Some Considerations on River Pollution Mechanism

By

Takeshi GŌDA and Shōichi NAMBU*

(Received October 23, 1958)

The characteristics of the diffusion and transportation of suspended pollutant solids in rivers, based on the results of laboratory experiments and field observations, are discussed.

First, in order to ascertain the effects of discharged sewage on the quality of downstream water, we studied analytically the changing rate of the concentration of pollutant matter in a river, and by comparing the theoretical results with experimental data, some quantitative relationships between the discharge of sewage and the dilution factor were obtained for two cases, one where the sewage is supplied intermittently to a river and soon distributed uniformly over the cross section, and the other where the effluent is discharged continuously from one side of the river.

Secondly, the transportation mechanisms of pollutant matter from the Neya River, which is regarded as the main source of pollution for rivers and canals in Osaka City, were investigated, and a few practical remedies are proposed for reducing the degree of pollution in the waters of the Osaka area.

1. Introduction

Generally, in a steady state, the local concentration of pollutants in a river depends on the discharge ratio of disposed sewage to the river water and on the hydraulic and biochemical characteristics of the river. In most cases, the changes in the local dissolved oxygen concentration in the direction of flow were noted, being easily estimated by Streeter-Phelps' Formula.

However, since this formula was developed by neglecting the effect of turbulent transfer and longitudinal mixing, it offers only a sectional mean value of the concentration, and is not considered applicable for evaluating the degree of dilution due to intermixing. Particularly in the case of predicting the concentration of pollutants at a downstream station located not so distant from the origin of pollution, Streeter's Formula may perhaps give unsatisfactory results.

---

* Department of Sanitary Engineering

Now, if a waste solution is discharged to a river continuously or intermittently, it distributes itself in the river water as it flows downwards, and after flowing a long distance, the concentration of the pollutant becomes uniform in the river section.

Most of the rivers in Japan are short and the flows are rapid because the slopes of the river bed in the upper and middle parts of the rivers are steep. Therefore, as stated above, the concentration of dissolved oxygen or putrescible organic matters at a downstream station can hardly be computed by conventional methods. Accordingly, in order to show the pollution characteristics of such rivers, we should analyse the local dilution and diffusion phenomena in an open channel.

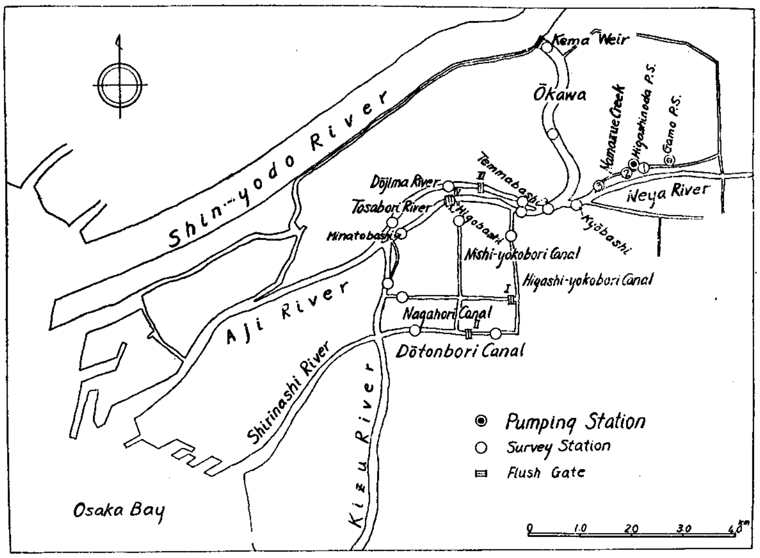

Fig. 1. Regional Sketch of Rivers and Canals in Osaka City.

In this paper, several fundamental studies, including the mathematical analysis of pollutant diffusion, are explained in reference to the results of our river pollution survey carried out in Osaka City from April, 1954[1),2),3)]. From the results of those various field observations, it was found that the degree of pollution was the highest at the Neya River in Osaka City, which is supposed due to the various kinds of discharges from sewage pumping stations along both sides of the River and its tributaries (Fig. 1). Therefore, the effects of discharged sewage from those pumping stations on the quality of Neya River water was analysed, as the first step of our survey.

