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The Impact of Monsoon on Seasonal Variability of Basin Morphology and Hydrology

An, Kwang-Guk

(*Korea Research Institute of Chemical Technology, Daejeon 305-600, Korea*)

호수 지형 및 수리수문학적 변화에 대한 몬순 영향. 안광국 (한국화학연구소)

본 연구는 1993～1994년 대청호에서 호수 형태 및 수리수문학적 변동에 대한 몬순강도의 영향을 평가하였다. 연구기간 동안, 강우, 유입수 및 방류량과 같은 수리수문학적 변수들은 뚜렷한 연간 대조를 보였다. 계절별 강우에 따르면, 강우량의 큰 격차는 7～8월 장마기간에 일어났으며, 강으로부터의 유입량, 방류량 및 수체류 시간에 영향을 주었다. 1993년 총 유입량은 1994년에 비해 4배 이상을 넘었으며, 특히 1993년 하절기 유입량은 1994년 하절기에 비해 8배 이상을 상회하였다. 연평균 호수의 수체류 시간은 1993년, 1994년에 각각 93.2일, 158.6일로서 뚜렷한 대조를 보였으며, 장마기간에 가장 큰 차이를 보였다. 호수의 형태적 특성은 연간 대조적인 수리 수문학적 차이를 반영하여, 호수면적, 체적, 만 형성도, 및 평균수심은 1993년에 장마전 부터 장마후까지 계속적으로 증가한 반면, 1994년은 같은 기간에 대해 감소하였다. 이런 결과는 1993년 호수물의 얕은 연안대와의 접촉 면적이 1994년에 비해 증가하여 저질과 영양염류 교환의 증가를 가져왔다. 또한 대청호 수계면적과 호수면적의 비는 평균 해수면 80 m에서 60.7로서, 국내 인공호인 소양호 및 안동호에서의 값보다 2～3배 컸고, 자연호 보다는 10배 이상 컸다. 이런 호수 형태 및 수리 수문학적인 특성은 부영양화 현상을 조절하는 가장 중요한 인자중의 하나인 호수내 영양염류 농도에 영향을 주는 것으로 사료된다. 기존의 영양염류 부하량 모델은 계절적으로 안정된 유입량 및 수체류 시간하에서 적용될 수 있다고 가정하기 때문에, 하절기 변동이 극대화되는 우리나라 상황에서 호수 영양염류를 산정 예측할 때 Mass-Balance Model 이용은 신중을 기해야 된다고 사료된다.

Key words : Hydrology, Morphometry, Monsoon, Water residence time, Korea, Reservoir

INTRODUCTION

Limnological analyses of a reservoir often require a detailed knowledge of hydrology and morphometry (Wetzel and Likens, 1991). This is because reservoirs are morphologically complex systems along the longitudinal gradients from the headwaters to the dam (Lind *et al*., 1993) and have dynamic hydrological characteristics depending on river inflow, discharge volume and its depths (Thornton, 1990; Wetzel, 1990). One of the dominant processes influencing the basin morphology and hydrology is a rainfall event (Jones *et al*., 1997). In the North American and European waterbodies, large limnological variations occur mainly in spring and fall when major precipitation occurs, whereas in Asian waterbodies it is coincided with the summer monsoon period (Jones *et al*., 1997). These regional patterns are modified by the timing and magnitude of rainfall and inflow (Gopal and Wetzel, 1995; Tundisi *et al*., 1993).

Lohman *et al*. (1988) pointed out that lake volume changed by 6 times and hydraulic residence time was minimum during the monsoon. Such

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* Corresponding authors: Tel: 042) 860-7345, Fax: 042) 860-7399, E-mail: kgan@pado.krict.re.kr

conditions alter directly or indirectly physical, chemical and biological properties (Walker, 1982; Soballe *et al*., 1992) and determine the magnitude of their variabilities within and among reservoirs (Kimmel *et al*., 1990; Lind *et al*., 1993), indicating that the morpho−hydrodynamic condition may be a primary factor influencing the reservoir functions and processes. Until recently, most studies of reservoirs in Korea have been conducted in evaluating trophic dynamics, light regime, and compositions and productions of phyto−/or zooplankton, but basic studies on physical factors, sediments, and morpho−hydrological characteristics are rare (Kim and Hong, 1992). Little is known about how basin morphology varies seasonally and the morphology is associated with hydrological characteristics in Korean reservoirs. This paper evaluates seasonal fluctuations of morpho−hydrological parameters and describes their relations to an intensity of the monsoon in Taechung Reservoir during 1993 ∼ 1994.

