1. Evaluation of Flow Regime in the Upper Reaches of Streams Using the Stochastic Flow Duration Curve

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ABSTRACT

A stochastic estimation of drought evaluation in the upper reaches of streams is needed in the planning of development and management for water resources and/or water use. In this paper, the stochastic flow duration (SFD) curve, which was presented by Sugiyama et al., (2002), is applied to five catchments located in eastern Japan and to two catchments in western Thailand. The result indicates that by using this curve it is possible to stochastically evaluate the severity of high, ordinary, and low flow regimes of streams. Moreover it is illustrated that the 10 year probability for the discharge exceeded 97 percent of time may be recognized as an index of low flow.

(Key Terms : surface hydrology, stochastic flow duration curve, flow regime, low flow index, Weibull plotting formula, Log-normal distribution)

INTRODUCTION

The flow duration curve is one of the informative methods that shows characteristics of the flow regime for a river basin, and has been used as a useful tool for various water resources problems, irrigation and/or hydro electric power planning since the end of 19th century. Because the effects of climate, topography, and geology are integrally represented in the flow duration curve, the curve is useful for the comparison of runoff characteristics between different land use areas (Takimoto et al., 1994). A method, which enables confidence intervals and return periods to be associated with the flow duration curve, proposed by Vogel and Fennessey (1994) is novel and convenient for the evaluation of the flow fluctuation in the rivers.

The flow duration curve of daily flows is drawn with the serially correlated data. However, such a curve is not appropriate for extracting stochastic hydrologic information for water resources problems. It is suggestive that Smakhtin (2001) recently emphasized, in a review for low flow hydrology, "Although the recent years have seen the increased interest to flow duration curve (FDC) on hydrology, water resources and river ecology, its application potential is not yet fully explored". An application of the stochastic flow duration curve (SFD) is more convenient for sustainable planning and/or management of water resources in the upper reaches of streams.

The aim of this paper is to show an improved procedure for constructing a flow duration curve and to stochastically evaluate flow regime, especially the severity of low flow in upper reaches of several streams in Japan and Thailand.

STOCHASTIC FLOW DURATION (SFD) CURVE

Definition of SFD Curve

A flow duration curve is generally drawn with discharge arranged in order of descending magnitude. Namely, the magnitude of a stream discharge is plotted as ordinates against the corresponding percent of time, the probability that an arbitrary discharge will be equaled or exceeded, as abscissas. If a flow duration curve is drawn by using an arbitrary flow return period at suitable

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time interval (abscissas), such a curve is very useful for stochastically evaluating the flow fluctuation of streams. In this paper, the stochastic flow duration curve is defined as one which is drawn by using the distribution characteristics of a set of probability plots of stream flow calculated by the Weibull plotting formula at suitable time intervals from 0 to 100 percent on the time axis. Under this definition, the stochastic flow duration (SFD) curves with an arbitrary return period can be drawn by examining the probability distribution of daily discharge time series for successive years. Then, it is possible to stochastically evaluate the severity of high, ordinary, and low flow regimes of streams.

Procedure of the SFD Curve

An improved procedure consisting of three phases follows.

Phase 1 :

① Construct a flow duration curve of a water year by plotting and arranging the daily discharge values in descending order (as shown in Figure 1A).

② Read the values of daily discharge parallel to the ordinate and cross to the flow duration curve at suitable intervals from 0 to 100 percent on the time axis (as shown in Figure 1B).

Phase 2 :

Continue above-mentioned ①→② steps for each of the given water years.

One needs at least 8-15 data points to successfully draw a new flow duration curve. In this paper, an interval increasing by 8 % each time and up to 100 % is used.

Firstly, examine the probability distribution for the daily discharge of a given N year data extracted at suitable time interval, and provide the appropriate probability density function.

The necessary steps in plotting the magnitude versus the probability are as follows :

③ Rank in ascending order of the discharge values read from each flow duration curve of a given N year term.

④ Calculate the plotting position with the following Weibull plotting formula, select the type probability paper to be used, and plot the data on the probability paper.

$$P = m / (n+1) \times 100\ \% \qquad (1)$$

Where, P is the probability of all events less than or equal to each discharge value, m is the rank of the event, n is the number of events on record.

