The role of dams in the XXI century

Achieving a sustainable development target

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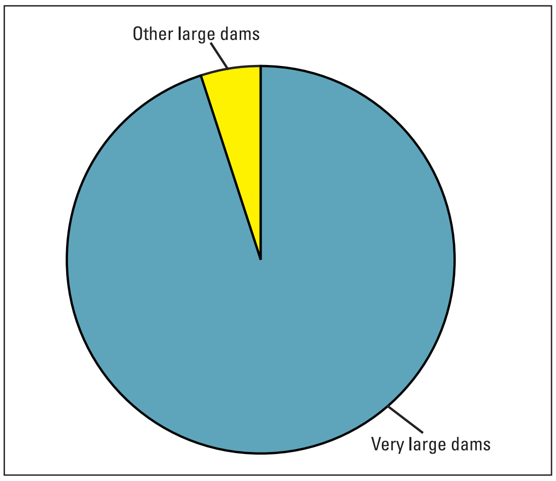
This report, prepared recently for ICOLD's Committee on Governance of Dams, analyses the roles of dams in the past, present trends in construction and upgrading, the future purposes of dams and their likely development during the XXI Century to maintain sustainable development. It represents a comprehensive study of the sustainability of dams from the technical, economic environmental and social points of view.

There are about 50 000 dams higher than 15 m and/or storing more than 3 × 10^6m^3 of water classified as 'large dams'; more than 100 000 smaller dams have storage volumes greater than 100 000 m^3 and millions more have less than 100 000 m^3 .The overall storage capacity is close to 7000 km^3 , of which 98 per cent is at 'large dams'. The live storage is in the range of 4000 km^3, or 10 per cent of the worldwide annual river flow volume. The overall area of reservoirs is 500 000 km^2, one third of the area of Earth's natural lakes.

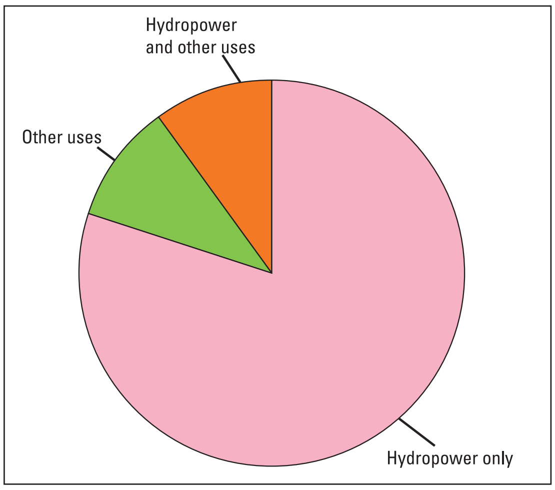
Some other notable points are that:

- 95 per cent of the investments in dams and reservoirs were made after 1950.
- 50 per cent of the world's overall storage capacity is achieved by only 100 very large reservoirs storing more than 10 km3 each, and 40 per cent more of the world's storage is within 2500 reservoirs; about 40 000 'large dams' store, on average 5 × 10^6m^3.
- 600 dams are higher than 100 m; 2000 are between 60 and 100 m high; and, 10 000 are between 30 and 60 high. Half of the 'large dams' are lower than 20 m.
- Thousands of large dams are built on very large rivers with spillway capacities of between 1000 and 100 000 m^3/s. But more than 80 per cent of 'large dams' are on rivers with average annual flow close to or less than 1 m^3/s, with spillways capacitiesof between 50 and 500 m^3/s.



Of the total reservoir volume in 2002 of 6800 km^3, 5000 very large dams (> 60 m) store 95 per cent; 45 000 other large dams store just 5 per cent.

Data in this paper are mainly based on an analysis and comparison of various ICOLD World Registers of Dams (1982 to 2003) and of the *World Atlas & Industry Guide of the International Journal on Hydropower & Dams*. Some other data are from specific reports from China and India.



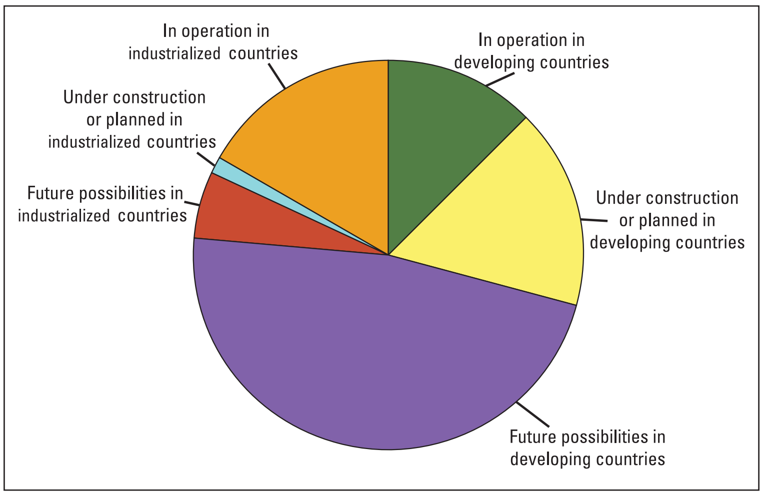
The uses of reservoirs in 2002 (total storage volume 6800 km^3). It can be seen that hydro accounts for more than 80 per cent.

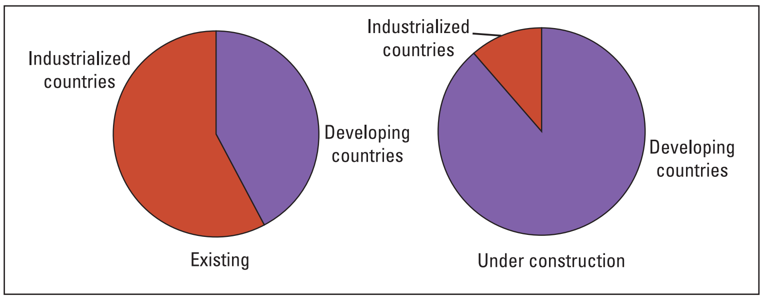
Thus, the analysis of dams would be clearer if the 'large dams' were classified into two categories:

(1) 5000 'very large dams', higher than 60 m and/or with storage of more than 100 × 10^6 m^3 and/or with a spillway capacity of more than 5000 m^3/s. This category provides more than 90 per cent of worldwide storage and its investment represents more than 80 per cent of the total investment in dams. A representative dam in this category may be 100 m high, constructed of rockfill or concrete, mainly devoted to hydropower. Its reservoir impounds a few km^3 with a 100 km^2 area. Its investment cost is US$ 500 million. It is gated.

