EFFECTIVE DISCHARGE CONTROLLING PLANIMETRIC GEOMETRY OF MEANDERING STREAMS BASED ON SPECTRAL ANALYSIS

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Abstract Meandering modes of 62 reaches are determined using Maximum Entropy Method. Spectral analysis indicates the existence of multiple meandering modes on a single reach at the same time. Planimetric geometry of meandering streams is likely to be a product of a wide range of discharges. The first meandering mode is influenced by the whole range of flows over 1.3 years return period, whereas the second one has the narrower effective range of flows from 1.2 to 5.0 years. Thirty-four reaches in the region of heavy snowfall indicate that the relationship between meandering modes and discharges reflects the regional characteristics of streamflows. The first meandering mode reflects the heavy flood flows related to rains generated by typhoons or fronts, whereas the second one may be influenced by the low flood flows below 1.1 years related to snowmelt.

Key words: hydraulic geometry, meandering stream, spectral analysis, discharge of specified return period

1. Introduction

With the development of quantitative studies on landforms since Horton's drainage morphometry, hydraulic geometry has been a major theme in fluvial geomorphology. Hydraulic geometry, which includes planimetric parameters of a meandering stream, not only represents the quantitative relations of fluvial phenomena, but extends into the inference of environmental changes through the restoration of paleohydrology. It has provided an approach to climatic geomorphology from quantitative aspects (*e.g.* Williams, 1984; Dury, 1985; Alford and Holmes, 1985).

Planimetric geometry of meandering streams brought a tendency to regard meandering patterns as regular. In previous studies, a single wavelength was selected as a typical mode which represented a whole stream, so that the possibility of more than a single modal wavelength (*e.g.*, Hjulström, 1949; Schumm, 1963) was ignored. It is, however, likely that heterogeneous wavelengths generated by past geological and hydrological conditions (Ackers and Charlton, 1970), or multiple effective discharges (Speight, 1967) exist. Furthermore, a typical wavelength was subjectively chosen at the discretion of researchers. While there are many planimetric parameters of a meandering stream, meander wavelength is the most useful parameter because of its excellent representation of meander forms and dimensions. Wavelength is defined by Leopold *et al.* (1964) as the straight line distance between alternating points of inflexion along the river course. This definition is widely accepted, but its ambiguity yields various measurement methods and deficiency of objectivity. It is necessary to establish objective criteria for determining and measuring meander dimensions.

There are two different views of meandering phenomenon which is regular on the one hand (*e.g.*, Ferguson, 1973; Chang, 1984) or random on the other hand (*e.g.*, Thakur and Scheidegger, 1970; Scheidegger, 1983). Ferguson (1975) suggested a compromise between the opposing views that planimetric properties of a particular reach are determined by local environmental constraints on the operation of a universal tendency toward meander development. Planimetric geometry of meandering streams is influenced by stochastic factors as well as deterministic ones. It is expected that real meandering streams are disturbed by the stochastic effects of environment resulting in irregular meander patterns.

The purpose of this study is to investigate actual hydraulic geometry of meandering streams under the recognition that meandering streams have an intrinsic tendency toward regularity as well as an extrinsic disturbance leading into irregularity. Meandering modes are determined using a time series analysis to increase precision and to minimize subjectivity because irregularity in meander patterns may be best studied statistically.

2. Spectral Analysis of Meanders

The randomly disturbed meanders can be hardly explained on deterministic factors alone, so that stochastic approaches to meander analysis have been employed. Spectral analysis, theoretically based on the Fourier transform, assumes that a stream is characterized not by a single modal meander but by a combination of modal meanders of different frequencies (*e.g.*, Speight, 1965; Chang and Toebes, 1970; Ghosh and Scheidegger, 1971; Ferguson, 1975; Sinnock and Rao, 1984; Harden, 1990). Spectral analysis, however, can be only applied to the stationary data that are unusual in geomorphology. Because a stream changes its characteristics at every junction, it is difficult to choose a reach for spectral analysis with holding its characteristics stationary. The resolution of spectrum, however, depends on the number of data, so that the application of spectral techniques to streams is inevitably limited. Furthermore, previous methods such as DFT (Discrete Fourier Transform) and FFT (Fast Fourier Transform) have an inherent problem. Assumption of an infinite function for a definite observed wave produces unreal frequencies through link effect. MEM (Maximum Entropy Method), in which an auto-regressive function can be inferred by maximizing the entropy of information, has been recently attracted from practical aspects. Using MEM, it is possible to analyze a short series of data and to yield the high resolution of

