

# How to Purify a Polluted Lake Quickly—A Case Study from Shanghai, China

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## Abstract

Water pollution has become a serious worldwide problem, especially for lakes with a large stagnant water body. Is it possible to develop high quality water from a heavily polluted river system quickly? This paper introduces an innovative technology termed SPP (separation, prevention and protection) for this purpose. Its feasibility is preliminarily examined using Dianshan Lake in Shanghai as an example. Due to its very high population density and intensive industrial activities, almost all waterways in Shanghai are heavily polluted, including the lake. However, the data analysis shows that clean water always appears after heavy rains, especially in its suburban areas. Once the 1<sup>st</sup> flush water is discharged to downstream, high-quality water can be developed from its Dianshan Lake by using the SPP strategy. The Vollenweider model is used to analyze SPP's feasibility. The results show that the water quality of the Dianshan Lake can be remediated as a drinking water source within 120 days if the SPP strategy is applied. It is suggested that Jinze reservoir's water should come from the Dianshan lake, not Taipu River to improve the quality of water supply. It is highly recommended for other cities in the world to consider the SPP technology if needed.

## Keywords

Dianshan Lake, Water Shortage, Water Pollution, SPP Strategy, Total Phosphorus (TP)

## 1. Introduction

The total water volume of Earth is about  $1.41 \times 10^9 \text{ km}^3$ . The volume of freshwater resources is around 35 million  $\text{km}^3$ . But the primary renewable source of freshwater comes from continental rainfall, which generates a global runoff 40,000

- 45,000 km<sup>3</sup>/year. This nearly constant water quantity needs to support the entire ecosystem and total population. The latter is steadily increasing by roughly 85 million per year [1]. Hence, the amount of freshwater per person keeps decreasing steadily. In 2000s, about 80 countries with 40% of the world's population, were experiencing water stress, and about 30 of these countries are suffering water scarcity during a large part of the year [2], this number is expected to reach 34 by the year 2025 [1]. Now about 2/3 of the global population suffer from freshwater scarcity [3].

Apart from the natural water scarcity, freshwater quality in rivers and lakes is also deteriorating due to pollution, which therefore intensifies the shortage. Every day, more than 2 million tons of wastewater drain into the world's water bodies, which pollutes 1500 km<sup>3</sup> of water annually due to dispersion and mixture, six times more water than exists in all the rivers of the world [4]. Consequently, many previous water sources become gradually dead/dying, even cess-pools of waste.

China is one of the examples, its highest economic growth rate in the world resulted in  $68.5 \times 10^9$  tonnes of wastewater from its point sources in 2012 (<http://chinawaterrisk.org/resources/analysis-reviews/8-facts-on-china-wastewater/>). Consequently, rivers and lakes commonly suffer from the eutrophication process, water quality is being decreased. Most of the medium-sized lakes at the urban-rural fringe are in eutrophication or hypereutrophication status. Eutrophication, especially in lakes, has become a serious environmental problem in China, especially for those functioning as a source of urban water supply. In this aspect, Shanghai, the most developed and largest city in China is a typical example. Its experience and lessons may be useful for other cities for their urban planning and development.

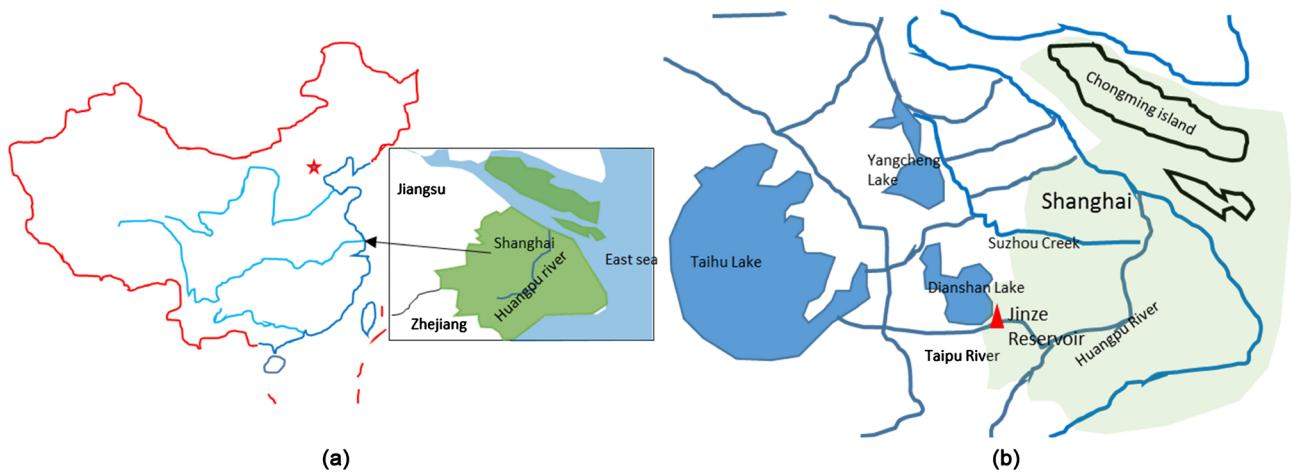
## 2. Huangpu River and Shanghai's Water Supply

Shanghai is situated in the delta of the Yangtze River in the middle portion of the Chinese coast. The total area of Greater Shanghai is 6340 km<sup>2</sup> on the south side of the Yangtze River and the east side of Tai Lake, with a population of 24.5 million in 2018. The municipality has a border with the provinces of Jiangsu and Zhejiang to the north, south and west, and is bounded to the east by the East China Sea as shown in **Figure 1**.

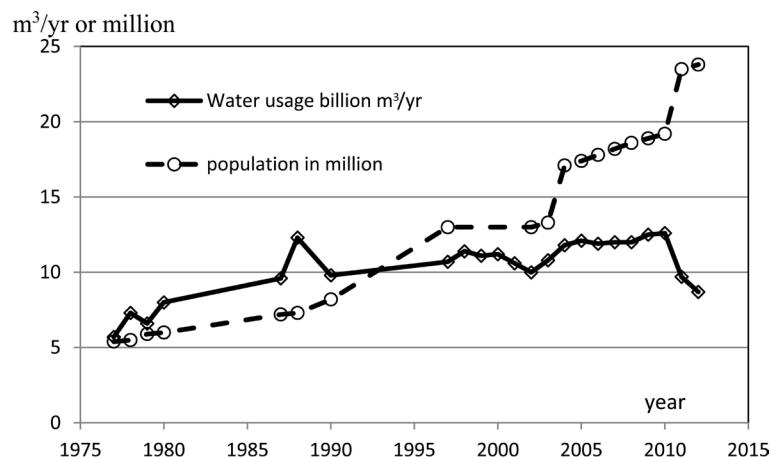
The Yangtze River is the third-longest in the world and the longest river in Asia, its catchment is about 20% of China's land area, and the river basin is home to one-third of China's population. Its runoff stands at  $951.3 \times 10^9$  m<sup>3</sup>/year, about 52% of the national total. The Tai lake is China's third largest freshwater lake, covering a water surface area of 2238 km<sup>2</sup>, having a water volume of  $4.66 \times 10^9$  m<sup>3</sup> [5]. On average, the lake discharges about 70% - 80% of its water, or  $10.6 \times 10^9$  m<sup>3</sup>/year to the Huangpu River, the mother river of Shanghai. Along its flow path, there are lakes and creeks like Dianshan Lake, Taipu River and Suzhou Creek. The total water availability for Shanghai from the Yangtze

and the Tai Lake is about  $962 \times 10^9 \text{ m}^3$  per year. This is a strikingly water-rich city surrounded with abundant water resources.