MATERIALS AND METHODS

Reservoir description

Taechung Reservoir is located in the middle of South Korea (36° 50′N, 127° 50′E) and was formed in December 1980 by impounding the Keum River about 150 km upstream from its estuary. Major tributaries of the reservoir are Seowha Stream in the middle of the reservoir, and Bouchoung Stream, Soung Stream, and Youngdong Stream in the upper−end of the reservoir. About 40% of the total catchment area of 4,134 km^2 drains into the Seowha (4%), Bouchung (18%), Soung (16%), and Youngdong (2%) streams. The remaining 60% of the catchment area drains into the Kuem River, indicating that major source of water input is from the Keum River.

Morphometric parameters

In this reservoir, morphometric variables including reservoir surface area, volume, mean depth, shoreline length, and shoreline developmental ratio were calculated to compare seasonal patterns in response to precipitation and rainfall. Total surface area of the reservoir was calculated with each surface area at 5 m contour interval. The volume of the basin was calculated from the integral of the areas of each stratum at 5 m interval depths from the surface to the point of maximum depth. Mean depth was estimated as the volume divided by total surface area ($z = V/A_0$). Shoreline length (L) was determined by rotometer (Wetzel and Likens, 1991). Shoreline development ratios (D_L) were estimated as the ratio of the length of the shore line (L) to the circumference of a circle of area (Wetzel, 1983). Also, the surface area, volume, shoreline length, and mean depth in the mainstem sites and embayment sites [see the map (An, 2000)] were separately calculated.

Theoretical Water Residence Time (WRT in days) was calculated using lake surface area, volume and inflow on each sampling date and season in the reservoir (Knowlton and Jones, 1990). Rainfall and inflow data during 1981 ∼ 1994 were obtained from Taejon Meteorological Station and Taechung−Dam Management Office, respectively. To estimate WRT values, the movement of reservoir water was considered as a plug−flow along its main axis so that the WRT was based on the volume of water up−reservoir from a particular location and the sum of inflows over the preceding months. Therefore, WRT values would equal the length of pre−sampling time required for inflow to equal the volume up−reservoir from the sampling site (Knowlton and Jones, 1990). Also, water deficit was calculated as the difference between accumulated inflows and outflows. Herein, the terms of the premonsoon (January−June), monsoon (July−August), and postmonsoon (September−December) were used for describing temporal conditions of reservoir morphology and hydrology.

RESULTS AND DISCUSSION

Monsoon hydrology

Seasonal patterns of monsoon rainfall: Since construction of the dam in 1980, annual mean precipitation varied among years. Years of greatest rainfall were 1985, 1987, and 1993 in which the annual average was > 1,400 mm. Years of least rainfall were 1982, 1988, and 1994 in which the annual average was 800 mm (Fig. 1A). During 1981 ∼ 1994, more than half of the annual precipitation occurred during July−September (Fig. 2A). Winter was dry with precipitation accounting for 9% of the total annual during December through February. The seasonal patterns

