Evaluating the contribution of reservoir dams located upstream of the Tokyo metropolitan area during low flow periods

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Original Ariticle

Evaluating the contribution of reservoir dams located upstream of the Tokyo metropolitan area during low flow periods*

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Abstract

Flow duration curves (FDCs) using inflow (Qin) and outflow (Qout) data does not accurately determine the flow contribution of reservoir dams. Analysis based on FDCs could lead to an incorrect conclusion that a reduction in flow occurred due to misinterpretation of zero Qout data. Zero Qout was often recorded when high precipitation occurred because the dam gate was operating to prevent flood flow. To avoid this problem (i.e., misinterpretation of zero Qout data), we proposed an alternate method that evaluates the increase in water flow induced by reservoir dams (Qout − Qin) in relation to Qin which indicates natural water flow without modification by reservoir dams. Based on this method, we evaluated 7 reservoir dams that were located upstream of the Tokyo metropolitan area. For 6 of the 7 reservoir dams, Qout − Qin was > 0 when Qin was at its lowest. These results showed clear contribution of the 6 reservoir dams to increasing flow which contrasts to the results when FDC analysis is applied. As Qin and Qout data for the main reservoir dams in Japan are readily available, our method can be easily applied to evaluate the contribution of reservoir dams to increasing low flow.

Key words：drought, flow duration curve, low flow, outflow, reservoir dam, Tokyo metropolitan area

1. Introduction

In Japan, forest covers most mountainous regions which are located upstream of agricultural and urban areas. Thus, forested areas are considered to be a source of water resources (Sawano *et al.*, 2005; Komatsu *et al.*, 2008a).

Reservoir dams have been developed in forested areas to increase low water flow and secure water resources in Japan (Toyama, 1974; Ueda, 1996; Ohkuma, 2007). Recently, reservoir dam development has drawn criticism from the viewpoints of biological and environmental conservation (Nakazato, 2000; Hoyano, 2001, 2004; Yorimitsu, 2001; Harada and Yasuda, 2004). Researchers and journalists have proposed forest management as a

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* 小松　光・久米朋宣・大槻恭一：首都圏上流域のダム貯水池が渇水時流量に与える影響

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possible alternative for the development of reservoir dams (e.g., Yorimitsu, 2001, 2004; Fujiwara, 2003; Amano and Igarashi, 2004), because forest management alters the forest water cycle (e.g., Lesch and Scott, 1997; Lane and Mackey, 2001; Brown *et al.*, 2005; Simonin *et al.*, 2007). They suggest that low water flow could be increased by use of forest management techniques, such as thinning coniferous plantation forests or converting them to broad-leaved forests.

For effective water resources management, it is necessary to evaluate the contribution of forest management and reservoir dam development to low water flow (Suzuki, 2004). Researchers have recently begun to evaluate the contribution of forest management to water flow (e.g., Kosugi, 2004; Nakane, 2004; Komatsu, 2007; Komatsu *et al.*, 2007a,b,c, 2008b, 2009a,b). However, very few attempts have been made in Japan to evaluate the effect of reservoir dams on flow rates.

Kume and Kubota (1998) is, to our knowledge, the only study in Japan that has examined the contribution of reservoir dams to increasing flow during low water periods. They evaluated the contribution of 11 reservoir dams located in the uppermost stream of the Tokyo metropolitan area by comparing daily inflow (Qin) and outflow (Qout) of the reservoir dams. Qin indicates runoff from the forested area located upstream of the reservoir dam, while Qout indicates the flow modified by the reservoir dam. Thus, comparing Qin and Qout enables an evaluation of the reservoir dam's effect on water flow originating from the upstream forested area.

Though the concept of Kume and Kubota (1998) is suggestive for evaluating the contribution of reservoir dams to increasing flow, the methods used in the study can be problematic. They expressed the inflow and outflow regime using flow duration curves (FDCs) and evaluated the contribution of reservoir dams to low flow by comparing the minimum Qin and the minimum Qout. However, zero Qout could be recorded during dam gate operation for preventing flood flow when high precipitation occurs, implying that the zero Qout could be recorded outside rather than during a drought period. Therefore, the analysis based on FDCs could lead to a misinterpretation that the zero Qout recorded during high precipitation indicates a reduction in water flow, because FDC analysis does not consider when zero Qout is recorded.

