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Dynamic Changes of Dissolved Oxygen during Summer Monsoon

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하절기 장마동안 용존산소의 역동적 변화. 안광국 (한국 화학연구소)

본 연구는 1993년부터 1994년까지 대청호의 17개 지점에서 계절적 산소농도 및 심층 산소 결핍율을 조사하였다. 1993년 본류로부터의 유입수는 7～8월의 장마철에 최대를 보였으며, 이는 상류의 수온 성층 및 무산소층을 파괴하여, 심층 무산소대는 호수 중 하류역에 제한되었다. 이 기간동안 무산소층은 호수전체 부피의 10% 이하에 불과하였다. 반면, 1994년 하절기에 무산소층은 호수 전역에 걸쳐 분포하였고, 산소포화도는 30% 이하를 유지하였으며, 무산소대의 체적은 수체 총부피의 85%를 차지하였다. 호수내 산소의 급격한 감소는 냉수성 어종(빙어)의 대량폐사를 야기시켰다. 하절기동안 상대적 산소결핍도(Relative Areal Oxygen Deficit, RAOD)는 1993년에 -0.024 mg O_2 cm^{-2} d^{-1}로 산소함량이 증가한 반면, 1994년에는 0.080 mg O_2 cm^{-2} d^{-1}로서 산소의 빠른 감소율을 보였다. 계산된 무산소도(Anoxic Factor, AF)는 RAOD와 동일 페턴을 보였으며, 1993보다 1994년에 50 d 이상 증가를 보였다. 수심별 평균 여름 산소농도의 계산에 따르면, 1993년의 경우 대부분 지점에서 강(River)의 특성(6～11 mg/l DO) 을 보인 반면, 1994에는 수체 전역에서 전형적인 호수 특성(＜4 mg/l DO)을 보였다. 유입량에 대한 용존산소의 회기분석에 따르면, 산소 변화는 장마철 유입량의 크기에 의해 결정되었다($R^2 = 0.99$). 이런 결과는 대청호에서 하절기 용존산소를 조절하는 1차적 요인이 하절기 강우의 강도라는 사실을 제시한다.

Key words : Monsoon, Oxygen, Hypoxia, Anoxia, Reservoir, Korea

INTRODUCTION

Lake eutrophication and trophic state have frequently been evaluated by dissolved oxygen content (Walker, 1979; Chapra and Dobson, 1981; Nurnberg, 1996). Loss of dissolved oxygen (DO) is an important measure of water-quality degradation due to the relationship between O_2 concentration and biological stress and because O_2 levels control chemical oxidation/reduction reactions in aquatic ecosystem (Molot *et al.*, 1992). Oxygen depletions or deficit rates in lentic systems have been expressed hypolimnetic oxygen deficit (HOD, mg DO m^{-3} of hypolimnetic volume d^{-1}), areal hypolimnetic oxygen deficit (AHOD, DO m^{-2} of hypolimnetic area d^{-1}; Hutchinson, 1957) or anoxic factor (AF, days per year or per season; Nurnberg, 1996) and were predicted by phosphorus loading, chlorophyll, or primary production (Vollenweider and Janus, 1982; OECD, 1982; Reckhow, 1988).

Reservoir studies (Haberle, 1981; Lind, 1987; Knowlton and Jones, 1989; Molot *et al.*, 1992) have suggested that oxygen content vary spatially (vertical, horoizontal, and longitudinal heterogeneity) and temporally (seasonal and interannual heterogeneity) in response to flow regime. Recently, anoxia models of reservoirs in North America (Cole and Hannan, 1990) demonstrated

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that hypolimnetic anoxia is greater in high flow years than in low-flow years, and the anoxic zone develops downreservoir faster during a year of high spring and summer rain than during either a normal or drought. Such patterns may differ in reservoirs influenced by the Asian summer monsoon due to seasonal differences in major rainfall distribution (spring and fall in non-monsoon regions vs. summer in monsoon-regions). Surprisingly, little is known about how monsoon flow and precipitation influence oxygen concentrations and depletion rates in a morphologically complex reservoir. This paper presents dynamic variation of anoxia in relation to the intensity of the monsoon and the longitudinal gradients in Taechung Reservoir during 1993～1994.

