RUN-OFF ESTIMATION IN STORM SEWER SYSTEM USING EQUIVALENT ROUGHNESS*

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Synopsis

The rational method has been often used to estimate the storm water run-off in combined sewerage system. But rigorously, this method still remains unreasonable hydraulically because the motion of flow is usually not taken into account correctly. Therefore, in this paper, the fundamental factors concerning the process of calculation are revised by the method of characteristic curves introducing the equivalent roughness of drainage area. The inlet time must be taken equal with the time which is needed for the standard characteristic curve to cover the distance from the upstream end of drainage area to its downstream end and also the flow-down period with the shortest time required for the curve in sewer samely, while, especially, the former must be related to the width of the area and the equivalent roughness. When the drainage area is comparatively larger and the retardation occurs, the maximum rate of run-off decreases proportionally with the equivalent roughness, so that the run-off coefficient may better be represented by the equivalent roughness. Moreover, it was pointed out theoretically that the maximum rate of run-off could become larger value if retardation occured, according to the type of rainfall intensity curve.

The characteristics of the equivalent roughness can be explained in relation to the width of drainage area and the density of sewer net, and it may become very small value in the street area in which side gutters or sewers are fully equipped, but may become larger in the suburban undeveloped district. If the sewerage system consists of circular pipes the overall equivalent roughness in the whole drainage area can be calculated approximately by only the roughness in the smallest end area and accordingly the run off analysis can be made without the assumption of pipe diameters.

1. Introduction

A general classification of waste water in the sewerage is made such as domestic sewage, industrial waste, rain water and ground water. In most cases of design, the amount of storm water, which does not appear usually, would definitely rule the construction cost of whole sewerage system. Especially, any plan of combined sewerage system will result in the problems of hydraulic complexity, water contamination due to the limit of ability of sewage treatment plant and storm water overflow[1),2),3)] and the economies based on the capacities of sewer, overflowing device and plant. With regards to the above third problem, the new plan or extention work of sewerage in foreign countries seems to adopt the separate system[3)] and recently the same trend appears in Japan. The separate system, however, needs also independent canals or sewers for rainfall drainage. The reasonable plan for sewerage system must be based upon perfect planning theory of both systems and should not be made from a simple economic comparison.

The original purpose of storm run-off calculation in sewerage system is same as the flood discharge plan in rivers. Main differences seen in the processes of calculation for sewerage are narrower drainage area and more artificial elements in street area, especially, the slow timely change of velocity is negligible in rivers, but in the sewerage system the change of run-off phenomena is very rapid in general because the object is heavy storm in short period. Consequently, it is impossible to put the elements of unsteady flow out of consideration. Various formulas for storm water run-off calculation, however, come from empirical results or conventional theories and have been used for long time with little investigations, which result in

* Presented at the 17th Annual Meeting of J.S.C.E., May, 1962.

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relatively small rates of run-off for reduction of construction cost.

It is so difficult to analyse the storm run-off phenomena rigorously that the correct analytical formula could not be presented except giving a process of calculation. However, with analysis of hydraulic mechanism of sewer flow using appropriate assumption proved to make a reasonable design of sewerage system. One of the factors which delayed the clearing of problems both for the sewerage and rivers is the difficulty in evaluating actual flow rates in channels, but recently in Japan, remarkable research results on the flood run-off in rivers have been obtained, for example, application of the unit graph or synthetic unit graph method[4),5)], and completion of analog computer[6)] for run-off calculation.

In this paper, the results of hydraulic studies, on the reasonable design of combined sewerage system or storm sewer system and also the basic principles for planning including the control of water quality and economic factors, are described. The theoretical basis is the approximate analytical method using the characteristic curves derived by Dr. Iwagaki[7),8)], and modifying this method for the run off analysis of mountain district the author already published the practical procedure in which the concept of equivalent roughness of equivalent drainage basin and logarithmic representation of the standard characteristic curves were introduced[9)]. Subsequently, many researchers studied the factors on above mentioned procedure in relation with the various basin characteristics[10),11)].

In the present investigation, several discussions are made on the usual formulas for storm run off calculation in sewers, then so-called rational method is intended to revise using above mentioned procedure, which is considered more profitable for the artificial street area, especially, it is emphasized to clarify the hydraulic significances of several important factors, inlet time, flow-down period, run-off coefficient, rainfall duration.

2. Discussions on the Conventional Formulas for Storm Run-off in Sewers

The existing formulas for calculation of storm water run-off in sewers are divided into two groupes, one of which is the empirical formula represented by Bürkli-Ziegler formula and another the theoretical such as the rational formula. In general, the former is written as follows.

$$Q_{max}=CiF(\sin\theta'/F)^{1/j}, \quad \cdots\cdots(1)$$

in which Q_{max} denotes the maximum rate of run-off in sewer, C the run-off coefficient, i the timely rainfall intensity, F the area of drainage, $\sin\theta'$ the surface slope of the drainage area and j the integer. The special characteristics of the empirical formulas were hitherto discussed referring to many practical examples, but it must be emphasized again that they should be applied under the same conditions of drainage area as they were obtained because of the dimensionally incorrect multiplication with the retardation coefficient $(\sin\theta'/F)^{1/j}$.

