and groundwater mining.

Water conservation

Water conservation implies improving the availability of water through augmentation by means of storage of water in surface reservoirs, tanks, soil and groundwater zone. It emphasizes the need to modify the space and time availability of water to meet the demands. This concept also highlights the need for judicious use of water. There is a great potential for better conservation and management of water resources in its various uses. On the demand side, a variety of economic, administrative and community-based measures can help conserve water. Also, it is necessary to control the growth of population since large population is putting massive stress on all natural resources.

Since agriculture accounts for about 69% of all water withdrawn, the greatest potential for conservation lies in increasing irrigation efficiencies. Just a 10% improvement in irrigation efficiency could conserve enough water to double the amount available for drinking. In India, sprinkler irrigation is being adopted in Haryana, Rajasthan, Uttar Pradesh, Karnataka, Gujarat and Maharashtra. The use of sprinkler irrigation saves about 56% of water for the winter crops of bajra and jowar, while for cotton, the saving is about 30% as compared to the traditional gravity irrigation. An important supplement to conservation is to minimize the wastage of water. In urban water supply, for example, almost 30% of the water is wasted due to leakages, carelessness, etc. while most metro cities face deficit in supply of water. It is, therefore, imperative to prevent wastage. In industries also, there is a scope for economy in the use of water. Prices of water for all uses should be fixed, keeping in mind its economic value, control of wastage, and the ability of users to pay. As water is becoming scarcer, pricing will be an important factor in avoiding wastage and ensuring optimal use.

Watershed management

For an equitable and sustainable management of shared water resources, flexible, holistic approach of Integrated Water Resources Management (IWRM) is required, which can cater to hydrological variations in time and space and changes in socio-economic needs along with societal values. Watershed is the unit of management in IWRM, where surface water and groundwater are inextricably linked and related to land use and management. Watershed management aims to establish a workable and efficient framework for the integrated use, regulation and development of land and water resources in a watershed for socio-economic growth. Local communities play a central role in the planning, implementation and funding of activities within participatory watershed development programmes. In these initiatives, people use their traditional knowledge, available resources, imagination and creativity to develop watershed and implement community-centered programme.

Currently, many programmes, campaigns and projects are underway in different parts of India to spread mass awareness and mobilize the general population in managing water resources. Some of these are being implemented by the Central/State Governments, while others have been taken up by various Non-Governmental Organizations (NGOs). For example, Hariyali (meaning 'greenery') is a watershed management project, launched by the Central Government, which aims at enabling the rural population to conserve water for drinking, irrigation, fisheries and afforestation as well as generate employment opportunities. The project is being executed by the Gram Panchayats (village governing bodies) with people's participation; the technical support is provided by the block (sub-district) administration. Another good example of water conservation efforts is the 'Neeru-Meeru' (Water and You) programme launched in May 2000 by the Government of Andhra Pradesh. During the last three years, an additional storage space of more than 18,000 lakh m^3 has been created by constructing various water-harvesting structures such as percolation tanks, dugout ponds, check dams, etc. through peoples' participation. Tarun Bharat Sangh (Young India Association) or TBS is an NGO which promotes sustainable water management through rainwater harvesting in Rajasthan. Since 1986, TBS has helped in building or restoring nearly 10,000 water harvesting structures in Alwar and neighbouring districts in the Aravalli hills of northeastern Rajasthan. The central message of TBS is that good water management requires good land management. Emphasis is also put on protecting forests. The efforts of villagers are visible in the form of rising water table and regenerated forests on the rocky slopes of Aravalli hills. Despite some of the above success stories, so far there is no appreciable improvement on watershed resources utilization at national level. Undoubtedly, coordinated watershed development programmes need to be encouraged and awareness about benefits of these programmes must be created among the people.

Rainwater harvesting

Rainwater harvesting is the process to capture and store rainfall for its efficient utilization and conservation to control its runoff, evaporation and seepage. Some of the benefits of rainwater harvesting are:

- It increases water availability
- It checks the declining water table
- It is environmentally friendly
- It improves the quality of groundwater through dilution, mainly of fluoride, nitrate, and salinity, and
- It prevents soil erosion and flooding, especially in the urban areas.

