Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.20488

70 (2017) 106–116
April

Characterization of raw water resources in northern and central Taiwan

F.C. Lo[a], K.L. Lin[b], T.Y. Pai[c], S.L. Lo[a], H.Y. Chiu[d], T.C. Chang[e], S.W. Lo[f], M.H. Liu[g], C.A. Chang[d], S.C. Wang[g], C.F. Chiang[h], K.P. Chao[h], W.Y. Lo[i], Y.L. Chu[j], H.M. Lo[g,]*

[a]*Graduate Institute of Environmental Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC, emails: fangchenlo@hotmail.com (F.C. Lo), sllo@ntu.edu.tw (S.L. Lo)*
[b]*Department of Environmental Engineering, Ilan University, Yilan 260, Taiwan, ROC, email: kllin@niu.edu.tw*
[c]*Master Program of Environment Education and Management, National Taichung University of Education, Taichung 40306, Taiwan, ROC, email: bai@ms6.hinet.net*
[d]*Department of Applied Chemistry, Chaoyang University of Technology, Taichung 41349, Taiwan, ROC, emails: hychiu@ymail.com (H.Y. Chiu), cachang@cyut.edu.tw (C.A. Chang)*
[e]*Graduate Institute of Environmental Engineering and Management, National Taipei University of Technology, Taipei 10608, Taiwan, ROC, email: cchang@ntut.edu.tw*
[f]*Department of Life Sciences, National Central University, Taoyuan 32001, Taiwan, ROC, email: shengwenlo1995@gmail.com*
[g]*Department of Environmental Engineering and Management, Chaoyang University of Technology, Taichung 41349, Taiwan, ROC, Tel.: +886 4 23323000; Fax: +886 4 23742365; emails: hmlo@cyut.edu.tw (H.M. Lo), jliu@cyut.edu.tw (M.H. Liu), scwang1@cyut.edu.tw (S.C. Wang)*
[h]*China Medical University, 91 Hsueh-Shih Rd., Taichung 40402, Taiwan, ROC, emails: amur.chiang@gmail.com (C.F. Chiang), kpchao@mail.cmu.edu.tw (K.P. Chao)*
[i]*National Taichung University of Science and Technology, 129 Section 3, San Min Rd., Taichung 404, Taiwan, ROC, email: loeric0206@gmail.com*
[j]*Department of Mechanical Engineering, National Taiwan University of Science and Technology, Taipei 106, Taiwan, ROC, email: chu80108chu@hotmail.com*

Received 4 May 2016; Accepted 5 January 2017

ABSTRACT

Water quality standards of raw water resources are getting more stringent in Taiwan. This is due to the higher number of potential contaminants released to the water bodies leading to the potential risks to the human health. Raw water resources, including one river and three reservoirs representative of the major raw water resources in northern and central Taiwan, at four locations were selected to measure turbidity, electrical conductivity (EC), oxidation and reduction potential (ORP), pH, alkalinity, total organic compounds (TOC), zeta potential, particle size, Al, Fe and heavy metal contents. Natural organic matter (NOM) was also examined using high-performance size-exclusion chromatography to distinguish the different molecular weight distribution of organic compounds, such as humic acids, that might affect the subsequent raw water treatment. TOC is highly related to NOM, biochemical oxygen demand (BOD_5) and chemical oxygen demand, and the influent standard is 4 mg/L in Taiwan. EC, ORP, pH, alkalinity, TOC and zeta potential had values of 231.68–350.60 μS/cm, 210.5–271.55 mV, 8.17–8.58, 65.65–86.25 mg/L, 1.54–2.73 mg/L and –16.58 to –22.60 mV, respectively. However, average turbidity (128.24 NTU) and average particle size at the Daiji River (5,067.56 nm) were higher than those at the Shimen, Yongheshan and Liyutan Reservoirs (2.20–6.39 NTU and 1,105.12–1,627.26 nm, respectively). These measured data and metal contents (the latest three years' data, at least two seasons including summer and autumn) met the regulatory standards in Taiwan. Water quality index (WQI) containing dissolved oxygen solubility, faecal coliforms, pH, BOD_5, nitrates, total phosphates,

* Corresponding author.

temperature deviation, turbidity and total solids indicated good conditions for three reservoirs and medium condition for Daiji River. NOM, which might produce potential disinfectant by-products, had similar patterns and contained humic acids and low molecular weight acids (LMWs), with the intensity order of Yongheshan Reservoir > Shimen Reservoir > Liyutan Reservoir > Daiji River. The Carlson trophic state index and field-emission scanning electron microscope plot of filtered solid of raw water showed the potential risk of algae to drinking water safety.

Keywords: Raw water resources; Natural organic matter; WQI; Particle size; CTSI

1. Introduction

Clean and safe drinking water is essential for human health [1]. Due to potential risks from influent of raw water resources, Taiwan has regulated a more stringent standard than before. Thus, the monitoring of the influent quality is essential for the government to ensure the safety of drinking water. The World Health Organization (WHO) [1] has regulated a number of standards for the safety of drinking water. Many countries have enacted basic criteria to ensure their own drinking water more safe than before. Apart from the WHO standard, Taiwan has also integrated the standards of many countries, such as the USA, the UK, the EU, Japan, Australia and New Zealand. In addition to the safety of drinking water, the quality of the influent raw water has been gaining increased consideration. This is mainly due to potential risks from a number of different contaminants released to the water bodies. Thus, treatment of influent raw water is now being more rigorously regulated in order to reduce the potential health risks.

In Taiwan, groundwater, river water, and surface water from lakes and reservoirs are generally used as water supply [2–7]. Among these sources, river and reservoir water are the main resources [8] for water supply and are treated before use. Recently, climate change has resulted in an unstable water flow quantity and quality [9]. Variation in natural organic matter (NOM) has led to an increased potential of water eutrophication, leading to difficulties in the water treatment plants [10,11]. The concentration of NOM is also an important issue in water treatment due to the potential production of disinfectant by-products (DBPs), which are detrimental to human health [12]. Thus, NOM has been investigated by several researchers with the aim to characterize its properties, including humic acids and size fractions [13–17]. At present, NOM, particle size distribution (PSD) and zeta potential (ZP) that might affect the flocculation performance of water treatment were not monitored by regulation in Taiwan. In addition, water quality index (WQI) that could show the quality of influent will be reported in this study.

In this study, we investigated four raw water resources representative of major raw water resources located in central and northern Taiwan: the Daiji River (Fengyuan water supply plant) and Shimen, Yongheshan, and Liyutan Reservoirs (Pingzhen, Dongxing and Liyutan water supply plant, respectively). The basic parameters as regulated will be examined. PSD, ZP, NOM, WQI and Carlson trophic state index (CTSI) were also measured and calculated. The results of this investigation can provide basic information for the management of raw water resources in Taiwan.

