

Runoff-induced vertical thermal dynamics in a canyon-shaped reservoir during the summer monsoon

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Abstract. During the summer rainy season, double thermoclines were observed in a small canyon-shaped reservoir. The physical processes leading to thermocline evolution are examined from the vertical temperature profile observed along the reservoir before and after rain. Observations show that their evolution is related to the inflow of runoff, which is colder than the reservoir surface water and post-rain fair-weather conditions. Tongue-like distributions of turbidity, conductivity and nutrient concentrations downstream from the headwater clearly reveal the presence of runoff-induced intermediate inflows. In addition to supplying nutrients, the inflow provides the oxygen-deficient intermediate layer with a rich supply of dissolved oxygen. Concurrently, in the upper part of the reservoir runoff-induced inflows may drive the oxygen-deficient bottom water to shift downstream along the layer beneath the runoff-induced inflow. The water mass between the two thermoclines may operate as a source of nutrients for algal development in early autumn when the upper thermocline is destroyed by the convective overturn owing to the surface cooling.

Extra keywords: double thermocline, rainy season, runoff-induced inflow, thermal layer.

Introduction

In lakes or reservoirs that function as water sources associated with human activity, an understanding of hydrodynamics in relation to water circulation is important for water quality management. During the summer months, in particular, a comprehension of the vertical temperature structure is practically and economically necessary in order to ensure the supply of water of an appropriate temperature for drinking, agricultural and industrial purposes. This is because water temperature affects the growth of crops and cultured organisms, the cooling of machines and drinking suitability. In temperate monsoon-climate limnological regimes, water quality tends to deteriorate during summer, primarily as a result of strong thermal stratification, together with suspended-sediment (or nutrient) laden runoff. These conditions cause phytoplankton blooms and the associated depletion of dissolved oxygen (An 2000).

The general seasonal variability of the vertical temperature structure and the controlling physical processes in lakes and reservoirs are widely acknowledged (e.g. Imberger and Patterson 1990; An *et al.* 2001; Condie and Webster 2002; Naselli-Flores 2003; Sun *et al.* 2003). The key, common physical processes affecting seasonal variability in the vertical

temperature structure are wind stress, air–water interactions owing to surface heat fluxes (solar radiation, long wave radiation, evaporation and sensible heat) and horizontal exchanges of heat owing to fluvial inflows and outflows (e.g. Imberger 1985; Imberger and Parker 1985; Ambrosetti *et al.* 2002; Dallimore *et al.* 2004). Notably, under a summer monsoon climate with heavy rainfall, the physical and biogeochemical processes in limnological regimes are significantly affected by floods during the rainy season (An *et al.* 2001; Kim *et al.* 2001).

Temperature differences between river inflows and lake (reservoir) waters markedly influence lake circulation. In the Colorado River–Lake Mead System (Anderson and Pritchard 1951) and in the Thompson River–Kamloops Lake System (Carmack *et al.* 1979), for example, temperature differences have been observed to cause less-dense fluvial inflows to concentrate at the surface in winter, at intermediate depths in summer and near the bottom in spring and autumn. In Lake Burragorang, Australia, Romero and Imberger (2003) observed nutrient-laden underflow induced by denser, winter floodwaters. Similarly, An (2001) observed inflow currents in Taechung Reservoir, Korea, caused by runoff during the summer monsoon rainy season, revealing a thermal-structure

change in the vicinity of the headwater. Sun *et al.* (2003) observed double thermoclines in the Juam Reservoir of Korea in summer, although this phenomenon was not the focus of their paper. This interesting finding is the motivation for the present study. Our primary aim is to examine this anomaly in the vertical thermal structure of reservoirs during the summer-monsoon rainy season and to understand the effect of runoff on variability in this structure in a small, but long, narrow artificial reservoir.

Background and observations

Korea is directly influenced by a monsoon climate. Between 50 and 70% of the annual precipitation falls in the summer rainy season (July–August) (An 2001) and, in some years, typhoon events (commonly July–September) make a significant contribution to this rainfall. Along with increased demands for water by humans, this concentration of precipitation has necessitated the construction of large reservoirs in many Korean gorges to supply secure drinking, agricultural and industrial water and to mitigate flooding. As a result, most streams and rivers in Korea have been modified to create reservoirs.

The Juam Dam was constructed in the middle of the Boseong River in 1990 for the main purposes of summer flood mitigation and the supply of drinking water to the surrounding populations of Gwangju City and Jeonnam Province (Fig. 1). A typical Korean artificial reservoir, Juam Reservoir, was created upstream of the Juam Dam. The dam is 330 m in length, 57 m in height and has five 4.35-m wide gates in the left corner. The number, height and timing of gate openings are variable and depend on the volume of runoff. Typically, the gates are opened two or three times per year. Juam Reservoir has an average water volume of $\sim 4.5 \times 10^8 \text{ m}^3$ with an approximate drainage area of 1010 km^2 and a mean depth of 15 m (Kim *et al.* 2001). The reservoir is $\sim 17 \text{ km}$ long between the upstream and downstream stations. An intake tower, connected to water filtration plants, is situated in front of the west corner of the dam ($\sim 100 \text{ m}$ upstream from the dam) (Fig. 1). The depth of the water intake varies between 4 and 8 m from the surface to keep the temperature of the water supply constant ($\sim 24^\circ\text{C}$ in summer). The amount of inflow from Songgwang Stream is comparable to the amount of outflow from the intake tower just downstream.

In 2000, the daily averaged annual inflow to the reservoir was $26 \text{ m}^3 \text{ s}^{-1}$ and the maximum inflow of $665 \text{ m}^3 \text{ s}^{-1}$ occurred on 4 August (Fig. 2). Heavy inflows of $>400 \text{ m}^3 \text{ s}^{-1}$ resulted from the passing of two typhoons (Prapiroon and Saomai) in late August and mid September 2000. During these events, the gates on the Juam Dam were opened to control the flood. In contrast, the daily averaged annual outflow in 2000 was $\sim 27 \text{ m}^3 \text{ s}^{-1}$, which is equivalent to the amount of water used for human activity ($\sim 20 \text{ m}^3 \text{ s}^{-1}$) and discharge ($\sim 7 \text{ m}^3 \text{ s}^{-1}$) during the periods between typhoons.

