

includes the non-reservoir option as an important component, and the systems approach for design and management of reservoirs. Chapter 3 compares reservoirs with non-reservoir alternatives attempting to judge their advantages and disadvantages in an objective way. Typically, a reservoir serves multiple purposes in the presence of conflicting objectives, so that when comparing alternatives, a number of single-purpose projects must be compared to a multi-purpose reservoir. Demand management is considered important wherever it is possible as an alternative to or a combinatorial part of reservoir options.

Chapter 4 presents the engineering and systems analytical techniques for efficient use of existing reservoirs. Section 4.1 discusses some basic principles of reservoir analysis, as well as basic requirements imposed by the sustainability paradigm. Section 4.2 illustrates the importance of the hydrological input for reservoir design and management. Section 4.3 illustrates four possible ways to address the requirements of sustainability in reservoir analysis: De Novo programming for reservoir development, reassessment of existing reservoirs, cost/benefit allocation for reservoir redevelopment and the Least Marginal Environmental Impact (LMEI) rule for reservoir sizing.

Chapter 5 presents case studies of existing reservoirs in Norway, Egypt, USA and Japan, the current status of reservoir management and the directions of the future managerial innovation. They are not necessarily examples of sustainable reservoirs that this report considers as model cases. Rather, it is admitted that there are no model cases. The case studies show how each reservoir is struggling with the changing needs of society which may serve as lessons in other situations.

Chapter 6 concludes this report with the authors' views on the current status of reservoirs and the directions in which to go in the form of a set of checklists to be used as a practical reference at respectively the planning, design, construction, operation and maintenance stages.

## **1.3 CURRENT STATUS OF RESERVOIRS**

In this section, the current status of reservoirs is reviewed in respect of numbers and sizes, land efficiency with respect to hydropower generation, sedimentation and the future needs of reservoirs.

### **1.3.1 Number, size and shape of reservoirs**

According to the World Dam Register (ICOLD, 1988), there were 36 235 large dams (defined as higher than 15 m) in the world in 1986 in a total of 133 countries (79 ICOLD member countries and 54 non-member countries). There were 427 dams in 1900 and about 29 900 dams were built between 1951 and