2. Materials and methods

2.1. Study area

Four locations were selected for investigation. One raw water resource was the Daiji River, which supplies the Fengyuan treatment plant. The other three were Shimen, Yongheshan and Liyutan Reservoirs, supplying the Pingzhen, Dongxing and Liyutan treatment plants, respectively. Those locations of raw water resources are representative of major raw water resources in northern and central Taiwan. Particularly, the turbidity after treatment is easy to exceed the internal control value of 0.2 NTU and the standard value of 2 NTU during the raining period. Fig. 1 shows a map of the sampling locations. The treatment processes of raw water are described in Table 1. The sampling point is nearby Fengyuan water supply plant at a tributary from the Daiji River (longitude/latitude, 120.7798148/24.2837500). The average flow rate of Daiji River is 31 m^3/s. The basin area of Daiji River is about 1,235.73 km^2. Raw water of Pingzhen water supply plant was collected from Shimen Reservoir

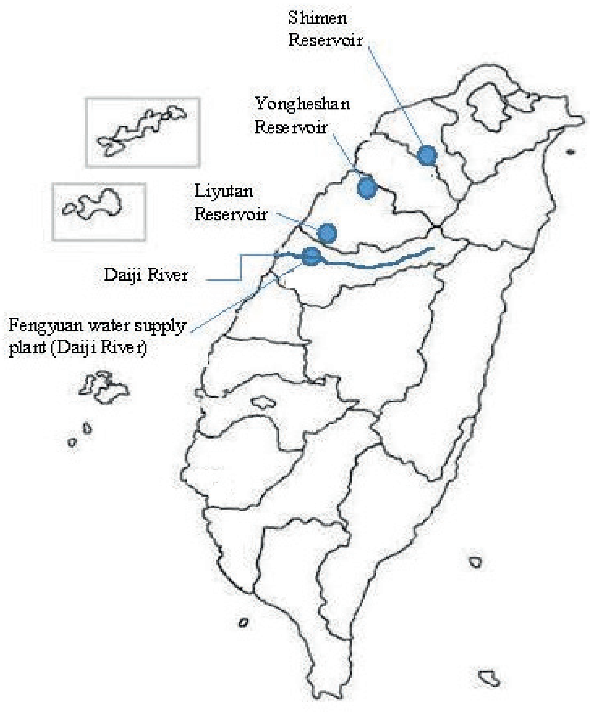

Fig. 1. Map of the sample locations in Taiwan.

Table 1
Basic information of treatment process of raw water in four water supply plants selected in Taiwan

Water supply plant	Treatment process	Resource of raw water	Unit description
Fengyuan	Collection well → coagulation tank → flocculation tank → sedimentation tank → rapid filter tank → clean water tank	Daiji River	Coagulation tank: 40 m × 12 m × 4 m, retention time 37 s. Flocculation tank: 16 tanks, 4.8 m × 4.8 m × 5.9 m, with vertical flocculator, retention time 19.2 min. Sedimentation tank: 8 tanks, 39 m × 10.85 m × 4.9 m, overflow rate 163.3 m^3/m^2 d, retention time ~26.5 min. Rapid filter tank: 16 tanks, 13.6 m × 6 m × 4 m, filter rate 110.77 m/d.
Pingzhen	Collection well → coagulation tank → flocculation tank → sedimentation tank → rapid filter tank → clean water tank	Shimen Reservoir	Coagulation tank: 4 m × 4 m × 4.29 m, retention rate 20 s. Flocculation tank: 4 tanks, 17.7 m × 14.85 m × 5.17 m, retention time 30 min. Sedimentation tank: 8 tanks, 40 m × 7.2 m × 5 m, inclined tube, retention time ~10 min. Rapid filter tank: 12 tanks, 13.2 m × 9.45 m × 4.35 m, filter rate ~100–200 m/d.
Dongxing	Collection well → coagulation tank → flocculation and sedimentation tank → rapid filter tank → clean water tank	Yong-heshan Reservoir	Coagulation tank: 16.2 m × 4.2 m × 6 m, retention time 294 s. Flocculation and sedimentation tank: OTV type (France), 2 cones, upper diameter 23.6 m, lower diameter 14.4 m, total depth 8.5 m, with recycling sludge by pump, retention time 40 min. Rapid filter tank: with continuous automatic back washing facilities (HARDINGE), 4.887 m × 34.2 m × 2.1 m, filter rate ~100–200 m/d.
Liyutan	Collection well → coagulation tank → flocculation tank → sedimentation tank → rapid filter tank → clean water tank	Liyutan Reservoir	Coagulation tank: 4 tanks, diameter 2.2 m × height 1.5 m, retention time ~75 s. Flocculation tank: 12 tanks, 13.4 m × 10 m × 5.6 m, retention time ~30 min. Sedimentation tank: 6 tanks, 27 m × 28.6 m × 5.6 m, retention time ~9 min. Rapid filter tank: 18 tanks, 14.4 m × 5 m × 2 m, filter rate ~100–200 m/d.

(121.2424100/24.8034780). The total and effective volume of Shimen Reservoir is 391,200,000 and 209,865,000 m^3, respectively. The normal depth of Shimen Reservoir is 245 m. The river basin area of Shimen Reservoir is about 763.4 km^2, and the Shimen Reservoir area is about 8 km^2. Raw water of Dongxing water supply plant was sampled from Yongheshan Reservoir (120.9235040/24.6599080). The normal depth of Yongheshan Reservoir is 85 m. The river basin area of Yongheshan Reservoir is about 4.8 km^2, and the Yongheshan Reservoir area is about 1.6 km^2. Raw water of Liyutan water supply plant was sampled from Liyutan Reservoir (120.7964780/24.3401740). The normal depth of Liyutan Reservoir is 300 m. The river basin area of Liyutan Reservoir is about 53.45 km^2, and the Liyutan Reservoir area is about 4.38 km^2.

2.2. Water sampling

Raw water of the Daiji River was collected from a tributary connected to the river and pumped via a pump station near the tributary to the Fengyuan water treatment plant. Raw water sampling from Shimen, Yongheshan and Liyutan Reservoirs for the Pingzhen, Dongxing and Liyutan treatment plants, respectively, was different from the Daiji River sampling. Raw water was sampled from reservoirs 100 m offshore at a depth of 50 cm. Sampling was undertaken following the guideline for river, lake and reservoir sampling by Taiwan EPA (NIEA W104.51C) [18]. If river width is less than 6 m, then only the central sampling site is needed to collect the water sample. As river is wider than 6 m, the left, central and right sampling site of the river is needed. If the depth of river is less than 1.5 m, the water sample is collected at the depth of 0.6 m. If the river depth ranges between 1.5 and 3 m, then water sampling is collected at the depth of 0.2 and 0.8 m. If the river is deeper than 3 m, then sampling depth is at 0.2, 0.6 and 0.8 m. All collected samples are mixed with equal volume for further analysis. The tributary flows through near the Fengyuan water supply plant, and the water is pumped and used as the raw water resource. The tributary is around 5 m wide and 2.5 m depth. Thus, water was centrally sampled at the depth of 0.2 and 0.8 m, and was mixed with equal volume. The water sample was carefully stored for further examination of water quality. As regard to water sampling of reservoirs, water sample is collected at surface level, mid-level and bottom level at the depth of 0.5 m, mid-level height, and 1 m above the bed. If the depth of reservoir is deeper than 50 m, then two samples need to be collected. The water sample of three reservoirs was collected at surface level by boat because only this water level was used as raw water resources. The Van Dorn water sampler was used to collect the water sample. As water sample was collected, pH, water temperature, electrical conductivity (EC) etc. were measured at field site and then was brought back to laboratory and stored in refrigerator for further analysis. The water sample for metals analysis was acidified to pH 2 and stored in refrigerator for further examination.

