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Novel SPP Water Management Strategy and Its Applications

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1. Introduction

Clean freshwater is the most precious resource in the world and the development of water resources has had a very long history, as early as humans changed from being hunters and food collectors to modern civilization. At very early stage, people had to rely on creeks, rivers and lakes for their water demand that was relatively small, and today humans have accumulated the knowledge and techniques for water storage, building artificial lakes or reservoirs to meet their huge water demand due to industrialization and urbanization. The world's earliest large dam was the Sadd-el-kafara Dam built in Egypt between 2950 and 2690 B.C. Up to now, water from lakes and reservoirs is still the main source for people's water supply. However these large water bodies suffer two problems incurred by nature and human being, one is *sedimentation* and the other *water pollution*. Two of them jointly reduce the available amount of clean water and deteriorate the water quality. Consequently, approximate 1.1 billion people lack of safe drinking water and between 2 and 5 million people die annually from water-related disease (Gleick, 2004). It is understandable that with the population growth in the world, it is difficult to provide sufficient clean water to meet the demand; on the other hand, our natural systems are under pressure from drought (too little), floods (too much), pollution (too dirty), climate change, and other stresses. This creates serious challenges for water management.

Within a generation, water demand in many countries is forecast to exceed supply by an estimated 40%. In other parts of the world prone to flooding, catastrophic floods normally expected once a century could occur every 20 years instead.

Currently, there are about 40,000 large reservoirs worldwide used for water supply, power generation, flood control, etc. The total sediment yield in the world is estimated to be 13.5×10^9 tonnes/a or 150tonnes/km^2 and about 25% of this is transported into the seas and oceans and the rest 75% is trapped, retained and stored in the lakes, reservoirs and river systems (Batuca and Jordaan, 2000). Consequently the silting process is reducing the storage capacity of the world's reservoirs by more than 1% per year. As a result of sedimentation, 300-400 new dams would need to be constructed annually to maintain current total storage (White, 2001). On the other hand, due to climate change, the natural erosion rates will be accelerated. UN experts warned that a fifth of the current storage capacity of reservoirs worldwide or 1,500 km^3 will be gradually lost over the coming decades as global warming may increase the severity of storms and rains. Thus, one may conclude that the worst enemy of sustainable water resources management is sedimentation (USBR, 2006).

In 1998 the U.S. Environmental Protection Agency has identified that sediment in waterways is the largest single pollutant in the ecosystem (National Water Quality Inventory Section 305(b) Report to Congress), because sediment transported downstream can fill reservoirs, reduce its capacity and impair aquatic habitats. Detrimental effects to fish and aquatic invertebrate have been directly related to increases in the magnitude and duration of suspended sediment concentrations (Newcombe and Jensen, 1996 and Kuhnle et al., 2001). It is found that eutrophication can result from a high sediment load that has elevated levels of colloidal material, phosphorus and nitrogen that are transported in association with the sediment (Davis and Koop, 2006).

Water pollution, the main threat of water quality, began with the industry revolution, and the word “pollution” is an adaptation of the Latin “pollutionem”, meaning defilement from “polluere”. To many people, water pollution means the introduction into natural water of foreign substance, but strictly speaking, the water pollution refers to the introduction into water of any substances that makes water hazardous to public health. The impurities or foreign substances could be organic, inorganic, radiological or biological, and its presence in water tends to degrade water’s quality or impair the usefulness of the water. The substances in water can be classified into three groups as shown in Fig. 1, i.e., dissolved; suspended and colloidal.

A dissolved substance is one which is truly dispersed in the liquid, and cannot be removed from the liquid without accomplishing a phase change such as: distillation, precipitation, adsorption, extraction or passage through ionic pore sized membranes. Suspended solids are large enough to settle out of solution or be removed by filtration. The lower size range of this class is 0.1 to 1 mm that is about the size of bacteria. The suspended solids can be removed from water by physical methods such as: sedimentation, filtration and centrifugation. Colloidal particles are in the size between dissolved substances and suspended particles. They can be removed from the liquid by physical means such as very high forced centrifugation or filtration through membranes with very small pore spaces. When light passes through a liquid containing colloidal particles, the light is reflected, which is measured by turbidity.

The typical impurities in water can be further divided based on its density (equal to or larger or less than the density of water) or size:

Algae (0.3-100 mm),
Bacteria (0.1-100 mm),
Viruses (0.003-0.3 mm),
Fungi (1-90 mm),
Giardia cysts (5-16 mm),
Colloids (0.01-7 mm),
Suspended solids (0.3-100 mm),

Humic acids (0.01-0.1 mm),
Post filters particles (0.4-10 mm),
Flocculated particles (1-100 mm).

Until 1800s, most materials used in homes and industries were natural products. In 1900s petroleum was used widely, in 1940s explosion in chemical production and in 1930s to 1950s chemicals like fertilizers and pesticides were invented and found very effective. On the other hand, the urbanization and modern agriculture have changed people's living habit and have greatly enhanced the food productivity. Consequently, domestic/agricultural waste water has also increased significantly with the same trend as industrial wastewater. The United Nation and World Bank's statistics shows that the world discharges 400 billion tons of wastewater every year, resulting in that 5,000 billion ton of clean water being polluted. Among them, China releases 60 billion ton of wastewater every year into rivers and lakes, greatly damaging its ecosystem. As a result of the rapid growth in industrial development, urbanization and population, the world's water resources are grossly polluted by human, agricultural and industrial wastes, to the point that vast stretches of rivers are dead and dying and lakes are cesspools of waste.

