

On the scale diseconomy of large reservoirs in land occupation

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Abstract In total 7936 reservoirs in the world have been analysed with respect to their gross capacity V (10^6 m³) and inundated area A (km²), resulting in the overall relation $V = 9.2A^{1.1}$. If a power function is assumed for the cross section of a river valley, then the relation implies that $A \sim h_0^{8.8}$ and $V \sim h_0^{9.8}$, i.e. very high powers of the dam height h_0 . The particular A - V relation for individual countries depends on the regional topography. Mountainous countries like Switzerland, Japan, Turkey and Italy reside above the average, meaning that they are land efficient. Several large reservoirs in continental countries like former USSR, Brazil, Thailand and Mexico are below the average thus being classified land inefficient. Many large reservoirs built primarily for hydropower purposes occupy huge areas (also relative to the energy production), thus showing a scale diseconomy in land occupation. It is concluded that a reservoir should not exceed a size where the same benefits could be obtained from alternative means with less marginal environmental loss.

INTRODUCTION

In the introduction to the World Bank's new environmental policy on dams and reservoirs (World Bank, 1989), Goodland (1990) showed a striking list of relations between the area inundated by dams and the installed capacity for hydroelectric generation (mostly hydropower purpose reservoirs). The list indicated that some reservoirs produce more than 1000 kW ha⁻¹, e.g. Paulo Afonso, Brazil, but some less than 10 kW ha⁻¹, or even less than 1 kW ha⁻¹ such as Akosombo, Ghana. Goodland *et al.* (1992) stated about the criterion to be satisfied for construction of a dam: "Could one, admittedly arbitrary, criterion or cut off point be 30, as in Tucurui? ... If the ecosystem to be flooded is intact primary tropical forest, the ratio should be much higher (say 100); if the ecosystem is agricultural or degraded land, then the ratio should be set lower."

The list and the statement brought up numerous criticisms against its socio-economic and environmental rationale, such as:

- (a) The list includes reservoirs that are not primarily serving hydropower purposes. Many reservoirs are built for multipurpose objectives including irrigation, water supply, flood control etc. and have been used very successfully in those aspects. It is irrelevant to measure the reservoir efficiency only by the electricity being generated.
- (b) The societal priority and conditions are different in each country. Many developing countries cannot afford to import energy, and the domestic energy source is, if available at all, very important for their own economic and social development.

- (c) The inundated land in rain forest areas is rich in wildlife and bio-species, but not so in arid and semiarid regions.

Although such debates may never end, it must be true that "area inundated is the key issue. ... Optimizing the trade off at the margin of reservoir capacity is more influential than between having or not having a reservoir" (Goodland *et al.*, 1992).

This paper reviews the global status and regional variation of the relation between reservoir inundation and storage, and it emphasizes a scale diseconomy in land occupation of large reservoirs.

STORAGE-AREA RELATION OF RESERVOIRS IN THE WORLD

In relation to dam reservoir statistics of the world, the World Dam Register of 1984 and 1988, compiled by the International Commission on Large Dams (ICOLD, 1984, 1988), is the main and only source book available so far. It contains size, type, purpose and other information of more than 20 000 large dams of 133 countries, where large dams are defined as those being higher than 15 m. As for Japanese dam reservoirs, a comprehensive source book has been published by the Japanese Dam Association (1990). The following analyses are based on the above mentioned two source books.

Figure 1 shows the relation between the gross capacity V (in 10^6 m³) and the inundated area A (in km²) of 7936 reservoirs (7602 dams from ICOLD (1984, 1988) and 334 dams from the Japanese Dam Association (1990), selected among those where both capacity and inundated area data are available. Although some data are not necessarily reliable and some are obviously incorrect (there are examples of average water depths of reservoirs being greater than 1000 m and less than 10 cm), the data as a whole demonstrate quite well a general tendency of the A - V relation of reservoirs in the world. The relation reads:

$$V = 9.208A^{1.114} \quad (1)$$

On an average, 1 km² of inundation creates about 10^7 m³ of storage capacity.