The Neya River pours into the Ōkawa at Kyōbashi as shown in Fig. 1, then flows downwards through the central district of Osaka, and finally reaches Osaka Bay. Therefore, it has a significant effect on the quality of the river water in the lower district and, furthermore, since the Ōkawa has several branches which run through the down town area which has developed on a low alluvial plain, the greater parts of the streams and canals in Osaka City are affected by the tides. The pollutants from the Neya River are retained for a long time in its lower reaches. Such a phase of river pollution is a typical one for the usual tidal waterways. This is why we must learn the mechanisms of transportation of pollutants under various hydraulic conditions and find out some effective remedies to prevent the increasing degree of pollution in this area.

2. Effect of disposed sewage on the quality of river water

There are fourteen stations along the river sides of Neya River and its tributaries where both domestic sewage and industrial waste are disposed into the river at an average rate of 40,000 m³/day per station. In this article, we shall investigate the effects of discharged sewage from Higashinoda and Gamo Pumping stations (both located on the right side of Namazue Creek, one of the tributaries of the Neya River) on the water quality of the creek in accordance with the results of our basic theory and laboratory experiments.

(**a**) Data obtained by operating Gamo Pumping Station

At Gamo Pumping Station, the accumulated sewage is usually discharged intermittently for 10 to 30 minutes per operation with a flow rate 90 m³/sec. The width of the Namazue Creek near this station is 9.2 m. From our observations, the sewage discharged into the creek seemed to be distributed uniformly over the cross section after 5 minutes. Since, there were no discharges from other pumping stations during the period of observation, the suitable data for comparison with the results obtained by our fundamental and theoretical formula, which is developed as follows.

If a batch of sewage, of volume V and concentration of pollutants q_0, is discharged to a channel with a cross sectional area A for a short time, and assuming that the pollutants instantaneously spread uniformly between the upper $(x=-\xi)$ and lower section $(x=+\xi)$ around the point of discharge, the changing rate of the concentration at downstream station is expressed by

$$\frac{\partial C}{\partial t} = D_x \frac{\partial^2 C}{\partial x^2} - KC \qquad (1)$$

and the boundary conditions in this case are

$$\left.\begin{aligned} C(t=0,\ x) &= C_0 = \frac{q_0 V}{2A\xi}, & -\xi \leqslant x \leqslant +\xi \\ C(t=0,\ x) &= 0, & \xi \leqslant |x| \leqslant \infty \end{aligned}\right\} \qquad (2)$$

Accordingly, a mathematical solution satisfying Eq. (2) is shown as

$$C = \frac{q_0 V}{4A\xi} \exp(-Kt)\left[\operatorname{erf}\left(\frac{\xi - X + ut}{2\sqrt{D_x t}}\right) - \operatorname{erf}\left(-\frac{\xi - X + ut}{2\sqrt{D_x t}}\right)\right] \qquad (3)$$

where, C; concentration of pollutant matter in the river at time t (ppm),

C_0; initial concentration of pollutant matter in the river (ppm),

q_0; original concentration of pollutant matter (ppm),

V; volume of discharged sewage (m^3),

X; $=x-ut$, distance from the origin of discharge (m),

u; mean velocity of flow (m/sec),

K; biochemical decay constant (1/sec),

t; time (sec) and

D_x; material transfer coefficient (m^2/sec).

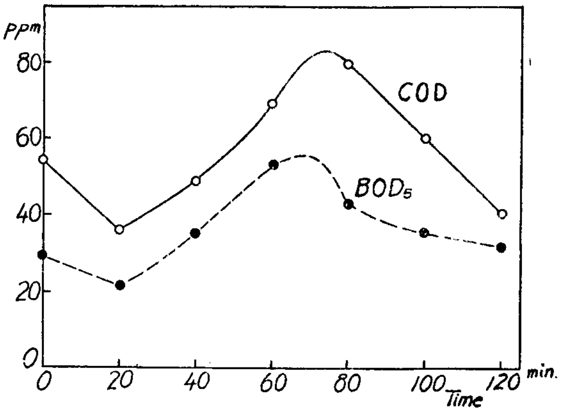

Fig. 2. Observed BOD_5 and COD Values at Station ① during 8 minutes operation of Gamo Pump. St..

