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# 2.6 Dams – structures and functions – on a global scale

KLAUS D. AURADA & RAIMUND RÖDEL

***SUMMARY:*** *Nearly 15% of the global annual discharge could be stored in the 28,000 reservoirs world-wide. Benefits of dams and reservoirs are hydropower generation and irrigation water supply, flood protection, domestic and industrial water supply, fish farming, recreation and navigation. Hydropower accounts for 19% of the global power supply. In seven countries more than 50 % of the farmland is irrigated with water from dams. Due to the transformation of freely flowing rivers into lakes large dams and reservoirs cause environmental impacts. Evaporation losses, increased emissions of methane or hydrogen sulphide and increased health risk due to habitat providing for carrier organisms stand for impacts to the reservoir lakes itself. The biggest impacts in upstream and downstream basins are sediment trapping and river fragmentation. Large reservoirs reduced world-wide sediment load by 20% and affect erosivity in the river channel and estuarine environments. Fragmentation influence riparian habitats and obstruct the migration of aquatic organisms. 52% of the worlds large river basins are fragmented.*

The large dams, i.e. the dams that are more than 15 m high, number 28,000 world-wide. There are also many dams of smaller height. More than 21,000 × $10^6$ m³ water could be stored in connected reservoirs (ICOLD 2003), equalling nearly 15% of the global annual discharge.

At the beginning of the 20th century, dams were built primarily for flood protection and water supply. Today, their main purposes are hydropower generation and irrigation water supply. Most dams have multiple purposes. Secondary purposes which sometimes conflict with the main ones are flood protection, domestic and industrial water supply, fish farming, recreation and navigation.

Eleven nations harbour 75% of all large dams, led by the USA, China and India. Less than 5% of the total number are contributed each by Spain, Japan, Canada, Korea, Turkey, Brazil, France and Mexico.

The five dams with the largest reservoir volumes are the Kariba Dam at the Zambezi (Zimbabwe and Zambia), the Bratsk Dam at the Angara (Russia), the Aswan High Dam at the Nile (Egypt), the Akosombo Dam at the Volta (Ghana) and the Daniel Johnson Dam at the Manicouagan (Canada). Each of these reservoirs has a storage capacity of nearly 150,000 × $10^6$ m³ or more (ICOLD 2003).

Most of the world's dams were built between 1960 and the mid-1980s. Before 1960, most dams were built in industrialised countries (cf. *Tab. 2.6-1* and *Fig. 2.6-1)*). The proportion of dams erected after 1960 amounts to 90% of the 4664 Chinese dams, to 70% in India and to 73% in Africa. In North America and Europe, the technically most suitable sites in the mountain areas have already been appropriated.

The escalation in the rate and scale of large-dam construction until 1990 was mainly a result of economic activity. Today, dam development no longer depends on regional