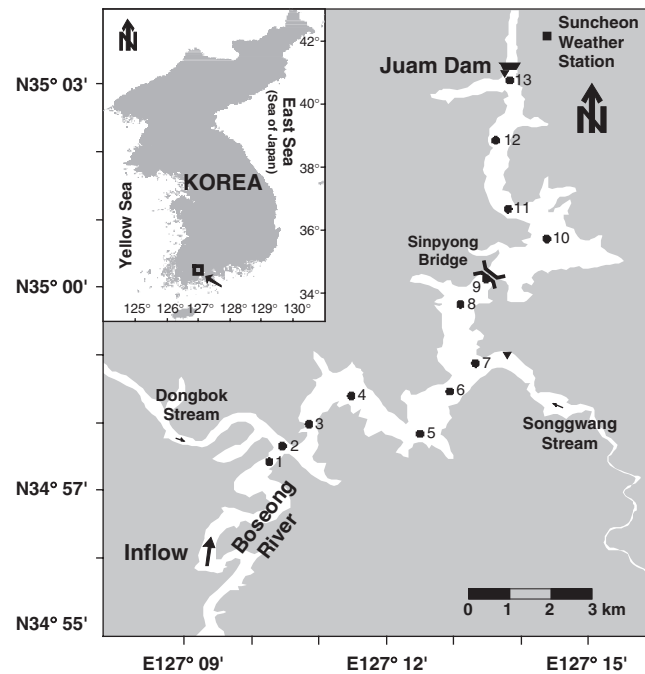


Fig. 1. Map of the study area, the Juam Reservoir in Korea. Circles, triangles and a square indicate the 13 observation stations, two intake towers and a weather station, respectively.

The annual estimated residence time is ~ 200 days, whereas during the periods of heavy inflows ($>300 \text{ m}^3 \text{ s}^{-1}$) the approximate residence time is less than 17 days.

Vertical temperature, turbidity, dissolved oxygen (DO) and electrical conductivity (EC) observations were made at Stations 1–13 downstream from the headwater towards Juam Dam during pre-rain conditions (14 June), 1 day after rain (12 July and 5 August) and several days after rain (31 July and 8 and 11 August) during the summer of 2000. Measurements took $\sim 2 \text{ h}$ from the downstream to upstream limits of the survey. The start timings of each survey were 1450 hours for 14 June, 1150 hours for 12 July, 1310 hours for 31 July, 1120 hours for 5 August, 1410 hours for 8 August and 1030 hours for 11 August. In all deployments, a Hydrolab Minisonde multiprobe (Loveland, CO) was used to examine the vertical temperature, turbidity, DO and EC structure of Juam Reservoir. The DO probe was calibrated using commercially prepared standard buffer solutions. On 14 June and 12 July, a conductivity–temperature–depth recorder (CTD) (Sea-Bird SBE 19; Bellevue, WA) with a sampling interval of 2 Hz was also used, in order to measure the vertical profile temperature in more detail. On 12 July, in addition to the vertical temperature, turbidity, DO and EC measurements, water samples were collected from five stations, at depths of 0.5, 5, 10, 15, 20, 25 and 30 m, and analysed for nutrient concentration. This analysis followed the method of Parsons *et al.* (1984). Summertime (1 June–12 August) variability in meteorological parameters near the reservoir, including wind speed, air temperature and

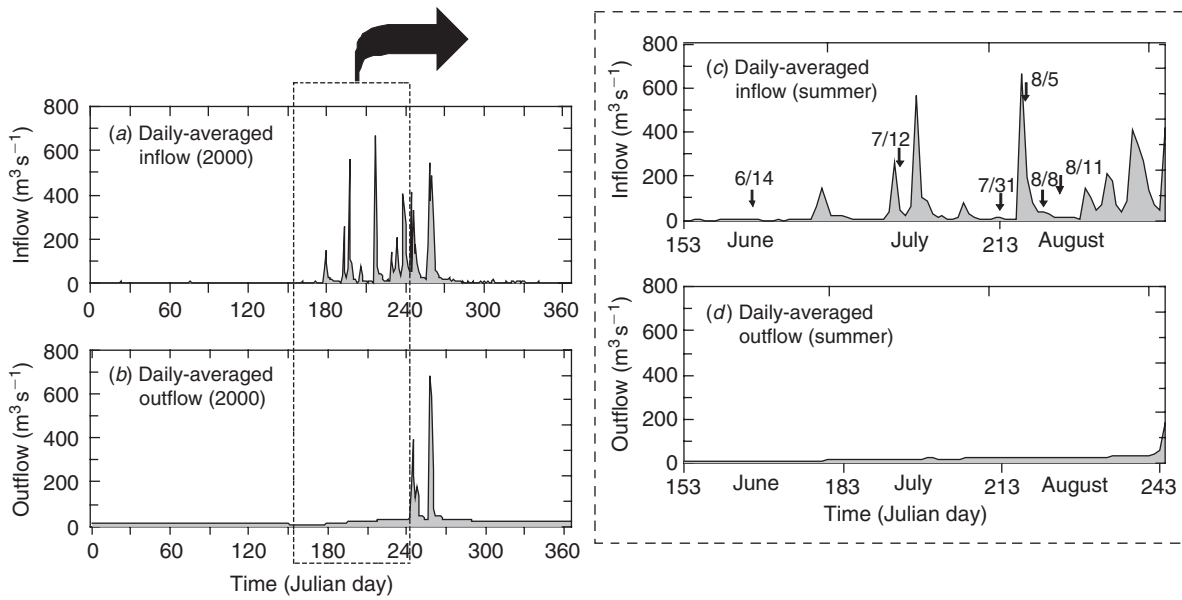


Fig. 2. Daily-averaged inflow ($\text{m}^3 \text{s}^{-1}$) from streams to the Juan Reservoir (a) and daily-averaged outflow ($\text{m}^3 \text{s}^{-1}$) from the Juan Reservoir (b) in 2000. Panels (c) and (d) show magnified, summer (June to August) sections of (a) and (b). The arrows in panel (c) indicate inflow discharges on various observation days.