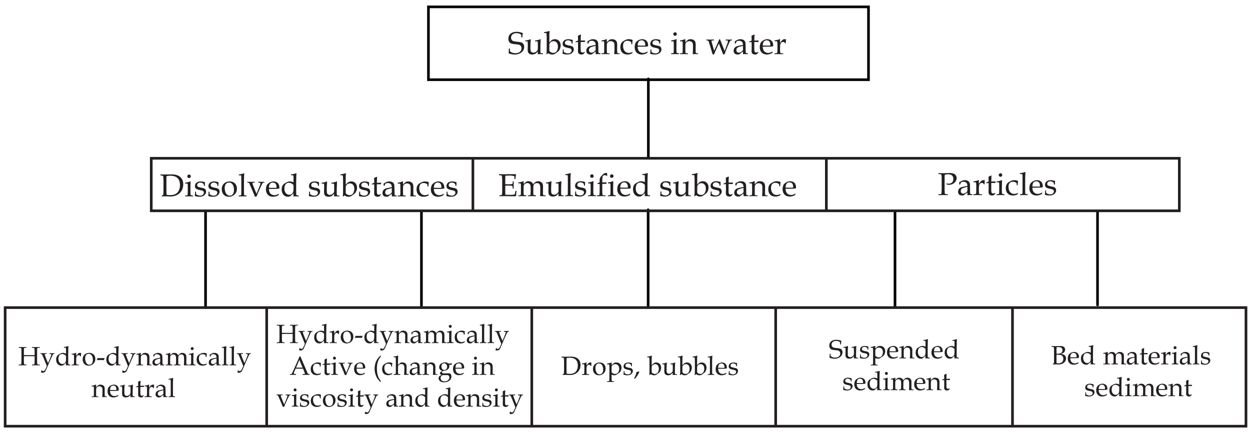

Fig. 1. Classification of substances in water

The world's current strategies in relation to water management are mainly focused on construction of reservoirs, wastewater reuse, desalination technology, alongside non-engineering methods like marketplace allocation etc. Increasingly, water planners have to take into account societal responses to proposed technologies as illustrated by the opposition to new dams, not to mention the hostile public reception met by wastewater and desalination strategies. Thus, it is worthwhile investigating other alternative water management strategy as long as it proves to be cost effective, energy thrifty and environment-friendly. By far, reservoirs and lakes play an important role for the modern society. As mentioned above, the biggest challenge is that the incoming rivers to these large water bodies are severely polluted by contaminants particle or solvable pollutants in water. The almost stagnant water together with high temperature, suitable sun shine and nutrients often leads to the algal blooms on vast scales that have become a major water quality issue for ecosystems throughout the world. It is an urgent threat facing surface water resources today, because of their ecological, aesthetic, and human health impacts. Blooms involving toxin-producing species pose serious threats to animals, plants and humans. Bloom occurrence is visible evidence that humans now strongly effect almost every aspect of our ecosystem. Just like the carbon dioxide emission and climate change, human activities have dramatically increased the emission of nutrients, contributing to increase in phytoplankton biomass and even algal blooms formation in receiving water bodies, e.g. rivers, lakes, coastal waters and reservoirs. With rapid economic/development and population growth worldwide, harmful algal blooms have become more frequent, more extensive, and more severe (Hallegraeff, 1993, Heisler, et al. 2008).

Algal blooms typically appear in slow moving water bodies with excess nutrients e.g. phosphorus, and nitrogen etc., when sunlight, turbulence, transparency, salinity and temperature are suitable. Over the past four to five decades despite extensive and intensive research, many key questions in eutrophication science remain unanswered (Smith and Schindler, 2009). The causes of these blooms are very complex. Never-the-less, in practice there is a pressing need to provide sufficient clean water to our society. The need is urgent to develop reliable methods and strategies to control the algal blooms in our water sources, i.e., lakes or reservoirs. Such a method should be able to restore water quality of these water sources to an acceptable (i.e., no harmful blooms) level in a short of period, e. g. 3-5 years, and also it should be technically feasible, cost-effective and environment-friendly.

Therefore, a big question to ask is how to manage our water resources, and our target is to provide the society enough clean water to sustain their other activities. Any effective strategy of water management should be able to manage or mitigate the disasters caused by floods (too much), droughts (too little), deterioration of water quality (too dirty) and siltation (too turbid). The above mentioned clearly shows that all problems of water supply are directly or indirectly related to the contaminated particle management that affects either water quantity or water quality.

One such method exists (Yang, 2004) and its application is described below. After reviewing the existing problems in water management, Yang and Liu (2010) proposed an effective method to control water quality in lakes; the “separation, protection and prevention” or SPP strategy comes from the following facts:

1. Algal blooms and siltation often appear in slowly moving water bodies. At the same nutrient level, fast moving water has less likelihood to induce massive algal blooms. Large-scale and sustained blooms are not a common occurrence if nutrient loading is very low, or blooms are governed by environmental factors (e.g. temperature, light extinction, nutrients), but equally important are the physical processes such as flow velocity, turbulence, mixing process and dispersion. Similarly, fast moving water has less siltation problems, all reservoirs/lakes are silted by high-sediment laden flows. Hence, it is important to separate clean water from water with too dirty and too turbid waters.
2. For typical watersheds, rivers always play a major role in assimilating or carrying off municipal and industrial wastewater as well as runoff from the catchment. Reservoirs/Lakes receive a major portion of their pollutants/sediment from river inflows; therefore excessive wastewater/sediment inputs can cause serious ecological problems in the ecosystem. However, rivers also constitute the main clean water sources to a lake/reservoir. River water quality is heterogeneous spatially and temporally. In order to manage water quality in a lake, the temporal and spatial variation in water quality must be understood. The typical hydrograph for a catchment is simplified in Fig. 2 where Q is flow rate, Q_r is runoff due to rainwater and

groundwater without being polluted, Q_w is the domestic and industrial wastewater discharge, Q_s is the sediment discharge, Q_a is the rate of wastewater from agriculture or the non-point source pollutant. The year-round rainwater is unsteady, and floods often appears in wet seasons, but wastewater rate from industry and domestic sources is relatively constant year-round even their concentrations in the rivers are not even after mixing. Inflow-river waters are heavily polluted in the dry period while pollutant concentrations are reduced during the wet (flood) period after mixing of clean rainwater with the domestic and industrial wastewater. But this does not mean that the wastewater concentration in flood period is always low as the first flush of storm often drives the non-point source pollutants to the waterways, thus the peak of Q_a appears before the peak of Q_r. Different from the agricultural wastewater, sediment discharge concentration is roughly proportional to the river flow, i.e., very high during wet season, very low in dry seasons.

3. Currently, throughout the world it is rare to find an integrated water resources management plan that can reduce the external nutrients, and at the same time mitigate flood disaster and solve the water shortage problems, i.e., simultaneously solve four problems of flooding (too much), droughts (too little), algal blooms (too dirty) and siltation (too turbid) for a given basin where reservoirs/lakes are located.

Based on these realizations, Yang and Liu (2010) proposed the following SPP strategy to manage different waters in a lake/reservoir:

- Clean water and wastewater should be *separated* spatially and temporally;
- Clean water should be stored and *protected* and wastewater should be discharged as fast as possible, i.e., the detention time of wastewater in the lake should be as short as possible, whilst the residence time of clean water should be as long as possible.
- One of the effective ways to *prevent* water deterioration is to maintain water movement since moving water has the self cleaning capacity (self-degradation, self-decomposition and self-purification), and high turbulence shears dispersed planktonic flocs and limits sessile microbial growth.

The objectives of this chapter will be 1) to show how to manage the water and the particles it carries simultaneously, thus the floodwater is regulated for the use in drought seasons, and the lakes/reservoirs' storage capacity is protected with the damaged ecosystem being restored; 2) to compare the new strategy of water management with existing strategies, and the case studies will demonstrate whenever the SPP strategy is applied, the water related disasters can be mitigated, vice versa.

2. SPP strategy

Normally, a natural or artificial lake may comprise multiple incoming and outgoing rivers that collect the rainwater/wastewater from upstream of the lake and drain the lake water to downstream, respectively. The SPP strategy is achievable if an internal levee with sluice gates is built in the lake. By doing so, flood disasters (too much water) of the watershed will be significantly reduced, water shortage problem (too little water) can be alleviated simultaneously, the siltation rate is reduced (too turbid) and clean water resources are protected against pollution. These two levees around the lake shoreline together would form an artificial canal or by-pass channel (BPC) as shown in Fig. 3. The inner bank of the canal would be built in the lake and could be constructed using dredged sediments to deepen the BPC.