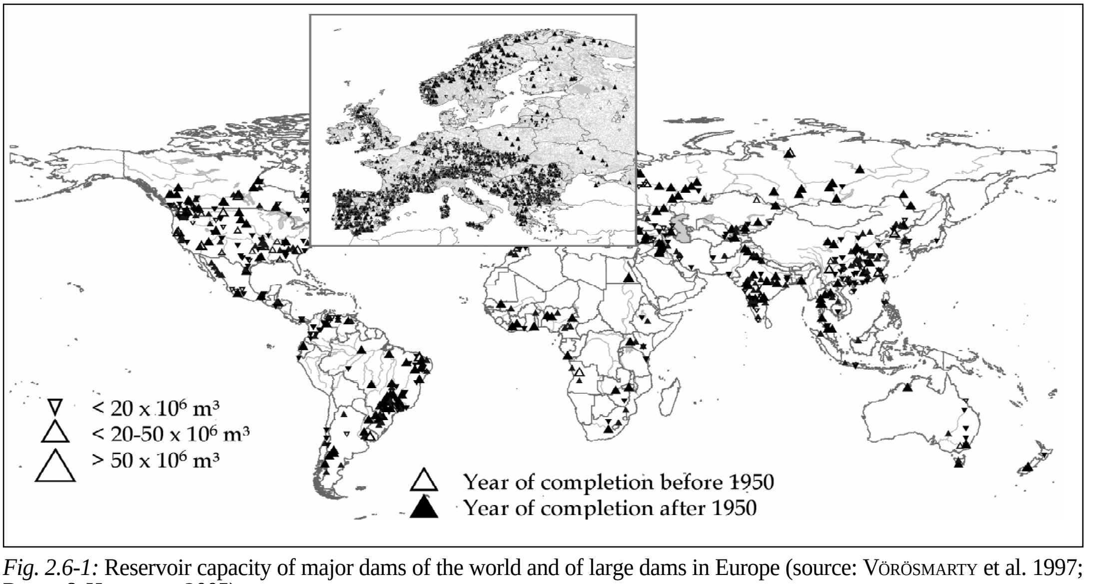


*Fig. 2.6-1:* Reservoir capacity of major dams of the world and of large dams in Europe (source: VÖRÖSMARTY et al. 1997; RÖDEL & HOFFMANN 2005).

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***Table 2.6-1:*** Growth of continental reservoir capacity (storage capacity > 0.1 km³) (ICOLD 1998, SHIKLOMANOV & RODDA 2003)

| | ***North America*** | | ***South America*** | | ***Europe*** | | ***Asia*** | | ***Africa*** | | ***Australasia*** | | ***global*** | ***Impoundment coefficients*** [a] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Time slice*** | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***[%]*** [a] | ***[km³]*** | ***min*** | ***average*** | ***max*** |
| –1900 | 8.4 | 0.11 | 0.3 | 0.00 | 3.3 | 0.11 | 1.7 | 0.01 | 0.1 | 0.00 | | | 13.8 | 0.04 | 0.03 | 0.02 |
| 1901–50 | 353.1 | 4.48 | 9.1 | 0.08 | 125.0 | 4.31 | 19.6 | 0.15 | 15.1 | 0.37 | 10.6 | 0.45 | 532.5 | 1.66 | 1.25 | 0.92 |
| 1951–60 | 607.5 | 7.70 | 37.9 | 0.32 | 300.0 | 10.34 | 313.2 | 2.32 | 396.2 | 9.78 | 30.7 | 1.30 | 1,685.5 | 5.26 | 3.94 | 2.93 |
| 1961–70 | 1,141.5 | 14.47 | 134.8 | 1.12 | 489.4 | 16.88 | 953.2 | 7.06 | 760.6 | 18.78 | 46.2 | 1.96 | 3,525.7 | 11.01 | 8.25 | 6.12 |
| 1971–80 | 1,480.5 | 18.76 | 386.3 | 3.21 | 593.0 | 20.45 | 1,437.3 | 10.64 | 934.3 | 23.07 | 88.6 | 3.75 | 4,920.0 | 15.36 | 11.51 | 8.54 |
| 1981–90 | 1,657.4 | 21.01 | 735.4 | 6.11 | 642.3 | 22.15 | 1,758.8 | 13.02 | 990.9 | 24.47 | 94.5 | 4.00 | 5,879.3 | 18.35 | 13.75 | 10.21 |
| 1991–96 | 1,692.1 | 21.45 | 971.5 | 8.08 | 645.0 | 22.24 | 1,980.4 | 14.66 | 1,000.7 | 24.71 | 94.8 | 4.02 | **6,384.5** | **19.93** | **14.93** | **11.09** |

[a] Impoundment coefficient: the ratio of total reservoir volume to continental annual discharge (the average continental discharges between 1921 and 1985 are given in SHIKLOMANOV & RODDA 2003)

economies (NILSSON et al. 2005). In 2005, dams were being planned or constructed in 46 large river basins. Forty of them are located in non-OECD (Organisation for Economic Co-operation and Development) nations, e.g. the dams at the Rio de la Plata (29 dams planned or under construction), at the Shatt Al Arab or in the Ganges-Brahmaputra river system (26 resp. 25 dams planned or under construction).

## Discharge volume controlled by dams/reservoirs

In 1970, nearly 11% of the global annual discharge was controlled by dams. The current proportion can be estimated as 15%. The impact intensity of impoundments on a hydrograph recorded at a gauging station can be expressed as the impoundment coefficient. The impoundment coefficient is the ratio of the cumulated upstream reservoir capacity to the annual discharge. As a rule, impoundment coefficients below 1 indicate that the water is redistributed only intra-annually (due to hydropower generation and flood protection). VÖRÖSMARTY et al. (1997) calculated impoundment coefficients for a set of large basins. *Fig. 2.6-2* shows the impoundment coefficients for gauging stations in Eurasia in 1990.