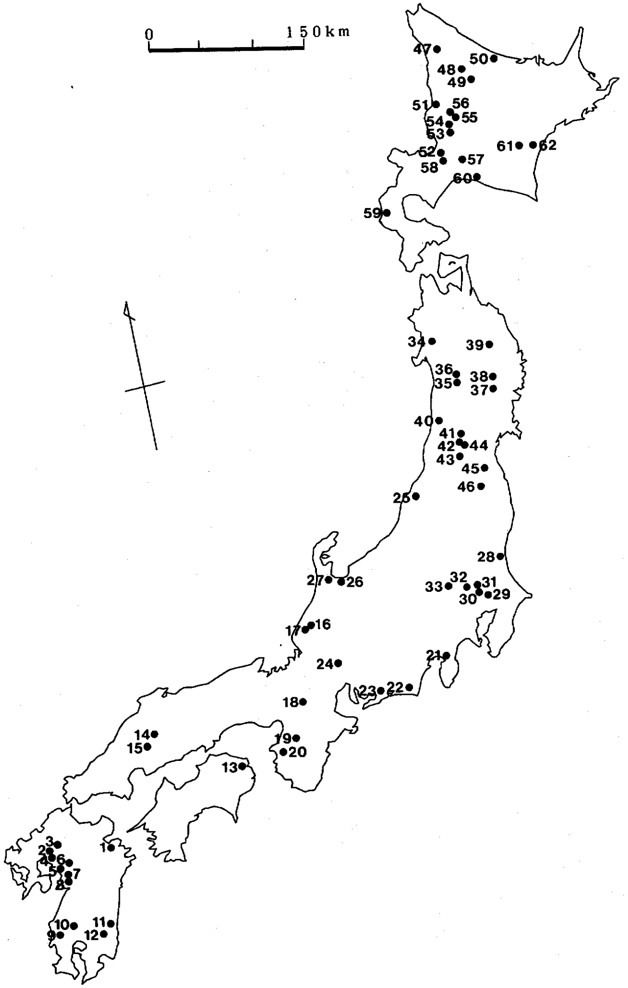


Fig. 1 Studied rivers and gauging stations

NO	RIVER	GAUGING STATION	NO	RIVER	GAUGING STATION
1	Nanase	Gomazuru	32	Watarase	Fujioka
2	Chikugo	Senoshita	33	Tone	Iwamoto
3	Chikugo	Katanose	34	Yoneshiro	Futatsui
4	Yabe	Funagoya	35	Omono	Omagaribashi
5	Kikuchi	Tamana	36	Tama	Nagano
6	Kikuchi	Bunda	37	Kitakami	Otokoyama
7	Shira	Yotsugibashi	38	Kitakami	Asahibashi
8	Kase	Dairokubashi	39	Kitakami	Terabayashi
9	Sendai	Onobuchi	40	Mogami	Sagoshi
10	Sendai	Arata	41	Mogami	Inashita
11	Honjo	Arashida	42	Mogami	Nagasaki
12	Oyodo	Hiwatashi	43	Matsu	Nishiotsuka
13	Yoshino	Chuobashi	44	Su	Sushiarai
14	Basen	Minamihatajiki	45	Abukuma	Fushiguro
15	Gono	Yoshida	46	Abukuma	Akutsu
16	Kuzuryu	Nakatsuno	47	Teshio	Maruyama
17	Kuzuryu	Fukadani	48	Teshio	Nayoroohashi
18	Daido	Kurozu	49	Teshio	Tsukumobashi
19	Kino	Hashimoto	50	Shokotsu	Kamishokotsu
20	Kishi	Kishi	51	Rumoi	Owada
21	Kano	Tokura	52	Ishikari	Ishikariohashi
22	Kiku	Kamo	53	Ishikari	Tsukigata
23	Toyo	Togo	54	Ishikari	Hashimotocho
24	Nagara	Chusetsu	55	Ishikari	Osamunai
25	Agano	Maoroshi	56	Uryu	Tadoshi
26	Jintsu	Jintsuohashi	57	Yubari	Maruyama
27	Oyabe	Nagae	58	Toyohira	Kariki
28	Kuji	Sakakibashi	59	Goshiribetsu	Imagane
29	Kokai	Kawamata	60	Mu	Mukawakako
30	Kinu	Mitsukaido	61	Tokachi	Obihiro
31	Kinu	Hirakata	62	Tokachi	Moiwa