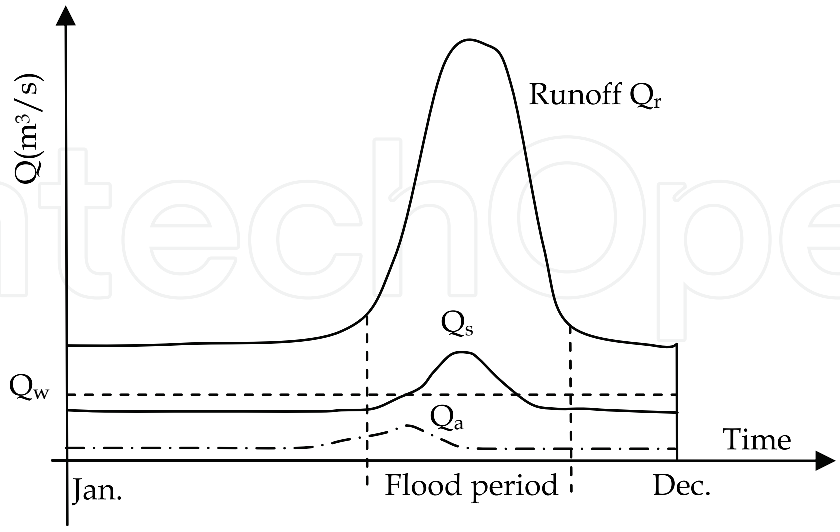

Fig. 2. Simplified hydrograph of runoff and wastewater yielded in a catchment

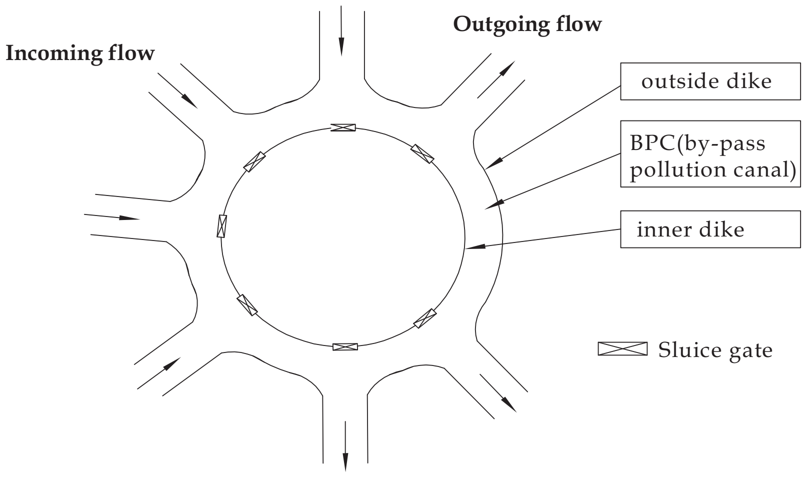

Fig. 3. Simplified water system for a lake and the proposed infrastructure for water resources development and pollution prevention

Separation in space and time: The sluice gates would be used to regulate the unwanted water. If the river water is heavily polluted or sediment discharge is very high, the sluice gates will be closed so that all polluted water by-passes the lake and is discharged to the downstream of the catchment via the lake outlets. During flood periods, nutrient concentration is very low, except first flushes, the water quality from all inflow rivers will be relatively good. In such case, the sluice gates will be opened so that clean floodwater can enter the lake and be stored. Thus the water separation can be conducted based on the quality of river water in time (flood/drought) and space, i.e., good quality water enters to the lake for storage; but unwanted water runs to the downstream via BPC. Without the BPC, the lake receives all sediment particles from the rivers, with the BPC, the sedimentation rate is reduced to the particle volume carried by the stored water that is only a small fraction of all sediment yielded by the catchment.

Protection against external pollution: when the good quality floodwater enters the lake, this water is protected by the inner levee as the sluice gates are closed when the incoming river water quality becomes poor later. Thus the external contaminants in the rivers cannot mix with the clean water in the lake. In this stage (drought periods), the river water and the lake water are separated and the clean water is fully protected.

Prevention of water degradation: As most of unwanted water (heavily polluted and high sediment-laden) will be concentrate in the BPC where the cross-section area is much smaller relative to the lake, thus for a certain discharge at the outlet, the velocity in the BPC will be rather fast. Consequently, the high level of turbulence will disperse all aggregated flocs and to purify the water, and the flow is capable to carry the sediment to the downstream without deposition. It may be hard to imagine that the water quality in the "by-pass canal" will be better than the water without the canal in the same conditions. This seems counter-intuitive as most of unwanted water would flow in the canal surrounding the lake. But this is possible because, as mentioned early, hydrodynamic parameters are also a dominant factor for eutrophication and sedimentation, responsible for the appearance of algal blooms. It is often observed that higher velocities can prevent blooms/siltation from developing, and slow water movements create an almost quiescent environment where phytoplankton grow quickly with favourable nutrient, light and temperature conditions because microbial particles can stick together to organic aggregates.

Too Much: The above analysis shows that the proposed scheme can well solve the "unwanted water" (i.e., too dirty and too turbid) problem. Furthermore, the flood disaster can also be mitigated. Under natural conditions, i.e., without BPC in Fig. 3, the highly contaminated river water with first flushes at the beginning of flood period occupies a lake's storage capacity. Consequently, the active storage is not sufficient to accommodate the following peak flow and flood disaster occurs. SPP approach can considerably reduce the dead storage of a lake as all unwanted water is discharged to the downstream via BPC and does not occupy the lake's capacity, thus it significantly increases the effective flood-control storage of the lake.

The flood disaster can be mitigated, because the sluice gates are normally closed during dry period, so that the water level in the lake is very low due to regulation and water use after last year's flood period. Then just before the onset of the rainy season, water level in the lake is very low, and the low level can be kept until the arrival of peak flow, during which the sluice gates is open, thus the water level in BPC and the rivers can be lowered to acceptable level for disaster mitigation.

In other words, with BPC, the lake can be operated intentionally, and the lake's storage volume can be kept to accommodate the coming floods. The strategy of transforming a lake to a flood retention zone can greatly expand its capacity for flood control. During flood seasons, the sluice gates are opened when the water level in the rivers reaches the designed high level. Once opened, the velocity of flood wave propagation will be increased as very low water level in the lake increases the hydraulic gradient, then the scheme can greatly mitigate flood disasters. At the same time it transforms the floodwater to clean lake water that is protected from pollutants by enclosing levee with the sluice gates.

