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RESERVOIRS OF GUANGDONG PROVINCE, SOUTH CHINA: AN INCREASING THREAT OF EUTROPHICATION

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ABSTRACT

Man-made lakes are abundant in Guangdong province (South China) but are distributed irregularly. Since 1950s, about 6700 reservoirs (>10^6 m^3) with total volume $39.8\times10^9 m^3$ have been built. The largest one, Xinfengjiang reservoir, contributes one third to the total volume. Half of the reservoir storage is situated in the Dongjiang river watershed in which the designed capacity is low, only 1.82×10^9 m^3. In 1998, water demand in Guangdong was 44.7×10^9 m^3, with one third coming from reservoirs. In total, 75% of reservoir water supply was contributed by small (<10^7 m^3) and very small reservoirs, and 25% by large and medium reservoirs. An annual amount of 1.1×10^9 m^3 is supplied to Hong Kong by one medium-sized reservoir (Shenzhen reservoir), and 8.31×10^6 m^3 to Macau by four small reservoirs. In spite of the importance of reservoir water, the protection of this resource remained largely ignored prior to 2005. The deterioration of reservoir water quality stimulated the local government to initiate the first program for a systematic survey of the eutrophication of 20 typical and important reservoirs used for drinking water supply in 2000. The trophic state index (TSI, Carlson index) was calculated on the basis of TP, TN, SD and chlorophyll-a concentration. The index showed that most reservoirs were mesotrophic, tending towards eutrophy. Only few reservoirs (two) situated in the upstream zone were oligotrophic. Four reservoirs located near towns in the downstream zone were eutrophic. Compared with the data of a fishery survey in the 1980s, the trophic level over the past 20 years had significantly increased. After a first water bloom observed in Tangxi reservoir in 1997, the fact that Cyanobacteria bloomed in seven large reservoirs indicated a rapid deterioration of water quality. Besides the common domestic waster water and fertilizers lost from agricultures, fish production through fertilization and ice-fish introduction is another factor leading deterioration of water quality and eutrophication.

Keywords: Reservoirs; water supply; eutrophication.

RESUMO

RESERVATÓRIOS DA PROVÍNCIA DE GUANGDONG, SUL DA CHINA: UMA AMEAÇA CRESCENTE DE EUTROFIZAÇÃO. Lagos artificiais são abundantes na província de Guangdong (sul da China), mas são distribuídos de forma irregular. Desde 1950, cerca de 6.700 reservatórios (> 106 m3), com volume total 39,8 × 109 m3 foram construídos. O maior deles, Xinfengjiang reservatório, contribuir com um terço do volume total. Metade do armazenamento do reservatório está situada na bacia do rio hidrográfica Dongjiang, na qual a capacidade projetada é baixa, apenas 1,82 × 109 m3. Em 1998, a demanda de água na província de Guangdong foi de 44,7 × 109 m3, com um terço proveniente de reservatórios. No total, 75% do abastecimento de água de reservatório teve a contribuição de reservatórios pequenos (<107 m3) e muito pequenas, e 25% por reservatórios de grande e médio porte. Um montante anual de 1,1 × 109 m3 é fornecido para Hong Kong por um de reservatório médio porte (Shenzhen reservatório), e 8,31 × 106 m3 para Macau por quatro reservatórios pequenos. Apesar da importância da água de reservatórios, a proteção deste recurso permaneceu em grande parte ignorada até 2005. A deterioração da qualidade da água de reservatório estimulou o governo local a iniciar o primeiro programa para um levantamento sistemático da eutrofização de 20 reservatórios típicos e importantes utilizados para abastecimento de água potável em 2000. O índice de estado trófico (TSI, Índice de Carlson) foi calculado com base no TP, TN, SD e na concentração de clorofila-a. O índice mostrou que a maioria dos reservatórios estava mesotrófica, tendendo a eutrofia. Apenas alguns reservatórios (dois), situado na zona a montante estavam oligotrófica. Quatro reservatórios localizados perto de cidades na zona a jusante estavam eutróficos. Comparados com os dados de uma pesquisa da pesca nos anos 1980, o nível trófico ao longo dos últimos 20 anos tinham aumentado significativamente. Depois da primeira flor de água observada no reservatório de Tangxi, em 1997, o fato de que Cyanobacteria floresceu em sete grandes reservatórios indicava uma rápida deterioração da qualidade da água. Além do desperdício doméstico comum de água e fertilizantes perdidos de agriculturas, a produção de peixe através da fertilização e a introdução da pesca no gelo são outros fatores que levam a deterioração da qualidade da água e eutrofização.

Palavras-chave: Reservatórios; abastecimento de água; eutrofização.