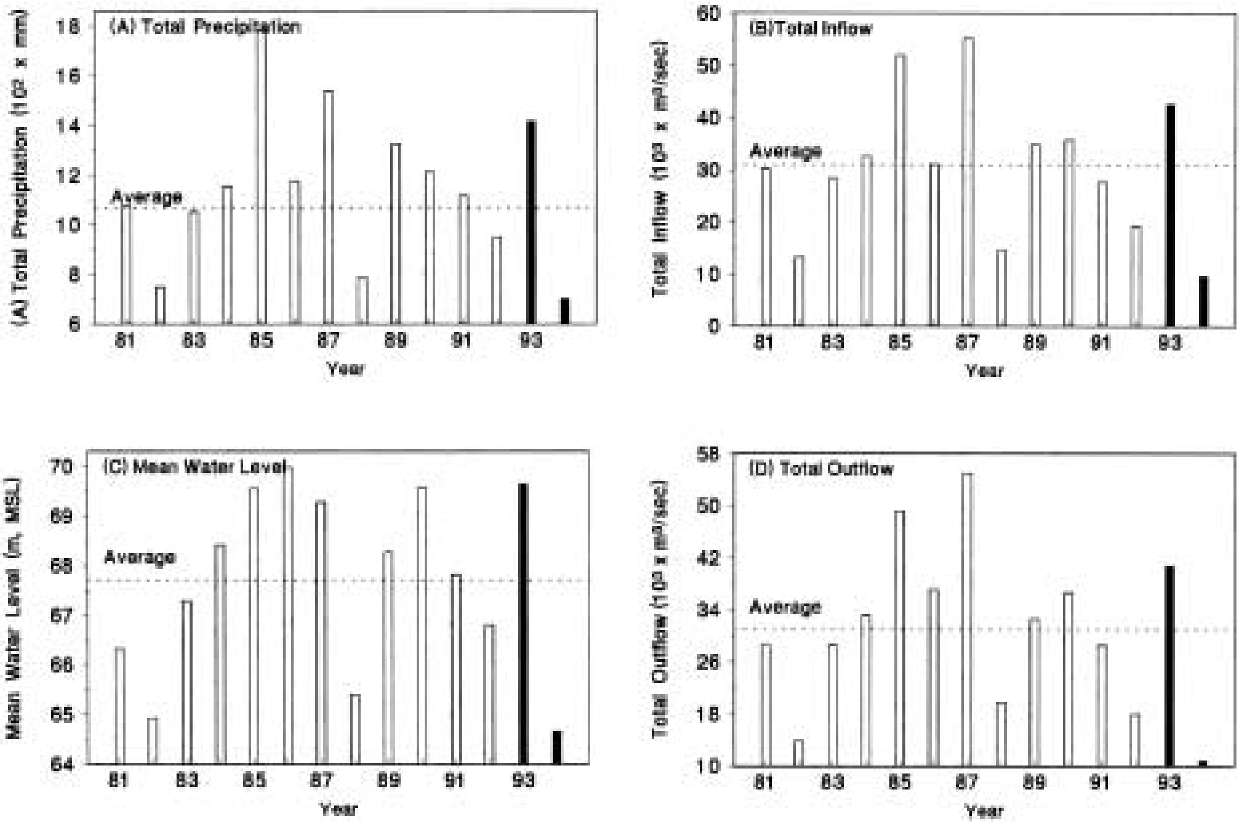

Fig. 1. Interannual variation in hydrology during 1981～1994. Dotted horizontal line indicates an average value in each hydrological variable during 1981～1994. The shaded bar indicates data in 1993 and 1994.

differ with those in North American and European temperate regions where rainfall occurs mainly in spring and fall and most limnological paradigms were developed (Jones *et al*., 1997).

The major difference in rainfall between the two years of study occurred during the July～August monsoon (Fig. 2A). Total precipitation during monsoon 1993 was 660 mm which comprised 43% of total annual precipitation, but during monsoon 1994 it was only 251 mm. In 1993 rainfall during July～August was 164% larger than the mean value during 1981～1992, whereas rainfall in 1994 was 50% less than the mean (Fig. 2A). Precipitation was similar during the remaining periods of these two years (Fig. 2A). The intense distribution of monsoon rainfall during the short period is similar to other Asian regions but differs with North American and European regions (Jones *et al*., 1997)

Response of water level to the precipitation: Mean monthly lake stage during 1981～1992 showed a typical pattern with the highest level in September, immediately after the summer monsoon, and lowest in June before the monsoon (Fig. 2C). In 1993 the mean level was significantly ($p < 0.001$) greater than the average during 1981～1992, but the seasonal pattern was similar to that of the 12-year average. In 1994 levels were similar to the 12-year average during January-June but were markedly low (i.e., MSL $<$ 65 m) during July-December.