This study first illustrates the problem of the FDC analysis based on inflow and outflow data observed on reservoir dams located upstream of the Tokyo metropolitan area. Next, an alternate method is proposed which avoids this problem. The alternate method evaluates the increase in water flow induced by reservoir dams (Qout − Qin) in relation to Qin which indicates natural water flow without modification by reservoir dams. Based on this method, this study evaluates the contribution of the reservoir dams to increasing flow.

2. Data used

Qin and Qout data of 7 reservoir dams located in the uppermost stream of the Tone

River (Fig. 1), which supply water resources to the Tokyo metropolitan area, were used. Table 1 displays capacity and drainage area of each reservoir dam.

Daily Qin and Qout data were obtained from the Database of Dams (http://www2.river.go.jp/dam/), owned by the Ministry of Land, Infrastructure and Transport, Japan. Data from two additional reservoir dams (Yagisawa and Shinaki reservoir dams) located in the uppermost stream of the Tone River were also available from the database. However, these reservoir dams were excluded as Qin and Qout did not balance in the Yagisawa reservoir dam, because the reservoir dam was accompanied with pumped-storage power plant (http://www2.river.go.jp/dam/). The Shinaki reservoir dam was excluded as its main role was deacidification of water rather than river flow control (Fujiwara, 2003; Association of Concerned Citizens for Yamba Dam Project, 2005).

Data, measured between May and October of 1994, of the 7 reservoir dams were analyzed. Precipitation in this period was less than usual. Figure 2 shows seasonal changes in precipitation at Maebashi and Utsunomiya (Fig. 1) in 1994 in addition to the 30-year average. Precipitation in June and July of 1994 was less than the 30-year average (Figs. 2a and 2b). As a result, water restriction was carried out during 22 July – 19 September, 1994 in the Tokyo metropolitan area. This restriction was one of the longest to have occurred in this area during the period between 1993 and 2007 when Qin and Qout data were available from the Database of Dams (http://www2.river.go.jp/dam/). The period of analysis (i.e., May – October 1994) covered the whole period of the water restriction. Thus, our analysis would be suited for evaluating the possible contribution of reservoir dams to increasing flow when water resources are scarce.

Table 1 Capacity and drainage area of reservoir dams analyzed in this study.

Name	Location	Capacity (10^6 m^3)	Drainage area (km^2)	Mean inflow during 1993-1996 (m^3s^{-1})	Mean outflow during 1993-1996 (m^3s^{-1})
Kusaki	36°33'N, 139°22'E	51	254	9.63	9.67
Aimata	36°43'N, 139°54'E	20	111	5.43	5.41
Shimokubo	36°08'N, 139°01'E	120	323	5.44	5.58
Sonohara	36°38'N, 139°10'E	14	493	12.73	12.60
Kawamata	36°53'N, 139°31'E	73	179	7.34	7.36
Ikari	36°54'N, 139°42'E	46	271	9.63	9.61
Naramata	36°52'N, 139°04'E	85	60	4.81	4.77

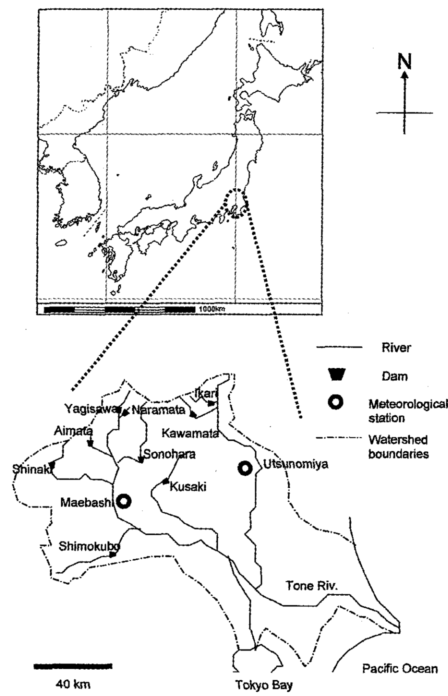

Fig. 1. A map showing the location of the reservoir dams examined in this study.