INTRODUCTION

In the 21st century, water is on the way of becoming a limiting resource worldwide, as it has been for a while in basins like that of the Nile River (Allen 2010). As is well known, water use by the human households constitutes only a fraction of total water demand; industry and agriculture are the greatest users, and since agriculture is either expanding or becoming more intensive, and new areas are being added to the industrial output of the planet, demand on freshwater is growing.

Groundwater reserves are already heavily taxed, so in many parts of the world, attempts are made to harness surface water better. The damming of rivers, or the construction of pumping reservoirs is a widespread response to increasing water demands, especially in areas where relief permits, and the more so since many reservoirs serve several purposes simultaneously. Some uses may be conflicting, however. For example, navigation and emergency water storage are not usually compatible.

As in most human undertakings, negative side-effects of great-scale water storage may occur: on human livelihood (population displacements), on biodiversity (destruction of spawning grounds), on availability of fertile land (often situated in valleys). Damming may sometimes even be a measure for correcting earlier mistakes (mining)

Reservoirs have been built for multiple purposes (*e.g.* water supply, flood control, power generation) on all continents except Antarctica. They are constructed intensively in regions where natural water reserves are inadequate (Straskraba & Tundisi 1999). In China, there are approximately 86,000 reservoirs in excess of 10^6 m^3, and with a total volume of 466×10^9 m^3 (Liu 1996). The majority is located in the south, where about 80.2% of the nation's water resources is found and that harbours 57.9% of the human population. Guangdong Province, one of the provinces of this southern region, differs from many other provinces by a scarcity of natural lakes (only 13 km^2). In order to meet water needs, given the temporal and spatial irregularities, intensive reservoir constructions took place during the 1950s and 80s. With an ever-increasing water demand, providing usable water is now the primary purpose of most reservoirs in Guangdong.

The province of Guangdong extends along the coast of the South Chinese Sea, forming a triangle that covers some 178,000 km^2. It is transitory between tropical to subtropical zones, bounded by 109°40' to 117°20' E and 20°14' to 25°31' N, where the southwest monsoon and the southeast trade prevail in summer. Since 2005, it has become more populous than Henan and Sichuan, with ca 80 10^6 regular inhabitants, augmented by ca 30 10^6 economic migrants. The largest city is Guangzhou, the capital, with ca 10 million inhabitants, but the economic growth zone of Shenzhen, with 6.5 10^6 inhabitants, is rapidly catching up. Providing about 12% of China's economic output, Guangdong has one of the largest GDP per capita of China. Mountains and hills cover about 30% of its surface area, and are situated mainly in the north, while plains occupy ca 24 %. Most of the plains are heavily exploited for valley agriculture, with rice the primary crop (two annual harvests) followed by various fruit. Industry has expanded strongly in the past two decades, with all sectors (textile, but also heavy metal industries and mining) well represented. Of late, the tertiary sector has started deploying.

Early in the 1980s, rivers began to suffer from increasing pollution because of a combined population growth and economic development. Although water pollution has been a problem for a long time and some attempts have been made to prevent it, rivers – especially downstream - are still subject to degradation. All reservoirs located downstream show some degree of a degraded water quality, with a clear trend of eutrophication. For example, Shenzhen reservoir, a medium-sized reservoir that primarily supplies water to Hong Kong, is currently strongly eutrophic. In 2000, the local government initiated the first program for a systematic survey of eutrophication of those reservoirs supplying drinking water. In this paper, we summarize the characteristics of the reservoir water resource and provide a first survey of its eutrophicaton.

RESERVOIR WATER RESOURCES AND WATER SUPPLY

RESERVOIR WATER RESOURCES

The inter-annual average precipitation in Guangdong is 1744 mm with an annual runoff of 180×10^9 m^3. Under the effect of the southwest monsoon and tropical storms, precipitation is abundant during the wet season, from April to October, and contributes about 70-85% to annual total precipitation. The scarcity of natural lakes used to result in most of the flood water flowing out to the sea directly. In the dry season, only 15-30% of annual precipitation is received. Many rivers, especially small ones, risk drying out. Precipitation is also irregular spatially, ranging between 400 and 2800 mm, with a minimum of 400 mm in Leizhou Peninsula (west Guangdong). In dry years, coastal and limestone areas are subject to water shortage, and evaporation far exceeds precipitation.