Although the line in Fig. 1 is a combined average of reservoirs from many locations with different topographies, a generalized valley topography may be conceptually assumed. If the longitudinal river gradient is θ everywhere and the valley cross section shape is uniquely described by a power function $h = f(x)$, where h is the land surface elevation above the river bed and x is the horizontal distance from the river, then the A - V relation of any reservoir falls on a linear line on logarithmic paper, the location and slope of the line depending only on the gradient θ and the valley section shape $f(x)$. Thus, if the shape function is:

$$h = f(x) = ax^b \quad (2)$$

then the A - V relation becomes:

$$V = \alpha A^\beta \quad (3)$$

where:

$$\alpha = \frac{\theta(b+1)}{2(2b+1)} \left[\frac{2ab}{\theta(b+1)} \right]^{\frac{1}{b+1}} \quad (4)$$

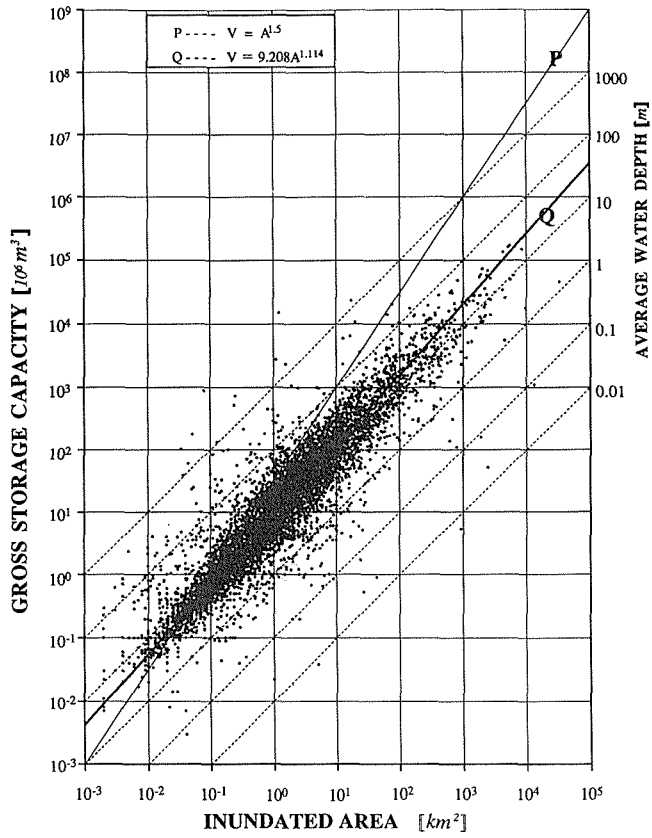


Fig. 1 Area-volume relation of reservoirs in the whole world.

$$\beta = 2 - \frac{1}{b + 1} \tag{5}$$

The parameters a and b can therefore be determined from (1) as:

$$h = 0.1327x^{0.1287} \quad \theta = \frac{1}{1000} \tag{6}$$

and

$$h = 0.0987x^{0.1287} \quad \theta = \frac{1}{100} \tag{7}$$

where both x and h are in km. The inundated area A and storage volume V can also be determined as:

$$A \sim h_0^{8.772} \quad V \sim h_0^{9.772} \tag{8}$$

where h_0 is the dam height.

The land efficiency with respect to dam height follows obviously from the parameters of the valley section shape. In the case of a straight line $h = ax$, or $b = 1$, the A - V relation becomes:

$$V \sim A^{1.5} \quad (9)$$

Hence the area and the volume of reservoirs increase with the dam height in powers of 2 and 3, respectively:

$$A \sim h_0^2 \quad V \sim h_0^3 \quad (10)$$

as the three-dimensional geometrical similarity holds.

