Diurnal Changes of Water Temperature in a Stream-A Survey of the Natori River and an Irrigation Canal-

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Diurnal Changes of Water Temperature in a Stream

— A Survey of the Natori River and an Irrigation Canal —

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Most of plains of Japan are utilized for paddy fields and rivers are the main source of irrigation water. The water from rivers is distributed by weirs into canals and is used to irrigate paddy fields.

In northern Japan with its rather low temperatures the rice crop is strongly affected by the temperature of the air and the water supplied. In this sense, the changes of water temperature flowing in rivers and in canals to the paddy fields, are important considerations.

Along the channels, the amount of heat exchange per unit volume and unit time (heat exchange ratio) will be large in the upper stream and small in the lower stream due to the different depths and the disturbances of the water surface. And heat exchange will be little in artificial underdrains of generating stations, but large in ordinary irrigation canals with generally shallow depths.

The writer analysed from the standpoint of the temperature change of flowing water and the heat exchange ratio diurnal changes of water temperatures observed on clear days along the Natori River and an irrigation canal.

1 Diurnal changes of water temperatures in the Natori River

The Natori River is about 55 kilometers in length and flows from the Ōu Mountains to the Pacific Ocean. Four observation points with temperature recorders, A_1-A_4, were set up at about every 10 km along the river. Point A_1 is about 9 km from the river head and the point A_4 about 40 km. The speed of the stream was measured at eight points between A_1 and A_4, and the time when the water flowed through each section was estimated from this. Between A_3 and A_4, there are two hydroelectric stations, and the water is divided by covered underdrains at two places–the combined length of the underdrains being about 4 km (Fig. 1). Above the two weirs thus constructed, the river forms two pools, the combined length of which is about 1.2 km and which have much to do with the changes of water temperature in the section between A_3 and A_4.

The clear weather lasted for 4 days, from the 9th to the 12th of October 1967, and the water level measured at point A_3 changed little. The observation on the

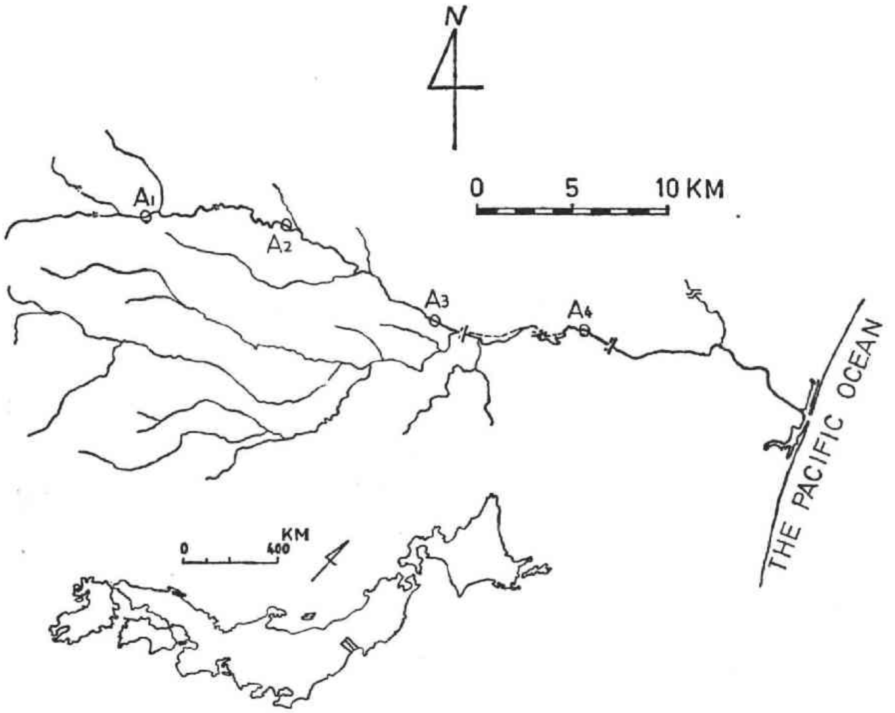

Fig. 1 Index map of the Natori River
The weir (:|) and the underdrain (----)

9th was excluded because the weather of the previous day must have affected the data of the 9th.

