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1.7 Natural surface waters as sources of freshwater – A way out of the global water crisis?

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SUMMARY: *In many parts of the world, freshwater requirements can no longer be met, despite the fact that the withdrawal of freshwater was increased by a factor of nine during the 20th century. The most serious consequences of inadequate freshwater supply are decreasing food production on irrigated land and serious threats to human health. Present attempts to alleviate water shortages mainly aim at increasing the quantities of water that can be made available. However, both large dams and large-scale irrigation projects lead to high water losses and to adverse environmental impacts that in the worst cases can offset their potential benefits. Due to the combined effects of population growth and economic growth, resource consumption including freshwater, is expected to rise further during the coming decades, especially in the lesser developed countries. Large-scale projects are planned in both China and India to redirect water from regions with excess water, to regions with water shortage. Negative environmental and social consequences of these and similar measures could be enormous.*

It is argued in this paper that a change of paradigm is necessary to solve the current freshwater crisis: Most important is greater emphasis on water quality, instead of merely attempting to increase the quantities of available water. Natural freshwater bodies could better serve as sources for freshwater than large reservoirs. However, because most large freshwater bodies are heavily polluted, using them more extensively would require a thorough clean-up. The experience in many industrial countries has shown that freshwater ecosystems recover from degradation within 10–20 years. The use of natural surface waters as sources of freshwater requires the definition of critical loading thresholds for plant nutrients and noxious substances in order to secure their water quality.

Freshwater is a renewable resource. Nevertheless, global water supply is restricted because only water that is regenerated by the hydrological cycle can be utilised in a sustainable fashion. Due to the unprecedented growth of the world population during the 20th century, the capacity of the hydrological cycle to meet the demands of humanity has reached its limits. Humanity now uses 26% of total terrestrial evapotranspiration and 54% of the runoff that is geographically and temporally accessible (POSTEL et al. 1996). To give a few figures:

- During the past 50 years, the global demand for freshwater has doubled.
- As many as 1.2 billion people in 1990 did not have access to water of adequate quality for drinking and hygiene, and 1.7 billion people lacked access to adequate sanitation services (GLEICK 1996).
- Every year, about 5 million people die of diseases related to the inadequate supply of freshwater (WWAP 2003).

In this article I first examine the mismatch between water supply and demand and subsequently will discuss the usage of surface waters as sources of freshwater. The conclusion will be that ecosystem health is an essential pre-requisite for the usage of inland waters as sources of freshwater.

World population growth, water supply, and water demand

Between 1900 and 2000 the world's population has increased from ca. 1.8 billion to 6.0 billion. Until about 1940, the average human being suffered from water stress. Due to intense technical efforts, the amount of water withdrawn world-wide has risen by a factor of nine during the 20th century. As a result, the average quantity of water available to the individual was substantially improved. However, since about 1990, rising water withdrawals no longer can keep pace with the continued growth of the world population (GLEICK 2001, *Fig. 1.7-1*). A water supply of 1,700 m³ per person and year is considered abundant. A range of 1,000–1,700 m³ per person and year is considered limited, but still allows the satisfaction of the basic needs. Water is becoming scarce at levels below 1,000 m³ per person and year, and inadequate to meet the demands of the population at levels below 500 m³ per person and year (*Table 1.7-1*).

The most serious consequences of inadequate water supply are twofold:

- **Shortage of water for irrigation severely jeopardises food production:** FALKENMARK (1997) has estimated that at minimum 900 m³/year *per capita* are needed for food sufficiency. On average, it is estimated that water use efficiency of irrigation is only 38% in developing countries (WWAP 2003). In most of the worst affected countries, ditch irrigation is used which leads to water losses, mainly by over watering[1] and evaporation. Even by applying simple »low-tech« improvements such as treadle pumps, losses can be cut in half (POSTEL 2001). Water use efficiencies by using sprinkler irrigation systems are between 60 and 85%. By drip irrigation systems, water losses can be lowered to 2% (ROGERS et al. 1997). In Northern China, agricultural productivity per volume of irrigation water has increased by a factor of three from the time-span 1966–78 to 1989–98, respecti-

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Table 1.7-1: *Per capita* water supply in some countries, as of 1995. The left column includes countries with abundant water; in the central column countries with limited water supply are listed. The right column includes countries whose water supply is insufficient to meet all essential demands. All of the last-mentioned countries use fossil groundwater[3]. Source: ENGELMAN et al. 2000).

Country	m^3/year	Country	m^3/year	Country	m^3/year
India	1,882	U.K.	1,207	Kuwait	10
Iran	2,031	South Africa	1,238	Libya	107
Germany	2,080	Somalia	1,337	Saudi Arabia	111
U.S.A.	8,902	Lebanon	1,463	Israel[2]	346
Austria	10,998	Peru	1,559	Egypt	851

vely, due to more efficient water use (WWAP 2003).

- **Shortage and contamination of water for domestic use:** GLEICK (1996) has recommended that in private households, 50 litres/person are needed dayly as absolute minimum, which adds up yearly to 18 m^3/person. In 1996, this minimum was not available in 55 countries. The situation is worst in sub-Saharan Africa and Southeast Asia[4]. Not all worst-hit countries have arid climates. Inefficient supply systems (water pipes and valves) cause losses of 30–40% (WWAP 2006)[5]. However, even more serious are the consequences of poor water quality, especially due to inadequate hygiene. Diseases caused by infections from water are among the largest causes of premature death in developing countries, exceeded only by respiratory ailments and HIV/AIDS[6] (WWAP 2006; *Table 1.7-2*).

Children are most seriously affected by infectious diseases, especially by diarrhea. Ironically, most water-related infectious diseases are easy to treat. Virtually all countries with high birth rates also suffer from severe water stress. Some of them are extremely poor; some of them are stricken by social unrest and civil war (*Table 1.7-3*).