In reality, the A - V relation to be applied is given by (1) and accordingly $b = 0.1287$. This implies that the inundated area and the volume of reservoirs increase with much higher powers of the dam height: $h_0^{8.8}$ instead of h_0^2 and $h_0^{9.8}$ instead of h_0^3 , respectively. The acquired storage V is also inefficient, $A^{1.1}$ instead of $A^{1.5}$.

A large reservoir inundates increasingly more land than a small reservoir in the case of such a high power. Thus there is little scale merit in constructing large reservoirs if the environmental impacts due to inundation are taken into account. It may be fair to say that from an ecological point of view there is a scale demerit in constructing large reservoirs.

REGIONAL VARIATIONS IN THE AREA-STORAGE RELATION OF RESERVOIRS

The relationship (1) is an aggregation of relations from various geographical regions. In different regions, A - V relations differ considerably, depending on the river slope θ and the valley section shape $f(x)$. Figure 2 shows the relationships of reservoir area and storage in selected countries.

The A - V relations of these countries may be classified into three groups. The first one is the standard type, falling around the average line. The second is the land efficient type, residing above the average line, while the third, the land inefficient type, is falling below the average line. It is quite interesting that many countries are of the standard type. In fact, the other two types are rather rare. In some countries, unique relations can be observed.

The countries that fall in the standard group include USA, India, Australia and Korea, where some reservoirs exceed 10 km^3 ; South Africa, Romania, Norway, Spain and France having reservoirs exceeding 1 km^3 ; and Austria, Germany and former Czechoslovakia with no reservoirs above 1 km^3 . The efficient group includes Switzerland and Japan with most of the reservoirs well above the average; Italy, slightly above the average; and Turkey, where many reservoirs greater than 1 km^3 are above the average. The inefficient group includes Thailand and Mexico, slightly below the average; former USSR, where many large reservoirs greater than 10 km^3 fall below the average; and Brazil, where many small ones less than 0.1 km^3 are well below, while the larger ones are only slightly below the average. Sweden is unique, most reservoirs less than 0.1 km^3 are much below the average, while many of larger ones are on the average. Small reservoirs in Zimbabwe less than 0.1 km^3 are also slightly below the average, while the large ones greater than 1 km^3 are on the average. Many Yugoslavian reservoirs are scattered widely around the average, including many below the line. The British reservoirs consist of two groups. Most are on the average line, but some small ones are far above.