Major River inflow and discharge: Major sources of water to Taechung Reservoir are inflows from the parent river and direct precipitation onto the reservoir. During 1981～1992 major inflows occurred during the July～August monsoon (Fig. 2B) and accounted for 64% of total annual inflow. Peaks in inflow and outflow coincided with rainfall during the monsoon (Fig. 2B, D). In 1993, daily inflow ranged from 7.9×10^5 m^3 on May 27 to 3.1×10^8 m^3 on 13 July. This inflow equaled $<$ 1% and 43%, respectively, of the average volume of Taechung Reservoir in 1993. Inflow in 1993 and 1994 was 138% and 31%,

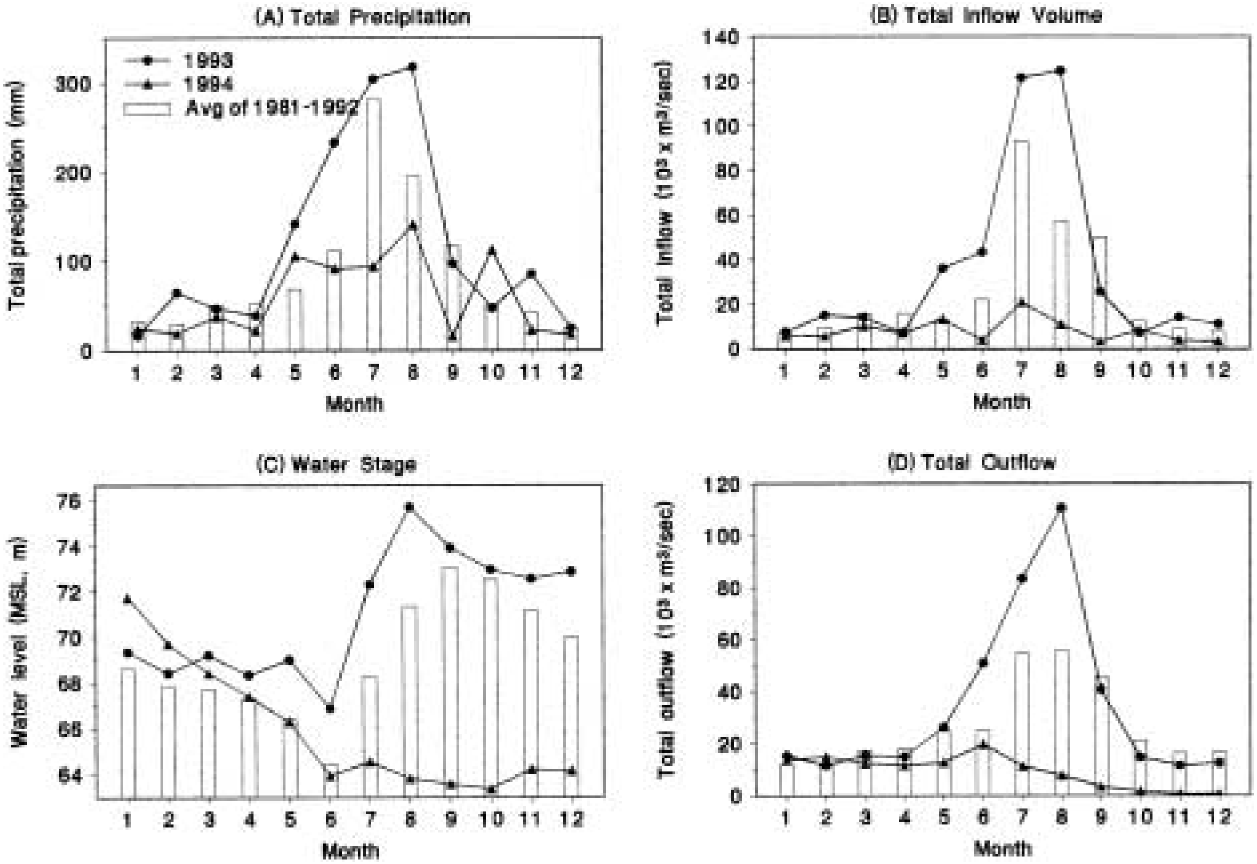

Fig. 2. Comparison of monthly change of hydrological variables among data in 1993, 1994, and the average of 1981～1992.

respectively, of average inflow during 1981～1992 (Fig. 2B).