On the other hand, the basic equation of the rational method,

$$Q_{max}=CiF, \quad \cdots\cdots(2)$$

is correct theoretically, but this form gives ultimate possible rate of run-off if the rain water is completely drained with no stagnation. Thereafter, Q_{max} appears when the rain waters are concentrating from whole parts of drainage area, and for this reason the design principle taking the rainfall duration T equal to the time of concentration is established. From such a standpoint, the statistical computation is done for the relation between the rainfall duration T and intensity i and so those investigations on the probable intensity-duration curves were made to raise their accuracies for practical application[12),13)]. However, it is the matter of course that all though the run-off coefficient is multiplied simply to discount the rate of run-off, the rational formula often gives exessive amount of storm run-off if the retardation is not considered. In application of the rational method, the corresponding factor to the retardation coefficient in the empirical method is taken into account in calculation of time of concentration and also in determination of the design value of i. Hence, the practical form of the rational formula is written as follows,

$$Q_{max}=Cf(T)F, \quad \cdots\cdots(2')$$

where $f(T)$ is the rainfall intensity i represented by the function of T. If the function

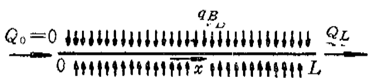

Fig. 1 Upper end reach of sewer with uniform lateral inflow of of storm water.

$f(T)$ is evaluated reasonably related to the various characters of drainage area, an accurate rate of storm run-off would be obtained rather than using the empirical formulas.

One of the problems in applying Eq. (2) or (2′) is the assumption of taking the flow-down velocity constant for the identical conditions of slopes and sewer diameters without reference to the effect of surface storage of rain water, and another is the inconvenience caused by the reassumption of velocity with the calculated rate of run-off. This procedure is signified hydraulically as follows.

Now, consider a reach of sewer as shown in **Fig. 1** and take L as the length of the reach, A the sectional area of flow in sewer, Q the flow rate, t the time, x the distance along the flow and q_B as the lateral inflow rate of storm water per unit length of sewer. When a certain value of q_B is suddenly supplied into the sewer, which contains no storm flow at the upstream end ($x=0$), the equation of continuity of flow in sewer is

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_B. \quad \cdots\cdots(3)$$

Let U be the mean flow velocity in a cross section of the sewer, Eq. (3) becomes

$$\frac{\partial A}{\partial t}+U\frac{\partial A}{\partial x}+A\frac{\partial U}{\partial x}=q_B. \quad \cdots\cdots(3')$$

If the radius and slope of the sewer shown in **Fig. 1** are uniform, from the above assumption in the rational method,

$$U=\text{const.} \quad \cdots\cdots(4)$$

becomes the equation of motion in the sewer. Substituting Eq. (4), Eq. (3′) is rewritten as

$$\frac{\partial A}{\partial t}+U\frac{\partial A}{\partial x}=q_B, \quad \cdots\cdots(3'')$$

and therefore, the characteristic representation of Eq. (3″) becomes

$$\frac{dx}{dt}=U, \quad \frac{dA}{dt}=q_B. \quad \cdots\cdots(5)$$

Eqs. (5) signifiy that on a straight characteristic line of constant slope U, as illustrated in **Fig. 2**, the relation, $dA/dt=q_B$, exists. Therefore, the value of A at an arbitrary section of the sewer is evaluated by integrating the second

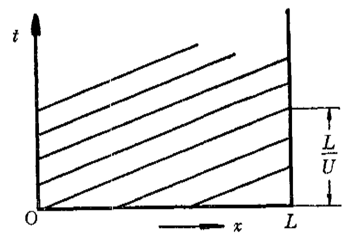

Fig. 2 Characteristic straight lines in the rational method.

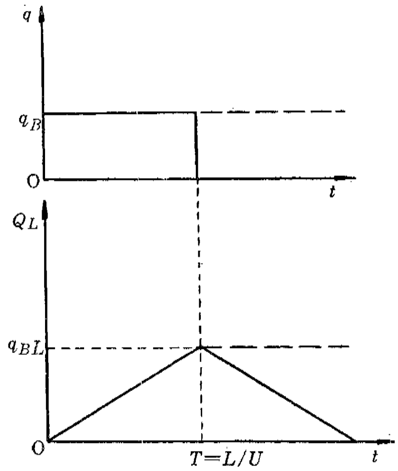

Fig. 3 Storm run-off at the downstream end of sewer obtained by the rational method.

equation of (5) along the characteristic line, and when the initial condition, at $t=0$, $A=0$, is set A and Q at the unsteady condition is formulated as the next equations.

$$A=q_Bt=q_B\frac{x}{U}, \quad Q=q_Bx. \quad \cdots\cdots(5')$$

As A and Q are always 0 at the upstream end $x=0$, the flow in sewer turns into steady condition with advance of the standard characteristic line[9] which starts from $x=0$ at $t=0$, and at the lower end the rate of run-off Q_L becomes steady and maximum value, $Q_{L,\max}=q_BL$ at the time $t=L/U$. After the inflow q_B stopped suddenly, with the similar consideration, the variation of Q_L at the lower end of sewer is shown as **Fig. 3**. Here, it is understood that the rainfall or inflow duration T must be taken as the flow-down period L/U for selecting the magnitude of i or q_B.