spectrum. MEM seems to be a solution of some problems derived from the intrinsic shortcoming in the Fourier transform process or the length of a reach influencing the resolution.

Meandering streams of Japan have been artificially channelized in order to prevent floods. Present planforms of meandering streams can be hardly thought to remain natural. Topographic maps compiled during the Meiji or Taisho Era were employed as the information source for spectral analysis. Sixty-two reaches were selected across the whole of Japan (Fig. 1). Reaches with large confluences were excluded. Gauging stations of discharges are located in reaches or neighbor them.

Spectral analysis, however, requires a single value for each sampling point on the Cartesian plane. Because looping streams yield some sampling points associated with multiple values (Fig. 2), an alternative method of sampling is required for a single-valued function. Using topographic maps of selected areas, x and y coordinates of points were digitized along the center of channel paths. These coordinates were interpolated to produce equally spaced points at any interval which was normalized proportional to each drainage area (Fig. 3). A parametric spline interpolation was used owing to an accurate representation of a channel path (Fig. 4). A whole channel path was quantized as two types of an one-dimensional spatial series of direction(θ/d) and curvature ($\Delta\theta/d$) as a function of the distance(d) along the channel path (Fig. 5). Because the two series could be thought to provide the same information essentially, frequencies of spectral peaks were determined by means of the comparison of them (Fig. 6). A meandering mode was estimated from the length of channel path and the inverse of each spectral frequency.

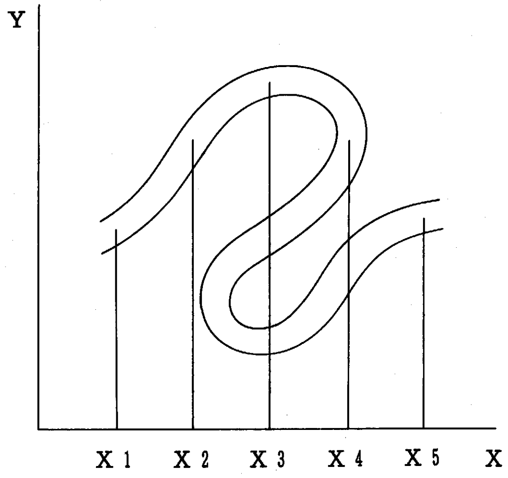


Fig. 2 A meandering stream path on the Cartesian plane
Looping streams yield sampling points (X3 and X4) associated with multiple values which are inappropriate for spectral analysis.