Before 2010, almost all water used in Shanghai came from the Huangpu River. But the Huangpu River's rapid deterioration of water quality has forced the shift of water supply from the Huangpu River to the Yangtze River, and the latter supplies about 70% - 80% of water used and the remainder still comes from the former. Currently, water consumption by the city is about  $12 \times 10^9 \text{ m}^3/\text{year}$  for industrial, domestic and agricultural users. Among them, only 1/5 of the water used is treated to drinking standard, *i.e.*, about  $2.4 \times 10^9 \text{ m}^3/\text{year}$  in 2018. **Figure 2** shows the rising trend of population and water usage from 1977-2012, which clearly shows that the water usage steadily increased with the population growth before 2005. In the extremely dry year-1988, the water consumption reached  $12.3 \times 10^9 \text{ m}^3$ . Currently, the water supply is constant at about  $12.5 \times 10^9 \text{ m}^3/\text{year}$  with a slight reduction after 2010. To diversify its sources and to lower the risks to water supply, in the future the Huangpu River needs to provide 20% - 30% of tap water, *i.e.*,  $0.48 - 0.72 \times 10^9 \text{ m}^3/\text{year}$ .



**Figure 1.** Location map of Shanghai (a) and its main water networks (b).



**Figure 2.** Freshwater used in Shanghai and its population growth from 1977-2012 (missed data in 1981-1986, 1992-1996, and 1998-2002).

The Huangpu River is about 114 km long, dividing the city into east and west portions, called Pudong and Puxi. This river is used for multi-purposes including drinking water, shipping, fishery, flood discharge, tourism and many other functions. Its water quality keeps declining from its source at the entrance from the Tai lake to the lower reach, its upper reach is protected as the sources of drinking water include the Dianshan Lake and Taipu River, but the water in this area is often polluted due to the rapid urbanization and industrialization [6].

In China, surface water is classified into 5 classes as listed in **Table 1**, the best water quality is class I and the worst is class V<sup>+</sup>. The lowest acceptable level of potable water is class III. Class IV can only be used for industrial water, and Class V for agricultural water. Class V<sup>+</sup> cannot be used for any purposes. In 2004 and 2005, the annual average concentration of ammonia nitrogen at the intakes of Huangpu River exceeded 1.3 mg/L and 1.2 mg/L, respectively [7], worse than the class V. In 2011, only 29.4% of its waterways in Shanghai had water quality better than class III. In 2015, the water quality in Dianshan Lake was worse than Class V based on Shanghai Environmental Protection Bureau (<http://www.sepb.gov.cn/fa/cms/shhj//shhj2143/shhj2149/2015/02/88730.htm>).

Dianshan Lake appeared to be hyper-eutrophicated [8]. The Huangpu River is an open system and has been used as a navigation channel. Any accidents can

**Table 1.** China's classification for surface water quality standards in mg/L (GB3838-2002).

|                                 | Class I<br>(clean) | Class II<br>(fairly<br>clean) | Class III<br>(general) | Class IV<br>(polluted) | Class V<br>(heavily<br>polluted) | Class V+<br>(seriously<br>polluted) |
|---------------------------------|--------------------|-------------------------------|------------------------|------------------------|----------------------------------|-------------------------------------|
| Dissolved Oxygen                | >8                 | >6                            | >4                     | >3                     | >1                               | <1                                  |
| Permanganate Index              | <2                 | <4                            | <6                     | <20                    | <50                              | >50                                 |
| BOD <sub>5</sub>                | <1                 | <3                            | <5                     | <15                    | <30                              | >30                                 |
| COD                             | <15                | <15                           | <20                    | <30                    | <40                              | >40                                 |
| TP river/(lake)                 | <0.02 (0.01)       | <0.1 (0.025)                  | <0.2 (0.05)            | <0.3 (0.1)             | 0.4 (0.2)                        | >0.4 (0.2)                          |
| TN                              | <0.2               | <0.5                          | <1.0                   | <1.5                   | <2.0                             | >2.0                                |
| NH <sub>4</sub> <sup>+</sup> -N | <0.15              | <0.5                          | <1.0                   | <1.5                   | <2.0                             | >2.0                                |
| Volatile Phenols                | <0.001             | <0.005                        | <0.01                  | <0.1                   | <0.5                             | >0.5                                |
| Cyanide                         | <0.01              | <0.05                         | <0.1                   | <0.5                   | <2                               | >2                                  |
| Arsenic                         | <0.01              | <0.04                         | <0.08                  | <0.3                   | <1                               | >1                                  |
| Mercury                         | <0.00001           | <0.0005                       | <0.001                 | <0.01                  | <0.05                            | >0.05                               |
| Chromium                        | <0.01              | <0.02                         | <0.05                  | <0.2                   | <1.0                             | >1.0                                |
| Cadmium                         | <0.001             | <0.005                        | <0.01                  |                        |                                  |                                     |
| Lead                            | <0.01              | <0.05                         | <0.1                   |                        |                                  |                                     |
| Copper                          | <0.005             | <0.01                         | <0.03                  |                        |                                  |                                     |
| Petroleum                       | <0.05              | <0.3                          | <0.5                   | <1.0                   | <3.0                             | >3.0                                |

Note: data in parenthesis is for lakes and reservoirs; BOD<sub>5</sub> = biochemical oxygen demand in 5 days; COD = chemical oxygen demand; NH<sub>4</sub><sup>+</sup>-N = Ammonia-nitrogen; TP = total phosphorous; TN = total nitrogen.

cause public panic and a great risk in water supply. For example in 2013, there were 52 tons of petrochemical oil leaked in January, and in March about 16,000 diseased pig carcasses found on its water surface. Consequently, in 2014 the Shanghai government planned to construct a new reservoir, called as Jinze reservoir near Dianshan Lake to minimize risks, with a storage capacity of about 5 million m<sup>3</sup> to supply about 5 million nearby people at a flow rate of 3.5 million m<sup>3</sup>/day.

The new reservoir was excavated just beside the Dianshan Lake, because the water body of Dianshan Lake has been polluted and the water quality is worse than class V currently. Research by China Eastern Normal University shows that the restoration of Dianshan lake to drinking water standard may take 10 years and  $1.5 \times 10^9$  Yuan RMB using existing biological technology (information was obtained from personnel communication). This research outcome led to the government's decision to create a new reservoir beside the Dianshan Lake. The objective of this research is to investigate whether the Dianshan Lake can be remediated quickly and cheaply for drinking purpose. The newly emerged technology SPP is discussed; its application to the Dianshan Lake and its feasibility are examined.