Too Little: This innovative strategy of water management can also alleviate the water stress in a lake, because under natural conditions, water from the lake keeps losing by gravity via its outlets, and the water level quickly drops after flood period. If the proposed scheme is applied, the clean water will be protected, and sufficient high quality freshwater during flood period will be kept in the lake through the drought period until the next rainy season just like a reservoir. In other words, the water level is still high even after flood period. This water can be used by the human society to sustain their developments. Most importantly, during dry periods, all sluice gates are closed, the inner levee protects the lake water against external pollution, and it also prevents unnecessary loss of lake water.

The core idea of SPP is that the water should be separated based on its quality or turbidity; the unwanted water should be prevented mixing with the clean water, and good quality water must be stored and protected. In other words, the residence time of unwanted water in an ecosystem should be as short as possible; while the detention time of wanted water (or clean water) should be as long as possible.

3. Successful cases by applying SPP strategy (too turbid)

The idea of SPP for lake and reservoir water management is new, but this does not mean that the similar strategy has never been applied by far. In this section, we will discuss two cases to show that if SPP is not applied, the water related problems cannot be solved, while if the strategy is applied, all problems become solvable.

In 1854 Dr John Snow demonstrated the connection between water supply and Cholera as shown in Fig. 4. Several years later, Thomas Hawksley in Nottingham suggested that water supply systems should be piped to prevent external pollution.

Here the suggestion of pipe transport implied the idea of “separation, prevention and protection”. Like the enclosed levee shown in Fig. 3, the pipe can *separate* clean water from the polluted water, and only clean water is allowed to enter the pipe network; likewise, the pipe protects the clean water inside the system and prevents the external pollutions. Consequently, the problem of waterborne illness death rate like Cholera, typhoid fever and dysentery had rapidly dropped to a very low level as shown in Fig. 5. This is probably the first time in history using the strategy of SPP for water resources management, and the concept of pipe water has been widely accepted in the world since then.

However, for large water system, so far there is no direct example of SPP strategy in application. Sometimes, people were forced to adapt the strategy of SPP to solve their problems. One of the examples is the Sanmenxia Reservoir in the middle reach of Yellow River, China. Yellow River basin is one of the largest basins in the world, and it is notorious in the world for high sediment transport rate in the middle reach. Between 1919 and 1960, the measured data at Sanmenxia Station showed that the mean annual runoff was 42.3×10^9 m^3 and the long-term average annual sediment load was 1.57×10^9 t with the average concentration of the river water being 49.8 kg/m^3, the highest in the world.

Sanmenxia Reservoir is created by the Sanmenxia dam. It is a large-scale multipurpose project, and the first one constructed on the main stream of the Yellow River. The construction of the dam was started in 1957, and the impoundment of water commenced in September 1960. The dam height is 106m at the pool level 323m with the storage capacity of 3.6×10^9 m^3.

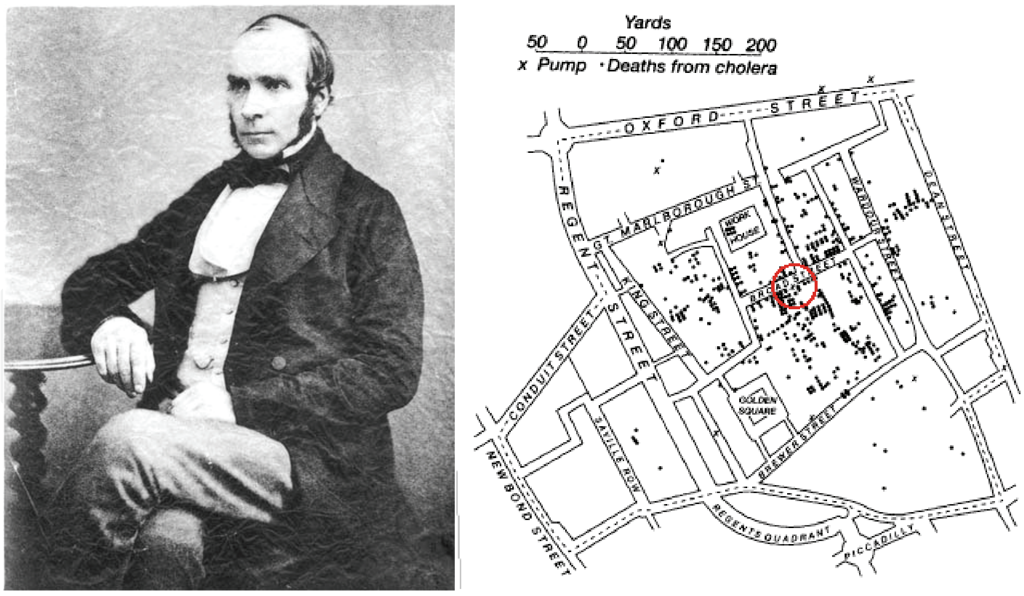

Fig. 4. Dr. John Snow and the map he used in 1854 to identify the source of cholera; this discover leads to the first application of SPP strategy in water management

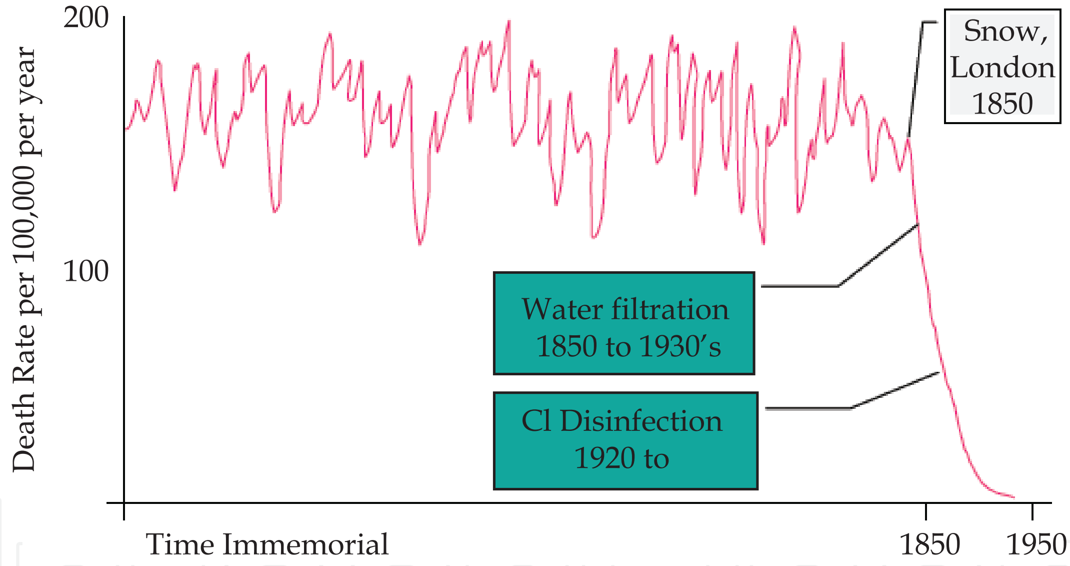

Fig. 5. Death rate of human being in the history, indicating the application of SPP could immediately reduce people's death rate

In its planning stage, engineers and decision makers used the same practice as they did for other reservoirs, i.e., no special measures had been taken to separate incoming water based on its quality, and nothing had been done to protect the reservoir water and to prevent external high turbidity water. Consequently the reservoir storage capacity was decreasing at an astonishing rate in the reservoir, which caused the unacceptable negative impact of rapid development of backwater sediment deposition. In 4 years time, the accumulative sediment silted in the reservoir reached alarming level, i.e., 4.44×10^9 m^3, in other words, the reservoir's storage capacity had almost totally lost. Under such circumstance, engineers were forced to reconsider the strategy of water management, and the dam had to be reconstructed to minimize the adverse effect of reservoir sedimentation.