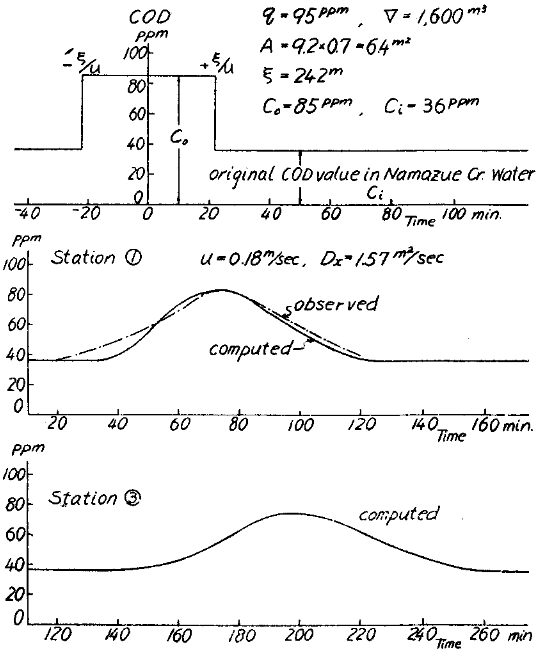

Fig. 3. Analysis of the Changing Rate of the Concentration of Discharged Polluted Matters from Gamo Pump. St. at Stations ① and ③.

In Fig. 2 the BOD_5 and COD values observed at station ① are both plotted against time. These data were obtained by an operation of the Gamo Pumping Plant for eight minutes. Comparing the data, shown in Fig. 2, with the results of the theoretical computation from Eq. (3), it appears that the theoretical results are in good accordance with the observed data, as shown by Fig. 3, and therefore, that the effect of discharged swage from Gamo Pumping Station on the water quality of Namazue Greek, at various hydraulic conditions, can be calculated exactly.

(**b**) Higashinoda Pumping Station

The width of Namazue Creek is so much larger, about 20 m, near the discharge

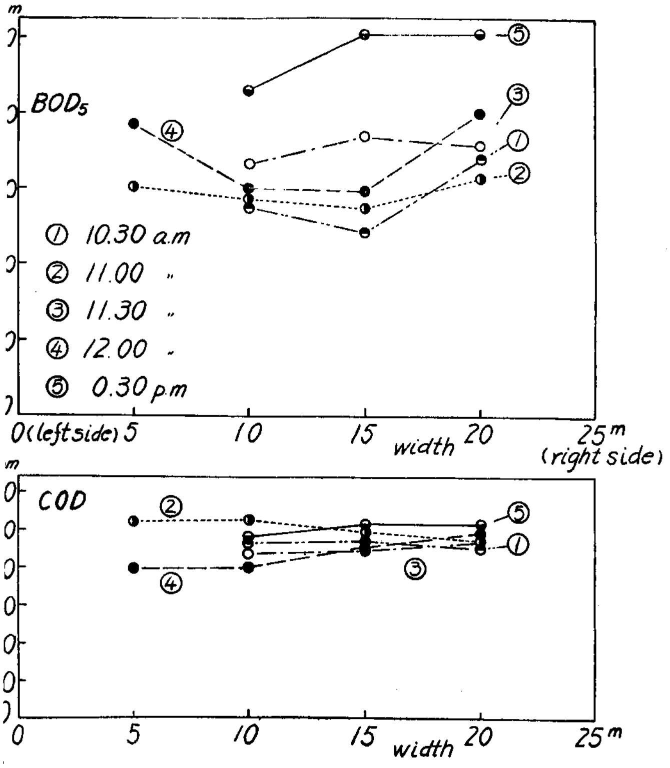

Fig. 4. Distributions of BOD_5 and COD at Station ② in Namazue Creek during a Continuous Operation of Higashinoda Pumping Station.

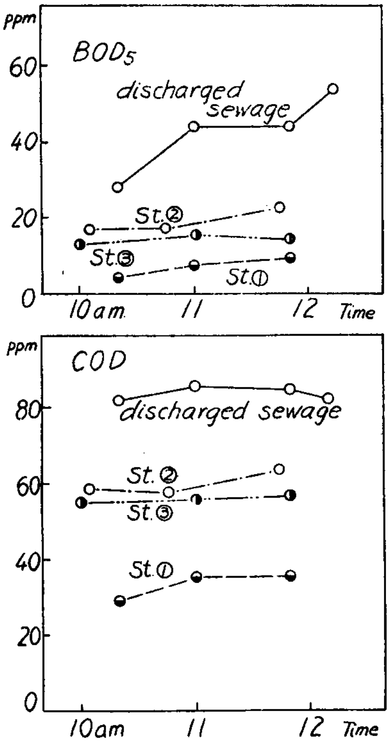

Fig. 5. BOD_5 and COD Values at Stations ①, ② and ③ in Namazue Creek during a Continuous Operation of Higashinoda Pumping Station.

of the Higashinoda Pumping Station, that a considerable distance is required for the sewage discharged from this plants to distribute itself uniformly over the cross section. Fig. 4 shows the local BOD_5 and COD values at Station ②. These results seem somewhat irregular, but as the difference between the observed values are small, no significant tendency could be found in them. Therefore, the concentration of pollutant matter may be regarded as constant over the cross section at Station ②. The water quality fluctuation of Namazue Creek in the direction of flow, when the Higashinoda Pumping Station was in continuous operation, was investigated and the results are shown in Fig. 5.