But 'very large dams' also include lower dams with very large storage volumes and/or very large spillways. On average, such dams are about 30 years old, and their anticipated life is well beyond one century. Few have been decommissioned.

Hydropower potential and hydro in operation. World economic potential is about 9000 GWh/year of which 2800 GWh/year is in operation and 1400 GWh/year is under construction or planned. Most future possibilities are in developing countries.





Dams higher than 60 m in operation and under construction. 2600 were built between 1950 and 2002 (50 per year).

(2) 45 000 other 'large dams' have reservoir areas of less than 10 km^2 (most less than 1 km^2), an average height of less than 25 m and an average in flow of 1 m^3/s. These dams are usually earthfill structures, mainly devoted to irrigation. Although some thousands of these dams required an investment between $10 million and 100 million, the average cost has been much lower, often close to $1 million or even less for more than 20 000 dams built by hand in Asia before 1980. However these quite small dams were a key asset for food and water for hundreds of millions people. On average, these dams are about 40 years old. The total lifespan may be less than one century for many small reservoirs, but will be more than one century for most of them.

1. Current trends in dam construction

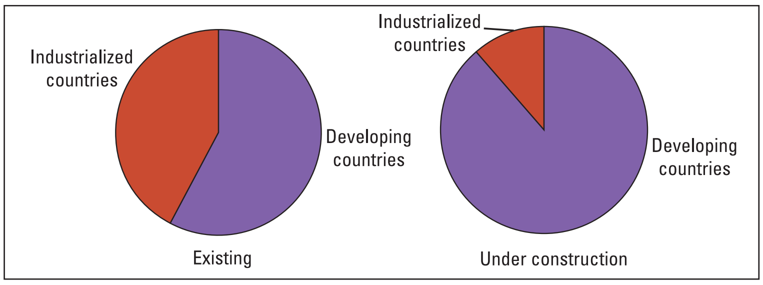
Various criteria may be used to evaluate the present trends in construction:

- The number of large dams completed per year during the 1960s or 1970s was five or ten times the present number, and this is often used to demonstrate "the dramatic decline in the trend of dam building over the past two decades". As the unit value varies from 1 to 1000 and the reduction in number applies essentially to the smaller 'large dams' this reference has no serious meaning.
- The storage: 80 per cent of the existing overall storage is for hydropower; the water storage per kWh/year varies considerably according to the countries (0.5 m^3/kWh in Europe, 5 m^3/kWh in Russia or Africa) and to the construction period (more than three before 1980 and about one today). The lower storage increase since 10 or 20 years essentially results from the reduction of this ratio of m^3/kWh/year. Overall storage is a poor representation of the overall usefulness of dams.

Overall investment is a better indication of dam building activity. The actualized value of all dams built since 1950 is estimated at about US$ 1500-2000 billion and the annual rate in the 1990s at 30-40 billion, that is, 2 per cent of what was achieved in 50 years.

The cost varies more with the height and spilling capacity than with the storage. Most of the investment has been and is in dams higher than 60 m: 2600 were built between 1950 and 2002 (50 per year) and 350 are under construction. 150 dams higher than 150 m were built before 2000 (3 per year), and 35 are under construction. And half of the 30 world spillways of more than 50 000 m^3/s have been built in the past 20 years.

Dams higher than 150 m: 150 were built between 1950 and 2000; 35 are under construction.



Thus, over the past 20 years, if there has been a strong decline in the number of 'large' dams completed each year, no such decline occurred for the 'very large' dams. There has also been, over the last 20 years, a dramatic decline in dam investments in industrialized countries; but large industrializing countries, which focused 30 years ago on many quite small dams built by low cost labour, are now spending vast amounts on very large schemes.

2. Future needs and economically feasible potential

2.1. Hydropower

At the beginning of the 21st century, in 2004, hydropower, with a capacity of 740 GW (plus 100 GW at pumped-storage plants), supplied 2800 TWh/year, about 20 per cent of the world electricity energy and a high percentage of the grid peaks. About half of existing production is in the most industrialized countries

More than 80 per cent of present hydro energy is at 2000 large schemes of 1 TWh/year on average, and it is likely that most of the future will be based also on very large schemes. But more than 50 000 small hydro plants have and many more in the future will have a local role in alleviating poverty.

Beyond its direct benefit of providing clean renewable power, it is well known that hydropower has several other advantages and should be viewed within the context of total watershed management. The storage may be annual, but will more often be used for daily or weekly peaks in power grids. It may also favour the new clean energies, such as wind or solar plants.

The advantage of energy storage for daily peaks justifies many present and future high head pumped- storage plants with very large unit power, even with a higher cost per kWh. Another advantage is the ability of hydro plants to adapt quickly to changes in supply needs, thus improving the frequency control. Hydropower is therefore very attractive within a regional, national or international grid. These advantages are favoured by the fact that transmission lines which used to extend for hundreds of kilometres before 1970 now extend for thousands km; in the future virtually all hydropower will be used within grids and its utilization will thus be optimized. There are also two major consequences of these easy transmissions: the most remote very large hydropower resources (such as in Siberia or Congo) will find consumers, and the need for annual storage for hydropower will be much less than it was 40 years ago when many hydropower schemes were not combined with other electric suppliers. The hydropower will be more devoted to daily or weekly peaks which require much less storage.

There has been, and there will be throughout the 21st century, some decommissioning of rather small hydropower schemes, but upgrading or installing additional equipment may balance decommissioning or sedimentation impact. Climate change will probably increase production in the most northern areas, and reduce it in other areas with an overall small reduction. It is also possible that a larger part of the existing huge storage of hydro schemes will be more devoted to drought and flood mitigation, with a small reduction in power production. It is, however, likely that in 2050 the annual production of the schemes in operation at present will be around 90 per cent of what it is now.

The most industrialized countries have implemented 70 per cent of their economic potential (which is about 1800 TWh/year) and have planned 5 per cent more. The other countries have implemented 20 per cent of their economic potential (6400 TWh/year) but are implementing or have already planned 20 per cent more.

The world's technically feasible potential is evaluated at close to 14 400 TWh/year, of which 8200 TWh/year (about 57 per cent) was considered as economically feasible in 2004; the probable huge increase in oil costs, the likely premiums to clean energy, the high costs at present accepted for other clean sources of energy may increase this figure, possibly by 15 per cent. An implementation up to 75 per cent throughout the century would mean around 7000 TWh/year, or 2.5 times the present production.