Total inflow in 1993 was four times greater than that of 1994 (0.83×10^9 m^3), and summer inflow in 1993 was 8 times greater than summer 1994 (Fig. 2B). These differences produced distinct interannual variation in water balance (Fig. 3); there was a marked increase (positive value) in storage volume after mid–July 1993, and a consistent deficit (accumulated inflows–outflows) in 1994 by discharge at the dam. Based on the water deficit, the entire reservoir volume was replaced 3 times during June～August by river water, whereas it was replaced only once during the entire year in 1994 due to low rainfall.

Fluctuations of theoretical water residence time: The seasonal pattern of water residence time (WRT) was similar between 1993 and 1994, but mean WRT in 1993 was shorter than in 1994 (Fig. 4); Annual average WRT in 1993 was 93.2 d (median mean = 92 d) and daily WRT values varied from 7 d to 177 d, while in 1994 annual average was 158.6 d (median mean = 165 d) and daily WRT ranged between 107 d and 200 d (Fig. 4). The mean WRT in 1994 was similar to the value (171.6 d) from a previous stu-dy of Taechung Reservoir (Kim and Hong, 1992), but the mean in 1993 was > 70 d shorter. This result indicates that annual mean of WRT within the reservoir varies interannually depending upon the rainfall and inflow. The difference in WRT between the two years was maximized in summer monsoon and minimized during January～April (Fig. 4). Thus, mean WRT during the 1994 monsoon was > 70 d longer than during monsoon 1993, and the longest WRT (> 180 d) occurred during minimum rainfall in 1994. This outcome suggests that the intensity of the monsoon during the short periods (July～August) mainly determined annual WRT in this reservoir. Therefore, the use of single annual mean WRT for lake conditions may not be appropriate because of the dramatic monsoon fluctuations in hydrology. Nutrient loading models have used the WRT as a one of the impor-