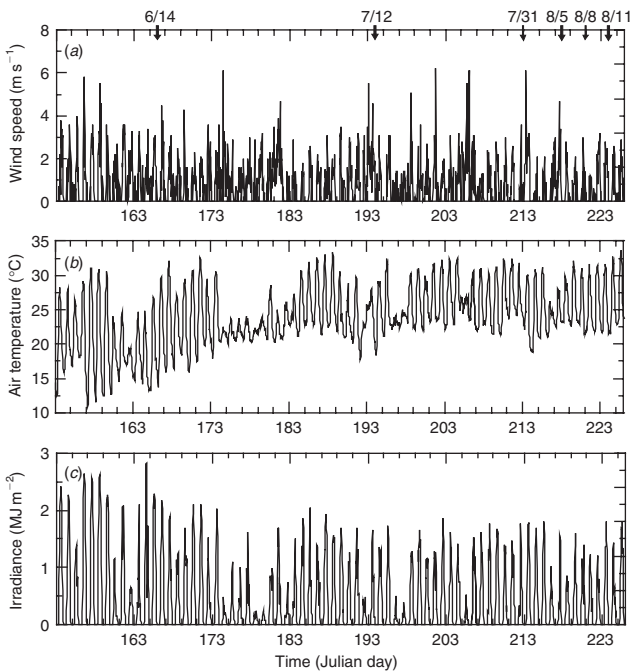


Fig. 3. Variability in (a) wind speed, (b) air temperature and (c) solar irradiance measured at the weather stations near the Juan Reservoir (a) and (b) in Suncheon, and (c) in Gwangju during summer (June 1–August 12).

solar irradiance, is illustrated in Fig. 3. As may be expected in a typical East-Asian summer-monsoon climate, relatively weak wind speeds, high air temperatures and high irradiances were recorded: that is, monthly-averaged values were

$0.94(\pm 1.11) \text{ m s}^{-1}$, $21.4(\pm 4.5)^\circ\text{C}$ and $0.5(\pm 0.25) \text{ MJ m}^{-2}$ in June; $0.81(\pm 1.0) \text{ m s}^{-1}$, $25.5(\pm 3.3)^\circ\text{C}$ and $0.41(\pm 0.14) \text{ MJ m}^{-2}$ in July and $0.76(\pm 1.2) \text{ m s}^{-1}$, $25.3(\pm 3.3)^\circ\text{C}$ and $0.35(\pm 0.15) \text{ MJ m}^{-2}$ in August respectively.

Results

As illustrated in Fig. 4a, the vertical temperature profile along the longitudinal axis of the reservoir at the Boseong River inflow during pre-rain conditions on 14 June 2000 showed the presence of a strong thermocline with a 13°C temperature gradient ($9\text{--}22^\circ\text{C}$) in the subsurface layer between 4 and 8 m deep (equivalent to a relative altitude of 22–26 m). Relatively weak surface temperature gradients occurred owing to surface net heat loss during 2 days of overcast sky conditions (9–11 June) as indicated by the low irradiance shown in Fig. 3c. During that period, wind speeds increased by $>3 \text{ m s}^{-1}$ in the afternoon, a factor which might also contribute to the formation of the surface mixed layer.

A strong thermocline ($9\text{--}22^\circ\text{C}$) was also observed 1 day after rain on 12 July at 21–26 m relative altitude (Fig. 4b). In addition, the surface water level had risen 4 m owing to large inflows of runoff into the reservoir (Fig. 2c). On 31 July, the vertical temperature structure exhibited a double thermocline in the water column (Fig. 4c). Specifically, there was a thermocline in the subsurface layer from 29 to 33 m relative altitude, with a relatively weak vertical temperature gradient from 23 to 29°C , whereas another thermocline was located in the middle of the water column between 19 and 25 m relative altitude, with a relatively strong vertical temperature gradient from 8 to 21°C .