MATERIALS AND METHODS

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. In this reservoir, water temperature and dissolved oxygen concentration (YSI O-Model 51B meter) were measured twice a month from 17 sites [site 1 in the headwater to site 17 near the dam; see An (2000)] during 1993～1994. Concentration of total phosphorus (TP) was measured using the ascorbic acid method after persulfate oxidation (Prepas and Rigler, 1982). Chloro-phyll-*a* (Chl) concentration was measured by using a spectrophotometer (Bechman Model DU -65) after extraction in hot ethanol (Sartory and Grobbelaar, 1984). Analyses of TP were performed in triplicate and Chl was measured in duplicate.

The relative areal oxygen deficit (RAOD) was calculated as the oxygen concentration per square meter of hypolimnetic area per days during summer period (/or stratification period; Hutchinson, 1957). Anoxic Factor (AF) was calculated as a duration of anoxia multiply by anoxic sediment area) per lake-surface area (Nurnberg 1995).

In this study the headwater, middle, and downlake zone typically indicate sites 1～4, 5～9, and 10～17, respectively. I used the terms of riverine, transition, and lacustrine to represent the functional zones, based on theoretical water residence time, total phosphorus, and non-volatile suspended solids within the reservoir (see An and Jones, 2000a). Also, I used the terms of the premonsoon (January～June), monsoon (July～August), and postmonsoon (September～December) in describing temporal conditions of dissolved oxygen. During the study, monsooon hydrology including rainfall, inflow and outflow is available in An and Jones (2000b).

RESULTS AND DISCUSSION

During the study, surface DO averaged 9.2 mg/l and varied from 6.7 to 12.8 mg/l (Fig. 1). The annual average did not differ between the two years, but during monsoon (July～August) mean DO concentration in the epilimnion was significantly greater ($p < 0.01$) in 1993 (9.6 mg/l) than 1994 (7.9 mg/l). This difference appeared to reflect differences in flow regime, water residence time, and rainfall between the two monsoons.

Subsurface depletion of DO began in the headwaters in both years and eventually descended downlake. In premonsoon 1993, dissolved oxygen declined with depth more rapidly in the headwaters (surface to bottom range: 3.5～10 mg/l) than downlake (surface to bottom range: 6～10 mg/l, Fig. 1 (I), (II)). This pattern was similar during premonsoon 1994 (Fig. 1 (III), (IV)). In both years, oxygen depletion started to develop within the hypolimnion of the headwaters (location 49 km) and expanded vertically up through the water column and downlake (Fig. 1). The initial depletion in the headwaters was probably due to a combined effect of warmer hypolimnetic temperatures (>5～10°C), greater carbon loading (algal chlorophyll-*a* range = 9～31 μg/l), and smaller hypolimnetic volume compared to downlake (Temp. = 4～7°C; chlorophyll-*a* = 1～5 μg/l).

The contrasting interannual flow pattern during monsoon, however, modified the pattern of anoxic development. During monsoon 1993, vertical dissolved oxygen was homogeneous (>8 mg/l) in the headwaters (Fig. 1 (I)) as a result of the large inflow and uniform mixing, but metalimnetic oxygen minima (near 10 m) occurred downlake due to an interflow current. In contrast, during monsoon 1994 oxygen declined sharply with depth in the headwaters and rapid anoxia (<4.0 mg/l) developed in meta-hypolimnions of the entire reservoir (8 m-bottom, Fig. 1 (III)). The rapid anoxia in the 1994 monsoon was attributed to high autochthonous organic content and decreased turbulent mixing result-