Table 2
Analytical methods and instrumental type for the examination of raw water resources selected in this study

Analytical parameters/instrumental type	Analytical method (Taiwan EPA)/AWWA
pH/pH-meter (SP-2300, SUNTEX)	pH analytical method in water—Electrode method (NIEA 424.52A)
ORP/ORP (Pro1030, YSI)	Measured by ORP meter
EC/EC (LF 330, WTW)	EC analytical method in water—EC meter method (NIEA W203.51B)
Turbidity/turbidity meter (2100P Turbidimeter, Hach)	Turbidity analytical method in water—Turbidity meter method (NIEA W219.52C)
Alkalinity/potentiometric titrator	Alkalinity analytical method in water◎Titration method (NIEA W449.00B)
Residual chloride/UV meter (DR 2800, Hach)	Measured by UV spectrometer
Metals/IRIS Intrepid II, Thermal Electron Corporation	Metals and trace elements analytical method in water—ICP-AES method (NIEA W311.53C)
Zeta potential/zeta potential meter (ZETA/ZC3000)	Zeecom2 software is used for analysis
TOC/TOC analyzer (TOC/Aurora Model 1030)	TOC analytical method in water—incineration/IR measurement method (NIEA W530.51C)
Particle size distribution/high performance particle sizer (HPPS/HPP-5001)	DTS software is used for analysis
Structure of total solid (FE-SEM, JERL, JSM-6700F)	Image of the surface topology of any solid material with very high spatial resolution
NOMs (HPSEC, EEMs)	To evaluate molecular sizes of humic substances from different sources

2.3. Water parameter measurement

Water sampling were measured for turbidity, EC, oxidation and reduction potential (ORP), pH, alkalinity, total organic compounds (TOC), ZP, particle size, Al, Fe and heavy metals. NOM was determined using high-performance size-exclusion chromatography (HPSEC) to distinguish the different molecular weight distribution of organic compounds such as humic acids and low molecular weight acids (LMWs). Microstructure of total solids in water was examined by field-emission scanning electron microscope (FE-SEM). Table 2 shows analytical instruments and methods. Raw water analysis was carried out according to the analytical methods published by Taiwan EPA and AWWA [18,19].

2.4. Water quality index (WQI) calculation

WQI was calculated according to the report by Ott [20]. Nine parameters were used for WQI calculation including dissolved oxygen (DO) solubility (%), faecal coliforms (CFUs/100 mL), pH, biochemical oxygen demand (BOD_5, mg/L) , nitrates (mg/L), total phosphates (mg/L), temperature deviation (ΔT, °C), turbidity (NTU) and total solids (mg/L). The corresponding weights of these parameters (W_i) are 0.17, 0.15, 0.12, 0.1, 0.1, 0.1, 0.1, 0.08 and 0.08 according to Ott [20], respectively. WQI was calculated via following equation:

$$\text{WQI} = \sum_{i=1}^{n} I_i \times W_i \tag{1}$$

where WQI is a weighted linear sum of the subindices; I_i is subindex (0–100) of nine parameters depending on concentrations of nine parameters (Figs. S-1–S-9). W_i is the corresponding weights of these nine parameters, which are 0.17, 0.15, 0.12, 0.1, 0.1, 0.1, 0.1, 0.08 and 0.08 as mentioned above, respectively.

The calculated WQI values of 0–25, 26–50, 51–70, 71–90 and 91–100 correspond to very bad (red colour), bad (orange colour), medium (yellow), good (green colour) and excellent (blue colour) water quality, respectively [20].

3. Results and discussion

3.1. Basic parameter analysis

Turbidity (NTU) at Daiji River (128.24 ± 638.53) was found higher compared with those at Shimen Reservoir (6.39 ± 7.42), Yongheshan Reservoir (2.20 ± 0.73) and Liyutan Reservoir (3.28 ± 2.51). EC ranged from 224.9 to 350.6 µS/cm, ORP from 210.5 to 271.55 mV, pH from 8.17 to 8.58, alkalinity from 65.65 to 86.25 mg/L, TOC from 1.54 to 2.73 mg/L and ZP from –16.82 to –22.60 mV. In addition, average particle size at Daiji River (5,067.56 nm) was higher than those at Shimen, Yongheshan and Liyutan Reservoirs (1,105.12–1,627.26 nm). The higher particle size of raw water from the Daiji River might be caused by turbulences at the riverbed particularly found in raining or typhoon day. In contrast, the water turbidity of reservoirs is not easily affected by the sedimentation sludge that might possibly be affected at raining period, typhoon day or the algal bloom. The higher particle size at Daiji River might be the main reason for the difficulties of water treatment in the raining season. In addition, heavy metals contents were under the water influent standard. Cd, Cr, Cu, Ni, Pb, Zn, As and Hg were measured to be not detected (ND; which is below the method of detection limit [MDL]), ND, ND ~ 0.004, ND, ND ~ 0.007, ND ~ 0.015, ND ~ 0.005 and ND, respectively. These measured data met the regulatory standard in Taiwan. The CTSI also showed that Shimen and Liyutan Reservoir had the potential to cause the water eutrophication. Table 3 shows the analytical results.