Obviously, Eq. (4) is not satisfactory as the equation of motion for sewage flow, and when a rigorous expression replaces Eq. (4), the magnitude of dx/dt will be greater than U[14]

and also U is not constant.

The detention formula

$$Q_{max} = Cf(\alpha T)F, \quad \cdots\cdots(6)$$

where α is a constant larger than unity, was proposed by Dr. Itakura[15] in 1955 for the purpose to reduce the excess amount of storm run-off compared with the actual one. This method is based on the principle of less velocity due to the storage effect of rain water detention in sewer so that the delayed period of T is adopted. But the concept of Eq. (4) still remains. It must be noted that the detention method will be available for the storm run-off calculation for sewers of relatively gentle slope and that the theoretical procedure of this method has enough room for improvement.

On the other hand, recently, it appears to be tried further to produce new empirical formula including various factors. Ordinary the relationship between the rainfall duration and intensity is contained in it as in the rational formula. However, since the empirical formula is not founded on such a theoretical basis, the intention of this procedure, changing the intensity i according to the extent of drainage, in addition to the direct accounting of slope, area, etc., is considered to be quite obscure essentially.

The determination of the run-off coefficient C is also the important problem in application of not only the rational formula but the empirical. In the present time, it still remains as experimental coefficient. There exist two different meanings for the run-off coefficient, one is defined mathematically as follows referring to the effective amount of rainfall in a serial rainfall,

$$C = \frac{[\text{Total Run-off in a Drainage Area}]}{[\text{Total Rainfall in a Drainage Area}]} \quad \cdots\cdots(7)$$

which is often used in run-off analysis for rivers; the other is defined according to Dr. Itakura's proposal[15] as

$$C = \frac{[\text{Maximum Rate of Inflow to Sewer}]}{[\text{Rainfall Intensity}] \times [\text{Drainage Area}]}, \quad \cdots\cdots(8)$$

the concept of which suggests the exception of inflow to sewer having no effect on the maximum rate of run-off. Whether Eq. (7) or (8) is used, the experimental procedure to evaluate the value of C must fit each definition. It will be easily presumed that C based upon Eq. (8) has close relation with the inlet time to sewer.

As mentioned above, the problems in the storm run-off computation were pointed, but they are all attributed to the necessity of analysing the fundamental equations of unsteady motion of storm water in the drainage area and sewers. Recently, in the United States, the storage equation is often used for the storm run-off calculation in a series of side gutter, tributary and trunk sewers, combining Muskingum method and Manning's law of resistance[16]. Although this process of calculation is considerably complicated, it might be noticeable on the standpoint of theoretical treatment.

3. Applilication of the Approximate Method of Calculation Using Characteristic Curves to the Run-off in Sewers and Drainage Area

In this chapter, prior to discuss the hydraulic significances of the factors in the rational method, the procedure of the logarithmic representation of the characteristic curves, the introduction of the equivalent roughness[9], and several notes on the practical application to the run-off estimation will be described briefly.

As the rate of flow or mean velocity in sewer becomes, in general, maximum at partially flowing condition before flowing full, some allowance must be added to the calculated sectional area in the design of sewer section. Accordingly, the theories of open channels are applicable also to sewers so far as the maximum design storm flow is concerned.

In applying the approximate method of calculation of the characteristic curves for the uniform sectioned canal with lateral inflow, it is required that the slope of the sewer under consideration is relatively steep and damping of flow rate is not so remarkable. Although the vertical alignment of sewers is influenced by the slope of ground surface, it may be advisable, in general, to lay them steeper as possible, and besides, the storm flow in the combined sewer also has a role of sweeping down the deposites originated from dry weather flow. Accordingly, $\sin\theta$, the slope of sewer, is required to be taken more than 1/200 or 1/300[17]. In case the slope of sewer is not enough steep due to the flatness of ground, it will be deduced, in the same way as the economic design of the low head main pipe in water supply, that the drainage system with pumping up is rather economical.

In the next, the sectional shape, slope and roughness of sewer and the lateral inflow rate due to rainfall must be assumed to be uniform in an appropriate reach of the sewer. However, the facts that the sewers are artificial structures and the shape of a drainage area from which a reach of sewer accepts the rain waterinflow↗ ↗is almost rectangular by the plain arrangement of streets would produce no practical obligations concerning the above assumption, and also it is considered that the application of the approximate method of characteristic curve to sewerage is more suitable than to river basin.

