# Chapter 1

# Introduction to Water Resources Systems

The objectives of this chapter are:

- To introduce the subject matter of this book;
- to explain the need and availability of water including the magnitude of the quantities involved;
- to provide an overview of systems approach; and
- to explain the challenges in water sector in the time to come.

Earth is a blue planet. Three quarters of it are covered with water, a unique substance. The journey of evolution of life began in water and it is the major constituent of a human being – an average human contains about 50 liters of water. On account of its peculiar molecular structure, it is a nearly universal solvent. The movement of water on the earth has been one of the main causes in shaping the topography. Water also has a high thermal inertia due to high specific heat and therefore the oceans have important influence on heat cycle of the earth. The culture, food, and life style of a place are closely knitted together and depend on climate. It is well known that water is central to the climate of a place. Along with all the benign features, water is also a paramount vehicle to convey the fury of nature. The water-centered hazards, like floods and droughts, have caused havoc since the dawn of civilization. According to the beliefs of some religions, the life on this planet is certain to be destroyed one day by a great deluge.

Since the dawn of civilization, mankind has shown a preference to settle near rivers due to assured supply of water, facility of navigation, and fertility of river valleys. Even today, a considerable portion of world population lives in areas adjacent to water bodies. Every continent has a number of major cities which are located on the ocean coasts and banks of rivers, for example, New Delhi (Yamuna), Washington DC (Potomac), London (Thames), Paris (Seine), Cairo (Nile), Manaus (Amazon), Tokyo, New York, Sao

Paulo, and Sydney. While the cities enjoy the benefits due to the proximity of a source of water, man has harmed the sources of water in many ways by unwise exploitation. People living close to rivers often become victims of misery and upheaval in the wake of devastating floods which have accompanied mankind throughout its history. Due to these reasons, man always had a desire to somehow tame and control the nature in general and rivers in particular, and use them for beneficial purposes. To fulfil this objective, man has been closely observing, measuring and attempting to understand hydrological processes and developing techniques for control and management of water resources. This book is an attempt to take the reader on a journey to visit some tools and developments which are the results of the quest of the mankind over many centuries.

The practice of hydrologic observations dates back to historic times. The *Arthasashtra* of Cautilya (a famous administrator/economist in ancient India) discusses rainfall measurements which were the basis of revenue collection. Varahamihira (AD 505-587), an ancient Indian philosopher, had discussed the topics like formation of clouds, signs of immediate rain, rainfall quantity, and exploration of groundwater in his treatise by the name *Brihat Samhita*. The Egyptians have been systematically measuring the flow of River Nile for a very long time. An open masonry water well was built in the first century AD at the upstream end of an island in the Nile at Cairo. The marks on the inner wall of this well constitute a water-level gauge which was calibrated by Pliny-the-Elder (A.D. 23-79) in terms which illustrate the social importance of the water level in the river (These were: disaster, abundance, security, happiness, suffering, and hunger. See Fig. 1.1). Around the second century BC, Romans had built many aqueducts in Iberian peninsula whose ruins can still be seen in places like Segovia. The rainfall records of more than 100 years duration are available at many stations around the world. However, the early hydrological design practices were not very scientific and the designs were mostly based on empiricism, thumb rules or heuristics.

In many countries, the computer-based analysis and design techniques have been in vogue since the 1950s. With the advent of computers, the systems analysis techniques were introduced in the water resources area in the 1960s. One of the earliest comprehensive works on river basin simulation was published by Maass et al. (1962). They had offered the following on digital simulation: "Until digital computers of the magnitude of the (IBM 650 or Univac I) were constructed, the solution of large scale simulation problems was not feasible. Even the storage capacities of these computers were not commodious enough.... (River basin simulation) had to await elaboration of the very large computers of the IBM 700 class, with an internal magnetic-core storage capacity of up to 32768 words." This was the status of computer application in the 1960s when no interactive color graphic displays were available, there were no digitizers, color laser printers, mice, disk capacities of the order of giga bytes, and Internet. Compared to this, today the CPU memory of a typical desk-top PC is measured in mega bytes and disk capacity in giga bytes, its processing speed is also faster by thousands of times and a variety of peripherals can be easily interfaced to it. A number of software, including compilers, editors, spreadsheet, word processing and utilities, are loaded on each machine. The wider availability of powerful computers in the last few decades has led to a proliferation of mathematical models and studies dealing with water resources systems.

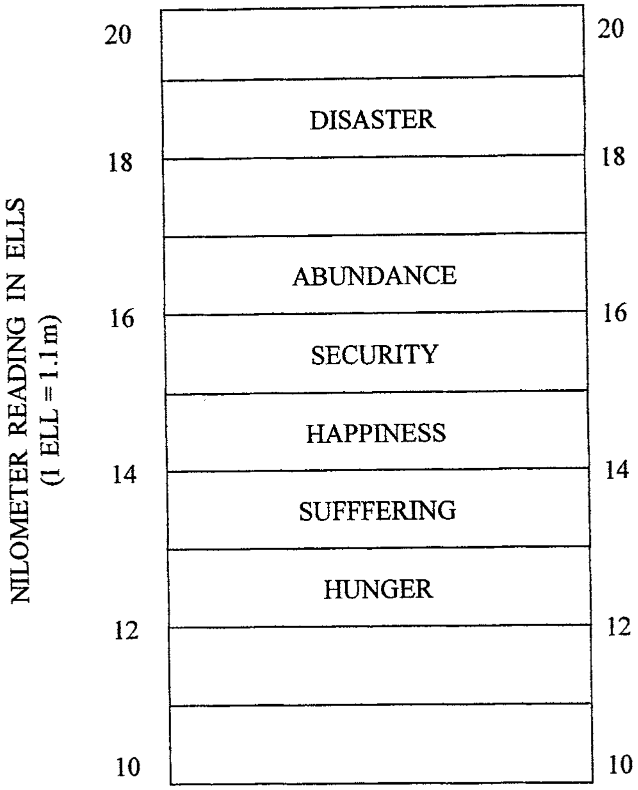

Fig. 1.1 Nilometer built by Pliny-the-Elder [Source: Dooge (1988). Copyright © IAHS. Used by permission].

It is a bit disappointing to note that the use of modern tools for day-to-day management of water resources development projects is quite limited. There is a feeling in many quarters that despite all the developments of sophisticated models and techniques, there has not been significant improvement in planning, design and operation of water resources projects. Hence the "age old problems" still remain unsolved: there are more than a billion people who do not have access to water supply and three billion people still do not have adequate sanitation. The data also suggest that there is a slow-down in the growth and productivity of irrigated lands. Besides, "new problems", mostly related to environmental degradation, are cropping up. The quality of river water is degrading rapidly in many rivers despite attempts to reverse the trend. The rate of freshwater fish species extinction is five times that of salt water species. Water diversions for irrigation are having devastating effects on water bodies, e.g., the Aral Sea in Central Asia is shrinking and may soon reduce to a fraction of its original size. Deforestation/land degradation (impacts on flooding and siltation of reservoirs), salinization and water logging, and water contamination by chemicals, fertilizers, and human waste are all serious issues in many parts of the world. The ground water aquifers are being mined at an unprecedented rate. About 10% of the world's agricultural food production now depends on mined ground water. Water tables are falling as much as a meter per year in many parts of the world.

Water is a nature's gift whose availability in a region is limited by climate and topography. Traditionally, water has been considered a social commodity being a "basic requirement" for life. In ancient times, a fundamental premise was that anybody who is thirsty should not be denied water, whatever be his income and purchasing power. This privileged social status of water was based on the doctrine of 'essential service' or 'public service' depending on the country. Of late, due to various reasons among which scarcity being the chief, water and related services are becoming more and more an economic asset with production and conservation costs, utilization values, opportunity costs, and demands that vary with price.

Water is required for various day-to-day activities of mankind. Therefore, before attempting to solve the problems of water resources planning and management, it is necessary to examine the various uses and needs of water.

## 1.1 NEED FOR WATER

The need for water is derived from a variety of activities in which it is used as shown in Fig. 1.2. These activities are vital for existence and development of human society. Because usable water is limited in its availability, it has an economic value. Furthermore, different activities require water of differing quality. For example, water of high quality is needed for domestic use while the quality may be compromised for sanitation use. Clearly, all uses of water cannot be supported to the fullest extent and a management policy has to be developed that can prioritise water use following established criteria. There may be conflicts and interactions amongst different water uses, and these, in turn, interact with water elements. The management policy has to incorporate all these considerations.

The term 'water withdrawal' refers to water removed from a source. Some of this water may be returned to the original source with changes in the quality. The term 'consumptive use' refers to water which is not available after satisfying the intended purpose, e.g., drinking and evaporation are consumptive uses. The term 'water demand' is often used to denote the quantity of water required for a purpose. Basically, the uses of water can be divided into two categories: withdrawal (off-stream) and in-situ (in-stream). The withdrawal uses are those for which water is diverted from its natural place of occurrence. The water used for agriculture, industry and municipal purposes are a few examples of this type. The in-situ uses are those for which water need not be diverted and include recreation, wild life habitat, minimum flow requirement, and hydroelectric power generation (in most cases).

The utility of water lies in the various productive functions that it can perform. Traditionally, municipal and agricultural water supply have been the usual uses. These two (particularly in an agrarian economy) are viewed as social objectives and cannot be given up even if alternate use of water gives a higher benefit. Other important uses are hydropower, navigation, and recreation. The objectives of water resources development are more varied now. Pollution control, repulsion of saline water, preservation of natural rivers, beautification, groundwater replenishment, and a host of other equally non-quantifiable and competitive purposes now demand equal attention along with economic purposes.

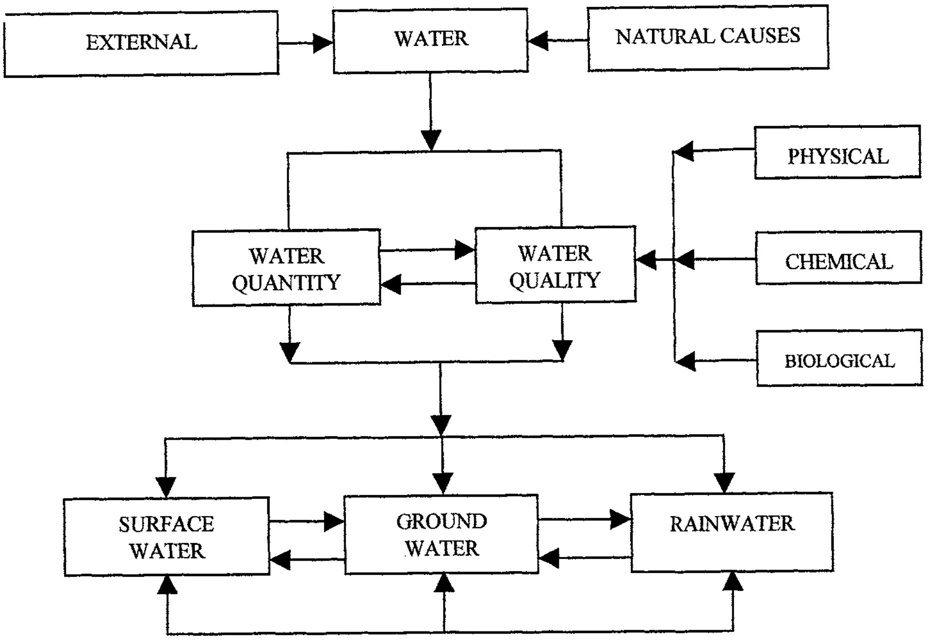

Fig. 1.2 Sources and quality of water from the perspective of its use.

The issues of water demand and its supply are specific to time and place. There has been continuous increase in the water use over the world since the time such records are available. It has been estimated that the total water use at the beginning of the last century was about 600 $km^3$/year. This rate witnessed a sharp increase and the global water use by the year 2000 is likely to be about 5300 $km^3$/year. Thus, there was a tenfold rise in the water use in the last century. As the population of the world is rising, the demand for water will also continue to increase in the 21st century. A number of projections of the future world population have been made and it is estimated that the population of the world will stabilize sometimes after the year 2060. The rate of urbanization would further rise and by 2025, about 4 billion people are likely to live in urban areas.

Estimates of water use in the various continents at different times in the 20th century are given in Table 1.1.

Gleick (1997) has estimated sector-wise water requirements for the year 2025. The domestic water use has been estimated assuming that the world's entire population has access to a "basic water requirement" of at least 50 liters/person/day and regions using more than that amount would implement measures that would reduce per-capita domestic water use to the present level in the developed nations which is around 300 liters/person/day. In this scenario, the total domestic water needs would be approximately 340 $km^3$/year. In the agricultural sector, all regions are assumed to attain a minimum consumption of 2,500 calories per person per day. There are likely reductions in water needed to grow these diets as a result of changes in the water-intensive components of diets, particularly meat, and changes in irrigation efficiency, cropping intensities, and irrigated area. Taking into account the increase in population, the agricultural water consumption would be about 2,930 km$^3$/year. The industrial water withdrawals would be at around 1,000 km$^3$/year and an additional 225 km$^3$/year will be lost due to reservoir evaporation. Thus, the total global water withdrawals are projected by Gleick (1997) to be approximately 4,500 km$^3$ in 2025. This figure is little low compared to the estimate of Shiklomanov (1998).