### **3. SPP (Separation, Prevention and Protection) Solution and Its Application to Dianshan Lake**

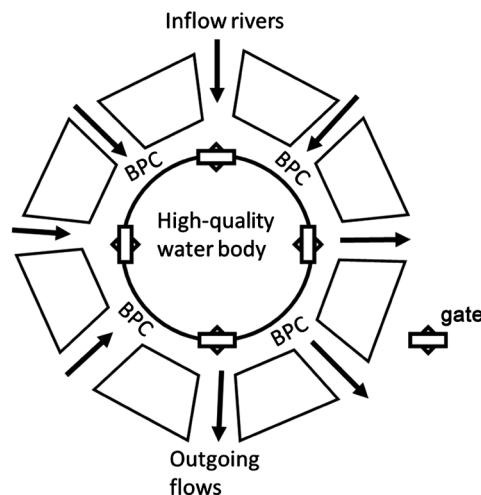
The worldwide problem in water resources development is how to develop and maintain good quality water in a large water body. In 1996, the UN Center for human settlements predicted, in a conference, that Shanghai would be one of the dozen cities in the world with the most severe water crisis [9], induced by pollution. To solve this problem, recently a patented technology SPP (Separation, Prevention and Protection) has been developed [10], which can drain polluted water out of lakes without mixing with clean lake water, then the quality of lake water can be restored quickly [11]. The required facilities include levees and water gates on the levees as shown in **Figure 3**, in which a natural lake is represented by a circle with many inflow and outflow rivers, a by-pass canal (BPC) is proposed to be constructed inside the lake with some water gates.

The inflow has low quality during the dry period or the earlier stage of storm, *i.e.*, first flushes. But high quality water follows the 1<sup>st</sup> flush as most of it is rainwater. The rainwater and polluted water always alternate in time. The SPP scheme requires to separate tempo-spatially the incoming water based on its water quality. The temporal separation is to distinguish the good quality water over time. The good quality water should be stored in the lake via the water gates in **Figure 3**, but the poor quality water should be discharged via the by-pass canal by closing the water gates, thus the spatial separation based on quality can be achieved. Inner levees and gates are required to construct to protect the clean water, and to prevent the external pollution by the BPC which can maintain a high velocity for the unwanted/polluted water. Therefore, the incoming water would be regulated by the gates, once opened fully the lake is restored as natural lake without SPP, but when all gates are closed, the BPC actually functions as a river system with a

high velocity. Therefore, SPP may develop clean water from a polluted river system as long as the quality of incoming water is unstable by discharging pollutants downstream via the BPC. It is worthwhile discussing the feasibility of this technology, and the Dianshan Lake in Shanghai is selected as an example.

The Dianshan Lake is the largest freshwater lake in Shanghai connecting with the Huangpu River. Its surface area covers  $63.8 \text{ km}^2$  at water level 2.5 m, average depth 2.11 m (see **Table 2**), the highest level was 3.71 m in August 1954 and the lowest level 1.76 m above sea level in April 1963. The water level is also influenced by the tide [8]. The residence time is approximately 29 days, annual temperature is about  $15.5^\circ\text{C}$ , annual sunshine time 2071 hours, the frost-free season lasts about 235 days, annual rainfall is about 1037 mm, annual evaporation about 900 mm, average wind speed is about 3.7 m/s, and water velocity 0.03 - 0.1 m/s [12]. In 1988, the runoff was about  $1.74 \times 10^9 \text{ m}^3/\text{year}$ , of which about 67% of incoming water flowed from the Tai Lake via inlets like Dazhuku (33%) and Jishuigang (35%). The Lanlugang discharged about 71% of the outflow. **Table 3** shows the hydrological conditions measured [12].

**Figure 4** shows the water quality measured from 1984-2010 [13], the TN and TP increased steadily from 1984 (TN = 0.83 mg/L, TP = 0.06 mg/L) to 2007 (TN



**Figure 3.** Scheme of by-pass pollution canal (BPC) in SPP strategy.

**Table 2.** Relationship between water level, surface area and volume.

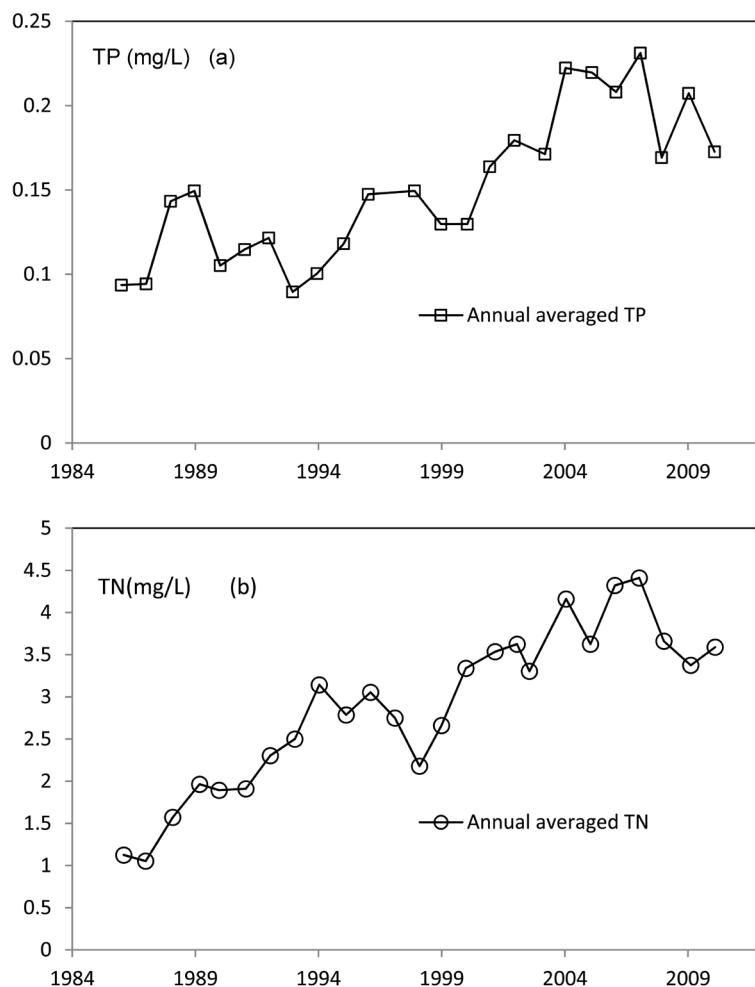
| Water level (m)                | 0.12 | 0.5 | 1  | 1.5  | 2    | 2.5  | 3    | 3.5  | 4    |
|--------------------------------|------|-----|----|------|------|------|------|------|------|
| Surface area ( $\text{km}^2$ ) | 0    | 25  | 56 | 61.5 | 63.8 | 63.8 | 63.8 | 63.8 | 63.8 |
| Volume ( $10^6 \text{ m}^3$ )  | 0    | 4   | 40 | 52   | 84   | 115  | 148  | 179  | 211  |

**Table 3.** Monthly water volume to Dianshan Lake in 1988.

|                                      | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. | total |
|--------------------------------------|------|------|------|------|-----|------|------|------|------|------|------|------|-------|
| Water volume (million $\text{m}^3$ ) | 153  | 148  | 199  | 147  | 146 | 129  | 101  | 167  | 121  | 120  | 140  | 164  | 1735  |

= 4.53 mg/L, TP = 0.237 mg/L). 3 large scale algal blooms were reported in 2007 and 5 blooms in 2008. Cheng and Li [8] asserted that the lake has become hyper-eutrophicated since 1999. Intensive research has been conducted to investigate the sources of nutrients as listed in **Table 4**, the consensus is that the primary pollutants are nitrogen and phosphorus substance, and TP is a controlling parameter.