Traditionally, Guangdong Province has been divided into 10 river districts (Table1): (1) Xijiang river watershed, (2) Beijiang river watershed, (3) Dongjiang river watershed, (4) Hanjiang river watershed, (5) the Pearl delta area, (6) rivers of the east coastal area, (7) rivers of the west coastal area, (8) Guihejiang River watershed, (9) system of Donting lake, and (10) system of Boyang lake. Guihejiang River watershed, system of Donting Lake and system of Boyang Lake are the three smallest watersheds, with total area only 3.33×10^9 m^2, about 1.9% of the province's total. Xijiang, Beijiang and Dongjiang rivers are the three largest rivers in Guangdong. They all originate in adjacent provinces and join up in the Pearl delta area; the whole river system is known as the Pearl River, the fourth longest river in China. Natural runoff is compensated not only by local rainfall, but also by flows from upstream in the adjacent provinces. Total water resources in Guangdong consist of precipitation (180×10^9 m^3) and of runoff imported from the adjacent provinces (233×10^9 m^3), with a total of 419×10^9 m^3. Because only few natural lakes (with area 13 km^2) occur in Guangdong region, building reservoirs by damming rivers is the only way to store water temporally and spatially. As a result, seven large ($>10^9$ m^3), 22 medium ($>10^8$ m^3) and 6674 small ($>10^6$ m^3) reservoirs with a total volume of 39.8×10^9m^3 (in 1999) have been constructed. A volume of 22.5×10^9 m^3 is contributed by large reservoirs and only 4.4×10^9 m^3 by medium ones. The largest is Xinfengjiang reservoir with a volume of 13.9×10^9 m^3, about one third of total reservoir volume.

RESERVOIR DISTRIBUTION

Reservoir distribution is shown in Table1. In the Dongjiang River watershed, there are three large reservoirs: Xinfenjiang (13.9×10^9 m^3), Fengshuba (1.9×10^9 m^3) and Baipenzhu (1.2×10^9 m^3), make up 18.7×10^9 m^3 in volume and constitute about half of the total storage capacity in the watershed. The annual runoff is 26.9×10^9 m^3, corresponding to only c 6.5% of the total water resource of the province. Rivers in this watershed are therefore strongly reservoir-regulated. Runoff in all other watersheds is high, up to 412.9×10^9 m^3, with a reservoir volume of 19.7×10^9m^3. In these areas, rivers are less regulated by reservoirs. In the Xijiang river watershed, runoff is 219.6×10^9 m^3, with reservoir volume 0.996×10^9m^3, distributed over small and very small reservoirs and the river is rather weakly regulated. In 1998, a large through-flowing reservoir, (Feilaixia reservoir, 1.9×10^9 m^3) was constructed on Beijiang River for water supply, power generation and flood control.

Table 1. Water resources in Guangdong (in 1995).

Watershed	River runoff ($10^6 m^3$)		Total reservoir volume ($10^6 m^3$)	Designed reservoir water supply capacity ($10^6 m^3$)
	Local upstream	From		
Guihejiang river	2714	6500	125	162
Xijiang river	12104	207500	996	1498
Beijiang river	48210	3300	3526	4913
Dongjiang river	23917	3000	18650	1820
Hanjiang river	15244	11200	1511	1191
Rivers in the west coastal area	31428	1800	5984	3032
Rivers in the east coastal area	19323	0	3275	2140
Rivers in Pearl delta area	26713	294100	4271	2687
Water system of Dongting lake	84	0	8	7
Water system of Boyang lake	135	0	4	6
Total	179872	233000	38350	17455

RESERVOIR WATER SUPPLY

Water supply to Guangdong

Based on statistical data for 1993, reservoir volume is 38.35×10^9 m^3 (excluding Feilaixia reservoir), with a designed water supply capacity of 17.45×10^9 m^3. Fig. 1 shows the reservoir volume and designed water supply capacity distribution in three reservoir types. With a volume of 13.32×10^9 m^3, small and very small reservoirs have a high supply capacity (13.07×10^9 m^3). Although large and medium reservoirs have a large volume of 25.03×10^9 m^3 and 65% of the total storage capacity, their designed supply capacity is 4.39×10^9 m^3, which corresponds to only 25% of total water supply. These conditions indicate that most reservoir water supply is contributed by small and very small reservoirs that have been exhaustively used. For example, in Xijiang river watershed, the runoff is $219.60 \times 10^9 m^3$, but reservoir volume is only 0.996×10^9 m^3 contributed by small and very small reservoirs, with a supply capacity of 1.50×10^9 m^3. Limited by volume, small and very small reservoirs cannot store enough floodwater to meet demand during the dry season. These small reservoirs have a limited potential for further enhancement of their water storage capacity in the future. Large and medium-sized reservoirs can regulate water storage for use annually. Although their volume is high, most of them have a low designed water supply capacity. Only in the west coastal area that often faces water shortage and has a well developed agriculture, large reservoirs (Hedi and Gaozhou reservoirs) are used efficiently for irrigation. But in Dongjiang river watershed, the three large reservoirs (Xinfengjiang, Fengshuba and Baipenzhu reservoirs) have a large volume of $17 \times 10^9 m^3$, with a low water supply capacity, $1.15 \times 10^9 m^3$. The province's water demand was $42.8 \times 10^9 m^3$ in 1993, and $44.7 \times 10^9 m^3$ in 1998, and about one third of this amount was contributed from reservoirs. Generally, if water supply becomes the primary purpose for most of the large and medium reservoirs, and their supply capacity is enhanced, amounts of vailable water could be significantly raised to better meet the demands of the future.