⑤ Fit a straight line through the estimated values by eye.

⑥ Read the discharge value down from the best fit line at the chosen probability value on the ordinate.

Continue above-mentioned ③→⑥ steps at suitable time intervals from 0 to 100 percent on the time axis (as shown in Figure 1C).

Secondly, read the discharge values equivalent to an arbitrarily return period using the best fit line.

Phase 3 :

⑦ Plot probability daily discharge values read at suitable intervals, and draw a smooth SFD curve (as shown in Figure 1D).

RESEARCH CATCHMENTS AND DATA SETS

Description of Research Catchments

Seven research catchments were selected with the restriction that there are no regulation or diversion structures in the upper reaches of streams. Approximate locations of the selected seven dams are shown in Figure 2. The catchments (No.1 ～5) are located in eastern Japan (Figure 2A), and the Srinagarind Dam (S-Dam) (No.6)and the Khao Laem Dam (K-Dam)(No.7) basins are located in the upper reaches of the Mae Klong River in western Thailand which borders with Burma (Figure 2B). The divide between S-Dam and K-Dam basins consists of a mountain range which has an altitude of about 2,000 m, causing a great difference in rainfall between the two basin areas (Table 1).

The basin area and hydrological data for the research basins are given (Table 1). From these specifications, the range in catchment areas is 45.9-10,880 km^2, the range in record lengths is 15-43 years, and the annual runoff depth averaged