Current and future strategies toward the resolution of the global water crisis

At present, over 98% of world population growth takes place in the underdeveloped regions of the world. In China and India alone, 32% of the world-wide population growth occurs (Population Reference Bureau, August 2005). Both countries already now face severe water problems. The situation is aggravated by the unprecedented economic boom in both countries[7], which will lead to increases in per capita water demand, both for industrial and domestic use. A simple way of estimating expected increases in overall resource demands is by assuming that the resource consumption by any given country is a function of the product population size multiplied by gross domestic product (GDP). On average, China's GDP is increasing at a rate of 9%/year, and its population grows by 0.6%/year. If the current trends continue, total resource demands will double in 7.6 years. India's GDP grows by 7.5% annually and its population by 1.6%. Provided that the current trends continue, resource consumption in India will double within the next 7.9 years.

In the following, current and planned attempts to solve the water crisis will be critically examined

Water storage in large reservoirs

During the past 50 years, 40,000 large dams have been constructed world-wide. The majority of large reservoirs lie in semi-arid and arid regions. The combined surface area of all major reservoirs on Earth is ca. 400,000 km^2, which is almost twice the surface area of the Laurentian Great Lakes (Superior, Huron, Michigan, Erie, and Ontario) taken together (244,000 km^2). The experience of the

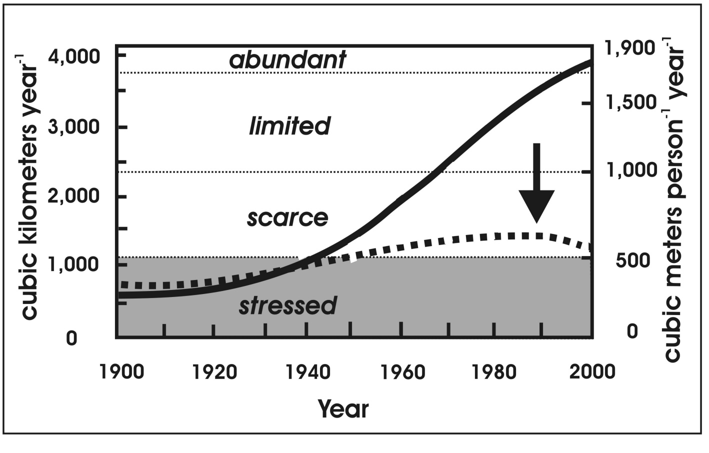

Fig. 1.7-1: Global annual water withdrawals during the 20th century. Total withdrawals: Left axis and solid line. *Per-capita* withdrawals: *Right axis* and *dotted line*. Also shown are the threshold values for the annual *per- capita* freshwater demand. If the current trend continues, the global per capita withdrawals in the near future will become insufficient to meet the most fundamental demands of humanity (*shaded area*, arrow). Modified after GLEICK (2001)

past decades has dampened the initial enthusiasm concerning large reservoirs. Large dam projects have grave environmental consequences and turned out to be rather short-lived. In recognition of their shortcomings, one of the forerunners of dam construction, the U.S.A., is beginning to dismantle dams (THE JOHN C. HEINZ III CENTER FOR SCIENCE, ECONOMICS, AND THE ENVIRONMENT 2002).

Despite of this, ambitious new dam construction projects are currently being launched along the River Nile (ROBINSON 2006). With a total length of 6,695 km, the Nile is the longest river on Earth. Currently nine large dams or barrages exist, the largest being the Aswan High Dam in Upper Egypt which was constructed in 1971. It provides 2,100 megawatts of electricity. Six more projects are planned, the largest of which is the Mirowe reservoir in Sudan that is to produce 1,250 megawatts of electricity. For its construction, 50,000 people would have to be resettled. Large projects are planned also in Uganda and Ethiopia which are among the poorest and most severely water-starved countries on Earth (*see Chart 13* in blurb). It is estimated that along the Blue Nile which provides 85% of all Nile water, 30,000 MW of electricity could be produced. Uganda's population now is 29 million and is expected to rise to 127 millions by 2050. Ethiopia's is expected to grow from currently 77 million, to 170 millions in 2050. The projects are supported by the World Bank as a way out of poverty. The countries involved attempt to co-ordinate their activities through the Nile Basin Initiative. Whether all the planned activities along the course of the river can be reconciled with each other is an open question. Possible environmental consequences of these and other large projects are summarised below:

Table 1.7-2: Water-related infectious diseases. Annualy statistics (Source: WWAP 2006).

Disease	*Number of people affected (millions)*	*Number of deaths*
Diarrhea	4,000	1.8 millions
Typhoid and Paratyphoid	17	600,000
Hepatitis A	1.4	none
Cholera	0.384	20,000

Table 1.7-3: The countries with the highest relative population growth rates, as of mid-2005 (Source: 2005 Population Reference Bureau, August 2005).

Country	*Relative growth rate (% /year)*	*Population doubling time (years)*
Palestine	3.4	20
Liberia	2.9	24
Saudi Arabia	2.7	25
Afghanistan	2.6	27
Nigeria	2.4	29
Sierra Leone	2.3	21
World average	1.24	56.2

• **Alteration of the water balance:** By increasing evaporation, especially in dry climate, water losses by evaporation are enhanced, thereby leading to diminished river discharge downstream. Regular seasonal flood events along many major rivers were essential for the natural cycle of floodplains, mainly by providing water »at the right time« and by delivering nutrient-rich sediments. In the Nile Valley now artificial fertiliser has to be applied and currently available freshwater is expected to be sufficient only until the year 2017 (HAMZA & MASON 2004).

