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APPLICATION OF HISTORICAL FLOOD INFORMATION TO PROBABILITY QUANTILE ESTIMATION FOR LAKE BIWA, JAPAN

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SYNOPSIS

A flood frequency analysis using historical flood information since the 18th century was carried out for Lake Biwa, central Japan. The probability distributions and the effects of incorporating historical flood data were examined by plotting positions on the Gumbel probability papers for the converted flood peak water level and the annual maximum rainfall total for 30 days reconstructed from historical documentary records. As results, when compared to the cases where only systematic gaged data are utilized, the inclusion of sample data plots for historical large floods revealed that the flood-frequency relationship for Laka Biwa is well described by the Gumbel distribution, and improved significantly the estimation precision of flood quantiles corresponding to return periods of several decades to a century, which is important for floodplain management or designs for flood control facilities in Japan.

INTRODUCTION

In planning of flood control facilities or floodplain management, one first needs to determine the design flood. In Japan, it has often been simply defined as the known ever-largest flood in the past, but it is usual today to consider the flood magnitude corresponding to a certain return period (or exceedance probability) estimated through a frequency analysis. However, the length of gaged hydrologic records available for flood frequency analysis is typically several decades to a century, which is not necessarily enough to estimate design flood with a large return period precisely. One of its pragmatic solutions is to obtain information about flood events that occurred before the installation of the gaging station.

Studies on methods of utilizing historical or paleoflood information for augmenting a systematic gaged record have largely progressed over the past several decades in the United States. For example, Stedinger & Cohn (19) assumed that historical/paleoflood data are available for events whose magnitude exceeded a certain threshold of perception, and formulated a procedure for incorporating several types of historical/paleoflood data into the method of moments and the method of maximum likelihood to estimate the parameters of flood frequency distribution. Moreover, as a result of Monte Carlo experiments, they concluded that the maximum likelihood estimators are better than the moment estimators in efficiency and flexibility. Hosking & Wallis (7) conducted a Monte Carlo study on the usefulness of a single estimate of an extreme paleoflood whose magnitude was found to be the maximum in a certain long period (say, 1000–10000 years), and pointed out that such a datum is of substantial value even with large error for estimating a flood quantile of large return period, especially in the case of short gaged record period and large magnitude (long recurrence interval) of the paleoflood. Cohn *et al.* (4) developed the expected moments algorithm (EMA), a new method of incorporating censored historical/paleoflood data into method-of-moments parameter estimation. They showed it is as efficient as maximum likelihood estimation despite its numerical simplicity. Hirsch & Stedinger (6) introduced the plotting position formulas applicable to historical/paleoflood data for the graphical evaluation of flood-frequency relationship.

Likewise, there are many works on the practical applications of historical or paleoflood hydrology to actual river basins. For example, Kochel & Baker (12) reconstructed a chronology of paleoflood stage and discharge spanning over 10000 years for the lower Pecos and Devils rivers in Texas in the United States by analyzing slack-water flood deposits and radiocarbon dating, and demonstrated its utility in estimating the return period of large floods. Jarett & Tomlinson (11) conducted at-site and regional flood frequency analyses for northwestern Colorado using nearly 100 paleoflood estimates over the last 5000 to 10000 years obtained by means of interdisciplinary paleohydrologic approaches. They stressed that such paleohydrologic approach can provide reasonable estimates of design floods compared to the deterministic PMP (probable maximum precipitation)/PMF (probable maximum flood) approach. Also, in China, investigations of utilizing flood records in abundant historical documents and relics dating back to ~2000 years ago for complementing short gaged records have been carried out on a nation-wide basis for decades (see e.g. Luo (14)). Moreover, methodology of paleohydrology has been applied to reconstruct recent floods that cannot be captured by existing gaging networks, such as those in small watersheds in data-sparse arid regions in central Australia or the western United States (see e.g. Baker *et al.* (1); House & Baker (9)).