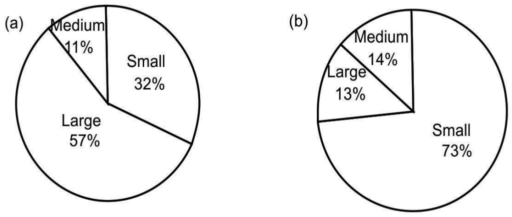

Figure 1. Reservoir volume (a) and designed water supply capacity (b) distribution in three reservoir types.

RESERVOIR WATER SUPPLY TO HONG KONG

Hong Kong, adjacent to Guangdong province, also has water resources that strongly vary seasonally. The annual rainfall varies from 901 to 3248 mm, with a mean value of 2214 mm. The summer monsoon, lasting from May to September, contributes 77% of the total annual rainfall, and rainwater flows down in mountain streams without natural lakes. As a result of its highly variable seasonal rainfall, Hong Kong depends on adequate storage for the maintenance its water supply. To this end, seventeen storage reservoirs, with a volume of $0.586\times10^9 m^3$ have been constructed. But these reservoirs cannot meet a water demand that increases 11% annually (Dudgeon 1996).

Increasing demand has forced Hong Kong to import water purchased from Guangdong province and created the Dongjiang water supply project, completed in 1960. The project is located in the downstream zone of of Dongjiang River. River water is sent to Shenzhen reservoir (0.046×10^9 m^3) by a multi-pumping system, and then piped to Hong Kong. After three enlargements, the water supply capacity now has reached 1.743×10^9 m^3. About 1.1×10^9 m^3 is transferred to Hong Kong, amounting to 8% of the total discharge of the river, and this meets 75% of the water demand of the city (Dudgeon 1995).

RESERVOIR WATER SUPPLY TO MACAU

The big city of Macau is also adjacent to Guangdong Province and suffers from water shortage. To solve this scarcity of water, two small reservoirs, Nanping and Zhuxiandong were constructed in the 1960s. These supply c 2.94×10^6 m^3 of water annually. But their supply capacity soon fell short of the increasing water demand of a growing population. In 1979, two more small reservoirs, Dajingshan and Meixi, therefore began supplying water to Macau, and the annual amount of supplied water rose to 5.37×10^6 m^3. At present, there are four reservoirs servicing Macau, and the annual amount has reached 8.31×10^6 m^3. The water demand of the adjacent Zhuhai city has been increasing with urbanization and increase in population too. Water supply in both Macau and Zhuhai has become more difficult after a first serious saltwater intrusion up the estuary of the Pearl River system in 2005 because of extensive human activity in the catchment. A new reservoir, Zhuying, is currently being built specifically to supply additional water to Macao. Zhuying reservoir, the largest pumped storage reservoir in Zhuhai city, will be completed in 2011 and store more than 40 million cubic meter by pumping water from Xijiang, the west branch of the Pearl River, in the dry season.

EUTROPHICATION

In spite of the importance of a guaranteed good quality water supply, reservoir water protection before 2000 remained largely ignored. The continuing deterioration of reservoir water quality finally persuaded the local government to initiate a program for a systematic survey of the eutrophication of reservoirs supplying drinking water. This made researchers and managers join forces for water quality management. In the program, that started in 2000, twenty reservoirs were selected representative of the river basins and river districts where most reservoirs are located, as well as representative in morphology and characteristics of their watersheds. The location and the characteristics of these reservoirs are shown in Figure 3 and Table 2, respectively. Reservoirs were sampled between June and December 2000, roughly corresponding to the flood and dry seasons. Samples were collected at locations close to the inflows and dams.

Table 2. Description of the investigated reservoirs.

Watershed	Reservoir	Elevation (m)	Watershed area(km^2)	Max. Volume (10^6m^3)	Normal volume (10^6m^3)	Mean retention time(yr)	Year of filling
Dongjiang river	Xinfengjiang	116.0	5734.0	13980.0	10800.0	2.00	1958
	Baipenzhu	75.0	856.0	1220.0	575.0	0.52	1987
	Shatian	68.0	26.8	21.7	14.2	0.68	1960
	Shiyan	36.0	44.0	31.2	16.9	0.47	1960
	Shenzhen	27.6	60.5	46.1	35.2	0.02	1960
Beijiang river	Chishijin	128.4	14.1	14.9	12.4	1.50	1958
	Xiaoken	225.2	139.0	113.2	54.3	0.37	1964
	Feilaixia	24.0	34000.0	1900.0	440.0	0.04	1998
Rivers in the west coastal area	Gaozhou	86.0	1022.0	1151.1	841.8	0.57	1960
	Dashahe	34.8	217.0	258.1	156.8	0.56	1959
	Dashuiqiao	56.5	196.0	143.0	100.7	1.00	1958
	Hedi	40.5	1495.0	1144.0	795.0	0.53	1959
Rivers in the east coastal area	Gongping	16.0	317.0	330.7	163.3	0.41	1962
	Chisha	12.0	23.0	1.1	1.1	0.04	1960
	Hexi	53.0	40.9	17.9	15.8	0.39	1958
	Tangxi	56.0	667.0	381.0	286.4	0.43	1959
Rivers in Pearl delta area	Liuxihe	235.0	539.0	378.0	326.0	0.46	1958
	Dajingshan	20.4	6.0	11.7	10.5	1.13	1975
	Qiuyishi	42.6	17.6	13.0	10.2	0.74	1960
Hanjiang river	Heshui	134.0	600.0	115.0	30.4	0.07	1957