Then, the procedure to obtain the logarithmic representation of the standard characteristic curve is as follows. Based on the equation of continuity (3) and the equation of motion of unsteady flow in partially flowing sewers with lateral inflow,

$$\frac{\partial U}{\partial t}+\alpha_m U\frac{\partial U}{\partial x}-(\alpha_m-1)\frac{U}{A}\frac{\partial A}{\partial t}+g\cos\theta\frac{\partial h}{\partial x}-g\sin\theta+\frac{n^2gU^2}{R^{4/3}}+\frac{\alpha_m U q_B}{A}=0, \quad\cdots\cdots(9)$$

the approximate representations of characteristics in relatively steep slope,

$$\frac{dx}{dt}=\left(1+\frac{2}{3\varepsilon}\right)U+\frac{(1-2/3\,\varepsilon)Uq_BR^{4/3}}{2\,n^2gQ+q_BR^{4/3}}, \qquad \frac{dA}{dt}=q_B \text{ or } \frac{dQ}{dx}=q_B \quad\cdots\cdots(10)$$

are derived, and also the relationship between the sectinoal area of flow A, mean velocity U and rate of flow Q becomes

$$Q=A\sqrt{\left\{\left(1+\frac{2}{3\,\varepsilon}\right)\frac{q_BR^{4/3}}{2\,n^2gA}\right\}^2+\frac{R^{4/3}}{n^2}\sin\theta-\frac{2(1-2/3\,\varepsilon)U(q_BR^{4/3}/2\,n^2gA)^2}{U+q_BR^{4/3}/2\,n^2gA}}-\left(1+\frac{2}{3\,\varepsilon}\right)\frac{q_BR^{4/3}}{2\,n^2g}. \quad\cdots\cdots(11)$$

Here, α_m denotes the correction factor of momentum, h the water depth, g the gravity acceleration, n the Manning's coefficient of roughness of sewer, R the hydraulic radius of sewer, and ε is $(R/A)/(dR/dA)$. Calculation of run-off at the lower end of the reach will be made as was described concerning the rational method, but the equation of the characteristic curves in Eqs. (10) differs from the one in Eqs. (5) and dx/dt is greater than U, as stated previously.

As the lateral inflow is supplied by rainfall, the actual value of q_B is considerably small, —for example—, if the rainfall with intensity $i=100$ mm/hr occurs in the drainage area of width $B=1000$ m, the value of $q_BR^{4/3}/2\,n^2gA$ in Eq. (11) is at most 10^{-2} m/sec nevertheless $R^{2/3}(\sin\theta)^{1/2}/n$ has the order of 1~2 m/sec, therefore, Eq. (11) will be simplified and Manning's law,

$$Q=\frac{A}{n}R^{2/3}(\sin\theta)^{1/2}, \quad\cdots\cdots(12)$$

becomes useful regardless of the rainfall intensity. In the hydraulic calculation of sewage sewers Ganguillet-Kutter's formula was hitherto used mainly, but recently, development of researches on the law of resistance to turbulent flow and the character of roughness n has made clear,

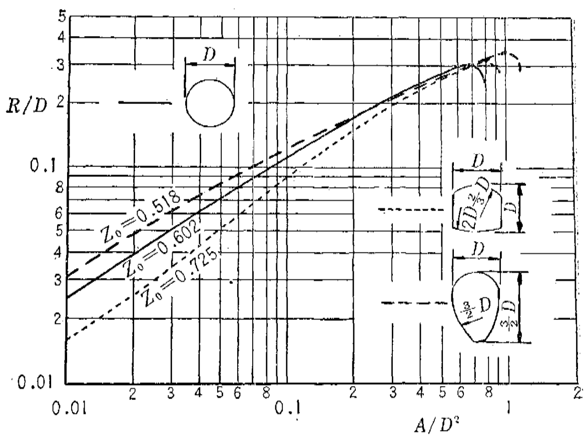

Fig. 4 Relationships between hydraulic radius and flow area in several kinds of sewer section.

so that, Manning's law of simple exponential form, Eq. (12), is applied in this paper.

Finally, thestorm run-off can be analysed using Eq. (12) and the relations $A=q_Bt$ and $Q=q_Bx$, which are established on the standard characteristic curves starting from $x=0$ where $Q=0$ at $t=0$. The combination of these relations is actualized by expressing the property of sectional form of sewers as

$$R=\kappa_0A^{Z_0}. \quad\cdots\cdots(13)$$

Fig. 4 shows the relationships between R/D and A/D^2 of several kinds of sectional shape used for sewers, in which D is the representative length such as the diameter of circular section. The presence of the maximum value of R/D at a value of A/D^2 is common to all sections and, there, the velocity of flow is maximum in the constant slope. The value of A/D^2 which yields the maximum rate of flow is slightly greater than the one that is corresponding to $(R/D)_{\max}$, but, according to the designing principle of sewer section mentioned previously the relationship between R and A would be covered in effect by the each left side of the peaks of the curves in **Fig. 4**, which certifies the propriety of Eq. (13).