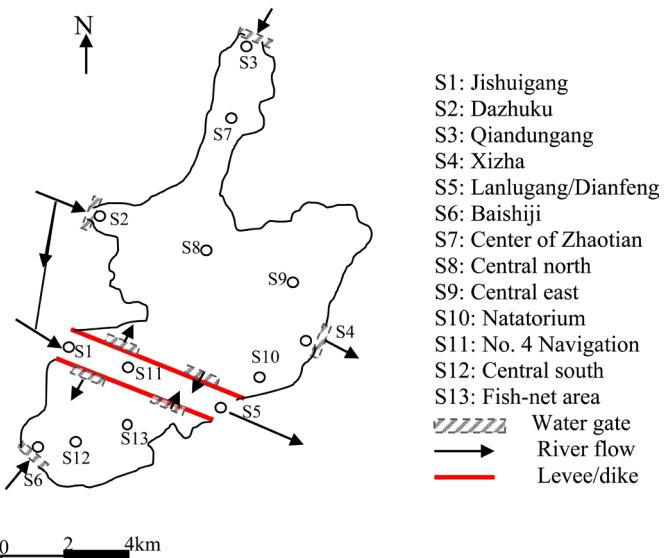
**Figure 5** shows the Dianshan Lake, in which the open dots with numbers represent measuring stations. The arrows represent the flow direction, shadowed



**Figure 4.** Annual mean TP and TN in Dianshan Lake from 1986 to 2010.

**Table 4.** Loading of TN and TP into Dianshan Lake.

| Authors                   | Year    | TN incoming (ton/yr) | TN outgoing (ton/yr) | Net TN loading (ton/yr) | TP incoming (ton/yr) | TP outgoing (ton/yr) | Net TP loading (ton/yr) |
|---------------------------|---------|----------------------|----------------------|-------------------------|----------------------|----------------------|-------------------------|
| Kung and Ying (1991)      | 1984-85 | 3167                 | 2868                 | 299                     | 152                  | 146                  | 6.0                     |
| Yuan and Wang (1993)      | 1988    | 4278                 |                      |                         | 255                  |                      |                         |
| Lu <i>et al.</i> 2010     | 2008    | 5790                 |                      |                         | 420                  |                      |                         |
| Wang <i>et al.</i> (2013) |         | 8337                 |                      |                         | 476.3                |                      |                         |



**Figure 5.** SPP application in the Dianshan lake where the BPC is formed by two red lines and water gates by shaded bars.

rectangular bars are the gates and the red parallel lines form the BPC to divert the heavily polluted water. The BPC from the Langlugang to the Jishuigang is a natural navigation channel. Although there are 59 rivers connects with the Dianshan Lake, 70% - 80% of incoming water flows from the Jishuigang and the Dazhugang, both are interconnected via small lakes and creeks before entering the lake. Therefore, if the Dazhugang gate is closed, the incoming water will be forced to the Jishuigang and finally be discharged out of the lake via the BPC to the Langlugang.

To minimize the size of stagnant water bodies, four gates are proposed on the BPC levees. This may be helpful to constrain algal blooms. If the gates at Baishiji and Qiandungang are closed, the heavily polluted water will be forced to flow to the downstream via the water networks. Therefore, the clean water is protected against external pollution. No accidents of water pollution like the dead pigs or chemical spills from ships can affect the quality of stored water.

Currently, about 70% - 80% of the lake water outflows via the Lanlugang and the remainder via the Xizha. Unlike the Lanlugang outlet, the Xizha outlet only discharges excessive floodwater during flood seasons to mitigate flood disasters as a gate has been installed. The SPP scheme in **Figure 5** includes a BPC that is about 150 m wide (the same as the upstream/downstream navigation channel) and 6000 m long, the volume occupied by the BPC is 0.2% of the total water volume shown in **Table 2**. Therefore, the construction of the BPC will not affect the lake's functions for navigation and water storage. In fact, the levees can be constructed using the dredged sediment, thus the lake's storage capacity may be slightly increased, and the construction cost for the BPC may be reduced and the inner pollution by sediment re-suspension may be limited.

With the aid of BPC and water gates, the water quality can be managed and the lake may be purified to the standard of drinking water. To examine its feasi-

bility, a series of scientific questions needs to be answered: a) in the future, can the lake water meet the Chinese government's standard for drinking water source, *i.e.*, class I - III? b) With the water quality in the lake currently being worse than class V, how long does the lake require to restore its quality to potable level? c) the SPP scheme may be useful to prevent external contaminants, but the internal contamination from the sediment re-suspension could also be critical for this shallow water, so how should the algal blooms in the lake be controlled?

#### 4. Feasibility Analysis of the SPP Scheme

**Water Quality:** Cheng and Li [8] analyzed the measured water quality data from 1986-2010 as shown in **Figure 5**. Their results show that the frequency of measured TN and TP roughly follows a normal distribution. The recent data from 1999-2009 shows the mean values ( $\mu$ ) of TN and TP are 4.34 and 0.2 mg/L, and the variations ( $\sigma$ ) are 1.71 and 0.08 mg/L, respectively [14].

We can define TN or TP of the incoming water as  $x$ , and severely polluted water means its concentration  $x > X$ . In other words, if the concentration of TN or TP in the incoming water is higher than  $X$ , all gates will be closed and this volume of the water will be discharged to the downstream via the BPC. The value of  $X$  can be specified and chosen by the decision maker. Therefore, one can estimate how much water or nutrients will be discharged to the downstream using the following equations:

$$Q_{out} = \bar{Q}Pr = \frac{\bar{Q}}{\sqrt{2\pi}\sigma} \int_X^{\infty} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (1)$$

$$W_{out} = Q_{out}C = \frac{Q_{out}}{\sqrt{2\pi}\sigma} \int_X^{\infty} xe^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (2)$$

where  $x$  is the concentration,  $\bar{Q}$  is the annual incoming water volume, **Table 3** shows that it is about  $1.735 \times 10^9$  m<sup>3</sup>/year,  $Pr$  is the probability that the concentration is higher than  $X$ , and  $C$  is the average concentration,  $Q_{out}$  and  $W_{out}$  are the water volume and nutrient mass to be discharged out of the lake, respectively.

Similarly one can determine how much water can be developed for Shanghai's water supply and the loading of TN or TP to the lake via the water gates. The equations are:

$$Q_{in} = \bar{Q}(1-Pr) = \bar{Q} \left[ 1 - \frac{1}{\sqrt{2\pi}\sigma} \int_X^{\infty} e^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \right] \quad (3)$$

$$W_{in} = Q_{in}C = \frac{Q_{in}}{\sqrt{2\pi}\sigma} \int_0^X xe^{-\frac{(x-\mu)^2}{2\sigma^2}} dx \quad (4)$$

where  $Q_{in}$  and  $W_{in}$  are incoming discharge and mass of pollutant.