The variations of water temperature from the 10th to the 12th are shown in figure 2 and table 1. The farther downstream the observation, the higher the trough of the curve appeared. A trough is observed at about 0700 in the upper reaches and at about 0900 in the lower. The highest peak of the temperature is at A_3, and at the lower point the peak temperature appeared later, especially at A_4 till 1900 or 2130. Therefore, the changes of water temperatures are largest at A_3 and the ascending times of water temperatures from the trough to the peak are shorter than the descending times from the peak to the trough the next morning, although at points in the lower reaches the difference is smaller.

The phenomena of water temperatures described above are synthetically shown in figure 4. The water passages on figure 4 is presumed from the current speed measured at eight points, and the variations of flowing water temperatures are read from these lines (shown in figure 2). The air temperature is higher than the water temperature in the daytime and it rises notably in all sections. In the

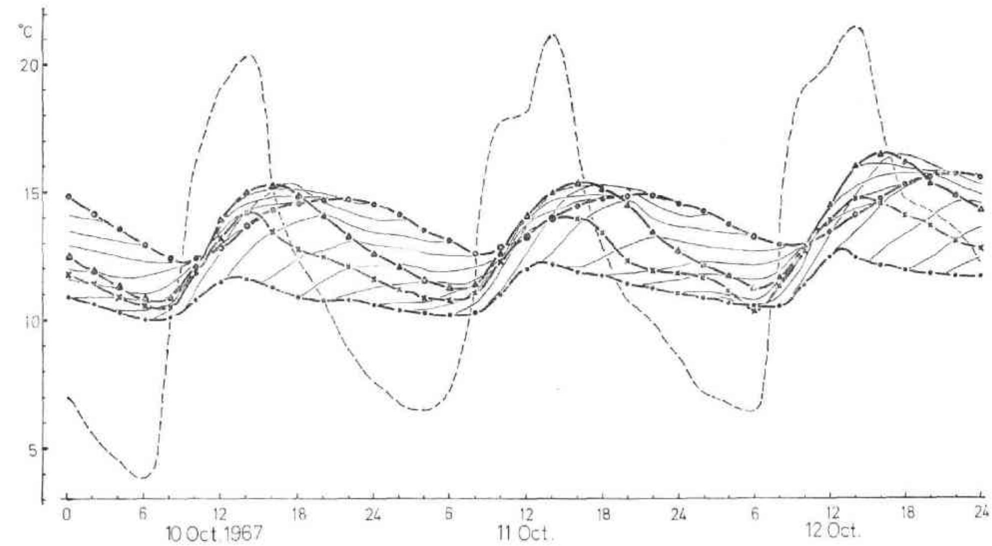

Fig. 2 Diurnal variations of water temperature at A_1 (—•—), A_2 (—×—), A_3 (—△—) and A_4 (—○—), air temperature (-----) and the temperature changes of flowing water (——) for 10th to 12th Oct., 1967

Table 1 The times of the peak and trough temperature and the periods of ascending

	A_1	A_2	A_3	A_4
The time of the peak (JST)				
10 Oct.	0730	0730	0700	0900
11	0700	0700	0700	0900
12	0700	0630	0700	0900
The time of the trough (JST)				
	A_1	A^2	A_3	A_4
10 Oct.	1300	1400	1530	1900
11	1300	1430	1530	2030
12	1300	1330	1600	2130
Period of ascending (hour)				
	A_1	A_2	A_3	A_4
10 Oct.	5.5	6.5	8.5	10.0
11	6.0	7.5	8.5	11.5
12	6.0	7.0	9.0	12.5

