DESIGN AND CONSTRUCTION OF DAMS, RESERVOIRS AND BALANCING LAKES

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Summary

The general data presented in sections 2 and 3 gives an idea of the extreme diversity of the millions of very large or very small dams worldwide. Dam design and construction methods for the most usual types of large dams are presented and justified in section 4. The possibility and usefulness of building as many dams in the twenty-first century as have been built in the twentieth is analyzed in section 6.

1. Introduction

For thousands of years, dams have been used to store water and to harness energy. However, 90% of global dam investments have been made after 1950, both in terms of the millions of small or medium sized dams and the thousands of dams higher than 50m. The characteristics of these dams vary greatly. This article gives basic data concerning dams and reservoirs, explains the reasons for typical dam designs and construction methods, and underlines the importance of the study of reservoirs' environmental impact. It tries to forecast the future of dams, and considers whether dams will contribute to the development of the world's poorest countries in the present century, much as they did for the world's richest countries in the last.

2. General Data in 2000

There are millions of dams: these artificial reservoirs thus create a storage of over 6000 billion m^3 of water.

- 97% of this total storage is created by the "large dams." As classified by International Commission on Large Dams (I.C.O.L.D.), large dams include the 40 000 dams higher than 15m and a few thousand lower dams with storage of over 3 million m^3.
- 2% of the total storage is created by over 150 000 small dams (5 to 15m high) with reservoirs between 100 000 and 3 million m^3.
- 1% is created by the millions of other small dams with reservoirs under 100 000 m^3.

Problems of design and construction refer essentially to large dams but may apply also to dams 10m high.

Among large dams there is extreme diversity of height, storage, river flow, range of cost, purpose, foundation, and dam types. The main differences are summarized below:

2.1. Number of dams over 15m according to height and dam material.

This information is provided in Table 1.

Height	Earthfill or rockfill	Concrete or masonry	Total
60-300 ^{m}	800	1,200	2,000
30-60 ^{m}	5,000	2,500	7,500
15-30 ^{m}	27,000	3,500	30,500

Total:	32,800	7,200	40,000

Table 1. Number of dams over 15m according to height and dam material

Over 50% of higher dams are in concrete but 90% of all dams under 30m high are fill dams.

2.2. Storage

The topography of dams and reservoirs varies considerably from narrow gorges and steep valleys to very flat areas and very long low embankments; reservoir volume may differ by a factor of 100 for two dams of the same height.

A rough split of total storage according to unit storage of dams is presented in Table 2.

Unit Storage (in millions of m^3)	Number of dams	Total Storage (in billions of m^3)	Total area (in thousands of km^2)
Over 1000	700	5,000	250
10 - 1000	10,000	1,000	80
0.1 - 10	150,000	150	40
Less than 0.1	Millions	50	30
Total:		6,200	400

Table 2. Distribution of total storage according to unit storage of dams

This total storage (6200 billion m^3) is sometimes compared with the yearly level of water utilization, which is in the range of 4000 billion m^3, and mainly put to use for agriculture. This comparison is questionable, as most dam storage is for hydroelectricity, and is often located in countries as Canada and Russia, where water needs are easily satisfied.

Natural lakes have a global volume 25 times that of the global volume of dam reservoirs existing in the year 2000, and a global area three times greater. The flow of many rivers is regulated by natural lakes, often with rather small changes in level. In theory, many natural lakes offer the technical potential for enormous artificial storage by building dams at the offtake. However, in unpopulated areas such potential storage is often not needed, while in long-populated areas significant changes in water levels may not be acceptable.

Storage in large natural lakes may, however, be important with small changes in level: in Siberia, for example, changing the level of Lake Baïkal (1600m deep) by only 1m allows the regulation of 40 billion m^3 of water for the Angara river. Large natural lakes also allow flood control of the Yang Tse in China, while in Uganda a 3m variation in Lake Victoria’s water level represents storage of 200 billion m^3 and may control the Upper White Nile.

The total artificial storage created in natural lakes represents about 10% of total dam storage. The corresponding dams are rather low, do not raise special problems, and are not studied specifically in this article.