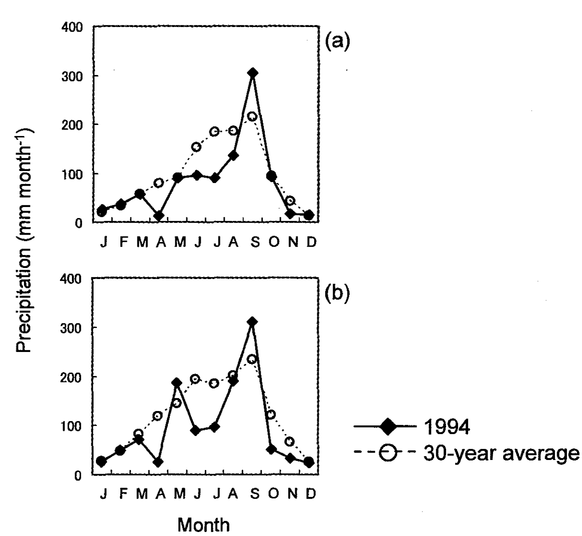

Fig. 2. Seasonal changes in precipitation at (a) Maebashi and (b) Utsunomiya in 1994 and the 30-years average. Data were derived from the Japan Meteorological Agency (http://www.jma.go.jp/jma/indexe.html).

3. Results and discussion

3.1. The problem of FDC analysis

Figure 3a shows FDCs for Qin and Qout based on Kusaki dam data during May - October 1994. The minimum Qout was lower than the minimum Qin, which can lead to an interpretation that the Kusaki dam decreased water flow during the lowest flow period.

In actuality, this interpretation is incorrect. Figure 4 shows temporal changes in Qin and Qout of the Kusaki reservoir dam. Qin was always greater than zero, while Qout was zero on August 1, 22, 25, September 8, and October 2. Peaks of Qin were observed on these days, indicating that precipitation occurred. Therefore, the zero Qout was caused by the operation of the dam gate to prevent flood flow. Qout was greater than Qin during July 11−15, July 24−25, and August 13−14 when Qin values were lower than other periods (Qin < 4.0 m^3 s^{-1}). This indicates that the Kusaki reservoir dam ameliorated the flow during this period (Fig. 4). Thus, the analysis based on FDCs (Fig. 3a) can cause misinterpretation of Kusaki dam's contribution and is problematic.

FDC analysis was performed for the other 6 reservoir dams (Fig. 3b-g) including an examination of the temporal change in Qin and Qout (data not shown). The same problem was observed for all reservoir dams except Ikari. For Ikari, zero Qout data were not recorded (Fig. 3f) and therefore the problem was not observed.

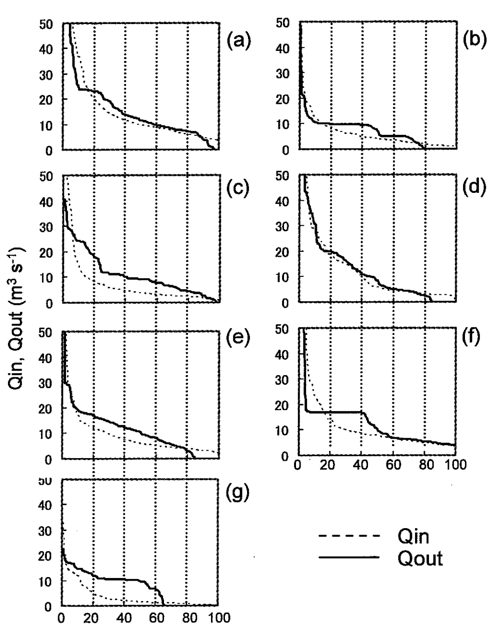

Fig. 3. Flow duration curves (FDCs) for Qin and Qout of (a) Kusaki, (b) Aimata, (c) Shimokubo, (d) Sonohara, (e) Kawamata, (f) Ikari, and (g) Naramata reservoir dams.

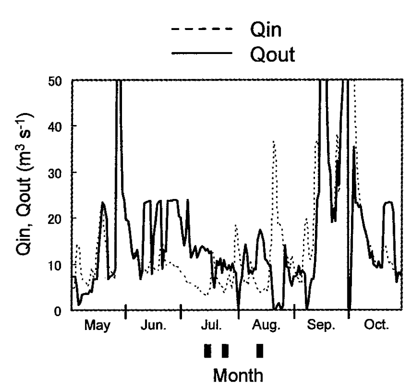

Fig. 4. Temporal changes in Qin and Qout of Kusaki dam during May−October, 1994. Periods with Qin < 4.0 m^3 s^{-1} were indicated by dots below the x-axis to highlight periods when Qin was most greatly declined.