Table 1.1 Historical Water Withdrawal, Consumption, and Projections [Source: Shiklomanov (1998)].

| Continent | Historical Estimates of Use (km$^3$) | | | | | | | | Forecasted Use (km$^3$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1900 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 1995 | 2000 | 2010 | 2025 |
| Europe | 37.5 | 71.0 | 93.8 | 185 | 294 | 445 | 491 | 511 | 534 | 578 | 619 |
| | 17.6 | 29.8 | 38.4 | 53.9 | 81.8 | 158 | 183 | 187 | 191 | 202 | 217 |
| North | 70 | 221 | 286 | 410 | 555 | 677 | 652 | 685 | 705 | 744 | 786 |
| America | 29.2 | 83.8 | 104 | 138 | 181 | 221 | 221 | 238 | 243 | 255 | 269 |
| Africa | 41.0 | 49.0 | 56.0 | 86.0 | 116 | 168 | 199 | 215 | 230 | 270 | 331 |
| | 34.0 | 39.0 | 44.0 | 66.0 | 88.0 | 129 | 151 | 160 | 169 | 190 | 216 |
| Asia | 414 | 689 | 860 | 1222 | 1499 | 1784 | 2067 | 2157 | 2245 | 2483 | 3104 |
| | 322 | 528 | 654 | 932 | 1116 | 1324 | 1529 | 1565 | 1603 | 1721 | 1971 |
| South | 15.2 | 27.7 | 59.4 | 68.5 | 85.2 | 111 | 152 | 166 | 180 | 213 | 257 |
| America | 11.3 | 20.6 | 41.7 | 44.4 | 57.8 | 71.0 | 91.4 | 97.7 | 104 | 112 | 122 |
| Australia | 1.6 | 6.8 | 10.3 | 17.4 | 23.3 | 29.4 | 28.5 | 30.5 | 32.6 | 35.6 | 39.6 |
| +Oceania | 0.6 | 3.4 | 5.1 | 9.0 | 11.9 | 14.6 | 16.4 | 17.6 | 18.9 | 21.0 | 23.1 |
| Total | 579 | 1065 | 1366 | 1989 | 2573 | 3214 | 3590 | 3765 | 3927 | 4324 | 5137 |
| (rounded) | 415 | 704 | 887 | 1243 | 1536 | 1918 | 2192 | 2265 | 2329 | 2501 | 2818 |

Note: The row above the dotted line gives water withdrawal and the row below the dotted line is for water consumption. Includes about 270 km$^3$ in water losses from reservoirs for 2025.

The major consumer of water in the last century was the agricultural sector which consumed more than half of the water used. According to the data given by Biswas (1998), agriculture accounted for nearly 90% of all water use in 1900 but its share has declined to about 62% by the year 2000. This trend is likely to continue into the 21st century, even though nutritional requirements of rapidly increasing world population have to be satisfied. The agricultural water requirement at the beginning of current century was about 10,000 km$^3$ of water per year. The demand for industrial and urban sectors was about 2500 and 240 km$^3$ per year; the rural sector required about 135 km$^3$ water annually. In terms of per capita water demand as per the current trend, the industrial and domestic sectors require about 180 m$^3$ per capita per year while the agricultural requirements are of the order of 700 m$^3$ per capita per year. It may be cautioned that these numbers are likely to change as the estimates are being continuously updated and one may come across different numbers from different sources. The lack of consistent and reliable data on both the supply and the use of freshwater creates serious problems in efforts to manage water resources.

Hydropower is the largest renewable source of energy and is the second largest source of electricity generation. The hydropower generation has many advantages: the plants have a high efficiency (of the order of 80-90%), can be started and shutdown quickly and hence are very useful as peaking plants, energy can be stored, and the reservoirs can be used for other purposes like irrigation, water supply, navigation, recreation. The operation and maintenance costs are low and there is no environmental pollution. All these properties make hydropower a desired source of electricity generation.

According to the estimates by Water Vision (2000), only about 33% of the economically feasible hydropower potential of the world has been developed so far. There are many 'pockets' of hydropower which are yet to be developed. For example, the Zaire basin in Africa contains 20% hydropower potential of the world and most of it is not harnessed. Similarly, the north-eastern region of India (chiefly the Brahmputra River and its tributaries) has about 30% of hydropower potential of India and only a negligible fraction of it has been developed. Keeping in view the technological developments, the cost of hydro-electricity generation in the near future is expected to be in the range 3 to 6 US ¢ per kWh. Furthermore, due to the development of turbines which can efficiently operate at low heads, it may be possible to modify many existing dams which are not presently operated for hydro-electric power and use them to generate power.

Water is an important input resource for many industrial activities. The electricity generation from fossil and nuclear fuels requires water for steam, cooling and general services. According to Herschy and Fairbridge (1998), the quantity required for condenser cooling is in the range 0.032 – 0.044 $m^3/s$ per MW. Besides, in coal fired plants, water is also needed for ash transport. The paper industry requires 40-400 $m^3$ of water per ton of paper, depending on the type of raw material. If a hydraulic method of coal mining is used, about 0.08 - 0.14 $m^3$ of water is needed per ton of coal produced. Coal slurry pipelines need 0.95$m^3$ of water per ton. It is estimated that about 0.163 $m^3$ of water per barrel (0.159 $m^3$) is needed to refine crude oil.

The transport of goods by water is highly fuel efficient with insignificant air pollution. The consumption of diesel per ton-km of goods by road is 0.04 liter, by railway 0.011 liter and by water 0.0056 liter. Navigation is not a consumptive use of water; a reservoir downstream of the navigable waterway can capture flows in the waterway and provide them for other beneficial uses.

Water is also required to sustain rivers and wetlands. River restoration has become a topic of interest in some developed countries and such projects can form part of a sustainable development plan for the river basin. The objectives of river restoration are normally to create a wider diversity of ecosystems and improve biodiversity by bringing the river into closer contact with its flood plain. A certain minimum flow is needed in a river to dilute pollution; water also washes away salts that would otherwise destroy farmlands.

### 1.1.1 Likely Future Trends of Water Demands

An analysis of data indicates that the rate of rise of water use has been about three times higher than the rate of increase in global population. If this figure is extrapolated then doubling the world population would entail a six fold increase in the total global water requirements. Coupled with increasing requirements for irrigation and industrial use, this is clearly not sustainable. Even now, water is treated as a free resource in many countries, although water deficits are being witnessed in many parts of the world. Furthermore, water is supplied either free of cost or the prices are kept artificially low in many countries due to influential lobbies and political reasons. However, as the demand versus availability worsens, it is likely that water prices will also have to be gradually increased, also as a means of controlling demands. As it becomes more and more expensive to provide one unit of water, farmers will be forced to use crop varieties which consume less water and adopt alternate means of irrigation. Water-efficient industrial processes will also be adopted on a large scale. The water use data (for example, see Seckler et al. 1998) also indicate that Asia is the continent which is the highest consumer of water. This is because Asia has very high population and agriculture, which consumes large amounts of water, is the main occupation of many Asians. In fact, there is a marked decline in percentage of water use for agriculture from low to high income countries as shown in Fig. 1.3.

Since an improved lifestyle requires more water, the improvement in standard of living of the people is also responsible for higher water demands. Despite much remarkable technical advancements, a large percentage of world population still does not have access to clean drinking water. As the governments are committed to providing clean drinking water to the entire population, the urban water use is expected to significantly rise by the year 2050 which is the time by which the world population is expected to stabilize. The provision of sufficient water for all the needs will also require substantially higher investments. The reason is that the cost of developing new sources is rapidly increasing due to the higher cost of construction materials, labor, as well as higher provisions for rehabilitation and resettlement of the project -affected persons. Environmental laws as well as water quality standards are becoming more and more stringent with time and this will also force the agencies to spend higher amounts in developing new water resources.

To meet additional land and water requirements to feed the increasing population, far more land will have to be cleared for agriculture, resulting in losses of forests, habitats, and biodiversity on a massive scale. There will also be increases in the demand for water for industry and municipal use. All this would have detrimental environmental impacts. The recent predictions about change in climate indicate that the water availability in various regions of the world is also likely to undergo changes in future.

As the deficit of water is increasing in many parts of the world, the conflicts due to water are occurring more frequently. These conflicts can be among the neighboring countries, among the adjacent states of the same country and sometimes even among the various communities in a city.

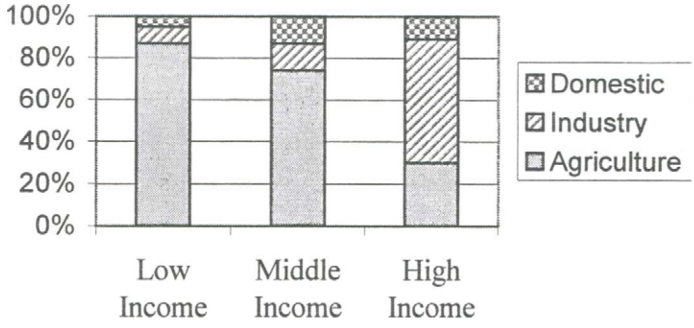

Fig. 1.3 Annual (1999 estimates) freshwater withdrawals [Based on data published in newspaper: The Hindu, dated June 18, 2001, New Delhi].

### 1.1.2 Water and Ecosystems

Ecosystems are the communities of interacting organisms and the physical environment in which they live. They consist of organic and inorganic matter and natural forces that interact and change. The components of ecosystem can be divided into two groups: biotic consisting of living beings and abiotic consisting of nonliving things. Humans are intimately familiar with the ecosystem because they live and interact with them regularly. In fact, every part of the earth is a part of an ecosystem. When studying and managing ecosystems, the scale or size is important. A small patch of forest is an ecosystem and so is a major river basin covering thousands of square kilometers. The major categories of ecosystems are coastal, forest, grassland, fresh water and agricultural systems. Besides the divisions of the ecosystems, the linkages between them are equally important. Although the human activities influence all the ecosystems to some extent, such an influence on fresh water systems is very pronounced. Both excessive poverty as well as excessive industrialization jeopardize ecosystems.

At present, all nations rich or poor, and all sections of the society affluent or deprived, are realizing the decline in the productive and assimilative capacity of ecosystems and their impact on life. Although our understanding of ecosystems has improved dramatically in the recent past, the ability or commitment to improve their quality has not increased proportionately. If the current pattern of ecosystems' use continues, there might be serious decline in their ability to yield the range of benefits, such as clean water and stable climate that they have been providing so far.

Historical evidence shows that water and environment had a major role in decline and fall of ancient civilizations. Obviously, the decline in the long-term productive capacity of ecosystems will have unhappy implications for human development and well being of all species. The pressure on ecosystems has tremendously increased from the latter half of the twentieth century onwards. This period has witnessed a population explosion, excessive industrialization and rapid rise in consumption of resources. All this has been at a cost to ecosystems and these pressures are likely to increase in the near future. Due to various reasons, governments world wide are not able to control or check unsound management practices. For example, the use of water for agriculture and electrical energy are subsidized to varying degrees in most countries. Algal blooms and eutrophication of freshwater systems and water borne diseases from fecal pollution of surface water is still a major cause of health problems in developing countries. Currently, about 40% of the world population experiences some kind of water shortage. The bio-diversity of fresh water ecosystems is threatened and a large number of species are feared to have become extinct in the last century.

To mitigate or manage the damage to ecosystems, an integrated approach is necessary that considers the entire range of services and optimizes the mix of benefits from an ecosystem and also across ecosystems. It is necessary to look beyond the traditional boundaries since ecosystems often cross the state and national boundaries. The successful management practices that preserve or increase the capacity of an ecosystem to produce the desired benefits in the future needs to be identified and implemented.

Too often in the past, water management had been limited to the sole quantitative aspect of water resources. A global approach to the management of all water-related ecosystems should be initiated in each river basin in addition to pollution control and the promotion of water recycling with a prospect of sustainable development. The root causes of water resources problems and their effects are shown in Fig. 1.4. Soil conservation, land use planning, forest management, protection of wetlands and aquatic ecosystems are crucial for water management. The same can be said about the management of solid wastes and sludge of treatment plants whose leaching can be a source of serious, sometimes irreversible, pollution of water bodies and aquifers.

## 1.2 AVAILABILITY OF WATER

For economic and optimum utilization, planning, design, and operation of water resources, the determination of the extent and availability of surface and ground water is the first requisite. The distribution of waters on the continents varies greatly in space and time. There are transitions of all kinds from one extreme to the other, i.e., the water surplus in the tropical rain forest regions is in sharp contrast with the deserts which are practically barren because of the scarcity of water. The human population, on the other hand, is distributed in quite a different manner. For example, regions with an immense abundance of water may be sparsely populated, e.g., Amazon basin, or densely settled, e.g., South Asia. The deserts which are without sufficient water, and the polar regions, where all the water is frozen, are both uninhabitable. Our ability to use water also depends on the frequency and magnitude of floods and droughts. In view of climate change, both are likely to become more severe.

The following major sources of water were identified by Cole (1998).