PHYSICAL AND CHEMICAL CHARACTERISTICS OF RESERVOIR WATER

Conductivity varied from 27 to 273 ms/cm, depending on the geology and land use of their watershed. High conductivity occurred in the reservoirs of Shiyan (273 ms/cm) and Shenzhen (196 ms/cm) that had been subject to intense eutrophication by inflowing nutrient-rich domestic and industrial wastewater. Surface temperature ranged between 27.0 and 33.6 °C in summer. Except for through-flowing (Feilaixia, Heshui, Chisha and Shenzhen reservoirs) and shallow small (Shiyan reservoir) ones, all reservoirs had typical summer thermal stratification (Figure 3). In winter, surface temperature declined and varied from 16.4 to 24.0 °C. Only deep reservoirs would still stratify, and the depth of the thermocline moved down. Stratification patterns of dissolved oxygen showed no difference among reservoirs. They all displayed clinograde profiles in summer.

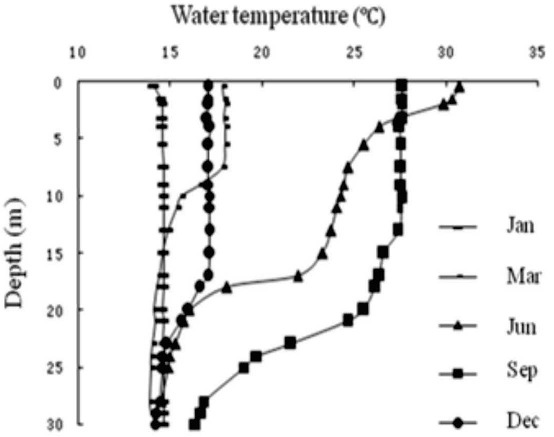

Figure 3. Thermal stratification in the lacustrine zone near the dam in Liuxihe reservoir.

Chl-*a* ranged from 0.6 to 32.4 µg/L, with a minimum in Xinfengjiang reservoir (oligotrophic) and a maximum in Qieyeshi reservoir (eutrophic). Secchi disk depth (SD) showed a strong relationship with chl-*a* (=7.31SD$^{-1.37}$, R^2=0.725) and varied from 0.4 to 6.3 m. Low Secchi disk depth occurred in Qieyeshi reservoir (0.4 m) and Shiyan reservoir (0.6 m), both with high chl-a concentration. In Heshui reservoir, soil erosion in the watershed resulted in high turbidity and low Secchi disk depth (0.6 m). In contrast, high values occurred in Xinfengjiang (6.3 m) and Liuxihe reservoirs (4.7 m), both with lower chlorophyll-a concentration.

Total phosphorus (TP) varied from 3 to 388 mg/L, with trace concentration in Xinfengjiang and Liuxihe reservoirs that suffered from P-limitation. High TP was found in Shenzhen (388 mg/L) and Shiyan reservoirs (189 mg/L) that were eutrophic. Total nitrogen (TN) ranged between 0.313 and 7.15 mg/L. Coupled with TP, high concentration was found in Shenzhen (5.93 mg/L) and Shiyan (7.15 mg/L) reservoirs, and low concentration in Xinfengjiang (0.46 mg/L) and Liuxihe (0.31 mg/L) reservoirs. The most abundant nitrogen form was NO_3-N, ranging from 0.08 to 5.00 mg/L in most reservoirs. NH_4-N only predominated in Dashuiqiao and Hedi reservoirs (in the west coastal area, where agriculture is quite developed). Although NO_3-N was the most prominent nitrogen form in Shenzhen reservoir that supplies water to Hong Kong, NH_4-N was predominant in its inflow, up to 4.85 mg/L. High concentration of NH_4-N caused an unpleasant smell to the reservoir water. In order to ameliorate the water quality, a pre-nitrification project to convert NH_4-N to NO_3-N was implemented in 1998; as a result, the concentration of NH_4-N declined to 0.03 mg/L near the dam.