Even in ancient days, people were familiar with the methods of conservation of rainwater and had practised them with success. Different methods of rainwater harvesting were developed to suit the geographical and meteorological conditions of the region in various parts of the country. Traditional rainwater harvesting, which is still prevalent in rural areas, is done by using surface storage bodies like lakes, ponds, irrigation tanks, temple tanks, etc. For example, *Kul* (diversion channels) irrigation system which carries water from glaciers to villages is practised in the Spiti area of Himachal Pradesh. In the arid regions of Rajasthan, rainwater harvesting structures locally known as *Kund* (a covered underground tank), are constructed near the house or a village to tackle drinking water problem. In Meghalaya, *Bamboo Rainwater Harvesting* for tapping of stream and spring water through bamboo pipes to irrigate plantations is widely prevalent. The system is so perfected that about 18–20 litres of water entering the bamboo pipe system per minute is transported over several hundred meters.

There is a need to recharge aquifers and conserve rainwater through water harvesting structures. In urban areas, rainwater will have to be harvested using rooftops and open spaces. Harvesting rainwater not only reduces the possibility of flooding, but also decreases the community's dependence on groundwater for domestic uses. Apart from bridging the demand–supply gap, recharging improves the quality of groundwater, raises the water table in wells/bore-wells and prevents flooding and choking of drains. One can also save energy to pump groundwater as water table rises. These days rainwater harvesting is being taken up on a massive scale in many states in India. Substantial benefits of rainwater harvesting exist in urban areas as water demand has already outstripped supply in most of the cities.

Water quality conservation and environment restoration

Implementation of water pollution prevention strategies and restoration of ecological systems are integral components of all development plans. To preserve our water and environment, we need to make systematic changes in the way we grow our food, manufacture the goods, and dispose off the waste[24]. In India, agriculture is the biggest user and polluter of water. If pollution by agriculture is reduced, it would improve water quality and would also eliminate cost incurred for treatment of diseases. Like all other inputs, there is an optimal quantity of fertilizer for given conditions and excess application does not improve the crop yield. Pricing of fertilizers and pesticides as well as appropriate legislation to regulate their use will also go a long way in stopping indiscriminate use. Industries need to carefully treat their waste discharges. Manufacturers may reduce water pollution by reusing materials and chemicals and switching over to less toxic alternatives. Industrial symbiosis, in which the unusable wastes from one product/firm become the input for another, is an attractive solution. Also, there is a need to encourage reductions or replacement of toxic chemicals, possibly through fiscal measures. Pollution taxes in the Netherlands, for example, have helped the country slash discharges of heavy metals such as mercury and arsenic into waterways by up to 99% between 1976 and the mid-1990s. Many countries discourage use of equipment, such as thermometers that contain mercury. Such measures in India would also be helpful. For this purpose, society and individuals should have a greater knowledge and ability to bring about the required changes. Widely and readily available technical help about 'how to do this' will accelerate the process.

Environmental improvement and restoration should be planned and implemented such that the freshwater resources are protected and their quality is maintained and/or enhanced. A broad perspective is needed that unites social, economic and environmental concerns in a landscape where upland forests and rangeland, wetlands, agricultural and urban areas are integrated. An understanding of watershed linkages allows long-term and sustainable solutions to a variety of natural resource problems. Model efforts in this direction include the capture, storage and safe release of water and the prevention of accelerated soil erosion through the structures and vegetation. While utilizing water and land resources, their ability to serve other uses is often degraded either inadvertently or due to carelessness. Efforts should be made to restore landscapes and ecosystems to more efficiently protect water quality, aquatic and wildlife. On the legislative front, laws are required to check littering as well as to implement 'polluter pays' principle. More importantly, these laws should be strictly enforced.