• **Increased erosion:** The lack of sediment load in the water downstream of large dams leads to enhanced streambed and coastal erosion. The Nile Delta is a drastic example, but coastal erosion is also common in other regions. As a consequence, coastal ecosystems such as mangroves are affected. Impacts of coastal erosion on the human civilisation can be expected because rising proportions of the world population settle in coastal regions, especially in developing countries.

• **Ecological consequences:** By the construction of large dams, vast areas are altered. Stream-, wetland-, and floodplain ecosystems, both up- and downstream, are irreversibly lost. Both aquatic and terrestrial animals are affected. Migration of fishes and other animals is prevented.

• **Hazards:** Some of the major dams are situated in seismically active regions; Turkey, China, and Northern India are examples. Dam failures in the aftermath of earthquakes can have devastating consequences. The main process triggering dam failures are landslides into reservoirs. Another hazard is the spread of waterborne diseases such as Malaria and Bilharzias.

The largest dam construction project currently underway is the Three Gorges Project, to be completed by 2009: It mainly aims at hydroelectric power (target: 18,200 megawatts, or 10% of China's need for electricity), and flood control. On the negative side are the destruction of the ecosystems of the Yangtze River, including the threat of extinction of species such as the Yangtze dolphin, resettlement of between 1.1 and 1.6 million people, and the destruction of land and of cultural treasures.

Redirection of water supply

Two possible strategies are possible: Large-scale irrigation schemes and trans-basin redirection of streams.

• **The Aral Sea Disaster:** The most notorious case of a failed irrigation project has been the destruction of the Aral Sea ecosystem by the use of the water of the two main tributaries Amu-Dar'ja and Syr-Dar'ja for irrigation of cotton plantations. The results of this ill-fated project are considered to be the worst environmental disaster caused by man until now: Between 1960 and 1998, the lake lost 60% of its area and 80% of its volume. The lake level dropped by 18 m. Salinity rose from 10 to 45 g/litre. The ecosystem structure of the lake was completely destroyed with devastating economic consequences for the local population due to the collapse of the fisheries which had been the main source of income for the local population (The Aral Sea Homepage, 1999).

Large projects with the aim to redirect water from regions with excess water to regions with water scarcity are under consideration both in China and India. In the following, both proposals will be briefly discussed.

• The South-North Water transfer Project of China: In the eastern provinces of China where most of the population lives, two vastly different regions can be distinguished: The humid South, basically along the Yangtze River, which is inhabited by 700 million people. As much as 80% of the water resources of the eastern provinces, as well as two thirds of the cropland are available in this region. In the North, mainly along the Yellow River, the situation is reversed: The region is inhabited by 450 million people. *Per capita* water availability is only between 300 and 500 m^3/year, well below the absolute minimum requirement. Nowhere else in the world, so many people are faced with so little water. The monsoon climate is characterised by extremely variable rainfall between years. Damaging droughts and floods are the consequence. In Northern China, rainfall is 70% below average every four years, and 50% above average every 20 years (Berkoff 2003). Two thirds of the cropland of China is located here, but only one third of the water. There is concern that, as a consequence of water shortages, agricultural production will decrease. The extreme water deficiency in Northern China is also evident from the lowering of the groundwater table. In the Beijing region, the groundwater table drops by ca. 1 m every year, in the worst affected regions up to 3 m. Over the past few decades, the discharge of the lower Yellow River has decreased markedly. Main causes are water storage and sedimentation of the 46 large upstream reservoirs, changes in land-use, and warming of the central Asian climate. The increase in agricultural, domestic and industrial water consumption, in step with socio-economic development, has substantially contributed to the problem. Due to the decrease in river discharge, no-flow and nearly no-flow events occur frequently. To date, the worst year for no-flow events was 1997, during which no water from the Yellow River flowed into the sea for a period of 330 days (Borthwick 2005).

Large projects are currently underway or planned, by which China hopes to overcome its water shortage. The main objective is to redirect water from the humid south to the dry north by systems of reservoirs and canals. Three major pathways are envisaged to link the Yanktse and Yellow River watersheds.

Altogether, 43 km^3 of water are planned to be transferred from the Yangtze to the Yellow river watershed every year. It is questioned, however, whether the preservation of comparatively low-quality agriculture in North-eastern China would justify the enormous costs. The overall project would involve the resettlement of some 300,000 people, a small figure, if compared to the Three Gorges Project (Berkoff 2003).

An additional perhaps even more controversial project is under discussion which would divert water from the Brahmaputra (Yarling-Tsangpo) before leaving Chinese territory in eastern Tibet to the yellow River watershed. It would require the construction of a 15 km long waterway through the Himalayas which, according to Chinese experts, could only be achieved by using nuclear explosives. This proposal has raised considerable international concern because of the intention to use of nuclear explosives during construction (Horgan 1996). Early objections did not take into consideration the environmental and geopolitical consequences to be expected if this project would go ahead. Since then, more attention has been paid on the environmental destruction to be anticipated in an extremely remote pristine area of exceptional value, as well as the implication for the downstream users of the Brahmaputra water (India and Bangladesh).

• The Indian River Linking Project: India reached the one-billion mark at the turn of the century (almost three times of its 1951 population of 361 million). India's population is projected to exceed China's population with 1.5 billion people by 2040. India's population density at present is 305 persons per square kilometre, which already is high, given the scarcity of all resources required for sustaining the population (South Asia Voice, 2006, http://india_resource.tripod.com/savoice.html). Water availability that is already extremely low in some regions will become a pressing national issue within the next few decades. The national average annual precipitation is 1,100 mm and the mean per-capita water availability is yearly ca. 1,800 m^3/person. However, regional differences are enormous. Whereas annual precipitation in Assam of 12,000 mm is one of the highest in the world, other areas are extremely dry (Rajastan: 11 mm).