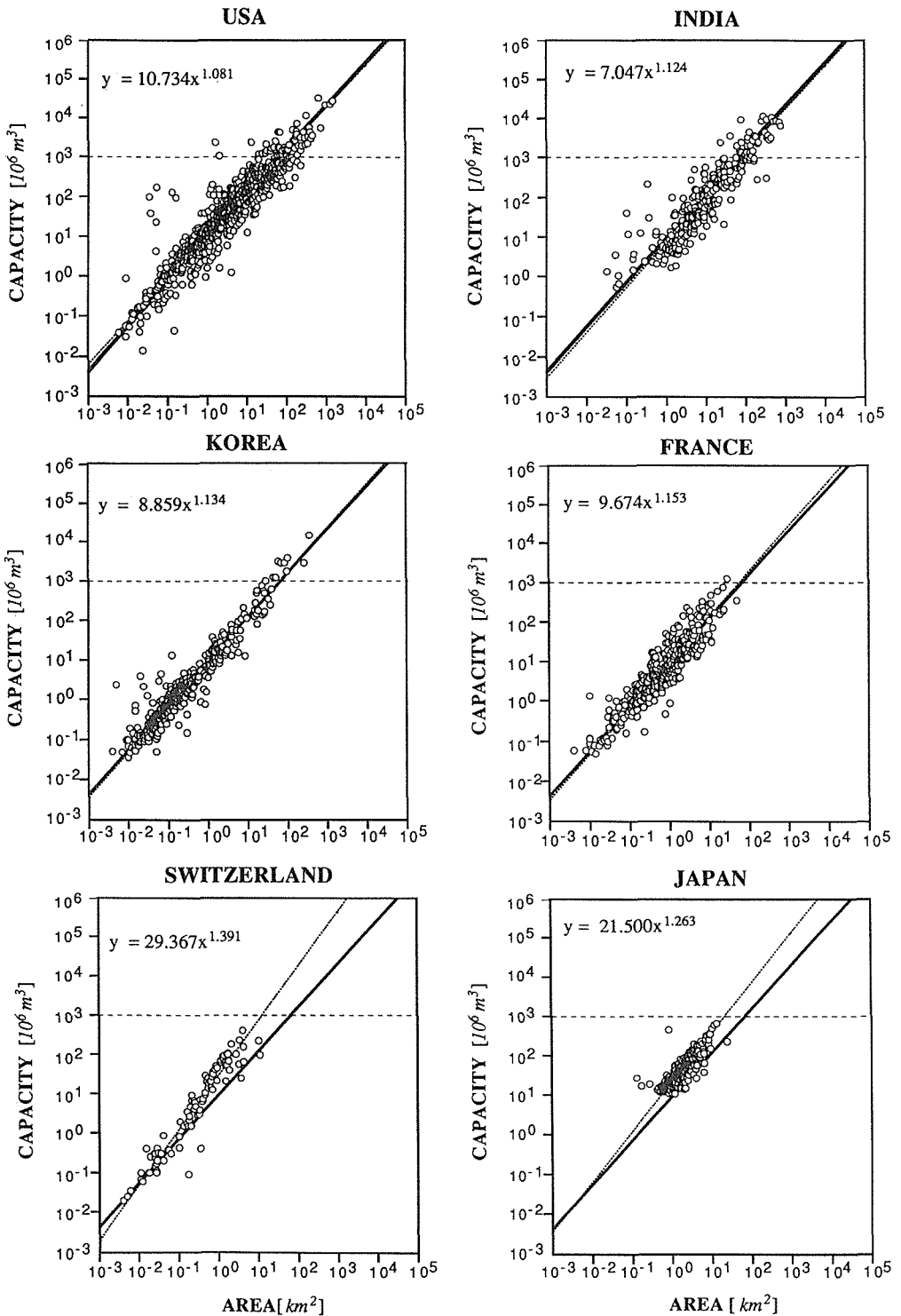


Fig. 2 Area-volume relation of reservoirs in various countries (continued over page).