Refering to Fig. 5, it is observed that when Higashinoda Pumping Station is operated continuously alone, the intermixing of the discharged sewage with the river water is almost complete before the water passes the section at Station ②. Accordingly, the local water quality is kept constant from Station ② to Station ③, where the Namazue Creek flows into the Neya River, unless the other lower stations are being operated.

For such a small stream as the Namazue Creek, it is important to determine

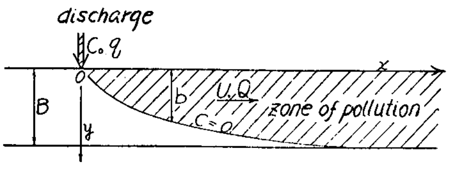

Fig. 6. Plan of a Channel.

the position of the cross section where the pollutant matter uniformly dispersed. Including this problem, we developed a mathematical analysis for the diffusion of suspended pollutant matter while a waste being supplied continuously at one side of a river.

Now, if a waste solution is injected continuously in a steady state flow at the point $x=0$ in a direction perpendicular to the flow, as shown in Fig. 6, then assuming that the mean velocity of flow in the channel U, the rate of discharge of waste q, and the lateral diffusion coefficient D_y are constant, and also neglecting the effects of longitudinal diffusion, we have

$$U\frac{\partial C}{\partial x}=\varepsilon\frac{\partial^2 C}{\partial y^2} \tag{4}$$

where C; concentration of pollutant matters in the river (ppm),

U; mean velocity of flow in the channel (m/sec) and

ε; $=D_y$, lateral diffusion coefficient (m^2/sec).

The boundary conditons for this case are

$$\left.\begin{aligned} C&=f(y), && \text{at } x=0\\ \frac{\partial C}{\partial y}&=0, && \text{at } y=0\\ \frac{\partial C}{\partial y}&=0, && \text{at } y=B \end{aligned}\right\} \tag{5}$$

The mathematical solution which satisfies the conditions of Eq. (5) is as follows.

$$C=\frac{1}{B}\left[\int_0^B f(y)dy+2\sum_{n=1}^{\infty}\exp\left\{-\frac{\varepsilon}{U}\left(\frac{n\pi}{B}\right)^2 x\right\}\cos\left(\frac{n\pi y}{B}\right)\int_0^B f(y)\cos\left(\frac{n\pi y}{B}\right)dy\right] \tag{6}$$

where, B denotes the width of channel.

With Eq. (6), we can estimate the local concentration of pollutants in any channel section. However, some complicated calculations are required to obtain the results, which are not always considered to be practical. Therefore, for convenience, we introduce the mean concentration, $\bar{C}$, which is expressed by

$$\bar{C}=\frac{1}{b}\int_0^b C dy \tag{7}$$

where, b denotes the width of the pollution in any section. Now, the boundary curve between the zone of pollution and of clean water satisfies the following equation, obtained by taking the left side of Eq. (6) as zero.

$$0=\int_0^B f(y)dy+2\sum_{n=1}^{\infty}\exp\left\{-\frac{\varepsilon}{U}\left(\frac{n\pi}{B}\right)^2 x\right\}\cos\left(\frac{n\pi b}{B}\right)\int_0^B f(y)\cos\left(\frac{n\pi y}{B}\right)dy \tag{8}$$

In cases where the original concentration of pollutant matter in the stream, before it is intermixed with sewage, can be neglected in comparison with that of the waste solution, $\bar{C}$ may written by

$$\bar{C} = \frac{qC_0}{Ub} \tag{9}$$

where, C_0 is the original concentration in the sewage.