3.2. Characterization of natural organic matter

TOC of four selected raw water resources ranged from 1.54 to 2.73 mg/L as shown in Table 3. However,

Table 3
Basic characteristics of raw water of four selected water supply plants in Taiwan

Water supply plant (raw water resource)	Fengyuan (Daiji River)	Pingzhen (Shimen Reservoir)	Dongxing (Yongheshan Reservoir)	Liyutan (Liyutan Reservoir)	Raw water influent standard
[a]Turbidity (NTU)	128.24 ± 638.53	6.39 ± 7.42	2.20 ± 0.73	3.28 ± 2.51	
[a]EC (μS/cm)	231.68 ± 22.33	224.9 ± 31.83	249.7 ± 24.53	350.6 ± 29.1	
[a]pH	8.58 ± 0.26	8.48 ± 0.53	8.17 ± 0.50	8.17 ± 0.40	
[b]ORP (mV)	271.55 ± 2.05	216.75 ± 10.54	210.5 ± 8.06	218.1 ± 7.50	
[b]Alkalinity (mg/L)	86.25 ± 5.30	65.65 ± 1.48	72.75 ± 0.78	79.1 ± 1.27	
[b]TOC (mg/L)	2.73 ± 0.88	1.54 ± 0.16	2.36 ± 0.22	2.63 ± 0.78	4
[b]Zeta potential (mV)	–16.82 ± 2.04	–18.14 ± 1.73	–22.60 ± 0.87	–19.58 ± 0.96	
[b]Particle size distribution (nm)	1,990–5,560	1,110–1,720	1,280–5,560	955–1,280	
[b]Average particle size (nm)	5,067.56	1,374.61	1,627.26	1,105.12	
[b]Al (mg/L)	ND	ND	ND ~ 0.0038	ND ~ 0.0046	
[b]Fe (mg/L)	ND	ND	ND	ND	
[a]Cd (mg/L)	ND	ND	ND	ND	0.01
[a]Cr (mg/L)	ND	ND	ND	ND	0.05
[a]Cu (mg/L)	ND ~ 0.004	ND	ND	ND ~ 0.001	
[a]Ni (mg/L)	ND	ND	ND	ND	
[a]Pb (mg/L)	ND ~ 0.007	ND ~ 0.006	ND	ND	0.05
[a]Zn (mg/L)	ND ~ 0.015	ND ~ 0.006	ND ~ 0.007	ND ~ 0.007	
[a]As (mg/L)	ND	ND	ND ~ 0.005	ND ~ 0.002	0.05
[a]Hg (mg/L)	ND	ND	ND	ND	0.002
[a]Se (mg/L)	ND	ND	ND	ND	0.05
[a]Mn (mg/L)	ND ~ 0.114	ND ~ 0.085	ND ~ 0.637	ND ~ 0.596	
[a]Ag (mg/L)	ND	ND	ND	ND	
[c]CTSI (four seasons)	–	52/63/47/50	46/48/46/45	43/52/47/50	

Note: Metals' MDL (mg/L): As (0.003), Hg (0.003), Se (0.001), Cd (0.0012), Cr (0.0012), Ni (0.0012), Cu (0.0017), Pb (0.003), Zn (0.0013), Fe (0.001), Al (0.013), Mn (0.001) and Ag (0.001).
[a]National Environmental Quality Monitoring Network (Taiwan EPA, 2014-2016).
[b]This study (two seasons including summer and autumn, 2015).
[c]Carlson trophic state index (CTSI) for Shimen, Yongheshan and Liyutan Reservoir at four seasons in 2015.

$$CTSI = [(TSI (SD) + TSI (Chl\text{-}a) + TSI (TP)]/3$$

$$TSI (SD) = 60 - 14.41 \times \ln SD$$

$$TSI (Chl\text{-}a) = 9.81 \times \ln Chl\text{-}a + 30.6$$

$$TSI (TP) = 14.42 \times \ln TP + 4.15$$

where SD is transparency (m); Chl-a is concentration of Chlorophyll a (μg/L); and TP is concentration of total phosphate (μg/L). CTSI < 40 represents oligotrophic state; 40 ≦ CTSI ≦ 50 represents general trophic state; and CTSI >50 represents eutrophic state.

compositions of raw water might be complex. NOM values of four selected raw water resources were characterized by HPSEC. The results are shown in Fig. 2. NOM showed similar patterns and contained humic acids, with the intensity order of Yongheshan Reservoir > Shimen Reservoir > Liyutan Reservoir > Daiji River. Humic acids and LMWs were found in raw water resources according to several reports [13–17]. Varying NOM values have caused the difficulty of water treatment and the potential DBPs leading to the potential risks to human health. Thus, organic high molecular weight flocculants have been recommended for the treatment of low turbidity raw water appearing as white colour conditions particularly found in the raining period.

3.3. Filtered total solids scanning by FE-SEM

Fig. 3 shows the FE-SEM plot of filtered total solids of raw water at the four resources. Total solids, leaf litter and algal bodies were found in all four raw water resources. The length of Daiji River is about 140 km. It originated from the Central Mountains of Taiwan. Turbidity increased as the river water flow increased. It is because that the scouring of river water flow increased, particularly found in the raining day causing the potential higher turbidity. Turbidity is found to be dependent on the increased water flow. Turbidity had great changes and was measured to be 128.24 ± 638.53 (NTU) as shown in Table 3. It was found to range from 1.7

to 7,942 NTU. Shimen, Yongheshan and Liyutan Reservoirs collect the water from the different river and tributary, and the total solids are easily to be settled to the bottom of reservoirs. The turbidity of Shimen, Yongheshan and Liyutan Reservoirs were found to be 6.39 ± 7.42, 2.20 ± 0.73 and 3.28 ± 2.51 NTU (Table 3), respectively. High and low turbidity ranges were found to be around 5–300, 1.2–25 and 1.1–11 NTU for Shimen, Yongheshan and Liyutan Reservoirs, respectively. The settled total solids as sludge in the bottom of reservoirs might reduce the storage space and decrease the lifespan of reservoirs. The treatment cost of bottom sludge is high though the drudged sludge might be used as building materials in construction industry.

It is noted that eutrophication by algae is easily found in reservoir or lake. Eutrophic state can be expressed by CTSI. Table 3 shows the CTSI of four seasons of three reservoirs. The

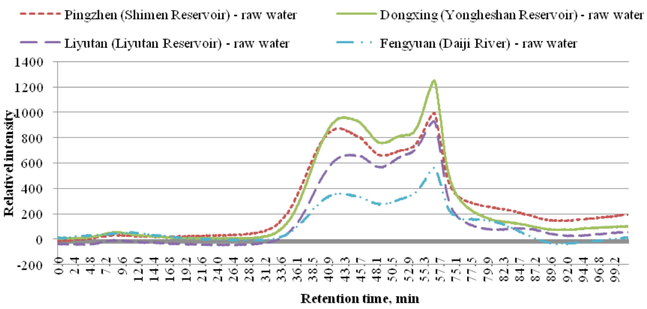

Fig. 2. HPSEC plot of four raw water resources in Taiwan.

CTSI of first (52) and second (63) season of Shimen Reservoir and the second season (52) of Liyutan Reservoir showed the potential eutrophication corresponding to the algae FE-SEM photos shown in Fig. 3. Daiji River also showed to have the algae in Fig. 3. However, it is not easy to cause the eutrophication in flowing river compared with the reservoir or lake. Algae have long been a problematic issue of eutrophication in lakes or reservoirs and are posing a potential risk for water treatment and water drinking safety. Algal bloom or algal toxin might impact the quality of raw water resources. Thus, control of algal eutrophication has been an important issue in Taiwan.