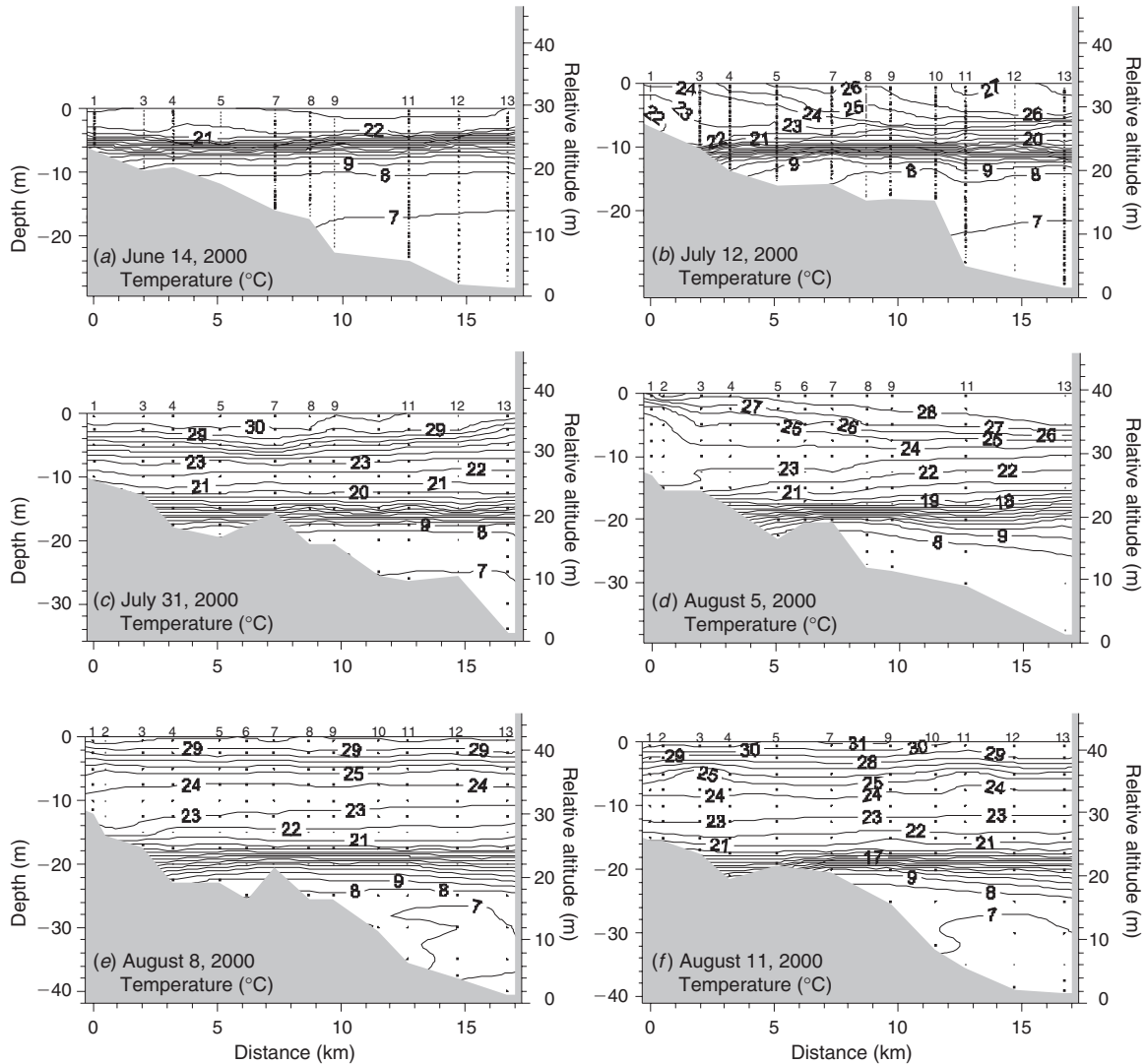


Fig. 4. Vertical temperature distributions along the longitudinal axis of the Juam Reservoir before rain (a), the day after rain (b,d) and several days after rain (c,e,f). Refer to Fig. 2 for the amount of runoff inflow during observation days. The numbers (1–13) correspond to the observation stations shown in Fig. 1 and the dots at each station indicate the observed depth.

As shown in Fig. 4d, the water surface temperature was 2°C lower on 5 August than on 31 July. This decrease in temperature was produced by rainfall on 4 August. The colder rainfall contributed to surface water cooling and, owing to density differences between the reservoir surface and rain waters, to vertical mixing, thereby decreasing temperature in the surface mixed layer. Because of the relatively weak wind speeds (daily-averaged values of 0.3–0.7 m s⁻¹) that occurred in early August, as shown in Fig. 3a, wind-induced surface mixing is likely to have been small. Further, because of the weak summertime wind speeds and relatively small diurnal (day–night) variations in air temperature (Fig. 3b), together with the higher cloud cover fraction (monthly-averaged values of >0.6), water surface cooling via sensible- and latent-heat fluxes and long wave radiation is smaller than

that expected during summer nights. Thus, the surface-mixed layer which is affected by nighttime cooling processes is likely to be limited to a couple of metres of water, resulting in the maintenance of a subsurface thermocline during summer.

In certain circumstances the uppermost layer of the thermocline may show daily evolution; it is intensified by strong surface heating as the day progresses and is broken down or eroded by wind stress and heat loss during the night. Accordingly, it is possible that a thin surface thermocline could have developed in our study area under conditions of strong solar radiation. However, our measurements were made at a depth of ≥0.5 m, a level below which is likely to have been significantly affected by daytime strengthening of the thermocline. Furthermore, solar radiation is weak during the rainy season, when most of our measurements were taken. Under these

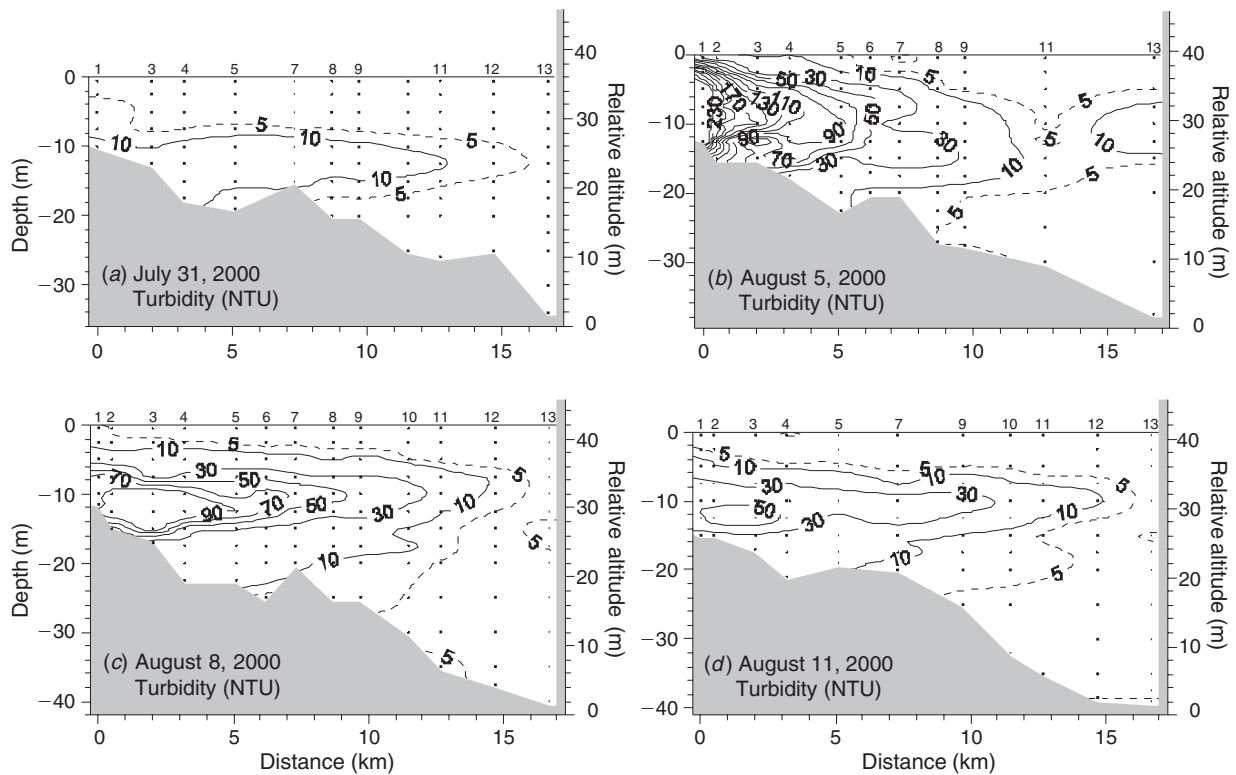


Fig. 5. Vertical turbidity section along the longitudinal axis of the Juam Reservoir (a) before rain, (b) the day after rain and (c,d) several days after rain.

conditions it is more likely that a developed surface diurnal thermocline would be destroyed owing to heat loss processes.