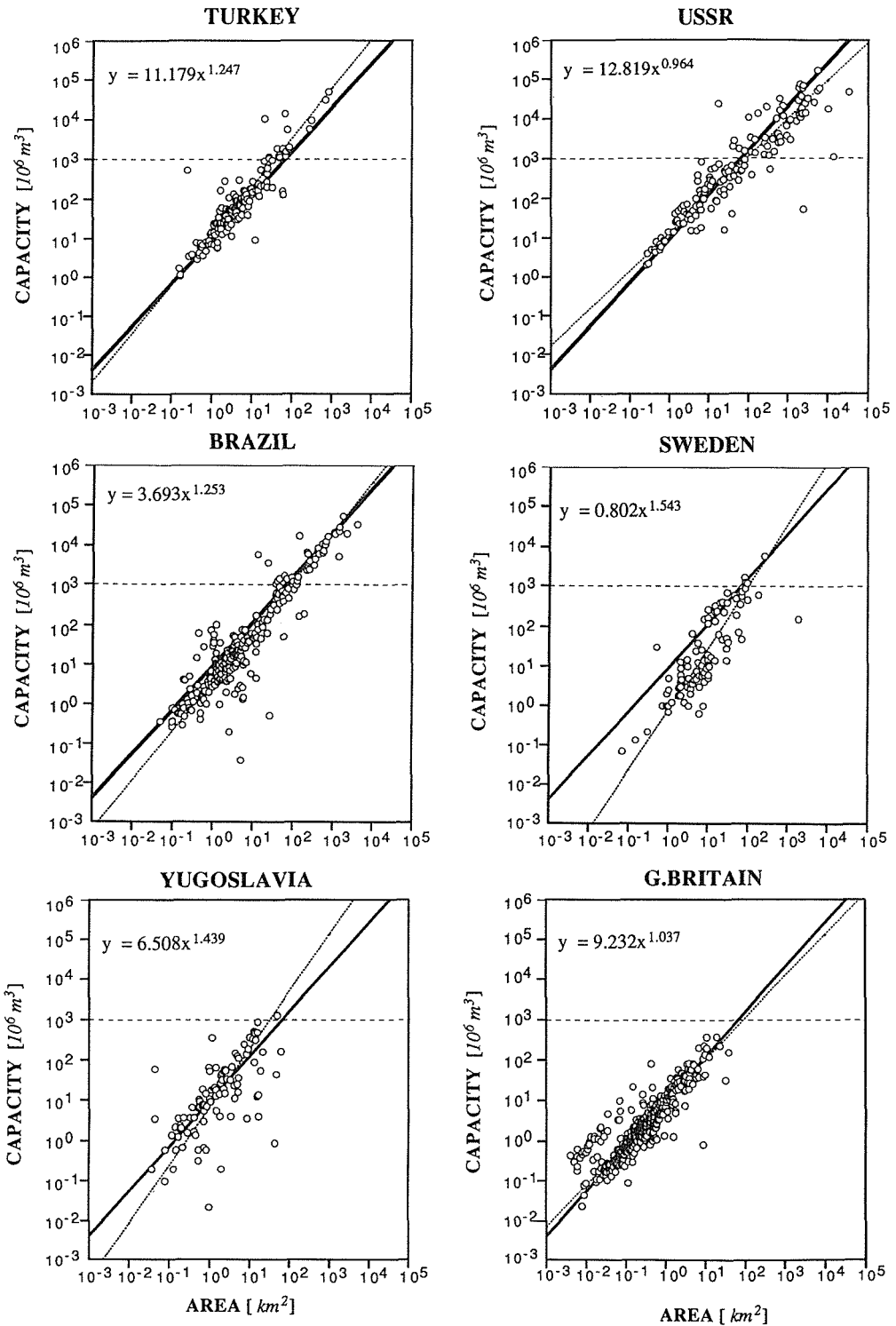


Fig. 2 continued.

In summary, many of the large continental countries and most European countries fall around the average line. Mountainous countries like Switzerland, Japan, Turkey and Italy fall in the land efficient group. Many large reservoirs in continental countries like USSR, Brazil, Thailand, Mexico are classified land inefficient. Thus, the *A-V* relations of reservoirs seem to reflect the topographical characteristics of the countries. If a country is mountainous, the reservoirs tend to be land efficient, while in a large flat country, they tend to be land inefficient. The very land inefficient reservoirs in Sweden, the highly land efficient ones in Britain, and the large scatter found in Yugoslavia etc. are subject to further investigations.

SCALE DISECONOMY OF LARGE HYDROPOWER RESERVOIRS

Table 1 shows the largest ten reservoirs of the world and two additional reservoirs with large inundated areas. It also shows the figures of the total of 2575 Japanese reservoirs in 1994. It is quite striking that the Akosombo dam with Volta Lake alone stores 150 km³ fresh water by inundating 8500 km². The storage and inundated area are respectively 7.8 and 6.8 times the storage and inundated area of all Japanese reservoirs.

It should be noticed that large reservoirs in general are constructed primarily for hydropower generation. Exceptions are the High Aswan and the Cahora Bassa dams,

Table 1 Some large dams in the world and the total of Japanese dams.