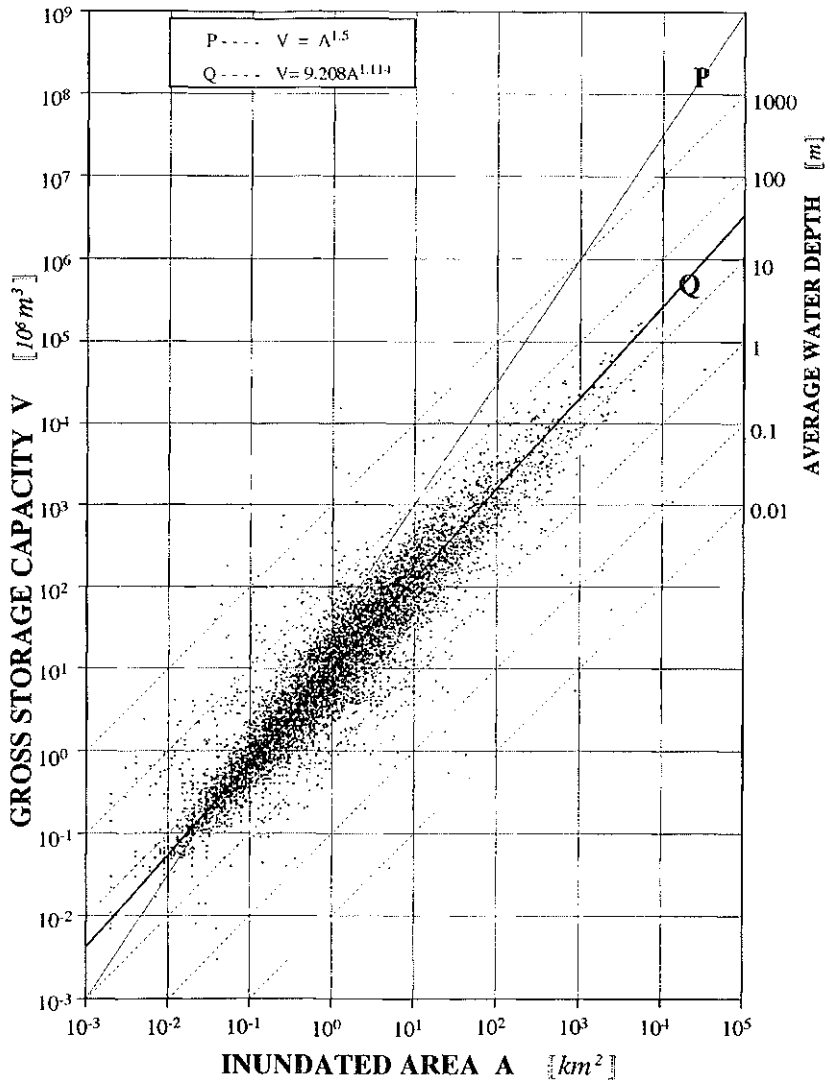


Fig. 1.1 Inundated area and gross storage capacity of reservoirs in the world (after Takeuchi, 1997).

1982. The rate of dam construction is decreasing in the long term, but in recent years it has not necessarily decreased. The average number of dams built during 1983–1986 was 267 annually. The total number of dams now must be approaching 39 000. The number of dams under construction in the world was about 1242 in 1994; 6.36% of which were dams higher than 100 m. For comparison, dams higher than 100 m constituted 1.1% of the 36 235 dams existing in 1986 (Veltrop, 1995).

Following the Russian tradition of global hydrology, Avakian (1990) estimated the total volume of reservoir capacities and the total inundated area in the world to be of the order of  $6000 \text{ km}^3$  and  $400\,000 \text{ km}^2$ , respectively.

The storage element corresponds to around 5% of the total precipitation on the land (119 000 km<sup>3</sup>) or 13% of the total runoff from the land (46 000 km<sup>3</sup>) (UNESCO, 1978) and the inundated area corresponds to the area of France. Thus quite a large part of the world's freshwater is stored in manmade reservoirs and the proportion is still increasing.

Figure 1.1 shows the relationship between the gross capacity ( $V$ ; 10<sup>6</sup> m<sup>3</sup>) and the inundated area ( $A$ ; km<sup>2</sup>) of 7936 reservoirs (7602 dams from *World Dam Register 1988* (ICOLD, 1988) and 334 dams from the *Yearbook of Dams 1990* (Japan Dam Association, 1990), selected from those that have both capacity and inundated area data). Although some data are not necessarily reliable as the average water depth becomes greater than 1000 m or less than 10 cm, it clearly demonstrates the general tendency of the  $V$ - $A$  relation of reservoirs in the world. The average relation is:

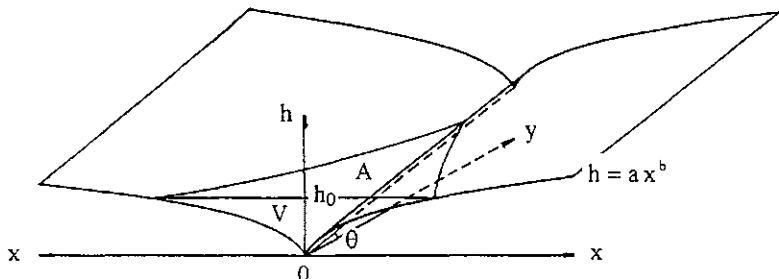
$$V = 9.2A^{1.1} \quad (1.1)$$

which was derived by the least squares method with respect to the distance normal to the regression line (instead of the distance in the vertical coordinate to the line). The coefficient of determination was  $R^2 = 0.869$  and the root mean square error or the standard error of estimate was  $SEE = 0.4137$ .