## The benefits of large dams

The management of water resources by means of reservoirs includes the storage capacities of the upstream basin (temporal snow cover, inter-flow from the unsaturated soil zone, groundwater from the saturated zone). It also includes the usable reservoir capacity including the flood protection capacity.

Dams offer no means to control the outflow from natural storages in the upstream part of the basin. The downstream flow regime, in contrast, can be controlled through the reservoir management which can reduce the risk and increase the utilisation potential of the water supply. From this viewpoint, individual reservoirs and reservoir cascades react as a socio-economic system (AURADA 2003, *Fig 2.6-3*). Up to a certain degree, this system can compensate for changes affecting the flow regime, like climate changes or altered schemes for water supply and flood protection.

## Flood control

The temporal and spatial flow variability of climate-dependent water resources entails both a supply potential and a hazard potential. The magnitudes of these potentials have changed in accord with the change in utilisation schemes.

A probability-orientated reservoir management concept defines the top and bottom limits of the acceptable water flow. $Q_{min}$ is the minimum quantity required to keep up water supply. The reservoir management should ensure that water flow never drops below $Q_{min}$, except for brief times during low-flow conditions.

$Q_{max}$ is the maximum acceptable flow quantity. It should not be exceeded except for short times during floods. A third parameter, $C_{max}$, defines the top limit of the water pollutant concentration (pollution/accident condition).

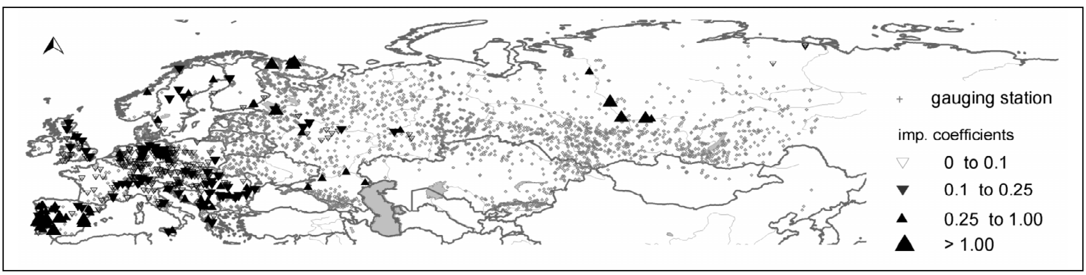


***Fig. 2.6-2:*** Impoundment coefficients for Eurasia in 1990.

Absolute hazard or supply safety can be guaranteed only within the tolerance limits $C_{max}$, and $Q_{max}$ to $Q_{min}$. The objective of water resources management should be to avoid a violation of these tolerance limits by low water events (dropping below $Q_{min}$), high-water events (overrun of $Q_{max}$) and sewage-burden accidents (overrun of $C_{max}$), or to keep their frequency and duration as low as possible.

## Hydropower

One of the greatest benefits provided by dams is hydropower. Currently, hydropower is produced in 150 countries and accounts for 19% of the global power supply. The Aswan High Dam accounts for 20% of Egypt's electricity production. There are 24 countries in which 90% of the national electricity production originates from hydropower (MIDDLETON 2003). The five dams with the world's highest annual energy production are the Itaipu Dam at the Parana (90,000 GWh/year), the Sanxia Dam (Three Gorges) in China (84,000 Gwh/year), the Guri Dam in Bolivia (52,000 GWh/year) and the Sayano-Shushenskoje and Bratsk Dams at the Yenissei River in Russia (both 22,500 GWh/year) (ICOLD 2003).

**Global hydropower potential**: A comparison of the hydropower potential with the actually produced amount of hydropower reveals that there is still an untapped potential for regional dam development in Asia, Africa and South America (cf. *Tab. 2.6-2*).

## Irrigation and water supply

Irrigation water supply is the second most important purpose of reservoirs. Water is a limiting resource of agriculture particularly in subtropical regions, where solar radiation and temperatures allow for a high vegetation productivity.