The installed capacity, at present 740 GW (+100 GW for pumped-storage plants) may increase even more for meeting peak power requirements and be multiplied by 3 up to 2500 GW. An increase of more than 2 per cent per year of the present capacities up to 2050, and 1 per cent later appears realistic. There is now 120 GW of capacity under construction worldwide, that is, 15 per cent of the installed capacity, and 300 GW more is planned.

In the 20th century, 80 000 TWh of hydropower was produced. In the 21st century, the plants completed in 2000 will produce about 250 000 TWh and the new ones about the same, the total (500 000 TWh), in other words, will be six times the production of the past century.

For social (resettlement) and environmental reasons, the water storage per kWh/year will probably be further reduced for new schemes, particularly in populated areas of Asia and it will be lower than in the last decade, and thus lower than 1 m^3/kWh.

An additional storage from 2000 to 2050 of about 2000 km^3, for a production increase of 2800 TWh/year, seems a reasonable evaluation. Half of the remaining potential is in five countries: China, India, Brazil, Russia and Congo.

2.2 Irrigation

Dams have been used worldwide for irrigation for many centuries and some are more than 500 years old. Few were higher than 20 m before 1950. More than 90 per cent of the total irrigation storage has been created since 1950.

About 40 per cent of the world population obtains food from the 250×10^6 ha of irrigated land of which 30 to 40 per cent is based on irrigation water supply from reservoirs; 12 to 15 per cent of the world population (700 to 900 million people) are fed thanks to dams. The relevant annual water volume is about 1000 km^3. The storage is not the same because it may be used twice in a year or partly kept over years; and some water in irrigated areas is direct rainfall.

Most irrigation storage by dams is within a few countries: China, India, USA and the former USSR. The total relevant dam storage for irrigation is about 500 km^3. Ten other countries: Australia, Brazil, Egypt, Iran, Mexico, Morocco, Nigeria, Pakistan, South Africa, Thailand altogether store about 200 km^3. The overall irrigation storage of other countries is about 100 km^3, of which an important part is in Southern Europe.

The overall storage for irrigation thus seems to be less than 1000 km^3; 80 per cent is in developing countries. Irrigated areas are in the range of 1 km^2 for the rather small reservoirs and in the range of 1000 km^2 for very large ones. Part of the storage of large reservoirs may not be used in a nearby area, but through releasing water during the dry season for further downstream use (for instance, for all Aswan dam irrigation storage). A major proportion of irrigation storage in used also for hydro and flood mitigation.

The evaluation of extra storage for irrigation throughout the 21st century is difficult. The need for food will double within 50 years and the area of available land is limited; the need for irrigated agriculture will more than double. Climate change will probably increase the water requirements for agriculture. Sedimentation reduces the storage volume at irrigation dams, by several km^3/year. The need for irrigation water storage, based in present methods, could thus be multiplied by three or four over 50 years, but there is a continuous progress in irrigation methods which will reduce demand considerably. The water stored at dams for irrigation by 2050 may thus be between 1.5 and 2.5 times what it is now. Part of this will be at multipurpose dams. Further increase may be lower.

The present trend varies considerably according to countries; of the 350 dams more than 60 m high under construction, 50 are completely devoted to irrigation and 100 partly. Some countries such as Turkey, Iran and Morocco devote great efforts to irrigation dams.

The acceptable cost per m^3 of storage capacity for irrigation dams is limited by the food market. In the range of US$ 1 per m^3 in industrialized countries, it was much lower 30 years ago in Asia for manually built dams but may in the future be in the range of $0.5 or more.

2.3. Water supply (for other purposes)

According to ICOLD data, there are 2500 large dams devoted totally to water supply and as many partly for this purpose, but it is difficult to evaluate the total relevant storage because:

- most reservoirs devoted only to water supply are quite small;
- many large reservoirs combine water supply and irrigation; and,
- many reservoirs which were not initially designed for water supply are now used partly for it.

An overall evaluation of the present world annual withdrawal for domestic use is 9 per cent of 3800 km^3, or 350 km^3. Dam storage is used only for a part of the population and during only part of the year. The relevant requirement is of the order of 50 km^3. The total world industrial withdrawal is double that of the domestic figure, but a very large proportion (for instance for cooling thermal plants) is released directly to the river. The utilization of reservoirs storage may thus be in the same range as for domestic use.

An overall storage of 100 km^3 for water supply thus seems a reasonable evaluation.

Between 2000 and 2050, the world population will probably increase by 50 per cent and the water consumption will increase considerably for most of them. The relevant water demand will probably increase more than threefold when climate change will reduce the water available during the dry season. There will thus be an extra need for water storage estimated at several hundred km^3.

The acceptable cost per m^3 may be much higher than for irrigation, especially in the case of populations with a higher standard of living.

Beyond the construction of new dams, extra storage may be obtained from an increased share of hydroelectric dams storage, or from an even limited heightening of existing dams.

2.4 Dry season releases

Part of the water stored for irrigation and water supply is also directly used through releases into the river during the dry season and downstream pumping. The total releases may be greater than that used directly for these purposes and keeping a minimum flow during the dry season along the full length of rivers will probably be an important target during the 21st century.

Most small rivers and many large rivers (especially in Asia and Africa) are completely dry for 3 to 8 months of the year. The related drawbacks, which have huge impacts on poverty, are increasing with the withdrawals, and climate change will probably extend them to many more large rivers throughout the century. Maintaining, during the dry season, a minimum flow of 10 or 20 per cent of the average annual flow may be a reasonable target to be applied, for instance to 20 or 30 per cent of the world's large rivers and most of the small ones.

Increasing for six months the flow of a river by 10 per cent of the average annual flow requires the storage of 5 per cent of this annual flow. Applying this to 10 000 km^3, (that is, 25 per cent of the world's annual flow volume) would require an extra storage of 500 km^3, partly included in the figures above for additional water supply or irrigation.

Maintaining minimum flows in rivers will also justify huge transfers of water between river basins through canals, tunnels and pumping. This has been widely done in the western USA, is under implementation in China, and under study in many other countries including India.

2.5 Flood mitigation

Very few dams completely control floods but many mitigate them; it is thus better to refer to 'flood mitigation' rather than to 'flood control'.

Many irrigation dams store the annual flood, but few dams store the flood of annual probability 10^{-3}. As for other structures for flood control (such as levees or detention areas), the main target, in the case of dams, is actually to mitigate the floods with an annual probability 10^{-1} to 10^{-2} by reducing their peak by 30 to 50 per cent; such reduced peaks are similar to the peak of floods with an annual probability of 1/10, which cause limited damage. Trying to mitigate much more exceptional floods is usually not cost effective.