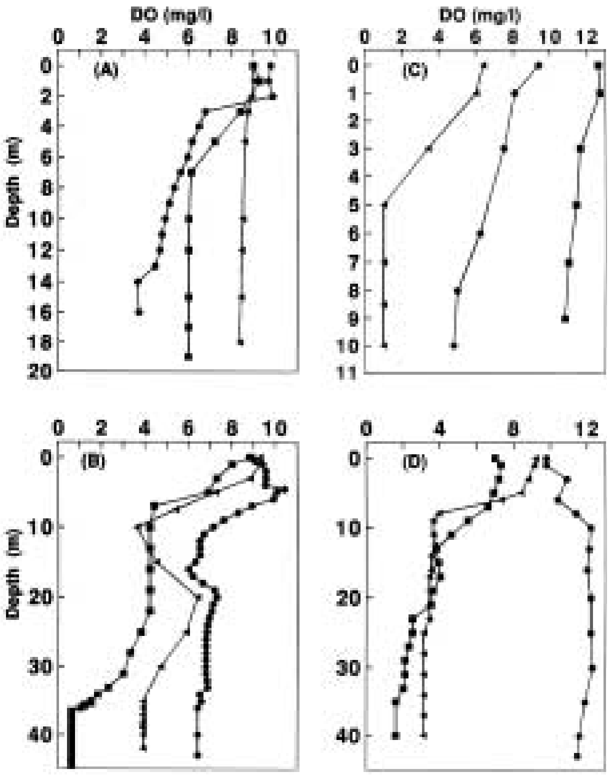


Fig. 1. Profiles of dissolved oxygen with seasons and zones of the reservoir in 1993 and 1994. (I): Headwater zone (Site 1) in 1993, (II): Downlake zone (Site 16) in 1993, (III): Headwater zone (Site 1) in 1994, (IV): Downlake zone (Site 16) in 1994. In the figure, dark circles, triangles, and squares indicate premonsoon (22 May in 1993; 16 May in 1994), monsoon (17 July in 1993; 26 July in 1994), and postmonsoon (16 September in 1993; 30 September in 1994), respectively.

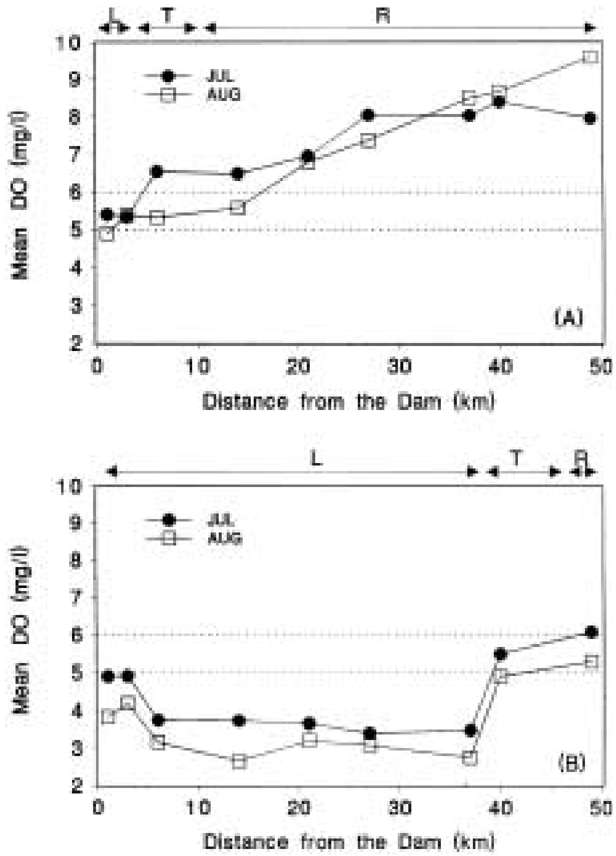


Fig. 2. Patterns of longitudinal zonation based on summer mean of vertical DO concentrations (mean DO per meter from the surface to bottom) during monsoon 1993 (A) and summer 1994 (B). Each data point indicates an average of vertical DO in the mainstem sites; the oxygen was the average of 2 m interval data in the headwaters (location 37～50 km, shallow area) and was the averaged 5 m interval data in the remaining sites (location 0～35 km, deep area). Capital characters of R, T, L indicate the riverine, transition, and lacustrine zone, respectively. Two dot horizontal lines of 6 and 5 mg/l indicate the boundary of mean DO between the riverine and transition zone, respectively.

ing from reduced inflow.

Longitudinal zonation in DO differed between monsoon 1993 and 1994 because of seasonal differences in water residence time, inflow magnitude, and rainfall (see An and Jones, 2000). Mean DO of entire water column was calculated at each site and the riverine and lacustrine zones were defined as having 11～6 and $<$5 mg/l DO during summer, respectively (Cole and Hannan, 1990). As shown in Fig. 2, during monsoon 1993, the riverine zone was predominate in the entire reservoir except near the dam (location 0～10 km). In contrast, during monsoon 1994, mean DO at most sites was $<$4 mg/l and the lacustrine zone was predominant in the reach between 0 and 40 km. This longitudinal zonation of DO suggests that the zonal characteristics is determined by the magnitude of monsoon inflow flow.