By contrast, in Japan, little effort has been made in terms of engineering applications of historical or paleoflood hydrology. Due to small catchment area and steep channels, Japanese rivers generally have large variability in discharge, consequently floods with a relatively small return period, typically 5 to 50 years, have been considered as the design flood. Thus there has been little necessity to use historical or paleoflood information. In recent years, however, as flood control facilities at the present design standard are improved, it is becoming increasingly important to enhance the estimation accuracy of the design floods corresponding to a larger return period such as 100 or 200 years. In Japan, unlike arid regions in the western United States, there is little possibility of finding well-preserved geomorphic evidence of extreme floods thousands of years ago because of active erosion, botanical or human disturbance. On the other hand, one can find many historical documentary records especially in the central part of Japan.

Lake Biwa is the largest lake in Japan (670 km^2 in area) and is situated on an important passage to Kyoto, the former capital city of Japan for 794–1869. Due to its geographical importance, the Lake Biwa basin developed since its early days and enjoys relatively abundant historical documents including quantitative hydrologic records. In this paper we investigate the flood frequency relationship for Lake Biwa based on probability plots of reconstructed historical flood data since the 18th century together with modern systematic gaged data, and examine the effects of utilizing historical data on the estimation accuracy of flood quantiles.

HISTORICAL FLOOD RECORDS OF LAKE BIWA

Since the discharge capacity of the only outlet river (Seta River) was limited considering its large catchment area (3850 km^2), inhabitants around Lake Biwa have long suffered from frequent occurrences of inundation caused by the raising of the lake level. They wrote many descriptions of flood magnitude in diaries and in letters, including inundation depth records of houses, gardens or rice fields and relative comparison records of the peak water levels between plural extreme floods. Also, reliable records of monthly lake level observations using scaled posts can be found in the official documents of a local government (feudal Zeze Clan) for 1721–1868 despite many missing records. Previously we summarized these quantitative historical lake level records and represented peak levels of each flood by the Biwako Standard Level (B.S.L.; 84.371 m a.s.l.), the present standard for lake level measurement (see Sho (15); Sho *et al.* (17)).

However, the discharge capacity of the Seta River fluctuated in the past because of sedimentation and occasional dredging of the riverbed. Also, at the beginning of the 20th century, a large-scale dredging work and the installation of a submerged dam (Nango Dam) at the control section of the Seta River enabled artificial discharge control. In order to use the peak water level data as a random variable for flood frequency analysis, it is necessary