Number	Name of dam (river, country)	Capacity (km ³)	Inundated area (km ²)	Purposes
1	Bratsk (Angara, Russia)	169.0	5470	HNS
2	High Aswan (Nile, Egypt)	162.0	6500	IHC
3	Kariba (Zambezi, Zambia)	160.4	5100	H
4	Akosombo (Volta, Ghana)	148.0	8482	H
5	Daniel Johnson (St Lawrence, Canada)	141.9		H
6	Guri (Orinoko, Venezuela)	135.0	4250	H
7	Krasnoyarsk (Lena, Russia)	73.3	2000	HN
8	WAC Bennet (Mackenzie, Canada)	70.3		H
9	Zeya (Amur, Russia)	68.4	2420	HNC
10	Cahora Bassa (Zambezi, Mozambique)	63.0	2580	IHC
i	Kuibyshev (Volga, Russia)	58.0	6150	HNIS
ii	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.
After: ICOLD (1988) and Japanese Dam Association (1990).

primarily built for irrigation purposes, but they are also hydroelectricity producing and would not have been so large if hydropower was not included. This applies for most of the gigantic reservoirs. They tend to become gigantic because of the head needed to produce profitable energy. A typical example is the Srinagarind Reservoir of the Mae Klong River, Thailand whose total capacity is $17\,745\,10^6\text{ m}^3$ with an effective storage equal to $7481\,10^6\text{ m}^3$, or only 42% of the total capacity. Thus, the percentage of dead storage is as high as 58%.

Large reservoirs are subject to strong criticism not only for social and ecological reasons, but also from an economic point of view. In many cases it is difficult to verify that the long term benefit obtained through a reservoir construction exceeds the cost of destroying the nature and the human activities developed during hundreds of years. If the marginal environmental and socioeconomic losses of a reservoir were calculated, only in very few cases the marginal benefit of the production would be positive because dA/dh is very large at $h = h_0$.

Table 2 compares the hydroelectric energy generated in the seven countries to which the reservoirs listed in Table 1 belong. The Japanese figure includes not only dam reservoirs but also run-of-the-river type hydropower generation and pump-up off-stream storage. Although climate, topography and other conditions are different, it is still surprising to see that the hydropower purpose reservoir Akosombo alone inundates nearly seven times more land of tropical rainforest than the total of 2500 reservoirs in Japan, while at the same time Ghana produces only about 1/20 of the hydroelectric energy of Japan, a factor more than 100 in land surface efficiency for electricity generation. It should be noted that five Russian reservoirs listed in Table 1 inundate more than 15 times the total of all Japanese reservoirs, and that former USSR as a whole only produces less than three times more hydroelectricity than Japan (UN, 1990).

If the marginal environmental impact is defined as the environmental losses including ecological and socioeconomic deterioration caused by the last unit increment of reservoir storage, a very large value is the likely outcome for the Volta Lake, Kuibyshev, Kariba, Guri and others in comparison with any of the Japanese reservoirs.

Table 2 Production of hydroelectric energy in 1990.

Country	Hydroelectric energy generated (GWh)
Ghana	5 235
Zambia	7 731
Venezuela	37 245
Brazil	207 230
USSR	233 000
USA	290 964
Canada	296 685
Japan	95 836

After: UN (1990).

The marginal environmental impact increases exponentially with the reservoir height, while the marginal economic benefit most likely will decrease with the height, or be constant, because the electricity and other benefits may be obtainable from alternative means. It is quite true, as Goodland *et al.* (1992) stated, "Optimizing the trade off at the margin of reservoir capacity is more influential than between having or not having a reservoir".

CONCLUSIONS

The overall relation $V = 9.2A^{1.1}$ implies the inundated area A increasing, on an average, with the ninth power of reservoir height. This indicates a scale diseconomy of large reservoirs in land occupation. Large reservoirs, especially hydropower reservoirs, inundate huge areas. The marginal environmental impacts are so large that frequently alternative means such as construction of a number of smaller reservoirs elsewhere, human adjustment to floods, and improvement of the traditional agricultural and industrial structure would achieve the same goals with much less adverse impacts. There are many disputes on the reservoir/no reservoir question. The most important issue to address, however, is the reservoir size and the location. There is no reason to create reservoirs of a size that implies a marginal environmental loss far beyond that of alternative means.

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