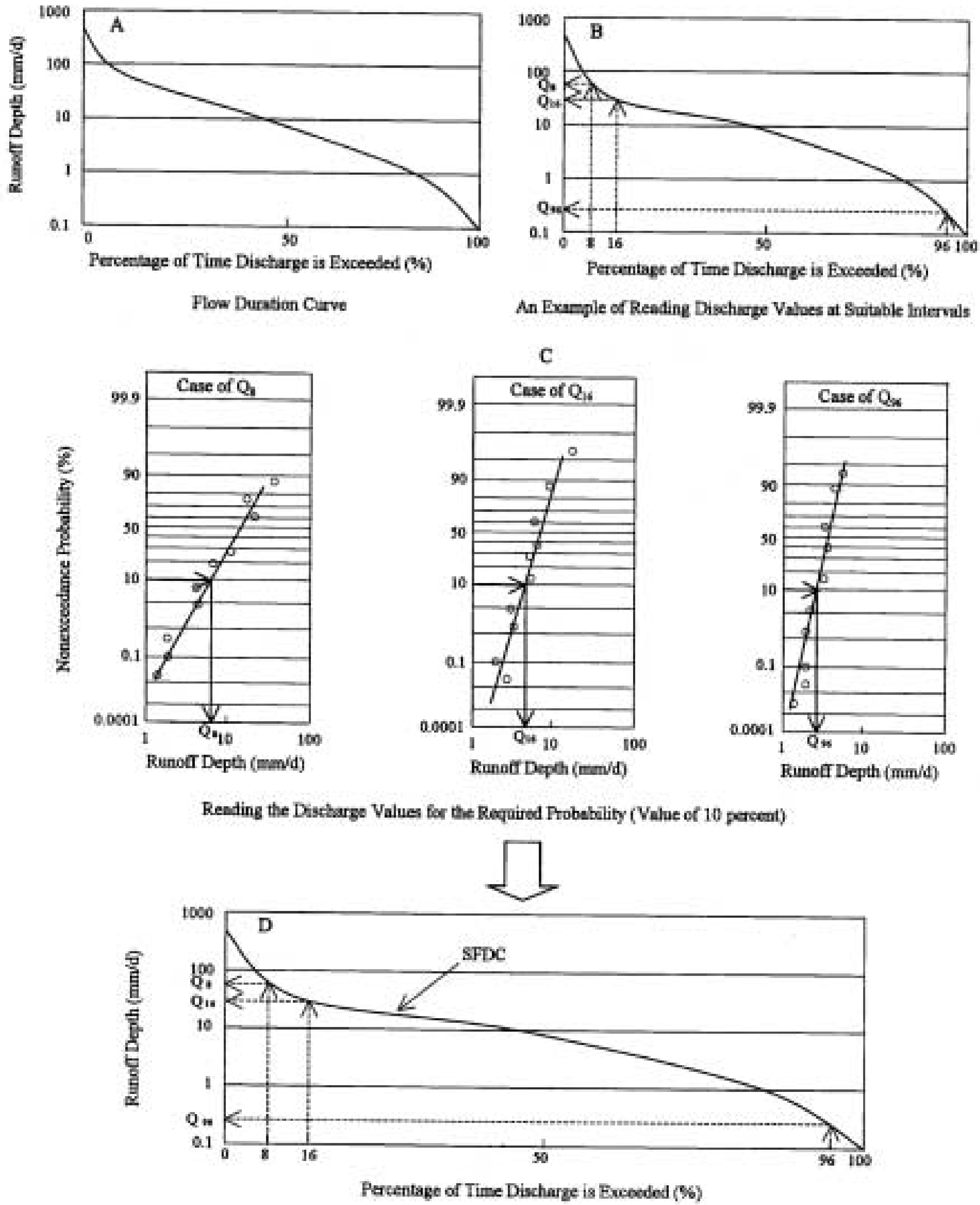

Figure 1 Daily Discharge Fitted on Log-normal Probability Paper and Reading the Discharge Values for the Required Probability (Value of 10 percent).

over the period of record ranges 400-4,407 mm/y. The annual precipitation (R) in Table 1 is estimated using point values observed at the dam sites, and may therefore be an underestimation of the average value over catchment.

There are several catchments (No.1,2,3 and 5) where annual runoff depth is greater than annual precipitation and the water balance is not satisfied. This discrepancy arises because these catchments are located in the upper reaches of streams in the heavy snowfall region. In these catchments, the average length of time that the snowpack exits, is about 4～5 months.

On the one hand, the climate characteristics

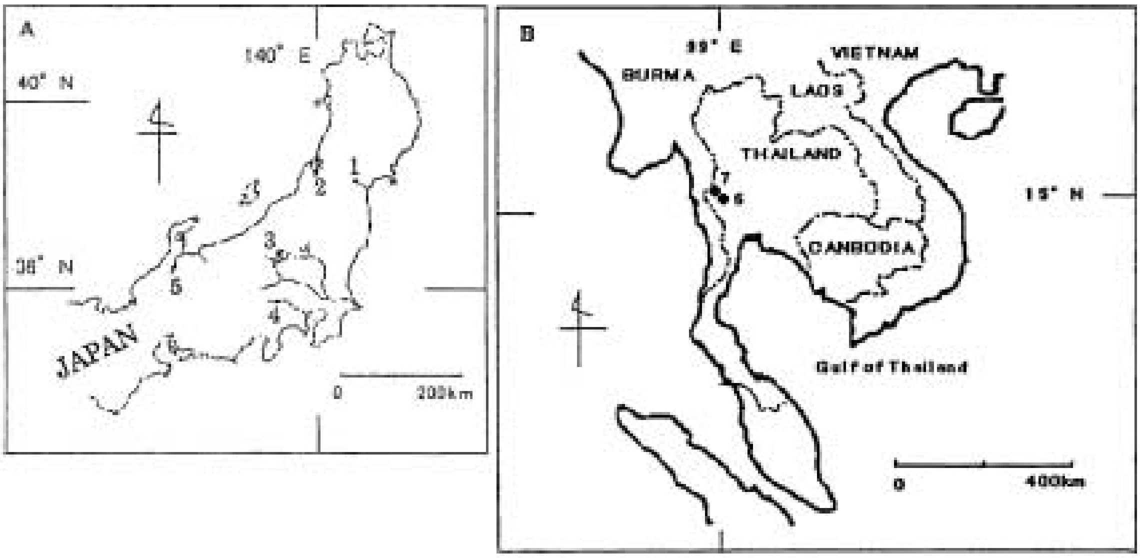

Figure 2 Location of Research Catchments.

of Thailand located in the tropical zone fundamentally depends on the direction of the monsoon wind, and the occurrence of depressions (mainly Typhoon). The southwest monsoon season begins in mid-May and ends in late October (namely, rainy season), and during this period heavy rain often occurs. On the other hand, the period when the northeast monsoon starts at the end of October and ends in February of next year is generally called the dry season.