The July 2000 rainfall event induced the maximum annual inflow, $665 \text{ m}^3 \text{ s}^{-1}$, as well as a weakening in the subsurface thermocline at 29–33 m relative altitude. Intrusion of $23\text{--}24^\circ\text{C}$ runoff at 26–34 m relative altitude was observed between Stations 1 and 7. Since the runoff from the stream was $>3.5^\circ\text{C}$ cooler than the reservoir surface water (28°C), it spread along isopycnals (lines of constant density) between the subsurface thermocline and the intermediate-depth thermocline from the Boseong River inlet towards the Juam Dam. The turbulence generated by this inflow may have influenced the weakening of both of these thermoclines, particularly, in the upper part of reservoir. Vertical turbidity distributions before and after rainfall reveal that the highly turbid (>320 NTU) flow from the river enters the middle of the reservoir water column at 28–34 m relative altitude in the shape of a tongue (Fig. 5). These vertical variations in turbidity indicate that the runoff carries a large quantity of suspended sediment into the reservoir, which then sinks through the water column between Stations 1 and 6 in the upper reaches of the Boseong River. Temperature inversions induced by the effect of the increased-density sediment-laden runoff were not found in the intermediate layer (see Fig. 4d).

In contrast to the subsurface thermocline, the intermediate-depth thermocline was not affected by runoff owing to its

relatively low temperature ($8\text{--}21^\circ\text{C}$). Observations 3 and 6 days after the rainfall events (Fig. 4e, f) show the existence of a double thermocline in the subsurface and intermediate layers, resulting in a four-layer thermal structure. The runoff layer, which is ~ 6 m thick, lies between these two thermoclines. The runoff water mass originated from heavy rainfall upstream, as illustrated in vertical turbidity sections downstream of the headwater in Fig. 5. The large amount of runoff-induced intermediate inflow caused the existing, strong sub-surface thermocline to remain relatively deep. From these results it can be inferred that runoff was the mechanism responsible for the development of the double thermocline observed on July 31 (Fig. 4c). In addition, results indicate that a subsurface thermocline may be intensified after heavy rain when strong solar radiation is sustained over several days, leading to the development of a double thermocline in the reservoir.

Discussion

In this paper we have identified the role of seasonal runoff-induced inflows in relation to the development of double thermoclines in a small, Korean reservoir. More generally, it is widely reported that strong thermal stratification develops in the surface-water column of reservoirs during summer owing to an increase in solar radiation; and vertical mixing, particularly between surface and bottom waters, is inhibited

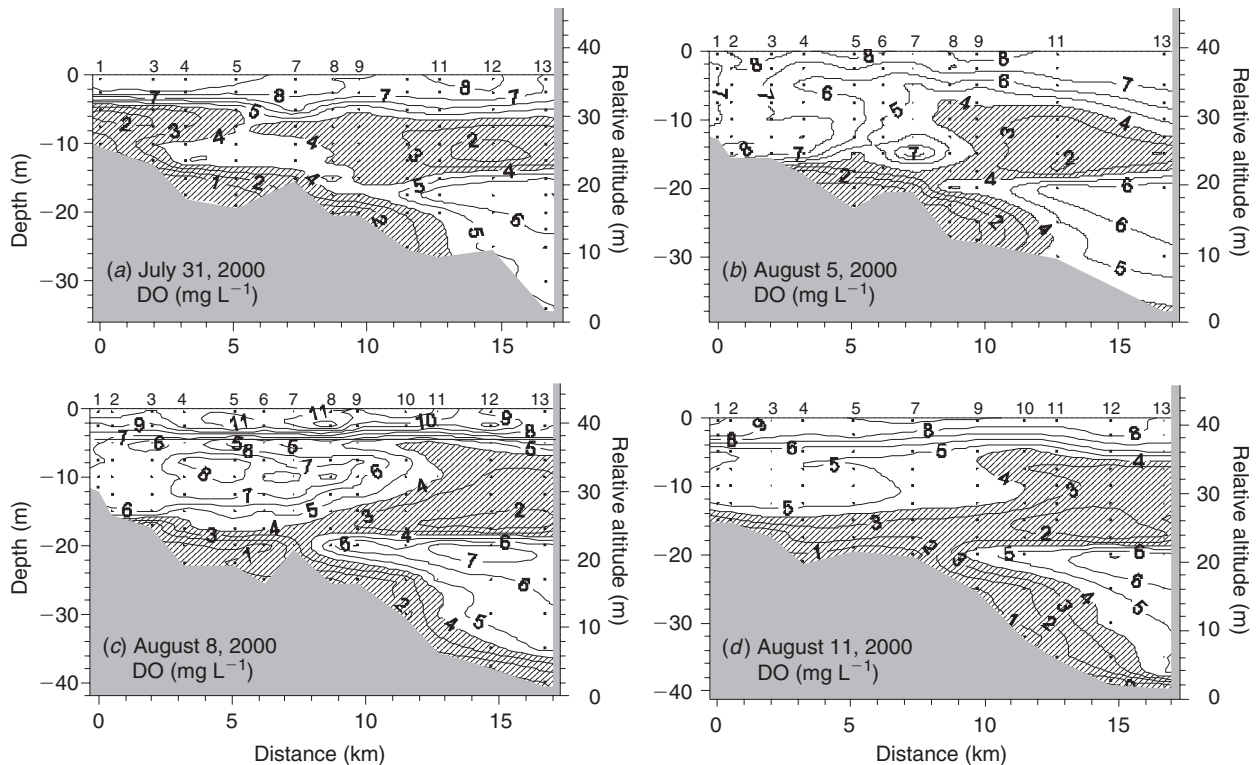


Fig. 6. Vertical section of dissolved oxygen (DO) concentration along the longitudinal axis of the Juam Reservoir (a) before rain, (b) the day after rain and (c,d) several days after rain. The shaded area indicates where DO concentrations are less than 4 mg L^{-1} .

by this stratification (e.g. Schiebe *et al.* 1975; Gu and Stefan 1995; Condie and Webster 2002).