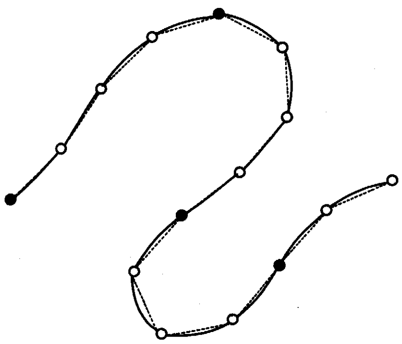


Fig. 3 Digitization and interpolation of equidistant points

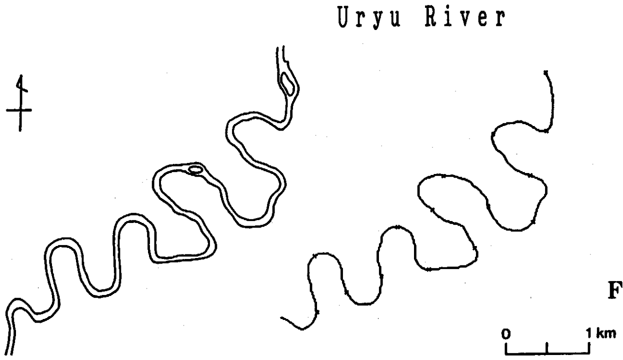


Fig. 4 Spline interpolation showing an accurate representation of a channel path

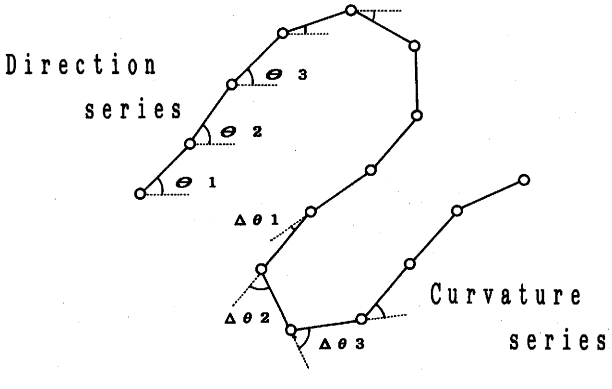
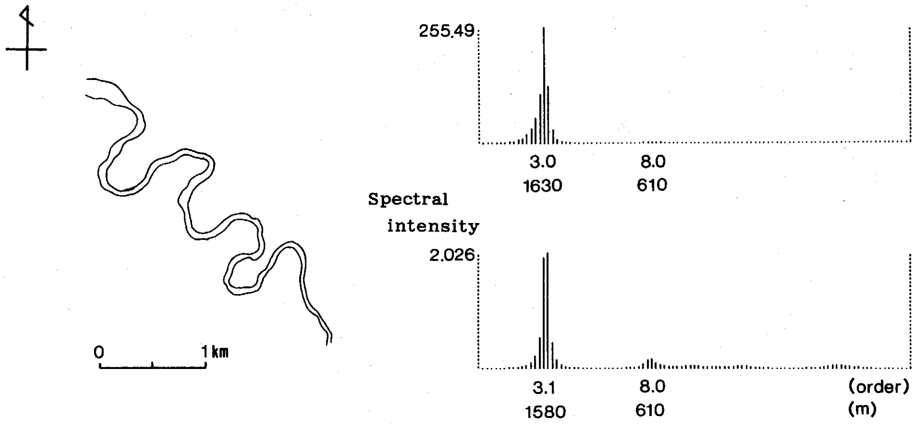
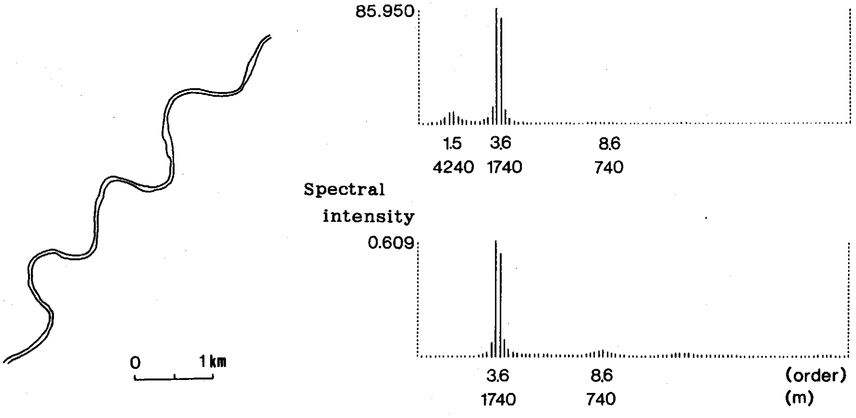


Fig. 5 Two types of quantization as a single-valued function



Goshiribetsu River



Yabe River

Fig. 6 Power spectra for direction and curvature series of Goshiribetsu River and Yabe River