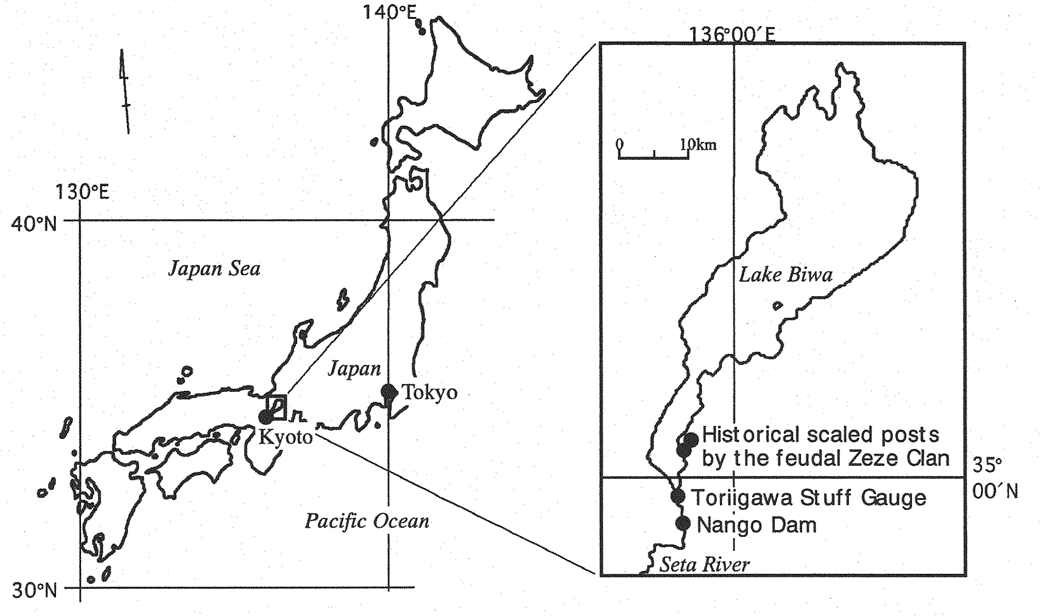

Fig. 1. Location maps of the study area.

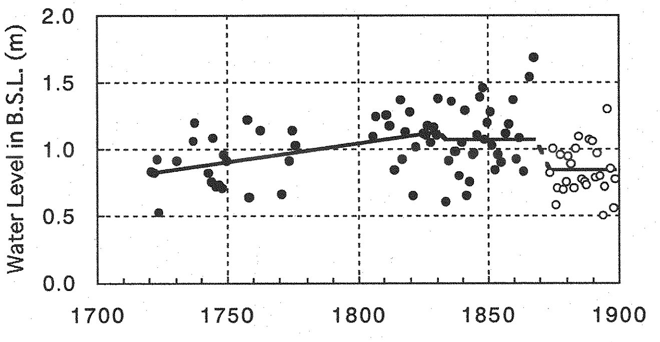

Fig. 2. Ordinary lake level before the late 19th century (solid lines). The closed and open circles indicate the yearly averages of monthly observations by the feudal Zaza Clan and daily observations at the Toriigawa Stuff Gauge, respectively.

to remove these time-dependent factors from the data (see Sho (15)). Thus, in this study we converted all the peak level data into those that would have realized under the condition of the stage–discharge relationship (H–Q) in the late 19th century. For the period after 1912, since gaged daily lake level and discharge data are available, lake levels can be converted on a daily basis by calculating the inflow into the lake through the stage–storage relationship (H–V) and applying the H–Q equation for the late 19th century. For the period before the mid-19th century, for which only fragmentary lake level data are available, we assumed that the variation of the discharge capacity of the Seta River is reflected in the variation of the ordinary lake level, i.e., flood peak levels were converted by simply subtracting the difference between the ordinary lake level at the time of flood occurrence and that of the late 19th century (B.S.L. + 0.833 m). The ordinary lake level for each year in the historical period was estimated from the regression lines fitted to the plots of historical monthly lake level observation data recorded by the feudal Zeze Clan against year (see Fig. 2; Sho (15)).

Since flood peak levels are easily affected by time-dependent or artificially controlled factors as mentioned above, it is common in Japan to conduct a frequency analysis with flood rainfall data and determine the design flood