During the study, hypoxia conditions varied dynamically with season in response to inflow. Herein, the definition of “hypoxia” as $<$4.0 mg/l DO followed the approach of Molot *et al.* (1992) for describing lake hypoxic conditions. As shown in Figs. 3 and 4, the boundaries and extent of the hypoxic zone were determined by flood events, density flow characteristics, and the time of

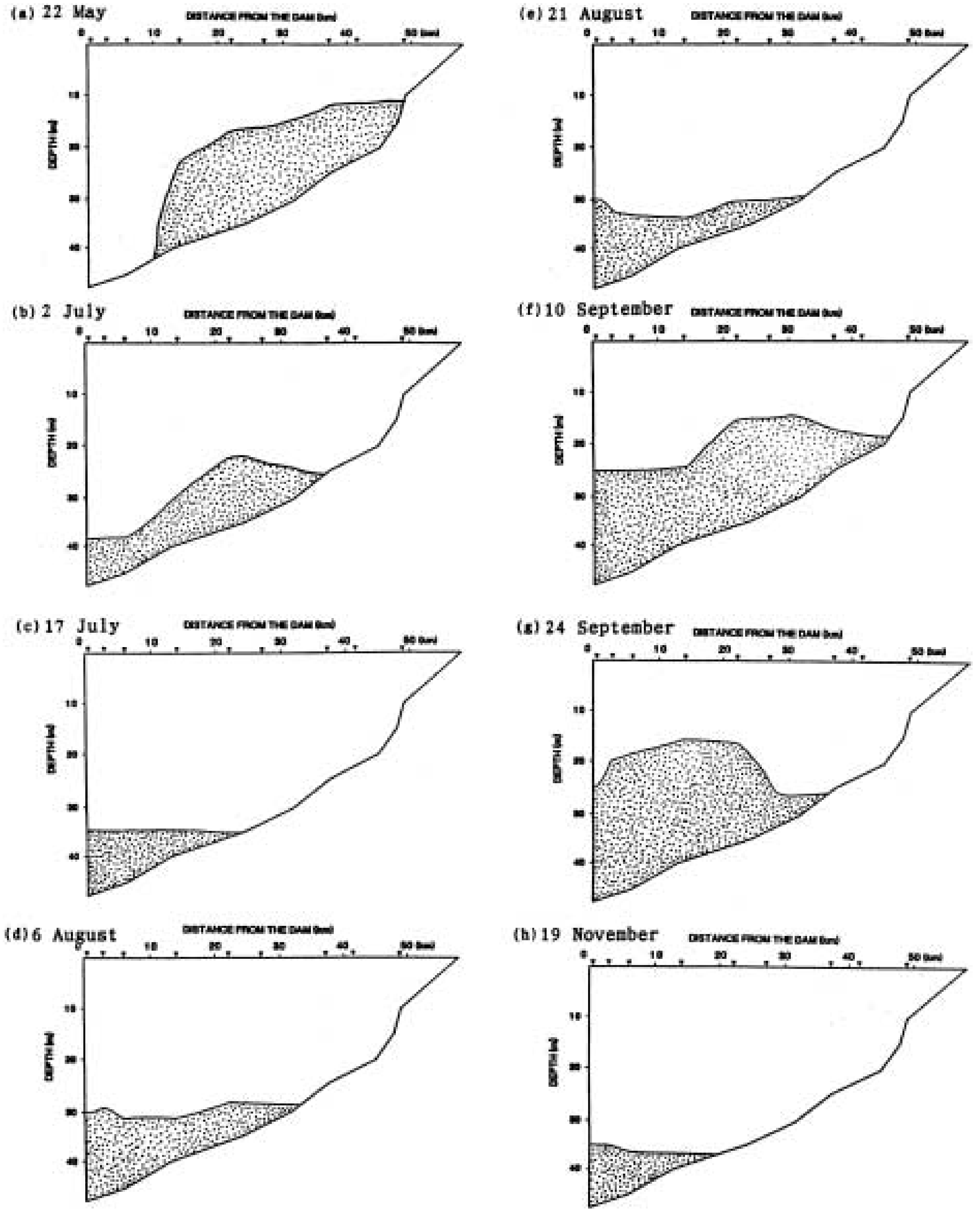


Fig. 3. Development of anoxia along the mainstem sites from the headwaters to the dam in 1993. (a): 22 May, (b): 2 July, (c): 17 July, (d): 6 August, (e): 21 August, (f): 10 September, (g): 24 September and (h) 19 November. The dotted area from the lake bottom indicate the hypoxic zone which was defined as dissolved oxygen of <4 mg/l after Molot *et al* (1992). The dark triangles indicate sampling locations of the reservoir.