The calculated results are shown in **Table 5** in which the probability of heavily polluted water is assumed and the concentration  $X$  is calculated based on Equation (1). Rows 2 - 3 show the  $X$  value of TN or TP in the incoming water which

**Table 5.** Calculated water quality in the lake if SPP is applied and the most polluted water is discharged out of the lake.

| $Pr =$   | 5%                                    | 10%                   | 15%                   | 20%                    | 25%                   | 30%                   | 35%                   | 40%                   |
|--|---------------------------------------|-----------------------|-----------------------|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| $X$ for TN (mg/L)                                  | 7.144                                 | 6.529                 | 6.112                 | 5.78                   | 5.493                 | 5.236                 | 5.0                   | 4.773                 |
| $X$ for TP (mg/L)                                  | 0.331                                 | 0.302                 | 0.283                 | 0.267                  | 0.254                 | 0.242                 | 0.23                  | 0.22                  |
| $Q_{out} \times 10^9$ (m <sup>3</sup> /year)       | 0.087                                 | 0.174                 | 0.260                 | 0.347                  | 0.434                 | 0.521                 | 0.607                 | 0.694                 |
| $Q_{in} \times 10^9$ (m <sup>3</sup> /year)        | 1.648                                 | 1.562                 | 1.475                 | 1.388                  | 1.301                 | 1.215                 | 1.128                 | 1.041                 |
| Total $\bar{Q} \times 10^9$ (m <sup>3</sup> /year) | 1.735                                 | 1.735                 | 1.735                 | 1.735                  | 1.735                 | 1.735                 | 1.735                 | 1.735                 |
| Residence time $T$ (days)                          | 32.8                                  | 34.6                  | 36.6                  | 38.9                   | 41.5                  | 44.5                  | 48                    | 52                    |
| $W_{out}$ for TN (ton/yr)                          | 696 ( $C = 0.8$ )<br>( $C = 7.5$ )    | 1305<br>( $C = 7.5$ ) | 1872<br>( $C = 7.2$ ) | 2429<br>( $C = 7.0$ )  | 3037<br>( $C = 7$ )   | 3543<br>( $C = 6.8$ ) | 4006<br>( $C = 6.6$ ) | 4442<br>( $C = 6.4$ ) |
| $W_{in}$ for TN (ton/yr)                           | 4944 ( $C = 3$ )<br>( $C = 2.7$ )     | 4217<br>( $C = 2.7$ ) | 3540<br>( $C = 2.4$ ) | 2914<br>( $C = 2.1$ )  | 2342<br>( $C = 1.8$ ) | 1944<br>( $C = 1.6$ ) | 1580<br>( $C = 1.4$ ) | 1145<br>( $C = 1.1$ ) |
| Total for TN (ton/yr)                              | 5640                                  | 5522                  | 5412                  | 5343                   | 5379                  | 5487                  | 5586                  | 5587                  |
| $W_{out}$ for TP (ton/year)                        | 34.8 ( $C = 0.4$ )<br>( $C = 0.375$ ) | 65<br>( $C = 0.375$ ) | 91<br>( $C = 0.35$ )  | 113<br>( $C = 0.325$ ) | 139<br>( $C = 0.32$ ) | 167<br>( $C = 0.32$ ) | 188<br>( $C = 0.31$ ) | 208<br>( $C = 0.30$ ) |
| $W_{in}$ for TP (ton/yr)                           | 247 ( $C = 0.15$ )<br>( $C = 0.14$ )  | 219<br>( $C = 0.14$ ) | 192<br>( $C = 0.13$ ) | 167<br>( $C = 0.12$ )  | 143<br>( $C = 0.11$ ) | 113<br>( $C = 0.09$ ) | 90<br>( $C = 0.08$ )  | 73<br>( $C = 0.07$ )  |
| Total for TP (ton/yr)                              | 282                                   | 284                   | 283                   | 280                    | 282                   | 280                   | 278                   | 281                   |
| TP lake (mg/L) by Equation (8) and $T =$ row 7     | 0.097                                 | 0.091                 | 0.084                 | 0.078                  | 0.071                 | 0.06                  | 0.05                  | 0.045                 |
| TP lake (mg/L) by Equation (8) and $T = 29$ days   | 0.085                                 | 0.076                 | 0.067                 | 0.058                  | 0.050                 | 0.039                 | 0.031                 | 0.025                 |

is going to be discharged to the downstream. Rows 4 - 5 are obtained using Equations (1) and (3). **Table 2** shows that the lake's water volume is  $V = 148 \times 10^6$  m<sup>3</sup>, its residence time can be calculated by

$$T = \frac{V}{Q_{in}} \quad (5)$$

and the results for  $T$  are shown in row 7.

Currently there are many equations available in the literature to predict the lake's water quality. The most often cited studies typically use the lake TP concentrations based on input values for the areal phosphorus loading rate, average water depth, hydraulic loading etc. The Vollenweider phosphorus loading model [15] has the following form:

$$TP_{lake} = \frac{W_{in}/A}{h(\sigma_1 + 1/T)} \quad (6)$$

where  $TP_{lake}$  = TP concentration in the lake and its outflow,  $A$  = lake surface area,  $h$  = water depth,  $\sigma_1$  is the first order rate coefficient for TP loss from the lake (year<sup>-1</sup>), it is a summation of rate coefficients for several first-order processes, but generally only the TP sedimentation of P-containing particles in the lake is considered and  $\sigma_1$  can be determined by:

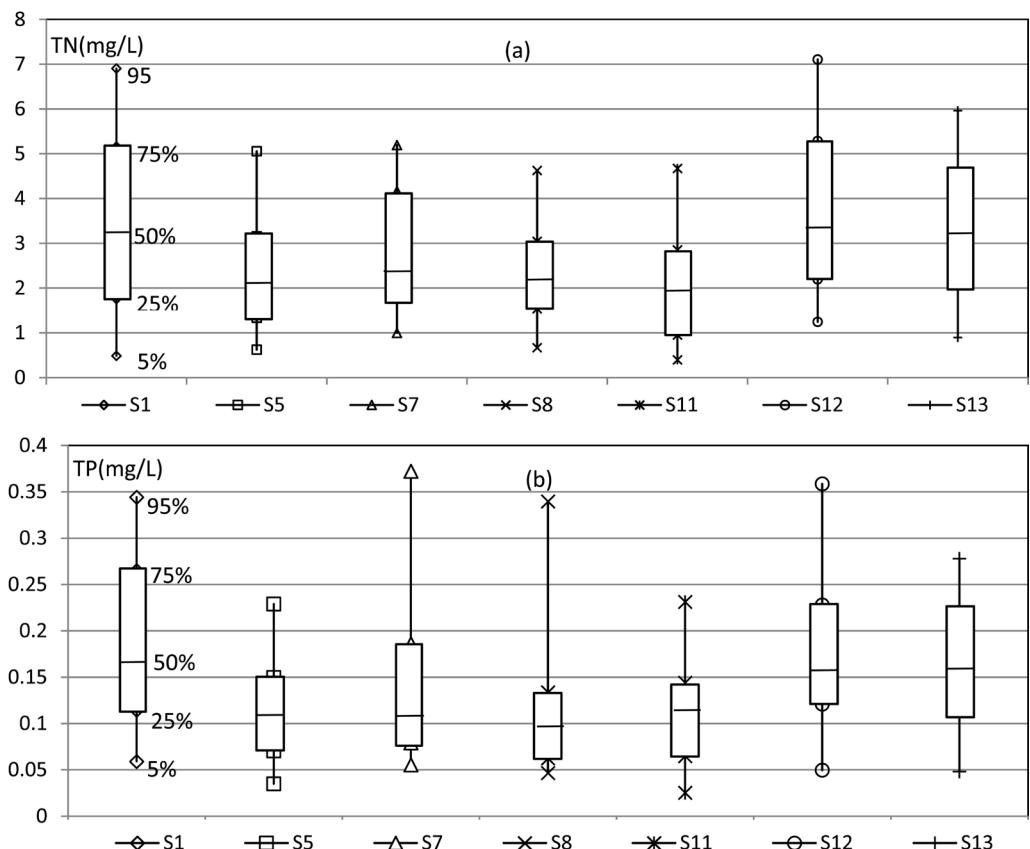
$$\sigma_1 = \frac{R_p}{T(1-R_p)} \quad (7)$$

