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Development of Reservoir Water Quality Index (WQI) Based on Long-term Physicochemical Parameters and Their Spatio-temporal Variations

Md Mamun and Kwang-Guk An*
Department of Bioscience and Biotechnology, Chungnam National University, Daejeon-34134, South Korea
✉ kgan@cnu.ac.kr

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Abstract: The main objectives of this study were to develop a Water Quality Index (WQI) model based on the physicochemical parameters in Daecheong reservoirs by using datasets of 1995-2016. The parameters included total phosphorus (TP), total nitrogen (TN), biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), chlorophyll (CHL), electrical conductivity (EC), dissolved oxygen (DO) and hydrogen ion concentrations (pH). The results had showed that physicochemical parameters varied spatially and temporarily as well as were correlated. TP was the most important key regulating factor for chlorophyll growth in the reservoirs. Seasonal summer TP influenced the autumn algal growth. The concentrations of total phosphorus (TP) was highest during the summer season (36±2 μgL^{-1}) while it was lowest in the winter season (15±1 μgL^{-1}). Summer monsoon directly influences the concentrations of total phosphorus in the reservoirs. Overall, the calculated WQI value suggested that site 1 (129.44) was in poor condition whereas sites 2 (116.06), 3 (103.51), 4 (89.3), 5 (82.007) and 6 (90.22) were in fair condition.

Key words: Chlorophyll, Daecheong reservoirs, nutrients, Water Quality Index (WQI) model.

Introduction

Recently, surface water pollution is one of the hot issues and has emerged as a global hazard to the aquatic ecosystem and therefore becomes a serious challenge for scientists, limnologists, ecologists, and water quality managers. Due to uncontrolled population growth and industrialization, the freshwater quality has been at stake in developed and developing nations (UN Water, 2010, 2016; Alam and Pathak, 2010; Kar, 2013). The demand for water and pollution has been increasing day by day and it has been considered as the most serious threat all over the world (Global Risks, 2015).

The healthiness of the freshwater ecosystem is diagnosed by physical, chemical and biological water quality parameters (Venkatesharaju et al., 2010). It is the degree of water condition with respect to human needs or purposes (Abbasi and Abbasi, 2012). There have been many methods suggested and applied to evaluate the quality of surface water. Among them, the water quality index (WQI) is a very comprehensive and easy method that gives the facts of water to a single value in a reproducible manner which was first proposed by Horton in 1965 (Abbasi and Abbasi, 2012; APHA, 2005; Simoes et al., 2008). Later on, numerous researches had been carried out for water quality assessment of various waterbodies using WQIs all over the world (Abdul et al., 2010; Akbal et al., 2011; Hector et al., 2012; Abdulwahid, 2013; Chrysoula et al., 2014; Will et al., 2015; Hefni and Romanto, 2015; Lobato et al.,

*Corresponding Author

2015; Ewaid and Abed, 2017; Kangabam et al., 2017). Likewise, a similar number of studies had been done in South Korea to assess the lake and reservoirs water quality (Lee et al., 2014).

South Korea is a highly industrialized and urbanized country. Surface water is being used for household activities, irrigation, raising livestock, aquaculture as well as a drinking source. Daecheong reservoir has greater importance and is one of the primary sources of drinking water of two megacities in South Korea like Daejeon and Cheonju (An and Park, 2003). Generally, the water quality status of the reservoirs is not only dependent on external and internal contaminant loads but also on weather (precipitation, temperature, and radiation) and hydrological (runoff volume and velocity) conditions (Hua and Zhang, 2017).

Nutrient enrichment or eutrophication in reservoirs is a common problem in many countries including South Korea, resulting in water quality deterioration (Lee et al., 2014; Mamun and An, 2017). Phosphorus is the key regulating factor for algal growth and is often considered as an important indicator of eutrophication (Vollenweider, 1968; An and Park, 2003). In South Korea, water quality of reservoirs are assessed by total phosphorus (TP), total nitrogen (TN), biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), chlorophyll (CHL), electrical conductivity (EC), dissolved oxygen (DO) and hydrogen ion concentration (pH).