The engineers and decision makers realized that there was no hope to solve the sedimentation problem without separation, then they divided the dam's operation into two time periods or two different modes of operation:

1. in flood seasons (July–October), turbid water is discharged to the downstream by lowing the water level at 305m, thus the flow velocity is high enough to carry the highly suspended load. In this period, if the flood discharge is greater than 2500 m^3/s, all the outlets of the dam will be opened to flush the sediment as much as possible.
2. in non-flood seasons (November–June), the relatively clear water is stored and the reservoir is operated at a high operational level, with the maximum level not exceeding a value between 322 m and 326 m, to store water for irrigation and hydropower generation in non-flood seasons;

After the separation, the new design was found effective, till now, the dam is still providing the basin with flood control, irrigation, and hydropower generation, even though some benefits are lower than the original design. The engineering experiences and management practices of Sanmenxia Dam are valuable assets to the sustainable management of reservoirs/lakes on sediment-laden or nutrient-rich rivers. It can be seen that the above operation strategy is similar to the SPP introduced in this chapter as the unwanted water (high turbid floodwater) has a short residence time in the reservoir, and the clean water in non-flood season (wanted water) has a relative long residence time for the eco-system. This project not only demonstrated the perils of existing water management, but also demonstrated that a sediment balance may be achieved across an impounded reach even in a large reservoir built on a river with an extremely high sediment load.

4. Flood control in Dong-Ting Lake, China (too much)

Different from the Yellow River basin where droughts (too little) and high turbid water (too turbid) are two key challenges for water resources managers, the Yangtze river basin where the Dong-Ting lake is located often has the threat of flood (too much). Yangtze River is the third longest river in the world, and its catchment area is about $1.91 \times 10^6 km^2$. The average annual water discharge is $918km^3$ and average annual load of suspended sediment is 500×106 t (1956-2003, Zhang 1995), respectively the fifth and fourth in the world (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Its middle reach is known as the country of a thousand lakes that serve as an efficient flood regulator, among which Dongting is the largest lake. Due to sedimentation and reclamation over the past 50 years only few lakes have been left in this region, and the total capacity has been significantly shrunk. This region plays an important role in China's economic development, and this can be inferred from the historical proverb "If southern and northern regions of Dongting Lake harvest, the whole China's prosperity is ensured"; but if this region suffers from flooding, the whole China's economical development will be badly affected.

Dongting Lake, used to be the largest freshwater lake in China before 1950. Now it has been shrunk to be the secondary largest lake in China due to high sedimentation rate. The lake valley is surrounded by mountains on the east, south, west and Yangtze River on the north. The population in this basin in 1997 was 15 million. Many rivers drain into the lake from mountainous south and west, besides three channels connect the lake to the Yangtze River, which dumps a major proportion of the sediment suspended from Yangtze River to the lake when the lake accommodates floodwater. The lake has only one outlet on the east side.

This lake annually receives 173 million tons of sediment, 83% of which are carried into the lake from the Yangtze River, and 17% from other inflow rivers. Over the past 150 years, the lake area has reduced from about 6000km^2 to about 2600km^2 due to both natural siltation and human activity, consequently flood modulation of the lake capacity has been reduced significantly from about 30km^3 in 1949 to 17km^3 in 1995, about 50% of the lake's capacity has been silted. It is certain that the lake will continue to shrink, and in the near future it may serve only as a river channel during the non-flood reasons (Du et al. 2001). In another 50-100 years, this lake may totally disappear if there is no human's interference.

Similar to other plain lakes, Dongting Lake has suffered many problems, if not solved properly, these problems may cause serious consequences to environment and bring about huge economic and life loss. These problems can be summarized as flood disasters in wet seasons (too much), water shortage for the ecosystem in dry seasons (too little), lake's shrinkage (too turbidity) and water pollution (too dirty).

Apart from too much and too turbid problems, the lake water was polluted by the incoming wastewater due to rapid industrial development and population growth and agriculture fertilization. In this fertile "land of fish and rice", farmers every year use 18k tons of pesticide and 1700k tons excessive fertilizer, which flows into the lake via the rivers. After 1990s eutrophication tendency has been accelerated, according to the monitoring data, 1996-2005 main pollutants are total phosphorus and total nitrogen (Guo et al., 2007).

Li et al (2009) summarized the problems in the Donting Lake area as a chain:

> Disaster in wet seasons : sedimentation → marshland expansion → water
> space shrinkage → flood level raised and flood disaster aggravated.
> Disaster in dry seasons : sedimentation → marshland expansion → water
> space shrinkage → water pollution and fish resource depletion → wetland and
> biodiversity reduction.

The average reoccurrence interval (ARI) of flood disaster was 83 years from 276 B.C.-1525, and ARI = 20 years from 1525-1853; ARI = 5 years from 1853-1949 and ARI = 4 year from 1949-2000, recently this area suffers the flood disaster almost every year. Obviously this is caused by the sedimentation that keeps reducing the lake's capability for flood retention (Yang, 2004).

All problems that the lake is facing can be well solved if the proposed SPP strategy is applied as shown in Fig. 6, in which the length of inner levee is about 240km. This is feasible because:

1) *Sedimentation*: in the current condition, almost all incoming sediment particles are deposited in the lake, i.e., 1730 million tons of sediment, and the lake functions like a sedimentation tank where the clean water run out of the tank. But with the inner dike, the incoming flow can be separated into wanted/unwanted waters, i.e., high turbid but safe floodwater will by-pass the lake and drain to the downstream. Only a small part of excessive floodwater is allowed to enter the lake, which can mitigate the flood disaster, and the majority of the water stored in the lake comes from the falling limb in the hydrograph shown in Fig. 2, thus clean and low turbid water is stored. Currently the lake's storage capacity is only 1/10 of the annual incoming water volume, if SPP is used and then the

sediment carried by this part of water will be deposited in the lake, approximately only 1/10 of the total incoming sediment, the remaining sediment will by-pass the lake and go to the downstream. Hence, if the SPP is applied, every year only 173 million tons of sediment will deposit in the lake, therefore the reduction of sedimentation rate will be

$$\frac{173-17.3}{173}=90\%$$

Thus the SPP strategy can reduce significantly the sedimentation rate, and the life span of the lake can be extended.