For 10% of the global land area, rivers do not flow to the oceans but to inland lakes or swamps. The area of these lakes varies yearly, according to rainfall, evaporation, and the volume of tributary inflow, and may be permanently reduced if upstream water utilization increases. In the former U.S.S.R., irrigation of an area of 50 000 km^2 from the water of the Syr Daria and the Amur Daria rivers has reduced the area of the Aral Sea by 20 000 km^2.

2.3. Investments

The total value of dams investments in the year 2000 was estimated to have been in the range of 1500 billion US dollars (excluding the cost of powerhouses). Over 90% of this investment has been made since 1950, at about the same yearly investment rate, with more dams in the 1960s and higher unit value recently. In the 1960s, most dam investments were in developed countries, but now most occur in developing countries. Yearly investments from 1990 to 2000 were in the range of 30 billion US dollars. The unit cost of large dams averages US$30 million, but may vary from over 1 billion to less than 1 million.

The average investment per m^3 of storage is $0.25; it is much less for large hydroelectric schemes, but may be well over one US dollar per m^3 for medium storage dams. In terms of area, the average cost per m^2 of lake is US$4, but costs may range from $1 for large schemes to $10 for small ones. Clearly, these values vary in relation to local economic and physical conditions.

Most dam investments are recent, but the hundreds of thousands of small dams (and water mills) built many centuries ago have had enormous impact on the progress of industry and agriculture in many parts of the world. And 4000 large dams (including 1000 over 30m high) were built between 1900 and 1950, bringing key experience to the design of later dams.

2.4. River flows

Hundreds of dams have been built on many large rivers with average flows between 1000 and 20 000 m^3/s, and a few thousand have been built on rivers with an average flow over 10 m^3/s. However, the great majority of large dams and small dams are built on rivers having an average flow in the range of 1 m^3/s or less.

River flows vary considerably through the year and, in the case of most medium and small rivers and many large ones, are virtually nil for months. This justifies the construction of most dams.

In small or medium catchment areas the peak flow during exceptional floods may reach 100 or 1000 times the average yearly flow. In very large rivers the peak flow may be ten times the average yearly flow. Consequently, the capacity of the spillways, which are the structures allowing flood water through the dams, is rather high:

- few hundreds are between 10.000 and 100.000 m^3/s.
- 3000 are between 1000 and 10 000 m^3/s
- 15 000 are between 100 and 1000 m^3/s

and the total capacity of large dam spillways is 20 million m^3/s whereas the average river flow worldwide totals one million m^3/s.

3. The purpose of dams

Dams have various purposes: the production of electricity; water storage for irrigation, industry, or human consumption; flood control; and also navigation and recreation.

Dams need to be considered both spatially and temporally:

- The utilization of dams varies considerably according to country. Over one-third of dams worldwide are multipurpose.
- A key characteristic of dams is their longevity: some operating dams are over one thousand years old and the great majority of dams built in the nineteenth century are still operating fully today. The best utilization of many existing dams varies according to the economic situation, and their operational targets may be usefully reviewed from time to time.

3.1. Hydroelectricity

Less than 15% of large dams produce electricity, but this percentage includes most of the world's highest dams and largest reservoirs. Roughly 50% of dam investments and 80% of relevant total water storage are devoted to hydropower. Most very large reservoirs are in unpopulated areas, such as in Canada or Russia, but large hydroelectric dams have been built in over 100 countries.

The total installed hydropower in the year 2000 was close to 700 000 MW for a yearly production of 2700 GWH, which is 20% of the total electric production worldwide. Hydropower increases by about 2% yearly, and achieving an annual total of 6000 to 8000 GWH by 2100 appears to be a reasonable target, with most of the increase being in developing countries.

High capacity electric lines favor large hydropower plants, but many thousands of mini- or micro-hydroplants have also been built around the world for local utilization. Hundreds of thousands of mechanical water mills had already been built some five hundred years ago using very small dams.