3. Discharges Based on Extreme Value Statistics

The discharge controlling channel form is called as the effective or dominant discharge. It is based on the assumption that one or more flows may be used to represent the averaged effect of the whole range of discharges experienced by the stream. The effective discharge is related to the frequency of occurrence as well as the magnitude of event as emphasized by Wolman and Miller (1960). Although many indices of the effective discharge were suggested, bankfull discharge has been widely accepted as the dominant or channel forming discharge and usually expressed as the return period of peak flows. There are, however, some disputes on the return period for bankfull discharge (Richards, 1982; Petts and Foster, 1985). It is consequently expected that the relationship of discharge to channel morphology should be investigated over a wide range of discharges. The wide range of discharges can be obtained by estimating flood frequency from the hydrological data of annual maximum discharge. In order to estimate discharges of specified return period, it is required to determine what type of theoretical probability distribution is best fitted to the hydrological data. Many models have been suggested on the theoretical probability distribution, including Fisher-Tippett's one in which three types of distribution exist. Gumbel distribution indicates the first type of probability distribution of extreme values which can be substituted for the distribution function of annual maximum flood peaks (Gumbel, 1958).

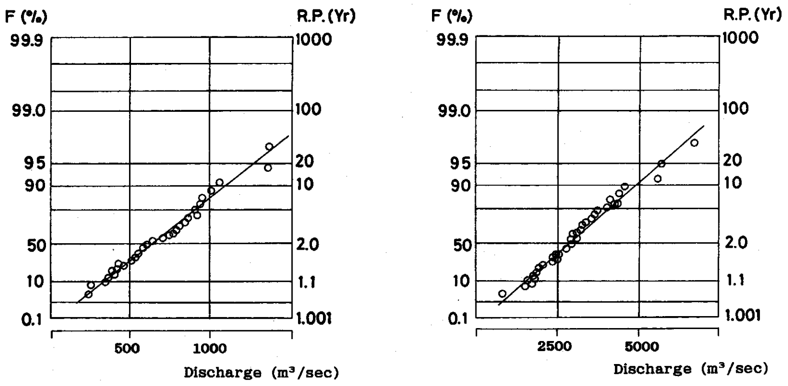


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Fig. 7 Estimation of discharge of specified return period based on Gumbel distribution

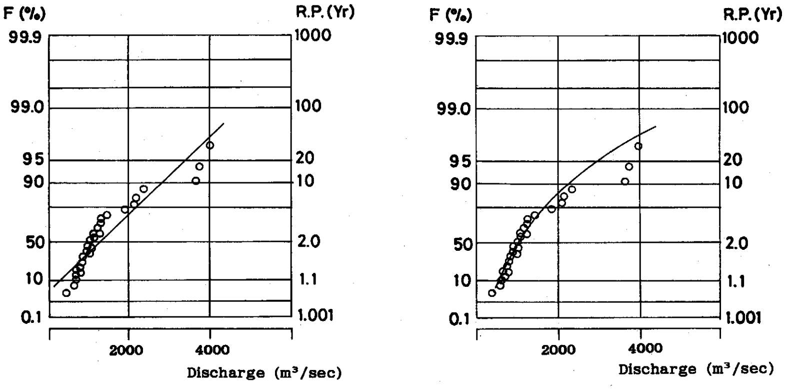

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Fig. 8 Correction of discharge of specified return period based on Logarithmic Gumbel distribution

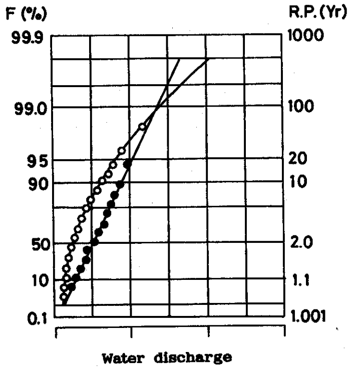

Fig. 9 Selection of an appropriate theoretical probability distribution (modified from Iwai and Ishikuro, 1970)

Using discharge data reports by the Ministry of Construction, discharges of specified return periods such as 1.1, 1.2, 1.3, 1.5, 1.58, 2.0, 2.33, 3.0, 5.0, 10.0, 20.0, 30.0 and 50.0 years were estimated respectively. The probability discharges were first estimated on the basis of Gumbel distribution (Fig. 7). However, one third of observed data which did not fit Gumbel distribution was corrected by Logarithmic Gumbel distribution as a transformed distribution (Fig. 8). In the absence of a theoretical justification for a particular model of probability distribution, selection is based largely on convenience (Richards, 1982). After the suggestion of Iwai and Ishikuro (1970), the application of observed data to two distributions was determined on the configuration of plotted points on a probability paper; the straight configuration was applied to Gumbel distribution and the convex to Logarithmic Gumbel distribution (Fig. 9).