Using Eq. (13), Eq. (12) is transformed to

$$A=\kappa Q^Z, \quad\cdots\cdots(14)$$

where

$$Z=\frac{3}{2Z_0+3},\quad \kappa=\left\{\frac{n}{(\sin\theta)^{1/2}\kappa_0^{2/3}}\right\}^Z. \quad\cdots\cdots(15)$$

Together with the relations, $A=q_Bt$ and $Q=q_Bx$, which are established on the standard characteristic curve, Eq. (14) yields the next two equations.

$$t=\frac{\kappa Q^Z}{q_B} \quad\cdots\cdots(16)$$

and

$$t=\kappa x\, Q^{Z-1}. \quad\cdots\cdots(17)$$

The former is the equation of the standard characteristic flow rate curve, in which the distance x in the standard characteristic curve is converted into the flow rate Q, and the latter is the equation of the equi-distance curve, and both are illustrated by straight lines on log-scale. Therefore, if Z and κ in Eqs. (15) are given, Eq. (16) and (17) may be drawn quite easily with the parameters of q_B and x respectively. From these logarithmic representations of standard characteristic curve, the graphical evaluation of Q at arbitrary t and x will be made rapidly changing q_B stepwise regardless of the initial and boundary conditions[9]. **Fig. 5** shows an example of standard characteristic curves in sewer. When $Q=0$ at $x=0$, the storm flow in the reach with inflow q_B should become steady at certain distance x, at which equi-distance line crosses the standard characteristic curve of q_B, moreover, when the initial condition of no flow along the sewer is considered, the timely

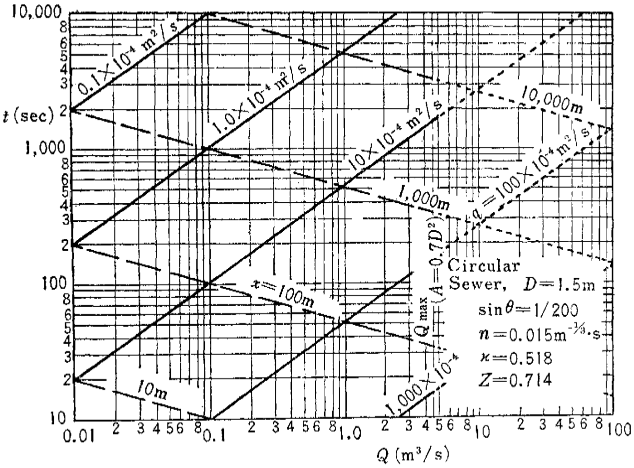

Fig. 5 Standard characteristic flow rate curves in circular sewer.

change of storm run-off rate before becoming steady coincides with the standard characteristic flow rate curve itself. In **Fig. 5**, the sewer capacity line according to its section and slope may serve the purpose of practical design, and it is also possible to vary partly the each gradient of two groupes of curves if the assumption of Eq. (13) is not satisfactory.

In the same manner as described above, the value of q_B would be obtained, that is, two dimensional unsteady flow, with downward inflow due to rainfall, in the drainage area must be solved and q_B is to be obtained as the flow rate at the downstream end of the area. However, exact computation may be so difficult that the actual drainage area is transformed to even rectangular area, the width and the length of which are B and L respectively,–in fact, the plan of the drainage area from which sewer accepts rain water can be often regarded as rectangular in the street area. The author proposed the equivalent roughness n_e for the transformed area in order to make it an equivalent regular drainage area, through which the inflow to sewer q_B is practically equal to the inflow from the actual area. Then, the approximate equations of characteristics for the flow in the equivalent drainage area are written as follows, corresponding to Eqs. (10) and (12) :

$$\left.\begin{aligned}\frac{dx'}{dt}&=\frac{5}{3}U'+\frac{U'ih'^{4/3}/3}{2n_e^2gh'U'+ih'^{4/3}},\\ \frac{dh'}{dt}&=i \ \text{ or } \ \frac{dq}{dx'}=i\end{aligned}\right\}\quad\cdots\cdots(18)$$

and

$$q=\frac{1}{n_e}h'^{5/3}(\sin\theta')^{1/2}, \quad \cdots\cdots\cdots\cdots(19)$$

where the primed symbols illustrate the corresponding values of x, U and h for the equivalent drainage area and q is the two dimensional rate of flow-down toward sewer in the area. The logarithmic representation of the standard characteristic curve to the flow in the equivalent drainage area can be also prepared as for flow in sewers, and

$$t=\frac{(n_e q)^{3/5}}{(\sin\theta')^{3/10}\, i} \quad \cdots\cdots\cdots\cdots(20)$$

and

$$t=\frac{n_e^{3/5}x'}{(\sin\theta')^{3/10}\, q^{2/5}} \quad \cdots\cdots\cdots\cdots(21)$$

are derived corresponding to Eqs. (16) and (17) respectively. **Fig. 6** is an example of the illustration of Eqs. (20) and (21), and as the boundary condition at $x'=0$ is steadily $q=0$ in many cases q_B will easily be obtained from the intersecting point of the standard characteristic flow rate curve of given i and the equi-distance curve of $x'=B$.

In practical design of storm sewers, it seems to raise the accuracy of calculation to divide the drainage area as finely to the smallest upstream part. However, such manner not only produces much trouble for calculation but also causes a doubt whether the various coefficients in the equations, which must be determined by assumptions or experiments, can be correctly estimated or not for individual small areas. Therefore, it might be rather reasonable to treat such group of small areas as an equivalent drainage area including the tributary sewers to some extent. The supposed storm flow in such a compound equivalent drainage area somewhat differs from the actual phenomenon, but when the surface run-off overcomes the lost rainfall due to ground saturation in the street area the law of resistance to turbulent flow like as Eq. (19) becomes useful.