Characteristics of Flow Data

Figure 3 shows the fluctuation of average daily inflows at a reservoir in successive years at each catchment. The peak snowmelt event in the heavy snow region occurs in early April in the Ookura Dam (No.1) and Toori Dam (No.5) basins, and at the end of April in the Arasawa Dam (No.2) basin. In the case of the Yagisawa

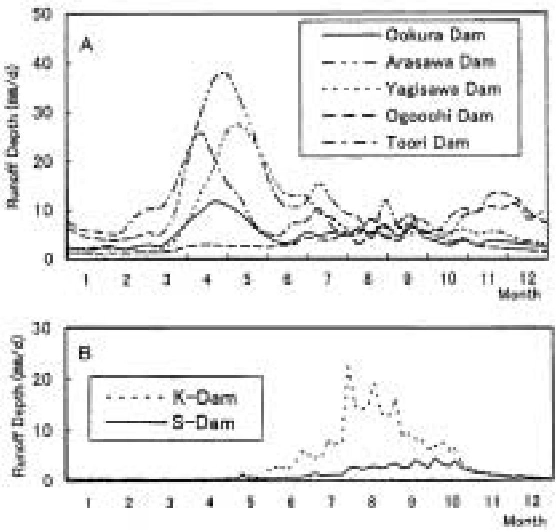

Figure 3 Average Daily Discharge of Successive Years in the Dam Basins.

Table 1 Description of Research Catchments

No.	Dam Station	Basin Area (km²)	Period of Record	R[1] (mm/y)	Q[2] (mm/y)
1	Ookura	88.5	1962~1999	1,357	1,687
2	Arasawa	162.0	1957~1999	3,099	4,407
3	Yagisawa	167.4	1967~1998	1,589	2,931
4	Ogoochi	262.9	1959~1998	1,577	1,069
5	Toori	45.9	1968~1998	3,177	3,371
6	Srinagarind	10,880	1982~1999	999	400
7	Khao Laem	3,720	1985~1999	1,725	1,391

[1] Average precipitation for the period of record.
[2] Average runoff depth for the period of record.

Dam (No.3) basin, located in the mountain ridge zone of Japan's main island, the peak discharge event comes close to early May. It is this characteristic that the peak event of the Yagisawa Dam basin is later than that of the Toori Dam and Ookura Dam basins. On the one hand, in the case of the Ogoochi Dam (No.4) basin which does not have a snowpack, the peak discharge event occurs from August to September during the typhoon season. In addition, this peak discharge is only at 1/5 that of the Arasawa dam basin which has heavy snowpack. These flow aspects indicate that snowmelt is valuable for water resources. On the other hand, in the case of S and K Dam basins located in the tropical monsoon zone (Figure 2B), which have trends of dry and wet seasons, the fluctuation of daily inflows at a reservoir is quite different from that of the Temperate Zone (Figure 2A). In addition, there is the remarkable difference of runoff depth between the two catchments (Figure 3B) arising due to the difference in monthly rainfall (Figure 4) during the wet season and/or catchment characteristics.

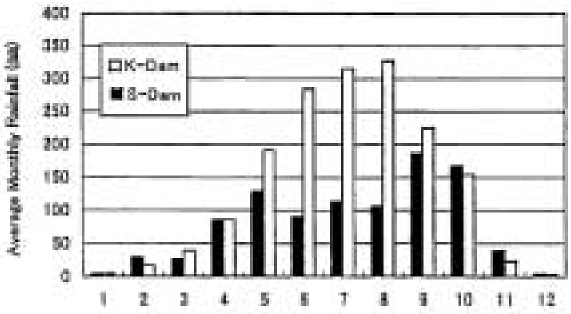

Figure 4 Comparison of Average Monthly Rainfall in the S and K-Dam Basins.