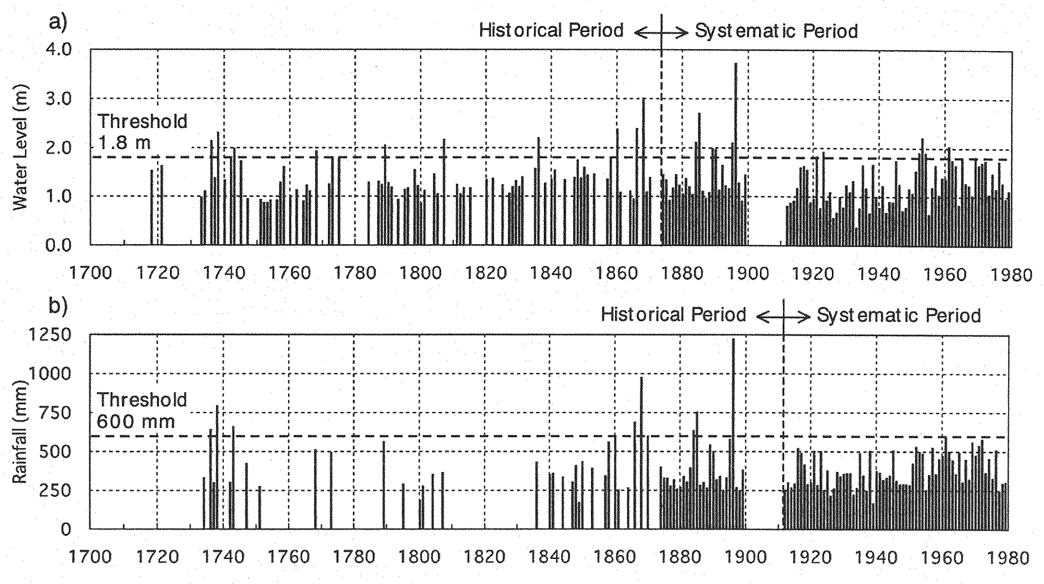

Fig. 3. Reconstructed chronologies of (a) converted flood peak water level, and (b) annual maximum areal rainfall total for 30 days.

through a rainfall–runoff model. Therefore, it is useful if the magnitude of historical floods can be denoted by not only peak water level but the corresponding rainfall. Rainfall into the drainage can be estimated from lake water level data by calculating the inflow into the lake based on the continuity of inflow–storage–outflow, given the H–V and H–Q equations and the rainfall–runoff relationship (including evapotranspiration) of the drainage. Previously we proposed an estimation model of the mean areal rainfall total for the duration of historical floods over the drainage basin of Lake Biwa, using the lake level records at the beginning and the end (peak) of the flood period and the shape of hyetograph estimated from daily weather records in old diaries to complement discrete water level data (see Sho *et al.* (18)). Although extreme rainfall for two days or shorter is usually employed as the random variable for flood frequency analysis in Japan, in this study we attempted to reconstruct flood rainfalls for 30 days by applying this model. This is because, unlike usual river flooding in Japan, total amount of rainfall for a considerably long period is closely related to flood occurrences in the case of Lake Biwa, where the inflow overwhelms the discharge capacity in the time of flooding. Also, considering the fact that the historical lake level observation record by the feudal Zeze Clan is available only on a monthly basis, it is not practical to set the flood period shorter than 30 days of which lake levels at the beginning and the end should be known.

The reconstructed chronologies of the converted peak water level and the mean areal rainfall total for 30 days together with the recent systematic gaged data are shown in Figs. 3a and 3b, respectively. In Fig. 3a, the mean areal rainfall totals for 30 days are reconstructed every year for 1874–1899 with the similarity in fluctuation to the flood peak water level though the systematic gaged record starts at 1912. The reason for this is that the daily lake water level record is available for this period while there are only sparse (monthly or even less) lake level data for the preceding period.

FLOOD FREQUENCY ANALYSIS WITH HISTORICAL DATA

In this section we attempt to incorporate the reconstructed historical flood data into a flood frequency analysis. Assuming that the converted peak water levels and the mean areal rainfall totals for 30 days shown in Fig. 3 to be the samples independently extracted from a homogeneous population of annual maxima, we examine the distributions of these two extreme hydrologic variables by probability plotting, and evaluate the effects of including historical information on the estimation reliability of flood quantiles.

Definition of the Systematic and Historical Period

We define the systematic period as the time period during which systematic gaged data of interest are available for every year, and the historical period as the prior period for which only data exceeding some threshold are available while the information of not exceeding the threshold is only given for the remaining years. The time spans of the systematic and historical periods in this study need to be determined first.

Continuous level observation of Lake Biwa started in 1874 when the Toriigawa Staff Gauge was installed at the outlet. Therefore, we determined the systematic period corresponds to 1874–1980 for the converted peak water level, except 1900–1911 during which the changing H–Q relationship due to improvement works at the Seta River makes it difficult to convert the lake level data. For the mean areal rainfall total for 30 days, we decided that the systematic period corresponds to 1912–1980 during which precipitation data at enough number of stations to calculate the areal mean are available on a daily basis. Concerning the historical period, we assumed that, for both the converted peak water level and the mean areal rainfall total for 30 days, it starts at 1718 for which the oldest quantitative flood record is obtained.