The relationship between chl-a and TP was described by chla = 59.20TP$^{0.77}$, R^2 = 0.731. The relationship between TN and chla was: chla = 5.31TN$^{1.21}$, R^2= 0.7163, Fig. 5c. TP and TN both were good predictors of chlorophyll-a. In this case, however, both variables co-varied and regression analysis alone was insufficient to decide which nutrient, if any, was limiting algal biomass in each individual reservoir.

Phytoplankton and cyanobacterial blooms

Ten species of Cyanophyta, 63 species of Chlorophyta, 18 species of Diatoms, two species of Chrysophyta, two species of Pyrrophyta, nine species of Euglenophyta and one species of Cryptophyta were observed in the pelagic plankton of the reservoirs (Hu *et al.* 2002). In reservoirs with high chlorophyll-a concentration, phytoplankton was dominated numerically by Cyanophyta (also called Cyanobacteria), with high abundance. In low chlorophyll-a concentration reservoirs, phytoplankton abundance was low (0.19×10^6 cells/L in Xinfengjiang reservoir) without apparent dominant species. Diatoms, Chlorophyta or Cyanophyta dominated numerically at medium chlorophyll-a concentration and phytoplankton abundance.

The dominant cyanobacterial species in these reservoirs were *Microcystis* spp., *Pseudanabaena* spp., *Cylindrospermopsis* sp., *Merismopedia* sp., *Chroococcus* sp., *Gloeocapsa* sp., *Dactylococcopsis* sp., *Anabaena* spp., *Raphidiopsis* sp. and *Gloeothece* sp. The first cyanobacterial bloom observed in Tangxi reservoir in 1997 was caused by *Microcystis aeruginosa* and lasted until 2003 when the water level was allowed to sink so low that the dam could be repaired (Figure 4). Tangxi Reservoir (23°28'N, 116°35'E) is a large reservoir built in 1960 by damming the midstream Huanggang River, and has a total volume of 3.81 × 10^8 m^3, a maximum depth of 37 m and a catchment of 667 km^2. It is located in Raoping County, 38 kilometers downstream from the county town of Huanggang, in the east of Guangdong Province. It provides most of the water for domestic, industrial, and agricultural use by the 670,000 inhabitants of the county. Huanggang River and Janrao River are the main feeding rivers. In total, there is a population of 235,900 inhabitants upstream; the annual domestic sewage of 1.43 × 10^7 tonnes and industrial sewage of 4.1 × 10^5 tonnes are discharged into the reservoir without any treatment.

Figure 4. The first water bloom observed in a Guangdong reservoir (Tangxi reservoir) in 1999, lasted until 2003. The right photo, taken in 2003, contrasts the color of surface water against that of purified drinking water.

ZOOPLANKTON

The pelagic zooplankton is surprisingly rich and varied. In total, a minimum of 61 species of Rotifera, at least 23 species of Cladocera and 18 species of Copepoda have been identified in samples collected in summer and winter (Lin *et al.* 2003). The majority of rotifer species are monogononts, and bdelloids are represented only by *Rotaria* spp. *Lecane*, *Trichocerca* and *Brachionus* are the species-richest genera, with most but not all species cosmopolitan. The most frequently observed genera include Keratella, *Brachionus*, *Polyarthra*, *Trichocerca*, *Asplanchna*, *Conochilus*, *Ploesoma*, *Ascomorpha* and *Pompholyx.* Daphniidae and Chydoridae constitute the two most species-rich cladoceran families. *Bosmina tripurae*, *Bosminopsis deitersi*, *Diaphanosoma orghidani*, *D. dubium, Ceriodaphnia quadrangula* and *Moina micrura* are most abundant in the limnetic zone. Large zooplanktors of palaearctic origin such as *Leptodora richardi* (not *L. kindtii*!) and *Daphnia galeata* are only observed at low density in large and deep reservoirs, and occur more commonly in winter samples. These deep impoundments provide these species a vertical refuge to maintain a low population (Wang *et al.* 2011, Xu *et al.* 2011). A mix between palaearctic-temperate and oriental-warm water species is characteristic of the zooplankton assemblages, and is weakest expressed in the rotifers, strongest in the copepods.

Ten Calanoid and 8 Cyclopoid species occur. Most of the Calanoida and a fair fraction of the cyclopid species are endemic to the tropics and subtropics of China. *Phyllodiaptomus tunguidus*, *Neodiaptomus schmackeri*, *Mesocyclops thermocyclopoides, Thermocyclops taihokuensis* and *Tropocyclops bopingi* are the most frequently observed taxa. Some salt-loving species are found in reservoirs with higher conductivity.