The aim of this research was how the concentrations of total phosphorus and total chlorophyll varied spatially and temporarily in the Daecheong reservoirs and how are the physicochemical water quality parameters correlated with each other and finally to develop a water quality index (WQI) for Daecheong reservoirs.

Materials and Methods

Description of the Study Area

The Daechong reservoir (Latitude 36°28′39″ and Longitude 127°28′51″) is the third-largest reservoirs in South Korea and showed monomictic type characteristics which lied in the middle reaches of Geum river (Figure 1; Chung et al., 2014; Wetzel, 2001). Daecheong reservoir has been used for multi-purposes including irrigation, hydropower electricity, flood control, and

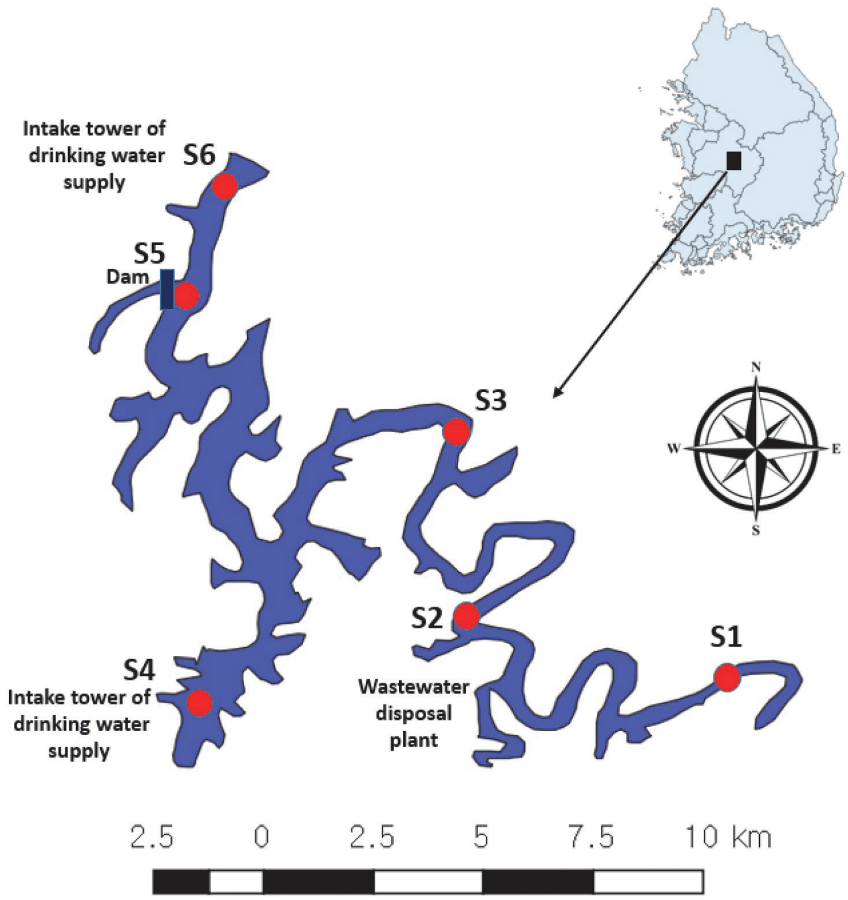

Figure 1: The map showing sampling sites of Daecheong reservoirs.

drinking sources. It is the major source of drinking water of two megacities (Daecheon and Cheonju) and supplies about 1.0 × 10^6 m^3 per day of drinking water to two million people in these two cities (Chung et al., 2014). It is an artificial type lake, long and dendritic in shape. The surface area of the reservoir is 72.8 km^2 and the maximum depth and width are 55 m and 1 km, respectively and the total capacity of the reservoir is 1490 × 10^6 m^3. The intake tower of drinking water was located on-site 4 and 6 for Daejeon and Cheonju city, accordingly. The dam site was located on-site 5.