The thresholds for the historical period need to be set next. Although the minimum value of available historical data is typically considered as the threshold of perception, in the case of this study, there are presumably many unrecorded floods exceeding the magnitude of the smallest historical flood recorded, for the availability of records does not depend solely on the magnitude for relatively small events. Furthermore, the degree of precision of the estimation of historical data tends to be lower for smaller events because of scarcity of information, which lessens the advantage of utilizing these data (see Sho *et al.* (16)). Thus, here we set the censoring threshold to 1.8 m for the converted peak water level so as to ensure that there is no unrecorded event exceeding the threshold and to select only high-precision data of large events. The number of data exceeding this threshold is 13 in both the historical and systematic period respectively. For the mean areal rainfall total for 30 days, daily weather records during the flood period is required in addition to lake level records for reconstructing the datum, increasing the risk of missing larger events. Since all the data exceeding the threshold must be available, we set the threshold to 600 mm as the value that is certainly exceeded by no unknown events. This threshold is exceeded by 10 events in the historical period and no events in the systematic period.

Plotting Position Formulas

The plotting position formulas to estimate p_i, the exceedance probability for the ith order statistic among n sample data, are generally denoted as:

$$\hat{p}_i = \frac{i-a}{n+1-2a} \qquad (1)$$

where $\hat{p}_i$ is the estimate of p_i and a is a constant that takes a value between 0 and 0.5. For example, when $a = 0$ and $a = 1$ in Eq. 1, the Weibull and Hazen formulas are obtained, respectively. When $a = 0.44$, Eq. 1 is the Gringorten formula, which is optimized for the Gumbel distribution (see e.g. Stedinger *et al.* (20)).

Hirsch (5), Hirsch & Stedinger (6) extended Eq. 1 to make it applicable to historical or paleohydrologic data exceeding a threshold and proposed the Exceedance formula:

$$\hat{p}_i = \begin{cases} \dfrac{i-a}{k+1-2a}\dfrac{k}{n}, & i = 1,\ldots,k \\ \dfrac{k}{n} + \dfrac{n-k}{n}\dfrac{(i-k-a)}{(s-e+1-2a)}, & i = k+1,\ldots,g \end{cases} \qquad (2)$$

where k is the number of data exceeding the threshold, out of which e belongs to the systematic period of s years, and g is the total number of data available (hence $g = k + s - e$). When $a = 0$, $a = 1$, and $a = 0.44$ in Eq. 1, the Exceedance-Weibull (denoted here as E-W), Exceedance-Hazen (E-H), and Exceedance-Gringorten (E-G) formulas are obtained, respectively.

Hirsch (5), Hirsch & Stedinger (6) examined the estimation precision of the exceedance probability and the corresponding probability quantile for $i = 1$ (the 1st order statistic) for each plotting position formula using Monte-Carlo simulation. As a result, they found that the Weibull and E-W formulas give estimates with a small bias in terms of exceedance probability in the case where the threshold is exceeded by several or more events. On the other hand, in terms of probability quantile, the Weibull and E-W formulas give substantially negatively biased estimates while the Hazen, Gringorten and E-G formulas generally give less biased estimates. Especially the E-G formula was shown to perform relatively good estimation over a broad range of distribution types and the number of above-threshold data. A similar result was obtained also for $i = 2$. In this study, placing importance on estimation precision in terms of quantiles, we employed the E-G formula to calculate plotting positions.