Recycle and reuse of water

Another way through which we can improve freshwater availability is by recycle and reuse of water. It is said that in the city of Frankfurt, Germany, every drop of water is recycled eight times. Use of water of lesser quality, such as reclaimed wastewater, for cooling and fire fighting is an attractive option for large and complex industries to reduce their water costs, increase production and decrease the consumption of energy. This conserves better quality waters for potable uses. Currently, recycling of water is not practised on a large scale in India and there is considerable scope and incentive to use this alternative. Estimates[25] show that recyclable water is between 103 and 177 km^3/year for low and high population projections.

Interbasin water transfer

The vast variation, both in space and time, in the availability of water in different regions of India has created a food–drought–flood syndrome with some areas suffering from flood damages and other areas facing acute water shortage. Karnataka, Tamil Nadu, Rajasthan, Gujarat, Andhra Pradesh and Maharashtra are the worst drought-prone states. Uttar Pradesh, Bihar, West Bengal, Orissa and Assam face severe flood problems. Inter-basin transfer of water in India is a long-term option to partly overcome the spatial and temporal imbalance of availability and demand of water resources.

The transfer of water from surplus areas to deficit areas is not a new concept. Many such schemes have been implemented all over the world. In India too, projects like the Periyar–Vaigai system, Indira Gandhi canal and Telugu Ganga stand as classic examples of inter-basin water transfer. In the seventies, the Garland Canal proposal of Dastur and the Ganga–Cauvery Canal proposal of Rao[26] were received with considerable attention. A National Perspective Plan (NPP) for water resources development was formulated by the Government of India in 1980s. The distinctive feature of the NPP is that the transfer of water is essentially by gravity and only in small reaches by lift pumping (not exceeding 120 m). This plan comprises two components: (a) Himalayan Rivers Development, and (b) Peninsular Rivers Development. While the second component will be an inter-state venture, the first will involve neighbouring countries too and thus will be an international venture. Some of the major benefits expected from inter linking of the rivers[7,8] are: (i) irrigation potential is to increase from 140 to 175 Mha; (ii) drinking water availability is to increase by about 12 km^3; (iii) peak flood discharge to get reduced by about 30% due construction of reservoirs; (iv) generation of 34,000 MW of electricity; and (v) possibilities of inland navigation to provide cheap transport.

Vulnerability to climate change and adaptation strategies

Climate change is a human-induced stress (at least in part) that is generally not yet taken into account. An annual mean global warming of 0.4 to 0.8°C has been reported since the late 19th century[27]. In India, the analysis of seasonal and annual air temperatures, using the data for 1881 to 1997 has shown a warming trend of 0.57°C per hundred years[28]. Substantial increases in greenhouse gases are likely in the future as a consequence of which global mean surface temperature is expected to increase by between 1.4°C and 3°C for low emission scenarios and between 2.5°C and 5.8°C for high-emission scenarios by 2100 with respect[29] to 1990. Lal[2] states that globally averaged precipitation is projected to increase, but at the regional scale both increases and decreases are projected. Global mean sea level is likely to rise by 0.14 to 0.80 m from 1990 to 2100.

Under changed climatic scenarios, a number of chain events like melting of glaciers, sea level rise, submergence of islands/coastal areas and deviant rainfall patterns, are likely to occur. Likely impacts would include a greater annual variability in the monsoon's precipitation levels, leading to more intense floods and droughts. Thus, climate change in future is expected to have implications on river flows in South Asia including India. Global climate change is likely to result in severe droughts and floods in India, with major impacts on human health and food supplies. Developing countries of temperate and tropical Asia already are highly vulnerable to the extreme climate events such as floods, droughts and cyclones. Climate change and variability would exacerbate these vulnerabilities. Annual and seasonal changes in climate would alter the frequency and severity of major droughts. Changing temperature and evaporation rates would alter soil moisture conditions and the amount of runoff from the catchments into reservoirs. There are some evidences of increases in the intensity or frequency of some of these extreme events on regional scales throughout the 20th century. The abnormalities generated due to climate change are likely to trigger shifts in the existing biodiversity patterns and demands for totally new set of land uses. The growing frequency and magnitude of extreme environmental events worldwide has intensified research interest in natural disasters as well as regional vulnerability and response capabilities.