Although this line is a combined average of many reservoirs in many locations, a standard topography can be conceived where the land surface is covered by valleys of a common shape. Namely if the longitudinal gradient of the river is  $\theta$  and the valley is ideally prismatic with  $h = ax^b$ , where  $x$  is the horizontal distance normal from a river and  $h$  is the elevation of the land surface above the riverbed. In such an open book shape, shown in Fig. 1.2, the  $A$ - $V$  relation of reservoirs (1.1) implies:

$$A \propto h_0^{8.8} \quad \text{and} \quad V \propto h_0^{9.8} \quad (1.2)$$

where  $h_0$  is the dam height (Takeuchi, 1997). A high power in (1.2) means that progressively more land is inundated when reservoirs become larger. Thus there is little scale merit in constructing large reservoirs as far as the environmental effects due to inundated area are concerned. It may be fair to say that from the ecological point of view there is a scale demerit in large



**Fig. 1.2** A hypothetical valley with cross-section  $h = ax^b$  and gradient  $q$  (after Takeuchi, 1998).

reservoir construction. Takeuchi (1997) demonstrated regional differences of land efficiency in reservoir size. He noted that in many large reservoirs in continental countries like the former USSR, Brazil, Thailand and Mexico, more land was inundated than the global average indicated by (1.1) corresponding to the same storage.

### 1.3.2 Land efficiency discussion of large reservoirs

Table 1.1 shows some of the largest reservoirs of the world. It is quite striking that the Akosombo Dam on the Volta Lake alone stores  $150 \text{ km}^3$  of freshwater inundating an area of  $8500 \text{ km}^2$ . It is also noticeable that most large reservoirs are primarily for hydropower generation. The High Aswan and the Cabora Bassa dams are primarily for irrigation and secondly for hydropower generation but would not be so large if hydropower were not included. This is true in most of the gigantic reservoirs. They tend to become gigantic to obtain enough head, to produce economically justifiable energy. A typical example is the Srinagarind Reservoir of the Mae Klong River, Thailand, which has a total capacity of  $17\,745 \cdot 10^6 \text{ m}^3$  but an effective storage of  $7481 \cdot 10^6 \text{ m}^3$ . The percentage of dead storage is as much as 58%.

There are many criticisms of large reservoirs not only from the social and ecological but also from the economic point of view. In some cases it is difficult to verify that the long-term benefit obtained by reservoir construction exceeds

**Table 1.1** Some large dams in the world and the Japanese total.

	Name of dam (river, country)	Capacity ( $\text{km}^3$ )	Inundated area ( $\text{km}^2$ )	Purposes
1	Bratsk (Angara, Russia)	169.0	5470	HNS
2	High Aswan (Nile, Egypt)	162.0	6500	IHC
3	Kariba (Zambezi, Zambia)	160.0	5100	H
4	Akosombo (Volta, Ghana)	148.0	8480	H
5	Daniel Johnson (St Lawrence, Canada)	142.0	2000	H
6	Guri (Orinoko, Venezuela)	135.0	4250	H
7	Krasnoyarsk (Lena, Russia)	73.3	2000	H
8	WAC Bennet (Mackenzie, Canada)	70.3	1650	H
9	Zeya (Amur, Russia)	68.4	2420	HNC
10	Cahora Bassa (Zambezi, Mozambique)	63.0	2580	IHC
11	Kuibyshev (Volga, Russia)	58.0	6150	HNIS
12	Rybinsk (Volga, Russia)	25.4	4550	HNS
	Total of 2575 Japanese reservoirs in 1994	18.7	1250	

H: Hydropower; I: Irrigation; C: Flood control; N: Navigation; S: Water supply.

1–10 are the ten largest reservoirs of the world in terms of gross capacity. 11 and 12 are two large reservoirs in terms of inundated area.

After: ICOLD (1988) and Japan Dam Association (1996); effective digits were adjusted.

the cost of destroying the natural regime and the human activities developed over hundreds of years. If the marginal environmental and socio-economic loss of a reservoir is calculated, few would exceed the marginal benefit of the production at the margin of the capacity because  $dA/dh$  is very large at  $h = h_0$ .