The dilution factor p becomes

$$p = \frac{C_0}{\bar{C}}. \tag{10}$$

Assuming that the lateral distribution of the injected waste at the original point takes the from

$$\left.\begin{aligned} f(y) &= C_S \cos\frac{\pi y}{2b_T}, & 0 \leqslant y \leqslant b_T \\ &= 0, & b_T \leqslant y \leqslant B \end{aligned}\right\} \tag{11}$$

and, substituting Eq. (8) for Eq. (11), we have

$$\sum_{n=1}^{\infty} \exp\left\{-\frac{\varepsilon}{U}\left(\frac{n\pi}{B}\right)^2 x\right\} \frac{\cos n\pi\frac{b_T}{B} \cdot \cos n\pi\frac{b}{B}}{1-\left(2n\frac{b_T}{B}\right)^2} = -\frac{1}{2} \tag{12}$$

In Eqs. (11) and (12), b_T represents the assumed value of b at $x=0$ when the additional loss of energy due to intermixing is not taken into account, and C_S means the corrected value of C_0 relating to b_T; it should be noted that the following relationship holds.

$$C_0 b_0 = C_S b_T \tag{13}$$

where, b_0 is the measured value of b at $x=0$.

In order to verify the validity of the above-introduced relationship, a series of experiments with model was carried out in our laboratory using a flume, 10.0 m in length, 0.20 m in width and 0.20 m tall. In the experiments, as shown in Fig. 7, sodium fluorescenite solution was injected at a point at one side of the flume to investgate the diffusion characteristics of the dye in the flowing water, which is supplied at a constant rate from a storage tank. The values of b, the actual width of the dispersed dyes, were measured at various section, and from the results, it was

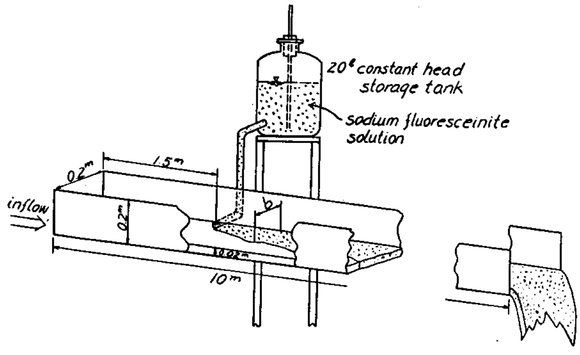

Fig. 7. Experimental Apparatus.

observed that fluid turbulence was very obvious near the point of injection, but it soon decreased to a steady state within a rather short distance. Under the condition that $q/Q=0.0136\sim 0.119$, $Q=260\sim 404$ ml/sec, where q is the rate of discharge of coloured solution, the lateral diffusion coefficient may be regarded as constant in the region $x/B>7.5$. Refering to Eq. (12), the value of b_T in the observations can be found as follows; the value of ε in Eq. (12) was determined such that the computed curve of b versus x would coincide with the observed one in the region of ε=constant or $x/B>7.5$. After that, by extrapolating the theoretical b-x curve, which has been obtained by using the final values of ε ($0.05\sim 0.12\,\mathrm{cm}^2$/sec) down to the section at $x=0$, the value of b_T can be finally found.

With regard to air pollution phenomena caused by the fumes in smoke, the effective initial height of the diffusing particles at the origin of pollution determines the initial condition to be adopted in the analysis of the transportation and diffusion of fumes in the atomosphere.

The effective height is evaluated as a sum of the actual stack height and the height of the initial rise of effluent fume, above the tope of the stack, due to the stack draft velocity and other dynamic conditions. Refering to several previous studies4),5), the excess rise due to both the stack draft velocity and the mean wind velocity has been called "the velocity rise" and the rise due to the temperature difference between the stack gas and the atomosphere has been called "the temperature rise".

Since b_T, in this problem, corresponds to the effective height, as mentioned above, and no temperature rise is included in this case, we may only consider the effect due to "the velocity rise".