Water resources assessment and planning assumes that the past records of variability are reflections of what will happen in the future. Climate change is likely to result in hydrologic conditions and extremes of a nature that will be different from those for which the existing projects were designed. The approaches for effectively dealing with climate change will have to be different from those that have been employed to manage variability in the past. It is also likely that the variability due to climate change may be beyond the range for which current projects have been designed and are being operated. A review of current coping strategies of populations already affected by climate variability is needed. The likely impacts of increased climate variability and climate change on the water resources are required to be assessed. The coping strategies need to be evolved considering major factors, viz. social, economic, institutional, etc. to reduce vulnerability and enhance adaptation to climate-related developments and events. Some part of the country facing the frequent drought are adopting the dry land farming practices to grow the crops which require less amount of water. However, there is a need to take up such studies for assessment of available water resource for different agro-climatic regions of India and various adaptation practices under the changing climatic scenarios.

Some recommendations to cope with the problems in a systematic and a planned manner are: (i) a nation-wide climate monitoring programme should be developed; (ii) while formulating new projects that influence climate, it should be ensured that no action is taken which causes irreversible harmful impact on the climate; (iii) improved methods for accounting of climate-related uncertainty should be developed and made part of decision making process; (iv) existing systems should be examined to determine how they will perform under the climate situations that are likely to arise; (v) water availability and demands in all regions, particularly in water-scarce regions should be reassessed in the new climate scenario; (vi) a re-examination of the water allocation policies and operating rules should be taken up to see how these need to be updated to handle extremes that are likely to arise; and (vii) there should be proper coordination among concerned organizations so as to freely share the data, technology and experience for capacity building.

Water demand reduction and management measures

The demand or water use reduction measures conserve the existing limited water supply through the practices which require less water and reduce wastage and misuse of water. These measures are directed towards making the existing inadequate supply, whatever it may be, serve water users as effectively as possible and a balance between supply and demand is achieved. Thus the fundamental nature of these measures is their effectiveness in accomplishing a temporary allocation of the limited supply in a manner which serves the users to bridge the gap between supply and demand. The various techniques used for the purpose are based either on giving economic incentives or penalties or involve rationing, legal sanctions and various other types of social or political pressures. These may be based on strategies that include legal restrictions, economic incentives and issuance of public appeals.

Legal restrictions on water use

One of the active strategies could include provisions of legal restrictions on use of water, mainly during the period of scarcity. In India a national water policy[1] has been adopted, which includes policy directions for development and management of water resources. Also, provision of legal restrictions on proper utilization of groundwater resources has been advocated at various fora in the country. In fact, Gujarat has already enacted such legislation and other states may also follow the suit. However, provision of legal restrictions should be carefully thought of and need mobilization of qualified water specialists to explore effective solutions. The legal strategies so adopted should be such which can be implemented with minimum probability of being rendered ineffective by injunctions and law suits.

Land use planning and cropping pattern

Another strategy that could be adopted refers to planning of land use especially in new land developments. Areas where water supply priorities are low can be planted with drought-resistant varieties of trees. For this purpose, these variety of trees need to be developed. Another strategy that could be suggested can be in the agricultural sector. Considerable information exists on time distribution of water requirements for various crops and various planting dates. This knowledge is required to be integrated systematically with water supply probabilities to develop planting strategies. The selection of cropping pattern as per availability of water will reduce adverse impacts of drought on potential water consuming crops. The plants suitable for water scare areas can be (i) with shorter growth period, (ii) high-yielding plants requiring no increase in water supply, (iii) plants that can tolerate saline irrigation water, (iv) plants with low transpiration rates, and (v) plants with deep and well-branched roots.