About 2500 large dams are devoted only to flood mitigation; and half are in USA. Some have a capacity of more than $100 \times 10^6 m^3$ but most are much smaller, and their overall storage is less than 100 km^3.

The impact of multipurpose dams is much greater; for instance, of 350 dams higher than 60 m under construction, only one is totally devoted to flood mitigation but 100 are partly for this purpose. And many dams, which are not designed for flood control, have however a serious impact, such as some 10 000 free flow reservoirs. with reservoir areas of more than 2 per cent of the catchment area: the storage within the volume corresponding to the maximum nappe depth over the spillway may reduce by 20 to 50 per cent the peak of a flood of yearly probability 10^{-2}. This mitigation may often be optimized further.

It is consequently difficult to evaluate the total storage devoted to floods, which is probably in the range of 500 km^3 (including 200 for China); most being used for other purposes as well (for example, irrigation or hydropower)

The number of flood fatalities has been reduced over the past 20 years, thanks to alarm systems and weather forecasting, and is today only several thousands per year but about 10 million are affected and millions of houses are damaged or destroyed every year.

The annual amount of flood damage (at present about US$40 billion) may be much more than $200 billion (at present value) by 2050 for two reasons:

- the value of houses and equipment is increasing, especially in what are today developingcountries and may increase by a factor of 3 in 50 years in relation to present costs;
- climate change may increase by 20 per cent on average the flood volumes and peaks. Such an increase means multiplying by 2 or 3 the probable return period of floods (and thus the amount of damage).

It is thus likely that the efficiency of flood mitigation dams will be multiplied by more than 5 and a relevant dam investment of US$10 or 20 billion per year may be justified as compared with a few billion at present. It should be also emphasized that centralized flood management, weather forecasting and computerized analyses favour the best use of storage for floods. However storage at dams will only be a part of structural investments including river embankments, low detention areas.

Future dams may generally be multipurpose, but dams devoted only to flood mitigation which are completely dry except for a few weeks per century may be very acceptable environmentally; their design may be quite different from multipurpose dams and their cost much lower for the same storage. The structure and/or operation of many existing dams may also be more adapted to flood mitigation.

The acceptable cost per m^3 of storage for flood mitigation varies considerably and will increase greatly throughout the century.

2.6 Navigation, recreation, aquaculture

These dams have little impact on the overall storage.

About 100 large dams are devoted only to navigation, and several hundred partly. They are usually quite low dams on large rivers of industrialized countries, where river navigation is important and environmentally friendly (for example, USA, Western Europe). There may be an important future for navigation in the large rivers of developing countries; one of the main targets of the Three Gorges dam in China is navigation.

There are more than 1000 'large dams' solely devoted to recreation (most in the USA) but they are usually small reservoirs and their cost and impacts are low. The essential use of dams for recreation is a partial function of more than 10 000 large dams for which recreation was or was not an initial target. Hundreds of thousands of kilometres of riverbanks downstream of dams which had been completely dry most of the year may now be used for recreation, and many very large reservoirs include huge tourist resorts. This utilization has a great future.

Aquaculture also offers great possibilities which have so far been used only to a limited extent.

3. Technical conditions of sustainability

There are three main conditions: safety, ageing, sedimentation:

3.1 Safety

Zero risk is virtually impossible to achieve. To keep risk to the absolute minimum, great care is taken, and should be taken, of dam safety.

The present overall risk of failure of existing large dams is about 10^{-4} per year, the main risk being the overtopping of embankment dams by floods. Upgrading of spillways will reduce this risk further and may also be necessary during this century when climatic changes will probably increase the magnitude and frequency of extreme floods. The percentage of fatalities within the population of areas inundated by dam failures is now considerably reduced by alarm systems and telecommunications (phone, radio, and so on) and in the range of 10^{-2}. The average annual risk of death by dam failure is thus in the range of $10^{-2} \times 10^{-4} = 10^{-6}$. However not all dams reach this level, and further improvements are necessary.

For new dams, there is a statistical failure risk at the time of first filling lower than 10^{-3} and a further annual risk lower than for existing dams, because the spillways of new dams are designed for very exceptional floods.

3.2 Ageing and maintenance

Hundreds of existing large dams were built before 1900 and 5000 before 1950. There is thus a great experience of maintenance and ageing; there are many areas and reasons for ageing in the foundation, the dam body, or in appurtenant works. The relevant care of these critical areas is a key part of dam engineering.

There have been relatively fewer problems in the body of embankment dams than in the body of concrete dams: the ageing of the old masonry dams is a serious problem which justifies much upgrading. The impact of very cold weather and ice on the thin concrete structures may be significant.

The cost of maintenance varies greatly according to dam type, but some general comments can be made:

- the annual average cost of ageing control and repairs is a small percentage of the investment in dams (only about 0.5 per cent);
- the improvements in designs based on the experience of ageing reduces the cost of the maintenance of new dams; and,
- few large dams and very few very large dams have been decommissioned or abandoned; for instance in France, of 40 'large' dams in operation in 1900, 36 are in operation a century later.

3.3 Sedimentation

This problem was underestimated worldwide 40 years ago, because it was a minor issue in most countries where the largest dams were built at that time, and because most studies focused on short-term benefits. This problem has now been underlined by difficulties encountered with some large reservoirs; it is now often globally presented, or at least understood, as one of the main reasons for alleged non- sustainability and limited future of dams. A simplified presentation is the following: "existing reservoirs lose 0.5 to 1 per cent of their storage yearly and are on average already 35 years old; the best dam sites have already been used and the yearly increase of storage does not and will not balance the yearly loss by sedimentation". It is thus understood that the existing reservoirs will have lost more than 50 per cent of their capacity (and benefits!) before 2050 and will have little usefulness by 2100. And the storage capacity (and benefits?) of future dams would be much lower than the present capacity and benefits of dams. The overall role of dams thus appears likely to reduce progressively during this century.

This approach is globally wrong, because the sedimentation problems are very low for more than 80 per cent of large dams, and because the loss of hydropower supply is not at all proportional to the loss of storage.

3.3.1 Loss of live storage

The sedimentation of a reservoir is directly linked to two parameters which vary enormously.

The sediment content in river flow; the total world sediment yield, is estimated at between 15 and 20 Gt/year by Walling and Webb [1997] and between 15 and 40 Gt/year by Morriss and Fan [1997] for a total water yield of about 40 000 km^3, that is, an average sediment yield of between 0.5 and 1 t/1000 m^3. But in fact 70 per cent of this sediment yield is from 10 per cent of the world's land area, and 2 per cent is from 50 per cent. This rate may even vary within a country: in China, the rate of the Yellow River is 40 times more than the rate of the Yangtze.