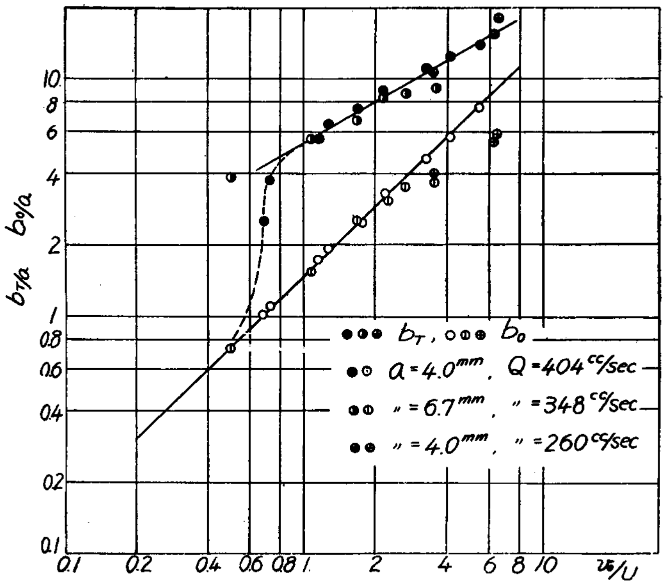

Fig. 8. Relation between v_0/U and b_T/a, b_0/a.

Now, the relation between b_T and v_0/U (v_0; the entering velocity of pollutant solution) in our experiments, as shown in Fig. 8, may be regarded as very similar to the air pollution phenomena, which is expressed inclusively by the the following formula:

$$\frac{b_T}{a} = \lambda \left(\frac{v_0}{U}\right)^{\xi} \tag{14}$$

where, a is the width of outfall, and

$$\xi = 1 \quad \text{for} \quad 0.5 > \frac{v_0}{U} \tag{15}$$

$$\xi > 1 \quad \text{for} \quad 0.5 < \frac{v_0}{U} < 1.0 \tag{16}$$

$$\xi < 1 \quad \text{for} \quad 1.0 < \frac{v_0}{U} \tag{17}$$

Furthermore, one of the authors has introduced[6] the following relation,

$$p \propto \frac{b_T}{a}\frac{U}{v_0} \tag{18}$$

and also has proposed a theoretical method to evaluate $\bar{C}$ for any downstream station.

After substituting Eq. (18) for Eq. (12),

$$p \propto \left(\frac{v_0}{U}\right)^{\xi-1}$$

is obtained finally. We may conclude the following: 1) If the value of v_0/U is less than 0.5, then p, the dilution factor, becomes independent of v_0/U. 2) In the range of $0.5 < v_0/U < 1.0$, p increases proportionally to v_0/U. 3) When $v_0/U > 1.0$, p is inversely proportional to v_0/U. Moreover, the distance of the section in which the distribution of pollutants becomes uniform, x_C, is only due to the value of b_T at $x=0$, and also, x_C is inversely proportional to b_T. Therefore, the mutual relations of x_C, v_0/U and p can be inferred from the above-mentioned conclusions.

3. Transportation mechanisms of polluted water from the Neya River through the waterways in the lower area

The hydraulic characteristics of rivers and canals in Osaka City are governed by rate of discharge from the Neya River and the tidal flows in Osaka Bay. At the present, the rate of inflow from the Yodo River to the Ōkawa is controlled at the Kema Weir by a standard flow rate of 80 m^3/sec, though it becomes somewhat larger at high water levels, and on the other hand, the discharge of the Neya River varies from 20 to 30 m^3/sec. Practically, however, after a heavy rainfall it often becomes as high as 80 m^3/sec. The tidal cycle of Osaka Bay is twice per day and the tidal range is 140 cm in the spring tidal stage. The back current in a flood tide is observed in most part of the water area, and the net duration of the positive downward flow for a tidal cycle is about 7 to 8 hours.

By our field experiments, tracing floats and routing the pollutant matters in the streams, the paths, through which the waste matters from the Neya River may travel downwards, are classified into the following three cases: 1) Ōkawa~Tosabori~Kizu, 2) Ōkawa~Tosabori~Higashi-Yokobori~Dōtonbori~Kizu and 3) Ōkawa~Tosabori~Nishi-Yokobori~Dōtonbori (or Nagahori)~Kizu.

The process of our analytical computation for the transportation mechanism in the waterways are shown as a set of time-travel diagrams on Figs. 9, 10 and 11. The diagrams were made by a cut and try calculation, succeedingly using the local velocity values observed intermittently during a 4 to 12 hour period at each stations as shown on Fig. 1. For example, refering to the *a*-curve in Fig. 9, a fraction of polluted water flowed into the Ōkawa at Kyōbashi Station was observed in the morning at nine