To address these issues, the River-Linking-Project was designed by which water would be diverted from water-rich regions, mainly in the north of India, to water-depleted regions (*Fig. 1.7-2*; Khalequzzaman et al. 2004).

The main objectives of the plan can be summarised as follows:

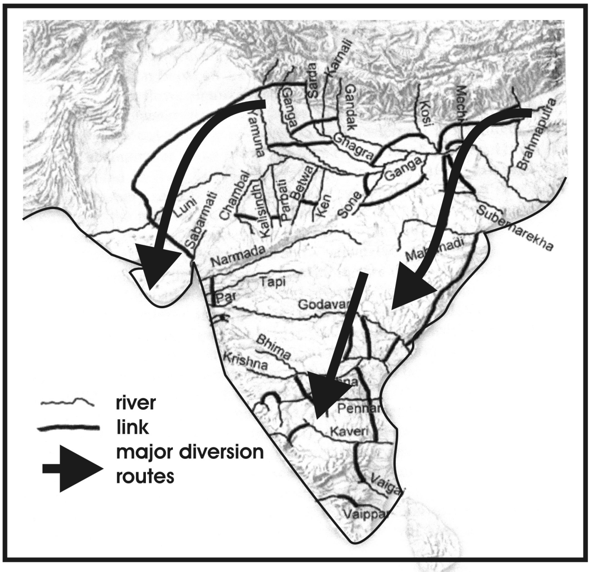

Fig. 1.7-2: Proposal of the Indian Interlinking of Rivers Project (IRLP), by which water from presumed water surplus regions, mainly from the upper Ganges and the Brahmaputra, is to be diverted to water deficit regions, mainly in western and central India. Modified from KHALEQUZZAMAN et al. 2004.

- To utilise surplus and/or as yet underused river flow to water-deficit regions areas in southern and western India,
- To control the twin problems of flooding and drought,
- To irrigate additional 400,000 km^2 of land,
- To produce additional food-grains,
- To generate 35,000 megawatts of electricity, and
- Additional anticipated benefits include flood control, navigation, water supply, fisheries, salinity control, and pollution control.

The proposed cost of the project has been calculated to U.S.$ 120 billion, that is, 20% of the Indian GDP, or 1.7 times the current annual budget if India.

The planned measures would require the acquisition of 2,940–4,000 km^2 of land and the displacement of ca. 490,000 people. Concerns about the consequences of this project focus on ecological and political aspects (KHALEQUZZAMAN et al. 2004). The most serious problem will be the decrease of the sediment loads of both the Brahmaputra and the Ganges. Decreasing sediment load in the Gulf of Bengal could lead to delta erosion that would be aggravated by the current sea-level rise which at present is 5–7 mm per year. Delta erosion could destroy coastal ecosystems including the largest mangrove in the world, the *Sundarban*. Since sediments carry nutrients, fertility of arable land will decline. If the water withdrawal would be evenly distributed over the year, the annual flow of the Brahmaputra would be only ca. 10% of the current flow.

Since India, unlike China, is a democratic country, official opposition can be expressed more freely, and measures can be taken. The states of Kerala, Bihar, West Bengal, Assam, Punjab, Chhatisgarh, and Goa have opposed the project, in addition to protests from NGOs and internationally renown individuals[8] .

Competition for water between different users

Both China's mineral resources and arable land are concentrated in the Northern provinces where water is scarce. Here 75% of crop production takes place on irrigated land (BUTLER 2005). Over the past decades, water allocation for agricultural production has diminished due to rising industrial water demand (*Fig. 1.7-3*). Main reason for this trend is the fact that industry is prepared to pay considerably more for water than is agriculture.

Due to a sequence of dry years, in combination with inadequate water resource management, water shortage in northern China has become more severe. Grain production has decreased by 20% between 1998 and 2003. The drop in grain production is mainly due to the shrinkage of harvested area (by 18% between 1998 and 2003), the loss of irrigation water, and the expansion of deserts (BROWN 2004). Industry likewise suffers from water shortage. Experts predict that water supply interruptions may occur in industries that are particularly dependent on water such as iron and steel, petroleum production and refining, chemicals, paper making, and dyeing. Hydroelectric power output also suffers from low runoff, by which industry is further affected (BUTLER 2005). Water shortage imposes serious constraints both on industrial and agricultural outputs (U.S. Embassy, Beijing, 1997). As a consequence, competition between different water users is becoming more severe.

In China, water on the average is priced 40% below its actual cost. In recognitions of this, prices for both domestic and industrial water in Beijing were raised by 28.5% in June 2004 (China Daily, Online Edition). It is expected that water prices in China will rise by 500–5,000% over the next ten years (BUTLER 2005). There can be little doubt

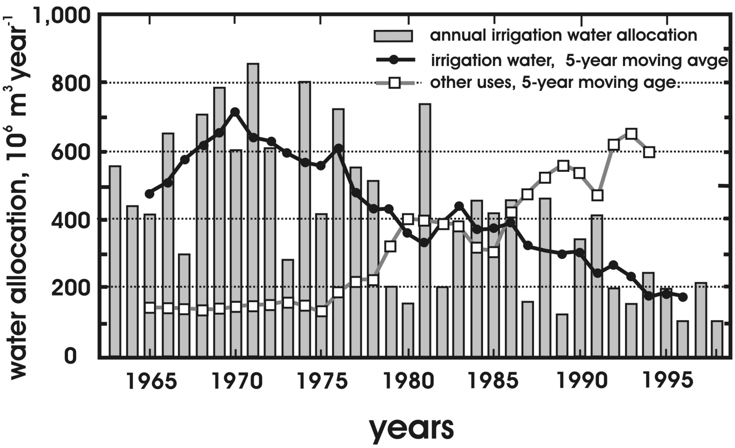

Fig. 1.7-3: Water allocation for irrigation and other uses in the Zhangshe District, at the Yellow River, Northern China, 1963–1998. The amount of water that could be used for agriculture steadily declined at the expense of other uses, mainly for industry (Redrawn after WWAP 2003).

that more realistic water prices will create incentives for more economic water use. However, the water problems are not restricted to the dry north. Most rivers and the groundwater of 90% of China's large cities are heavily polluted. As many of 700 million Chinese drink water contaminated by animal and human waste. Many cities use untreated industrial wastewater to irrigate crops, especially vegetables in suburban areas (Source: Jasper Becker, 2003, The death of China's rivers, Asia Times, Online).