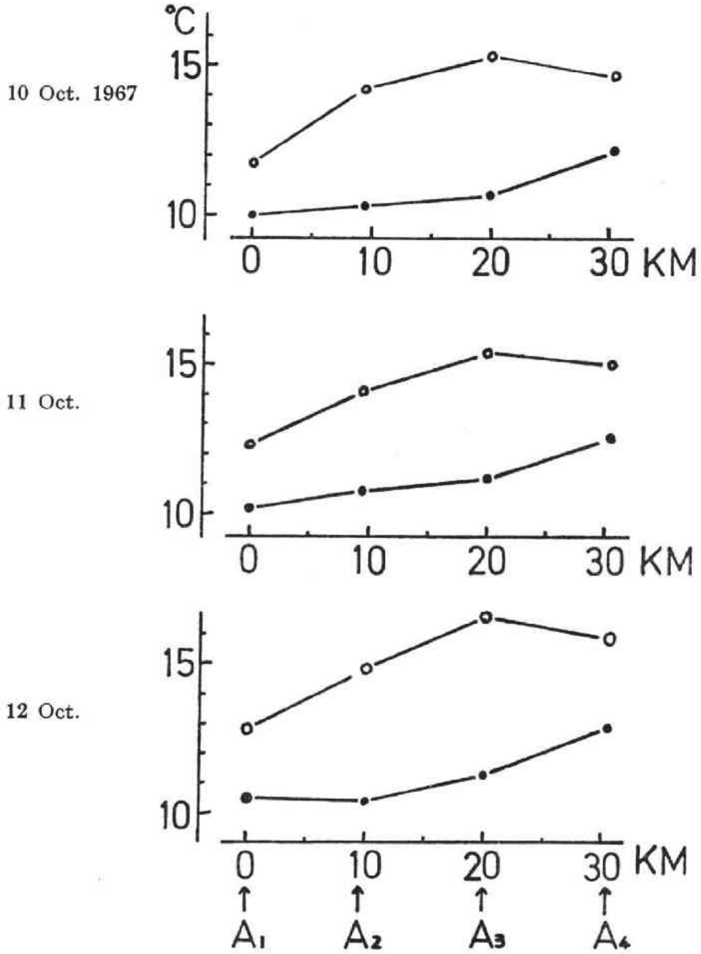

Fig. 3 Sequences of the peak (—○—) and trough (—•—) water temperature 10–12 Oct., 1967

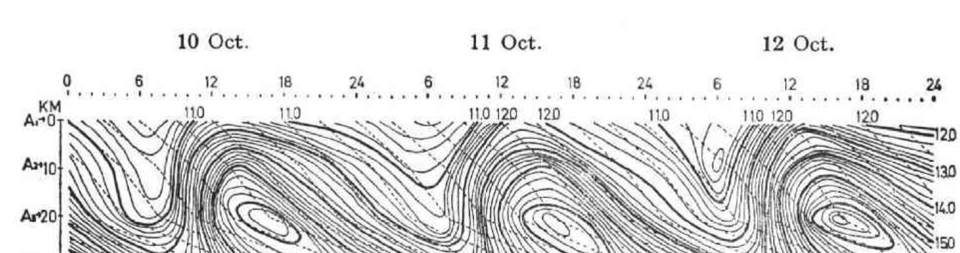

Fig. 4 Distance-time cross section of water temperature (——) and the passing ways of flowing water (-----) for 10th to 12th Oct., 1967