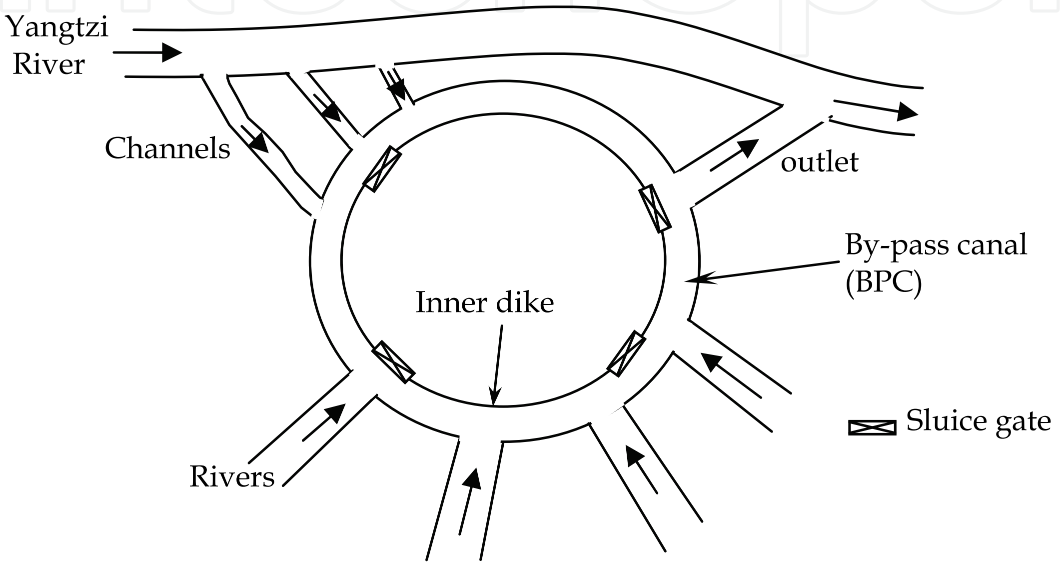

Fig. 6. Simplified river-lake system for the Dong-Ting Lake

2) Flood disaster: it has been mentioned that the cause of flood disaster is that the lake's storage is occupied by the runoff before the arrival of peak discharge, hence the excessive flood water incurs disasters. With the strategy of SPP, the floodwater can be separated as safe water and excessive floodwater. The former refers to that flow in BPC is safe, the incoming flow rate is less than BPC's design capacity and water level is below the BPC's design highest water level. The excessive floodwater is water that overflows the rivers and incurs the flood disaster if no retention area is provided for its temporally storage. All sluice gates are closed before the arrival of the excessive floodwater, thus in the rising limb in Fig. 2, all river flows together with sediment and non-point pollutants will by-pass the lake. Once the excessive peak flow that needs a retention area appears, the sluice gates are opened, at this time the lake is still empty, thus the flood disaster can be mitigated. After that, the water level in BPC will be lowered to the safe level, then all gates can be closed again to wait for the next flood wave, or if the weather prediction shows no more heavy rains in the catchment, the gates can be opened again to store as more clean water as possible for the next drought. Thus, at the end of wet season, the lake is full of good quality water.

3) Water shortage. Every year, after the flood season, this basin has a long dry period, and the basin often suffers the water shortage problem in this period. For example, in 2011, this region was struck by severe drought, affecting residents and agriculture, and more than a million people did not have adequate supplies of water. About 709,000 hectares of farmland in the basin had been hit and no water for irrigation. The central region of the lake had become a vast grassland. On May, 2010, the water surface area was only 780km^2, about 30% of normal water surface area.

But 10 months ago, in July, 2010, this lake suffered the flood disaster with the highest water level reading 32.9m above the sea level, and it had to rely on the upstream reservoir's regulation to mitigate the flood disaster. Thus, it is obvious that, without control, the lake cannot play a dominant role for droughts as the water has lost quickly after the previous flood. 2011 droughts can be avoided if the SPP strategy was applied and the floodwater in 2010 was impounded by the inner levees and gates shown in Fig. 6.

5. Algal blooms control in Tai-Hu Lake, China (too dirty)

Taihu Lake, the third largest freshwater lake in China, is located in the highly developed and densely populated Yangtze River Delta. The lake is shallow with an average depth of 1.89 m, but a large surface area of 2,238 km^2, and a volume of 4.66×10^9 m^3. The annual water input averages 7.66×10^9 m^3 and the residence time of its waters is about 300 days. There are over 219 inflow rivers or tributaries but only three main outflow rivers. The average of rainy days is 132 days/year and the average annual rainfall is about 1,145 mm. Rainfall varies seasonally with wet seasons between June and September, i.e., during the typhoon season or flood period, and the dry seasons from October to next May and constitutes the long dry period.

Taihu Lake plays multifunctional roles including floodwater storage, irrigation and navigation. It also serves as a major water resource for drinking, aquaculture and industrial needs, as well as being a source of entertainment and tourist interest. Its drainage basin extends over 37,000 km^2 and is bounded by the Yangtze River to the north, the East China Sea to the east and mountainous areas to the west. While the basin accounts for 0.4% of the total area of China and 2.9% of the nation's population, it provides more than 14% of China's Gross Domestic Production (GDP). The GDP per capita is 3.5 times as much as the contry's average and its urbanization level ranks the first in China. This basin is vital for eastern China, where the lake water supports more than 60 million people (about 600–900 person/km^2 on average), including the water supply to cities such as Wuxi, Suzhou, and Shanghai, one of the largest cities in the world.

With the tremendous economic growth and increased population in its basin, Taihu Lake has begun to suffer from various environmental stresses, including deterioration of its water quality with increasing nutrient and other chemical inputs. The lake is becoming increasingly eutrophicated and has experienced annual lake-wide cyanobacterial blooms in recent decades; this has affected the drinking water supply of surrounding cities. Taihu Lake now receives annually approximately 30,635,000 kg total nitrogen (TN) and 1,751,000 kg total phosphorus (TP) from a combination of municipal and industrial wastewaters and agricultural soil runoff; chemical oxygen demand on chromium (CODCr) is 131,223,000 kg (Qin et al, 2007).

Consequently, algae blooms have appeared and continued. The lake is often covered by algae blooms in summer, autumn and even spring. In 2007, a severe algae bloom caused a drinking water contamination crisis for 4.43 million people in Wuxi city. An article in Science (Yang et al. 2008) reported that the concentration of dimethyl trisulfide in a water sample collected on 4 June 2007 from the drinking-water intake was 11,399 mg/liter—high enough to yield strong septic and marshy odors.

More than 50% of rainfall in the catchment appears from June to September, so this period can be defined as the wet season, and the remaining 8 months is the dry season. Unlike rainwater, industrial and municipal wastewater releases have little seasonal variation. The hydrograph of rainwater and wastewater is simplified as shown in Fig. 2. Integrating the runoff Qr with respect to time from January to December, one has:

$$\int Q_r dt = V_o = 7.66 \times 10^9 (m^3) \tag{1}$$

where V_o = annual water yield in the basin.