3.4. WQI of raw water resources

WQI indicated the good conditions of raw water resources at three reservoirs while it indicated the medium condition at Daiji River as shown in Table 4 [20]. WQI is divided into five categories, ranging from very bad (0–25), bad (26–50), medium (51–70) to good (71–90) and excellent (91–100). In this study, the nine parameters containing DO, faecal coliforms, pH, BOD_5, nitrates, total phosphates, temperature variation, turbidity and total solids were used to calculate WQI. Raw water resources at Fengyuan (Daiji River) showed to have the medium conditions (68.03) due to the higher turbidity usually happened at Typhoon or raining day. Compared with the WQIs of other three reservoir, the rank order is Liyutan (Liyutan Reservoir) (78.89) > Dongxing (Yongheshan Reservoir) (77.14) > Pingzhen

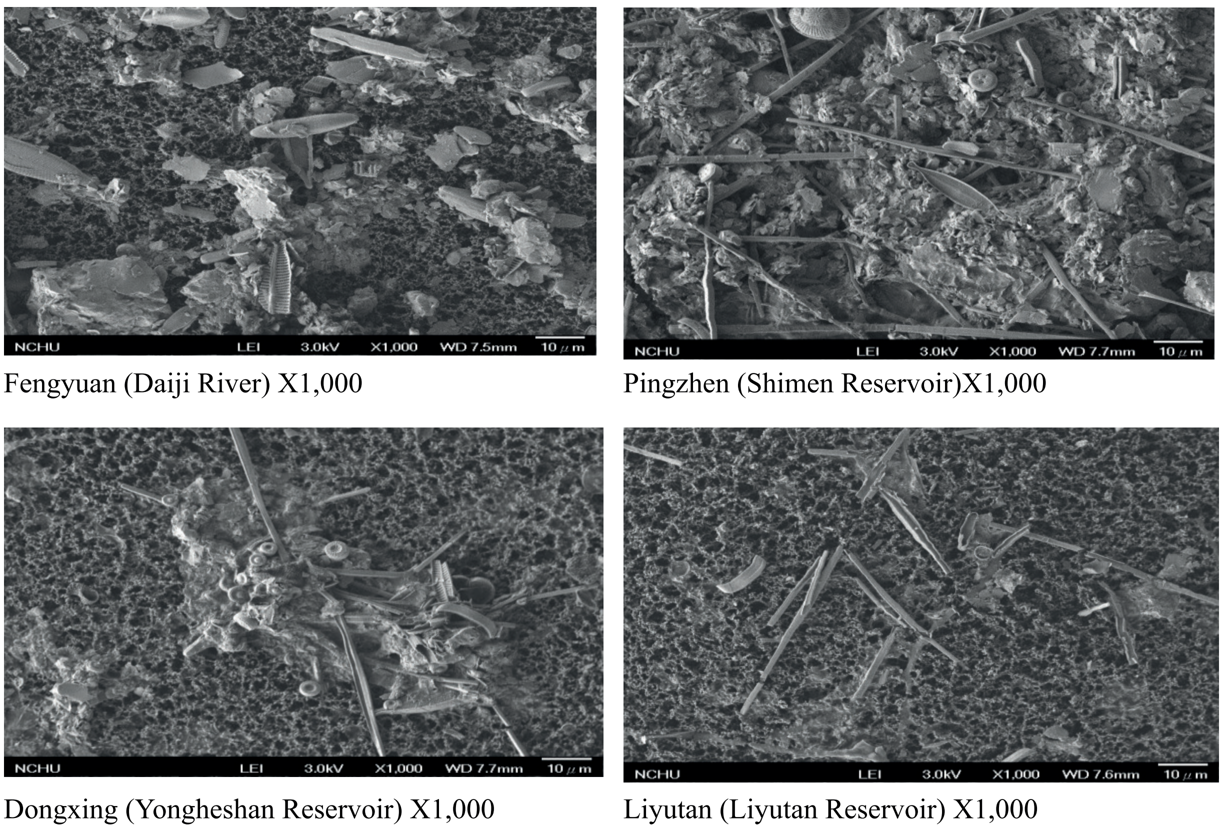

Fig. 3. FE-SEM plot of filtered total solids of raw water of the four selected water supply plants in Taiwan.

Table 4
WQI calculation results [20] of raw water of four selected water supply plants in Taiwan

Water supply plant (raw water resource)	Water parameters	Values of parameter	Values of subindex, I_i	Weight of parameter, W_i	Calculated values, numerical range, I_iW_i	Condition
Fengyuan (Daiji River)	DO, solubility (%)	108.6 ± 4.81	96	0.17	16.32	
	Fecal coliforms (CFUs/100 mL)	864.46 ± 1,754.31	21	0.15	3.15	
	pH	8.58 ± 0.26	65	0.12	7.8	
	BOD_5 (mg/L)	1.02 ± 0.09	85	0.1	8.5	
	Nitrates (mg/L)	0.65 ± 0.23	95	0.1	9.5	
	Total phosphates (mg/L)	0.046 ± 0.043	95	0.1	9.5	
	Temperature deviation (ΔT) (°C)	3.24	55	0.1	5.5	
	Turbidity (NTU)	128.24 ± 638.53	15	0.08	1.2	
	Total solids (mg/L)	25.67 ± 41.96	82	0.08	6.56	
	WQI				68.03	Medium
Pingzhen (Shimen Reservoir)	DO, solubility (%)	107.08 ± 17.22	96	0.17	16.32	
	Fecal coliforms (CFUs/100 mL)	40 ± 12	50	0.15	7.5	
	pH	8.48 ± 0.53	65	0.12	7.8	
	BOD_5 (mg/L)	1.13 ± 0.11	90	0.1	9	
	Nitrates (mg/L)	0.62 ± 0.05	95	0.1	9.5	
	Total phosphates (mg/L)	0.028 ± 0.014	95	0.1	9.5	
	Temperature deviation (ΔT) (°)	5.17	40	0.1	4	
	Turbidity (NTU)	6.39 ± 7.42	85	0.08	6.8	
	Total solids (mg/L)	5 ± 4.78	82	0.08	6.56	
	WQI				76.98	Good
Dongxing (Yongheshan Reservoir)	DO, solubility (%)	88 ± 36.96	92	0.17	15.64	
	Fecal coliforms (CFUs/100 mL)	400 ± 112	28	0.15	4.2	
	pH	8.17 ± 0.5	80	0.12	9.6	
	BOD_5 (mg/L)	1.61 ± 0.18	82	0.1	8.2	
	Nitrates (mg/L)	0.23 ± 0.03	95	0.1	9.5	
	Total phosphates (mg/L)	0.014 ± 0.003	96	0.1	9.6	
	Temperature deviation (ΔT) (°)	4.64	60	0.1	6	
	Turbidity (NTU)	2.2 ± 0.73	98	0.08	7.84	
	Total solids (mg/L)	2.64 ± 1.03	82	0.08	6.56	
	WQI				77.14	Good
Liyutan (Liyutan Reservoir)	DO, solubility (%)	93.21 ± 33.44	95	0.17	16.15	
	Fecal coliforms (CFUs/100 mL)	300 ± 92	30	0.15	4.5	
	pH	8.17 ± 0.4	80	0.12	9.6	
	BOD_5 (mg/L)	1.3 ± 0.15	85	0.1	8.5	
	Nitrates (mg/L)	0.34 ± 0.04	94	0.1	9.4	
	Total phosphates (mg/L)	0.016 ± 0.008	95	0.1	9.5	
	Temperature deviation (ΔT) (°)	3.94	70	0.1	7	
	Turbidity (NTU)	3.28 ± 2.51	95	0.08	7.6	
	Total solids (mg/L)	5.15 ± 4.15	83	0.08	6.64	
	WQI				78.89	Good