From the data of geographical features of the drainage area and the arrangement, diameters, slopes and roughness of sewers, the rate changes of storm run-off under various types of rainfalls at the intended spot will be analysed following the above procedure. These results

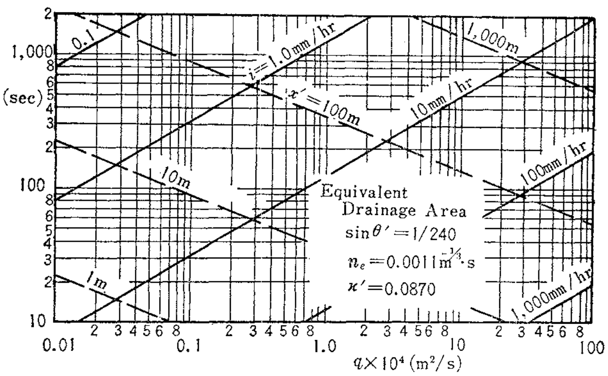

Fig. 6 Standard characteristic flow rate curves in equivalent drainage area.

serve as the fundamental attainments for the rate control of storm overflow or design of pumping drainage in lowland area.

In the following chapters, however, the object of study will be limited for the design problem of section or slope of sewers in new plan of combined sewerage system, or storm sewer system and fundamental considerations for the hydraulic significances of various factors in the process of the rational method using above analytical relations.

4. The Hydraulic Significance of the Inlet Time and Flow-Down Period

Now, consider the rectangular drainage area of width B, which is by one side of the upstream reach of sewer of length L and has no smaller sewers or side gutters, as shown in **Fig. 7 (a)**. **Fig. 7 (b)** illustrates the rainfall condition which begins at $t=0$ abruptly with constant intensity i. The effective rainfall intensity is once assumed to be the same as i which is containing no loss of rainfall for surface run-off.

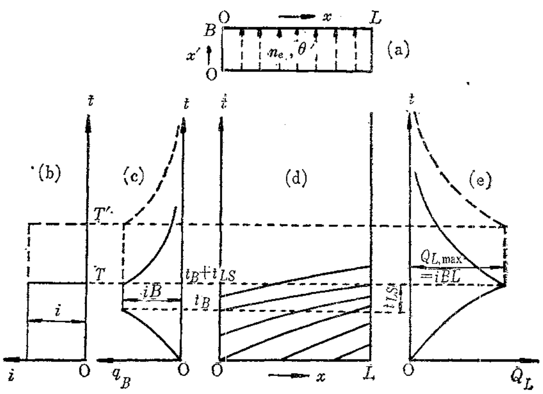

Fig. 7 Relationship between rainfall and run-off with no retardation.

If the drainage area is even like the roads the equivalent roughness n_e can be equated to n, but since there must be some unevenness it will be necessary to convert the area into the equivalent one having slope of $\sin\theta'$ parpendicular to the sewer and the equivalent roughness n_e. Then, the flow of storm run-off at the downstream end of the area $x'=B$ becomes steady after $t=t_B$ and using Eqs. (18) and (19) the depth h_B', flow rate q_B at $x'=B$ is given as follows.

$$\left.\begin{aligned} h_B' &= i\,t_B, \\ q_B &= iB = \frac{1}{n_e} h'_B{}^{5/3} (\sin\theta')^{1/2}. \end{aligned}\right\} \quad \cdots\cdots(22)$$

As the velocity U_B' at $x'=B$ is q_B/h_B', from Eqs. (22)

$$t_B = \frac{B\,h'_B}{q_B} = \frac{B}{U_B'}, \quad \cdots\cdots(23)$$

or

$$t_B = \left\{ \frac{n_e B}{(\sin\theta')^{1/2}\, i^{2/3}} \right\}^{3/5} \quad \cdots\cdots(24)$$

is obtained for calculation of t_B. In **Fig. 7(c)**, the increasing rate of q_B before $t=t_B$ is also obtained by the similar equation or by the standard characteristic flow rate curves like as **Fig. 6**, but this is not necessary for the present purpose.

In the next, as q_B in **Fig. 7 (c)** flows into the unit length of the sewer laterally, the rate of run-off at $x=L$ in the sewer is succeeded in calculation by means of the characteristics. The standard characteristic curves which starts from the upstream end of the sewer may increase the value of dx/dt gradually according to the increase of inflow rate q_B before $t=t_B$, after that, they take the constant time t_{LS} to cover the distance L. All of the characteristic curves which start from arbitrary points at $t=0$ are obtained by moving parallel with the one which starts from $x=0$ at $t=0$. These characteristic curves are shown in **Fig. 7 (d)**. The flow in the sewer becomes steady along the characteristic curve starting from $(0, t_B)$ on $x-t$ plane in **Fig. 7 (d)** and the change of Q_L at $x=L$ would have the steady and maximum value,

$$Q_{L,\max} = iBL, \quad \cdots\cdots(25)$$

at $t=t_B+t_{LS}$, and when the rainfall duration is T', Q_L begins to decrease at $t=T'$. From Eqs. (10) and (12), the scale of flow at $x=L$ are represented as follows,