*Natural rivers.* The rivers are fed by rainfall, or snow/glacier melt, or both. Their flows vary seasonally and in upland areas streamflow varies wildly ('flashy discharge') and may be contained by impoundment in reservoirs. The flow of a river that receives groundwater inputs will be more steady. Lowland rivers are partially sustained by effluents of used water, for example from sewage treatment works and from the irrigation return flow.

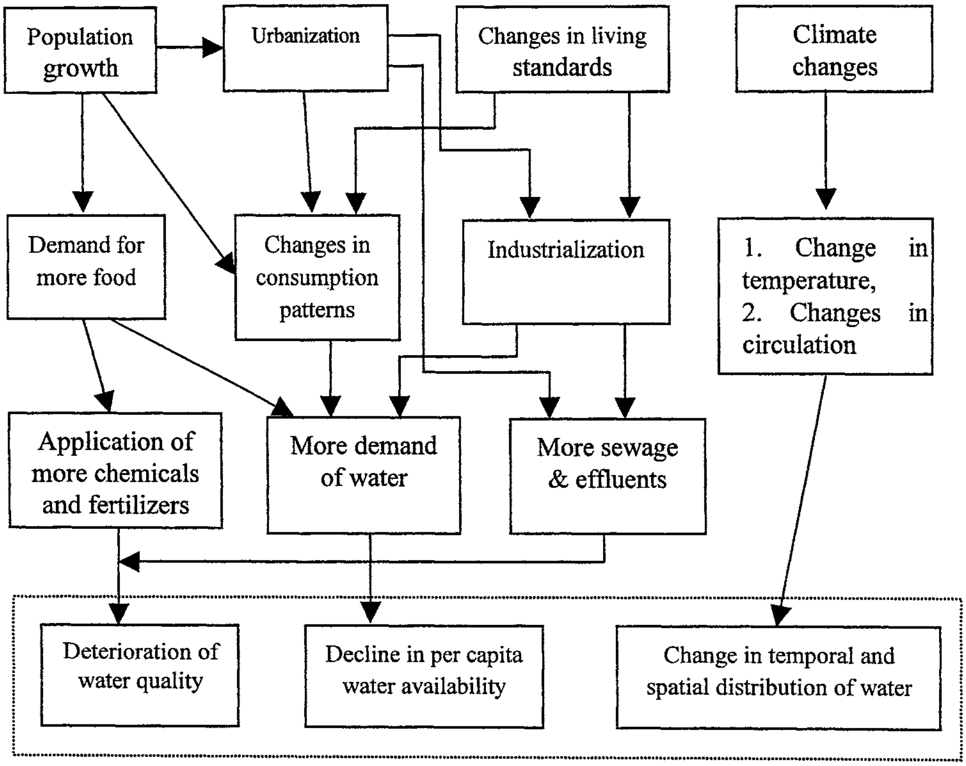

Fig. 1.4 Major root causes of water resources problems and their effects.

*Natural lakes*: These usually offer a limited supply, since their range of acceptable drawdown is severely constrained.

*Reservoirs*: Water is stored in a reservoir behind a dam for a number of uses. In climates with distinct wet and dry seasons, water stored in a wet season is withdrawn for use in the following dry season. In many parts of the world, reservoirs may have to cater for a long series of dry years. Reservoirs may be of the following types.

- Direct supply reservoir. Most upland reservoirs supply water by pipeline or canals, often by gravity flow and offer good quality water.
- River-regulating reservoirs, which are major water reserves and release water downstream to sustain its discharge in conditions of low natural flow.
- Pumped storage, in which river water is pumped into a (sometimes off-channel)

storage, for subsequent use. This arrangement is also used in hydropower projects to provide additional power for the peak period. During the off-peak hours, water from the lower reservoir is pumped back into the higher reservoir.

Estuary barrage which impounds an area that otherwise would be tidal. This is the ultimate means of trapping fresh water before it enters the sea. It entails making provision for the passage of migratory fish and providing locks for shipping.

*Tube wells*: are the main sources of ground water, usually with electric submersible pumps or with mechanical shaft-drive pumps. The yield range from 1 to 10000 $m^3$/day, depending on the aquifer characteristics, pump capacity, and available water. Open wells (bucket and winch, or hand-pumped) are small sources of water in rural areas.

*Springs*: These occur where aquifers crop out above impermeable rock. They very much depend on local hydrogeological conditions. Springs may be perennial, affording a reliable minor source of supply, or only seasonal, with no year-round availability.

*Saline waters*: Brackish waters, which have a salt content $> 0.1\%$ are amenable to desalination by reverse osmosis systems. Although the process is expensive, it is extensively applied in arid areas (e.g. the Arabian/Persian Gulf) where fuel is cheap. Even seawater can be treated; thus, it can also be desalinated by distillation processes. As explained above, recent advances in membrane technology has significantly brought down the cost.

### 1.2.1 Water Resources Assessment

In water resources assessment, the knowledge of hydrology, meteorology, geology, and coastal sciences is combined to provide a quantitative picture of the physical characteristics and possible variation in the availability of this natural resource. Such an assessment considers the total catchment and its meteorological inputs in various phases: (i) land phase, (ii) river phase, (iii) reservoir phase, and (iv) subsurface phase.

The relative quantities of the earth's water contained in each of the phases of the hydrologic cycle are presented in Table 1.2. Oceans contain 96.5 percent of the earth's water, and of the remaining 3.5 percent on land; approximately 1 percent is contained in deep, saline ground waters or in saline lakes. This leaves only 2.5 percent of the earth's water as fresh water. Of this fresh water, 68.6 percent is frozen into the polar ice caps and a further 30.1 percent is contained in shallow groundwater aquifers, leaving only 1.3 percent of the earth's fresh water mobile in the surface and atmospheric phases of the hydrologic cycle. The proportions of this water in the atmosphere, soil moisture and lakes are similar, while that in rivers is less and that in snow and glacier ice is greater. A small amount of biological water remains fixed in the living tissues of plants and animals. The data on the earth's waters cited here are taken from a comprehensive study of world water balance conducted in the Soviet Union. These values represent only estimates and are being refined.

It is remarkable that the atmosphere contains only 12,900 cubic kilometers of water, which is less than 1 part in 100,000 of all the waters of the earth. Atmospheric water would form a layer of only 25 mm deep if precipitated uniformly onto the earth's surface (Maidment, 1993).

Table 1.2 World Water Reserves [Source: UNESCO (1978), © UNESCO. Reproduced by permission of UNESCO].

| Item | Area $10^6$ km$^2$ | Volume 1000 km$^3$ | Depth of run-off (m) | Percent of total water | Percent of fresh water |
|---|---|---|---|---|---|
| World ocean | 361.3 | 1,338,000 | 3700 | 96.5 | -- |
| Ground water: | | | | | |
| Gravitational, capillary | 134.8 | 23,400[1] | 174 | 1.7 | -- |
| Fresh | 134.8 | 10,530 | 78 | 0.76 | 30.1 |
| Soil moisture | 82.0 | 16.5 | 0.2 | 0.001 | 0.05 |
| Antarctica ice | 13.98 | 21,600 | 1546 | 1.56 | 61.7 |
| Other ice and snow | 2.25 | 2,464 | 1848 | 0.179 | 7.04 |
| Ground ice in permafrost | 21.0 | 300.0 | 14 | 0.022 | 0.86 |
| Lakes : | | | | | |
| Fresh | 1.2 | 91 | 73.6 | 0.007 | 0.26 |
| Saline | 0.8 | 85.4 | 103.8 | 0.006 | -- |
| Marshes | 2.7 | 11.47 | 4.28 | 0.0008 | 0.03 |
| Rivers | 148.8 | 2.12 | 0.014 | 0.0002 | 0.006 |
| Biological water | 510.0 | 1.12 | 0.002 | 0.0001 | 0.003 |
| Atmospheric water | 510.0 | 12.9 | 0.025 | 0.001 | 0.04 |
| Total water | 510.0 | 1,385,984.6 | 2718 | 100 | -- |
| Fresh water | 148.8 | 35,029.21 | 235 | 2.53 | 100 |

[1] Ignoring ground water reserves in Antarctica, estimated at 2 million km$^3$.

The biggest river basin of the world is the Amazon basin in South America, covering an area of 6.915 million km$^2$; this is 38% of the total area of South America. The average discharge of this river at the mouth is 2,20,000 m$^3$/s (Herschy and Fairbridge, 1998) and the flow at Obidos can go up to 3,70,000 m$^3$/s during the wet-season with flow depth at 48m. The details of the world's rivers are available in Showers (1989). The longest river in the world is Nile whose length is 6670 km. The maximum observed discharges of some of the major rivers of the world are given in Table 1.3.

About half of the land area of the world is comprised of river basins (more than 200) which fall in the territory of two or more countries. The major river systems which drain a number of countries include Amazon, Congo, Danube, Ganga-Brahmputra, Indus, Mekong, Niger, Nile, Rhine, and Zambezi. The UN (1978) has listed such river basins. The development and management of many water resources projects which involve international river basins requires agreements among the concerned countries. Guidelines are available dealing with treaties among the basin countries. In many cases, sharing of water is a bone of contention among the riparian states and disputes among neighboring countries due to sharing of water resources are not unknown.

Table 1.3 Maximum observed discharges of selected rivers.

| Country | River | Station | Catchment Area ($km^2$) | Year-month-day | Discharge ($m^3/s$) |
|---|---|---|---|---|---|
| Austria | Danube | Vienna | 10,700 | 1899/9/18 | 10,500 |
| Brazil | Amazon | Obidos | 46,40,300 | 1953 | 3,70,000 |
| Burma | Irrawaddy | - | 3,60,000 | 1877 | 63,700 |
| Cambodia | Mekong | Kratie | 6,46,000 | 1939 | 75,700 |
| China | Changjiang | Yichang | 10,10,000 | 1870/7/20 | 1,10,000 |
| Egypt | Nile | Aswan | 30,00,000 | - | 13,500 |
| France | Rhine | Beaucaine | 96,500 | 1856/05/31 | 11640 |
| India | Brahmputra | Pandu | 4,04,000 | 1973/8/8 | 51100 |
| | Ganga | Farakka | 9,35,340 | 1971/8/22 | 70500 |
| | Godavari | Dolaishwaram | 3,07,800 | 1959/9/17 | 78700 |
| | Krishna | Vijaywada | 2,51,360 | 1916/11/2 | 33500 |
| | Narmada | Garudeshwar | 87,900 | 1970/9/6 | 69400 |
| Netherlands | Rhine | Lobith | 1,60,000 | 1926/1/4 | 12280 |
| Pakistan | Indus | Attock | 2,64,000 | 1929 | 23200 |
| USA | Mississippi | Columbus | 23,87,950 | 1937/02/27 | 70,792 |
| | Ohio | Cairo | 5,28,300 | 1937/02/04 | 55,218 |
| USSR | Lena | Kusur | 24,30,000 | 1944/06/11 | 194,000 |
| | Volga | Volgograd | 13,50,000 | 1926/5/29 | 51900 |
| Zambia | Zambezi | Kariba | 6,33,040 | 1958/03/05 | 16,990 |
| Zaire | Zaire | Kinshasa | 37,47,300 | 1970/12/2 | 67930 |

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When one narrows down the focus from continental stage to national stage, the order of values also reduces. Let us consider the water balance for a country (India). The geographical area of India is 3.29 million km$^2$. The average annual precipitation is about 4000 billion m$^3$. The average annual runoff accounts for 1869 km$^3$ which is about 4% of the global supply. Due to topographic and other reasons, only about 690 billion m$^3$ of surface water is utilizable. The total replenishable ground water potential in the country is about 432 km$^3$ and out of this, the utilizable quantity is about 396 km$^3$. Thus, the average annual utilizable water resource is 1086 km$^3$. The utilization in the year 1997 was: irrigation 524, domestic 30, industrial 30, power 9, and others 36, the total being 629; all figures are in km$^3$. The utilization is projected to rise to 784-843 billion m$^3$ by the year 2025.

Table 1.4 World Water Balance by Continent [Source: Table W56 of Herschy and Fairbridge (1998). Used with kind permission of Kluwer Academic Publishers.].

| Water balance elements | Europe | Asia | Africa | North America | South America | Australia | Total land area |
|---|---|---|---|---|---|---|---|
| | | | In km$^3$ | | | | |
| Precipitation | 7,162 | 32,590 | 20,780 | 13,810 | 29,855 | 6,405 | 110,000 |
| Total river runoff | 3,110 | 14,190 | 4,295 | 5,960 | 10,480 | 1,965 | 40,000 |
| Groundwater runoff | 1,065 | 3,410 | 1,465 | 1,740 | 3,740 | 465 | 11,885 |
| Evaporation | 4,055 | 18,500 | 16,455 | 7,850 | 18,800 | 4,340 | 70,000 |
| | | | Relative values | | | | |
| Ground water runoff as percent of total runoff | 34 | 26 | 35 | 32 | 36 | 24 | 31 |
| Coefficient of ground water discharge into rivers | 0.21 | 0.15 | 0.08 | 0.18 | 0.16 | 0.10 | 0.14 |
| Coefficient of runoff | 0.43 | 0.40 | 0.23 | 0.31 | 0.35 | 0.31 | 0.36 |

The data about the water balance for a country are useful for preparing national plans or when large-scale inter-basin water transfer projects are to be considered. However, water resource planning is carried out basin-wise and for this purpose the data of water balance of a basin are required. Consider the water resources of the Ganga basin in India whose area is 862769 km$^2$. On an average, this basin receives 120 cm of precipitation and runoff is of the order of 525 km$^3$. The utilizable water resources of a basin depend on factors, such as topography and land use, and for Ganga basin the utilizable surface water is 250 km$^3$. In this basin, the total replenishable ground water is 172 km$^3$.