Demand management for urban areas and industries

Demand management for urban areas and industries is another strategy which could be adopted to reduce demands in urban water supply or households and industries. However, before taking such measures it is necessary to study the actual savings the measures will result in based on practical data. Such information will help in planning curtailment of household demand during drought periods. Similarly, another strategy is to go for demand reduction approaches in the industry during periods of scarcity. Apart from ensuring leakage control, water technology to ensure efficient use of cooling and process water and necessary pollution control mechanisms. A sound water budgeting in industry can reduce the water demand to a considerable extent. The water conservation and reuse strategies should be planned at the time of setting up of a new industry to build in the conservation and reuse requirements from the beginning. Studies are required to develop production functions relating industrial policies to (i) availability of resource inputs like water, energy, etc. (ii) technology of production, (iii) waste water discharge constraint, etc. for devising measures of reducing water demands in the industry.

Environmental flow requirement

An environmental flow (EF) is the water regime provided within a river, wetland or coastal zone to maintain ecosystem and their benefits where there are competing water uses and where flows are regulated. Environmental flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of many benefits that healthy river and groundwater systems bring to society. EF normally include the flow requirements in rivers and estuaries for maintenance of riverine ecology. Some people view EF as wastage of water but clearly this is a narrow view.

Most Indian rivers have monsoon-driven hydrological regimes where 70–80% of the annual flow occurs in 3 to 4 months. Such rivers fall into the category of highly variable flow regimes. The total environmental flow requirement (EFR) for most of Indian rivers ranges between 20 and 27% of the renewable water resources. But these EFRs estimates may be considered as preliminary. These need verification through detailed, basin-specific assessments of the EFR. At the same time, it is important to appreciate that EFR allocations of less than about 20% of the mean annual flow are likely to degrade any river beyond the limits of possible re-habilitation. An additional factor, not yet considered in the assessment, is that a reduction in river flows decreases the ability of a river to cope with pollution loads. These loads are known to be massive in many Indian basins. Unutilizable portion of surface runoff in most Indian basins is adequate to meet the EFR. Only in a few basins, namely Pennar, west-flowing rivers in Kutch, Saurastra and Luni, Cauvery and east-flowing rivers between Pennar and Kanyakumari, the EFR exceeds the unutilizable runoff. In these basins, a part of the potentially utilizable water resources has to be earmarked for EFR. Sometimes, during the period of water scarcity it may be difficult to meet the EFR considering the importance of the demands from the other water sectors such as drinking water supply, irrigation, hydropower, etc. In such a situation, an optimum allocation policy may be evolved considering the potential demands and available supply. Efforts must be made to restrict the pollution loads to the rivers and other water bodies from the point and non-point sources of pollution in order to minimize the EFR.

Water pricing

Another strategy, which needs consideration, is changes in water pricing structures. Mostly water rates are based only on a portion of what it costs to obtain, develop, transport, treat and deliver water to the consumer. The costs are usually paid for in part by subsidies from the state using tax payers' money and therefore are not accurately reflected in an individual's water bill. The rates can be thought to vary with the availability either by an increase in price during period of abundant supply. The policy of peak demand pricing can also be effective in conserving water in which higher rates can be proposed for water use beyond a prescribed limit. Moreover, some economic incentives for using small amount of water can be given to consumers for encouraging water conservation. Studies are required on collection of economic data on other actions to induce conservation since reduction in water use will probably be attributable to both price increases and other factors. These efforts will be needed separately for residential, commercial and industrial sectors.

Desalination of water

Since 1970, there has been significant commercial development using various desalination technologies, including distillation, reverse osmosis and electrolysis. This technology is suitable for use in areas where freshwater is scarce, but saline water is available and energy is cheap. Compared to water recycling technologies, desalination presents fewer health risks. Desalination, as currently practised, mostly uses fossil fuels. Solar and wind energy are available in abundance in India and may be explored as alternative sources for this purpose in the coastal states. Between the high capital and energy requirements, desalinated water costs several times more than water supplied by conventional means. But the costs are now coming down. Current production cost is about Rs 50 per m^3 (*Times of India*, New Delhi, 30 July 2004). Many facilities in coastal region are using reverse osmosis for desalinization. For example, at Kalpakkam reactor, Tamil Nadu, 1.8 million litres of water is being produced per day. It is expected that as the costs come down, desalinization would become commercially viable in the next 6 to 8 years.