$$\left.\begin{aligned} A_L &= \int_0^{t_L} q_B\,dt, \\ Q_L &= \int_0^L q_B\,dx = \frac{A_L}{n} R_L{}^{2/3} (\sin\theta)^{1/2}, \end{aligned}\right\} \quad \cdots\cdots(26)$$

where A_L and R_L are the values of A and R at $x=L$, t_L the time required for the characteristic curves to cover the distance L and the integrations are performed along the curves. Therefore, the relationship between t_{LS} and L is

$$t_{LS} = \frac{L A_{L,\max}}{Q_{L,\max}} = \frac{L}{U_{L,\max}}, \quad \cdots\cdots(27)$$

or using the representation of Eq. (15) it is expressed as

$$t_{LS} = \frac{\kappa L^Z}{(iB)^{1-Z}}. \quad \cdots\cdots(28)$$

Although t_{LS} seems to be simple equational form of L/U, it is related only with $U_{L,\max}$ at $x=L$ regardless of the values of $U_{\max}$ varying from $x=0$ to L in the sewer.

Now, the timely change of Q_L is once neglected and let intend the problem to obtain only the maximum value of Q_L as iBL. Then, even if the rain ceases at $t=t_B+t_{LS}$, the same $Q_{L,\max}$ appears at that moment and Q_L decreases samely as $t>T'$. Therefore, based upon the rainfall duration-intensity relation, the intensity i should correspond to the duration T which is given as the sum of t_B and t_{LS}, the former is the time in which the standard characteristic curve covers the width B of the equivalent drainage area, and the latter the shortest time required for the curve in the length L samely. This process is equivalent to the principle of the rational method that the rainfall duration T has been taken equal to the time of concentration, the sum of the inlet time and flow-down period. For easier understanding, t_B and t_{LS}, hereafter, will be designated as the inlet time and flow-down period, respectively. Since the sum of these times is, at all, the shortest time needed for the characteristic curve to travel from the most distant spot in the equivalent drainage area to the down stream end of the sewer reach, therefore, the inlet time and the flow-down period would have the same theoretical significance. As seen from Eqs. (24) and (28), the flow-down period is affected by the assumption of sewer section and rainfall intensity, but the inlet time varies only with the value of i and holds its own value in the drainage area of width B and equivalent roughness n_e. Therefore, it may be required for design to evaluate n_e at first by the actual observation of t_B at several magnitudes of i. Up to the present time, the equation of motion (4) has been used for the estimation of the flow-down period, even though it is incorrect, as mentioned in chapter **2**, but for the inlet time a value of 5 to 15 minutes has been conventionally adopted without particular considerations.

5. Retardation with Large Roughness

When a storm of shorter duration period than the time of concentration to the intended spot occurs, the rain water precipitated on the all parts of the drainage area does not concentrate to the spot at the same time and so-called retardation appears. In this chapter, the retarded runoff phenomena due to the surface roughness, the equivalent value of which is n_{e1} as in **Fig. 8 (a)** and larger than n_e in **Fig. 7 (a)**, is discussed. In such cases, the inlet time may be prolonged, therefore, referring to the conventional principle of the rational method, the rainfall duration may also be taken longer and the rainfall of less intensity will be used for run-off without retardation. This procedure, however, means only the reduction of average intensity of rainfall owing to the extended duration of rainfall, in which larger intensity than the average must be contained. Subsequently, the intensity i for the duration T in **Fig. 7** can appear actually in the rough area with n_{e1}. This is shown again in solid line of **Fig. 8 (b)**.

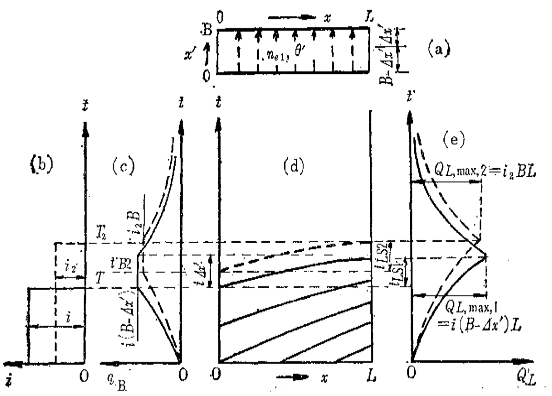

Fig. 8 Relationship between rainfall and run-off with retardation.