Analysis of Water Quality Parameters

The physicochemical water quality parameters were collected from the Korean Ministry of Environment (MOE, Korea) from 1995-2016 on monthly basis. The total phosphorus was assessed by the ascorbic acid treatment which had been standardized by Ministry of Environment, Korea (Korea; MOE, 2006). Total nitrogen (TN), biological oxygen demand (BOD), and chemical oxygen demand (COD) were measured using the chemical testing method standardized by the Ministry of the Environment (Korea; MOE 2006). Electrical conductivity (EC), dissolved oxygen (DO) and pH were determined by a portable multiparameter analyzer (YSI Sonde Model 6600). Total suspended solids (TSS) were measured through preweighed Whatman method. The concentration of chlorophyll (CHL) was determined using a spectrophotometer (Bechman Model DU-65) after extraction of hot ethanol (Marker et al., 1980).

Calculation of the Water Quality Index (WQI)

The Water Quality Index (WQI) for the Daecheong reservoir was calculated from physicochemical parameters where nine parameters were selected based on their importance in water quality, namely, TP, TN, BOD, COD, TSS, CHL, EC, DO and pH. The values used for each water quality parameter are the mean value of the sites during the study period. The standard value of water quality parameters for drinking purposes was used in this study which were recommended by World Health Organization (WHO, 2011), Ministry of Land, Transport, and Maritime Affairs, Korea (MLTM, Korea 2012), European Economic Commission, Romania (ECE, Romania, 2006).

The following equations were used for the calculation of the Water Quality Index (WQI) of Daecheong reservoirs (Horton, 1965; Brown et al., 1970).

$$\text{Rw} = \text{Aw}/\sum\text{Aw} \tag{1}$$

where *Rw* = Relative weight and *Aw* = Assigned weight. The physicochemical water quality parameter was assigned a weight from 1 (lowest effects on water quality) to 5 (highest effects on water quality) according to their effects on water quality (Varol and Debraz, 2015; Yidana and Yidana, 2010).

$$\text{Qi} = \frac{\text{Mv}}{\text{Sv}} \times 100 \tag{2}$$

where Qi = Sub-index of the water quality parameters, Mv = Monitored value of the water quality parameters, Sv = Standard value of the water quality parameters. The sub-index of the pH and DO was calculated by the following equations.

$$\text{Qi}_{\text{pH, DO}} = \frac{\text{Mv} - \text{Iv}}{\text{Sv} - \text{Iv}} \times 100 \tag{3}$$

where the Ideal value (Iv) for pH and DO is 7 and 14.6, respectively (Tripaty and Sahu, 2005).

So, the sub-indices of the water quality parameters were determined by the following equations.

$$\text{SI} = \text{Rw} \times \text{Qi} \tag{4}$$

The WQI has been calculated from sub-indices of the water quality parameters.

$$\text{WQI} = \sum\text{SI} \tag{5}$$

Based on calculated WQI values, the water quality of the reservoir was categorized from excellent to unsuitable for drinking (Table 1; Yadav et al., 2010; Shweta et al., 2013; Ramakrishnaiah et al., 2009).

Table 1: Water quality status and range of Daecheong reservoirs

Water quality	*Scale*
Excellent	0-40
Good	41-80
Fair	81-120
Poor	121-160
Very poor	161-250
Unsuitable for drinking	>250

Results and Discussion

Temporal Variations of Physicochemical Parameters

The physicochemical parameters of Daecheong reservoirs varied temporarily (Table 2). The concentrations of total phosphorus (TP) was highest in the summer season

Table 2: Variation of water quality parameters on the basis of season in Daecheong reservoirs

Water quality parameters	*Spring (Mean±SD) (Min-Max)*	*Summer (Mean±SD) (Min-Max)*	*Autumn (Mean±SD) (Min-Max)*	*Winter (Mean±SD) (Min-Max)*
TP (μgL^{-1})	16±1 (2-58)	36±2 (4-254)	30±1 (4-105)	15±1 (1-177)
TN (mgL^{-1})	2±0.03 (1-5)	2±0.02 (1-4)	2±0.02 (1-4)	2±0.02 (1-3)
BOD (mgL^{-1})	1±0.01 (1-2)	1±0.02 (0.4-3)	1.2±0.01 (1-3)	1.2±0.01 (1-3)
COD (mgL^{-1})	3±0.02 (1-4)	3±0.03 (2-7)	3±0.03 (2-7)	3±0.03 (1-5)
TSS (mgL^{-1})	2±0.09 (0.3-17)	6±0.09 (0.3-99)	4±0.1 (1-26)	2±0.06 (1-6)
CHL (μgL^{-1})	5±0.3 (0.1-78)	10±0.55 (0.2-100)	13±0.4 (1-50)	5±0.1 (1-21)
EC (μScm^{-1})	152±2 (84-318)	143±2 (67-307)	129±2 (48-198)	139±2 (1-293)
DO (mgL^{-1})	12±0.07 (6-12)	7±0.8 (2-14)	7±0.01 (2-18)	11±0.1 (8-18)
pH	8±0.01 (7-9)	8±0.02 (7-10)	8±0.02 (6-10)	8±0.02 (6-9)