Many programmes for assessment of water resources of the world are underway. The World Water Assessment Programme (http://www.unesco.org/water/wwap) is a UN-wide programme whose goals are to: assess the state of the world's freshwater resources and ecosystems; identify critical issues and problems; develop indicators and measure progress towards achieving sustainable use of water resources; and help countries develop their own assessment capacity. The programme has its secretariat at Unesco and will publish a *World Water Development Report* at regular intervals. The Global International Waters Assessment (GIWA) is a water programme led by the United Nations Environment Programme. The aim of GIWA (http://www.giwa.net) is to produce a comprehensive and integrated global assessment of international waters, the ecological status of and the causes of environmental problems in 66 water areas in the world, and focus on the key issues and problems facing the aquatic environment in transboundary waters.

## 1.3 TECHNOLOGY FOR MEETING WATER NEEDS

Without a major technological innovation, there is little hope of meeting the ever-increasing water demands. There is no doubt that new technological changes can help improve services for millions and reduce the stress on water systems around the world. At the same time, one should not and cannot ignore the wisdom of the past when dealing with water.

The traditional approach to capture rainfall has been to build dams which trap the excess river flows. As considerable volume of surface water remains to be tapped, dam construction is likely to continue to play an important role in many countries. However, construction of new dams is becoming difficult since most of the good sites are already developed and the remaining ones are technically difficult. In the United States, the dam construction activity has been virtually nonexistent during the past quarter of a century. The social and environmental issues are becoming more crucial and will have to be successfully resolved. Therefore, careful planning is necessary before a new project is constructed. Although water is a renewable resource, the dam sites are not.

The agricultural sector witnessed a green revolution in many parts of the world during the last four decades. After the success of that green revolution, what is needed is a super green revolution, a revolution that is more productive as well as more 'Green' in terms of conserving natural resources and the environment. To emphasize appropriate utilization of water resources, this revolution is termed as the 'blue' revolution. Special emphasis is needed for drought-prone areas to attain a reasonable degree of self-sufficiency in terms of food and fodder. It can be achieved by a combination of:

(i) ecological approaches to sustainable agriculture,
(ii) optimum use of fertilizers, pesticides and irrigation water (possibly through drip irrigation, computerized controlled sensors and application of water and fertilizers just-in-time and place),
(iii) greater participation by farmers in management of water and land resources, and
(iv) the application of improved seeds and biotechnology.

An important and promising area of innovation is biotechnology which is undergoing a revolution. It is fueled by the groundbreaking work in modern molecular genetics, and the breathtaking advances in informatics and computing. New high yielding plants are being developed that are more environment-friendly and more drought- tolerant.

These plants also have increased salt tolerance. These seeds, coupled with agronomic techniques suitable to farmers with small holdings, are necessary to yield *more crop per drop* of water. The benefits of this revolution can and must be harnessed for solving the challenges of water in the interests of the poor and the environment.

Desalination of salty water is sometimes seen as the supply-side solution. Till some years ago, desalination was not considered feasible except for very moderate demands. The recent breakthroughs in membrane technology have had profound effects in many areas, ranging from waste treatment to desalination. Consequently, the cost of desalination in recent years has declined sharply to less than a dollar per cubic meter. Based on the trends of development, it is expected that by the year 2025, the cost of desalination would come down to 20 US cents/m$^3$ for brackish water and 40 US cents/m$^3$ for seawater. This technology is likely to play an important role in supplying water for municipal and industrial uses in near-coast zones. Treated wastewater can be used for agricultural purposes, and new technologies can reduce the cost of this treatment.

## 1.4 WATER RESOURCES PLANNING

Water resources planning and development is concerned with modifying the time and space availability of water for various purposes so as to accomplish certain basic national, regional and local objectives. In most cases, the ability to achieve these objectives is limited by the non-uniform availability of water and other resources.

The water resources of a country are distributed unevenly in space and time and the issue is how best to develop them. There is a need to conserve and prudently utilise the wealth of water resources. The basic motivation for a government to plan and develop water resources usually lies in the improvement in national or regional welfare, increase in national income, national self-sufficiency and preservation of the quality of the environment. The objective of water resources planning and management is to provide the supplies of water in accordance with the temporal and spatial distribution of demands through river regulation and distribution systems.

Depending on the system configuration, the same quantity of water can be put to various uses. The water used for hydropower generation can augment the downstream flows and can also be picked up further downstream for irrigation or other uses. Similarly, the regenerated flows from the command areas of irrigation projects in the upstream reaches can be put to further use downstream. These interlinkages and interdependence of withdrawals at various locations and use for various purposes are to be taken into account in water resources planning and management.

According to Hall and Dracup (1970), the general goals of a society can be stated in terms of the following objectives of water resources systems development:

1. To control or otherwise manage fresh water resources of the cognizant geographical or political subdivision so as to provide protection against injurious consequences of excesses or deficiencies in quantity or quality.

2. To provide or maintain water in such places and times in adequate quantity and quality for human and/or animal consumption, wildlife food production and processing, industrial production, commerce and for recreational, aesthetic and conservation purposes as considered desirable by the body politic.
3. To accomplish all of the above with a minimum expenditure of the physical, economic and human resources available.

The formulation of objectives is an initial step in the planning and developmental process. The systems approach demands an explicit articulation of the objectives in the form of an objective function by which the output of the system can be determined, given the policy, the initial values of the state variables, and the system parameters. Systems analysis for water resources projects planning is carried out with the basic objective of meeting certain fundamental requirements in an optimal way, by satisfying some economic or other criteria of optimality. The task of water resources systems planning may be:

a) to plan new water resources projects for least cost or optimum output, or
b) to plan enlargement of a system in an optimal way so as to meet its present functional requirements in a better way or to fulfil some new functions.

Detailed plans help water resources utilization in many ways. Planning helps in assessment of the present situation in the basin, the situation desired, the gap between the two, and the means to bridge the gap. It also helps to set priorities. Second, planning offers a framework and focus for policy analysis and development and organise public participation for each individual decision. Third, when planning processes proceed in open and participatory mode, they result in wider public support and acceptance of the final plan. Lastly, planning has coordinating effect because, by virtue of its nature, it forces interaction among concerned agencies.

## 1.5 WATER RESOURCES DEVELOPMENT

In countries with limited water resources, comprehensive and rational water resources development is a necessary condition for optimum social and economic growth. There are various ways of classifying water resources projects; in the classification based on physical nature, the broad project categories are:

1. Surface storages: reservoirs, natural lakes with artificial control of outflows.
2. Channelization: irrigation canals, navigation canals, drainage works, dykes for flood protection, and erosion control measures.
3. Diversion of water: inter-basin water transfer projects.
4. Waste treatment and assimilation.
5. Ground water extraction and artificial recharge.
6. Catchment treatment for control of water yield and peaks.

In water resources development, there are many aspects of a question -- the problem is often complex and has multiplicity of goals and alternatives. Different persons can have diametrically opposite views on various aspects and yet each of them may claim to be right. For example, there are widely divergent opinions about the benefits of dams. In fact, this has been the topic of passionate and often bitter debates. After a dam has been constructed, it is nearly impossible and very expensive to restore the status quo. Evidently, there is only one chance to develop the best course of action, necessitating a logical procedure which can rationally eliminate alternatives and reduce thousands of decisions to a relatively few. All this should be on the basis of rather voluminous mass of information of divergent accuracy. The conventional methods for development and management of water resources are often not suitable for handling complex problems of planning and management of water resources at the river basin level. Systems engineering is a powerful technique for quantitative analysis of the planning and operational problems of large river basins, since it allows consideration of complex issues in their totality.

Water is already fully allocated and exploited in many basins. Gradually many basins are inching towards this distinction ! Therefore, the elbow room for water resources development is shrinking and in future people will have to work within tighter constraints. In this context, it is pertinent to refer to the concept of 'hardcore' and 'softcore' projects that was advanced by Yevjevich (1983). Referring to the development in the Nile basin, he labelled the large-scale water projects such as the old Aswan dam, the High Aswan dam, and the future projects of similar size and significance as the 'hardcore projects'. Many other water related activities will be needed in the basin in the form of widespread, medium or small-scale projects that will increase the available water, regulate flows by various types of storage, control sediments and salt, use water more efficiently, and solve other water-related problems. The investment for such projects will be equal to or greater than the hardcore projects if the maximum economic benefits are to be attained. These additional activities were termed as 'softcore projects' by Yevjevich (1983). He noted that without the hardcore projects, many softcore projects couldn't be implemented. Without the effects of softcore projects, many hardcore projects may not lead to the highest efficiency in water use and to the greatest benefits. Although these observations were made with particular reference to the Nile basin, they are equally valid and relevant to every basin that is subject to large-scale development. However, in concordance with information technology jargon, more familiar terms are 'hardware' to denote physical projects and 'software' to denote the management policies.

## 1.6 WATER RESOURCES MANAGEMENT

Worldwide, environmental systems are rarely managed as a cohesive whole. That is partly because air, soil, and water resources have been and continue to be managed by independent organizations having little interaction amongst them. For example, there are a host of organizations in the United States that have authorities to manage nation's water resources at the local, state, regional, and national level. The U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers are two of the federal agencies with broad authority for water resources management. Then there are the departments of water resources, natural resources, or environmental quality at the provincial (state) level having authority to manage water resources in their individual states. At the local (county or parish) level, there are the water boards, commissions, and the like that manage local water resources. Similar multi-agency systems exist in most countries.

The integrated water management is best accomplished within a spatial unit called river basin or watershed. Hirsch et al. (1977) coined the term *synergistic gain* to denote benefits due to joint operation of a system of reservoirs, in excess of the benefits from optimal individual operations. These gains arise as a result of the diversity of flows in several streams used in the water supply system. These gains are realized by employing a flexible operating policy and the ability to capture these gains is limited by physical constraints (such as canals to take water from source to demand center), and the ability to forecast future flows. Note that additional costs will have to be incurred to reap synergistic gains. Naturally, these should exceed the benefits.

The integrated water management can be viewed as a multi-dimensional process pivoted around the need for water, the policy to meet the needs and the management to implement the policy. Water elements encompassing physical, chemical, and biological aspects of water quantity and quality may constitute the first dimension. Water uses, including agriculture, water supply, energy generation, industry, fish production, recreation, transportation, etc., may constitute the second dimension. Clearly, these water uses have to be accomplished following a well-defined management policy balancing the demand for water amongst different uses. The strategy to implement this policy forms the third dimension. The management must be dynamic and evolve with time, in response to changing needs and objectives. Thus, these needs and objectives may form the fourth dimension.

The water elements, their interactions, and the effects of natural as well as external constraints on them, as shown in Fig. 1.5, constitute the foundation upon which the edifice of integrated water management is to be built. External constraints, such as economic, demographic, transportation and other forms of development, directly influence one or the other water elements. Likewise, climatic vagaries, climatic change, and climatic extremes, and a host of natural hazards are some of the natural causes that greatly influence the water elements and have significant impact on the integrated water management.

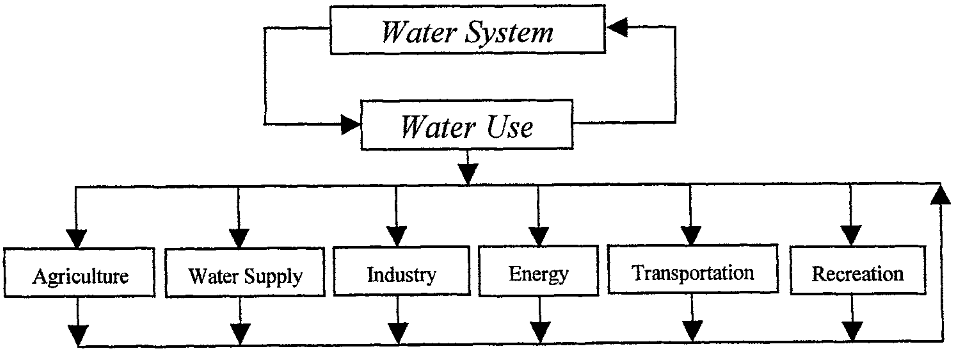

Fig. 1.5 Elements of a water system and their interactions.

Once a management policy is established, a strategy, including administrative infrastructure, has to be employed to undertake integrated water management as shown in

Fig. 1.6. The components of integrated water management are interactive, and hence the administrative set up must be flexible and responsive to changing goals. Thus, integrated water management requires integration of the various components discussed earlier--physical, biological, chemical, social, economic, ecological, health, and environmental. This can be accomplished through development and application of mathematical models. The physical, chemical, biological, environmental, and ecological components and their models must be embedded in the development of comprehensive watershed models.