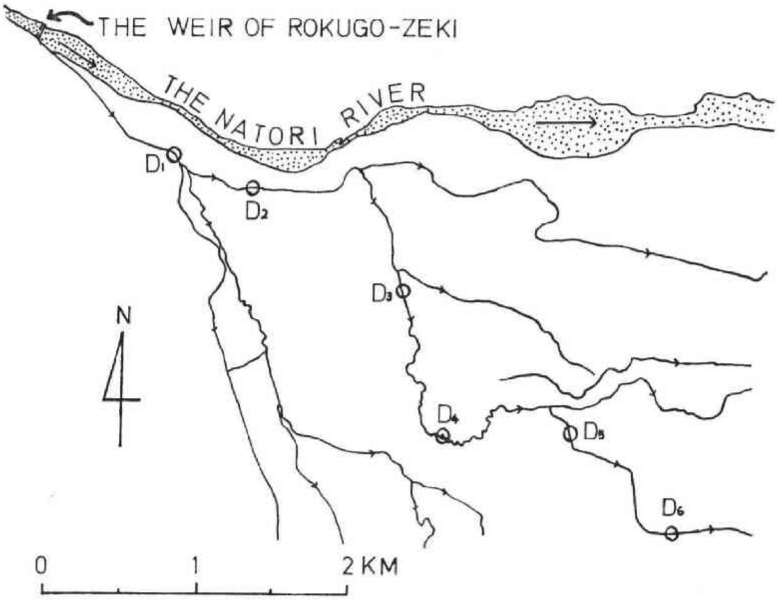

Fig. 5 Index map of the irrigation canals from the lower reach of the Natori River

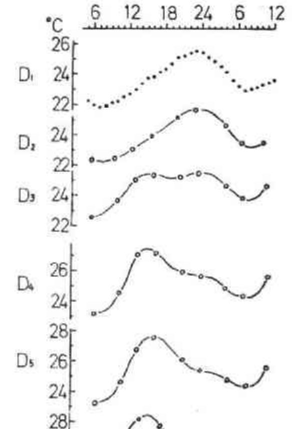

Fig. 6

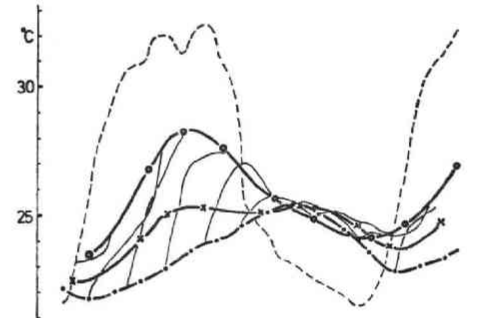

Fig. 7

Fig. 6 The diurnal variation curves of water temperature observed for the morning of 20th to the noon of 21st June, 1968

Fig. 7 Diurnal variations of water temperature at D_1 (—•—), D_3 (—×—) and D_6 (—○—), the air temperature (-----) and temperature changes of flowing water (——)

A_3-A_4 sections the ascent ceases at night and there is a descent from midnight to early morning, while the difference in air and water temperatures is largely negative. In the upper reaches, however, the water temperature hardly descends at all and the ascent ceases slowly during a period from midnight to early morning — the air temperature being lower by 8–10°C than the water temperature.

2 Diurnal variations of water temperature along an irrigation canal

The water of the Natori River is divided for irrigation by the Rokugo-Zeki weir at 1.5 km downstream from the point A_4. The water is conducted into a canal and is distributed to paddy fields. The purpose of observing the water temperature was to compare the diurnal variations in the canal with that in the lower reaches of the Natori River.

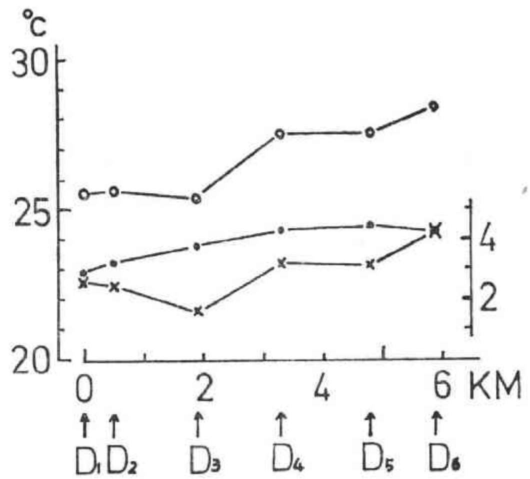

Fig. 8 Sequences of the peaks (—○—), the troughs (—•—) and the differences (—×—) of water temperature

Observation was conducted on clear and calm days from the morning of the 20th until noon on the 21st of June, 1968. A temperature recorder was placed at point D_1 and at five other points (D_2, D_3, D_4, D_5, D_6), the temperatures were measured every 3 to 5 hours. Based on these data, temperature curves were drawn for each point so that the water temperatures for any time could be read.