In this section, we investigate the possible contribution of runoff to the biogeochemical dynamics in the reservoir and discuss the potential effect on phytoplankton production of the development and destruction of thermoclines in runoff-reservoir systems. As shown in Section 3, in August 2000 runoff with an approximate temperature of 23°C flowed into, and spread along, the Juam Reservoir at intermediate depths. The concentration of this runoff at intermediate depths occurred owing to its higher density relative to surface waters and lower density relative to bottom waters. Figure 6a shows low concentrations ($<4 \text{ mg L}^{-1}$) of DO in intermediate and bottom waters along the longitudinal axis of the reservoir. The tributary water (Stations 1 and 2) is characterised by rich, shallow bottom organic matter and shows low DO concentrations owing to the mineralisation of organic matter before rainfall. The low DO concentration in bottom waters (Stations 4 and 5) indicates that these regions are dominant deposit areas of allochthonous organic matters transported by the runoff-induced heavy inflow as shown in Fig. 5b. Low-concentration DO conditions are referred to as 'hypoxia' when concentrations are below those needed to sustain most animal life (Molot *et al.* 1992; Karim *et al.* 2002). In general, hypoxia occurs in organic matter-rich bottom waters owing to

mineralisation processes by bacterial activity. It is interesting to note that near the dam (Station 12) the lowest DO concentration ($<2 \text{ mg L}^{-1}$) occurs in the intermediate, rather than the bottom, layer.

Figure 6b shows that 1 day after rain, the intermediate-depth water with low DO concentrations of $<4 \text{ mg L}^{-1}$ started to be gradually replaced downstream towards the dam by runoff-induced inflow with high DO concentrations of $>7 \text{ mg L}^{-1}$. This process of horizontal water replacement and displacement owing to the temporary large inflow may explain how the low-DO waters in the middle layer near the dam originate from the upper part of the reservoir. However, since DO is not conservative tracer, the use of non-reactive tracers such as stable isotopes is required to understand the accurate process of this low-DO water occurrence.

The large volumes of sediment carried by the runoff are deposited in the shallow upper part of the reservoir, as mentioned in Section 3. The resultant thermal stratification and vigorous biogeochemical processes in the benthic boundary layer can lead to DO deficiency and eutrophication, a condition commonly found in the upper part of canyon-shaped reservoirs (Mašin *et al.* 2003). An (2000) also observed DO enhancement by runoff in Korea's Taechung Reservoir and pointed out that variability in DO concentration in the reservoir is significantly affected by inflows of summer runoff.

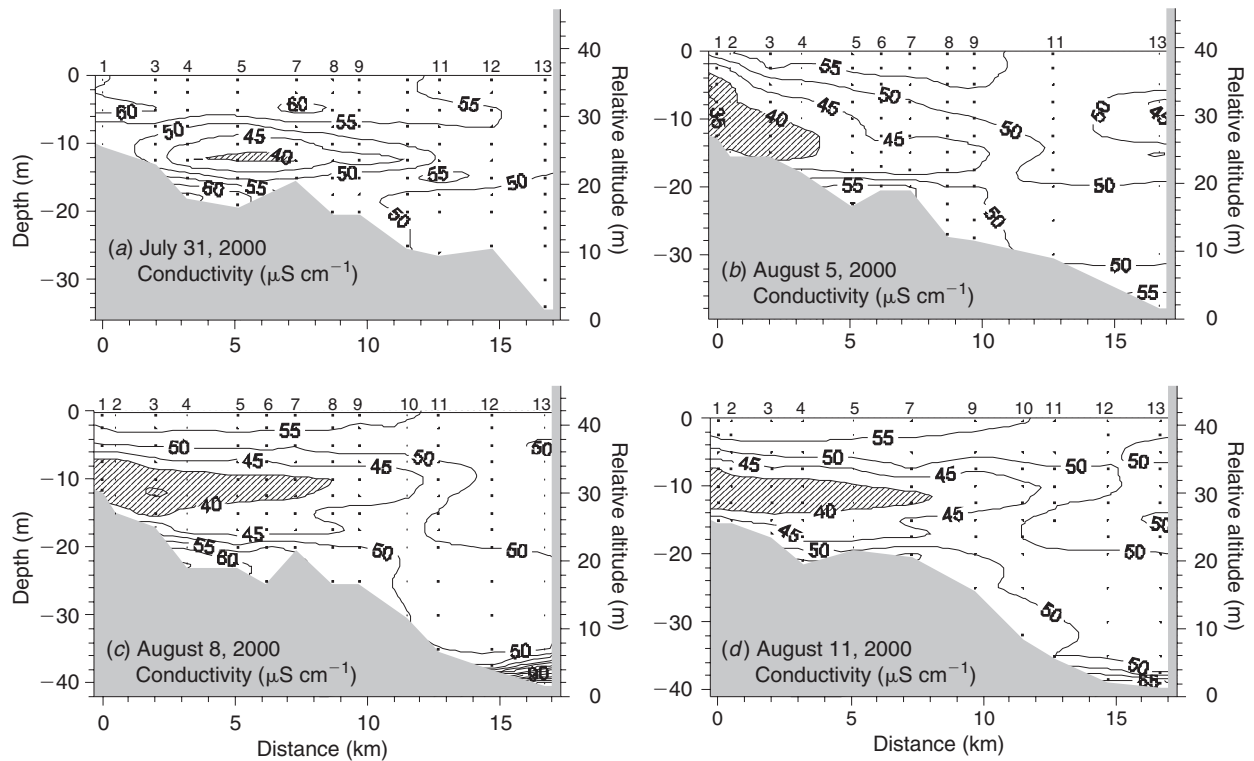


Fig. 7. Vertical section of electrical conductivity (EC) along the longitudinal axis of the Juam Reservoir (a) before rain, (b) the day after rain and (c,d) several days after rain. The shaded area indicates where values of EC are less than $40 \mu\text{S cm}^{-1}$.