where  $R_p = 1 - \text{TP}_{out}/\text{TP}_{in}$ . For the Dianshan lake, the average  $\text{TP}_{out}$  and  $\text{TP}_{in}$  shown in **Figure 6** are 0.11 and 0.17 mg/L, respectively, thus  $R_p = 0.353$ , inserting Equation (7) into Equation (6), one has

$$\text{TP}_{lake} = \frac{W_{in}/A}{h(\sigma_1 + 1/T)} = \frac{W_{in}(1-R_p)T}{V} \quad (8)$$

The calculated TP based on Equation (8) is shown in the last but one row. It demonstrates that if incoming water with  $\text{TN} > 6.6 \text{ mg/L}$  and  $\text{TP} > 0.08 \text{ mg/L}$  is discharged out of the lake, the lake water will be good enough for the drinking purpose (Class III) and annually  $1.128 \times 10^9 \text{ m}^3/\text{year}$  of water can be developed.

The primary pollutants are nitrogen and phosphorus substance in the lake [16]. As shown in **Table 5**, about half of the nutrients will bypass the lake when 25% of the water with the highest TP or TN flows out of the lake via the BPC. This is a huge reduction, but there is still half of the nitrogen and phosphorus substance remaining in the lake water, thus it is necessary to estimate the lake's water quality.



**Figure 6.** Spatiotemporal variation of trophic status of Dianshan Lake, the symbols at the top denote  $\text{Pr} = 95\%$ , the rectangular bars represent concentration from  $\text{Pr} = 25\%$  to  $75\%$ , the short lines inside the bars are  $\text{Pr} = 50\%$ , the lowest symbols stand for  $\text{Pr} = 5\%$ . The original data come from Cheng and Li [8].

Here we assume that annual runoff from the upstream is constant and equal to  $1.735 \times 10^9 \text{ m}^3/\text{year}$ , thus the residence time is a variable as shown in row 7. In fact this assumption may be conservative, as the amount of water from the Tai Lake to this region is about  $10.6 \times 10^9 \text{ m}^3$  per year, thus the residence time during wet seasons will not be as long as that shown in **Table 5**. If the residence time remains unchanged at 29 days, the last row of **Table 5** shows that Class II water can be developed at the rate of  $1.041 \times 10^9 \text{ m}^3$  per year.

Therefore, it can be seen that after the application of SPP to Dianshan Lake, about  $1.0 \times 10^9 \text{ m}^3$  per year of clean water can be developed and its water quality meets the Chinese government's standard for potable water. This is achievable as the heavily polluted water is discharged out of the lake, and the external pollutant is prevented from mixing with the clean water, thus the clean water is protected.

As shown in **Figure 4**, the current  $\text{TP}_0$  is about 0.22 mg/L. If SPP is applied to Dianshan Lake, it is useful to estimate how long it takes for the TP in the lake to be lowered to 0.05 mg/L (Class III). The mass conservation equation can be written in the following way:

$$V \frac{d\text{TP}}{dt} = Q_{in} (\text{TP}_{in} - \text{TP}) - S \quad (9)$$

where  $t$  is time,  $S$  is the sink rate for phosphorus substance, and  $S$  can be expressed by

$$S = V\sigma_1 \text{TP} \quad (10)$$

Therefore, integration of Equation (9) yields

$$\text{TP} = \exp\left(-\int \frac{Q_{in} + V\sigma_1}{V} dt\right) \left( \int \frac{Q_{in}}{V} C_{in} \exp\left(\int \frac{Q_{in} + V\sigma_1}{V} dt\right) dt + c \right) \quad (11)$$

where  $c$  = integration constant. Equation (11) can be further reduced into:

$$\text{TP} = \frac{Q_{in} C_{in}}{Q_{in} + V\sigma_1} + c \exp\left(-\frac{Q_{in} + V\sigma_1}{V} t\right) \quad (12)$$

At  $t = 0$ , the concentration is  $\text{TP}_0$ , thus the integration constant  $c$  can be determined as follows:

$$c = \text{TP}_0 - \frac{Q_{in} C_{in}}{Q_{in} + V\sigma_1} \quad (13)$$

Inserting Equation (13) into Equation (12), one has

$$\text{TP} = \frac{Q_{in} C_{in}}{Q_{in} + V\sigma_1} + \left( \text{TP}_0 - \frac{Q_{in} C_{in}}{Q_{in} + V\sigma_1} \right) \exp\left(-\frac{Q_{in} + V\sigma_1}{V} t\right) \quad (14)$$

From the last column of **Table 5**, one knows  $Q_{in} = 1.0 \times 10^9 \text{ m}^3/\text{year}$  or  $2.74 \times 10^6 \text{ m}^3/\text{day}$ ,  $C_{in} = 0.07 \text{ mg/L}$ , Equation (7) shows  $\sigma_1 = 0.01 \text{ day}^{-1}$ , thus Equation (14) becomes

$$\text{TP} = 0.045 + 0.175 e^{-0.0285t} \quad (15)$$

The predicted TP in the lake is shown in Equation (15), and the calculated re-

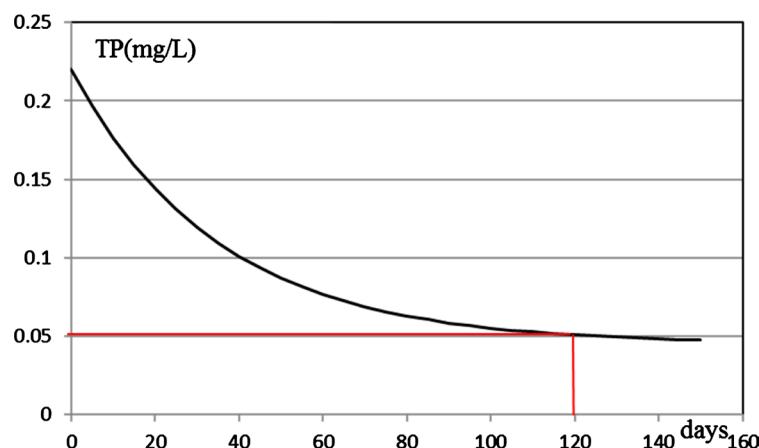
sult is shown in **Figure 7**, which predicts that in 120 days or 4 months, the lake's water quality can be restored to the class III level. It totally differs from other technologies that need to take up to 10 years to restore the water quality.