Variation at D_1 is affected by the lower reaches of the Natori River and its characteristics are, the appearence of a peak at 2300, and a longer time of ascent than descent. However, at the lower points the peaks appear before sunset and the times of ascent are shorter. The curve of the middle point D_3 has two peaks which means that this curve is a combination of two curves. One is a curve of the type seen at stations like D_1 and D_2 in the upper stream and the other is a type like D_6 observed at stations in the lower stream. The lowest peak is at D_3 and the trough rises until D_4 and thereafter remains at the same level. Consequently, the least relief of water temperature appears at D_3.

According to figure 9, the mass of warm water which appears at night in the lower reaches of the Natori River, can be traced at D_3. Another mass of warm water appears in the afternoon in the lower reaches of the canal. Flowing down the canal, the water temperature rises in the daytime and falls at night. Presumably this is in accordance with the relations between air and water temperatures.

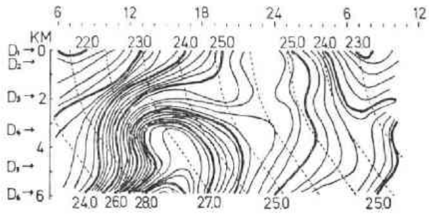

Fig. 9 Distance-time cross section of water temperature (——) and the passing ways of flowing water (-----) for the morning of 20th through the noon of 21st June, 1968

3 A simple simulation on diurnal variations of water temperature

The variation of water temperature at a point is not that of the water mass, but that of many masses passing one after another. The amount of heat the water receives will be different in the daytime and at night, and thus the time variations or the diurnal variations of water temperature at a single point occures. Therefore the diurnal variations should be discussed from the viewpoint of heat exchange while the water is flowing.

The heat exchange occurs mainly through the water surface, and the change of water temperature (Δt_w) is equal to the mount of heat exchange per unit volume, as follows:

$$\Delta t_w = \frac{Q}{H}$$

where Q: amount of exchanged heat per unit of surface area

H: depth of water

If the thermal circumstance is constant, the water temperature will change toward the direction in which Q will diminish until Q approaches zero. This stage of the water temperature will be called a terminal temperature of water*. That is to say, the water temperature will change toward a terminal temperature. The amount of heat exchange per unit volume will differ with the meteorological and river bed conditions, and the speed of reaching a terminal temperature will be different. If a coefficient (α') is able to show these effects, the temperature change should be in proportion to the difference between a terminal temperature (θ_∞) and the real temperature (t_w) of the water. The amount of temperature change will be represented as follows:

$$\Delta t_w = \alpha' (\theta_\infty - t_w)$$

and the water temperature after n-hours (t_{wn}) will be approximately as is shown in the next equation:

$$t_{wn} = t_{w0} + \alpha \sum_{i=0}^{n} \{(\theta_{\infty i} - t_{wi}) + (\theta_{\infty i+1} - t_{wi})\}$$

The initial water temperature of 10.0°C and next three thermal environments are assumed.

(A) 16.0°C∼24.0°C (B) 6.0°C∼14.0°C (C) −4.0°C∼4.0°C

The terminal temperatures will change linearly. They will be at their minima at 0600 and their maxima at 1400. The water temperature change will be affected in each of the three canals by the values of α, corresponding to the three thermal environments, 0.05, 0.10 and 0.20, respectively.