The criteria, as shown in Fig. 1.6, that form the foundation of the management policy must be developed following such considerations as cost effectiveness, economic efficiency, environmental impact, ecological and health considerations, socio-cultural aspects, to name but a few. The criteria must be practical, implementable, and must be acceptable to the society at large. Furthermore, they must be capable of responding to changing needs of the society. The resulting policy must satisfy such interactive social goals as equity, efficiency, environmental quality, etc.

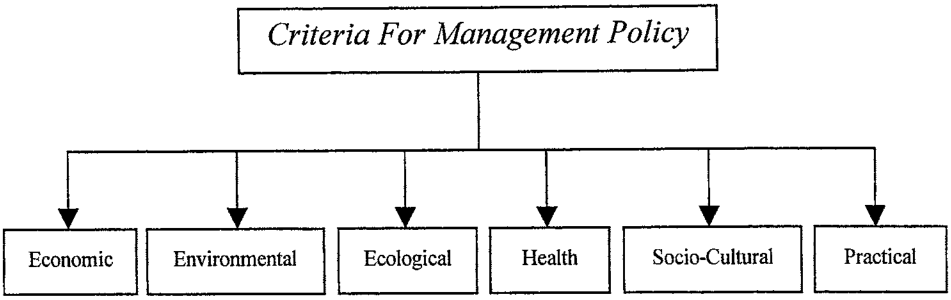

Fig. 1.6 Criteria for foundation of a management policy.

A model for integrated water management helps develop implementable solutions to water resources problems by combining into an optimization scheme all the essential component models. The model incorporates or accumulates all of the interactive forces or influences. Hence, it aids the decision-making process and keeps the policy results within the intersection of the social goals of the management policy and the legal constraints. Such a model is shown in Fig. 1.7.

The United Nations Water Conference in Mar del Plata in 1977, the International Conference on Water and the Environment in Dublin, and the Earth Summit in Rio de Janeiro in 1992 have articulated a set of principles for good water resources management. These are referred to as the *Dublin Principles* and are:

1. The "ecological principle" which requires that water be treated as a unitary resource within river basins, with particular attention to ecosystems.
2. The "institutional principle", which recognizes that water management requires the involvement of government, civil society and the private sector, and that the principle of subsidiarity be respected. It also gives special emphasis to the role of women in

water management.

3. The "instrument principle", which requires that water be recognized as a scarce economic good, and that greater use be made of "user pays", "polluter pays" and other market-friendly instruments.

For any water resources utilization to be effective and efficient, it is necessary that all the resources of a basin are managed in an integrated manner. By definition, the basin-level systemic management is essential for the integrated water resources management (IWRM) principle to succeed. In other words, it is essential to take a holistic approach to IWRM. The decisions on IWRM must be participatory, technically and scientifically informed, and taken at the lowest appropriate level, but within a framework at the catchment, basin and aquifer level which are the units by which nature bestows water.

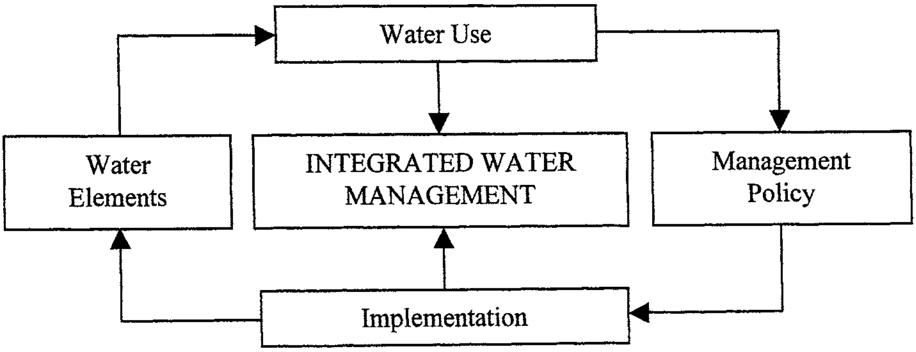

Fig. 1.7 Integrated water management.

Holistic river basin management is best practiced by agencies that operate at the basin level. There is a clear hierarchy in spatial domain: basin, sub-basin, etc. and many smaller units are nested within the larger one. The functions of the basin agencies must also reflect that hierarchy, with decision-making pushed down to the lowest appropriate level. It is equally imperative that decision making must be informed and scientifically and technically sound. Effective river basin management, thus, walks on two legs: (i) institutions where users make policies and decide on the raising and spending of money, and (ii) competent technical agencies which provide the institutions and users with the information necessary for management.

The technology can, must, and will change to adapt to the needs of the more water conscious world. The new technologies must be less wasteful, and more sensitive to the environmental and social dimensions of decisions. It is good to draw on traditional wisdom to the extent possible while harnessing the revolutionary changes which are taking place in the electronics and computer fields. But technology alone cannot bring about the more desirable future. It will require behavioral change at all levels of society everywhere. Moreover, technological change is not exogenous, it comes only if the society provides stimulation and incentives for innovation.

Despite much technological advancement, a lot remains to be achieved in the area of water resources development. Consider hydropower development which is an environmental friendly means to generate hydropower. In fact in French language, the term for hydropower is 'La Houille Blanche' which means the white coal. Although many areas of the world face shortages of electric power, worldwide only about 20% of the hydropower potential has been developed by 2000 as against 15% by 1990 (Veltrop, 1992). The technically feasible hydropower potential of the world has been estimated at 12900 TWhr/year and the economically feasible potential is about 7200 TWhr/year. Table 1.5 shows continent-wise percentage of hydropower potential developed.

The electricity supplied by hydropower far exceeds the capacity of any other renewable energy resource. Norway meets virtually entire (99.6%) electricity demand by hydropower. Twenty-five countries world-wide depend on hydropower for more than 90% of their electricity needs. Although there is dominance of fossil fuels for electricity generation, worldwide more than 60 countries currently use hydropower for half or more of their electricity needs. Most of the installed hydroelectric capacity resides in North America, Brazil, Russia, China, and Europe.

Major improvements can and have been made in the way in which water is managed. Participatory river basin management has become a reality in some countries. Due to various measures, per capita quantity of water used has actually declined in a few cases over the past decade. While serious water problems persist in rich countries, the situation is far more challenging in developing countries. On almost all counts – service coverage, reliability of meeting demands, and water quality – poor countries have much worse conditions, and they have rapid growth in demand for municipal uses, for agriculture, for industry and for the generation of electricity. Still worse, these countries have only a fraction of the financial resources available compared to industrialized countries.

Table 1.5 Continent-wise percentage of hydropower potential that has been developed [Source: Internet].

| Continent | Percentage of hydropower potential that has been developed | Percentage of electricity generated by hydropower |
|---|---|---|
| Africa | 7 | 2 |
| Asia | 20 | 39 |
| Australia | 40 | 2 |
| Europe | 65 | 13 |
| N. America | 61 | 26 |
| S. America | 19 | 18 |

Timely availability of reliable information is crucial in all management activities including those for water. The emerging information technology is helping to setup global, regional, and local databases. For example, AQUASTAT (http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat/main) is a global information system of water and agriculture, established by the Food and Agriculture

Organization of the UN. The objective of AQUASTAT is to provide users with comprehensive information on the state of agricultural water management across the world, with emphasis on developing countries and countries in transition.

The technological changes alone are not enough, and it is futile to believe that just by changing institutional arrangements, the desired results can be achieved. The crux of the problem lies in creation and adoption of appropriate technologies, adequate infrastructure (including manpower), and flexible and goal-directed institutional arrangements.

The scientists from the Centre for Ecology & Hydrology (UK) and the World Water Council (http://www.worldwatercouncil.org) have developed an international *Water Poverty Index* (WPI) which grades 147 countries according to five different measures – resources, access, capacity, use and environmental impact – to show where the best and worst water situations exist. The WPI assigns a value of 20 points as the best score for each of its five categories. *Resources* measure the per capita volume of surface and groundwater resources that can be drawn upon by communities and countries while *access* measures a country's ability to access water for drinking, industry and agricultural use. Many countries have the economic capacity to provide safe water supplies and sanitation to their whole populations. *Capacity,* another WPI component, defines a country's level of ability to purchase, manage and lobby for improved water, education and health and *use* is a measure of how efficiently a country uses water for domestic, agricultural and industrial purposes. In the last factor, *environment,* which provides a measure of ecological sustainability, issues included are water quality, environmental strategies and regulation, and numbers of endangered species. A country that completely meets the criteria in all five categories would have a score of 100.

According to WPI, some of the world's richest nations fare poorly in water ranking while some developing countries score high rank. The highest-ranking country, Finland, has a WPI of 78 points. WPI demonstrates that it is not the amount of water available that determine poverty levels in a country, but the effectiveness of how those resources are used.

## 1.7 WATER RESOURCES SYSTEMS

Before initiating discussion on water resources systems, the basic concept of a system is briefly discussed.

### 1.7.1 Concept of a System

A large number of definitions of the term *system* are available. A system may be defined as *a set of objects which interact in a regular, interdependent manner*. Sinha (1991) defined a system as a collection of objects arranged in an ordered form, which is, in some sense, purpose or goal directed. According to Mays and Tung (1992), a system is characterised by: 1) A system boundary which is a rule that determines whether an element is to be considered as part of the system or of the environment, 2) statement of input and output interactions with the environment, and 3) statements of interrelationships between the system elements, inputs and outputs, called feedback.

In the context of water resources, Dooge (1973) defined a system "as any structure, device, scheme, or procedure, real or abstract, that inter-relates in a given time reference, an input, cause or stimulus, of matter, energy, or information, and an output, effect, or response, of information, energy or matter".

*Systems analysis*, as applied to water resources, is *a rational approach for arriving at the management decisions for a particular system, based on the systematic and efficient organisation and analysis of relevant information.* The use of systems techniques requires digital computers and therefore, applications of systems analysis to water resources problems started only with the computer age in early 1960s. Votruba et al. (1988) defined systems approach as a comprehensive method of investigation of phenomena and processes, including their internal and external relationships. When scarce resources must be used effectively, systems analysis techniques stand particularly promising.

There are many ways to classify systems. A physical system is the one that exists in the real world. A sequential system is a physical system which consists of input, output and some working medium (matter, energy, or information) known as throughput passing through the system. Sinha (1991) classified systems as: a) static and dynamic systems, b) linear and non-linear systems, c) time-varying and time-invariant systems, d) deterministic and stochastic systems, e) continuous-time and discrete-time systems, and f) lumped parameter and distributed parameter systems. The output of a static system depends only on the current inputs while output of a dynamic system depends on the current and previous inputs. As explained by Mays (1997), the kernel of a time-invariant system does not change with time whereas it changes with time in a time-variant system. The kernel and inputs of a deterministic system are known exactly while these for a stochastic system are not known exactly. For a stochastic system, either the parameters in the kernel or the inputs are not known exactly and are described by statistical concepts. In a continuous time system, the time varies continuously while the inputs, outputs, and parameter values in the kernel are known at discrete time only.

Water resources systems are generally distributed with respect to time and space. For the purpose of solution, these systems may be divided into sub-systems and each sub-system may be treated as lumped. The hydrologic system is, therefore, a physical, sequential, dynamic system. For a catchment system, the input consists of water and energy in various forms. The input-output relationship of the system may be represented mathematically (Singh, 1988) by:

$$y(t) = \Phi[x(t)] \tag{1.1}$$

where $x(t)$ and $y(t)$ are, respectively, time functions of input and output, and $\Phi[]$ is the transfer function which represents the operation performed by the system on the input to transform it into an output. The well-known unit hydrograph is an example of a transfer function of the catchment system.

The concept of state is basic to the systems theory. The state represents the conditions of the system or is an indicator of the activity in the system at a given time. In water resources systems, the state typically may be the volume of water in the reservoir, the depth of flow of the river, or the head of ground water at a location.

If the behavior of the system can be altered by modification of the working of the system, the steps taken are known as exerting control. The control applied to hydrologic systems may be either natural or artificial. For example, in a catchment system, the climatic trend and cycles are the nature-applied controls that may alter the characteristics of the catchment. The man-made dams and reservoirs on river basins represent artificial controls.

Systems engineering is concerned with making decisions with respect to those aspects of a system on which some control can be applied. Water resources systems engineering can make most significant contribution to the process of decision making. Systems engineering was defined by Hall and Dracup (1970) as "*the art and science of selecting from a large number of feasible alternatives, involving substantial engineering content, that particular set of actions which will accomplish the overall objectives of the decision makers, within the constraint of law, morality, economic resources, political and social pressures and laws governing the physical life and other natural sciences.*" Thus systems engineering is useful in making selections from a large number of alternatives by way of elimination. The necessity for elimination may be readily noted by a very simple example. Suppose there are twenty farming areas and water is to be allocated to each of them. Let there be 100 alternative ways one could allocate water to any one area, each being different (say, in terms of quantity) and theoretically requiring an "evaluation" to see which might be the "best". For twenty areas, there would be $(100)^{20}$ different combinations. Suppose neither judgment nor systems analysis is used to find the "best" of these different combinations of allocations to the twenty areas. Let a high speed computer is employed and is capable of completely evaluating one alternative in 0.001 seconds, compare the "worth" of that alternative to any other and keep the best of the two. After one "earth age" (estimated by geologists as $3 \times 10^9$ years) it would be able to check out $9.45 \times 10^{19}$ of the possibilities, which is only an infinitesimal fraction of $100^{20}$.