(36±2 μgL^{-1}) while it was lowest in the winter season (15±1 μgL^{-1}). Summer monsoon directly influences the concentrations of total phosphorus in the reservoirs which concurred with some previous studies (Mamun and An, 2017). Mean values of total nitrogen (TN), chemical oxygen demand (COD) and hydrogen ion concentration (pH) did not show any kind of significant changes in the reservoirs over the four seasons. The biological oxygen demand (BOD) concentrations was little bit higher in autumn (1.2±0.01 mgL^{-1}) and winter (1.2±0.01 mgL^{-1}) compared to spring (1±0.01 mgL^{-1}) and summer (1±0.02 mgL^{-1}) in the reservoir waterbody.

During the summer season (6±0.09 mgL^{-1}), values of TSS was highest in the reservoirs compared to spring (2±0.09 mgL^{-1}), autumn (4±0.1 mgL^{-1}) and winter (6±0.06 mgL^{-1}). These results agree well with the viewpoint of some earlier studies that summer monsoon greatly determined the concentrations of total suspended solids in the waterbody (An and Park, 2003). Mean values of chlorophyll (CHL) was highest in autumn season (13±0.4 μgL^{-1}) compared to summer (10±0.55 μgL^{-1}), spring (5±0.3 μgL^{-1}) and winter (5±0.1 μgL^{-1}). It indicates that summer TP regulates the chlorophyll growth in autumn due to excessive nutrient loading which happens in summer by intense rainfall and high run-off which was similar to some previous studies (An and Park, 2002; Mamun and An, 2017). While it was different in North America and showed that spring TP influences the chlorophyll growth of summer (Pothoven and Fahnenstiel, 2013). The concentrations of electrical conductivity (EC) and dissolved oxygen (DO) showed in highest concentrations during spring than summer, autumn and winter.

Overall, the present study concurred with Zhang et al. (2016) findings, who suggested that summer monsoon pattern was observed in Asian countries as in China and South Korea which is responsible to change of physicochemical water quality of the reservoirs.

Spatio-temporal Variations of Phosphorus and Chlorophyll

The concentrations of phosphorus and chlorophyll showed heterogeneities spatio-temporarily (Table 3). In site 1, during summer (52 μgL^{-1}) the mean values of total phosphorus concentrations were highest compared to spring (21 μgL^{-1}), autumn (34 μgL^{-1}) and winter (20 μgL^{-1}) due to intense rain and high run-off. The mean values of TP were highest in sites 4 and 6 during autumn season (26 μgL^{-1} and 27 μgL^{-1}, respectively) in comparison with spring (14 μgL^{-1}, 15 μgL^{-1}, respectively), summer (23 μgL^{-1}, 25 μgL^{-1}, respectively) and winter (16 μgL^{-1}, 14 μgL^{-1}, respectively), accordingly. A similar pattern was observed for the concentrations of chlorophyll during the autumn season for sites 4 and 6. It indicated that autumn TP highly influences the autumn chlorophyll in site 4 and site 6. These sites (sites 4 and 6) are important among other sites as they are being used as drinking water resources for the two megacities (Daejeon and Cheonju). The present study indicated that the concentration of TP and CHL varied spatially and temporarily in the reservoirs which were similar to some previous studies (Mamun and An, 2017; An and Park, 2003, Kim et al., 2001).