The results of this estimation are shown in the figures 10 and 11. The appearences in the canals whose α is 0.05, is as follows:

1) In (A) and (C), there are notable breaking points of inclination in the distribution of peak and through temperatures, and as a result the maxima and minima appear in the distribution of the diurnal change.

2) In (B), the distributions of the peaks, throughs and their differences have

* The terminal temperature is represented in the next equation.

$$\theta_\infty = \frac{S + h \cdot \theta_a \left(1 + 2 \frac{de}{d\theta}\Big|_{\theta_a}\right) - k \cdot D}{h\left(1 + 2 \frac{de}{d\theta}\Big|_{\theta_a}\right)} = \theta_a + \frac{S - k \cdot D}{h\left(1 + 2 \frac{de}{d\theta}\Big|_{\theta_a}\right)}$$

where S: net radiation of water
θ_a: air temperature
h: coefficient of sensible heat transfer
k: coefficient of latent heat transfer
e: vapor pressure of water
D: saturation deficit

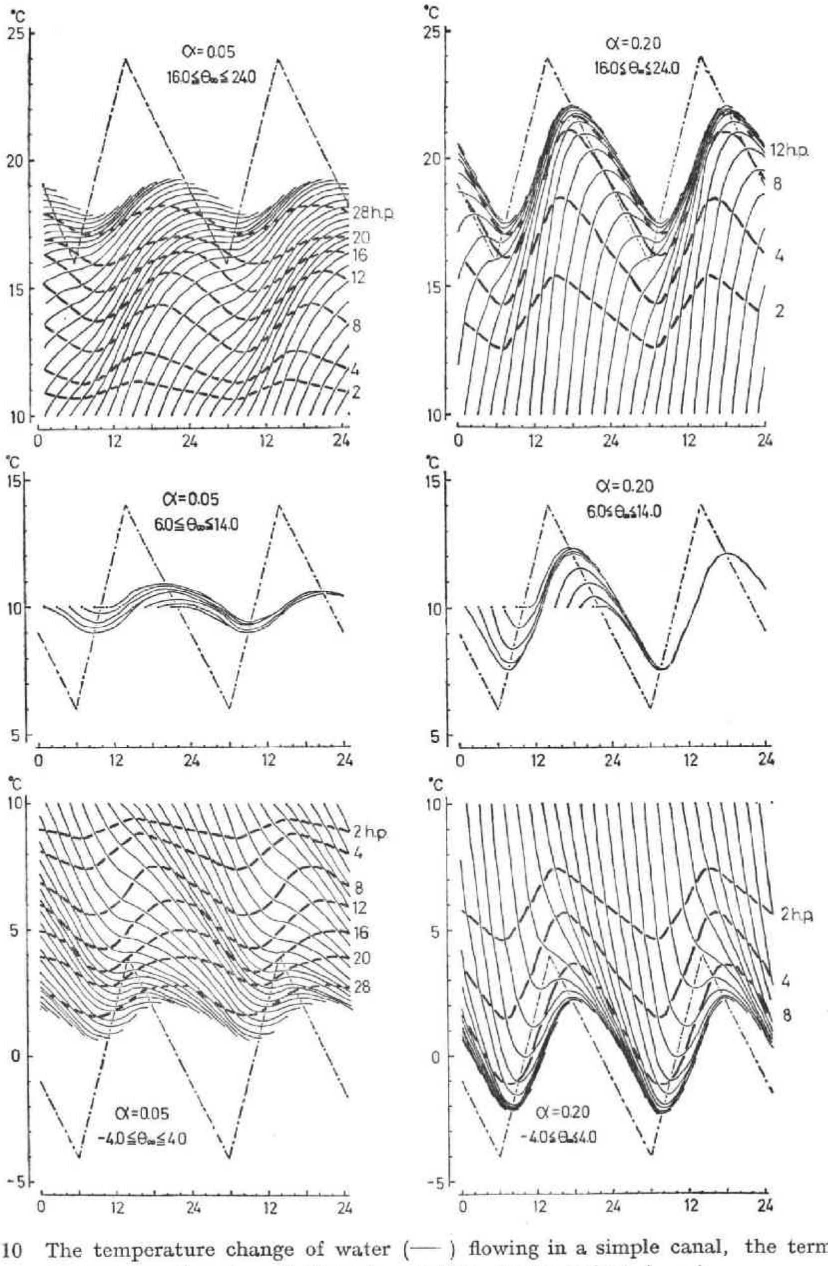

Fig. 10 The temperature change of water (—) flowing in a simple canal, the terminal temperature (-·-) and diurnal variation at the points (— —)