Data monitoring and information system

For planning, design and operation of the water resources projects, temporal and spatial data of various hydrometeorological variables as well as basin characteristics are required. However, in India the network of monitoring the hydrometeorological variables is inadequate. Also the data collection, processing, storage and dissemination are not well organized. In this regard, a comprehensive, reliable and easily accessible Hydrological Information System (HIS) is a pre-requisite. To achieve these objectives, there is a need to strengthen the existing monitoring network of data and develop the HIS by improving the data processing, analysis and dissemination techniques through proper coordination amongst the various agencies.

To improve the existing HIS in India, a giant step has been taken up by implementing the World Bank aided Hydrology Project Phase-I (HP-I). During the HP-I the data monitoring network has been strengthened and HIS has been developed for various river basins of the nine peninsular states of India, viz. Andhra Pradesh, Chhattisgarh, Gujarat, Madhya Pradesh, Maharashtra, Karnataka, Kerala, Orissa and Tamil Nadu. This information system will be useful for processing, storage and dissemination of the reliable and spatially intensive data on water quantity and quality in computerized databases. Special attention has been paid to standardize data observation and validation procedures so that data are of good quality and are compatible across various agencies. Infrastructure and human resources development aspects have been attended for sustainability of the system which should grow with developments in hydrology and allied technologies[30]. Data processing with decentralized hierarchical structure ensures a completely participatory approach. The system will promote greater interaction between different HIS agencies and also ensure uniformity of tools and procedures. Improvements in infrastructure and institutional support are beginning to reflect in terms of availability of organized hydrological databases and timely availability of better quality data to the users. It would only be fitting that the improved system further grows and the experience gained is utilized for similar improvements in all other states of India. Recent techniques, such as remote sensing and Geographic Information System (GIS) coupled with field-based monitoring stations may be utilized to monitor the data in real time and update the database.

Applications of decision support system in water resources

Recently, new advances in computer technology have enabled widespread improvement in water resources planning and management. One of the new trends in solution of water management problems has been to aggregate several models into integrated software, i.e. a knowledge based Decision Support System (DSS) that focuses on the interaction between the use and the data, models and computers. Rapidly advancing computational ability, development of user-friendly software and operating systems, and increased access to and familiarity with computers among decision makers are the important reasons for this growth in the fields of both research and practice. Automating the process with a DSS could effectively improve the water resources planning and management.

The aim has been to create a system in which the mechanics of linking one component with another are largely transparent to the user. Although time and effort is required in customizing the system for a particular river basin, its use has been designed to be as simple as possible. Communication is by means of a user-friendly interface, which makes extensive use of hypertext for guidance and colour graphics in presenting the results. A keyboard is not normally required since all the facilities are accessed by touching the appropriate icon representing the particular component. Moreover, the controls for operating a model will be familiar in as much that the icons mimic a video-recorder, viz. play, pause and stop. In this way, the person responsible for the actual project is able to make rational use of the system without an in-depth knowledge of modelling techniques. Under the Ministry of Water Resources, Government of India, a World Bank funded Hydrology Project Phase-II is likely to commence soon. In this project the development and applications of DSS for water resources planning is one of the major components.

A description of a typical DSS for Integrated River Basin Planning is available on the website (www.ncl.ac.uk/wrgi/wrsrl/projects/waterware/waterware/html). The salient features of this DSS are briefly discussed here. WaterWare is the outcome of EUREKA EU 487, a collaborative research programme involving some three universities, a research institute and two commercial companies. The aim was to develop a comprehensive, easy-to-use decision-support system (DSS) for integrated river basin planning which would be capable of addressing a wide range of issues such as: (i) determining the limits of development; (ii) evaluating the impact of new environmental legislation; (iii) deciding what, where and when new resources should be developed; (iv) assessing the environmental impact water-related development; and formulating strategies for river and groundwater pollution-control schemes; etc. This fifth-generation hydroinformatics system has the capacity not only to predict what is likely to happen under different scenarios but also to offer expert advice on decisions that need to be taken. Whilst modelling techniques are used for predictive purposes, the artificial intelligence is provided by a mixture of optimization techniques and expert systems. These are available to assist the user evaluate options, draw conclusions and determine appropriate actions. WaterWare has been designed to combine the capabilities of GIS, database technology, modelling techniques, optimization procedures and expert systems. At the present time, the system comprises a GIS, geo-referenced database and generic river-network editor, coupled to an increasing number of analytical components including groundwater pollution control, surface-water pollution control, demand forecasting, water-resources planning and hydrologic processes. New components such as estuaries are currently being added and existing components expanded to include further models and optimization techniques. Provided the new elements comply with the generic interfaces, there are no limits on replacing existing or adding further models. Indeed, it is likely that most components will eventually have more than one model from which to select, depending on the data availability and the degree of sophistication required.