In seven countries (including India and China), more than 50% of the farmland is irrigated with water from dams (MIDDLETON 2003). There are large irrigation schemes in Israel and the Middle East, in Egypt and Sudan (Toshka project and Gezira scheme), in India (Ganges River) and China as well as in Middle Asia (Aral Sea).

Four of the five reservoirs that support the largest areas of irrigated farmland are located in China. The Xiaolangdi Dam at the Huanghe supplies water for 26,667 km² irrigated land area, and the Aswan High Dam in Egypt supports 24,000 km², followed by the Sanmenxia, Longyanxia and Liujiaxia Dam, all situated at the Yellow River (Huanghe) (ICOLD 2003).

*Table 2.6-3* gives the irrigated area as well as the amount and intensity of water consumption per continent. Global water consumption has increased from 1,365 to 3,760 km³/year between 1950 and 1995 (Deutsche Gesellschaft 1998, 66). It is estimated to reach 4,700 to 5,200 km³/year in 2025 (VÖRÖSMARTY et al. 2000, 284).

## Environmental impacts of large dams

Large dams and their reservoirs have many environmental impacts. These may be related to the reservoir lake itself

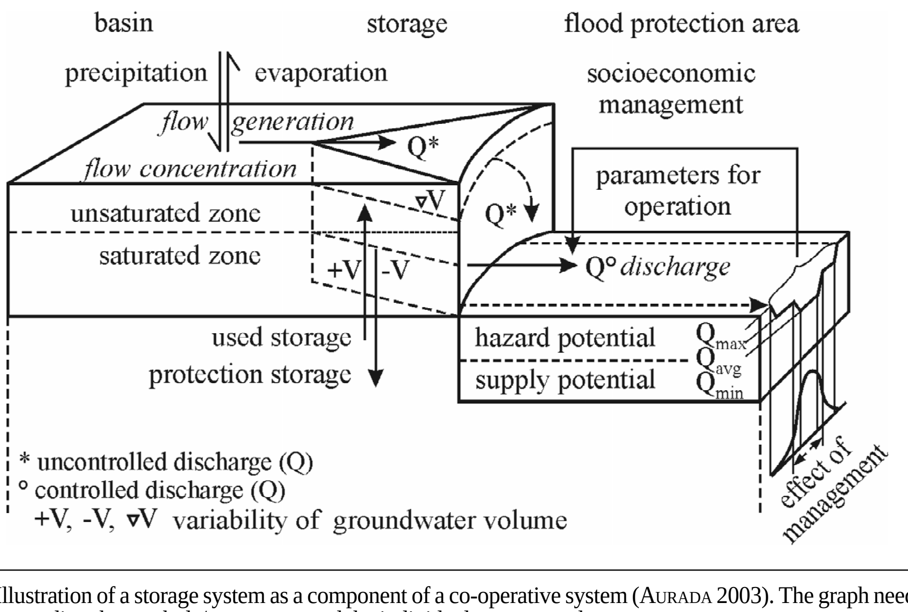


***Fig. 2.6-3:*** Illustration of a storage system as a component of a co-operative system (AURADA 2003). The graph needs more explanation regarding the symbols/parameters and the individual, represented processes.

***Table 2.6-2:*** Hydropower potential and actually produced amount of hydropower per continent in 2001 (modified from HORLACHER 2003, 13).

| *continent* | *Potential for hydro power generation* | | | *Actual hydro power generation* | | | *Hydro power schemes* | |
|---|---|---|---|---|---|---|---|---|
| | *theoretical*[a] | *technical*[b] | *economical*[c] | *installed power* | *generated power* | *hydro power used* | *under construction* | *planned* |
| | *[TWh/a]* | *[TWh/a]* | *[TWh/a]* | *[GW]* | *[TWh/a]* | *[GW]* | *[GW]* | *[GW]* |
| Europe | 3,220 | 1,035 | 791 | 175.6 | 593.4 | 75 | 1,978 | 8 |
| Asia | 19,400 | 6,800 | 3,600 | 241 | 793 | 22 | 68,664 | 154 |
| Africa | 3,876 | 1,888 | 1,100 | 20.6 | 80.6 | 7.3 | 1,806 | 75 |
| North America[d] | 6,312 | 1,663 | 1,000 | 158 | 700 | 70 | 3,931 | 12.1 |
| South America | 6,200 | 2,700 | 1,600 | 111.5 | 531.2 | 19.7 | 11,438 | 38.8 |
| Australia | 600 | 270 | 107 | 13.3 | 42.0 | 39 | 0.175 | 0.74 |
| Global | 39,608 | 14,356 | 8,198 | 720 | 2,740 | 33.4 | 87,992 | 288.6 |