Obviously, even simple problems involving just a few different values of the decisions cannot possibly be evaluated directly. In the problem cited, one could have used a bit of logic based on the knowledge of the twenty farming areas and the effects of different levels of water supply and picked a pretty good solution on the basis of judgment alone. However, even for simple problems, after applying judgment, there may still be a lot more potentially valuable alternatives that cannot be evaluated directly with the available time and money. It is for these situations that the science of systems engineering is best suited.

The theories and methods used in systems engineering are termed as systems analysis. Applied systems analysis is a general term including fields like operations research, decision-theory, benefit-cost analysis, planning and scheduling, design, theory of information, application of artificial intelligence in management, and decision-making. As noted by Votruba et al. (1988), in view of the importance of systems analysis, a famous institute, namely IIASA (International Institute for Applied Systems Analysis, Laxenburg, Austria, website: www.iiasa.ac.at), has been specifically set up for this purpose. The range of the fields and problems contained in applied systems analysis is apparent from the research program of this institute, which includes:

- Resources and environment: ecological problems, problems of water resources research, problems of food and agriculture, etc.
- Human settlement and services: problems of population, health, education, communication, etc.
- Management and technology: man-made artifacts, institutes, economic systems, technologies, etc.
- Systems and decision sciences: mathematical and computational problems in the analysis of large systems, etc.

### 1.7.2 Systems Analysis Techniques

The systems techniques can be grouped under four major categories as follows:

*a. Analytical optimization models and techniques:* This group includes optimization methods – they may be based on classical calculus and Lagrangian multipliers or mathematical programming and control theory. These modelling techniques are descriptive, i.e., they usually incorporate quantitative relationships between variables of the system. These are also prescriptive in the sense that the algorithm provides the optimal solution. The mathematical programming techniques include linear, non-linear, and dynamic programming, goal programming, and multi-objective optimization.

*b. Probabilistic Models and Techniques:* This group of techniques includes the techniques for analyzing stochastic system elements with appropriate statistical parameters. It encompasses all the descriptive techniques of stochastic processes to study the behaviour of some aspects of the system. The important techniques in this group are the queuing and inventory theory which are concerned with the study of queues or waiting times and inventory stocks. Such studies are associated with decisions regarding service and storage capacities. Often queuing models are combined with other optimization methods and utilize either analytical techniques or simulation and search approaches. Many reservoir problems are some type of inventory problems and have been solved using approaches that combine various techniques.

*c. Statistical Techniques:* This class of techniques includes multivariate analysis and statistical inference. The techniques of multivariate analysis, including regression and correlation, factor analysis, principal component analysis, and discriminant analysis, have numerous applications in the water resources area.

*d. Simulation and Search techniques:* Simulation is a descriptive technique. A simulation model incorporates the quantifiable relationships among variables and describes the outcome of operating a system under a given set of inputs and operating conditions. Most simulation models do not contain algorithms for seeking optimal solutions. However, such models usually permit far less drastic simplification and approximation than is required when using an analytic optimization model. Often a simulation model is run many times with various input and parameter data. The output of these runs describes the response of the systems to variations in inputs and parameters. If the simulation model includes an objective function, the values of the objective for several runs generate a response surface. The model then can be combined with sampling or search techniques that explore the response surface and seek near-optimal solutions.

Systems analysis techniques do not merely deal with the engineering aspects of water resources development but also cover a multi-disciplinary approach encompassing physical, social, economic, political, biological, and other characteristics of specific problems and situations. This powerful technique enables the planners, designers and water managers to evaluate alternative development scenarios and to place before the decision makers, the effects and advantages of various alternative feasible options. Mathematical analysis of water resources problems using systems approach is one of the most important developments in the water sector.

### 1.7.3 Characteristics of Water Resources Systems

Water resources systems can be defined as a set of water resources elements linked by interrelationships into a purposeful whole. As an example, a water supply reservoir for a small city, linked with a water distribution network, would constitute a system. In many respects, water resources systems defy rational description. To an engineer, these systems may be dams and weirs, tunnels, levees, pipelines, electrical power plants, water treatment and reclamation, spillways and similar physical works which have been constructed to provide certain benefits. An economist views them from the point of view of economic efficiency, income redistribution and stimulation of economic growth. To a lawyer, a water resources system is a device for the implementation of water rights. To those living in an arid environment, water resources systems mean food and fibre, homes and jobs, laws and politics. To many conservationists, water resources systems are unwanted interventions, responsible for the destruction of wild rivers, scenic beauty and wildlife habitat. Water resources systems indeed include all these points of view which could be physical, technological, sociological, biological, legal, geological and agricultural. The famous water resources expert, the late Prof. V.T. Chow, coined the term ‘hydrosystems’ to describe collectively the technical areas of hydrology, hydraulics, and water resources (Mays 1997). This term has also been used to refer to systems for ground water management, reservoirs, and water distribution systems, etc.

The elements of a water resources system can be either natural (rivers, lakes, glaciers, etc.) or artificial (reservoirs, barrages, weirs, canals, hydroelectric power plants, etc.). The relationships between the elements are either real (e.g., water diversion) or conceptual (e.g., organization, information, etc.). Most of the components of these systems are artificial and are constructed to attain a certain goal. Each element of a system may also be considered as a subsystem if it has the qualifications of a system. Whether a particular object or concept is to be treated as a subsystem depends mainly on the objective of the study. The decomposition of a system is to be done carefully. According to Hall and Dracup (1970), since certain interactions internal to the entire system will become inputs and outputs between subsystems, there is considerable logic in setting subsystem boundaries so as to minimise their number. All subsystem inputs become decision variables in the subsystem optimization, hence they may control the computational feasibility of the analysis. In general, the decomposition should permit a functional analysis so that subsystems can be replaced in the complete system analysis by an optimal input-output relationship. Besides, the decomposition model and the methods of analysis selected should permit a maximum of analysis of the consequences of imposing factors existing in the real system which were excluded from the analysis. This will help the decision maker in appreciating the problem in a rational manner.

## 1.8 ISSUES IN SYSTEMS APPROACH

Despite significant theoretical developments and availability of infrastructure facilities, the systems techniques are not routinely applied to planning and design of water resources projects. Rogers and Fiering (1986) carried out an extensive study in which they examined more than 2500 research papers of selected reputed journals dealing with water resources. It was reported that only 38 of 723 systems oriented paper dealt with identifiable water resources projects, only three of the 38 projects studied were built and only one of these was designed according to the optimization model presented in the paper. Although considerable time has elapsed since this study, the situation may be only marginally different now. This analysis also points towards a wide gap between theory and practice in planning and design. The situation in respect of applications for management is somewhat better. Then there are differences between developed and developing countries -- there is a resistance to the use of systems analysis by many government agencies in developing countries. The resistance is not always based on blind prejudices, it may be based on some genuine and reasonable doubts. According to Rogers (1980), the following five questions need to be satisfactorily answered to convince those who are opposed to systems analysis.

*Appropriateness:* Most of the applications of systems techniques have been made in developed countries. Decision-makers in developing countries are quite rightly suspicious of the direct transference of such methods into situations in which the distribution of resources, structure of society, and the governing institutions are so different. This question is best answered by successful case studies of developing country applications.

*Reliability of database:* In most developing countries, the data on economic, social and natural resources are usually very poor in the conventional sense of time series, spatial coverage and accuracy. Most systems analysis applications are very data intensive and very sensitive to the quality of data. In such situations, responsible administrators have every reason to be suspicious of the use of systems analysis. This question is best answered by showing how systems analysis can improve decision making even using the shakiest data and how it can also be used to evaluate the existing data and structure additional data acquisition. It can be argued that with a less reliable database the benefits from using systems analysis will be much greater than conventional analysis.

*Model credibility:* Obviously if no models have been attempted, how can one assess their credibility. Again, the answer is to rely upon case studies of other applications which are deemed credible by their sponsors. Note that there are many levels of application and many different user groups for systems analysis models. Some may find them credible while others may or may not.

*Manpower and equipment requirements:* In most developing countries, there is a shortage of skilled manpower and this is an important hindrance to the use of systems analysis in these countries. A long-term solution is to develop indigenous expertise by introducing relevant courses in academic institutions or through foreign training. The analysis could be tailored to the available resources and reliable personnel hired whenever the need arises.

*Time and money aspects:* The systems analysis studies cost more than the conventional techniques and require more time. But it should be borne in mind that the magnitude of benefits from water resources projects is very large. An improvement by a few percentages will translate into big amounts in real terms and costs will be much smaller than the benefits accruing due to improved planning and management.

The key to convince reluctant administrators to try to use systems analysis is to provide examples drawn from applications in similar situations.

### 1.8.1 Potential of Systems Analysis Approach

The systems analysis approach is promising and useful for problems dealing with management of scarce resources. Water resources are getting scarce worldwide in view of ever increasing demands. Every year, some new regions which earlier had surplus water, are entering the domain of water scarce or water stress areas. In such a scenario, applications of systems analysis should show a rapid increase. However, such a growth is not seen and there appears to be a resistance to the use of systems analysis by many government agencies. In developed as well as developing countries, the major responsibility for planning, development and management of water resources projects lies with government agencies. With the developments in information technology and the availability of high capability computers at much cheaper rates, there is undoubtedly an increasing use of computers in the analysis. However, just the use of computers will not make the development and management better. The inputs, the analysis techniques, and the implementation, all have to improve simultaneously so that extra benefits can be realized.

In many instances, the location and size of the projects is decided from political rather than technical considerations and as a result, there is not much scope for optimizing the decision variables. Another pertinent reason is that most of the good project sites have already been developed and now it is more a problem of developing the best among the less suitable sites. Furthermore, a large number of agencies are usually involved in the water sector and there is not much parallel communication and coordination among them. Due to this difficulty, the application of improved and relevant techniques is hampered.

An application of systems techniques requires a huge and reliable base of hydrologic as well as economic, demographic and social data which are usually not available in many countries. In the absence of such a database, values are assumed, based on experience and sometimes parameters of a completely unrelated distant region are used just because they are readily available.

In many situations there is a shortage of manpower with required skills in the concerned government agency and this limits the possibility of the use of refined techniques. Usually people with required skills are available only in academic and research institutes but the necessary coordination between these institutes and field organizations may be lacking. A large number of pilot projects have been undertaken in many countries wherein advanced techniques were applied to specific projects. However, it is common to see that after the project is over, the trained manpower is gradually transferred, the consultants withdraw from the scene and the infrastructure tends to wither away with time. Usually within a few years, things return to the pre-project stage. To overcome these problems, it would be necessary to create teams of dedicated and skilled workers, adequately motivated and compensated, within the concerned organization and there should be a commitment at the senior level for sustained support to maintain the created infrastructure.

Increasing withdrawals from the water bodies would impose intolerable stresses on the environment, leading not only to the loss of biodiversity but to a vicious circle in which the stressed ecosystems could no longer provide the services for plants and people. Unfortunately, precise figures for only limited regions are available to indicate freshwater availability and its quality. Systematically obtaining and updating such information is necessary for sound water management decisions in the future.

### 1.8.2 Economics in Systems Engineering

Among the major justifications of water resources projects is the role that they play as a catalyst for economic development. A geographic area may have all other necessary resources (e.g., soil, people, climate, location, etc.) for a high level of economic productivity but it is the availability of water that stimulates rapid growth. Therefore, in the water resources systems studies, the economic aspects play an important role. Economic analysis provides a criterion for ranking different water development and management policies. In any scheme of water resources development, it is necessary to prepare a number of technically feasible alternatives for meeting particular objectives and assess the related costs and benefits, both tangible and intangible, for each alternative.

Each technically feasible alternative has gross benefits and costs in a given time which are discounted to determine their net present worth. The difference between benefits and costs reflects the project's contribution to regional/national income. A multi-objective planning further expands the scope of analysis and involves broader social goals that water resources development might help to attain, like a larger national income, a more equitable distribution of income among people, and region and environmental protection. The importance of socio-economic factors in the execution of water resources development plans make it essential to undertake a socio-economic bench mark survey which provides useful inputs for development plans. The findings can also form a benchmark against which the future improvements in the economic welfare of the population resulting from the project can be assessed.

The definition of gains and costs from water projects must include a broad spectrum of effects on social goals rather than be limited to the readily quantifiable profits and expenses. There are many intangible factors which cannot be expressed quantitatively but influence the functioning of the hydro-economic system. Economic impacts are not necessarily uniform; the gains may accrue to some who may not necessarily be the direct users, while the costs may fall on them as well on others. These inequities in costs and benefits are somewhat corrected by subsidies, and taxes.

An important aspect of water management is the adoption of cost for water services. It is well-known that free water leads to wastage and consumption drops when water is metered. For example, in many irrigation systems where water is highly subsidized or free, only about 30% of the water supplied is actually used by plants. Where services are free, the result is inevitably politicization of the concerned agencies, inefficiency, and lack of accountability. Ultimately, subsidies are usually grabbed by influential groups while the poor end up paying high prices for inferior and unreliable services. Usually they also bear the brunt of environmental degradation.