Urgently needed: Change of paradigm in the management of global freshwater resources

The analysis on the preceding pages has shown that in the majority of cases, two principles have guided attempts to overcome the global freshwater crisis: (1) Strategies are primarily aimed at increasing the supply: The more water is provided, the better the demands of the water users can be met. (2) Emphasis has been mainly on water quantity; quality considerations have been only of secondary concern. Here I argue that avenues toward improving the current situation should follow the opposite direction: (1) Water allocation should be oriented by the actual demand, rather than by attempts to maximise the supply. (2) Considerably more emphasis should be on water quality. Supply-side oriented strategies are mainly based on large-scale technical solutions. In the majority of cases, adverse side effects such as the disruption of the natural water balance and ecological degradation are neglected. The fact is disregarded that only water of a certain quality can adequately meet the demands of the users. This argument is important in both directions: If the standards of high-quality users are not met (mainly private households and agriculture), human health and food security is put into jeopardy. If, on the other hand, high-quality water is allocated for uses that do not require this quality (for example, using drinking water for washing a car), water is essentially wasted. Also for other reasons the current policy leads to the wasteful use of freshwater: (1) Ample supply and artificially low water prices will not create incentives to conserve water. (2) Careless handling of water resources ultimately will create the need for more water.

China was chosen here as a case-study, not only because of the scale and severity of its water problems, but also because the conceptual flaws of its water management policies clearly show trends that are seen world-wide. In the concluding section of this paper it will be shown that small-scale solutions are more promising than mega-projects with unforeseeable side-effects, and that natural surface waters, if properly managed, can serve as optimal sources of freshwater.

Natural surface waters as biological reactors

Natural ecosystems consist of physical settings in which communities interact. A remarkable feature of these communities is their tendency toward stability by negative feedbacks, whenever physical conditions allow this. The main reason for this internal stability is the fact that most of the material is recycled within the system, and that only little waste is produced (*Fig. 1.7-5*)[9]. This is important, not only for the ecosystem functions, but also for the role of inland waters as sources of freshwater. By the interaction between the communities with different functions, external perturbations can to some degree be absorbed without major structural changes (homeostasis). The system thereby is capable of swinging back to its original condition, once external perturbations have subsided (resilience).

Inland waters are integral parts of the landscape surrounding them. They receive water from their watershed (drainage basin). In addition, water is introduced to the system directly from the atmosphere by precipitation (airshed). Whereas the contribution of water from the airshed is negligible in small lakes, it can be significant in large lakes, especially when the drainage basin is small compared to the lake itself. The water residence time within the system in question is a function of the volume of the water body, and is inversely related to the amount of water entering the system per unit of time (*Fig. 1.7-4*). Streams can be considered as water bodies with extremely short water residence times. The watershed not only delivers water, but also substances dissolved or suspended in the water. From watersheds undisturbed by human influence, mainly inorganic plant nutrients and mineral sediments are delivered[10]. By disturbed watersheds, also toxic and otherwise noxious substances are released.

Within the water body, the communities of organisms interact with the introduced substances. Inorganic nutrient salts are taken up by aquatic plants[11] that build up biomass (living substance). The plant biomass is subsequently consumed by animals that release the end products of their metabolism to the environment. Dissolved organic substances, mainly released by aquatic plants or animals are consumed by heterotrophic bacteria and fungi which decompose them into their inorganic constituents. The production of organic matter by photosynthesis generates molecular oxygen as a waste product during the cleavage of water. Because photosynthesis requires light, it is restricted to near-surface layers. Most of the oxygen produced during photosynthesis is released to the atmosphere.

During summer, when most of the biological production takes place, stagnant water bodies are thermally stratified: Warmer and therefore less heavy layers of water reside near the surface, and are separated from cold and therefore heavier water below. Both water layers usually are separated from each other by a layer with a steep temperature gradient (the thermocline). This prevents the exchange of dissolved material between the upper warm and the lower cold water layer (*Fig.1.7-5*).

Suspended particles, however, can sink from the warm surface layer across the thermocline to the cold deeper water. Therefore, when organisms die, their remains sink to the bottom. During the process, they at least in part are decomposed. Since most of the decomposition of organic matter is an oxidative process, oxygen is consumed. The consumption of dissolved oxygen in the cold deep waters cannot be compensated for. This has two reasons: (1) Deep waters cannot mix with surface waters due to their density difference, and consequently cannot take up oxygen by dissolution upon contact with the atmosphere. (2) In most cases, insufficient light is available in deep waters for oxygen-producing photosynthesis[12]. The more inorganic nutrients are introduced from the watershed, the more biomass is produced in the upper water layers by photosynthesis, and the more dead organic matter settles toward the lake bottom. Oxygen consumption by decomposition, therefore, is a function of the production of organic matter near the lake surface, which in turn depends on the influx of inorganic nutrients into the system from the watershed.

In undisturbed watersheds, a quasi-stable dynamic equilibrium is established: A constant amount of nutrients enters the system, producing biomass, leading to a certain extent of oxygen consumption in deep waters. If, however, watersheds are disturbed, this dynamic equilibrium is disrupted. As long as the influx of matter remains small, it can be absorbed by the system. If, however, a critical threshold is exceeded, the system can no longer absorb this perturbation, and the dynamic equilibrium is disrupted. In most cases the condition of the aquatic ecosystem deteriorates as a consequence.