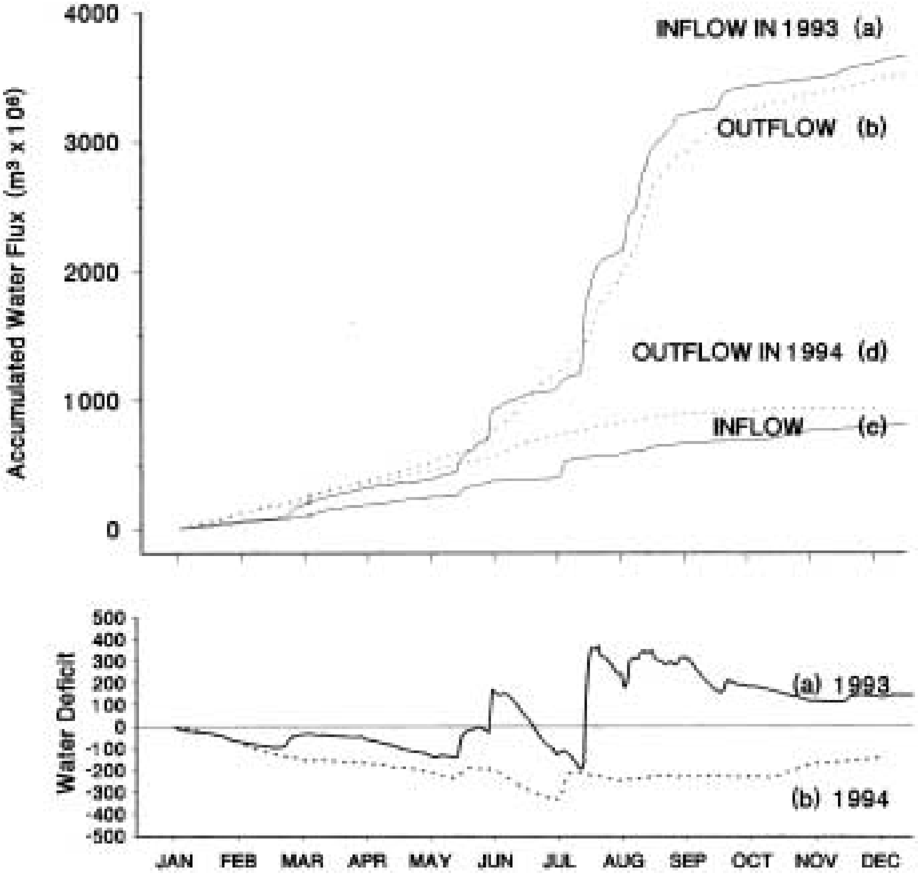

Fig. 3. Water balance budgets based on inflows and outflows and its deficit (accumulated inflow−accumulated outflow) in 1993 and 1994.

tant parameters in diagnosing reser-voir trophic state and suggest inverse relations of WRT to nutrient loads (OECD, 1982). Studies of lakes and reservoirs (Vollenweider 1968, 1976, 1990) demonstrated that such models can be applied in the steady state of hydrology in lake−reservoir systems. These findings suggest that simple applications of the mass balance models to waterbodies influenced dramatically by the Asian monsoon may not be appropriate due to the large monsoon fluctuations.

Reservoir basin morphometry

Total surface area and volume of reservoir were calculated by summation of each volume and area between 22 adjacent sections, respectively (Table 2). At an elevation of 80 m MSL (Mean Sea Level), the reservoir has a surface area (L) of 6.8×10^7 m^2, a volume (V) of 14.3×10^8 m^3, with a mean depth (z) of 21.2 m and maximum depth of 69m, and the drainage area (D) was 41×10^8 m^2 (Table 1). The D/L ratio, as a relative indicator of nutrient loading (Fee, 1979), is 60.7 and shoreline development ratio is 15.1 at 80 m MSL (Table 1). The D/L ratio in this reservoir is greater than Soyang (39.6) and Andong reservoirs (30.8), whereas it is much less than Paldang (527), Uiam (470), and Cheongpyeong (598) and Chuncheon (339) reservoirs. Also, the D/L ratio was much greater than the natural lakes such as Lake Biwa (4.7), Michigan (2.0), and Ontario (4.0; Kim and Hong, 1992). These comparisons suggest that D/L ratios in artificial reservoirs are much greater than those in natural lakes and match with nutrient loading from literature (Lind *et al.*, 1993).

Mean depth decreases from the dam to the headwaters due to inverse in the ratio of the surface area (L) : lake volume (V). During the study mean depth ranged from < 5 m in the headwaters to > 45 m near the dam with a sharp change at 20 ∼ 25 km upreservoir from the dam. About 68% of the reservoir mean volume and 61% of the surface area lies within a distance of 14 km from the dam. The mean depth of the reservoir within this zone was 23.4 m, indicating a typical deep lacustrine condition, while it was 16.5 m from 14 km to up−reservoir, indicating a shallow riverine reach which is directly affected by external input of