Governments in many developing countries are not in a position to meet the investment demands for water services. The main alternative is to attract private investment for municipal water supply and sanitation, irrigation, and hydropower. But the private sector will not enter into this venture unless they are sure of a reasonable return on their investments and there are no political risks. Naturally, this return has to come from those who benefit from the services provided. Thus, without full cost pricing, the present vicious cycle of wastage, inefficiency, and lack of reasonable services will continue. There will be little investment from the private sector, services will be of poor quality and rationed, there will be little left for investing in water quality and other environmental improvement. This vicious circle needs to be converted to a "virtuous cycle" in which users pay for the services they want and urban utilities provide these services efficiently and accountably. While doing this, government should provide safety nets for poor people. They must also ensure that subsidies be provided to people, not to service providers.

## 1.9 ADVANTAGES AND LIMITATIONS OF SYSTEMS APPROACH

The systems approach for the analysis of water resources systems takes a broad and flexible view. It is a very powerful tool, capable of dealing with large-scale problems. Selection of an optimal plan is achieved through a systematic search and evaluation of various alternatives which meet the objectives. It is flexible in suggesting modifications of the course of action to correct and compensate for any undesirable consequence of plans and operating decisions.

Essentially systems analysis consists of five steps:

a) Define the problem.
b) Identify the system, define its elements, and gather relevant data.
c) Define the system objectives and constraints.
d) Generate feasible alternatives that satisfy physical, social, political, economic and legal constraints on the system and its management.
e) Evaluate the alternatives for attaining system objectives and identify the most suitable among them.

As indicated in the previous section, usually the magnitude of benefits and costs of water resources projects is quite large. Therefore, a saving of cost or increase in benefit even by a few percentage points translates into a big sum of money and, therefore, is worth the effort.

The systems approach has many advantages over the conventional approach in water resources planning and development. The approach focuses on the selection of definite goals and objectives and on a systematic search for alternatives. It provides the systems planner with a modern technology to analyse the system scientifically and objectively. It forces the user to identify the known and not readily-known elements of the system. The approach regularly provides feedback information from each step in the analysis and thus provides flexibility for feedback correction and modification of the system. This feedback can also be used for adoption of new system definition, system elements and system objectives.

The high complexity of the present-day problems is an important reason to apply systems techniques. In single-purpose projects, the analysis is simple and the decision to build or not to build a project can be more easily evaluated on the basis of comparing the least-cost engineering design. But with today's increased concern for economic efficiency and environmental issues, it is now no longer a simple task to assess the allocation of water among competing demands, assess the benefits, select the best design from many alternatives and optimally operate the system. This forces the planner, the designer and the manager to take a wider view of the water resource system. The best in the spectrum of tools for this is the systems analysis. The following characteristics clearly bring out the demand for this approach:

1) Water resources projects typically involve large-scale, more or less permanent, physical changes in the environment, large lakes are created, irrigation water is provided, and flood plains protected. The impact on regional economy and society are immense.
2) The expertise of many traditional disciplines is simultaneously utilised (engineering, economic, agronomy, legal, social, and so on).
3) The size and capital-intensive characteristics of investments in water projects, especially in the face of budgetary constraints, and the fact that they have a major effect on the economy of the region, necessitates the desirability of achieving even small improvements over traditional solutions.
4) The overall project output achieved with the approach of systems analysis is likely to be better than that achieved by an experienced staff using conventional techniques.

A word of caution here. Systems analysis is not a suitable tool in the hands of those who lack full understanding of the water resources systems and the multiplicity of objectives. Most of the decisions related to water resources projects are quite irreversible in nature. It is equally dangerous when utilized by those who lack a reasonable appreciation of both the power and the limitations of the methods of systems analysis. A water resources systems analyst who does not recognize and integrate many quantitative and non-quantitative dimensions of the system (physical, social, economic, political, geological, etc.), to the greatest extent possible will only produce an academic exercise at best. A more likely result will be a serious mismanagement of a vital resource.

The systems approach presents some difficulties in its practical use for water resources planning and development. Most theoretical works on systems analysis are being done in universities and research agencies which may not be concerned immediately with practical problems. The mathematics and statistics involved in the systems approach are more advanced now. Due to this, there is a big gap between the theory and the practice. In this scenario, the transfer of technological advances to practical use is an important task. It is most urgent and important to fill in or narrow this gap so that new developments can be soon introduced into practical applications. This requires a group of people with both theoretical background and practical experience who are willing to organise technology transfer courses.

Another important concern is mathematical computations. Most water resources systems are complex and computations are lengthy. Fortunately, the computer hardware needed for such problems are now widely available, although software are quite expensive and may not be readily available. The availability of adequate data is another problem in the systems approach. When a complex system model is formulated, its utility is severely diminished if the requisite input data are not available.

Yet another difficult problem in analysing the entire water resources system is dealing with intangibles. Water resources problems are not so simple that they can be expressed entirely in mathematical terms. Whereas the mathematical systems analysis is helpful in dealing with tangible factors, the overall planning and management of water resources involves intangibles and one has to depend on the judgment and experience to evaluate the intangible effects. With increased dependence on computer for decision-making, the human element should not be eliminated. Fiering (1976) has succinctly warned against the overkill: "we seek optimal plans, optimal operating policies, optimal estimates of parameters, optimal anything... It has become a new religion". The need is to have the model *serve* the decision maker rather than *the model* driving the underlying and important decisions.

## 1.10 CHALLENGES IN WATER SECTOR

The new century poses new challenges in water management. Whether a water emergency turns into a disaster depends on whether the community can take effective measures without external assistance. The long-term impacts of water disasters are usually due to the lack of prompt restoration of services and interventions. The effects of climate change and phenomena, such as the El Niño Southern Oscillation (ENSO), also require urgent attention. The recent ENSO during 1997-8 was particularly severe in causing natural disasters that, according to estimates, affected about 160 million people. The slow time scale of droughts means that its onset may not be identified until it has persisted for considerable time.

Various organizations have prepared blue prints for water resources development, such as the World Water Vision by World Water Commission (2000). The ministerial conference of the second world water forum which took place in the Netherlands during March, 2000, identified seven challenges to water security in the 21st century. The web site of the *World Water Forum* (www.worldwaterforum.org) provides much useful information on this and related issues. These challenges are enumerated here.

## Meeting Basic Needs

Water is a basic human need, vital for life and health, but many of the world's poorest people cannot meet this need. Around 1.2 billion people (20%) do not have access to adequate and safe drinking water, while around half of the world's population does not have adequate sanitation. Each year between 3 and 4 million people, including more than 2 million children, die directly due to waterborne diseases. Poor sanitation also produces problems, such as worm infestations, that have a huge impact on nutrition. Bacterial infection is the main water quality problem: some areas of the world also have other water quality problems, such as fluoride, arsenic (West Bengal, India) or salinity.

Access to water is a basic human need and the issue of satisfying the basic water and sanitation needs has long been established. Despite this, the problem remains. Clearly the traditional supply-based approaches on their own are not enough to solve it and the appropriate and sustainable approach is to provide the poor with the means to solve the problem themselves. While 'appropriate' is place dependant, a number of elements need to be part of any program to address this most basic need: secure and sustainable supplies of good quality water, education and awareness, technological innovations, integrated service provision, and community involvement. The participation and mobilization of the community is essential while not forgetting that as the custodians of health and hygiene, women hold the key in any such effort.

## Protecting Ecosystems

Aquatic ecosystems in rivers and lakes, mangroves and other wetlands as well as water-dependent ecosystems are vital sources of many other resources, are repositories of bio-diversity and are crucial to the functioning of the hydrological cycle. In many parts of the world, these are declining in area and quality and if the current trends are not reversed, many of these will be unable to provide goods and services essential for societies to survive. Many rivers may turn into open sewers without any aquatic life forms and will transport pollutants and degrade coastal and marine ecosystems. The loss of species and habitats will dramatically reduce the world's biological diversity. The resulting declines in fish production will further jack up demands for protein from livestock production and agriculture.

The key to arrest detrimental development is to ensure that ecological processes and ecosystems integrity are central to all aspects of water resources planning and management. This can only be achieved through proper use of traditional conservation practices and sustainable management strategies. The most important measure to achieve this is to make conservation and rehabilitation of freshwater and related ecosystems a central tenet of water resources policies and integrated management. A balance between human needs and the intrinsic value of ecosystems needs to be established. Good governance, strong leadership, local empowerment and universal responsibility for sustainable water resources use are some of the pre-requisites. Also necessary is to create awareness, commitment, and exchange of knowledge on freshwater and related ecosystems.

### Securing the Food Supply

World food production depends on water availability. Agriculture is by far the largest user of water around the world, representing up to 90% of use in many developing countries. Foods from aquatic ecosystems, forests, etc. can be important in the diets of the poor, but the farm harvests are the backbone of food production around the world. Due to population growth and changes in consumption patterns, the demand for food grains is likely to increase by 30-40% in the next 25 years. Thus, there is an ever-increasing stress on agricultural systems.

Enhancing food security is a tough challenge. Meeting irrigation demands in a sustainable manner is possible only by way of greater water productivity through *more-crop-per-drop*. The agricultural use has a huge impact on the quantity and quality of water. Improved irrigation efficiencies and the advances in biotechnology will determine the future water security of the planet.

### Sharing Water Resources

River basins are the main source of freshwater. Due to various physical interactions within a river basin, it is the logical unit for water management. There are around 300 trans-boundary water resources and nearly half of the world population lives in shared river basins. There is a strong need for cooperative management of shared river basins. To achieve sustainable river basin management, riparian states should take into account the interests of other riparian states in the same basin.

The experience of co-operation in the Rhine basin, the North American Great Lakes, the Mekong, the Danube, etc. shows that countries can and do work together to address international water issues. The basin-wide planning requires formulation of clear objectives, technical co-operation (for data collection, monitoring, etc.), and participatory decision-making on shared river basins by the public and non-governmental stakeholders, contributing to strong river basin management. It would definitely improve decision making through greater information, and would help create a basis for implementation of policies and plans.

### Dealing with Hazards

Too much water puts people and property at risk; too little water affects life itself. Flooding, often linked to major storms, is among the worst of natural disasters. According to estimates, more than 66 million people have suffered from storm and flood damage worldwide during the past 25 years. Population growth is forcing more people in flood-prone areas and overexploitation of aquifers. A visit to any river bank near major cities in many developing countries will readily reveal the extent of the problem. The worst suffers are the uninsured poor, for whose benefit all the developments are planned ! Coming to droughts, there are more refugees due to water shortages than due to wars and the situation is likely to get worse.

Non-sustainable hydraulic interventions, land-use changes and excessive water use turn the variability of natural processes into hazards that affect whole regions, often with disastrous consequences. Floods and droughts are recurrent natural phenomena that cannot always be prevented, and cause large-scale suffering. Apparently, the damages due to floods and droughts are increasing over time. The climate changes are anticipated to increase the severity of major storms, floods, droughts and major shifts in climate patterns.

It is the responsibility of the government to provide security from floods, droughts and other natural hazards. A sustainable flood and drought management should be based on integrated approaches that combine structural tools (embankments, dams, deepen river course) and non-structural methods (forecasting and warning systems, contingency plans, etc.). Increasing flood damage must be prevented through town and country planning and by avoiding construction in high risk areas, especially floodplains. Unsustainable water use should be curbed, especially in water-scarce areas. Large human settlements should not be encouraged in such areas, agriculture should economize on water and new technologies, such as cheaper desalination techniques, should be explored.

### Valuing Water

Understanding and incorporating the full value of water into decision-making is an essential but as yet unrealized goal. Experience shows that wastage is less when people have to pay a price. Subsidies are widely given and, if transparent and targeted to disadvantaged groups, can be an effective tool. However, often they are 'across the board'. Cost recovery and pricing regimes are a problem and rarely give service providers (especially government agencies) a viable financial base. Effective water management is not possible unless the challenges of economic valuation and financial viability are overcome. For effective water resource management, the concerned agencies must have adequate resources for investment, efficient operation, and maintenance.

It is imperative to manage water in a way that reflects its economic, social, and cultural values, and to move towards pricing water services to cover the full cost of their provision. The approach should be based on the concept of equity and the basic needs of the poor. The challenge is in two linked areas: the valuation of water resources and charges for water services. Along with water conservation, demand management, the principle of 'polluter pays' needs to be practiced. These strategies will be effective only when stakeholders participate in defining charging regimes, charges are linked to the quality and reliability of services, and there is a mechanisms to protect the poor. However, this requires many political and social issues to be sorted out and in the era of coalition politics, has remote possibility in near future in India.

## Governing Water Wisely

The concept of river basin management (RBM) is widely accepted as a sound approach. But its application is not as wide because it requires a suitable institutional framework, supported by appropriate laws and policies. Good governance exists where government agencies responsible for water effectively allocate and manage water resources based on legitimate policies and laws are responsive to national social and economic needs and, in the long term, to the sustainability of the water resources in the country or region. To achieve good governance, it is necessary to create an enabling environment by encouraging and integrating private and public sector initiatives and to establish rules which allow clear transactions between stakeholders in a climate of trust. It is necessary to affix duties and responsibilities for management of rivers and aquifers because these affect large populations and yet no one appears to be responsible for them.