Hydroelectricity offers great advantages in electric networks, allowing adjustments to power supply to cope with peaks or quick changes in power demand. Further facilities to very important networks may be offered by large power plants operating between two lakes at very different levels: these plants supply power during peaks of demand and pump water up to the higher lake during nights and weekends. They are generally in the range of 1000 MW.

3.2. Water storage for irrigation, industrial, and human consumption

Such storage is the essential purpose of over two-thirds of all large and small dams. The corresponding total storage may hardly be assessed exactly, as it is partly shared with hydropower in many large schemes. The relevant useful storage is in the range of 1000 billion m^3, and is generally used for yearly storage, mainly for irrigation. The total investment in this storage is about one-third of dam investments.

In 2000, irrigation water taken from dams produced food for about 15% of the world's population (almost one billion people). It is estimated that during the first half of the twenty-first century, the population of Asia, Africa, and South America will increase by almost three billion people, and many further large dams may be built to provide food for them. In most of these countries, rivers are fully dry for half the year. Water storage for industrial and drinkable water is thus a key target, one that is partly reached by existing dams, often through multipurpose schemes.

3.3. Flood control

Most river valleys are occupied by growing populations. Buildings and homes not threatened by regular floods may be damaged by the highest floods of a century. Although weather forecasting and telecommunications have reduced human losses from floods, the amount of flood damage continues to increase worldwide. The purpose of flood control is to reduce by 20 or 50% the peak flow value of these highest floods.

Filling part or all of a reservoir's capacity during a flood peak may be cost-effective. About 20% of large dams are designed, partly or entirely, for this purpose, and many other dams have or may have a useful impact on flood peaks.
As one billion people live in areas exposed to floods, the utilization of dams for flood control should increase. Past investment in this has been about 10% of total dam investments, but the value of avoided damages is much higher, particularly in countries such as China, the USA and Japan.

However, although many flood control investments may be very cost-effective in the long term, they are often left unrealized. It is politically difficult to raise the money for them and to disturb local populations in order to avoid potentially high losses predicted to occur within 10 to 50 years.

3.4. Navigation

Five hundred large dams have been partly or completely built for navigation. They allow or improve heavy transport on many of the largest rivers around the world, such as the Nile, Yang Tse, Parana, Volga, Rhine, and Danube. These dams are most often special, low gated structures, and are sometimes called "barrages". One particular problem of such dams is to keep existing navigation facilities in operation during the various phases of construction.Dam reservoirs may also be necessary to supply water for the operation of locks, for instance, on the Panama Canal.

3.5. Recreation

Many small dams, and a small percentage of large dams, are designed specifically for recreation. However, a great number of both large and small dams are actually used for tourism and creation, even if they were not initially designed for that purpose.

4. Design and construction

4.1 General comments

The design of dams is a specialized and complex task for the following reasons:

- All dams are different.
- The consequences of dam failure may be disastrous.
- The force of water pressure is enormous.
- The level of acceptable leakage is low; usually it is in the range of liters per second, and often totals less than the losses by reservoir evaporation.
- The foundation is a key part of the structure and needs careful exploration and improvement.
- The control of floods is an essential element in dam design and may also be a difficult problem during construction on large rivers.
- The impact of reservoirs on the environment demands special study.
- Almost all materials used for dams are local: their characteristics have to be identified and improved upon. Each dam's design is based upon the optimized utilization of these materials as well as upon the possible construction methods and the available equipment to transport and improve millions of tons of various materials.

The history and progress of dam design and construction, the state of the art today, and possible future trends are presented below for the main types of dams: earthfill, rockfill, gravity structures, and arches.

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Biographical Sketch

As contractor, **F. Lempérière** has been responsible for the construction of 20 dams on large rivers, including the Nile, Rhône, Rhine, and Zambezi, and has been involved in the design of several dams. A member of I.C.O.L.D., he has served as Vice-Chairman of the Committee on Technology and as Chairman of the Committee on Costs. He is Honorary Chairman of the French Committee on Large Dams, and also chairs HydroCoop, a non-profit association for the international exchange of technology concerning floods, dams, and spillways.