3.2. Evaluating flow rates of reservoir dams based on an alternate method

To avoid the problem described above, we propose an alternate method for evaluating the contribution of reservoir dams to flow increase during water shortages. This method arranges Qout−Qin data according to the order of Qin (from higher Qin to lower Qin). Qin indicates natural flow without modification by the reservoir dam and Qout−Qin indicates flow increase induced by the reservoir dam. Thus, Qout−Qin values for low Qin reveals whether the reservoir dam increases flow when natural flow is low.

Figure 5 shows the results of evaluating the reservoir dams based on the alternate method. This figure divides Qout−Qin data into ten classes according to the Qin value and shows the average Qout−Qin value for each class. Qout−Qin values were negative for the two highest Qin classes (percent of time = 0−20%) and they were positive for moderate Qin classes (percent of time = 40−80%) for all reservoir dams. These facts indicate that these reservoir dams stored water when inflow was high and increased water flow when inflow was moderate. Qout−Qin values were positive even for the lowest two Qin classes (percent of time = 80−100%) except for Sonohara reservoir dam. This signifies that the reservoir dams, with the exception of Sonohara, contributed positively to the flow when inflow was most significantly declined.

The results obtained using our alternate method were quite different from those derived from the FDC analysis. The lowest Qout value was less than the lowest Qin value for all reservoir dams except Ikari (Fig. 3), according to the FDC analysis, which implies that the reservoir dams with the exception of Ikari did not contribute to increasing the flow. In actuality, all the reservoir dams except Sonohara contributed to increasing the water flow when inflow was most significantly declined, because Qout−Qin values were positive for the lowest two Qin classes (Fig. 5). Furthermore, the flow increase was more significant for Kusaki, Shimokubo, Kawamata, and Naramata reservoir dams than Ikari.

The variation in Qout−Qin values at the lowest Qin class amongst the reservoir dams indicates that the significance of the contribution to the flow varied between the reservoir dams. This variation correlated significantly ($p < 0.005$, Pearson's correlation coefficient test) to the variation in dam capacity (Fig. 6a). Therefore, larger reservoir dams contributed more significantly. These results were not qualitatively altered when using the average of Qout−Qin values for two lowest classes. The variation in the average of Qout−Qin values for two lowest classes correlated significantly ($p < 0.005$, Pearson's correlation coefficient test) to the variation in dam capacity (Fig. 6b).

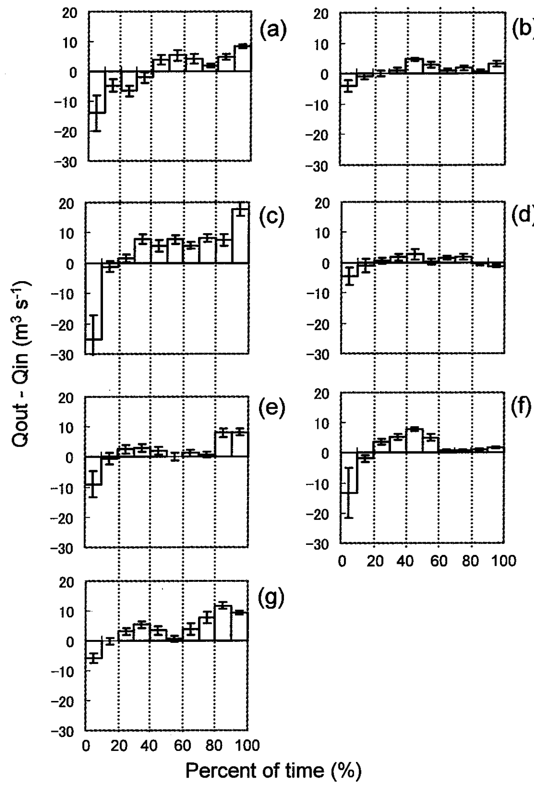

Fig. 5. Increase in water flow induced by reservoir dams (Qout−Qin) arranged from higher Qin to lower Qin: (a) Kusaki, (b) Aimata, (c) Shimokubo, (d) Sonohara, (e) Kawamata, (f) Ikari, and (g) Naramata reservoir dams. This figure divides Qout −Qin data into ten classes according to the Qin value and shows the average Qout −Qin value for each class. A vertical bar indicates the standard error for each class.