Note: The WQI (ΣI_iW_i) was calculated by $\sum_{i=1}^{n} I_i \times W_i$. WQI values of 0–25, 26–50, 51–70, 71–90 and 91–100 correspond to very bad (red colour), bad (orange colour), medium (yellow), good (green colour) and excellent (blue colour) water quality, respectively.
I_i is the value of the subindex according to the average value of parameters; W_i is the weight of the parameters.

(Shimen Reservoir) (76.98). The WQIs of the three reservoirs are close. However, raw water resources still need to be monitored continuously to ensure their quality due to the potential risks of contaminants released from the agricultural and industrial effluents. Table 4 shows WQI values for the four selected water resources.

4. Conclusions

Raw water of the four resources showed to have close values for EC, ORP, pH, alkalinity, TOC and ZP ranging from 231.68 to 350.60 μS/cm, 210.5 to 271.55 mV, 8.17 to 8.58, 65.65 to 86.25 mg/L, 1.54 to 2.73 mg/L, and –16.82 to –22.60 mV, respectively. Turbidity (NTU) was in the rank order of Fengyuan (Daiji River) (128.24 ± 638.53) > Pingzhen (Shimen Reservoir) (6.39 ± 7.42) > Liyutan (Liyutan Reservoir) (3.28 ± 2.51) > Dongxing (Yongheshan Reservoir) (2.20 ± 0.73). Fengyuan (Daiji River) showed to have higher turbidity and average particle size. CTSI and FE-SEM plot showed that Pingzhen (Shimen Reservoir) and Liyutan (Liyutan Reservoir) had the potential to cause the eutrophication. WQI of raw water resources at Fengyuan (Daiji River) showed to have the medium conditions (68.03) compared with the good conditions at Liyutan (Liyutan Reservoir) (78.89), Dongxing (Yongheshan Reservoir) (77.14) and Pingzhen (Shimen Reservoir) (76.98). Metals measured all met the influent standard. TOC and NOM results showed that the raw water still had the potential to cause the DBPs and health risks. Raw water resources need to be monitored continuously to ensure the safety of drinking water.

Acknowledgement

The authors are very grateful to the Taiwan Water Corporation, Taiwan, Republic of China, for providing funding for this work (T-102-B-07).

References

[1] Availableat:http://www.who.int/water_sanitation_health/publications/drinking-water-quality-guidelines-4-including-1st-addendum/en/
[2] D. Haldar, S. Halder, P. Das (Saha), G. Halder, Assessment of water quality of Damodar River in South Bengal region of India by Canadian Council of Ministers of Environment (CCME) Water Quality Index: a case study, Desal. Wat. Treat., 57 (2016) 3489–3502.
[3] F. Othman, S.A. Muhammad, S.A.H. Azahar, M.E. Alaa Eldin, A. Mahazar, M.S. Othman, Impairment of the water quality status in a tropical urban river, Desal. Wat. Treat., 57 (2016) 88–94.
[4] H. Liu, D. Pan, P. Chen, A two-year field study and evaluation of water quality and trophic state of a large shallow drinking water reservoir in Shanghai, China, Desal. Wat. Treat., 57 (2016) 13829–13838.
[5] C.-L. Lin, J.-X. Zhang, L. Lan, Analyses of rural drinking water resources quality in the north area of Shaanxi, Desal. Wat. Treat., 54 (2015) 637–641.
[6] T. Ahmed, A. Pervez, M. Mehtab, S.K. Sherwani, Assessment of drinking water quality and its potential health impacts in academic institutions of Abbottabad (Pakistan), Desal. Wat. Treat., 54 (2015) 1819–1828.
[7] G.B. Gholikandi, S. Haddadi, E. Dehghanifard, H.R. Tashayouie, Assessment of surface water resources quality in Tehran province, Iran, Desal. Wat. Treat., 37 (2012) 8–20.
[8] Available at: http://www.water.gov.tw/public/data/20170103084728443.pdf
[9] I. Yu, M. L.A. Felix, L.-H. Kim, S. Jeong, Analysis on flood frequency and water quality variations induced by abnormal climate, Desal. Wat. Treat., 53 (2015) 2339–2353.
[10] M.R. Teixeira, L.M. Nunes, The impact of natural organic matter seasonal variations in drinking water quality, Desal. Wat. Treat., 36 (2011) 344–353.
[11] W. Zhang, I. Lou, W.K. Ung, Y. Kong, K.M. Mok, Spatio-temporal variations of phytoplankton structure and water quality in the eutrophic freshwater reservoir of Macau, Desal. Wat. Treat., 55 (2015) 2237–2252.
[12] H.A. Abu Qdais, N. Al-Abed, Z. Al-Ghazawi, F. Abdulla, Prediction of trihalomethane formation in water distribution systems, Desal. Wat. Treat., 2 (2009) 166–173.
[13] C.H. Lai, Y.C. Chou, H.H., Yeh, Assessing the interaction effects of coagulation and membrane material on UF fouling control using HPSEC combined with peak-fitting, J. Membr. Sci., 474 (2015) 207–214.
[14] W.T. Li, Z.X. Xu, A.M. Li, W. Wu, Q. Zhou, J.N. Wang, HPLC/HPSEC-FLD with multi-excitation/emission scan for EEM interpretation and dissolved organic matter analysis, Water Res., 47 (2013) 1246–1256.
[15] M. Halim, R. Spaccini, E. Parlanti, A. Amezghal, A. Piccolo, Difference properties between humic acid and its size fractions separated by preparative HPSEC, J. Geochem. Explor., 129 (2013) 23–27.
[16] Q. Zhou, S.E. Cabaniss, P.A. Maurice, Considerations in the use of high-pressure size exclusion chromatography (HPSEC) for determining molecular weights of aquatic humic substances, Water Res., 34 (2000) 3505–3514.
[17] C. Pelekani, G. Newcombe, V.L. Snoeyink, C. Hepplewhite, S. Assemi, R. Beckett, Charaterization of natural organic matter using high performance size exclusion chromatography, Environ. Sci. Technol., 33 (1999) 2807–2813.
[18] Available at: http://www.niea.gov.tw/niea/WATER/W10451C.htm
[19] American Public Health Association, American Water Works Association, Water Environment Federation, Standard Methods for the Examination of Water and Wastewater, 19th ed., AWWA, Hanover, MD, 1995.
[20] W.R. Ott, Environmental Indices: Theory and Practice, Ann Arbor Science Publishers, Ann Arbor, Michigan, 1978, pp. 2, 5, 135–169, 202–213.