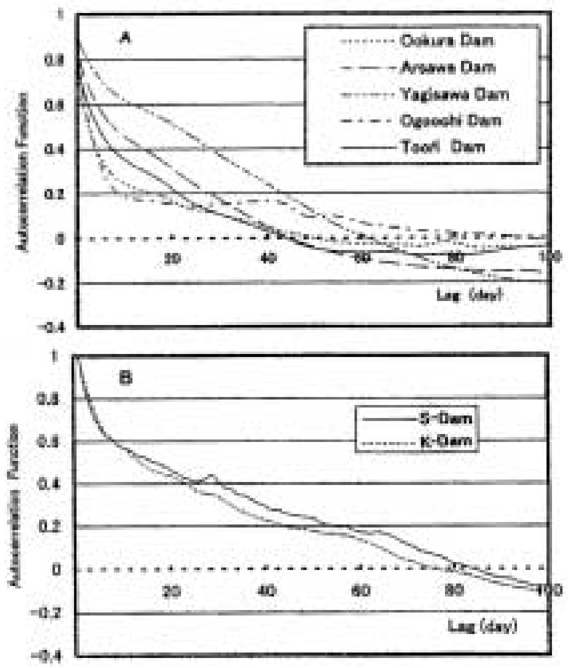

Figure 5 Autocorrelation Function of Daily Discharges.

Autocorrelation values of the daily inflow at each reservoir are shown in Figure 5. A comparison of given catchments in Figure 5A indicates that the sustained inflow to the reservoir in the Yagisawa, Arasawa, and Toori Dam basins located in the heavy snow region, depends on the amount of snowmelt in early spring. Snowmelt in late spring combines with heavy rain in the typhoon season in the Yagisawa Dam basin, so that daily inflows show much more persistence than the other basins. The persistent inflow period at the Ogoochi Dam basin is longer than the other basins. That behavior indicates the reliable baseflow contribution from the Ogoochi Dam basin is stronger than that for the other dam basins. From comparison of the autocorrelation functions of the S and K Dam basins (Figure 5B), it is apparent that the reliable baseflow contribution from the S-Dam basin is a little stronger than that from the K-Dam basin.

SFD CURVE : ITS APPLICATION AND DISCUSSION

Stochastic Evaluation of Flow Regimes in the Upper Reaches of Streams

The following describes the manner in which the flow duration curve is applied to stochastically evaluate the flow regime in the upper reaches of streams. By following Phase 2 and 3 previously presented (as shown in Figure 1), the SFD curves of given research catchments are drawn. Figure 6 shows examples of the SFD curve in the research catchments drawn by following the construction procedure presented. Since the abscissa represents the percentage of time during which specified discharge are equaled or exceeded in a water year, the presence of zeroes in the flow record (i.e, the two reservoirs in Thailand, No.6 and 7 in Figure 2), the abscissa is standardized by the day of daily flow being greater than zero in a water year. To draw the smooth SFD, it is necessary to shorten the time interval on the abscissa. Although a time interval of 30 days is generally used in this paper, for the construction of the lower end of the SFD curve, the probability discharge values at an interval of 5 days is used. It is due to the importance of this part of the SFD curve in the evaluation of the low flow persistence in catchments.

In Japan, the nonexceedance probability value of 10 % (10 year probability) of the discharge exceeded 97% of time (355 days) has generally been recognized as a design flow for water resources facilities based on the severity of droughts. Thus, in this paper, the approach of the SFD curve which is obtained for the discharge values of 10 year probability of nonexceedance constitutes a fundamental approach.

In this paper, because we focus on an evaluation of flow regime in a extreme drought year, the comparison between the SFD with the 10 year probability value and the flow duration curve for an extreme drought year is carried out. Part of these results are shown in Figure 6. Moreover, in this paper, a year showing minimum annual discharge during a given N year term is defined as an extreme drought year.

In the case of Figure 6A (Ookura Dam basin), the behavior of the two curves represented from approximately the 40 % of time to the 95 % of time is very similar. It can be seen that the flow regime from the ordinary flow to the low flow in the extreme drought year in the Ookura Dam