Table 1.2 compares the hydroelectric energy generated in the eight countries where the reservoirs listed in Table 1.1 belong. The Japanese figure includes not only energy generation at dam sites but also run-of-the-river and pumped generation schemes. Although the climate, topography and other conditions for hydropower generation are very different in different countries, it is still a surprising fact that the hydroenergy single-purpose Akosombo Reservoir alone inundates an area of tropical rainforest nearly 7 times more than the total of the 2575 reservoirs of Japan. Ghana produces about 1/20th of the hydroelectric power of Japan, a factor which is more than 100 in land surface efficiency for electricity generation. Five reservoirs in Russia listed in Table 1.1 inundate more than 15 times the total of Japanese reservoirs. Russia as a whole produces less than 3 times the hydroelectricity of Japan. Other countries show similar trends.

Japanese high efficiency in hydroelectric power generation with respect to inundated area is due to the extensive development of run-of-the-river type hydropower generation. This takes water from a river into an artificial channel or tunnel leading to a site where penstocks can be built and electricity can be generated with a high head. In this way large amounts of hydroelectricity can be generated without constructing a major dam and with only a small water intake weir. This type of hydroelectric generation is possible only in a mountainous country with steep slopes and considerable rain all year round and is impossible in relatively flat continental countries.

The first study of land efficiency on hydropower generation was presented by Goodland (1990) which showed the installed capacity of hydroelectric power generation per unit inundated area, under normal conditions, in  $\text{kW ha}^{-1}$  at various dam sites. As he admitted, the actual electric energy generated is a

**Table 1.2** Production of hydroelectric energy in 1997.

Country	Hydroelectric energy generated (GWh)
Brazil	250 000
Canada	331 000
Ghana	6 100
Japan	91 300
USA	296 000
Former USSR	228 000
Venezuela	63 000
Zambia	8 100

*After: World Atlas and Industry Guide (1997); effective digits were adjusted.*

better indicator but the data are not necessarily available. Comparison of Tables 1.1 with 1.2 is the best we can do so far.

It is important to note that a simple comparison, as above, may be misleading if it is narrowly interpreted. First, not all the giant reservoirs are constructed for hydropower alone. An evaluation should be based on the overall outcomes and impacts. Second, the alternatives available for each country to secure electric energy are restricted in various respects, for natural, social and economic reasons. Each country has to generate power by whatever means available. Third, the land efficiency cannot be assessed only by inundation. Inundation may save other kinds of degradation of land environment, such as by thermal pollution, increased CO<sub>2</sub>, nuclear risk potential etc. Thus, the trade-off goes beyond the simple consideration of reservoirs.

### 1.3.3 Reservoir sedimentation

Reservoirs receive sediment continuously from upstream. However small the sedimentation rates are, sediment accumulates and will eventually fill the whole reservoir if not deliberately released. Table 1.3 lists some statistics available on reservoir sedimentation. According to Milliman & Meade (1983), the world average annual sediment discharge to the sea is 13 billion tonnes, and according to Meybeck (1988), 2–5 billion tonnes are trapped behind dams each year. If this figure is correct, the 6000 km<sup>3</sup> of world reservoir storage will be filled on average in 1400–3600 years assuming that 1.2 tonnes of sediments occupy 1 m<sup>3</sup>. This sounds very far into the future if only average conditions are considered.

Lake Mead in USA is losing storage at the rate of 0.33% each year (Gottschalk, 1964) implying 300 years before it is completely filled. In the case of the Aswan High Dam, according to Shahin (1985), the mean annual suspended solid load passing through the Aswan site was, prior to the

**Table 1.3** Reservoir sedimentation rates.

Reservoir	Total capacity (10 <sup>6</sup> m <sup>3</sup> )	Annual sediment (10 <sup>6</sup> m <sup>3</sup> year <sup>-1</sup> )	Life time (years)
729 Japanese reservoirs* (> 10 <sup>6</sup> m <sup>3</sup> )	17 300	40.8	395
Lake Nasser (Aswan High Dam)	162 000	109.0†	1600
Lake Mead (Hoover Dam)	34 900	0.33%‡	300
World reservoirs	6 000 000	2–5 10 <sup>9</sup> t year <sup>-1</sup> ¶	1400–3600

\* Kobayashi (1996); effective digits were adjusted.