More than 50 per cent of rivers are dammed, and most sediments are trapped in reservoirs (80 per cent); half of the world's sediment yield may thus be trapped, that is, 10 to 20 Gt or 8 to 16 km^3 for an average density of 1.2 t/m^3. These figures should be increased because materials from the river bed could be mobilized between two dams on the same river. This may explain an overall cumulative world figure for reservoir sedimentation of about 600 km^3 for an average dam life of 35 years, or 17 km^3/year; a rough evaluation of 20 km^3/year (or 0.3 per cent of the 7000 km3 storage) seems reasonable for the future.

The 'hydrological size' of a reservoir is the ratio of the storage capacity to the annual flow: It varies from less than 1 per cent to more than 100 per cent. A value of 5 per cent with a sediment yield of 5t/1000 m^3 could cause a full sedimentation in less than 50 years. But a usual value of 50 per cent with a sediment yield of 1t/1000m^3 means a low rate of sedimentation (less than 10 per cent per century).

The impact of sedimentation is by no means the same for hydropower as for other dam functions. For hydropower, corresponding to more than 80 per cent of the total storage, part of the sedimentation is in the dead storage, with little or no impact, and part affects the live storage, where a reduction of 50 per cent means a much lower reduction in power production. A reduction of storage of 0.3 per cent per year means a reduction of power much less than 0.1 per cent of production, that is, less than 10 per cent in a century.

The impact is more significant for irrigation, water supply or flood mitigation. Many reservoirs have no dead storage; as they represent 20 per cent of the world storage, the yearly loss of useful storage is in the range of 20 per cent of 20 km^3 that is 4 km^3. The cumulative figure within a century will, however, be less than 400 km^3, because a reservoir fully silted in 50 years will not be re-silted again.

The global impact of the loss of storage therefore appears to be as follows:

- a hydropower production loss of less than 0.1 per cent per year; hydropower is thus certainly a sustainable energy; and,
- a need for further storage for other needs of less than 5 km^3/year, in the range of 10 per cent of the overall annual storage increase.

Apart from the direct impact on storage availability, the changes in water and sediment flow may modify the riverbed downstream, causing damage or requiring mitigation measures. Sand and gravel deltas may also appear at the upstream end of large reservoirs; they may be detrimental and raise the upstream level during floods or be a low cost source of construction materials. These impacts are serious, but may usually be acceptable or well mitigated.

Another serious problem caused by heavily silted rivers is the possible major erosion of mechanical equipment, especially the turbines.

3.3.2 Remedies

Although reservoir sedimentation is not the overall disaster it is sometimes made out to be, it can be a serious problem within a short time for many dams, and often has a major impact on the choice of appropriate solutions; in any case it requires a careful study of the long-term impact on most large reservoirs where small initial extra costs may help later mitigation measures.

Experience from worldwide incidents is the basis for a great number of the solutions developed since 20 years for mitigating sedimentation problems in the design of new dams and upgrading existing ones; further optimization is likely.

The sediment yield varies with the vegetation in the catchment area; reducing deforestation, modifying farming methods, treating some areas especially prone to erosion may be efficient but these are long term and often costly measures. The basic design can avoid most of the sedimentation if placing the main reservoir off stream and flushing the intake reservoir.

Most dams for irrigation and water supply are, or may be, empty at the end of the dry season. The risk of siltation is mainly for reservoirs storing a small part of the annual flow; most are in countries where floods occur within one or two months. Keeping the reservoir empty most of the flood season, that is, delaying by one month the reservoir filling, will avoid most sedimentation and double or treble the reservoir's life.

The method above (sluicing) is unlikely to be able to be applied at most hydro schemes, where losses of power production would be prohibitive, but flushing may be used at many schemes which are prone to siltation. Opening low or mid-level gates for a few days or weeks will scour a part of sediment or at least transfer it from the live storage to dead storage. The main drawback of this method may be the downstream impact of temporary high sediment concentrations and volumes during flushing. If properly studied and managed, this method may, however, be very useful for many reservoirs.

Mechanical sediment removal is generally too expensive at present: usually the cost is a few dollars per m^3 and the value of storage for irrigation hydropower less than $1. However, dredging may be justified for some water supply reservoirs, for the upper part of high hydro reservoirs for avoiding turbines wear, or for some limited part of many reservoirs. Dredging equipment specially designed for the reservoir data and to be paid for more than 30 years may in the future favour acceptable unit costs of mechanical removal for many dams.

There are two ways to reduce the problems of turbines wear: desilting structures upstream of plant intakes may be efficient for sediment diameters larger than 0.2 mm, but are often very expensive. Lessons from experience favour better turbine types and shapes, and their protection against erosion or cavitation. Avoiding or reducing power supply during some days of the year during floods with high sediment content may be cost effective.

Evaluating and mitigating sedimentation problems is thus an essential element of dam design and operation in many countries, and may modify the general layout, the dam design and the choice of discharge facilities. The progress is such that relatively few dam construction opportunities are abandoned as a result of sedimentation problems; and a very large number of hydropower schemes under construction or planned are in countries such as China or India, where the siltation problems are the most extensive, but where much progress has been made in mitigating them.

4. Environmental and social conditions of sustainability

Impacts of dams on the environment may be significant, especially for very large reservoirs. But 80 per cent of the large dams have a reservoir area of only about 1 km^2 and are on rivers with an average flow of less than 1 m^3/s, so their impact is low.

The impacts can be favourable or unfavourable. Today, knowledge and appropriate attention and care make it possible to mitigate many unfavourable impacts. But most existing dams were designed between 1950 and 1970, when this was not the case. Upgrading many existing dams and modifying their operation may often improve the environmental impact.

4.1 Lake area

The total area, worldwide, of all artificial reservoirs is 500 000 km^2. This global area is about 0.5 per cent of the continent area and has been essentially inundated in half a century (1950-2000). This has provided food, water and electricity to about 800 million people (1600 per km^2 of reservoir), 75 per cent of the reservoir areas are in countries with a low population density, such as America, Africa, and the Russian Federation. This may be compared with the global human impact on continents throughout 20 centuries. Human activities, apart from dam construction, have totally modified more than 20×10^6 km^2 (1×10^6 km^2 per century), essentially transforming forests into agricultural land, including millions of km^2 of irrigated wetlands (for example, paddy fields). These changes provided food to 5 billion people (250 per km^2). The dams to be built in the 21st century will supply about 1 billion more people with food, power and water for an increase of lake area of about 300 000 km^2 half (3000 per km^2).