It is necessary to stress that the reduction of TP cannot fully eliminate algal blooms. One of the examples is Vesijarvi Lake in Finland where the algal blooms lasted for more than 10 years after the external TP was reduced to 93% [17]. The internal pollution by sediment re-suspension may also play an important role for algal blooms in the lake, thus it is necessary to investigate the nutrient characteristics of lake soil at the bottom. Kang [13] analyzed the soil samples, and found that TN varied from 0.46 to 2.18 g/L and TP from 0.27 to 1.15 g/L, and the measured TN and TP along the sediment depth are shown in **Figure 8**. Based on the survey, she concluded that the surface sediment had been heavily polluted and the pollution levels were higher in the northern part than the southern part. She suggested that, in order to efficiently control the internal source pollution, it is necessary to have ecological dredging.

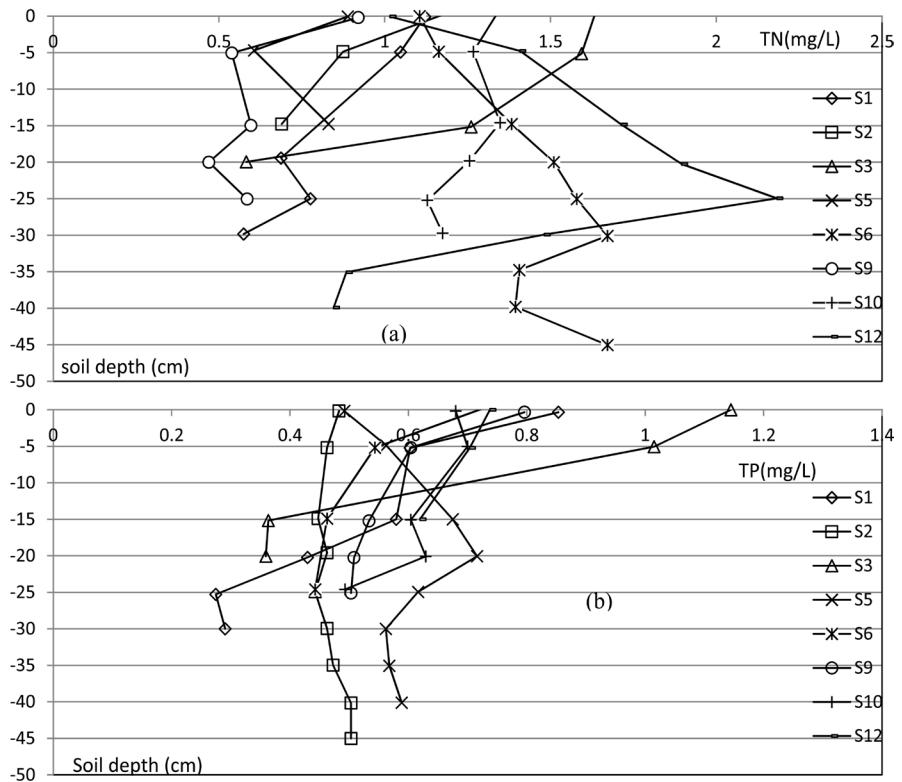
Ecological dredging could achieve better effects if the dredging is conducted after the construction of the BPC, when all the water in the lake is pumped out, the sunshine on the topsoil may eliminate the cells for algae. On average to remove the top 30cm sediment layer will be good enough to control the internal source pollution. This dredging will increase the lake's storage capacity to  $62.5 \text{ km}^2 \times 0.3 = 18.75 \times 10^6 \text{ m}^3$ . The polluted dredging soil could be used for the construction of BPC levees. To save dredging cost, it is suggested that the dredging area should be limited in the northern part of the lake near the proposed BPC as the data in **Figure 8** shows that the sediment in these regions is heavily polluted.

## 5. Discussion

The above shows that if the TP in the incoming water remains at the 2009 level, using the SPP scheme, about  $1 \times 10^9 \text{ m}^3$  water could be developed with water quality ranging from class II to III. In the rainy seasons the water quality may be



**Figure 7.** Calculated TP decay in the lake with time after SPP is applied based on Equation (15), it predicts that the lake's water quality can be restored to the Class III level after 120 days ( $\text{TP} < 0.05 \text{ mg/L}$ ).

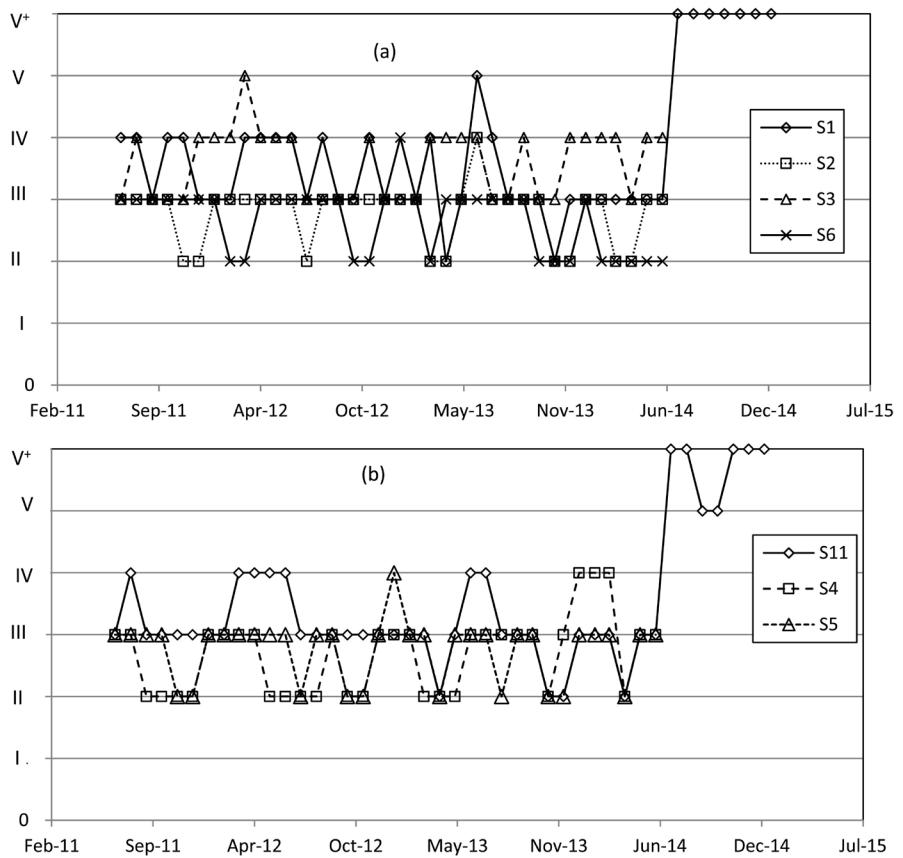


**Figure 8.** Vertical Profiles of TN and TP in the bottom sediment layer in Dianshan Lake.

class II and in the dry seasons Class III as it depends on the quantity and quality of incoming water. As mentioned, in the future about  $0.48 - 0.72 \times 10^9 \text{ m}^3/\text{year}$  of water is needed from the Huangpu River, but the Dianshan Lake can supply about  $1.0 \times 10^9 \text{ m}^3/\text{year}$  of water, sufficient to meet the demand.