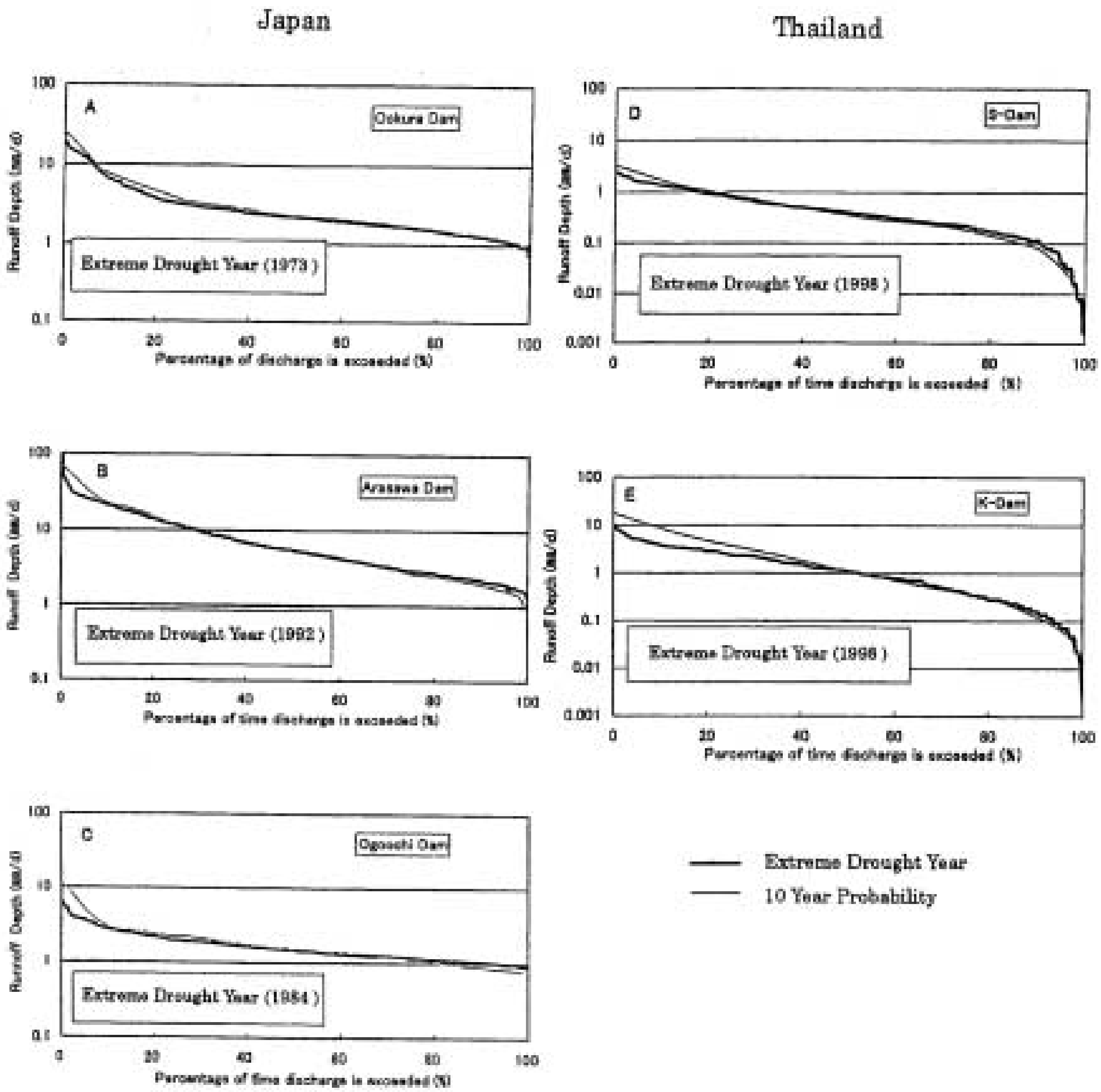

Figure 6 Stochastic Flow Duration Curves to Dam Basins.