## Targets

The ministerial conference of World Water Forum has also set indicative targets for the above seven challenges. In general, all the problems are proposed to be brought to the manageable limits within the next 15 years. For example, the proportion of people not having sustainable access to adequate quantities of affordable and safe water be reduced by half by 2015, or comprehensive policies and strategies for integrated water resources management be implemented in all countries by 2015.

It emerges from the above discussion that the main actions that need to be taken to solve the problems in water sector are: a) Integrated management of water and associated resources of river basins, b) participation of the community in development, conservation, and management of resources, c) improved agricultural practices, d) an extensive and reliable database and mechanism of information dissemination, and e) proper valuation of water. Sustainable development is now a necessity and not just a fashionable term. The water resources are a national property and should be managed accordingly. While managing them, the underlying objective should be balanced national growth rather than regional disparities and conflicts.

## 1.11 AN EXAMPLE WATER RESOURCES SYSTEM – SABARMATI SYSTEM

The real-life problems for which systems approaches are useful typically consist of many dams, weirs, and canal network. A real-life existing system of dams and weirs is described in this section. The data of this system will be used, to the extent possible, to demonstrate the application of various techniques that will be discussed in subsequent chapters.

The Sabarmati River is one of the major west flowing rivers of India. It rises in the Aravalli range at north latitude 24°40' and east longitude 73°20' in the Rajasthan state at an elevation of 762 m and flowing through the Gujarat state, outfalls into the Gulf of Cambay. The drainage basin of the river extends over an area of 21,085 sq. km and lies between longitude 71° 55' E to 73° 49' E and latitude 22° 15' N to 24° 54' N. The length of the basin is about 300 km and it is about 105 km wide. The topography of the Sabarmati basin is hilly in the early reaches up to the Dharoi dam after which, the river flows mostly in plains. The major tributaries of Sabarmati are Wakal, Sei, Harnav, Hathmati and Watrak. An index map of this system is shown in Fig. 1.8.

Four distinct seasons are noticed in the basin. During the winter season (December to February), light rainfall occurs sometimes. The temperature during the summer season (March to mid June) goes above 40° C and this season may have a few thunder storms. The monsoon sets in by the end of June and continues till the end of September. About 95% of the annual average rainfall is received during monsoons. Heavy showers generally occur in association with the monsoon depression. The upper reaches of the basin receive an average annual rainfall of over 900 mm while the lower reaches receive about 650 mm; the average annual rainfall for the whole catchment is about 785 mm. A good network of hydrological and meteorological stations has been setup in the basin. At various locations wireless stations have been established to communicate the information about rainfall and discharge to a central control office where it is used to make decisions concerning regulation.

To tap the water potential in the basin and to safeguard the downstream locations from flooding, a number of projects have been constructed on the Sabarmati River and its tributaries. One storage reservoir and three pick-up weirs have been constructed across the Harnav River for providing irrigation facilities in the command area. Harnav dam has dual purpose of flood control and irrigation. The catchment area at the dam site is 116 sq. km and the live and dead storage capacities of the reservoir are 19.97 and 1.70 M $m^3$, respectively. The FRL and HFL of the reservoir are at level 332.00 m and 332.25 m, respectively. The Harnav River spills excess water directly in the Dharoi reservoir.

The Hathmati dam across the Hathmati River has the dual purpose of irrigation and flood control. The catchment area at the dam site is 595 sq. km and its live and dead storage capacities are 148.93 and 3.90 M $m^3$, respectively. The FRL and HFL of the reservoir are at level 180.74 m and 183.18 m, respectively. On the Guhai River, a storage dam has been constructed for irrigation and flood control at a distance of 39 km from the source of the river. The catchment area of the Guhai River at the dam site is 422 sq. km. The dam was completed in the year 1990. The live and dead storage capacities of the reservoir are 57.04 and 5.30 M $m^3$, respectively. The FRL and HFL of the reservoir are at level 173.00 m and 173.77 m, respectively. The river Guhai joins the Hathmati River between the Hathmati dam and the Hathmati weir. The purpose of Hathmati weir is to divert water for irrigation. The Hathmati River joins the Sabarmati River about 55 km downstream of the Dharoi dam.

The most important dam in the Sabarmati basin is the Dharoi dam, located at 103 km from the source of the river. The latitude and longitude of the dam are 24° 00' N and 72° 52' E, respectively. The dam was completed in the year 1976. The total catchment area at the dam site is 5540 sq. km and the live and dead storage capacities of the reservoir are 775.89 and 131.99 M $m^3$, respectively. The purposes of the reservoir are (i) to moderate the incoming floods so that the controlled discharge at Ahmedabad city does not exceed 14160 cumec up to the inflow rate of 21665 cumec. Thereafter, if the inflow rate increases, the restricted outflow should be allowed up to 16992 cumec, (ii) to meet water supply

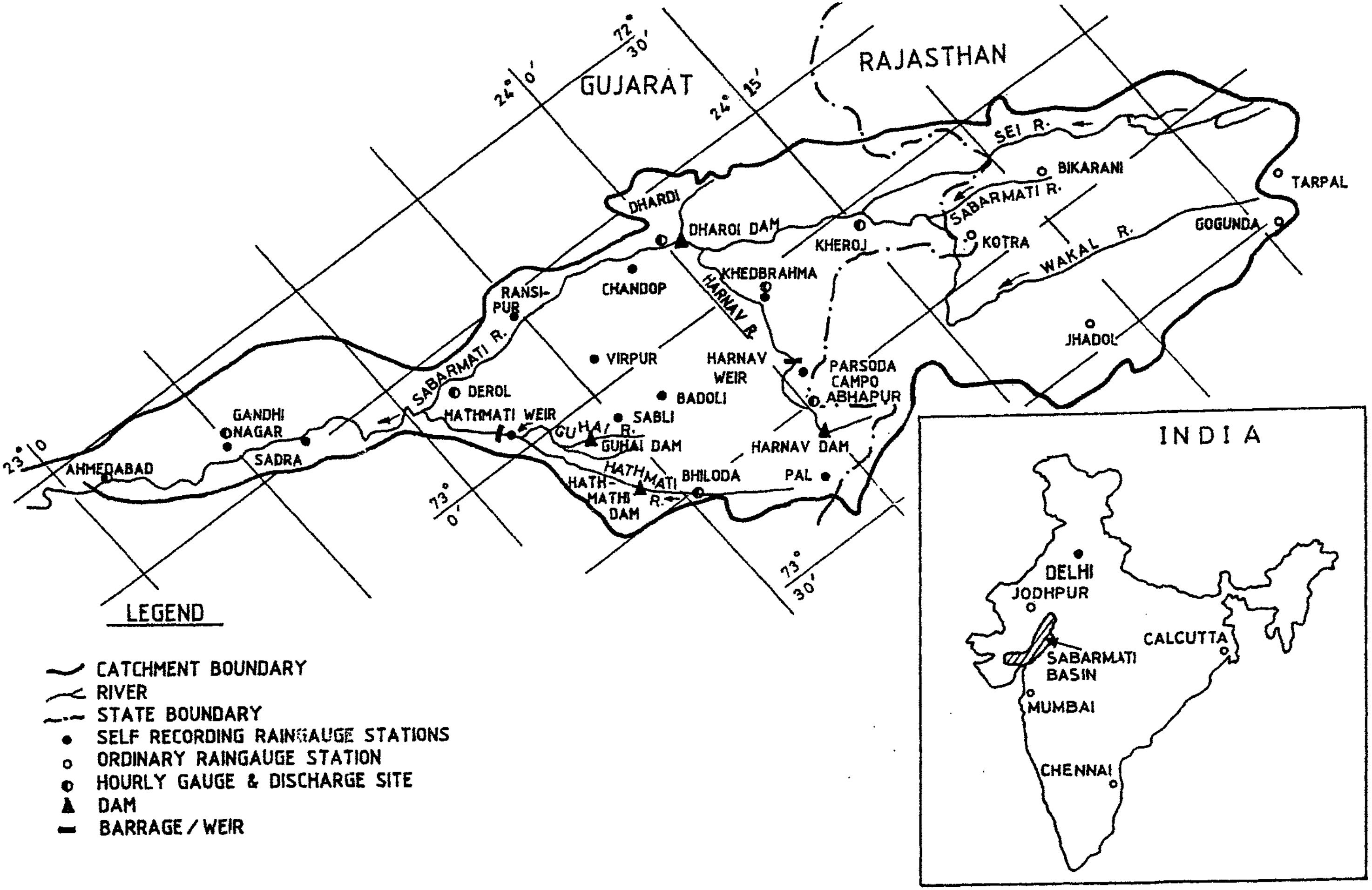

Fig. 1.8 Index map of Sabarmati System.

requirements for the cities of Ahmedabad and Gandhinagar, and (iii) to meet irrigation requirements in the command area.

The Wasna barrage is located across the Sabarmati River downstream of Ahmedabad city. The total catchment area at the barrage site is 10619 sq. km. The barrage holds water for drinking water supply to Ahmedabad city and feeds the Fatewadi canal system. Another purpose of the barrage is to augment the underground aquifers in the Ahmedabad region.

### 1.11.1 Regulation of Sabarmati System

For conservation purposes, the dams and weirs are to be operated such that the water supply demands are satisfied to the maximum extent and irrigation demands are met as much as possible. Since the facilities are interconnected, integrated operation of the system will be beneficial.

At times, the Sabarmati River sends down very heavy floods and some of these have caused devastation in Ahmedabad city, destroyed crops, changed the course of the delta channels and filled up harbor with silt. The highest known floods have occurred in 1875, 1941, 1950 and 1973. The peak of the design flood for the Dharoi reservoir is 27180 cumec while the volume of the design flood hydrograph is 3095.26 M $m^3$. The available storage space between FRL (189.59) and HFL (193.60) for flood moderation is 491.16 M $m^3$. The main cities that are located on the banks of the Sabarmati River are Gandhinagar and Ahmedabad. The safe channel capacity of the Sabarmati River at Ahmedabad is 14160 cumec. The Dharoi reservoir should be so operated that the total flow in the river at Ahmedabad, including the flow from the catchment downstream of Dharoi, does not exceed 14160 cumec. The inflow forecast for the Dharoi dam is issued based on observations at Kheroj gaging site upstream of the dam.

The catchment area of the Sabarmati basin up to Dharoi dam is 5540 sq. km and the same between Dharoi dam and the Ahmedabad city (intermediate catchment) is about 5079 sq. km. Although there are some small hydraulic structures in this intermediate catchment, their capacity for flood moderation is rather limited. The Hathmati dam is ungated and cannot effectively moderate any flood. In the Guhai dam, the capacity between FRL and the MWL is only 12.5 M $m^3$. Therefore, no effective moderation of flood can be achieved from these structures. Hence, the entire intermediate catchment from the downstream of the Dharoi dam up to the Ahmedabad city can be treated as uncontrolled. Most of this area is flat land in which agriculture is practiced except the headwater areas of the tributaries.

## 1.12 CLOSURE

With the rapid growth in population and rising expectations of better life, the limited water resources of river basins demand optimum utilisation through integrated and scientific planning and management. The competing and conflicting demands of water resources call for a comprehensive and total view for planning, development and operation of a water resources system. Systems analysis provides a rational approach for arriving at management decisions based on a systematic analysis of information. Application of systems analysis techniques to water resources problems can study various trade-offs and suggest the best, or near best, course of action among several feasible alternatives.

For detailed modeling of a water resources system that use large databases of varied disciplines, efficient computational devices are required. With the availability of computers in recent years, the application of systems techniques to various disciplines has increased rapidly. Integration of environmental aspects into water resources planning and management is also essential in the present circumstances.

Water is everybody's concern. While the past decisions in water sector were mainly based on techno-economic considerations, the influence of socio-political factors is gradually increasing. Water management involves every person on this planet from the simple act of how he or she personally uses water to the more direct involvement of how he or she sees others use water at home or on the job. Each has a role to play as a concerned citizen and member of a community. The design and operation of a water resources project requires more than technical knowledge – it involves human and societal skills and values. McCuen (1989) rightly comments that while the technical design can be standardized, it is rarely possible to standardize the value issue. He has summarized an elaborate discussion of the ethical conflicts in hydrologic practice by emphasizing that the hydrologist must consider the social impact of a design. A set of five core values has been proposed by Asmal (2002) as guidelines for future decision making. These are: Equity, Sustainability, Efficiency, Participatory decision making, and Accountability.

Water is going to be the issue of the next century as the ultimate resource and as a potential source of conflict. As noted by *the National Geographic* magazine (Oct. 2002 supplement) "A key issue dividing Israel and its Arab neighbors, for example, is control of the tributaries of the Jordan River and West Bank aquifers... Without oil, Middle East cannot live well; without water it cannot live." Recognizing the importance and necessity of sustainable water resources development, the UN has appropriately proclaimed year 2003 as the *International Year of Freshwater* (details are available at www.unesco.org/water/iyfw/). It is a challenge before water resources experts to provide scientific and socially acceptable solutions to water-related problems. President Kennedy of the U.S. was quoted by Grigg (1985) to have said: *Anybody who can solve the problems of water will be worthy of two Nobel Prizes: one for peace and one for science.* Hopefully, a water specialist will qualify for this distinction in the 21st century.

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