From June to September, the water volume can be estimated as half of the total water yielded from the catchment as its rainfall is half of the annual rainfall, i.e.,

$$\int_{June}^{Sept} Q_r dt \approx \frac{V_o}{2} = 3.83 \times 10^9 (m^3) \tag{2}$$

Similarly, the wastewater yielded in the basin can be determined by

$$Q_w \times 365(d) \times 86400(s/d) = W_o \tag{3}$$

where W_o = yearly total volume of wastewater yielded in the basin and discharged to the waterways.

Currently all wastewater flows into the lake and its average concentration C_o is

$$C_o = \frac{W_o}{V_o} \tag{4}$$

In the wet season from June to September, the concentration C_1 is

$$C_1 = \frac{4W_o/12}{V_o/2} = \frac{2}{3} C_o \tag{5}$$

where $4W_o/12$ is the amount of wastewater yielded in 4 months (wet season), whilst Vo/2 is the amount of clean water yielded in the same period. Eq. 5 shows that in wet seasons, the water in inflow-rivers is relatively clean when compared to the water in dry seasons.

Water Quality in the Lake: Yang and Liu (2010) estimated the amount of wastewater entering the lake if the scheme shown in Fig. 3 is used. They assumed that river water with good quality is 50% of the total water resources, and it will be allowed to enter the lake via the sluice gates with the amount of $3.83 \times 10^9 m^3$, and the lake's storage capacity is the sum of the dead volume and the effective volume, i.e., 4.6×10^9 m^3.

It should be stressed that while the rainwater from June to September flows into the lake via sluice gates, this does not mean that the sluice gates will remain open for the 4-month period. Instead they will always be closed even in the flood period if the river water is not clean enough. Thus, the first flush of each storm event will by-pass the lake in order to prevent the non-point source pollution. In the wet season, there is an average of 46.9 rainy days. The sluice gates will be opened, and only on these days will the floodwater be discharged to the lake. The concentration C_{in} on these days is

$$C_{in} = \frac{46.9W_o / 365}{V_o / 2} \approx \frac{1}{4} C_o \tag{6}$$

It can be seen that with the aid of sluice gates and BPC, the pollutant concentration entering to the lake can be significantly reduced. In other words, only 25% of contaminants yielded by its catchment in a year will be released into the lake to mix with the clean water while 75% of wastewater yielded in a year will by-pass the lake and be discharged to the downstream via the three outlets. While we have only discussed inflowing water concentrations, in principle, the concept can be extended to all other parameters, such as sediment inputs, BOD, TP, TN etc. Our estimation shows that if the SPP strategy is used, in about 3.5 years, the quality of lake water can be restored, the damaged eco-system can be remediated, and the algal blooms will disappear as nutrient levels decline.

Water Quality in BPC: Taihu Lake has a residence time of 300 days and the slow water movements together with high concentrations of nutrients contribute to the problem of algal bloom in lakes. However, if the residence time of water is short, say 0.1 to 1 days, the high velocity of the water in the By-Pass Canal will prevent organic aggregation and transport phytoplankton into low light environments; turbulence will also keep phytoplankton and aggregates dispersed. Thus, there should be no problem of algal blooms in the canal. Higher water velocities do and can improve water quality in Taihu Lake, and this has been found in the lake: East Taihu Bay is a long (27.5 km) and narrow (greatest width is 9.0 km) bay located in east of Dongshan Peninsula; it connects with the West Taihu Lake at a narrow interface. East Taihu has an area of 132 km^2 (5.9% of the total Lake Taihu surface area), with an average depth of only about 1.2 meters. The cross section of East Taihu Bay is much smaller relative to West Taihu Lake, but it is the main channel draining the lake. About 70% ~ 80% of the total outgoing discharge flows from this bay; therefore the flow velocity in this bay is higher than the velocity in the West Taihu Lake as this bay is much shallower and narrower. Similarly, water quality in the East Taihu Bay is better than the quality in the West Taihu Lake even the wastewater discharge received by the former bay is 4 to 5 times of the wastewater discharge received by the latter (Yang, 2004). This observation supports the inference that an increase of flow velocity can improve the water quality.

From the above discussions, it is reasonable to conclude that the proposed scheme shown in Fig. 3 could significantly improve the water quality of Taihu Lake. Improvements are based on clean water being stored and protected by the inner levee while polluted water is retained (and concentrated) in the surrounding canal with algal blooms prevented by high flow speeds. Moreover, it is possible to further improve water quality in the canal by ecological remediation techniques and/or by flushing the wastewater in the canal using the clean water from the lake. High velocity water has strong ecological self-purification capability.

6. Potential application of SPP strategy to other lakes in the world

In this section, some typical lakes in the world will be discussed, and the application of the proposed SPP strategy to these lakes will be assessed.

6.1 Dianchi Lake, China

Lake Dianchi is the sixth largest freshwater lake in China and a capital city of this province with population of 6 million is located adjacent to the lake (see Fig. 7). The lake is divided into two parts: the northern, smaller part is called Caohai, with a surface area of 7.5km^2 and an average depth of 2.5 m; the larger southern and main body of the lake is called Waihai, with a surface area of 292km^2 and an average depth of 4.4 m. There are more than 20 major rivers flowing into the lake from the east, south and north. The lake water has been used to support industrial development, urban drinking water, navigation, tourism and irrigation etc.

Due to the rapid growth of population and economic development in the basin (6 million in 2006, only 1.5 million in 1980), this lake has received more and more wastewater that is yielded from the catchment. In 1995, the wastewater was up to 185 million tons, among them, TP (total phosphorous) 1021 tons, TN 8981 tons, more than half of which was non-point source pollutants from the agricultural fertilizer or pesticide. The algal blooms have been emerged from the late 1980. The lake has been listed in the ''Three Important Lakes Restoration Act in China'' by the central government. Huge investment has been spent for the remediation, but none of them has been proved effective. The city currently faces a difficult dilemma: whereas on one hand many efforts have been undertaken to improve the local water environment, the pollution problem is still overwhelming. On the other hand, the city is growing and its dependence on the lake, though already severely problematic, is still growing (Huang et al., 2007).

Gray and Li (1999) reported that if Dianchi Lake is to have the high water quality as it had in the 1960s, the TP inflow through surface water should be less than 60 tons per year. Although the government has made many attempts to reduce the TP, Huang et al (2007) drew a pessimistic conclusion: ''The TP load reduction envisaged as realistic would only stabilises the lake water quality by about the year 2008; unfortunately, interventions could not return the lake to its former pristine condition.''

This is understandable as the government does not use the strategy of SPP. Similar to Taihu lake, once the proposed strategy is used, only the clean water is allowed to enter the lake, when the water crisis is curable. The required inner dike is about 163km for the lake to implement the SPP strategy, and the construction of this levee and its associated sluice gates is only a small fraction of the cost required by other alterative.