† Said (1993).

‡ Gottschalk (1964).

¶ Meybeck (1988).

construction of the Aswan High Dam, 125 million tonnes, 98% during floods. After construction, 2.5 million tonnes are now flowing downstream from the dam. This implies that 30 km<sup>3</sup> of dead storage set aside for sediments, out of the total 164 km<sup>3</sup>, will be filled in some 300 years and the whole dam will be filled in 1300 years. The estuary sand bank at the mouth of the Nile retreated 4 km in 30 years since the completion of the Aswan High Dam in 1964 (Biswas, 1992). Sedimentation, together with the sea water intrusion, is one of the major reasons that Vietnam opposes the development of dams on the main channel of the Mekong River.

Sediment yields, however, differ greatly region by region. In East and Southeast Asia where about two thirds of world sediments discharge to the sea, there are many reservoirs filled in a much shorter time. In northeastern Thailand, a number of reservoirs built for irrigation purposes were filled soon after completion with sediments derived from deforested areas. There are a number of dams in Japan, mostly smaller than 10<sup>7</sup> m<sup>3</sup>, built on very steep mountains for hydroelectric power generation that often experience a rapid filling by sedimentation, for example within 10 years of completion. Although the head for hydropower generation does not change, small effective storage results in little temporal adjustability of power generation.

Various sediment flushing techniques such as sediment outlet gates and bypass channels have been developed. Most methods are still at an experimental stage. The example of the Dashi-Daira Dam of the Kurobe River, Japan, provides an important lesson (Investigation Committee on Sediment Release Impact of Dashi-Daira Dam of the Kurobe River, 1995). It is a concrete gravity dam 76.7 m high with 901 10<sup>6</sup> m<sup>3</sup> storage for hydropower generation completed in 1985 with two built-in 5 m × 5.5 m sediment discharge gates at 30 m from the bottom. After large landslides upstream, attempts were made to release sediments from the gates in 1991. This had an unexpected impact. The sediment contained a lot of humus and logs which under anaerobic conditions resulted in the production of hydrogen sulphide gas which was carried 28 km to the sea. The sediments were responsible for destroying many aquatic weeds in the sea and putting local fishermen out of work. This is not necessarily an extraordinary case, similar experiences have been reported elsewhere in Japan.

### **1.3.4 Factors controlling the future needs of reservoirs**

Main controlling factors for the future needs of reservoirs would be the growth of developing countries, the environmental conservation movement in developed countries, the need for hydroelectric power energy and the anticipated climate variability and change, which will be briefly reviewed below.

***Developing countries*** In developing countries where the population growth is expected to double in the next half century the need for additional water resources is tremendous. It is necessary for food production for sustaining the population, for grazing pasture for cattle for higher food standards, for supplying mega-cities where more and more people and activities are concentrated and for hydroelectric power necessary for industrialization. Most of the extra water supply will come from surface water, because groundwater depletion can cause serious land subsidence in humid regions and non-renewable groundwater extraction in arid regions is too costly. Surface water can only be stored and transferred by means of reservoirs. Regardless of the environmental concern, their development will be indispensable. The only issue will be how to construct reservoirs which are acceptable in terms of sustainable development.

In a humid region, reservoirs are also necessary for flood control. Loss of life, property and agricultural products cause serious social problems, as seen in Bangladesh, China, Philippines, Korea and also many developed countries such as Japan, USA and several European countries.