Appendix

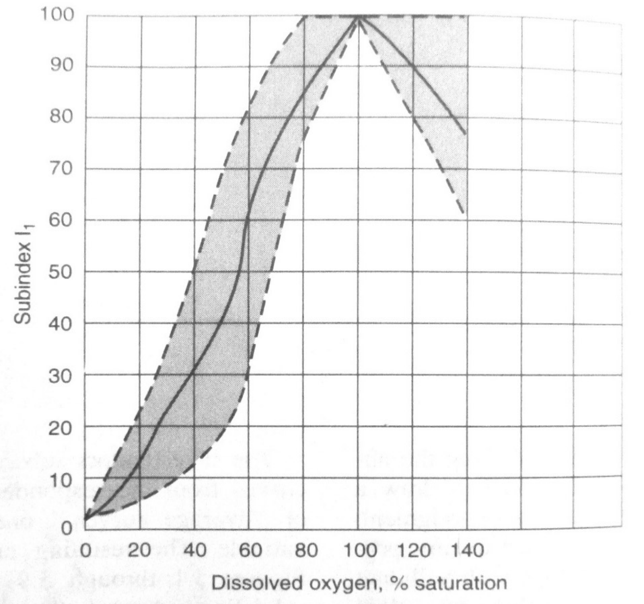

Fig. S-1. Subindex function for DO in the NSF WQI (for DO > 140%, I_1 = 50) [20].

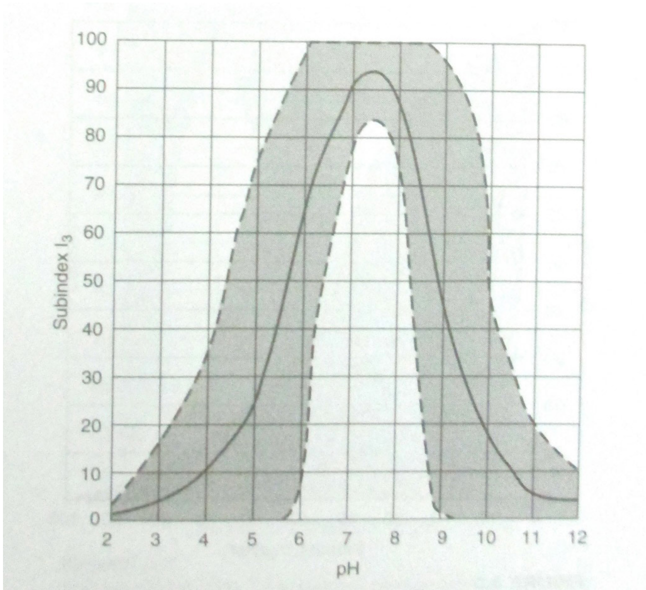

Fig. S-3. Subindex function for pH in the NSF WQI [20].

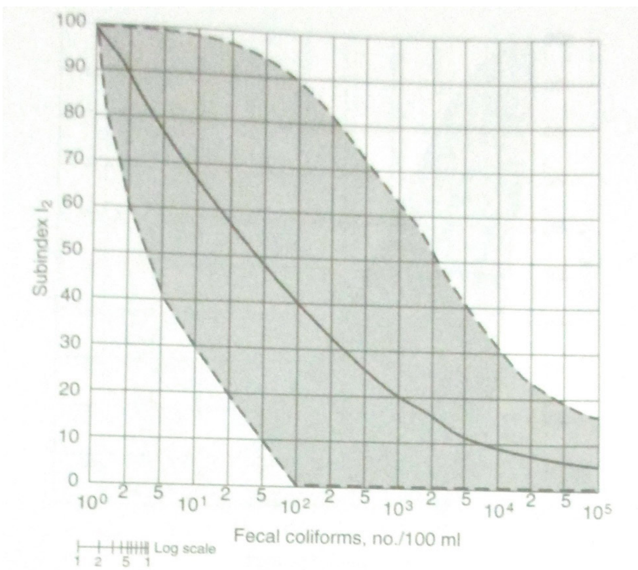

Fig. S-2. Subindex function for fecal coliforms (average number of organisms per 100 mL) in the NSF WQI (for fecal coliforms > 10^5/100 mL, I_2 = 2) [20].

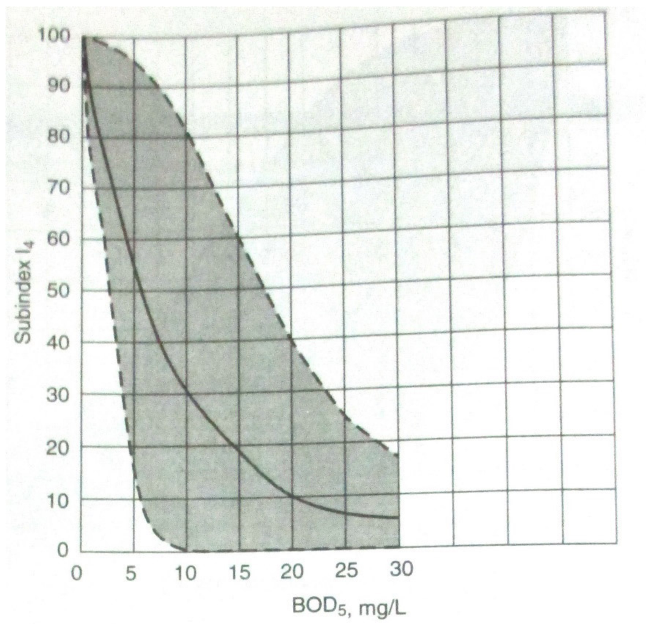

Fig. S-4. Subindex function for BOD_5 in the NSF WQI (for BOD_5 > 30 mg/L, I_4 = 2) [20].