Calculation of Water Quality Index (WQI)

The Water Quality Index (WQI) for the Daecheon reservoirs was calculated by arithmetic index equations specified previously (Horton, 1965; Brown et al., 1970). The detailed calculation has been presented in Table 4, which shows the monitored values (Mv) of nine selected physicochemical parameters, standard drinking water values (Sv) according to World Health

Table 3: Spatio-temporal variation of phosphorus and chlorophyll in Daecheong reservoir

Sites	*Spring*		*Summer*		*Autumn*		*Winter*	
	TP (μgL^{-1}) Mean: (Min-Max)	*CHL (μgL^{-1}) Mean: (Min-Max)*	*TP (μgL^{-1}) Mean: (Min-Max)*	*CHL (μgL^{-1}) Mean: (Min-Max)*	*TP (μgL^{-1}) Mean: (Min-Max)*	*CHL (μgL^{-1}) Mean: (Min-Max)*	*TP (μgL^{-1}) Mean: (Min-Max)*	*CHL (μgL^{-1}) Mean: (Min-Max)*
S1	21	9	52	14	34	15	20	6
	(5-58)	(0.1-78)	(13-254)	(2-37)	(11-105)	(2-50)	(5-177)	(1-17)
S2	18	5	51	14	33	13	16	4
	(4-58)	(0.3-28)	(9-217)	(1-67)	(11-86)	(2-42)	(5-78)	(1-11)
S3	17	5	41	11	32	12	14	4
	(6-55)	(0.3-28)	(6-180)	(1-100)	(10-85)	(1-36)	(1-50)	(1-13)
S4	14	4	23	9	26	13	16	5
	(4-30)	(0.3-13)	(6-109)	(1-27)	(4-55)	(2-38)	(5-76)	(1-15)
S5	11	4	22	5	29	9	12	4
	(2-40)	(0.3-22)	(4-79)	(0.2-37)	(5-101)	(1-28)	(5-38)	(1-17)
S6	15	4	25	9	27	15	14	5
	(4-43)	(0.6-23)	(7-69)	(0.4-87)	(12-62)	(3-48)	(4-47)	(0.6-21)

Table 4: Calculation of Water Quality Index (WQI) for Daecheong reservoirs with its status

Sampling sites	*Parameters*	*Standard value (Sv)*	*Ideal value (Iv)*	*Monitored value (Mv)*	*Sub-Index (Qi) of the parameters*	*Assigned weight (AW)*	*Relative weight (Rw)*	*SI = Rw × Qi*	*WQI =∑SI*	*WQI status*
S1	TP (µgL^{-1})	10	0	33.44	334.4	5	0.2	66.88	**129.44**	**Poor**
	TN (mgL^{-1})	1.5	0	1.92	128	4	0.16	20.48		
	BOD (mgL^{-1})	5	0	1.28	25.6	2	0.08	2.04		
	COD (mgL^{-1})	5	0	3.07	61.4	2	0.08	4.91		
	TSS (mgL^{-1})	5	0	5.26	105.2	3	0.12	12.62		
	CHL (µgL^{-1})	25	0	11.64	46.56	5	0.2	9.31		
	EC (µSCm^{-1})	250	0	147.74	59.09	2	0.08	4.72		
	DO (mgL^{-1})	5	14.6	9.46	53.54	1	0.04	2.14		
	pH	7.5	7	7.79	158	1	0.04	6.32		
S2	TP (µgL^{-1})	10	0	29.36	293.6	5	0.2	58.72	**116.06**	**Fair**
	TN (mgL^{-1})	1.5	0	1.91	127.33	4	0.16	20.37		
	BOD (mgL^{-1})	5	0	1.23	24.6	2	0.08	1.96		
	COD (mgL^{-1})	5	0	3.06	61.2	2	0.08	4.89		
	TSS (mgL^{-1})	5	0	4.2	84	3	0.12	10.08		
	CHL (µgL^{-1})	25	0	9.53	38.12	5	0.2	7.62		
	EC (µSCm^{-1})	250	0	148.29	59.316	2	0.08	4.74		
	DO (mgL^{-1})	5	14.6	8.9	59.375	1	0.04	2.375		
	pH	7.5	7	7.66	132	1	0.04	5.28		
S3	TP (µgL^{-1})	10	0	25.95	259.5	5	0.2	51.9	**103.51**	**Fair**
	TN (mgL^{-1})	1.5	0	1.79	119.33	4	0.16	19.09		
	BOD (mgL^{-1})	5	0	1.17	23.4	2	0.08	1.872		
	COD (mgL^{-1})	5	0	2.98	59.6	2	0.08	4.76		
	TSS (mgL^{-1})	5	0	3.15	63	3	0.12	7.56		
	CHL (µgL^{-1})	25	0	8.01	32.04	5	0.2	6.40		
	EC (µSCm^{-1})	250	0	143.6	57.44	2	0.08	4.59		
	DO (mgL^{-1})	5	14.6	8.93	59.06	1	0.04	2.36		
	pH	7.5	7	7.62	124	1	0.04	4.96		