a theoretical potential: potential of energy of all streams unless physical, technical or economic restrictions ***TWh/a = TWh/year***
b technical potential: potential under condition of technical, ecological and infrastructural restrictions
c economical potential: relation of hydropower potential to all other kinds of energy production.
d including Central America

***Table 2.6-3:*** Global water supply and utilisation (modified from UNESCO 1978).

| | *Total area* | *Irrigated area* | *Total discharge* | *Groundwater supply* | *$D_{reg}$ 1900*[a] | *$D_{reg}$ 2000*[b] | *$D_{usable}$ 1900* | *$D_{usable}$ 2000* | *Population [$10^9$]* | | | *Percentage of utilisation* | | *Change in water consumption* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *[$10^6$km²]* | *[$10^6$km²]* | *[km³/a]* | *[km³/a]* | *[km³/a]* | *[km³/a]* | *[km³/a]* | *[km³/a]* | *1985* | *2000* | *2025* | *1970* | *2000* | *scen1* | *scen2* | *scen3* |
| Europe | 10,500 | 0.273 | 3,210 | 1,120 | 3 | 422 | 1,123 | 1,542 | 0.667 | 0.780 | 0.682 | 10.0 | 15.4 | 1.9 | 30 | 31 |
| Asia | 43,475 | 1.690 | 14,410 | 3,750 | 2 | 1,350 | 3,752 | 5,100 | 2.930 | 3.630 | 4.800 | 10.4 | 12.9 | 2.3 | 60 | 66 |
| Africa | 30,120 | 0.118 | 4,570 | 1,600 | 0 | 1,240 | 1,600 | 2,840 | 0.543 | 0.750 | 1.440 | 2.8 | 3.2 | 10 | 73 | 92 |
| N-America[c] | 24,250[b] | 0.317 | 7,450 | 2,160 | 8 | 950 | 2,168 | 3,110 | 0.395 | 0.480 | 0.601 | 7.2 | 10.5 | 4.4 | 23 | 28 |
| S-America | 17,800 | 0.095 | 11,760 | 4,120 | 0 | 286 | 4,120 | 4,406 | 0.267 | 0.330 | 0.454 | 0.6 | 0.9 | 12 | 93 | 121 |
| Australia | 8,950 | 0.026 | 2,390 | 575 | - | 38 | 575 | 613 | 0.022 | 0.030 | 0.033 | 1.0 | 2.5 | 2.0 | 30 | 44 |
| **total[d]** | **135,095** | **2,520** | **43,790** | **13,325** | **14** | **4,286** | **13,339** | **17,611** | **4.830** | **6.000** | **8.010** | **5.9** | **7.8** | **4.1** | **50** | **61** |

a. AVAKYAN (1998) b. ICOLD (1998) and WCD (2000)
c. including Central America d. excluding the polar regions
scen1 = only climate change scen2 = only population increase scen3 = global change and population increase
$D_{reg}$ = regulated water supply $D_{usable}$ = Water supply km³/a = km³/year
increase of irrigation area and population after KLAUS & STEIN (2000, 128)
water resources after UNESCO (1978), supplemented for1900 and 2000
percent of utilisation: 1970 after UNESCO (1978), 2000 after KLAUS & STEIN (2000)
scenarios of change after VÖRÖSMARTY et al. (2000, 284)

but can be also observed in the upstream and downstream basins.

When the reservoir is filled, inundation affects terrestrial ecosystems and eliminates turbulent river reaches. The transformation of freely flowing rivers into lakes can cause increased emissions of gases like methane or hydrogen sulphide resulting from the anaerobic decomposition of submerged vegetation. Similarly, heavy metals may be released under anoxic conditions.

Another possible impact is a change in the local climate. Increased evapotranspiration leads to increased local humidity. The peak rainfall season in Central Ghana has shifted from October to July/August since the completion of Lake Volta (THANH & TAM 1990).