For the required water gates, the inflatable rubber dam is highly recommended as this is a shallow lake with a small hydraulic head, a rubber dam is suitable for the operation and maintenance. Rubber dams are inflated by pumping air/water inside, and deflated if discharging the air/water. The BPC is formed when the rubber dams are inflated, but the BPC may disappear when they are deflated.

Finally the proposal can be justified using the recent measured data from the inlets/outlets and southern/northern lake, which is shown in **Figure 9** and **Figure 10** in the period of 2011-2015, measured and published by Shanghai Environmental Protection Bureau, in which the ordinate Roman numerals are the water class as shown in **Table 1**. **Figure 9(a)** and **Figure 9(b)** clearly show that the water quality was worst in July 2014 when the first flush of a typhoon storm mixed with the clean lake water which led to the water being class V<sup>+</sup>. This is how the first flush pollutes the clean water in the lake, as it is an open system to external pollution. **Figure 9(a)** also shows that the quality of incoming water is unstable, and good quality water always appears in S6 (Baishiqiao) and S2 (Dazhuku). The poor quality water mainly comes from S3 (Qiandonggang) and S1 (Jishuigang). For these inlets, good quality water (class III or better) always

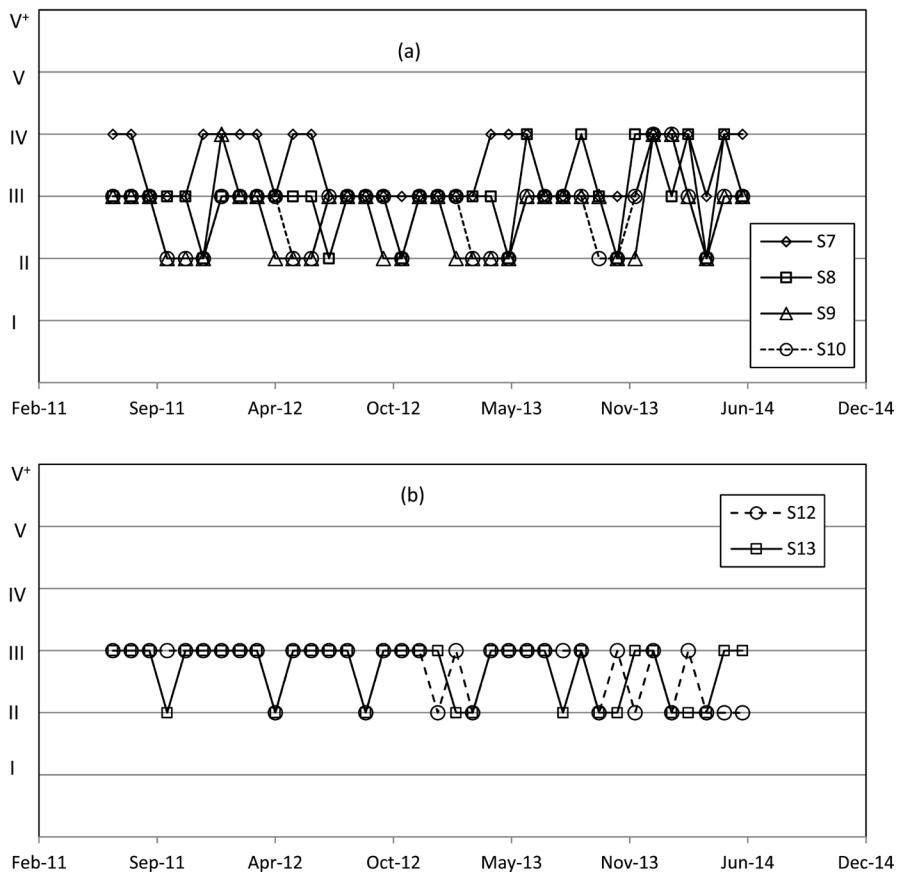


**Figure 9.** Water quality measured at the Dianshan Lake's inlets (a) and outlets (b) in the period of 2011-2015.

appears during July-October, because poor and good quality of water always intermittently appears in the river system, and first flush is the main source of pollution. **Figure 9(b)** shows that the water quality in the outlets is much better than that of the incoming water, implying that the Dianshan lake receives poor quality water, but discharges good quality water to the downstream, thus the SPP strategy should be applied.

This paper shows that the lake water can be purified to the standard of drinking water if SPP is applied and a BPC is formed, and the water quality data shown in **Figure 10** supports this conclusion. In **Figure 5**, the lake is divided into two parts by the BPC proposed, and water quality in the northern part is shown in **Figure 10(a)** and its southern part in **Figure 10(b)**. It can be seen that the water quality in the southern lake meets fully the drinking water standard, *i.e.*, class II and III in natural condition. It can be predicted that the water quality will be improved further once SPP is applied as only water better than class III is allowed to enter the protected southern lake.

The data in **Figure 10(a)** shows that water quality in the northern lake does not reach the standard of drinking water during 50% of the recorded time. Most of the poor water quality appears in S8 and S7, and relatively good water quality occurs in S10 and S9 where it cannot meet the drinking water standard for only



**Figure 10.** Water quality measured in northern (a) and southern (b) water bodies from 2011-2014.

4 months or 11% of the time.

Therefore, from [Figure 9](#) and [Figure 10](#), one can see that that the Dianshan lake can be transformed into a drinking water source if SPP is applied to prevent external pollution of the type which occurred in July, 2014 or alike. The southern lake can immediately supply good quality water to Shanghai, but the northern lake would take longer time to improve its water quality to the drinking standard.

## 6. Conclusions

Water quality-induced water shortage is becoming a serious worldwide problem, especially for developing countries. Shanghai, one of the largest cities in China, is a typical example. In order to alleviate the water shortage, recently a new technology termed SPP (separation, prevention and protection) has been proposed aiming to develop incoming clean water from a polluted river system. The incoming water is separated into clean (or wanted) water and polluted (or unwanted) water, the wanted water will be stored and the unwanted water will be discharged via a bypass pollution canal (BPC). This study takes the Dianshan Lake, the largest lake in Shanghai as an example to investigate the feasibility of SPP, and the following conclusions can be drawn:

1) The measured data shows that the quality of incoming water is unstable, but follows a normal distribution, indicating that the incoming water to the lake can be broadly divided into two groups-wanted or unwanted water. External pollution is under control once the unwanted water should be discharged out of the lake with a short resident time, and the wanted water can be developed for drinking purposes. Importantly, polluted water should not be allowed to mix with the lake water. Clean water should be stored with a long residence time.

2) The mathematical model shows that the Dianshan Lake's water quality can meet the Chinese government's standard for drinking purpose (Class II or III), if 35% of incoming water with the highest TN or TP bypasses the lake. It is predicted that the algal blooms can be controlled fully if the internal source pollution is also controlled by ecological dredging. The estimation shows that at least  $1 \times 10^9 \text{ m}^3$  clean water can be developed every year from the lake once SPP is applied. The construction period for the SPP and ecological dredging may take 1 - 2 years. It is highly recommended that Jinze reservoir's water should come from the Dianshan lake, not from the Taipu River directly, in order to improve the quality of water supply.

3) This study shows that SPP is feasible and effective to solve the water quality-induced water shortage in water-rich areas. When compared with other methods of restoration in a polluted ecosystem, SPP is more straightforward and effective as it prevents external pollution to mix with the clean water, but in the future more research is needed to observe its effectiveness and performance.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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