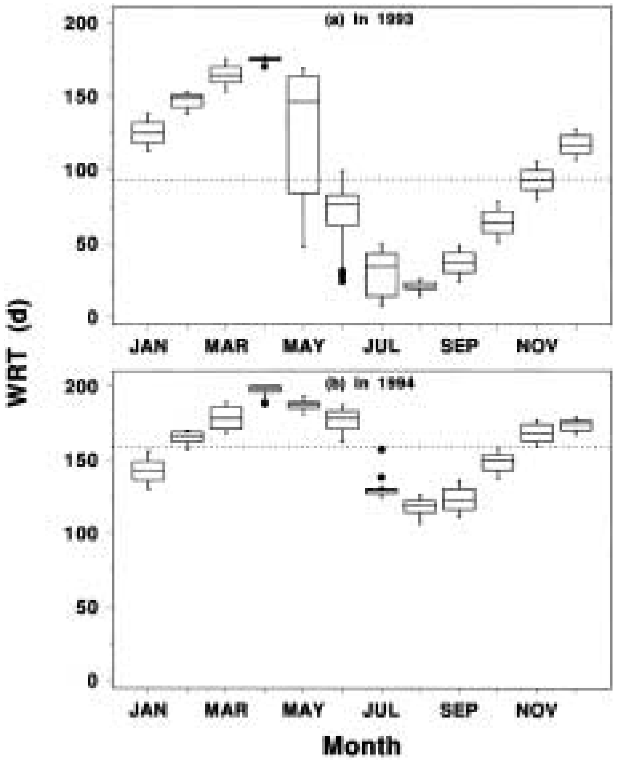

Fig. 4. Theroretical water residence time (WRT) in 1993 and 1994. Each data point averaged daily data in each month.

Table. 1. Morphometrical characteristics of Taechung Reservoir and their changes in 1993, 1994, and at 80 m MSL (Mean Sea Level) that indicates maximum level for water storage against flood damage.

Parameter	1993	1994	80 m (MSL)
Mean water level	69.6	64.7	80.0
Drainage area (D, 10^8 m^2)	41.3	41.3	41.3
Surface area (L, 10^7 m^2)	5.1	4.3	6.8
Total volume (V, 10^8 m^3)	7.1	4.5	14.3
Shoreline length (10^5 m)	1.4	1.1	4.4
Shoreline development ratio	5.5	5.1	15.1
Mean depth (m)	13.8	10.4	21.2
Maximum depth (m)	58.6	53.6	69.0
Drainage area: Surface area (D/L Ratio)	80.9	96.0	60.7
Drainage area: Volume ratio (D/V, m^{-1})	5.8	9.3	2.9
Surface area: Shoreline ratio (m)	365	364	154

Table 2. Reservoir volume, surface area, and shoreline length in each adjacent section. The characters of "M" and "E" indicate the mainstem sites (sites 1, 3, 4, 7, 8, 10, 14, 15 and 16) and embayment sites (sites 2, 5, 6, 9, 11, 12, 13, and 17) in the reservoir, respectively. The reservoir was divided into 22 sections ("a" to "v") as follows. The sectional map of Taechung Reservoir is available in An (2000).

Location	Sampling site	Section #	Surface area (10^5 m^2)	Volume (10^6 m^3)	Shorline develop. ratio	Mean depth (m)
M	1	(a+b)	62.8	83.3	5.60	13.2
E	2	c	14.8	13.0	2.71	8.8
M	3	d	25.5	42.2	3.53	16.5
M	4	e	32.2	56.9	4.06	17.7
E	5	f	31.1	39.5	5.51	12.7
E	6	h	7.9	10.5	2.75	13.2
M	7	(g+i)	43.7	101.3	4.70	23.2
M	8	j	19.1	50.9	4.63	26.7
E	9	k	29.4	50.8	4.29	17.3
M	10	l	59.7	158.9	4.59	26.6
E	11	m	19.5	34.2	3.41	17.6
E	12	(n+o)	82.3	135.8	4.14	16.5
E	13	p	20.2	45.5	2.36	22.5
M	14	q	55.5	168.5	3.14	30.4
M	15	r	48.0	154.7	2.64	32.2
E	·	s	17.5	31.4	4.88	18.0
E	·	t	32.6	66.0	3.35	20.2
M	16	u	30.1	99.3	2.22	33.0
E	17	v	43.7	74.6	3.25	17.1

Table. 3. Comparison of lake surface area, total volume, shoreline development ratios (Shoreline L.) and the mean depth with seasons and years in mainstem sites (sites 1, 3, 4, 7, 8, 10, 14, 15 and 16) and embayment sites (sites 2, 5, 6, 9, 11, 12, 13, and 17) of the reservoir.