Distance from the stream head is taken as time by hour. For example 2h.p.: diurnal variation of water temperature at the point of two hours lower reach from the stream head.

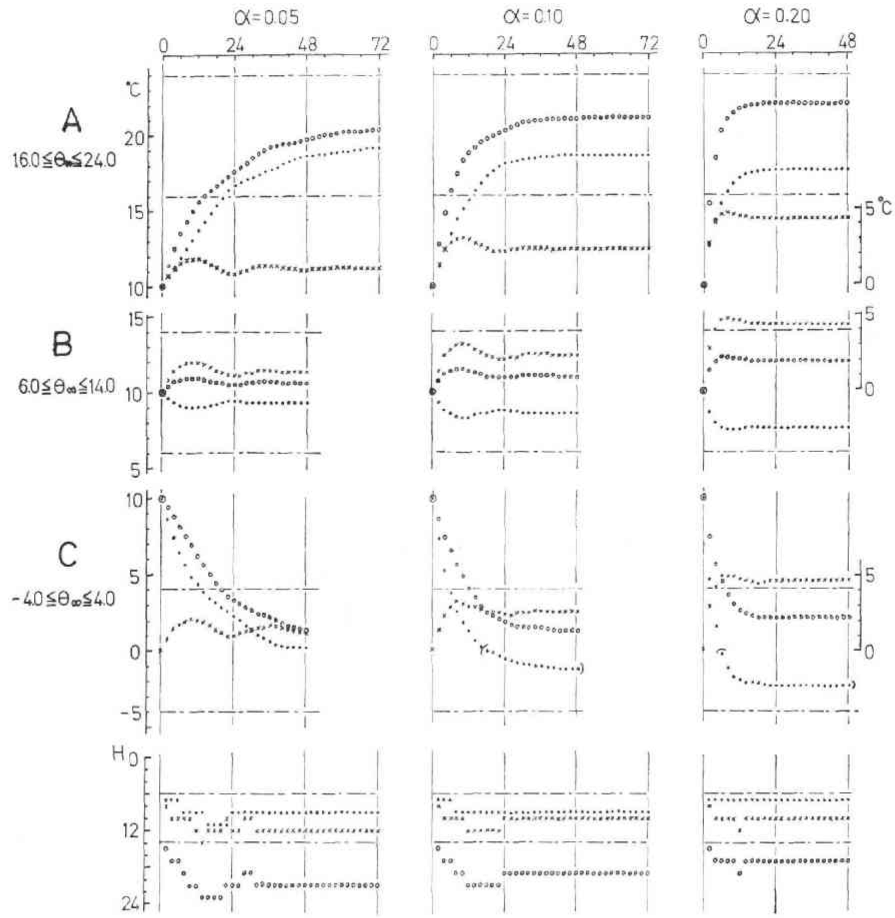

Fig. 11 Above nine panels show the distributions of the peaks (○), the troughs (•) and the different temperatures (×) calculated and bottom three panels show the distributions of the peak times (○), the trough times (•) and the duration of ascendings (×).

maximum and minimum points. These amplitudes become smaller toward the lower reaches and these values appear to approach certain asymptotes as in (A) and (C). The times of the peaks and the troughs are delayed toward the lower reaches and the latest is at midnight, but in the lower reaches below a certain point, these occur somewhat earlier and then are constant at the end. The time lag of the peak of water temperature at a point from that of the terminal temperature, is longer by about twice than that of the trough. And in the upper reaches the times of ascent are shorter than the descents, but the differences in time become smaller or are often reversed in the lower reaches.