Conductivity, which represents the total concentration of soluble salts in water, is also a good indicator of biogeochemical processes and hydrodynamic processes in reservoirs or lakes associated with runoff-induced inflows. As shown in Fig. 7, relatively low EC ($< 40 \mu\text{S cm}^{-1}$) is present at intermediate depths. As with the vertical distributions of temperature, turbidity and DO, EC also exhibits 'tongue-like' distributions along the downstream part of the reservoir after rain (Fig. 7b), revealing the intrusion of runoff-induced freshwater at medium depths. In addition, the relatively high EC ($> 55 \mu\text{S cm}^{-1}$) in the bottom waters (Stations 4 and 5) with low DO concentration is likely to be related to the mineralisation of organic matter.

The observations from 12 July 2000, 1 day after rain, clearly illustrate the process whereby nutrient and DO-rich, sediment-laden, fresh, low-EC runoff plunges into the intermediate layer of the reservoir waters, which are of a similar density, displacing the low-DO reservoir bottom water downstream towards the dam (Fig. 8). Thus the intermediate-depth low-DO water originates from the low-DO bottom water of the upper reservoir where runoff-derived organic matter is deposited and mineralised by bacterial activity, resulting in relatively high EC values. This water is spread out along the longitudinal axis of the reservoir by large runoff events (note that the slight differences in the depth of the maximum observed

gradients between nutrients and turbidity arise owing to differences in observation intervals; that is, the vertically stratified water samples taken for nutrient analysis were sampled at coarser depth intervals than were the turbidity measurements).

Accordingly, a water mass with high concentrations of nutrients exists at intermediate depths within the reservoir (Fig. 8d). After the rainy season, this runoff-induced middle layer may be maintained owing to an enhanced (sub)surface thermocline, thus being sandwiched between two thermoclines (see Fig. 4). This process is illustrated in Fig. 9, which shows summertime changes in the DO and vertical thermal structure of the reservoir caused by runoff-induced inflow pre-rain, during rain and after rain.

Solar radiation weakens with the seasonal change in the solar elevation from summer to autumn (i.e. the net heat flux at the water surface becomes negative) and, as a result, the surface-developed thermocline is gradually destroyed. When this occurs, the nutrient-rich intermediate water, which exists between the two thermoclines, may become an important nutrient source for algal growth in early autumn, particularly when nutrient deficiency exists in the surface water column. It should be noted that we did not observe the potential effects of the intermediate water on phytoplankton autumn blooms in 2000 owing to the passing of two typhoons in late August and mid September.

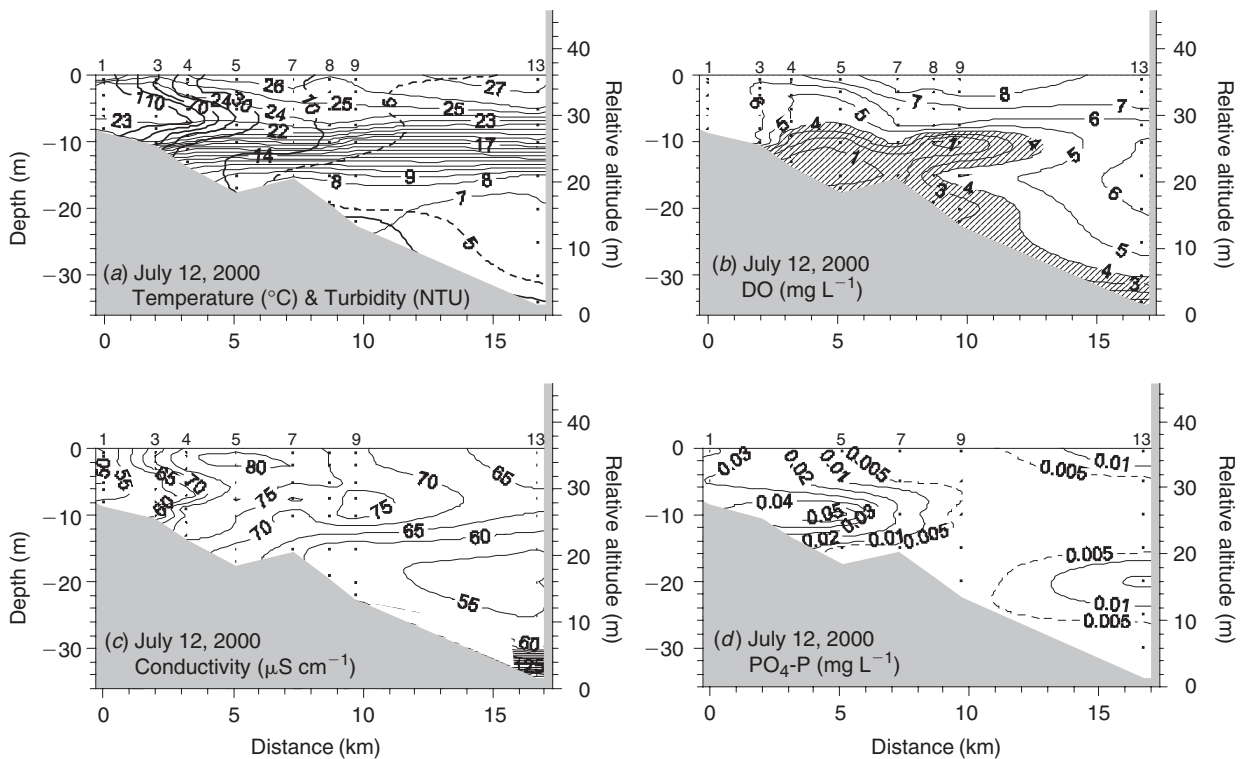


Fig. 8. Vertical sections of temperature (thin line) and turbidity (bold line) (a), dissolved oxygen (DO) concentrations (b), electrical conductivity (EC) (c) and phosphate (d) along the longitudinal axis of the Juam Reservoir on 12 July 2000 (1 day after rain).