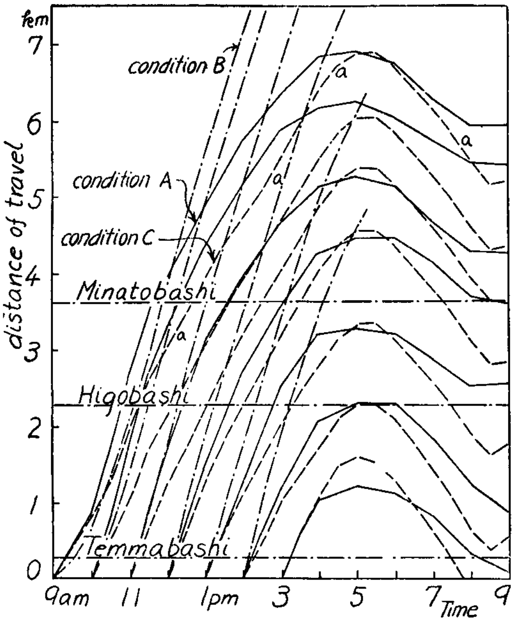

Fig. 9. Time-Travel Diagram ((1)-Course, Taking the Origin of Distance at the Inflowing Point of Neya River into Ōkawa.)

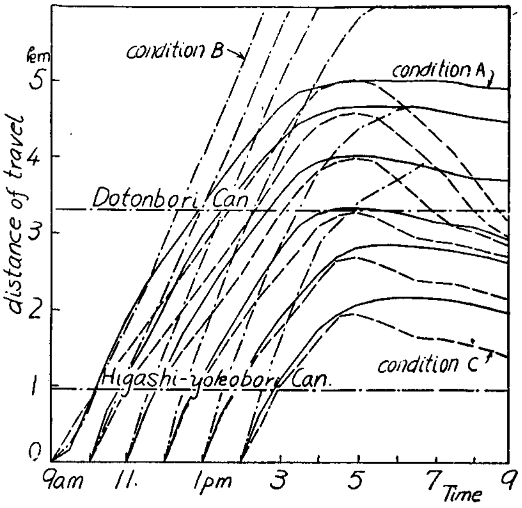

Fig. 10. Time-Travel Diagram ((2)-Course, Taking the Origin of Distance at the Same Point as Fig. 9).

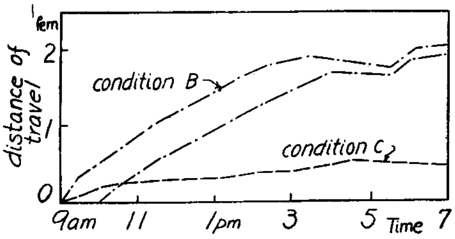

Fig. 11. Time-Travel Diagram ((3)-Course, Taking the Origin of Distance at the Separated Point of Nishi-yokobori Canal from Tosabori River.)

o'clock. It reached Higobashi Station at a quarter to one. The farthest distance of travel from the origin is assumed to be 7.2 km in one tidal cycle but, owing to the upward back flow for about 2 km in one tidal cycle.

Each group of curves in Figs. 9, 10 and 11 represent three different flow condition; A, the usual state, B, increasing flow after a rainfall and, C, a rather small discharge of the Ōkawa, in comparison with that of the Neya River, by control at the Kema Weir. Data plotted in Fig. 12 are for the rates of discharges observed simultaneously at Temmabashi Station.

If the suspended pollutants travel in such a course as the Ōkawa~Tosabori~Kizu, the farthest distance of transportation from the origin is estimated as about 7 km, for a case of ordinary discharge, on the basis of the diagram in Fig. 9. However, when the discharge of the Ōkawa is much smaller than that of the Neya River, the net rate of travel should be smaller than the above, because there may be 1.5 km of negative travel due to the back current in a flood tide condition. Furthermore, when the discharge in the upper section is increased after rainfall, it is clearly verified that the rate of travel per unit time becomes much larger.

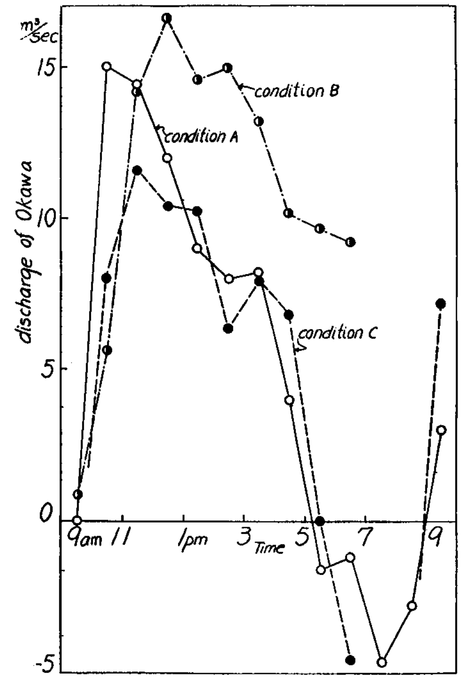

Fig. 12. Discharge of Ōkawa at Temmabashi Station on three flow conditions of the observations.