It has also been observed that the high pressure that the stored water excercises on the bedrock can favour earthquakes. SOBOLEVA & MAMADALIEV (1976) reported an increased probability of earthquakes at the Nurek Dam in Tajikistan.

Lakes provide a habitat for snails and other carrier organisms of schistomiasis (also known as bilharzia). Therefore, reservoir lakes increase the health risk for the local population. A second socio-economic impact is resettlement. 1,130,000 people lost their home during the realisation of the Sanxia Dam (Three Gorges) in China (ICOLD 2003).

Reservoirs and reservoir cascades greatly affect the downstream river basin. River regulation leads to changes in the flow regime, like decreased flood peaks and, consequently, smaller inundation areas. It can also reduce discharges and affect water quality and temperature, flow velocity and sediment transport.

## Sediment traps

Sediment trapping is a problem for both the reservoir itself and the connected river. The siltation of reservoirs strongly reduces their useful lifespan. SYVITSKI et al. (2005) reported a pre-dam suspended sediment load of about $3 \times 10^3$ kg/s for the Nile River. Today, there is only about 0.5 kg/s. This means that the related dam has a sediment trapping efficiency of virtually 100%. The suspended load of the Ebro in Spain has been reduced from 110 kg/s under pre-dam conditions to 10 kg/s. This corresponds to a trapping efficiency of 92% (VÖRÖSMARTY et al. 2003).

Reduced sediment transport to downstream areas affects the erosivity of the river channel and leads to changes in estuarine environments. Reservoir sedimentation also has economic impacts. LAHLOU (1996) reported that siltation diminishes total reservoir capacity in Morocco by 0.5% each year. Taking into account only the 84 large dams of the country, this means average yearly losses of $50 \times 10^6$ m³ drinking water, $60 \times 10^6$ kWh hydroelectric power, and 5,000 ha irrigated cropland.

The large dams of the world have exerted a major influence on the global sediment flux ever since the Industrial Revolution. Human activities like urbanisation, deforestation, agriculture and mining have deeply changed the environment and highly increased soil erosion and riverine sediment transport. Reservoir construction has reduced sediment fluxes by orders of magnitude. SYVITSKI et al. (2005) calculated the global modern-time sediment flux to be 12.6 billion tons per year, or 10% less than in the pre-industrial world. Large reservoirs reduce the sediment load in rivers by 20% world-wide, while 6% is trapped by small reservoirs. Without reservoirs, the global amount of suspended sediment transported down rivers would be about 16.2 BT/year. This means that 3.6 BT suspended matter per year are trapped behind dams and continue to fill up reservoirs. This number highlights the vulnerability of dam reservoirs due to the consequent loss of storage capacity.

SYVITSKI et al. (2005) describe large regional differences in the amount of sediment retained by reservoirs (cf. *Table 2.6-4*). Reservoirs in Asia and Africa retain 31% and 25%, respectively, of the continental sediment load. The most efficient sediment traps (47% average retention) are located in the cold temperate zone. In general, the greatest proportion of the continental sediment load is trapped in reservoirs located in mountainous and high-mountain areas (22 to 31%), except in tropical regions where the sediment load in the lowlands is exceptionally high due to massive deforestation.

The sediment trapped in reservoirs includes particulate matter as well as phosphorus, iron and silica. BRYDSTEN et al. (1990) describe the effects of river regulation in northern Sweden. Regulation decreased the transport of P and Fe particles by 10 to 15% and traps them in reservoirs. Reduced sediment transport can be also explained by reduced river bed erosion which in turn is caused by the regulation-related decrease in the intensity of high-runoff events.

## Fragmentation

Reservoir operations impede channel development, drain floodplain wetlands and reduce the dynamics of deltas due to changed flow regimes. Dams have a direct influence on riparian habitats. They obstruct the migration of aquatic organism and are thus one of the causes for the loss of freshwater species (NILSSON et al. 2005).

NILSSON et al. (2005) investigated 153 of the large river systems of the world which account for 60% of the world's river runoff. They quantified channel fragmentation and flow impacts caused by dams.