Eco-hydrological approach to water resources management

The eco-hydrological approach to water resources management considers the water flow domain and water use domain for categorizing the water as green and blues. The green water concept refers to the water used in growth of economic biomass, i.e. rainfed food, timber, fuel-wood, pastures, etc. as well as the ecosystems biomass growth, i.e. plants and trees in wetlands, grasslands, forests, etc. The blue water concept refers to economic use of water in society, i.e. irrigation, industry and domestic uses as well water flow required for ecosystem functions such as aquatic freshwater habitats etc. Green and blue water approaches indicate that there is plenty of water around and the conventional blue water crisis is misleading. However, almost all water is involved in securing ecosystem service which supports human livelihoods and provides us resilience to cope with shocks. The water crisis is therefore different in character not primarily about direct human use, but just balancing water between humans and nature.

Virtual water transfer

By definition virtual water is the water embedded in a product, i.e. the water consumed during its process of production. Virtual water refers to all sorts of production where water is used, e.g. it is not restricted to grain only. The production includes other inputs or investments like energy, labour, soil, market, etc. The concept emerged in the 1990s and receives more and more attention from people concerned with water management and in particular with water related to food production. The water requirements of food are by far the highest. It takes 2 to 4 litres per day to satisfy the drinking water needs of a human being and about 1000 times as much to produce the food[31]. In this way, the concept of virtual water is important for food production and consumption. The importance of virtual water at global level is likely to increase as projections show that food trade will increase rapidly, i.e. doubling for cereals and tripling for meat between[32] 1993 and 2020. Therefore, the transfer of virtual water embedded in the food that is traded is becoming an important component of water management on global and regional level, particularly where water is scarce. India is a vast country with large spatial and temporal variations in availability of water resources. Hence, it is important that virtual water is properly assessed in terms of its value in space and time. It also needs to be analysed how virtual water is considered at policy level on food trade, water management and agriculture.

People participation and capacity building

For making the people of various sections of the society aware about the different issues of water resources management, a participatory approach may be adopted. Mass communication programmes may be launched using the modern communication means for educating the people about water conservation and efficient utilization of water. Capacity building should be perceived as the process whereby a community equips itself to become an active and well-informed partner in decision making. The process of capacity building must be aimed at both increasing access to water resources and changing the power relationships between the stakeholders. Capacity building is not only limited to officials and technicians but must also include the general awareness of the local population regarding their responsibilities in sustainable management of the water resources. Policy decisions in any water resources project should be directed to improve knowledge, attitude and practices about the linkages between health and hygiene, provide higher water supply service levels and to improve environment through safe disposal of human waste. Sustainable management of water requires decentralized decisions by giving authority, responsibility and financial support to communities to manage their natural resources and thereby protect the environment.