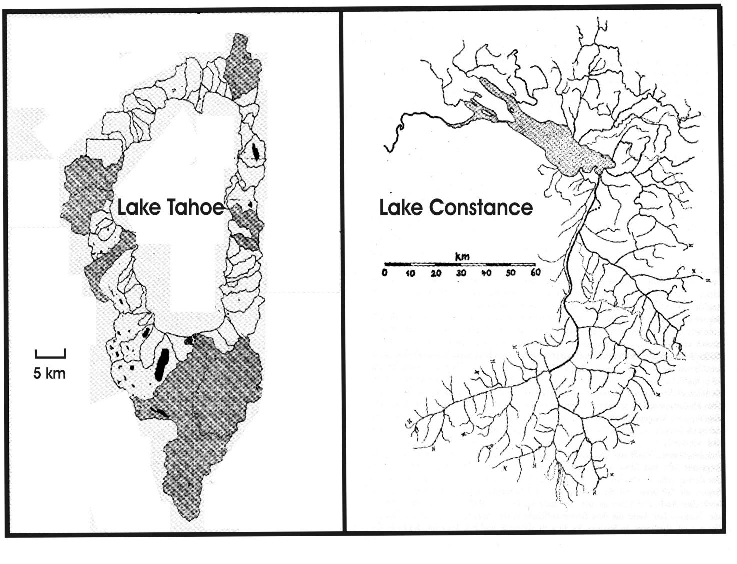

Fig.1.7-4: Comparisons of two lakes having vastly different lake-watershed ratios. Both lakes have comparable surface areas (Lake Tahoe, California/ Nevada: 503 km^2, Lake Constance, Germany/Austria/Switzerland: main basin: 470 km^2), but Lake Tahoe is tree times as deep and voluminous (mean depth: 313 m, volume: 156 km^3) as Lake Constance (men depth: 100 m, volume 50 km^3). The area of the Lake Tahoe drainage basin (not including the lake itself) is only 830 km^2, whereas that of Lake Constance is ca. 10,000 km^2. Therefore, the theoretical water retention time (the time required for the complete renewal of the water stored in the lake if all water would be renewed at the same rate) in Lake Tahoe is ca. 700 years, whereas in Lake Constance it is only 4.5 years.

The critical loading concept

The sensitivity of lake systems to external perturbations to a greater extend depends on properties of the physical environment than on the communities of organisms inhabiting the system. Most important variables are the water retention time and the mean depth of the lake system. At least in principle, they can be expressed in simple quantitative terms[13]: (1) the slower the renewal of the water, the longer will substances remain in the system and affect communities and their dynamic interactions. (2) The deeper a lake, the more diluted any substances entering the lake will be. Since effects of dissolved substances depend on their concentrations, more dilute substances will be less effective.

The thresholds at which inland waters are perturbed, therefore, is determined mainly by the relationship between the watershed size[14] and the lake volume, which is a function of the surface area, multiplied by the mean depth of the lake. Shallow and/or waters with long water retention times are more susceptible to external disturbances than are deep and/or rapidly renewed water bodies. Rivers are usually much shallower than lakes. But their water is renewed at a many times higher rate (the water retention time is extremely short). As a consequence, rivers as a rule can absorb considerably larger quantities of substances before being disturbed than lakes.

The critical load is the minimum amount of material introduced to a system that is causing a disruption if the ecosystem functions. It defines the absorption capacity threshold of a system. From what has been said earlier, we can conclude that deep and/or rapidly renewed water bodies have higher absorption capacity thresholds and hence critical loads than shallow and/or slowly renewed systems. To take the example of *Fig. 1.7-4*: Lake Tahoe is three times as deep as Lake Constance and has a tree times larger volume, which means that material is diluted three times more. However, since the water retention time of Lake Tahoe is 110 times longer than that of Lake Constance, we can expect that Lake Tahoe is considerably more susceptible to external perturbations than is Lake Constance. Actual observations confirm this.

The principles by which critical loading thresholds of inland water systems are determined were first developed with respect to the influx of plant nutrients, by which the productivity of the system is increased (VOLLENWEIDER 1968, 1975, 1976). Since at the same time, the existing dynamical equilibrium is disrupted, excessive nutrient loading leads to a deterioration of water quality. This complex syndrome has been called eutrophication. It is the most common disturbance of aquatic ecosystems (see Box).

The suitability of natural inland water ecosystems as sources of freshwater

Water quality is mainly determined by the quantity and nature of substances dissolved or suspended in the water. Since, as mentioned, ecosystem perturbations are dependent on the concentrations of the substances causing these

Box: Environmental degradation of inland water bodies due to hyper-critical loading

Eutrophication (over-fertilization): The most common cause is the influx of phosphorus-rich water, mainly from domestic sewage. The result is increased biological productivity, however at the expense of diminished water quality (turbidity, oxygen depletion in deep waters.

Consequences - Changes in fish populations to lower-quality species: Extreme cases are fish kills, mainly due to oxygen depletion in deep water; noxious algal blooms.

Pollution (pesticides, heavy metals, endocrinous substances): A multitude of alien substances is introduced into freshwaters, mainly by industry, but also from domestic sewage. A particular problem is the accumulation of substances that cannot be degraded by the community the food chain as well as in the bottom sediments. Consequences: Elimination of biota, toxicity of water.