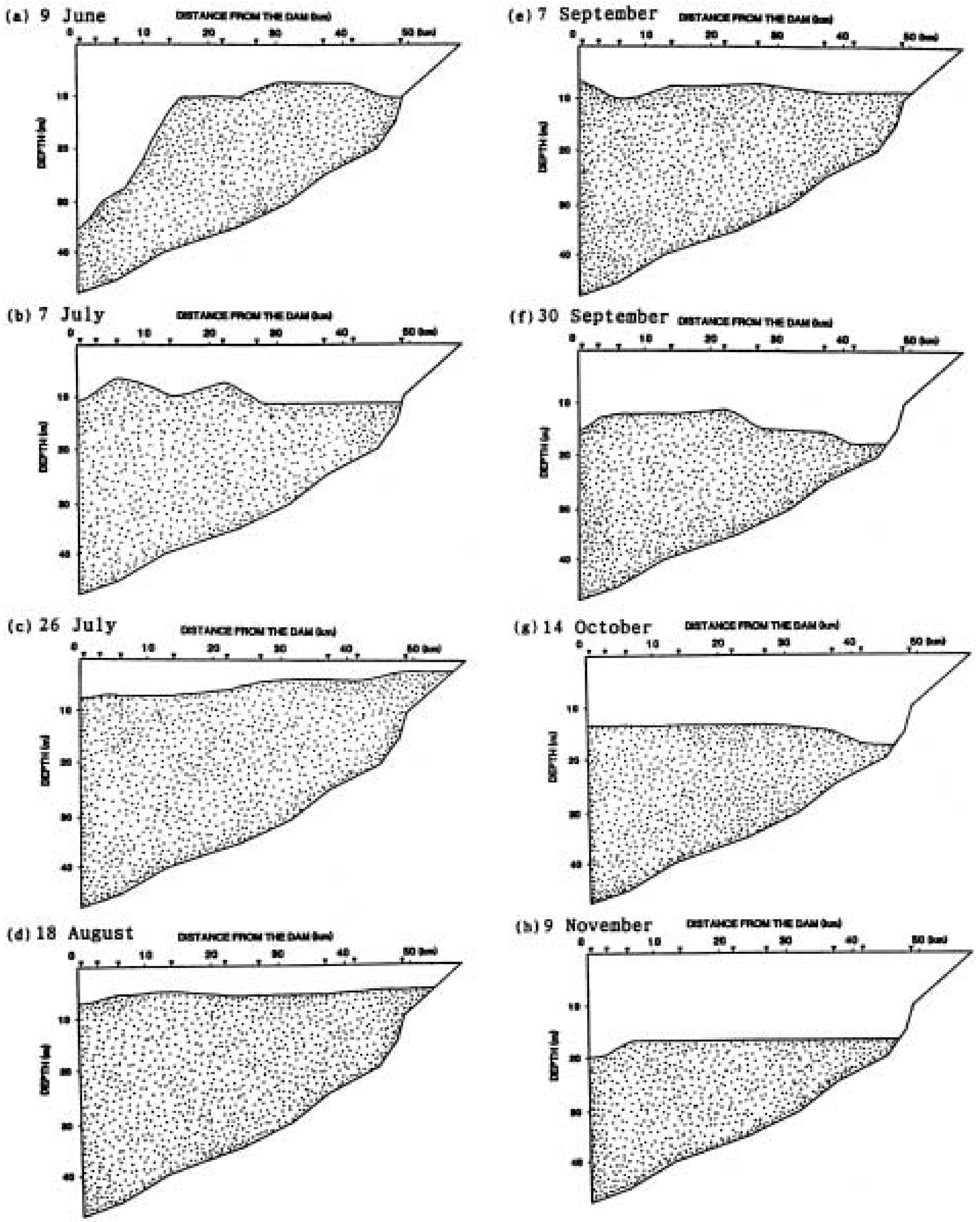


Fig. 4. Development of anoxia along the mainstem sites from the headwaters to the dam in 1994. (a): 9 June, (b): 7 July, (c): 26 July, (d): 18 August, (e): 7 September, (f): 30 September, (g): 14 October, and (h): 9 November. The area from the lake bottom represent the hypoxic zone which was defined as dissolved oxygen of < 4 mg/l.