(*Contd.*)

S4	TP (μgL^{-1})	10	0	19.45	194.5	5	0.2	38.9	**89.3**	**Fair**
	TN (mgL^{-1})	1.5	0	1.58	105.33	4	0.16	16.85		
	BOD (mgL^{-1})	5	0	1.03	20.6	2	0.08	1.64		
	COD (mgL^{-1})	5	0	3.46	69.2	2	0.08	5.53		
	TSS (mgL^{-1})	5	0	3.34	66.8	3	0.12	8.01		
	CHL (μgL^{-1})	25	0	7.63	30.52	5	0.2	6.10		
	EC (μSCm^{-1})	250	0	127.21	50.8	2	0.08	4.07		
	DO (mgL^{-1})	5	14.6	9.76	50.41	1	0.04	2.01		
	pH	7.5	7	7.77	154	1	0.04	6.16		
S5	TP (μgL^{-1})	10	0	18.66	186.6	5	0.2	37.32	**82.007**	**Fair**
	TN (mgL^{-1})	1.5	0	1.65	110	4	0.16	17.6		
	BOD (mgL^{-1})	5	0	1.03	20.6	2	0.08	1.64		
	COD (mgL^{-1})	5	0	2.8	56	2	0.08	4.48		
	TSS (mgL^{-1})	5	0	2.34	46.8	3	0.12	5.61		
	CHL (μgL^{-1})	25	0	5.3	21.2	5	0.2	4.24		
	EC (μSCm^{-1})	250	0	140.07	56.028	2	0.08	4.48		
	DO (mgL^{-1})	5	14.6	8.5	63.54	1	0.04	2.54		
	pH	7.5	7	7.51	102	1	0.04	4.08		
S6	TP (μgL^{-1})	10	0	20.22	202.2	5	0.2	40.44	**90.22**	**Fair**
	TN (mgL^{-1})	1.5	0	1.56	104	4	0.16	16.64		
	BOD (mgL^{-1})	5	0	1.17	23.4	2	0.08	1.87		
	COD (mgL^{-1})	5	0	3.04	60.8	2	0.08	4.86		
	TSS (mgL^{-1})	5	0	2.59	51.8	3	0.12	6.21		
	CHL (μgL^{-1})	25	0	8.03	32.12	5	0.2	6.42		
	EC (μSCm^{-1})	250	0	139.26	55.704	2	0.08	4.45		
	DO (mgL^{-1})	5	14.6	9.91	48.85	1	0.04	1.954		
	pH	7.5	7	7.92	184	1	0.04	7.36		

Organization (WHO 2011), Ministry of Land, Transport, and Maritime Affairs, Korea (MLTM, Korea 2012), European Economic Commission, Romania (ECE, Romania 2006), assigned weight (Aw) according to their significance in water quality and calculated the relative weight (Rw), sub-index of the parameters (Qi), sub-indices of water quality parameters (SI) and finally WQI and categorized their status. According to the WQI calculation, the highest WQI values were obtained from site 1 (129.44) and categorized as a poor water quality status and the remaining sites are in fair condition according to their WQI values (S2 - 116.06, S3 - 103.51, S4 - 89.3, S5 - 82.007 and S6 - 90.22, respectively).

Recommendations

As it was the first study for the development of the WQI Index of Daecheong reservoirs, so we recommend further studies on this reservoir; add some important water quality parameters and make a strategic plan to assess the physicochemical parameters.

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