Estimation of Flood Quantiles and Its Precision

The probability plots of the converted peak water levels and the mean areal rainfall totals for 30 days on the Gumbel probability papers are shown in Figs. 4a and 4b, respectively. Plots of above-threshold historical data together with systematic data based on the E-G formula (right graphs) are compared to cases where only systematic data are utilized (left graphs). In each case, the lognormal (broken line) and Gumbel (solid line) distributions were fitted as the flood-frequency curves. In this study we examined the goodness-of-fit particularly to the Gumbel distribution, which is mainly employed in flood frequency analyses for Lake Biwa (see e.g. Biwako Construction Office, Kinki Regional Construction Bureau, Japan Ministry of Construction *et al.* (3); Ikebuchi & Maeda (10)). The curve fitting was performed so as to minimize the sum of the absolute deviations from all the plots (including the 1868 and 1896 events) in water level or rainfall (see Hirsch (5)):

$$\sum_{i=1}^{g}\left|Q_i - \hat{F}^{-1}(1-\hat{p}_i)\right| \qquad (3)$$

where Q_i is the ith order statistic and $\hat{F}^{-1}$ is the inverse of the cumulative distribution function fitted.

Quantiles corresponding to the return periods of 100 and 200 years estimated from the fitted frequency curves for each case are shown in Table 1. 100- and 200-year flood estimates based on both historical and systematic data are smaller than those excluding historical data in terms of water level (Table 1a), while larger in terms of rainfall (Table 1b). This is because the late 19th century, in which the occurrence of several extreme floods concentrate, belongs to the systematic period in terms of water level and to the historical period in terms of rainfall (see Fig. 3).

As may be seen from Fig. 4, in terms of both water level and rainfall, the sample data plot close to a straight line in the right graphs compared with the left ones. Especially for the mean areal rainfall total for 30 days, the bending line of the sample data plots appears to show that these samples come from two separate populations when based on the systematic 69 samples (Fig. 4b, left), but these plots align nearly on a single straight line except two extraordinary events of 1896 and 1868 in the case of adding the historical samples (Fig. 4b, right). This indicates that it became apparent by including historical data that the flood-frequency relationship for Laka Biwa can be properly described by the Gumbel distribution. These results are essentially true also in the case where the lognormal distribution is employed, though the fitted frequency curves appear to be slightly more flexible to the bending lines of data plots.

Moreover, focused on the interval corresponding to return periods of ~20 to ~100 years, reduction in the deviation of sample data plots from the fitted frequency curves is evident as well as increase in the number of plots in the right graphs in Fig. 4. This is evidence that the estimation precision of around 20- to 100-year floods, which is crucial for floodplain management or designs for flood control facilities in Japan, was largely improved by incorporating historical flood information in the cases of this study.

SUMMARY

In this study, the effects of incorporating historical flood information into a flood frequency analysis were