As natural lakes, reservoirs formed by dams progressively stimulate many activities such as fishing or recreation. Drawdown areas are often of great value to agriculture and livestock in Asia and Africa.

4.2 Modification to river flows

The total annual flow of rivers which are dammed is more than 20 000 km^3. The total dam storage volume is 7000 km^3, of which a part is permanent and was filled in 50 years (50×10^9 m^3/year). Temporary storage totals 4000 km^3; 200 km^3 is lost by evaporation. About 1000 km^3 of water is stored for irrigation and water supply, of which a few hundred km^3 are released into the river. The overall reduction in flow is 1000 km^3, that is, less than 5 per cent of the annual flow.

Globally dams withdraw 20 per cent of the flow of rivers, essentially during the flood season, and release back to the rivers 15 per cent, a large part of it during the dry season.

A reduction in flow during the dry season can often be avoided and most dams have, or may have, a very favourable impact by increasing this flow. In this respect, 30 countries use rules of Environmental Flow Requirements (EFR) and impose a minimum flow, usually about 10 per cent of the average annual runoff. This approach could be adopted by all countries with rules optimized for each existing or new reservoir.

For a small reduction in the project benefits, most existing reservoirs could permanently guarantee a substantial flow in a river that is naturally completely dry during several months of the year. For a small reduction in the project benefits, most existing reservoirs could permanently guarantee a substantial flow in a river that is naturally completely dry during several months of the year. This key positive impact of dams on the environment is often forgotten.

Reducing floods by storage in a reservoir has various impacts; 90 per cent of large dams are in catchment areas smaller than 500 km^2. Consequently, floods are usually flash floods, rising within a few hours. Mitigating most of these floods usually has a much more positive than negative effect on the environment. But for some very large reservoirs, a major reduction in the whole flood season flow can have a serious negative impact on the downstream floodplain ecosystem. This requires careful study and mitigation through a programme of controlled floods. The daily fluctuations of hydropower dams supplying peak power may or may not be damaging. Their impact can be often mitigated by a small downstream dam storing few hours of flow peak.

4.3 Visual impacts

Large embankment dams require very large quarries and borrow pits. Locating them in the reservoir area reduces the impact of these works on the environment and may not be much more expensive. Most dams are earthfill structures lower than 30 m, virtually always with a straight axis from abutment to abutment. They could often appear more natural for about the same cost with a slightly curved shape, smooth connections to banks and grass planted on the crest and on the downstream face.

4.4 Impact on fauna

Creating lakes on 0.5 per cent of the continents has reduced the area available for terrestrial fauna and those living close to the rivers are displaced by the raising reservoirs. However, the length of watered banks adjacent to lakes is not reduced and is often increased; a permanent minimum flow for most small and medium rivers is favourable to terrestrial fauna.

The impact on fish is clearly more important. The impact is positive where increased dry season releases guarantee some flow throughout the year; it may be negative for permanent rivers or at least favour changes in local species through changes in the flow regime, in water temperature and nutrient content and through the fragmentation of the rivers. Mitigation by the development of new species, or fish passes, or by compensation through the development of fisheries in the lake, requires great care to be successful. Where fisheries were essential for the local economy and traditions, dam designs should have been seriously modified and some dams avoided.

4.5 Social impacts

Dams have had major positive and some negative social impacts. Direct positive impacts are the supply of food, energy and water to 15 or 20 per cent of the world population.

The most significant negative impact has been the resettlement of about 25 million people from reservoir areas, over the past 50 years. Resettlement has been on quite a small scale in industrialized countries. Most cases have been in Asia. Even there, 90 per cent of the 'large' dams, with a reservoir area in the range of 1 km2, have caused only very limited problems. The major problems have resulted from about 1000 dams which have each displaced some thousands or tens of thousands of people; 15 displaced some hundreds thousands people, and the Three Gorges dams more than 1 million.

While the number of resettled people (500 000/year) appears to be high, it should be compared with about 800 million people who are provided with food as direct result of dams. Dams also reduce the number of people (by some millions) who lose their homes as a result of flooding each year.

But even if resettlement is most often justified by the benefits of dams, displaced people have sometimes received only a small part of the benefit of the projects: financial compensation has often been too low and the need for a specific organization to manage successful resettlement has sometimes been overlooked in the past.

Over the past 20 years this problem has been handled better; an important part of the total investment is generally devoted to a well managed resettlement scheme, which may require as much time and organization as the dam construction itself. The Three Gorges dam project is devoting half of its huge investment to resettlement at a cost of US$10 000 per capita (more than 10 years of income in China).

The higher unit cost of resettlement in the future will not favour very large lake areas. It is often possible to reduce considerably the reservoir area, and the resulting resettlement, with an acceptable reduction in performance. For instance, using very large reservoirs for hydropower in Africa used as much area for supplying 100 TWh/year as in Europe for supplying 500 TWh/year.

Although the benefits of dams will more than double during the 21st century, the lake area will probably increase by only 3000 km^2 per year instead of 10 000 km^2, as was the case before 2000.

Dams also have indirect social impacts: many are positive, such as providing the possibility of either keeping or developing a new activity to benefit the local population. Most irrigation dams have been built in areas where half of the employment is in agriculture, and so the development of irrigated agriculture has benefited many more people than directly displaced by the reservoirs. However, some indirect effects have been negative, such as the impact on existing fishing activities.

Similarly, although the global effect on health is largely favourable, some large reservoirs in tropical areas have seriously increased diseases such malaria and bilharzia and such problems need careful study and mitigation.

Until recently, few studies were made about the global indirect impact of very large dams. In the past 10 years, a number of reports have focused on the negative indirect impact of some very large dams. From recent studies during the 21st century, it is likely that anthropogenic greenhouse gas emissions will seriously affect the climate, and consequently have an impact on rivers in most countries, reducing considerably the flow during the dry season and/or seriously increasing extreme floods. But hydropower generation will limit greenhouse gas emissions (in terms of avoided fossil fuel generation) and dams can help to reduce droughts and floods.

5. Mitigating climatic changes

During the 21st century, it is likely that the anthropogenic greenhouse gas emissions will seriously affect the climate, and consequently have an impact on rivers in most countries, considerably reducing flow during the dry season and/or seriously increasing extreme floods. But hydropower generation will limit greenhouse gas emissions (in terms of avoided fossil fuel-based generation) and dams can help to reduce droughts and floods.

If the present hydropower capacity were to be replaced by a proportional increase in the other existing electricity sources, this would require more than 1000 extra thermal plants of 500 MW, burning 250 Mt of petrol or gas each year, and 400 Mt of coal and 150 extra nuclear plants of 1000 MW.