Remarks

Water is one of the most essential natural resources for sustaining life and it is likely to become critically scarce in the coming decades, due to continuous increase in its demands, rapid increase in population and expanding economy of the country. Variations in climatic characteristics both in space and time are responsible for uneven distribution of precipitation in India. This uneven distribution of the precipitation results in highly uneven distribution of available water resources both in space and time, which leads to floods and drought affecting the vast areas of the country. Better and scientific structural and non-structural measures are required for mitigating the floods and droughts. Mathematical models are needed for forecasting the monsoon rainfall accurately, which may be utilized by the decision makers and farmers for adopting appropriate strategies for management of droughts and floods. There is a need for increasing the availability of water and reducing its demand. For increasing the availability of water resources, there is a need for better management of existing storages and creation of additional storages by constructing small, medium and large sized dams considering the economical, environmental and social aspects. The availability of water resources may be further enhanced by rejuvenation of dying lakes, ponds and tanks and increasing the artificial means of groundwater recharge. In addition to these measures, interbasin transfer of water provides one of the options for mitigating the problems of the surplus and deficit basins. However, for interbasin transfer of water the scientific studies need to be carried out for establishing its technical and economic feasibility considering the environmental, social and eco-hydrological aspects.

Integrated and coordinated development of surface water and groundwater resources and their conjunctive use should be envisaged right from the project planning stage and should form an integral part of the project implementation. There is a need for proper management of groundwater resources, which presently require adequate inputs including manpower, financial inputs, technologies, etc. Some of the important measures which may be taken up for sustainable development of groundwater resources include improving public water supply, use of energy pricing and supply to manage agricultural groundwater draft, increasing rain-water harvesting and groundwater recharge, transfer of surface water in lieu of groundwater pumping, increasing the economic growth and reduction in dependence on agriculture and formalizing the water sector.

The components of the hydrologic cycle are being affected because the hydrological processes are no longer stationary due to point and non-point changes taking place in the river basins. An accurate assessment of available surface and groundwater resources, considering the man-made changes, is needed for planning, design and operation of the water resources projects as well as for watershed management. There should be a periodic reassessment of the surface and groundwater potential on a scientific basis, taking into consideration the quality of water available and economic viability of its extraction. Since the hydrological processes are continuous and quite complex, an accurate assessment of quantities of water simultaneously passing through all these processes is quite a difficult task. Mathematical modelling of hydrological processes would provide an opportunity to both the research hydrologists and the water resources engineers involved in developing the integrated approaches for planning, development and management of water resources projects for sustainable development as well for preserving the ecosystems.

The available information and data collected so far by different operational and field organizations, scientific groups and engineering community are inadequate for planning, development and management of the vast water resources in the country. The time series data of the hydrological and meteorological variables, the space-oriented data and relation-oriented data are generated in a fragmented manner for specific locations and extrapolated to larger regions or river basins. Thus, in this regard, a comprehensive, reliable and easily accessible Information System for water resources data is a pre-requisite. The effort made in the World Bank aided Hydrology Project–I, is an important step in this direction. DSS are required to be developed for planning and management of the water resources projects. Such systems provide an integrated approach for water resources management considering the various water-related disciplines together with socio-economic aspects. These systems may be utilized for studying the different scenarios of water demand for arriving at the optimum allocation of water for various demands under varying water availability conditions.

Climate change is posing a challenge before the water resources engineers. Hydrological studies are required to be taken up for assessment of water resources under changing climatic scenarios. For predicting the future climatological variables on micro, meso and macro watershed scales, a comprehensive general circulation model is required to be developed for India, giving due consideration to the global scenarios. With the rapid industrialization and increasing use of fertilizers and pesticides, the quality of surface and groundwater resources is deteriorating. The movement of pollutants in the rivers, lakes and groundwater aquifers needs to be regulated. In this regard, regular water quality monitoring programme has to be launched for identifying the areas likely to be affected because of the water quality problems. For maintaining the quality of freshwater, water quality management strategies are required to be evolved and implemented. Minimum flow must be maintained in the rivers for meeting the criteria of EFR. The eco-hydrological approach based on the concepts of blue and green waters may be considered as an integral part of the water resources management practices by balancing water between human beings and nature. Also, the concept of virtual water transfer requires to be introduced at policy level for food trade, water management and agriculture. The capacity building and awareness programmes may be organized for the users and public for encouraging their effective participation in water management practices and developing ethical concepts for making efficient use of water resources. Capacity building is also needed for the water resources managers and developers for updating the knowledge and technology in the area of water resources management.

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