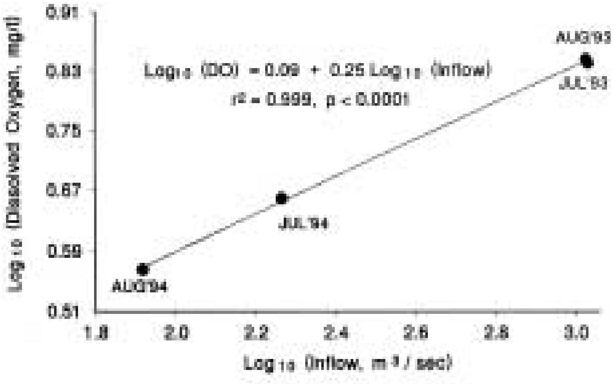
overturn.

Following the onset of thermal stratification in May 1993, hypolimnetic hypoxia developed from the headwaters to location 10 km near the dam (Fig. 3A). The anoxic layer was between 15 m and the bottom in the headwaters and from 23 m to the bottom downlake except near the dam site (Fig. 3A). The longitudinal progression of hypoxia observed is typical of many reservoirs (Wiedenfeld, 1980; Cole and Hannan, 1990).

During monsoon 1993, total volume of hypoxic water markedly decreased, compared to the premonsoon, due to large inflows. In early monsoon (1 July), density currents disrupted the hypolimnetic hypoxia layer in the headwaters (sites 1∼4), thereby confining the anoxic layer to the lower 0∼30 km of the reservoir (Fig. 3B). In mid-monsoon (17 July), the zone was confined to the downlake reach between the dam and 23 km. The volume of hypoxic water decreased >2 fold relative to early monsoon and comprised <10% of the total lake volume (Fig. 3C). The marked decrease in the anoxic volume was due to hypolimnetic discharge and replacement of lake water by interflows. This supposition is supported by observed increases in meta-hypolimnetic temperature (>5°C). Subsequently, as inflow and water withdrawal decreased in mid-monsoon (6 August), the hypoxic zone expanded to the upper end of the mid-lake (location 32 km), and the thickness of hypoxic layer increased along the main axis between the dam and the headwaters (Fig. 3D, E).

Hypolimnetic hypoxia rapidly developed mid-lake after large floods (July∼August) in 1993. In early postmonsoon 1993 the thickness of anoxia increased by >8 m mid-lake (location 25∼35 km) than elsewhere (Fig. 3F, G). The rapid development of hypoxia may be a result of active decomposition of autochthonous organic matter accumulated at the bottom (Cole and Hannan, 1990) with a minor influence of allochthonous organic matter.

This supposition is supported by an increase of algal standing stock >80 μg/l that resulted from an improved transparency after floods. In fact, Chl values were <7 μg/l in the headwater during monsoon 1993 when transparency measured as Secchi depth was <0.3 m and water residence time was <5d (An and Jones, 2000a). This finding agrees with studies of reservoirs that anoxia in the transition zone after floods is often attributed to an increased algal productivity (Wiedenfeld, 1980; Cole and Hannan, 1990; Thornton, 1990).



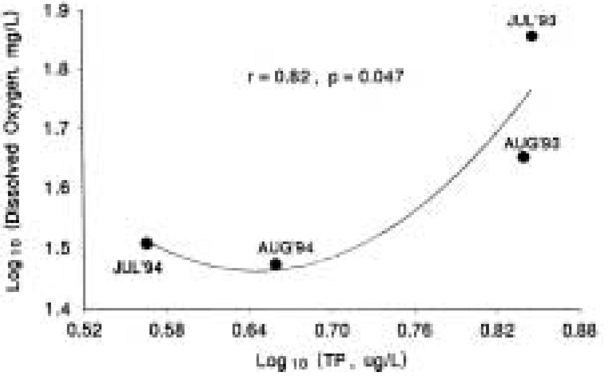


Fig. 5. Relation of dissolved oxygen (mg/l) to inflow (m^3/sec) and monthly mean in-lake TP during summer. Data of dissolved oxygen indicates a monthly in-lake average measured at 1 m interval from top to bottom at 17 sites. Values of TP are monthly averages mat 17 sites during summer 1993 and 1994 and inflow data indicate a total inflow volume in each month.