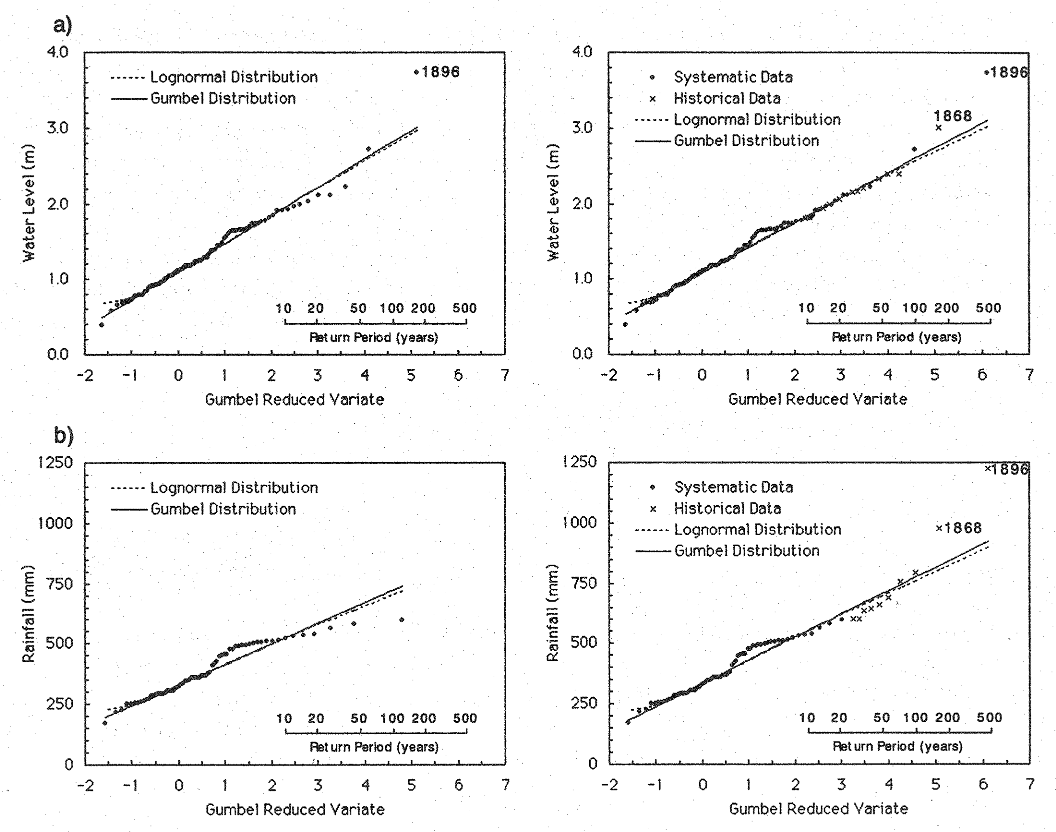

Fig. 4. Plots on the Gumbel probability papers and the fitted flood-frequency curves, (a) converted flood peak water level, and (b) annual maximum areal rainfall total for 30 days. The left and right graphs correspond to the case where only systematic data are utilized and where historical data are incorporated, respectively.

Table 1. 100- and 200-year flood quantiles estimated for each case, (a) converted flood peak water level, and (b) annual maximum areal rainfall total for 30 days.

a)	Systematic Data Only (1874–1980)		Historical & Systematic (1718–1980)	
	Lognormal	Gumbel	Lognormal	Gumbel
100-year	2.78	2.82	2.57	2.61
200-year	3.03	3.08	2.78	2.84

b)	Systematic Data Only (1912–1980)		Historical & Systematic (1718–1980)	
	Lognormal	Gumbel	Lognormal	Gumbel
100-year	702	722	762	777
200-year	753	782	824	843

evaluated for Lake Biwa using the reconstructed records of the converted peak water level and the mean areal rainfall total for 30 days for since the 18th century. As a result of plotting the systematic and the above-threshold historical data on the Gumbel probability papers, additional sample data plots for historical large floods revealed that the data sets were consistent with the Gumbel distribution and improved significantly the estimation precision of flood quantiles corresponding to return periods of ~20 to ~100 years.

One of common problems in historical or paleoflood hydrology is the uncertainty of historical information. Incorporation of historical data with substantial errors can lower the reliability of the flood frequency analysis despite increase in the number of sample data (see e.g. Kuczera (13)). In the case of this study, errors in historical samples are estimated to be small enough (~5% or less) for extreme floods, while substantially large (up to ~30%) for smaller events (see Sho (15)). Monte Carlo simulations with the process of error generation in historical samples will provide useful information to make the best use of historical data, such as the optimal magnitude of the censoring threshold (see Hosking & Wallis (8); Sho *et al.* (16)).

In Japan, few studies on historical or paleoflood hydrology have been made in the context of application to engineering. The results of this study show the potential of historical hydrology in Japan, though the total rainfall for 30 days that is the random variable employed here is not typical in flood frequency analyses. Further practical researches for various river basins are hoped hereafter.