During the 21st century, existing and planned hydropower will save about 50 Gt of petrol or gas (more than 10 years of overall present utilization) and 100 Gt of coal, and avoid the construction of 500 nuclear plants with a 50 year operating life. The direct increase in greenhouse emissions through the creation new lakes in tropical areas is globally a very small part of this saving.

In most countries, warming of the climate will reduce flows during the dry season and many permanent rivers may well dry up completely during some months when human needs will greatly increase; dams are practically the only solution for maintaining the present situation or for improving it.

Climatic changes, in addition to urbanization and deforestation, will probably increase the scale of exceptional floods, with negative impacts on populations and the environment. Dams will help to mitigate floods and to maintain prevailing conditions.

During the 21st century dams will in fact help to keep many rivers in their present condition. Let us hope that many dams in the future will thus be supported by ecologists who today criticize dams for modifying these conditions!

6. Existing dams

On average, the lifetime of most large dams will be more than 100 years and much longer for the 5000 very large dams representing 80 per cent of the dams' benefits. The dams existing in 2000 will thus still be able to supply by far the largest part of the present benefits in 2100.

During their long life, the targets and management of large dams may and should be modified and optimized according to changing needs and economic conditions, as well as possible climatic changes. Two phases may be broadly considered:

The initial phase, in the range of 30 years: the total annual costs for settling investment and financing costs and for operation and maintenance are between 5 and 10 per cent of the investment and the income is optimized for balancing them while meeting the initial environmental commitments.

After about 30 years (the second phase), the investment is paid for, the annual costs are much lower, in the range of 2 per cent, and the conditions for relicensing may be different from the initial ones. It may be the right time for reviewing, in detail, the best targets according to changed conditions. This review should include the possibility of upgrading the dam and powerplants, optimizing operation and devoting more effort on improving the environmental impacts. Similar reviews should be made later at 20 or 30 years intervals.

Upgrading should not be limited to safety; it may include an increase of power capacity for peaking or a reservoir level increase: an increase of the maximum reservoir depth by 5 per cent, could mean an increase to the live storage by about 20 per cent. These increases are likely be easier for most free-flow reservoirs and may be cost effective for a number of gated ones. With or without upgrading, it may be fully justified to reduce, to some extent, the power production (while keeping the peak capacity) and to devote more storage to other targets, particularly for mitigating droughts and floods. It may also be justified to add a power plant to an irrigation dam.

Operation of the project may be modified to help reduce siltation and increase the dry season releases.

The analysis of various relevant options deserves important studies for optimizing the choices. The governments which are deeply involved in the initial investments should take great care in performing these reviews.

7. The implementation of new dams

Current trends show that most future hydro development will be based on large rather than small hydro; the other needs are more directly linked with the storage volume, and will require, during the 21st century, some 2000 km^3 of additional storage; this will not been met by small reservoirs. The main investment during the 21st century will probably be, as now, in 'very large dams', with an average cost of some hundreds of millions of dollars (some more than $1 billion). There will probably be more dams higher than 100 m, but fewer very large volume hydropower reservoirs than in the past.

The very large dams require long and detailed studies and political decisions. They also require huge investments, and international loans may be useful and sometimes essential. Even where dams are by far the best solution, it may be easier for governments to choose gas turbines and to import subsidized food (with unknown future costs) than to spend huge amounts for benefits of dams to be perceived later. The possibility to build dams is made much more difficult in view of the aggressive actions of some opponents.

Resettled people are directly affected and claim for fair compensation or a share of benefits: this is well justified and was overlooked in many past schemes. The evaluation and agreement of a fair compensation may not be easy.

Ecological organizations may be very useful when cooperating in studies and suggesting solutions for mitigating negative impacts and improving the positive ones. But unfortunately, some of them are opposed to all dams. In these cases, they use many techniques to prevent the construction of dams, such as disseminating misinformation, campaigning to prevent international loans and using all possible legal (and sometimes illegal) actions.

The misinformation is mainly based on an unbalanced presentation: true serious negative impacts of some very large dams (often designed 50 years ago) are emphasized and generalized to "dams" (in general) while positive impacts are minimized or totally forgotten. The data used by anti-dam organisations may be totally wrong. For instance, the World Commission on Dams (WCD) published in 2000 the result of its work of four years concerning the assessment of the effectiveness of large dams in the world. In its report, the WCD multiplies by more than two the overall area of reservoirs (increasing it by 600 000 km^2!) and multiplies by 2 or 3 the overall sedimentation and by 5 or 10 its impact, thus totally underestimating the useful life of dams. But it almost totally overlooks the positive impact of dams in relation to the greenhouse effect.

There are also opponents to the benefits of dams, such as the competitors for energy and food supply; many developing countries consider international anti-dam actions as part of an economic war against their self-sufficiency and their economic progress.

Dam opponents also use many forms of legal action: this may be effective for delaying very large schemes and for completely preventing the smaller ones for which promoting entities cannot face long and costly procedures. Not surprisingly, many opponents to dams suggest authorising only the small schemes and to impose much more complex legal procedures for the implementation of dams.

The impacts of such opposition to dams vary significantly according to the countries.

In the most industrialized countries, with populations totalling one billion people, many additional dams could be cost effective, but are not essential for the welfare of the population because it is not increasing ; most hydropower potential is already used and the needs of water for irrigation are limited. Ecologists are active and have political strength. Consequently, in Western Europe and North America, only 30 dams higher than 60 m are under construction (3 per cent of the existing ones) and 2 per cent of the existing hydropower capacity. The fact that dams are probably the best solution for mitigating the extent of climatic change and its impact on drought and floods has not yet been taken in account. Ten or twenty years may be required for modifying this approach and also for accepting the fact that further hydropower is by far the cheapest renewable energy.

In the developing countries, with populations which totalled 5 billion in 2000 and likely to reach 7 billion by 2050, requirements for energy and water are enormous, and most countries wish to be self-sufficient. The trends in dam construction are thus mainly linked to economic and financing conditions. Countries totalling half of this population, for example China, India, Turkey, and Iran, have planned and are developing large proportions of their potential. In Asia (apart from Japan and Russia) there are 230 dams higher than 60 m under construction (as compared with 750 existing ones); 10 per cent of the remaining hydropower potential is under implementation and much more is planned (as in South America). In these countries, the essential part of investment is by local financing resources.

The situation is different in most of the poorest countries, where foreign loans are essential. In Africa, only 1 per cent of the hydropower potential is at present under implementation. The ecologists' opposition to international loans for dams is thus mainly harming the poorest countries.