More than 50% of the world's temperate broadleaf and mixed forests as well as temperate grassland and savannahs are affected by river fragmentation. The most heavily affected river systems are located in deserts and arid shrublands as well in Mediterranean forests and shrublands. In these biomes, river regulation and consequent flood reduction diminish the productivity of floodplains and thus

***Table 2.6-4:*** Pre-human and modern-times sediment load in the world's landmasses and ocean basins (source: SYVITSKI et al. 2005).

| Landmass | *Area (Mkm²)* | *Pre industrial load (million tons per year)* | *Recent load (MT/year)* | *Sediment trapped behind dams (%)* |
|---|---|---|---|---|
| Africa | 20 | 1,310 ± 250 | 800 ± 100 | 25 |
| Asia | 31 | 5,450 ± 1,300 | 4,740 ± 800 | 31 |
| Australasia | 4 | 390 ± 40 | 390 ± 40 | 8 |
| Europe | 10 | 680 ± 90 | 680 ± 90 | 12 |
| North America | 21 | 1,910 ± 250 | 1,910 ± 250 | 13 |
| South America | 17 | 2,680 ± 690 | 2,450 ± 310 | 13 |
| Ocean basin | | | | |
| Arctic Ocean | 17 | 580 ± 120 | 420 ± 60 | 5 |
| Atlantic Ocean | 42 | 3,850 ± 800 | 3,410 ± 420 | 14 |
| Indian Ocean | 15 | 3,810 ± 1,020 | 3,290 ± 410 | 15 |
| Inland seas (endorheic) | 5 | 470 ± 180 | 140 ± 30 | 30 |
| Mediterranean and Black Sea | 8 | 890 ± 280 | 480 ± 60 | 30 |
| Pacific Ocean | 18 | 4,430 ± 1,100 | 4,870 ± 910 | 26 |
| **Global** | **106** | **14,030** | **12,610** | **20** |

***Table 2.6-5:*** Percentage of affected and unaffected areas and discharges in the world's large river basins (source: NILSSON et al. 2005).

| | *North and Central America* | *Asia* | *Europe* | *South America* | *Africa* | *Australasia* |
|---|---|---|---|---|---|---|
| Area unaffected | 39 | 55 | 26 | 70 | 38 | 30 |
| Area affected | 61 | 45 | 74 | 30 | 62 | 70 |
| Discharge unaffected | 50 | 62 | 33 | 89 | 71 | 93 |
| Discharge affected | 50 | 38 | 67 | 11 | 29 | 7 |

have a significant impact on aquatic species. Only 29% of the global tundra biome area is affected by river fragmentation. This low proportion results from the flatness of the landscape which makes it unsuitable for large dams (NILSSON et al. 2005).

In total, 52% of the world's 253 large river basins are fragmented, while 119 (41%) have unfragmented tributaries. Most of the unfragmented river basins, numbering 40, are located in North and Central America. Asia is the continent where the greatest proportion of the surface area (74%) remains unaffected by river fragmentation. In Europe, almost all river systems are fragmented; only small basins in northern Europe remain unaffected (cf. *Table 2.6-5*).

## Conclusions

This paper introduced a wide range of effects of large dams on large-scale hydrology. Reservoir cascades in big streams increase the safety of the water supply for agricultural and domestic uses. Irrigation made possible by reservoirs has contributed to regional development and poverty alleviation. A well-known example is India's Green Revolution in the 1960s and 70s. Hydropower has stimulated industrial development in several countries. Large dams have helped to significantly reduce the risk of flooding in downstream areas.

On the other hand, dams and reservoirs are an important factor in global environmental change. Water retention and extraction can affect large regions in complex ways. WBGU (1997) describe the causal webs relating to large dam projects as the »Aral Sea Syndrome«. Analyses of causal webs can highlight the limits of the desired development and help to avoid negative consequences.

The effects of dams on a global scale were described by VÖRÖSMARTY et al. (1997), SYVITSKI et al. (2005) and NILSSON et al. (2005). Further research is needed to asses the effects quantitatively. One global issue is the deterioration of reservoir capacity due to sediment trapping. How large is its impact on regional water supply?

Impact assessment will be facilitated when global databases of geo-referenced dams have become available. Dam databases are being developed in Sweden (University of Umeå), Germany (University of Greifswald) and Japan (Yamanashi University). The Water Systems Analysis Group at the University of New Hampshire and the FAO are also making valuable contributions to this field of research♦