Additional elements to the zooplankton include, at the larger end of the size spectrum, the carnivorous larva of the dipteran *Chaoborus*, pelagic typhloplanid flatworms (also carnivorous), and, at the smaller end of the spectrum, a number of protists, including a rich variety of testate amoebae pertaining to the large genus *Difflugia.*

Macrozooplankton (Cladocera, adult Copepods and copepodids) densities were between 1 and 400 ind./l, but generally below 50 ind./l, and were dominated by copepodids. Microzooplankton (rotifers, nauplii and protozoans) densities were between 7 and 680 ind./l and are usually dominated by nauplii. The highest zooplankton density was observed in Tangxi reservoir that was suffering from a small *Microcystis aeruginosa* bloom; macrozooplankton had a density of 402 ind./l and microzooplankton 432 ind./l. Low macro- and microzooplankton densities were coupled with low chlorophyll-a concentration. In Xinfengjiang reservoir, the densities were only 6 and 7 ind./l for macro- and microzooplankton, respectively. High densities of zooplankton did not necessarily couple with high chlorophyll-a concentration. Two hypotheses were postulated: (1) phytoplankton biomass was not fully utilized by zooplankton, and an increasing part of phytoplankton was channeled through the microbial loop, and (2) zooplankton biomass was controlled top-down by a large stock of planktivorous and filter-feeding fish (Straskrabova *et al.* 1994).

TROPHIC STATUS INDEX

A Trophic State Index (TSI) inspired from Carlson (1977) was calculated for each reservoir, based on the concentration of TP, TN, chlorophyll-a and Secchi disk depth (SD). The values varied from 23 to 66 (Figure 5). Xinfengjian and Liuxihe reservoirs are oligotrophic, and Hedi, Qieyeshi, Shenzhen and Shiyan reservoirs are eutrophic. The other 14 reservoirs are mesotrophic. Among these, Dajingshan, Heshui, Dashuiqiao, Tangxi and Hexi reservoirs are rapidly trending towards eutrophy.

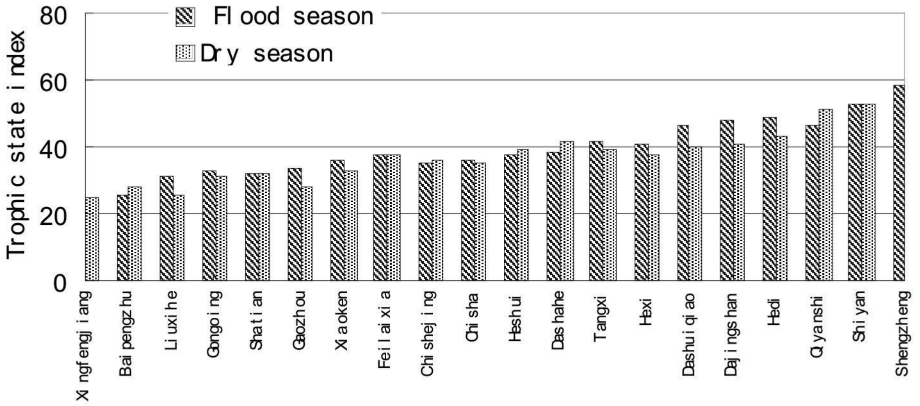

Figure 5. Trophic state level (TSI) of the investigated reservoirs, TSI was calculated on the basis of variables measured near the dam.

As could be expected, the trophic state was only low in headwater reservoirs, and increased toward the lower reaches in Dongjiang and Beijiang river watersheds. In Dongjiang river watershed, trophic state varied from oligotrophic (Xinfengjiang reservoir) upstream to eutrophic (Shenzhen and Shiyan reservoirs) downstream. Reservoirs in Beijiang river watershed were all mesotrophic. Heshui reservoir was the only reservoir investigated in Hanjiang river watershed. It is located upstream and is mesotrophic.

In the Pearl River delta area, Liuxihe reservoir is a mountain reservoir situated in the upper reach of Liuxihe River (a small tributary to the Pearl River) that does not receive domestic and industrial wastewater; its trophic state is closest to oligotrophic. In contrast, Dajingshan and Qieyeshi reservoirs are mesotrophic and eutrophic, respectively; both receive nutrient-rich wastewater.

In west and east coastal areas, reservoirs are located on different small rivers that directly flow out into the sea. Hedi and Dashuiqiao reservoirs are situated in Leizhou peninsula, with low annual precipitation (400 mm). Evaporation often exceeds precipitation. The majority of the reservoir water, especially from Hedi reservoir, is used for irrigation. Land use affects water quality. Hedi reservoir is eutrophic and Dashuiqiao reservoir is mesotrophic trending towards eutrophy. The other reservoirs in these two areas are mesotrophic.