Location	Year	Season	Surface area (10^6 m^2)	Total Vol. (10^7 m^2)	Shoreline L. (10^4 m)	Mean depth (m)
Mainstem sites	1993	Premonsoon	29.8	57.6	21.0	18.4
		Monsoon	33.2	68.4	22.9	20.3
		Postmonsoon	33.8	71.6	23.2	20.9
		Premonsoon	29.3	50.9	20.7	16.6
		Monsoon	26.4	41.0	19.0	14.3
		Postmonsoon	25.8	39.7	18.7	14.1
Embayment sites	1994	Premonsoon	18.7	20.8	15.7	10.6
		Monsoon	5.4	14.7	13.1	9.0
		Postmonsoon	14.9	14.0	12.7	8.8
		Premonsoon	19.4	22.5	16.2	11.2
		Monsoon	23.7	32.7	19.6	13.4
		Postmonsoon	24.5	35.0	20.2	13.9

nutrients and sediments (Kimmel *et al*., 1990).

Reservoir morphology differed between 1993 and 1994 in response to rainfall (Table 3). Morphometric variables such as surface area, total volume, shoreline, and mean depth in 1993 increased consistently from premonsoon to postmonsoon and over this same period in 1994 they decreased (Table 3). Shoreline lengths, surface area and volume were a function of water elevation; maximum in postmonsoon 1993 when water level was highest and minimum in postmonsoon 1994 when it was lowest. As water levels declined after summer 1994, surface area of the embayments in the headwaters greatly decreased (Table 3). Surface area of the entire reservoir in 1994 was 16% less than in 1993, and the total volume in 1994 was smaller by 37% (Table 1). The mean volume in the mainstem area in 1993 and 1994 was 6.58×10^8 m^3 and 4.38×10^8 m^3, respectively while the volume in the embayments was 3.0×10^8 m^3 and 1.6×10^8 m^3, respectively. Thus, water volume in the embayments in 1994 was only 27% of the total volume, whereas in 1993 46% of the total volume was in embayments (Table 3). Shoreline development ratio, mean depth, maximum depth and shoreline length in 1994 also decreased compared to 1993 (Table 1). Under the circumstances, the area of littoral zones having active nutrient exchages decreases, thereby declining overall in-lake nutrient concentration (Wetzel, 1983). An (2000), in the study of Taechung Reservoir, found that total phosphorus in 1994 was much less than in 1993, dissolved-P proportion of TP in 1994 was >10% greater than that of 1993, and particulate P proportion in 1994 was less (An, 2000). These outcomes suggest that distinct interannual differences of the morphological variables in Taechung Reservoir influenced annual budgets of in-lake phosphorus as well as relative proportion of nutrients, thereby influenced overall eutrophication process of the reservoir.

ABSTRACT

This paper demonstrates the influence of intensity of the monsoon on morpho-hydrological fluctuations in Taechung Reservoir during 1993～1994. During the study, hydrological variables including rainfall, inflow, and discharge volume showed distinct contrast between 1993 and 1994. Interannaul differences in rainfall occurred during the monsoon in July～August monsoon and influenced inflow, discharge, and water residence time (WRT). Total inflow in 1993 was four times greater than that of 1994, and summer inflow in 1993 was 8 times greater than summer 1994. Annual Mean WRT was 93.2 d in 1993 vs. 158.6 d in 1994 and the largest differences occurred between monsoons of 1993 and 1994. Morphometric variables reflected the interannual contrasts of hydrology, so that in 1993 surface area, total volume, shoreline development, and mean depth increased consistently from premonsoon to postmonsoon and over this same period in 1994 they decreased. This outcome indicates that the

area of shallow littoral zones in 1993 was greater than in 1994. Also, the drainage area to surface area (D/L) at 80 m MSL was 60.7 which was much greater than values in Soyang and Andong reservoirs and natural lakes world−wide. The morpho−hydrodynamic conditions seemed to influence in−reservoir nutrient concentration which is one of the most important factors regulating the eutrophication processes. I believe, under the maximum hydrodynamic fluctuations in Korean waterbodies during the monsoon, applications of mass balance models to man−made lakes for assessments of external loading should be considered because the models can be used under the seasonally stable inflow and water residence time.

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