basin can be evaluated as the flow regime having a 10 year probability. And the discharge exceeded 97 % of time in the extreme drought year is approximately equal to the discharge value of the SFD curve. This aspect indicates that this flow regime is uncomfortable for planning if a water resources planner will evaluate a flow regime with the 10 year probability. It may be argued that a more severe probability of occurrence (i.e. longer than 10 year) should be adopted for the design of water resources facilities in the Ookura Dam basin. In Figure 10B (Arasawa Dam basin), daily discharge in the extreme drought year until about 20 % of time is lower than the value extracted from the SFD curve with the 10 year probability, although the two curves show similar behavior until about 70 % of time. And as the time % increases, this aspect reverses. In particular, the discharge exceeded 97 % of time for an extreme drought year is higher than the value extracted from the SFD curve with the 10 year probability. Also in the case of the Ogoochi Dam basin (Figure 6C), the flow duration curve for the extreme drought year from the high flow range to approximately 55-70 % of time is shown under the SFD curve with the 10 year probability. However, as time % increases, the runoff depth in the extreme drought year is higher than the value extracted from the SFD curve, and the flow regime exceeded about 97 % of time shows a desirable tendency that represents low flow persistence. From these aspects, it can be seen that these dam basins (B and C in Figure 6) have strong persistence characteristics during the low flow period.

Examples from the S and K - Dam basins are shown in Figure 6D and E. In the case of S-Dam basin, the SFD curve is shown under the curve of the extreme drought year from approximately 40 % of time to the end of the curve. In contrast, K-Dam basin (Figure 6,E) has the tendency that as time % increases after approximately 55 %, the curve for the extreme drought year is shown under the SFD curve with the 10 year probability. Interestingly, the amount of rainfall in the K-Dam basin is much greater than the S-Dam basin, which indicates that this aspect may be dependant on catchment characteristics. By following this aspect, it is apparent that the low flow regime in the S-Dam basin is less severe than that in the K-Dam basin, and the K-Dam basin may require the severity of low flow with probability of occurrence longer than 10 year for water resources planning. It is concluded that the S-Dam basin is a more reliable source of water during prolonged drought conditions within the annual cycle.

Equivalence between $Q97_{10}$ and $Q_{10,7}$

In the United States, a value of the 10 year probability for annual minimum flow averaged over a consecutive period of 7 days ($Q_{10,7}$) of a given year has been used as an index of low flow (for example, Singh, et al.,1971). Our goal in this section is to discuss whether a value of the 10 year probability for the discharge exceeded 97 % of time ($Q97_{10}$), which is widely used as an index of low flow in Japan, is equivalent to $Q_{10,7}$. Figure 7 shows the plotted data for the annual minimum flow averaged over 7 days which were estimated using the Weibull plotting formula (equation (1)). Except for one single point in the Toori Dam basin (Figure 2, No.5), all the plotted data for the catchments in Japan fit well to a straight line. And so in case of the S and K-Dam basins in Thailand, it is apparent that discharge data for the annual minimum flow averaged over 7 days follow the log normal distribution function with some deviations from a straight line because the

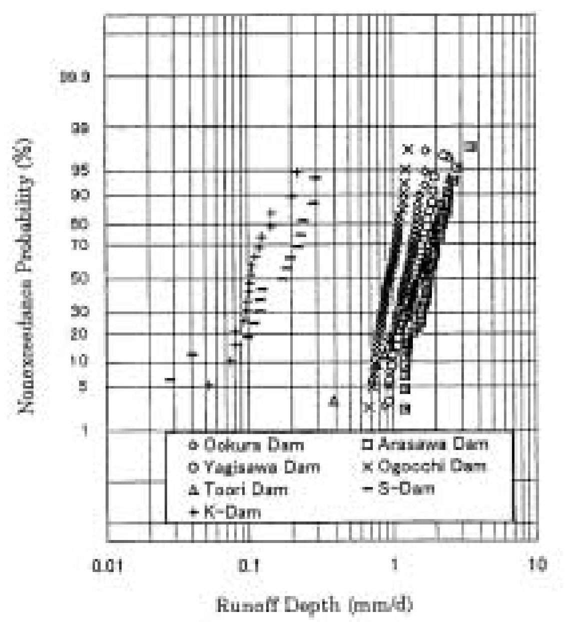

Figure 7 Distribution of the Lowest Average Flow over a Consecutive Period of 7 Days on a Log-normal Probability Paper.