Fall overturn started partially from the headwaters in late postmonsoon 1993 (24 September) when temperature difference between the surface and bottom was <3°C, resulting in disrupting the hypoxia. The thickness and the boundary of the anoxic zone began to shrink toward the dam as fall overturn progressed downlake (Fig. 3H). This resulted in confinement of the anoxic zone to the downlake area during the late postmonsoon and the volume of anoxia was similar to mid-monsoon (17 July). The complete overturn downlake occurred early December 1993 and this condition continued by March 1994, indicating a warm monomictic reservoir. During the entire overturn, in−lake DO averaged 8.1 mg/l based on average DO per meter from the surface to bottom.

In contrast, in 1994 hypolimnetic hypoxia was most pronounced during the monsoon, resulting in fishkills. In premonsoon (9 June) hypoxia developed from the headwaters to the dam (Fig. 4A). During monsoon (July∼August), low inflow and water withdrawal from the dam accelerated rapid development of hypoxia in the headwaters, and the hypoxic stratum downlake extended from 10 m to the bottom (Fig. 4B). Thus, >85% of total lake volume was subject to hypoxic conditions with oxygen concentrations <30% saturation (Fig. 4C, D). The hypoxia persisted until late fall 1994 (30 September, Fig. 4F). Severe hypoxia caused fishkills in the headwater−middle reach (location 22∼49 km) during late summer 1994 (August−early September). The major fish species affected was *Hypomesus olidus*, a coldwater fish. The fishkill was accompanied with a massive occurrence of freshwater jellyfish and these attained concentrations of approximately 1∼3 individuals per litter in the surface water. The coldwater fishkill and occurrence of jellyfish may be resulted from a combined effect of high surface temperature >30°C and prolonged anoxia near the surface (Hyman, 1940; Wetzel, 1983; Molot *et al.*, 1992). Such biological impacts by anoxia are similar in both lentic and lotic ecosystems in non−monsoon regions (Hellawell, 1986; Hamilton *et al.*, 1997) where hypolimnetic O_2 is <4 mg/l (Molot *et al.*, 1992).

Overall, in−lake DO during summer was a function of seasonal hydrology. Hypolimnetic hypoxia, measured as a relative areal oxygen deficit (RAOD; Hutchinson, 1957), showed a distinct contrast between summer 1993 and 1994 (Table 1); in summer 1993, mean RAOD was −0.024 mg O_2 cm^{-2} d^{-1} between 9 June and 18 August, indicating an increase of hypolimnetic DO, whereas in summer 1994 it rapidly decreased at the rate of 0.080 mg O_2 cm^{-2} d^{-1}. Also, the anoxic factor (AF; after Nurnberg, 1995) was >50 d greater in 1994 (76.5 d) than 1993 (21.3 d) (Table 2). These results suggest that hypolimnetic anoxia was evidently greater in 1994 than 1993. Rapid anoxia in 1994 seems to be a combined effect of epilimnetic temperature >30°C, strong stratification of the whole reservoir by reduced inflow, and autochthonous organic loading (estimated as algal standing stock) of >3 fold relative to the 1993 summer (Cole and Hannan, 1990; Molot *et al.*, 1992; Nurnberg, 1995).

Table 1. Calculation of the Relative Areal Oxygen Deficit (RAOD; after Hutchinson 1957) in summer 1993 (9 June∼21 August) and summer 1994 (9 June ∼18 August).

(I) Summer 1993:
(a) Calculation for 9 June 1993

Strata (m)	Lake Volume ($\times 10^6$)	Mean DO (mg L^{-1})	Total O_2 in strata (metric tons)
15∼20	16.735	4.6	77.650
20∼25	11.947	3.9	45.995
25∼30	8.432	3.1	25.908
30∼35	4.052	3.0	12.155
			Sum: 161.708

(b) Calculation for 21 August, 1993 :
Sum : 219.676 (metric t)
Difference of the sum between the date (a) and (b) :
−57.968 t or −57.968 × 10^9 mg
The surface area of hypolimnion at 15 m :
32.77 × 10^9 cm^2
Relative Areal Oxygen Deficit : −0.024 mg cm^{-2} d^{-1}