***Developed countries*** The situation is quite different in developed countries where the population is becoming stabilized and the most economic dam sites have already been developed. The municipal water demand is still increasing due to increasing standards of living, but agricultural and industrial water demands are becoming stabilized because there is little further expansion of irrigated land and the rate of recycling of industrial water has been increasing (77% in Japan, 1994).

Water shortages are, however, fairly common in developed countries, too. Some Japanese cities are suffering from water shortages almost every year, due to frequent dry spells on a large regional scale. A large part of Japan, especially the southwestern part, had only 50–60% of the average annual precipitation in 1978, 1989 and 1994, and some experts speculate that this is connected with global climate change. Such a tendency naturally creates the demand for further water resources development for large urbanized areas.

However, it seems that the public are not sympathetic to the construction of more dams. On the contrary, the trend is that more and more people demand better management of water for safe and efficient water use. Efficient allocation of water rights among users, a priority use for urgent needs such as a temporary re-allocation of agricultural or hydropower water rights for urban water use during drought periods, the emergency import of water from other regions as well as various water saving operations are now options being increasingly supported by broad public opinion. The municipal water use in northern Kyushu, which has experienced some of the worst droughts that have occurred in Japan several times in the last 20 years, is less than 300 litres per day per capita, the lowest in Japan excluding the cool region of Hokkaido (National Land Agency, 1995). This clearly reflects the recent global

environmental movement. Recycling of goods, concern for the life cycle of artificial goods, preservation of nature and the like are becoming a common virtue in the consciousness of the people. Water is no exception.

Nonetheless there are about 600 new dam construction plans endorsed by various levels of governments in Japan. Many of them are in conjunction with flood control, which is the responsibility of the central government and the local government has the incentive to get subsidies. Its 100% implementation may, however, be far in the future if indeed realized at all. A large number of rainfall-induced disasters in Japan are localized landslides and mudflows for which large reservoirs are of no help.

At the 18th ICOLD Congress, Beard (1994), the Bureau of Reclamation Commissioner at that time, stated that "the dam building era in the United States is now over". He continued: "We will emphasize water conservation, demand management and efficient use, including reuse, whenever possible. Every problem we must address has a common theme. That is: there isn't enough water in the river. This sounds elementary, but it isn't. Most western streams [in USA] are over-allocated and under stress. Excessive use has been condoned—even encouraged—and legitimate in-stream uses have been ignored or prohibited. To solve these problems, we cannot build new reservoirs. Instead, we will have to encourage the movement of water from one use to another. We believe conservation, demand management, efficiency improvements, and reuse offer the best opportunities for doing this, if structured to provide real economic benefits to all participants."

The Elwha Dam (132 m high; built in 1913) and the Glines Dam (64 m high; built in 1927) on the Elwha River, Olympic, Washington will be demolished based on the Elwha River Ecosystem and Fisheries Restoration Act of 24 October 1992. Although the Congress has not yet made an appropriation for the removal costs, the service of the dams for hydroelectric power generation, extending three quarters of a century, will come to an end, and the original flow regime of the river for natural fish habitats, such as salmon on which the S'Klallam Indians used to live, will be restored (Sumi, 1996). There are in fact rather special reasons for the decision, the main one being the Treaty of 1855 between the US Government and the S'Klallam Indian Tribe which ensured the tribe the fishing rights in exchange for the right to the land (Nagase, 1998; <http://www.olympus.net/personal/sklallam/index.htm>).

Although the decision regarding Elwha River rhymes with Beard's (1994) statement, it is by no means evident that the statement has been generally accepted in the USA. Nevertheless, in developed countries an environmental concern is now prevailing, which has a great impact also on reservoir construction for water supply, flood control and hydropower. The social preference for human adjustment instead of continued emphasis on the control of nature reflects a movement of society towards a new paradigm for human existence.