Summary and conclusions

During the summer rainy season in the Juam Reservoir, hydrological and geochemical dynamics are controlled by runoff-induced inflow. The mechanism for the occurrence of a double thermocline can be explained from a thermal dynamic point of view as follows. In general, large volumes of runoff-transported sediment are deposited in the upper part of the reservoir. A strong thermocline develops in the surface or subsurface layer before the summer rainy season. This stratification of the reservoir, in combination with the active biogeochemical processes in the benthic boundary layer, causes the occurrence of bottom hypoxia. In particular, this takes place in the shallow upper part of the reservoir early in the rainy season. During this season, since the temperature of runoff is low relative to that of the reservoir surface water, the runoff-induced inflows intrude into an intermediate layer of the reservoir. The fresh, runoff-induced inflow with high DO and low EC concentrations contributes to improving DO concentrations in intermediate-level reservoir waters downward from the upper part of the reservoir, with improvements relative to the amount of rain. Concurrently, the DO concentrations in the waters beneath the intermediate inflow in the vicinity of the dam may deteriorate as low-DO waters, which are entrained from the bottom of the upper reservoir by strong runoff-induced intermediate inflows, are displaced towards the dam. The frequent, large inflows of runoff during summer

may cause this low-DO water from the upper reservoir to be further displaced along the longitudinal axis of the reservoir.

The runoff-induced inflows are also characterised by high nutrient concentrations. As a result, when periods of fine weather are sustained after runoff events, the surface water layer becomes strongly stratified and a thermocline develops above the runoff-induced intermediate layer. The surface water column is depleted of nutrients during summer owing to uptake by phytoplankton. Under conditions where little runoff has been contributed to this nutrient-deficient surface-water column during summer, the intermediate-depth nutrient-rich waters may provide nutrients for algal growth in early autumn when the surface thermocline breaks down.

In conclusion, the vertical-thermal and biogeochemical dynamics of the Juam Reservoir during the summer rainy season are strongly affected by the occurrence and volume of runoff-induced intermediate inflow. This inflow is characterised by low temperature and EC, DO- and nutrient-rich turbid waters, and leads to a complex vertical stratification of the reservoir waters. Further investigations will be made into the effects of runoff on the hydrodynamics of the entire reservoir as well as into its physical and biogeochemical dynamics and interactions during summer and early autumn, in particular, with regard to the preservation of water quality. Along with comprehensive, systematic observations of environmental parameters, including concentrations of

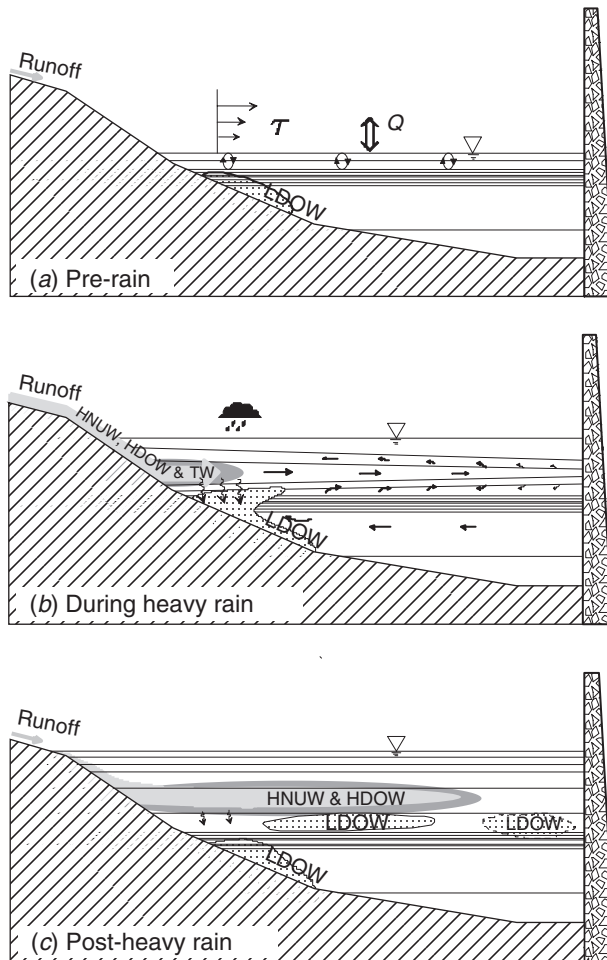


Fig. 9. Schematic diagram of progressive changes in the vertical-thermal structure and dissolved oxygen (DO) concentrations in Juan Reservoir as a result of runoff-induced intermediate inflows during summer. Note the presence of LDOW (low dissolved oxygen water), HNUW (high nutrient water) and TW (turbid water) layers and isothermal lines (see horizontal lines). Panel (a) shows the thermal stratification in the subsurface layer during pre-rain conditions. τ and Q indicate wind stress and net heat flux in the water surface, respectively. Panel (b) illustrates changes in the vertical-thermal structure owing to runoff-induced nutrient- and DO-rich, turbid intermediate inflow. The arrows indicate the possible circulation during the event. This inflow leads to the entrainment of LDOW at the benthic boundary layer in the upper part of the reservoir. The large amount of sediment carried by the runoff is deposited in the upper part of the reservoir. Panel (c) shows the development of another thermocline in the surface layer and the displacement of a large volume of LDOW towards the dam several days after heavy rain. Another parcel of LDOW (see the dashed line) is situated in the vicinity of the dam, having been moved there as a result of a previous heavy rain event.

chlorophyll-*a* and nutrients and of phytoplankton species, a numerical-ecosystem model coupled with a physical model may be a good approach for this future research.

Acknowledgments

We would like to thank Mr. Youn-Jong Sun for data pre-processing support. The authors wish to thank three

anonymous reviewers for their helpful comments on the manuscript. This work was supported by grant no. RO1-2004-000-10771-0 from the Basic Research Program of the Korea Science & Engineering Foundation.

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Manuscript received 22 November 2004; revised 17 March 2005; and accepted 31 March 2005.