Based upon the results of our investigations, it is recognized that the proper control of the many sewage pumping stations installed along the Neya River and its tributaries may be most effective for prevention of a longer detention of putrescible matters at the downstream water area. Under normal conditions such as shown on Fig. 9, almost all the polluted water being poured into the Ōkawa can be flushed away through the Tosabori River, three hours after a high tide, if those pumping stations are operated for this period only, and if the inflowing sewage for the remaining time is stored in reservoirs, if possible. Accordingly, we have discussed the sites, capacities, number and structural details for such storage, and our proposals will be ready in the near future. In addition, it was proved that if the discharge is large as shown on Fig. 9, the pumping stations should be operated during the whole ebb-tide period. On the other hand, when the polluted water is transported through the other courses such as Ōkawa～Tosabori～Higashi-Yokobori～Dotōnbori～Kizu or Ōkawa～Tosabori～Nishi-Yokobori～Dōtonbori～Kizu, the positive rate of transport would be considerablly decreased and the organic matter being carried in the Higashi-Yokobori～Dōtonbori Water Course would be retained during at least one tidal cycle in this area. As shown in Fig. 1, there are four tainter gates (I, II, III, and IV) installed transversally across the streams in this area, which are operated sometimes to flush down the deposit materials on the river beds. Now, if the gates I and II are closed at an ebb-tide condition, the flow towards Higashi-Yokobori Canal is checked, accordingly, it is seldom possible for the wastes supplied from the Neya River to enter this area. But for the Nishi-Yokobori Canal, since any effective control of the flow is impossible, the rate of discharge at this site may become remarkablly larger by closing the gates I and II, and then a considerable increase in transportation efficiency may probably be expected.

Consequently it can be concluded that the closing of gates I and II for a definite time period during ebb-tide condition is one of the most effective and practical remedies, for reducing the degree of pollution in the water area of the Higashi-Yokobori, Nishi-Yokobori, Dōtonbori and Nagahori Canals.

4. Summary

The authors investigated analytically the dilution mechanism of disposed sewage to the waterways in the city of Osaka for the two typical cases; 1) the waste solution is discharged intermittently to a steady state uniform flow and soon disperses uniformly over the cross section, and 2) the waste solution is discharged continuously at one side of the same stream. For the case 1), Eq. (3) was found to be appropriate to evaluate the changing rate of suspended pollutant matter concentration at any downstream stations. Moreover, for case 2), the ratio of the discharging velocity of waste solution to the mean velocity of the stream, v_0/U, proved to be a significant parameter. The dilution factor, p becomes independent of v_0/U, for $v_0/U<0.5$, and increases proportionally to v_0/U for $0.5\leqq v_0/U\leqq 1.0$, but becomes inversly proportional to v_0/U when $v_0/U>1.0$.

Furthermore, as the results of several investigations on the rate of transport and on the routing of pollutant matters supplied from the Neya River, two practical remedies to reduce the pollution of the downstream water area of Osaka City were proposed. These are, 1) the sewage pumping plants installed at the upper region should be operated accurately in accordance with the tidal condition, 2) the four gates, especially gates I and II, should be operated so that the putrescible matters from the Neya River may not enter the Higashi-Yokobori Canal and also that the flushing intensity of the flow in the Nishi-Yokobori Canal may increase during this period.

This research has been carried out as one of the extensive studies on stream and coastal sanitation, being performed in our laboratory, under the direction of Prof. S. Iwai, whom the authors wish to thank very much.

References

1), 2), 3) S. Iwai, T. Goda, T. Tsutsui and S. Nambu, "Report of the 1st, 2nd and 3rd Surveys on the Hydraulics and Water Qualities of Rivers and Canals in Osaka City" Bulletin, Osaka Mun. Office, (1956), (1957), (1958).
4) Air Pollution Handbook, McGraw-Hill Book Co. Inc., (1956).
5) Meteorology and Atomic Energy, U. S. Dept. Commerce Weather Bureau., (1955).
6) S. Nambu, Trans. J. S. C. E., 59, 26, (1958).