**Table 1.4** Technically exploitable hydropotential and hydrogeneration in 1997.

Region	Technically exploitable hydropotential (GWh year <sup>-1</sup> )	Hydrogeneration in 1997 (GWh)	Hydropotential used (%)
World	14 000 000	2 460 000	18
Europe*	1 190 000	511 000	43
North/Central America	1 500 000	668 000	45
South America	2 600 000	450 000	17
Former USSR	2 510 000	228 000	9
Asia†	2 260 000	236 000	10
China	1 920 000	167 000	9
Japan	134 000	91 000	68
Africa	1 670 000	67 000	4
Australia/Oceania	270 000	41 500	15

After: *World Atlas and Industry Guide* (1997); classification and effective digits were adjusted.

\* Excluding former USSR.

† Excluding China and Japan.

**Hydroelectric power** Hydroelectric power is the other major potential source of reservoir needs. Especially in developing countries, hydroelectric power is one of the key elements for economic development and an important means of getting foreign currency. It is also expected to be a clean energy source together with the use of biomass, geothermal, wind, wave, solar and other methods of power generation. According to Table 1.4, after the *World Atlas and Industry Guide* (1997), the technically exploitable hydroelectric power is estimated as  $14 \cdot 10^6$  GWh year<sup>-1</sup> and that currently exploited is  $2.46 \cdot 10^6$  GWh year<sup>-1</sup>, 18% of the potential. The potential is particularly large in many developing countries.

Note that the primary electricity is the gross energy used for producing electricity. It was assessed at the equivalent of 1.0 efficiency for wind and hydroelectric generation (at the heat value of electricity 1 kWh =  $3.6 \cdot 10^6$  J), at 0.33 for nuclear and 0.1 for geothermal.

It should be noted, however, from the figures in Table 1.5, that the energy consumption of the world is so large that even a full development of

**Table 1.5** Commercial energy production in 1991 (in peta J =  $10^{15}$  J).

Total	Liquid	Gas	Solid	Primary electricity:		
				Hydro	Nuclear	Geothermal and wind
334 890	93 689	132 992	76 275	8 049	22 669	1261
100%	28.0%	39.7%	22.8%	2.4%	6.8%	0.38%

After: World Resources Institute (1994).

hydropotential would barely solve the energy problem. The world energy consumption is estimated as 330 000 peta J in 1991 by the World Resources Institute (1994), of which hydroenergy is 8000 peta J or only 2.4% and nuclear energy is only 6.8% based on gross energy or 2.0% based on generated electricity. The proportion of hydroenergy is even less in developing countries because of the construction of fewer large dams. It would therefore mean significant new construction if their huge hydropotential were to be fully utilized. But, at the same time, it means that even when those countries become developed, hydropower can only play a minor role in global energy production.

This raises the question of how hydropower development can justify its severe ecological effects when it can only meet such a small proportion of the total energy demand. It is said that the impact of reservoirs is not a global issue by comparison with fossil fuels and nuclear energy which have such a direct impact on the global climate and environment. It would be true that the extinction of some species or the decrease of numbers of large mammals as a direct result of reservoir construction does not affect the energy and water circulation of the earth, but such arguments are not tenable with sustainable development and the principle of inter-generational equity.

***Climate variability and change*** Climatic variability and change due to global warming could be a decisive factor in the future needs and potential of water resource development in any region. Although its exact timing, magnitude, seasonal patterns and regional characteristics are as yet unknown, some climatic variation and change seem to have already started with the more frequent occurrence of extreme events all over the world. Climatic variability and change would have a major impact on water resources in the 21st century and later. But the counter measures to minimize the effect of significant climate change would not be just more construction of reservoirs or the extension of existing technologies. It would necessitate an increase in social adaptability to a large variation of climate and eventually the gradual but drastic shift of land-use patterns and population distribution. For the as yet uncertain climatic variation and change, we should not start by constructing additional large reservoirs, large dikes etc. but should prepare for future scenarios by improving our ability to cope with the current problems.

## **1.4 CRITIQUES OF PRESENT RESERVOIRS**

### **1.4.1 Introduction**

Availability, variability, and reliability are key issues to users of water resources. Reservoirs are an obvious means to improve the characteristics of