Acidification (acid rain, especially nitric and sulfuric acids): Soft waters (that is, waters with low contents of Ca and Mg) are particularly susceptible to acidification because of the low buffering capacity of the water (keeping the pH of the water above neutrality). Acidification has negative impacts on ionic balances of freshwater biota. Moreover, acidification can lead to the solubilization and the subsequent release of toxic metals (especially aluminum and heavy metals) from the bottom sediment.

Consequences - Elimination of fish populations

Introduction of non-indigenous species: (introduction by accident or of usable species): Frequently, introduced plants and animals out-compete indigenous species. In particularly grave cases, alien predatory species feed upon indigenous species.

Consequences - Elimination of indigenous species and alteration of food webs. This problem is particularly serious in lakes with endemic species (that is, species that only live in one particular lake) that are threatened by extinction. This is important in ancient lakes such as Lake Baikal, Lake Victoria and the other East African Rift Lakes).

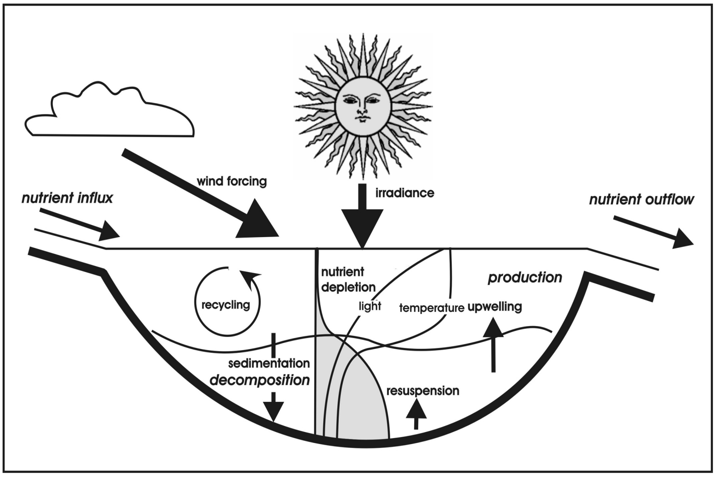

Fig. 1.7-5: Nutrient cycling in the physical setting of lakes. Nutrients enter the lake from the watershed. Only in the upper layers enough light is available for photosynthetic production of algal biomass that serves as food source for zooplankton and ultimately fish. Consumption of organic matter leads to the recycling of both carbon and nutrient salts. Because of the thermocline, only small amounts of nutrient salts can enter the productive layer by upwelling (upward-mixing across the thermocline). Limiting nutrients are depleted. By sedimentation, dead organic matter (detritus) is lost from the productive layer. In deep waters, part of the organic matter is decomposed (mineralized); part is deposited at the lake bottom. Small quantities of particulate matter are re-introduced into the deep water by resuspension. Original.

perturbations, the principle of critical loading can be readily applied to assess the suitability of an inland water system as sources of freshwater. Only undisturbed aquatic ecosystems are suitable sources of water for human use, because only here we can expect that concentrations of noxious substances will be at sub-critical levels. Human-induced disturbances of the natural environment obviously are unavoidable. Defining critical loading thresholds, therefore, are essential bases of any impact assessment as a guiding principle for planning decisions and for the resolution of conflicts of interest between different stakeholders.

Unfortunately, at present critical loading thresholds have only been defined for nutrients causing eutrophication, which is the most common cause of environmental degradation[15] . If natural waters are to be used more extensively, definition of critical loading by otherwise noxious substances is indispensable.

Natural inland water bodies are better suitable as sources of freshwater than are man-made reservoirs. The first and foremost reason for this is that especially the construction of large reservoirs has many negative consequences, as discussed in this article. The second reason is that artificial water bodies are not in a state of dynamic equilibrium. For this reason, their capability to absorb and buffer external perturbations is difficult to predict.

In order to have undisturbed or little disturbed natural water bodies at our disposal as sources of usable freshwater, we have to keep external loading below critical threshold levels. If, however, these systems already have been disturbed beyond critical levels in the past (and this, unfortunately, is the case in most large rivers and lakes), we have to take effective measures to minimise these perturbations.

Despite the depressing current condition of most large inland waters in developing countries, there is cause for some optimism. The quality of most freshwater systems in the rich industrial countries had been heavily affected by human impacts until two to three decades ago. Concerted protective measures, mainly the prevention of further loading by nutrients and noxious substances, has led to substantial improvements. In some extreme cases, water quality was restored by technical measures (DINAR et al. 1995). Lake Constance is an encouraging example of ecosystem recovery, whose water quality today is as good as it was over 50 years ago, before eutrophication set in, mainly as a consequence of the influx of untreated or insufficiently treated sewage in the entire watershed. The construction of sewage treatment plants with 80% phosphate removal in the watershed and the diversion of sewage in the immediate surrounding of the lake have allowed a recovery beyond expectation (*Fig. 1.7-6*).

This, and similar positive experience elsewhere, should encourage us to clean up surface waters in the lesser developed countries world-wide. Because the availability of freshwater is dependent not only on quantity, water quality improvement is an essential step toward improving freshwater supply. The second equally important step is to increase water use efficiency by minimising water losses. This is true for the water supply of big and rapidly growing cities where water losses are mainly caused by leaky supply systems. This is true even more for the water supply of agriculture, which at present consumes more than two thirds of all freshwater world-wide. Even by simple and affordable irrigation devices, the utilization of the scarcely available freshwater can be substantially increased. As described in this article, large supply schemes such as the ones planned in China and India, as well as the 40,000 large dams world-wide and the ones to be built un the Yangtze and along the River Nile, among others, have many and unforeseeable ecological consequences and moreover are extremely costly. The alternative is less spectacular and at a much smaller scale, but nevertheless will be more effective in the end.