4. Relationship of Meandering Modes to Discharges

The existence of multiple meandering modes on a single reach at the same time has been suggested by some researchers. It includes twofold oscillations by composition of two oscillatory components (Fujiyoshi, 1945) and multiple modes generated by climatic changes (Hjulström, 1949) or related to self-affinity in fractals (Sinnock and Rao, 1984). The spectral analysis reveals that two thirds of reaches have two or more dominant peaks (Fig. 6). It implies the simultaneous existence of multiple meandering modes on a single reach. Even regular reaches show weak spectral peaks of high frequency, so that visual determinations of some typical wavelength seem to be insufficient.

The coefficient of determination (r^2) of the first meandering mode to discharges fluctuates around 0.63 with increasing discharge over 1.3 years return period (Fig. 11-a). The weak peak with r^2=0.64 appears in the range from 1.5 to 2.33 years. For the discharge of 1.58 years (Fig. 10-a), the best fit is given as

$$M_1=106.0Q_{1.58}{}^{0.48}$$

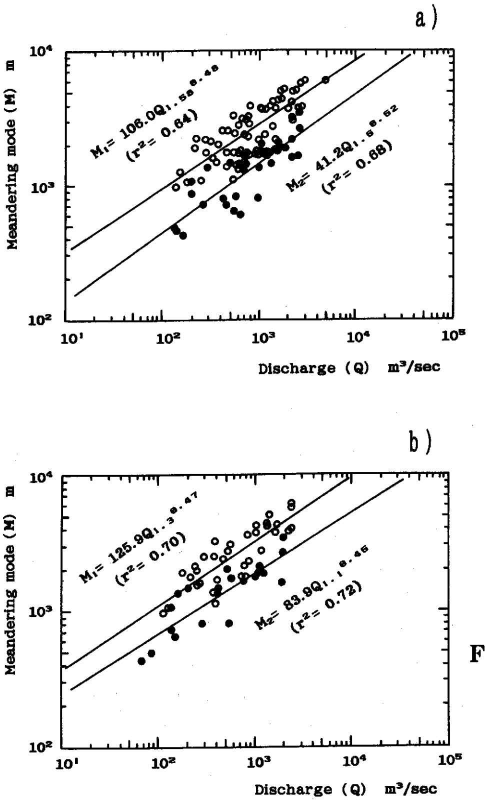

Fig.10 Relationship between meandering modes and discharges of specified return period for the Japanese rivers
a)Whole region; b)Heavy snowfall region
○ : 1st meandering mode
● : 2nd meandering mode

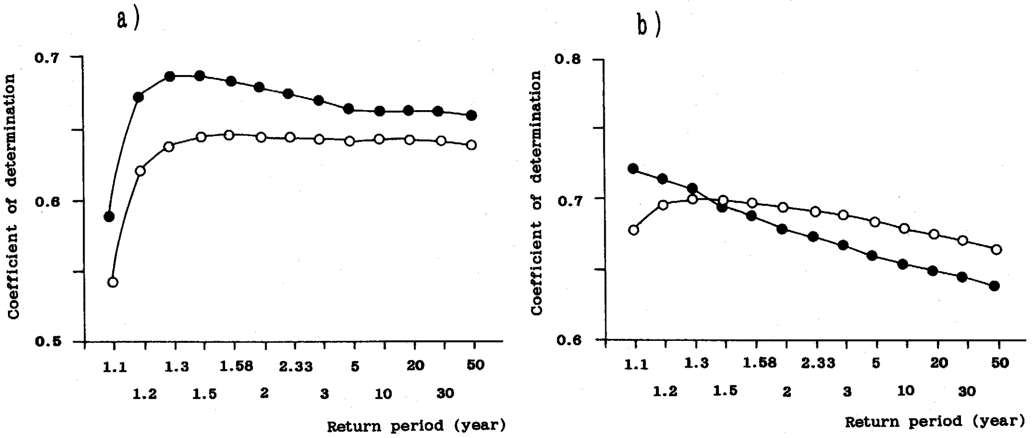

Fig.11 Changes in the coefficient of determination of meandering modes to discharges of specified return period for the Japanese rivers
a)Whole region; b)Heavy snowfall region
○ : 1st meandering mode ● : 2nd meandering mode