8. Economic sustainability

In the short term, building thermal plants, importing food, and accepting flood damage is less expensive than building dams and more easily sustainable financially. But dams are usually much more sustainable economically.

A rough analysis is relatively easy for hydropower, which has a direct financial return. The cumulative overall investment for more than 800 GW at a present rate of US$1 to 1.5 million per GW is in the range of $1000 billion (including the cost of plants) with a further increase of about 2 per cent per year or $20 billion.

A rough analysis may be based on a cost of loan interest during construction of 20 per cent of the investment, an annual cost for operation and maintenance (O&M) and upgrading of 3 per cent of the cumulative investment, and an income of ¢4/kWh now and ¢5/kWh later.

In 2000, the expenses for investment and interest were $24 billion (1.2 × 20), the O&M: 3 per cent of $1000 = $30 billion, that means, a total annual expense of $54 billion for an income of 2800 TWh × $40 million/TWh = $110 billion.

By 2050, the annual investment and interest (at present values) may be slightly higher, in the range of $30 billion, the O&M costs doubled ($60 billion) and the total annual expenditure $90 billion, for an income of $5000 × 50 million = $250 billion.

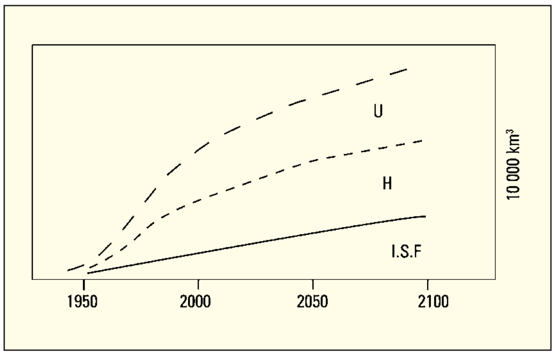
Assuming a further slower increase, the figures could be, by 2100, an annual cost of about $90 billion ($15 + 75 billion) for an income of $350 billion.

The long life of dams and their low cost of O&M will create, during this century, an excess of direct hydropower benefits as compared with costs close to $15 000 billion. This figure does not include the huge indirect saving corresponding to a reduction of 5 per cent in the overall climatic change (0.2°).

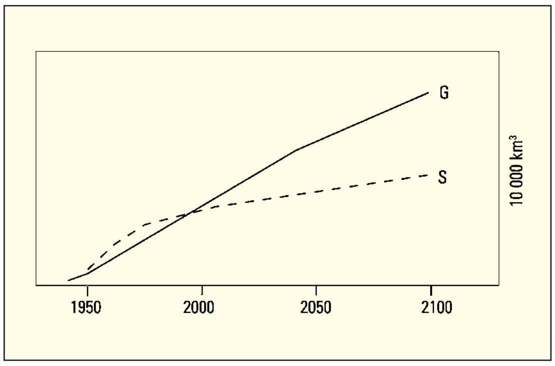
The evaluation of costs and benefits is more difficult for other functions of a dam, because the direct financial income is zero or a part only of the benefit to the customer.

For flood mitigation, the evaluation of average savings by the three most relevant countries (China, Japan and USA) are very high as compared with investments. By 2050, it is likely that the savings in flood damage resulting from dams will be more than $50 billon/year, much more than the relevant annual investments and O&M costs.

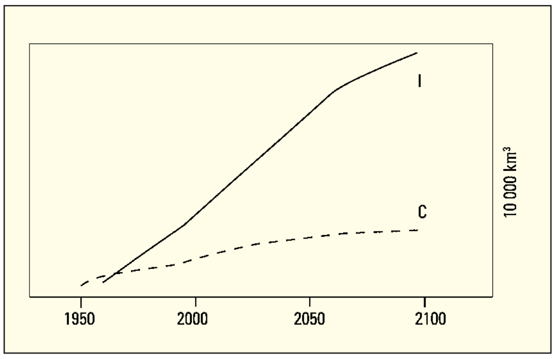
The direct financial income from water supply and irrigation is usually a small part of the corresponding value. The present cumulative investment is more than $500 billion at present values, and will probably double between 2000 and 2050. The relevant annual cost in 2050 can be very roughly estimated at $20 bil-



Likely reservoir volume in the 21st century: live storage used for irrigation water supply and flood mitigation (I.S.F.); live storage for hydro alone (H); and dead or silted storage (U).



Likely hydropower in the 21st century: total GWh/year (G) and cumulative storage (S) for hydropower.



Likely hydro total annual costs (C) and income (I) in the 21st century.

lion for investment and loan interests and $20 billion for O&M, that is, a total cost of $40 billion. The corresponding benefit will be food and water supply for 1.5 billion people: a unit annual value of $100 or $200 (for people having by then an annual income of more than $10 000) seems a low evaluation of $150 to 300 billion.

In 2050, the overall annual benefit of dams will be equivalent to some $500 billion for an overall expenditure of less than $150 billion.

9. Likely storage and lake area during the 21st century

A rough estimate of the storage during this century can be based on the following hypothesis:

- A hydropower supply increasing from 2800 TWh in 2000 to 5500 TWh in 2050 and 7000 TWh in 2100.
- An irrigation storage volume doubled during the century, most of the increase being before 2050.
- Other benefits (water supply, drought and flood mitigation) multiplied by 3 or 4 during the century, mostly after 2050.
- Annual reservoir sedimentation of 20 km^3/year, kept at the present level through various solutions (sluicing, flushing). Mostly of this refers to hydropower, with little impact on power supply.
- The increase in hydropower supply will require a much smaller storage volume than in the past (possibly 30 per cent), but the increase of other storage will be proportional to the needs.

10. Conclusion

It can be concluded that the overall benefits of dams during the 21st century will be five times what they have been since 1950; Technical, economic and environmental problems should not prevent the implementation of these extremely beneficial structures.

About 90 per cent of the water resources development potential is in countries which urgently need safe water and an electricity supply, for social and economic development. But the major required initial investments and complex procedures may delay them if there is inadequate public support.

The dissemination of fair and balanced information on the benefits of dams and the management of remaining drawbacks are thus essential. ◊

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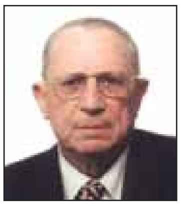
This paper, prepared by the ICOLD Commmittee on Governance of Dams, is subject to final approval by the ICOLD Executive Meeting, and is therefore not the final position of ICOLD. However, it is already published (and a presentation based on it will be given at the ICOLD Symposium in Barcelona in June), as it includes a large amount of data which demonstrate the usefulness and sustainability of dams.



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