REFERENCES

1. Baker, V.R., G. Pickup, and H.A. Polach : Desert paleofloods in central Australia, *Nature*, Vol.301, pp.502-504, 1983.
2. Baker, V.R., R.H. Webb, and P.K. House : The scientific and societal value of paleoflood hydrology, in *Ancient Floods, Modern Hazards*, P.K. House, R.H. Webb, V.R. Baker, and D.R. Levish, eds., pp.1-19, AGU, Washington DC, U.S.A., 2002.
3. Biwako Construction Office, Kinki Regional Construction Bureau, Japan Ministry of Construction and Kansai Regional Bureau, Water Resources Development Public Corporation (eds.) : Report of Investigation Project on Historical Floods and Flood Frequency of Lake Biwa, Part II, pp.3-22, 1987, (in Japanese).
4. Cohn, T.A., W.L. Lane, and W.G. Baier : An algorithm for computing moments-based flood quantile estimations when historical flood information is available, *Water Resources Research*, Vol.33, No.9, pp.2089-2096, 1997.
5. Hirsch, R.M. : Probability plotting position formulas for flood records with historical information, *Journal of Hydrology*, Vol.96, pp.185-199, 1987.
6. Hirsch, R.M. and J.R. Stedinger : Plotting positions for historical floods and their precision, *Water Resources Research*, Vol.23, No.4, pp.715-727, 1987.
7. Hosking, J.R.M. and J.R. Wallis : Paleoflood hydrology and flood frequency analysis, *Water Resources Research*, Vol.22, No.4, pp.543-550, 1986.
8. Hosking, J.R.M. and J.R. Wallis : The value of historical data in flood frequency analysis, *Water Resources Research*, Vol.22, No.11, pp.1606-1612, 1986.
9. House, P.K. and V.R. Baker : Paleohydrology of flash floods in small desert watersheds in western Arizona, *Water Resources Research*, Vol.37, No.6, pp.1825-1839, 2001.
10. Ikebuchi, S. and M. Maeda : Estimation of design rainfall and water level with systematic and historical flood information, *Annuals of the Disaster Prevention Research Institute, Kyoto University*, No.34 B-2, pp.103-125, 1991.
11. Jarrett, R.D. and E.M. Tomlinson : Regional interdisciplinary paleoflood approach to assess extreme flood potential, *Water Resources Research*, Vol.36, No.10, pp.2957-2984, 2000.
12. Kochel, R.C. and V.R. Baker : Paleoflood hydrology, *Science*, Vol.215, No.4531, pp.353-361, 1982.
13. Kuczera, G. : Uncorrelated measurement error in flood frequency inference, *Water Resources Research*, Vol.28, No.1, pp.183-188, 1992.
14. Luo, C.-Z. : Investigation and regionalization of historical floods in China, *Journal of Hydrology*, Vol.96, pp.41-51, 1987.
15. Sho, K. : Estimation of historical hydrologic environment of Lake Biwa and its application to hydrologic engineering, Doctoral dissertation, Kyoto University, Kyoto, Japan, 2003, (in Japanese).
16. Sho, K., S. Iwasaki, M. Nagao, and A. Tominaga : Effect of introducing uncertain historical hydrologic data on quantile estimation accuracy, *Journal of Hydroscience and Hydraulic Engineering*, Vol.18, No.1, pp.45-52, 2000.
17. Sho, K., M. Nagao, and A. Tominaga : Reconstruction of water level data of historical floods at Lake Biwa using old documents, *Annual Journal of Hydraulic Engineering, JSCE*, Vol.44, pp.371-376, 2000, (in Japanese).

18. Sho, K., M. Nagao, and A. Tominaga : Reconstruction of historical flood data for Lake Biwa basin using daily weather records of old diaries, *Journal of Hydraulic, Coastal and Environmental Engineering*, No.656/II-52, pp.15-25, 2000, (in Japanese).
19. Stedinger, J.R. and T.A. Cohn : Flood frequency analysis with historical and paleoflood information, *Water Resources Research*, Vol.22, No.5, pp.785-793, 1986.
20. Stedinger, J.R., R.M. Vogel, and E. Foufoula-Georgiou : Frequency analysis of extreme events, in *Handbook of Hydrology*, D.R. Maidment, ed., Chapter 18, McGraw-Hill, New York, U.S.A., 1993.

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