The second meandering mode that is two to four times shorter than the first one, yields a higher coefficient of determination compared with the first one (Fig. 11-a). The best correlation with r^2=0.68 appears at 1.3 and 1.5 years (Fig. 10-a). The effective discharge has been usually expressed by a single specific event or a narrow range of flows. A single discharge, however, may be too oversimplified to represent all flows influencing channel form as suggested by Kennedy(1972). The result of this study indicates that a wide range of discharges influences planimetric geometry of meandering streams. The discharges of 1.3 years for the first meandering mode and 1.2 years for the second one seem to be threshold values below which the relationship between meandering modes and discharges becomes sharply weak. The range of effective discharges varies with meandering modes. Compared with the first meandering mode showing no specific upper limit of the range, the second one has the discharge of 5.0 years as the upper limit over which the relationship of the meandering mode to discharges weakens. That the wide range of discharges with a threshold value is preferable to a single specific discharge as the effective discharge supports Pickup and Rieger's suggestion (1979) that channel form is a weighted sum of effects of all input discharge events. Every competent event has consequently some influence on channel morphology and dimension.

The runoff properties of Japanese streams reflect the regional characteristics based on climate (Sakaguchi *et al.*, 1986). Because streams in the region of heavy snowfall have particular characteristics related to snowmelt flows, 34 reaches were chosen based on climatic regions. The first meandering mode shows r^2=0.70 in the range from 1.2 to 2.33 years and has the best correlation with 1.3 years (Fig. 10-b) given as

$$M_1=125.9Q_{1.3}{}^{0.47}$$

The second meandering mode indicates an increase in the coefficient of determination with decreasing discharge. The best correlation with r^2=0.72 appears at 1.1 years (Fig. 11-b). However, higher correlations above r^2=0.72 are expected to appear at low discharges below 1.1 years such as the mean discharge of the month of maximum discharge suggested by Carlston (1965) or the monthly mean discharge in 10 percent of the months by Speight (1967). During the spring, snowmelt floods occur annually in the region of heavy snowfall. Snowmelt floods have a characteristic of a low magnitude and long duration. Arai (1983) emphasized that flood flows are related to a duration as well as an amount of precipitation. The duration is responsible for the characteristics of runoff in the region of heavy snow fall. The first meandering mode reflects the heavy flood flows related to rains generated by typhoons or fronts and the second one does the low flood flows of snowmelt. In general, hydrological data of the region of heavy snowfall have good fitness to Logarithmic Gumbel distribution rather than Gumbel one. This indicates that hydrological data of this region consist of two flow populations related to heavy rains and snowmelt respectively. Two meandering modes of reaches in the region of heavy snowfall have relations to each flow population. The relationship between meandering modes and discharges consequently reflects the regional characteristics of streamflows which are, in turn, different in climatic zones.

5. Conclusions

The actual relationship between meandering modes and probability discharges is investigated. Meandering modes of 62 reaches are determined using Maximum Entropy Method of spectral analysis. Spectral analysis reveals that two thirds of reaches have two or more dominant peaks. This indicates the existence of multiple meandering modes on a single reach at the same time.

Planimetric geometry of meandering streams seems to be a product of a wide range of discharges rather than a single discharge. The first meandering mode is influenced by the whole range of flows over 1.3 years return period, even though it has the best correlation with 1.58 years ($M_1=106.0Q_{1.58}{}^{0.48}$). The second meandering mode which is shorter than the first one, has the narrower effective range from 1.2 to 5.0 years.

Thirty-four reaches in the region of heavy snowfall indicate particular characteristics related with climate. The first meandering mode has the best correlation with 1.3 years ($M_1=125.9Q_{1.3}{}^{0.47}$) and reflects the heavy flood flows related to rains generated by typhoons or fronts. On the other hand, the second meandering mode is expected to be largely influenced by discharges below 1.1 years which indicate the low flood flows related to snowmelt. The relationship between meandering modes and discharges reflects the regional characteristics of streamflows which are different in climatic zones.

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