6.2 Lake Biwa, Japan

Lake Biwa is located in the central part of Japan, and it is the largest lake in Japan with a surface area of about 681 km^2, water volume about 27.6 km^3, average depth of 44 m and the maximum depth of 104 m. The lake extends north to south for about 65km, and there are about 40 inflow rivers with residence time of 5 years and a single outlet river, located at the southernmost end of the lake. Lake Biwa consists of a larger north basin and a smaller south basin, and it is a valuable water resource for 14 million people living in this area.

Fig. 7. The Lake Dianchi basin in China

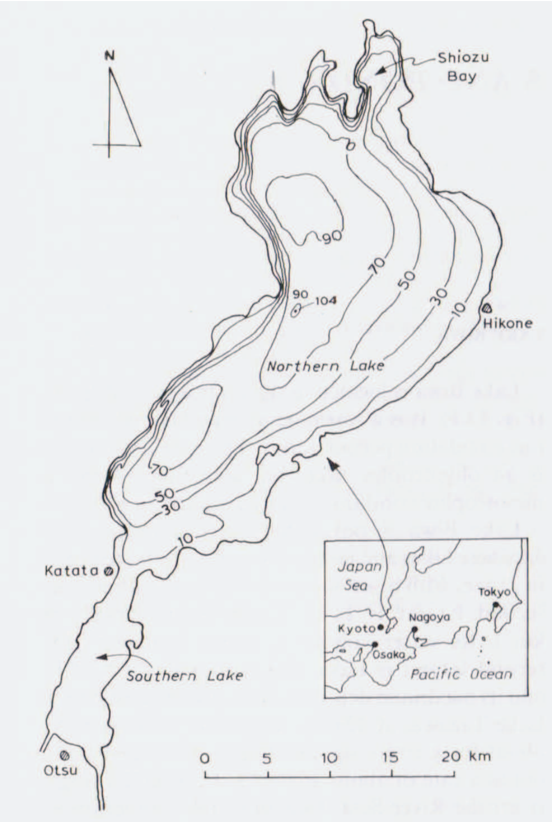

Fig. 8. The Biwa Lake, Japan (after Mori et al. 1984)

The problems that the lake has include: the eutrophication of the lake caused by wastewater, which led to algal blooms in the lake has started in 1980s. After that, even the percentage of domestic wastewaters treated in the basin had increased from 1.7% in 1975 to 78.2% in 2004, and the removal rates of N and P have also been improved, the chemical oxygen demand and the NO_3 and PO_4 concentrations in the surface layer water have not been improved as expected (Nakano, et al. 2008). The analysis shows that the lack of improvement in the water quality of the lake is that the environmental loads from nonpoint sources are unexpectedly greater than those from point sources such as domestic wastewater. Especially, N and P of agricultural origin have a great effect on the eutrophication of the lake. This citation clearly indicates that without SPP strategy, it is impossible to provide very clean water to the users with the control of point-source pollution only, as the agricultural wastewater has been increased steadily to increase the food production.

Application of SPP strategy to the lake: The cause of nutrophication in Biwa lake is very clear: no measured has been taken to separate the agricultural wastewater with the clean rainwater, because this lake has not had the industrial and domestic wastewaters like other lakes in the world. In other words, the water quality of lake Biwa can be improved significantly if N and P from agricultural sources are reduced significantly, but so far no any technology except SPP can reach this goal.

Currently, all N and P yielded from farm lands in the basin are collected by the lake, and eventually it mixes with the clean lake water and the mixing leads to the eutrophication in the lake. However, if the 133km inner dike is constructed along the 10m contour, then all unwanted river water with high concentration of N and P will by-pass the lake, and only the clean river flow is allowed to enter the lake. Thus the N and P level in the lake can be significantly lowered to an acceptable level, and no algal blooms will occur.

7. Conclusions

Meeting increasing water demand has always been one of the main challenges of civilization and could be the most difficult problem in the 21st century. With the rapid growth of population together with agricultural and industrial development, the clean water demanded in the 21st century would be increased considerably. On the other hand, the wastewater produced by human being would also increase significantly. The limited clean water may become scarce due to the climate change that may reduce the rainwater supply, increase the evaporation loss, and wastewater pollution that has extremely deteriorated quality of water, especially in large water bodies. In this circumstance, if there is no effective strategy to manage our water resources, the modern civilization may collapse that had happened in the history. Aiming at this, this book chapter proposed the SPP water management strategy. The following conclusions can be drawn from this study:

1. The analysis shows that the water must be managed for its quality and quantity simultaneously. In other words, the appropriate water management must include particle management or impurity management;
2. Currently the water has been separated into many groups, like wastewater, river water rainwater, floodwater etc. It is suggested that the water can be further separated as wanted and unwanted water based on the purpose of water management. Generally, the unwanted water includes heavily polluted or highly turbid water, and the wanted water could be excessive floodwater or clean river water;

3. The SPP strategy refers to water separation, clean water protection and prevention from external pollution. Currently in the world, all reservoirs and lakes' water are exposed to external wastewater with no countermeasures taken to protect the stored water, and the incoming river water has never been separated. Consequently, all clean lake/reservoir water has been polluted and the storage capacity is quickly lost by sedimentation.
4. In this book chapter, we discussed some typical lakes/reservoirs in China and Japan, like Sanmemxia Reservoir, China's second, third and sixth largest lakes and Lake Biwa in Japan. To solve problems in these lakes, the SPP strategy is very effective. The water quality can be restored to acceptable level in a short period and the life span of these lakes can be extended significantly. All construction needed for SPP is only an inner dike with sluice gates. The longest dike for these lakes is about 240km, and the maximum height of these dike is about 10m.
5. Generally, for a given catchment, there always exist threats like flood disasters (too much), droughts (too little), deterioration of water quality (too dirty) and siltation (too turbid). SPP strategy is effective to all these problems.
6. In this book chapter, we only outlined the application of the SPP to the mentioned lakes, but in principle, the strategy is valid to all other large water bodies. Next, more detailed research like physical and/or numerical models are needed before it can be used in practice. Eventually, it is subject to the decision maker/politician's decision.

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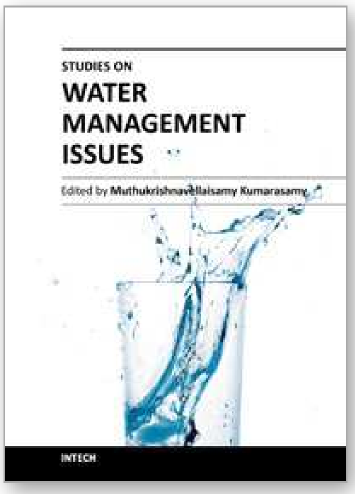

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This book shares knowledge gained through water management related research. It describes a broad range of approaches and technologies, of which have been developed and used by researchers for managing water resource problems. This multidisciplinary book covers water management issues under surface water management, groundwater management, water quality management, and water resource planning management subtopics. The main objective of this book is to enable a better understanding of these perspectives relating to water management practices. This book is expected to be useful to researchers, policy-makers, and non-governmental organizations working on water related projects in countries worldwide.

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