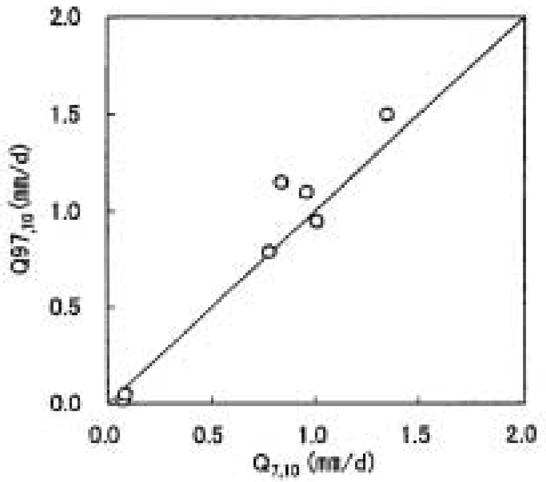

Figure 8 Relationship between the Discharge Exceeded 97 % of time ($Q97_{,10}$) and the Lowest Average Flow over a Consecutive Period of 7 Days ($Q_{7,10}$), Occurring at an Average of One in 10 Years.

data are few.

The relationship between $Q_{10,7}$ and $Q97_{10}$ is shown in Figure 8. It can be seen that the correlation of two hydrological values is high although the number of points plotted is rather small. This observation implies that a value of the 10 year probability for the discharge exceeded 97 % of the time can be recognized as an index of low flow.

CONCLUSIONS

In this paper, the definition and the construction procedure for the SFD curve (Sugiyama et al., 2002) are presented (as shown in Figure 1), and applied to five research catchments located in eastern Japan, and to two catchments in western Thailand. The result indicates that by using the SFD curve it is possible to stochastically evaluate the severity of high, ordinary, and low flow regimes of streams. The 10 year probability for the discharge exceeded 97 percent of time may be recognized as a useful index of low flows.

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LITERATURE CITED

Singh, K.P., 1971. Model Flow Duration and Stream Flow Variability, Water Resources Research, 7(4) :1031-1036.

Smarkhtin,V.U., 2001. Low Flow Hydrology : A Reviw, Journal of Hydrology, 240, : 147-186.

Sugiyama,H, V. Vudhivanich, A.C. Whitaker and K. Lorsirirat, 2002. Stochastic Flow Duration Curves for Evaluation of Flow Regimes in Rivers, Journal of the American Water Resources Association (In press).

Takimoto,H., T.Tanaka, and H. Horino, 1994. Does Forest Conserve Runoff Discharge during Drought ? -A case study of Gojo Yoshino area-, Trans. JSIDRE, 170 : 75-81 (in Japanese).

Vogel R.M. and N.M. Fennessey, 1994. Flow-Duration Curves I : New Interpretation and Confidence Intervals, Journal of Water Resources Planning and Management, ASCE, 120 (4) : 485-504.

SATELLITE SYMPOSIUM : DISCUSSION

Dr. Hironobu Sugiyama Presentation :

Question : In deriving the SFD curve, do you need to prepare year by year? And then construct the frequency distribution curve at certain probability level?

Answer : The SFD curve is defined as a curve, which is drawn by using the distribution characteristics of a set of probability plots of stream flow calculated by the Weibull plotting formula at suitable time intervals from 0 to 100% on the time axis.

Question : In am very interested to know more of this stochastic approach to flow duration frequency analysis. Are there any basic references on this?

Answer : I hope you read “Stochastic Flow Duration Curves for Evaluation of Flow Regimes in River” published in Journal of American Water Resources Association (Dec. 2002).

Question : Did you adjust low flow data so that the effects of artificial influences (upstream diversions ; ground water pumping etc.) are removed? Please explain.

Answer : Research catchments are selected with the restriction that there are no regulation or diversion structures in the upper reaches of streams.

Question : What probability distributions did you assume to represent the variability of the low flows? Was it normal? Lognormal? Log Pearson? Gumbel?

Answer : A distribution for daily discharge is usually represented with a straight line on lognormal probability paper.

Question : Do you think that 10year probability for the discharge exceeded by 97% of time is enough as an index of low flows in Japan?

Answer : This index of low flow is useful in Japan. But if rainfall situation is affected by climate change, we have to reconsider 97% level.

Question : Could the SFD curve be used for small watershed or very small river? Such as watershed area below $10km^2$ with no enough records and at times there is no water in some seasons?

Answer : The SFD curve will be able to apply for various watershed areas except for arid district. It is important to collect daily flow date in the long term.