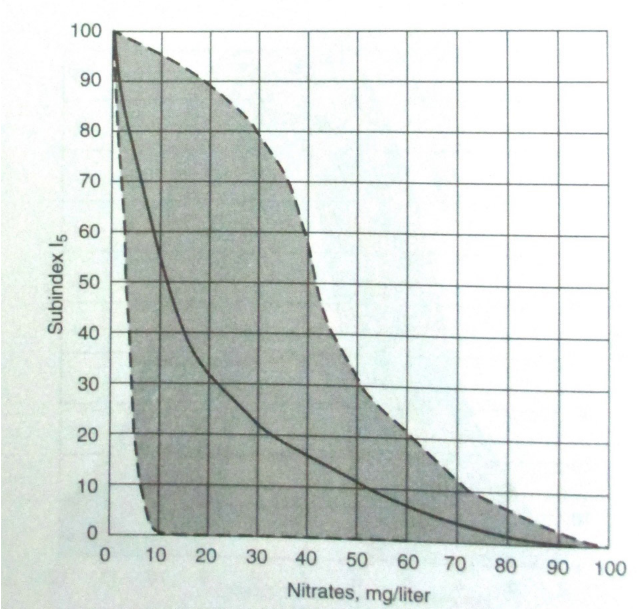

Fig. S-5. Subindex function for nitrates in the NSF WQI (for nitrates > 100 mg/L, $I_5 = 1$) [20].

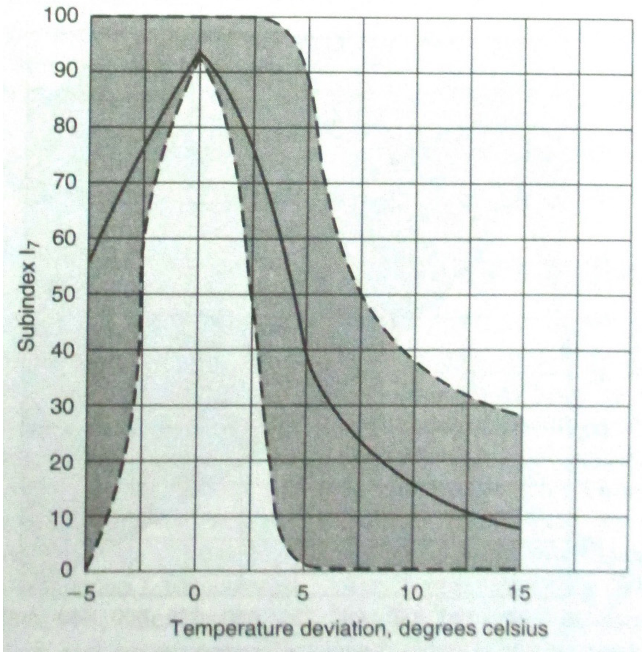

Fig. S-7. Subindex function for temperature deviation from equilibrium (ΔT) in the NSF WQI (for $\Delta T > 15°C$, $I_7 = 5$) [20].

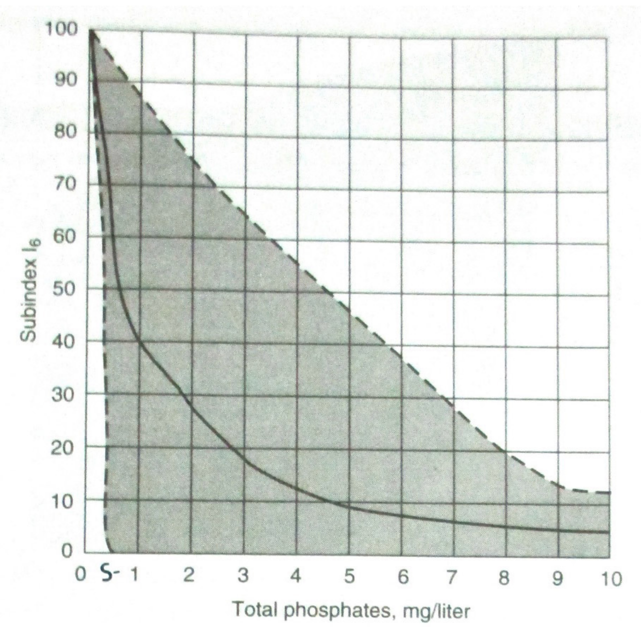

Fig. S-6. Subindex function for total phosphates in the NSF WQI (for total phosphates > 10 mg/L, $I_6 = 2$) [20].

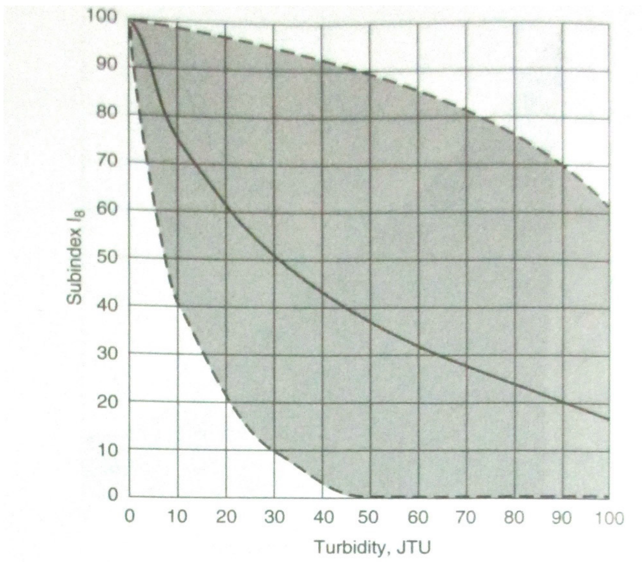

Fig. S-8. Subindex function for turbidity (Jackson turbidity units) in the NSF WQI (for turbidity > 100 NTU, $I_8 = 5$) [20].

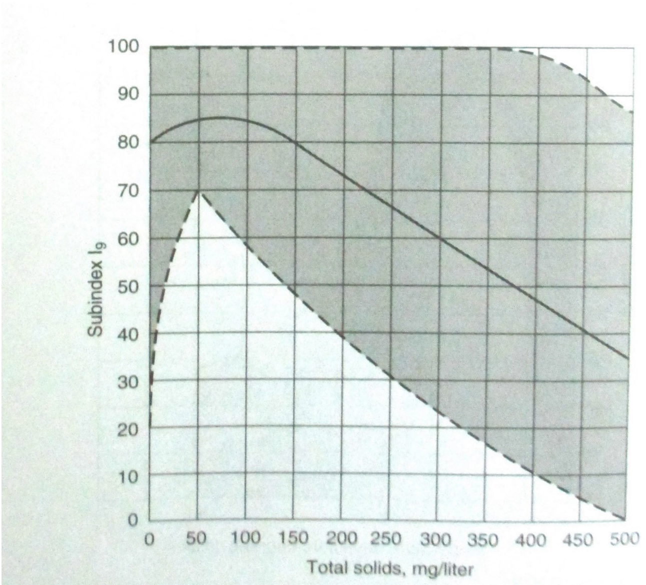

Fig. S-9. Subindex function for total solids in the NSF WQI (for total solids > 500 mg/L, I_9 = 20) [20].