In the canal with a high heat exchange ratio, the tendency for such sequences to occur is less marked. In every case the peaks and troughs tend to be included in the ranges of variation of the terminal temperature. In the canal with a high heat exchange ratio, the peak and trough temperatures are close to the upper and lower limits of the terminal temperatures, the diurnal changes are larger, the time lags of external values are smaller and the times of ascent are shorter.

In the actual stream, the heat exchange ratio would be variable with the meteorological and river bed conditions and it would be important to ascertain the sequences of water temperatures and the patterns of diurnal variations.

4 Comparison of the diurnal variations of water temperatures between the real stream and the simple ideal canal

A terminal temperature may be higher than the air temperature, because of insolation in the daytime of a clear day, and lower at night due to negative net radiation and the lower stability of the air. Since a terminal temperature has not been observed, the heat exchange ratios are estimated from the air temperatures as explained above, and then the real streams are compared with the simple canal.

In the case of the Natori River, the value of the heat exchange ratio is about 0.1 in the upper stream section A_1-A_3, and 0.03 in the lower reaches A_3-A_4. These values suggest that the heat exchange is active in the upper reaches but not in the lower. This also corresponds with the river bed conditions of the natural river in the section A_1-A_3 and with the lower reaches which have two weirs and underdrains. The trough temperature in diurnal change becomes higher down-

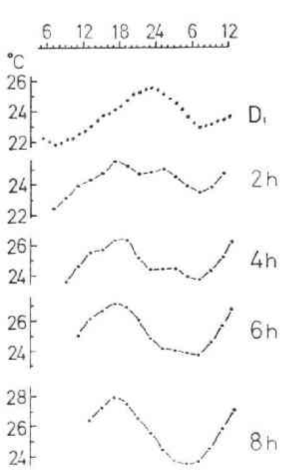

Fig. 12 Diurnal variation calculated on the ideal simple canal which heat exchange ratio with air temperature is assumed as 0.10.
2h: At the point of two hours distance downward from D_1
4h: At the point of four hours distance downward from D_1
6h: At the point of six hours distance downward from D_1
8h: At the point of eight hours distance downward from D_1

stream, but the peak temperature at A_4 is lower than at A_3 and the appearance of the peaks and the troughs is much later in the section A_3-A_4. It will be presumed that such tendencies as are observed at A_4 are abnormal, or that point A_3 is just on the boundary, as indicated by the fact that the heat exchange ratio becomes suddenly smaller along the flowing stream, although this is not inconsistent with the distinction of the temporary values of the heat exchange ratio between the upper and lower sections. However, it is not consistent with the ideal, simple canal in that the temperature ascends at night in the upper stream when the air is cooler than water, and especially since there is a heat supply from the river bed or from an inflow of ground water.

When the diurnal variations of water temperature at D_1 were given, the temperature changes of the water in the canal with a heat exchange ratio 0.10 were estimated. As a result of this estimation, various patterns of diurnal variation appear. In order, from upper to lower stream, there are two peaks in the diagram, each of which with a step where the curve turns downward and with a faster rise and a smooth fall immediately corresponding to the trends observed in the curve of diurnal variation.

The sequence of the peak and trough temperatures and the patterns of the diurnal changes along the Natori River and the irrigation canal are very characteristic. They may correspond with the order of the apparent heat exchange ratio which is estimated from the air temperature. If a canal contains upper reaches with a heat exchange ratio of 0.20, and lower reaches with that of 0.05, and if its breaking point is the 36 hour point from the stream head in the thermal environment of (A), above described, correspondence may be assumed from the calculated results in an ideal simple canal, that the heat exchange ratio will drop suddenly.

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