(II) Summer 1994:
(a) Calculation for 9 June 1994

Strata (m)	Lake Volume ($\times 10^6$)	Mean DO (mg L^{-1})	Total O_2 in strata (metric tons)
15∼20	14.634	6.5	95.121
20∼25	9.924	6.3	65.521
25∼30	6.437	5.9	37.978
30∼35	3.812	4.9	18.679
			Sum: 217.299

(b) Calculation for 18 August, 1994 :
Sum: 64.264 (metric t)
Difference of the sum between the date (a) and (b) :
153.035 t or 153.035 × 109 mg
The surface area of hypolimnion at 15 m :
27.23 × 10^9 cm^2
Relative Areal Oxygen Deficit : 0.080 mg cm^{-2} d^{-1}

I believe, however, the primary factor regulating the in−lake DO in summer 1993 was large inflow from the watershed. Regression analysis of in−lake DO against inflow during summer showed that the variation of DO, based on monthly in−lake mean from top to bottom at 17 sites, was mostly explained (R^2 = 0.99, p<0.001) by inflow, indicating an importance of the monsoon intensity in determining the in−lake DO concentration. This outcome does not agree with the general model for North American reservoirs (Cole and Hannan, 1990) where anoxia in late

Table 2. Calculation of Anoxic Factor [AF = (duration of anoxia x anoxic sediment area)/lake-surface area, Nurnberg (1995)] in 1993 and 1994. Anoxic sediment area was estimated as area of hypoxia (anoxic) water <4 mg/l DO near 1 m above the bottom as suggested by Nurnberg (1995). Duration of anoxia was approximately estimated as a thermal stratification period in 1993 and 1994.

	1993	1994
Anoxic Sediment Area (km^2)	35.1	53.1
Lake Surface Area (km^2)	51.0	43.0
Duration of Anoxia	31	62
Water Residence Time during summer (d)	24	124
Anoxic Factor (AF) (day per summer)	21.3	76.5

summer is typically greater in high-flow years than in low-flow years. Greater anoxia in high-flow years occurs because large inflows in spring are accompanied by large nutrient inputs, resulting in decreased oxygen with increased primary production in summer (OECD 1982). Thus, hypolimnetic oxygen depletion rates have often been predicted by phosphorus loading, chlorophyll, or primary production (Ryding, 1980; Vollenweider and Janus, 1982; OECD, 1982; Reckhow, 1988; Nurnberg, 1995, 1996). However, in Taechung Reservoir oxygen depletion rates, measured as a relative areal oxygen deficit (Hutchinson, 1957) or anoxic factor (AF; Nurnberg, 1995), were smaller in the high-inflow year (1993) than during low-inflow year (1994). Also, maximum in-lake DO in summer 1993 was observed during peak inflow when in-lake TP was highest (>150 μg/l). This indicates that when the hypolimnion was rapidly flushed during the monsoon (mean water residence time <30 d), the functional relationship between anoxia and lake trophic state was uncoupled. These outcomes suggest that the primary factor regulating the oxygen content in this system during summer is the intensity of the monsoon rainfall (or inflow) and trophic state seems to be secondary factor.

ABSTRACT

Seasonal oxygen content and deficit rates were evaluated from 17 sites of Taechung Reservoir during 1993~1994. In 1993, river inflows peaked during the monsoon in July~August and disrupted thermal stratification and anoxic layers in the headwaters, thereby confining the anoxia to the mid-lake and downlake reach. The volume of anoxic water with <4 mg/l DO comprised only <10% of the total lake volume in this period. In contrast, during monsoon 1994, 85% of total lake volume was subject to hypoxic conditions with oxygen concentrations <30% saturation, resulting in massive fishkills (*Hypomesus olidus*). Relative areal oxygen deficit (RAOD) was -0.024 mg O_2 cm^{-2} d^{-1} during monsoon 1993, whereas it rapidly decreased at the rate of 0.080 mg O_2 cm^{-2} d^{-1} during monsoon 1994. Anoxic factor (AF) showed a same interannual pattern as the RAOD and was greater >50 d in 1994 (76.5 d) than 1993 (21.3 d). Thus, the reservoir showed a river-characteristics (6~11 mg/l DO) in 1993 while lacustrine conditions (<4 mg/l DO) dominated in 1994. Regression analysis showed that the variation of summer DO was mostly determined ($R^2 = 0.99$, $p < 0.0001$) by inflow. These findings suggest that the primary factor regulating the oxygen content in this system during summer is an intensity of the monsoon rain.

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