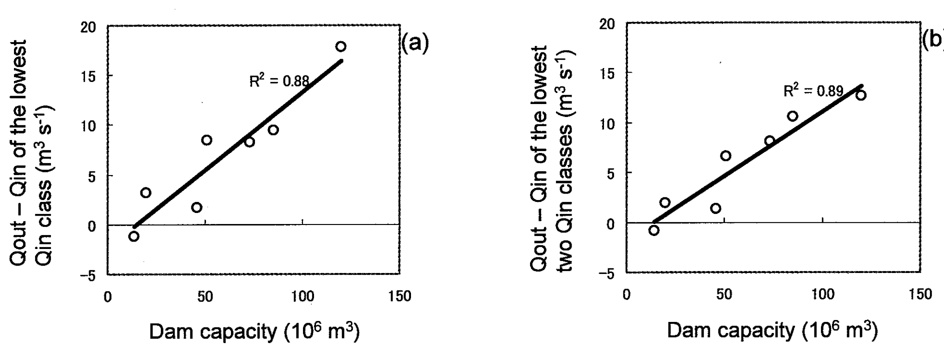

Fig. 6. Relationships (a) between dam capacity and increase in water flow induced by reservoir dams (Qout−Qin) of the lowest Qin class (percent of time = 90−100%) and (b) between dam capacity and increase in water flow induced by reservoir dams (Qout−Qin) of the lowest two Qin classes (percent of time = 80−100%). Regression lines in Fig. 6a and 6b, determined by the least-squares method, are written as $y = 0.157x - 2.37$ and $y = 0.129x - 1.73$, respectively.

4. Conclusions

This study illustrated that incorrect conclusions can be caused when applying the analysis based on FDCs. In addition, an alternate method was proposed to evaluate flow increase induced by reservoir dams (Qout−Qin) in relation to inflow (Qin).

We applied this method to 7 reservoir dams located in the uppermost stream of the Tokyo metropolitan area. The results showed a clear contribution of these reservoir dams to increasing low flow. Six of the seven reservoir dams increased the flow even when inflow was at its lowest. Significance of the contribution varied between the reservoir dams and the variation was related to dam capacity. This relationship enables us to predict the amount a new dam would contribute to flow during low periods.

As stated above, this study proposed a method to evaluate contribution of reservoir dams to increasing low flow. This method is useful, because it requires only Qin and Qout data, which are readily available for the major reservoir dams in Japan from the Database of Dams (http://www2.river.go.jp/dam/).

Though the contribution of forest management practices to increasing low flow has not been currently quantified, doubtless it will occur in the near future (Komatsu et al., 2009a). At that point, the effectiveness of forest management and reservoir dam development for securing water resources can be clearly evaluated. Thus, the method and findings shown in this study can be used as a basis for proposing effective water resources management.

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首都圏上流域のダム貯水池が渇水時流量に与える影響

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要　旨

ダム貯水池への流入量（Qin）と流出量（Qout）をもとにした流況曲線による解析は，ダム貯水池の渇水時流量の調節への貢献を正確に表現しないことがある．流況曲線を用いた解析において，Qout＝0のデータはダム貯水池による渇水時流量の低下と解釈されるが，現実にはQout＝0のデータはしばしば降水量の大きいときに記録されており，このことはQout＝0のデータが洪水緩和のためのダム制御によるものであることを意味している．このように，流況曲線による解析はQout＝0のデータを誤って解釈するという問題があるため，本論は，この問題を避けるための代替的な方法を考案した．この方法は，ダム貯水池による流量増加（Qout－Qin）を，ダム貯水池がなかった場合の流量に相当するQinとの関係から評価するものである．この方法を，首都圏上流域にある7つのダム貯水池に適用したところ，6つのダムにおいて，Qinの値が解析期間中でもっとも小さいときに，Qout－Qinがゼロより大きかった．この結果は，この6つのダムが渇水時流量の増加に貢献していたことを意味している．この結果は，流況曲線による解析結果と異なるものであった．日本の主要なダム貯水池におけるQinとQoutのデータは公表されているため，本論で提案した方法は，日本のダム貯水池が渇水時流量の増加に貢献しているか否かを評価するのに役立つものである．

キーワード：渇水，流況曲線，渇水時流量，放流量，ダム貯水池，首都圏