RESERVOIR FISHERIES

In the 1970s, the Chinese authorities encouraged the culturing of fish, especially in small and shallow reservoirs where production is high and fish harvesting is relatively easy and effective (Liu & Cai 2002). Seven fish species have been cultured extensively in reservoirs, namely silver carp (*Hypophthalmichthys molitrix*), bighead carp (*Hypophthalmichthys nobilis*), *Ctenopharyngodon idellus, Cyprinus carpio*, *Carassius auratus*, Nile tilapia (*Oreochromis niloticus*) and mud carp (*Cirrhinus molitorella*). To improve natural food to fishes, some reservoirs were fertilized to enhance production, but such fertilization was forbidden after 2000 because it caused a deterioration in water quality (Jing *et al.* 1993). Many reservoirs had high production in the first years, but it rapidly declined in large and deep reservoirs. Only a few shallow, mesotrophic reservoirs have maintained a high fish production until now. For example, Xiangang reservoir has produced about 200,000 kg of fish per year since 1990, comprised of 30 % of silver carp and 60 % of bighead (Figure 6). This reservoir was built in 1963, and has a total volume of 1.36×10^8 m^3, and a mean water depth of 7m. The surface water area for fishery is about 900 hm^2. However, before 1990, its fish production had been about 130,000kg per year. To increase plankton biomass, about 170 tonnes of fertilizer (ammonium bicarbonate and single superphosphate) had been applied until 1999 when the water became mesotrophic (2002). In 1990s, the ice-fish *Neosalanx pseudotaihuensis* was introduced into many large and deep reservoirs, but restricted in a few reservoirs due to low production and difficulty of harvesting (Liu 2001). Several species of tilapia also were introduced to reservoirs, but their adults showed a decreasing body size after few years. Taking advantage of its high reproductive rate, the tilapia almost outcompeted such traditional species as silver carp and bighead. Therefore, efforts were made to eliminate tilapia by physical and biological methods. Predator species such as *Lateolabrax japonicus* and *Clarias fuscus* were stocked to eliminate small tilapia (Xie *et al.* 2007). However, *Lateolabrax japonicus* and *Clarias fuscus* were found to also kill cultured species. Large, and therefore voracious individuals of *Lateolabrax japonicus* (over 30 kg) and *Clarias fuscus* (10 kg) became common in reservoirs. It also became clear that reservoir fisheries based on fertilization and the introduction of ice-fish had a negative impact on the plankton community and nutrient cycling. A reasonable strategy, based on a sound ecological assessment, to manage fish resources in reservoirs and to control eutrophication is therefore still wanting (Hu *et al.* 2010).

Figure 6. Fish harvesting in the highly productive, shallow Xiangan reservoir (left) and the stocked *Clarias fuscus* that eliminated tilapia from reservoirs (right).

CONCLUSIONS

The characteristics of reservoir volume distribution in Guangdong Province are: low river runoff with high reservoir volume, and high river runoff with low(er) reservoir volume. Most rivers except Dongjiang River are little regulated by the existing reservoirs. Reservoirs, especially small and very small, play a significant role in water supply. At present, reservoir water can quantitatively meet the increasing water demand in Guangdong province. But the investigation shows that reservoir trophic states are trending towards eutrophy. Interpretation of limnological data from studies at a regional scale is seriously affected by limitations at the spatial and temporal scales at which data acquisition is made. The first survey was designed to collect general data on water quality, focusing on eutrophication. The variance generated at short time scales or small spatial scales may not be taken into consideration, and the survey mainly provided historical information on reservoir eutrophication.

Since this first survey in Guangdong province, cyanobacterial blooms have spread to several large reservoirs. For example, *Microcystis* bloomed in Nanshui reservoir located in northern Guangdong in 2007 and a mixed bloom of *Anabaena* and *Microcystis* affected Dashahe reservoir in 2005 and Gaozhou reservoir in 2009. Nutrient loading in most reservoirs is mainly contributed by fertilizer loss from rice fields, poultry and livestock and domestic wastewater released without any treatment in the countryside. After these large-scale water blooms, the local government began to realize the seriousness of water pollution, and many significant decisions were made with an aim at water resources protection. Another two surveys of harmful Cyanobacteria and internal loading in the reservoir were completed in 2003-2004 and 2007-2008 (Han *et al.* 2006, Han 2010).

Efficient management of water resource is, however, also beyond science: it challenges the traditional administrative system of China. In Guangdong Province, water resource management has been in the hands of several governmental administrative departments. The Water Resources Department takes charge of surface water and flood control, the Committee of Urban Construction oversees urban water supply and drainage, the Bureau of Agriculture manages agricultural water usage, and the Bureau of Environmental Protection controls wastewater discharge and water quality protection. Coordination between these departments is weak and the overlap of responsibilities negatively influences water resource management. As a result, the Chinese central government has been strongly reforming the current management system of water resources and now tries to establish a unified institution having a responsibility over water resources, control of wastewater, and water supply. This unification is currently underway in each agglomeration below the province level and such institutions have begun to work in several important cities, such as Shenzhen and Zhuhai.

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