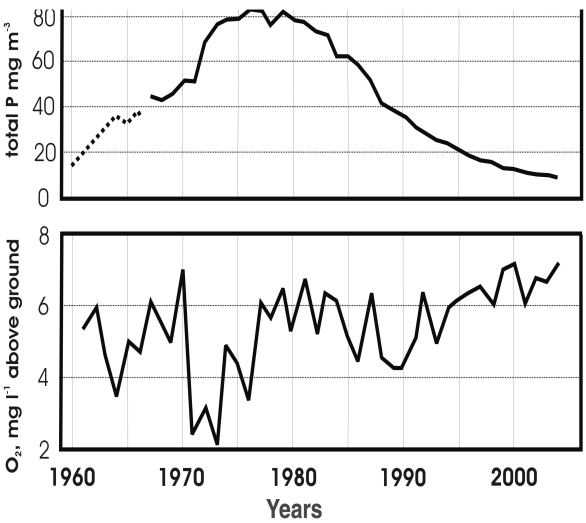

Fig. 1.7-6: Long-term trends of concentrations of dissolved oxygen during summer stratification (*lower panel*), and of phosphorus content (*upper panel*) in the main basin of Lake Constance (Obersee) between 1960 and 2000. *Dotted line*: Maximum winter concentrations of total phosphorus, *solid line*: Annual mean values of total phosphorus concentrations. The increase in phosphorus concentrations was caused by the massive influx of domestic sewage which is high in dissolved phosphorus. Because phosphate is the nutrient salt limiting algal growth in Lake Constance, the productivity matter during thermal summer stratification caused a decrease in the concentrations of dissolved oxygen above ground. The eutrophication process led to a deterioration of water quality. The diversion of sewage and the construction of sewage treatment plants within the entire drainage basin of Lake Constance have lead to declining phosphorus levels, lower primary productivity and increasing oxygen concentrations above ground. By the combination of these effects, the water quality of Lake Constance today is comparable to the water quality around 1950. The main political incentive for the improvement of the water quality of Lake Constance has been the fact that this lake provides drinking water for over 5 million people. Source: IGKB 2005.

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[1] When too much water is applied during irrigation, excess water cannot be taken up by the plants. Large amounts of water either percolate through the soil unused, or evaporate. When too little water is applied, especially in dry climate, water evaporates within the soil whereby salt accumulates.

[2] The smaller water consumption by Israel as compared to Egypt, despite similar climatic conditions, is due to (1) considerably more efficient irrigation techniques and (2) the use of »*virtual water*«, that is, the import of goods (mainly food) whose production requires ample water.

[3] In the United Arab Emirates, over 10 times, in Saudi Arabia 7 times, and in Libya 3.7 times more water is used from fossil aquifers than is provided by the hydrological cycle (Engelmann et al. 2000).

[4] To give a few examples (liters/(person×day), values for 1990: Gambia and Male: 4.5, Mozambique and Uganda: 9.3, Cambodia: 9.5, Albania: 15.5, Bangladesh: 17.3, Angola: 18.6 (Source: Gleick 1996).

[5] For example, the amount of water lost due to inefficient infrastructure in Mexico City would be sufficient to meet the water demands of the city of Rome (Gleick 2001).

[6] Altogether in 2002, infectious diseases were responsible for 26% of all premature deaths. The following fatalities (in millions) were recorded: Respiratory infections: 4.0, HIV/AIDS: 2.8, Diarrhea: 1.8, Tuberculosis: 1.6, Malaria: 1.3 (UNWWAP-2, 2006).

[7] Since 1978, Chinas annual GDP growth averaged 9% with maxima as high as 13% (*Why Is China Growing So Fast?* (Hu & Khan 1997) International Monetary Fund). India's economy has been growing by 6–8% annually over the past 5 years (*World Economic Forum 2005*).

[8] However, protesters do face threats in India, as the famous Indian writer Arundhati Roy demonstrates in her book *Public Power In The Age Of Empire* (Open Media Pamphlet Series), 2004.

[9] »Waste production« in aquatic environments mainly is by the deposition of sediments at the bottom. Sediment accumulation rates usually are small: In lakes, rarely more than 1 mm of sediment accumulate per year. In the ocean, sediment accumulation rates as a rule are at least one order of magnitude smaller. This is in stark contrast to the cycling of matter in our civilization in which mainly new material is put into one-way use, and large quantities of waste are released to the environment.

[10] Especially in small aquatic systems the input of dead organic matter, both dissolved and particulate (detritus) from the watershed can be significant.

[11] Organisms capable of living on inorganic matter are called *autotrophic*. The energy requirements of the nutrient salt uptake and the synthesis of body substance (*primary production*) is met either by utilizing solar radiant energy (*phototrophy*), as in green plants, or free energy liberated by oxidative processes, mainly of inorganic material (*chemolithotrophy*), as in some bacteria. Heterotrophic organisms utilize organic matter both as nutrient and energy source (*chemo-organotrophy*), as animals, fungi, and many bacteria (*secondary production*).

[12] As a rule of the thumb, photosynthesis proceeds to depths down to which ca. 1% of the sunlight entering the lake penetrates. The »*euphotic depth*« is a function of water transparency and in most inland lakes ranges from 1 to 10 m.

[13] Closer inspection has revealed, however, that the relationship is more complex and non-linear due to internal feedback mechanisms (Vollenweider 1968).

[14] Actually, not the area of watershed size is important, but the amount of water (and of other material) released within the watershed. Water runoff depends on the amount of precipitation minus losses by evapotranspiration.

[15] In the vast majority of inland water ecosystems, phosphorus is the dominant inorganic nutrient controlling plant growth and hence overall productivity. Therefore, Vollenweider's critical loading model is mainly related to phosphorus. Total phosphorus levels of 10 mg/m³ are acceptable. Critical loading levels are defined as rates of external phosphorus inputs that will lead to total phosphorus levels of 20 mg/m³, or more.