As n_{e1} is larger than n_e, it may be considered that the standard characteristic curve, which starts from $x'=0$ at the beginning of rainfall, just reaches the line of $x'=B-\Delta x'$ at $t=T$. As the initial condition is the same with respect to x', the values of q at $t=T$ become

$$\left.\begin{array}{ll}\text{for} \quad x'=B-\Delta x'\sim B, & q=i(B-\Delta x'),\\ \text{for} \quad x'=0\sim B-\Delta x', & q=ix'.\end{array}\right\} \cdots(29)$$

Replacing n_e, t_B and B in Eq. (24) with n_{e1}, T and $B-\Delta x'$ respectively, the relationship between $\Delta x'$ and T is obtained as follows,

$$\Delta x'=B-\frac{(\sin\theta')^{1/2}}{n_{e1}}\; i^{2/3}T^{5/3}. \cdots\cdots\cdots\cdots\cdots(30)$$

q_B and h_B' at $x'=B$ hold constantly the values $i(B-\Delta x')$ and iT until the standard characteristic curve arrives there at $t=T+t_{\Delta x'}$, and then begin to decrease. After $t=T$, the characteristic curve changes to the straight line as $i=0$, and $t_{\Delta x'}$ can be calculated from Eqs. (18) and (19) as

$$t_{\Delta x'}=\frac{3}{5}\frac{n_{e1}\Delta x'}{(iT)^{2/3}(\sin\theta')^{1/2}}. \cdots\cdots\cdots\cdots\cdots\cdots(31)$$

The variation of q_B is illustrated as solid line in **Fig. 8 (c)**.

Next, for the flow in the sewer, it is realized generally that the more the inflow rate q_B is supplied from the drainage area the faster the standard characteristic curve gets to the downstream end, therefore, the rate of storm flow Q_L will become maximum when the standard characteristic curve with the least value of t_L reaches $x=L$. Like this, the property of the minimum flow-down period, t_{LS}, is similar as the case of **Fig. 7**. If t_{LS} is longer than $t_{\Delta x'}$, the standard characteristic curve, which results in the maximum value of Q_L, may be considered to start from $x=0$ approximately at

$$t \fallingdotseq T-(t_{LS}-t_{\Delta x'})/2,$$

but the value of $Q_{L,\max}$, which is slightly less than $i(B-\Delta x')L$, stated in the following case, can not be expressed in general form.

In ordinary conditions, however, the value of t_{LS} in the sewer may be considerably small, moreover, if the condition $t_{LS}<t_{\Delta x'}$, due to relatively large n_{e1} and therefore large $\Delta x'$, is considered, the characteristic curves in the sewer and the variation of Q_L are shown with solid lines of **Fig. 8 (d)** and **(e)**, respectively.

Rewriting t_{LS} and $Q_{L,\max}$ as t_{LS_1} and $Q_{L,\max,1}$ in the present case, the maximum value of Q_L holds

$$Q_{L,\max,1}=i(B-\varDelta x')L \quad\cdots\cdots(32)$$

for $t=T+t_{LS_1}\sim T+t_{\varDelta x'}$, and T corresponds to the inlet time and t_{LS_1} the flow-down period, the latter is evaluated by the next equation and, of course, is longer than t_{LS} in Eq. (28).

$$t_{LS_1}=\frac{\kappa L^Z}{\{i(B-\varDelta x')\}^{1-Z}}. \quad\cdots\cdots(33)$$

Now, compare the maximum rates of storm run-off Q_L for the case of roughness n_e stated in the last chapter with the case of n_{e1}, regardless of the times required for their appearance from the beginning of rainfall. Referring to Eqs. (25) and (32), the ratio of their flow rates is

$$\frac{Q_{L,\max,1}}{Q_{L,\max}}=\frac{B-\varDelta x'}{B},$$

and introducing B from Eq. (24) and $B-\varDelta x'$ from Eq. (30),

$$\frac{Q_{L,\max,1}}{Q_{L,\max}}=\frac{n_e}{n_{e1}}\left(\frac{T}{t_B}\right)^{5/3} \quad\cdots\cdots(34)$$

is derived. If the drainage area in **Fig. 7 (a)** is taken as the standard one, the maximum value of Q_L is to be proportional to the reciprocal of n_{e1}, and it may be concluded from such consideration that the run off coefficient, C, by Dr. Itakura, in Eq. (8) may have the similar significance as the equivalent roughness in the equivalent drainage area defined by the author. The hydraulic performance of the maximum storm run off in the case of larger roughness, above described, would be realized under the same slope of the drainage area with the standard one, so that the value of C in Eq. (8) is necessary to be changed in term of the slope. Furthermore, following the rational method, in the drainage area which seems to have a small value of C in Eq. (8), the less rainfall intensity is often taken due to the prolonged rainfall duration, resulting from the already increased inlet time, although it is quite uncertain. Therefore, multiplying such a run off coefficient of the similar meaning with roughness in addition, the process of rational method may be not only inconsistent theoretically but unreasonable because of containing independent unknown factors.

Using the equivalent roughness, however, the storm run-off phenomena will be treated reasonably unifying those factors, that is, the maximum rate of run-off must be discounted according to Eq. (34), or must be taken as $iBL=iF$ after correct calculation of t_B from n_e, T and the corresponding value of i. The selection of these two procedures will be discussed in the next chapter.

6. The Relation between Rainfall Intensity Formula and Maximum Rate of Storm Run-off

Even if the rational method is smoothly accepted it can easily be presumed that the type of rainfall duration-intensity formula could make the maximum rate of run-off larger, when retardation occurs for the shorter period of rainfall duration than the time of concentration. Using the results of studies for the cases of **Fig. 7** and **8**, the decision of the rainfall duration for designing storm sewer can be done as follows.

The broken line in **Fig. 8 (b)** shows the new rainfall with the intensity i_2 for duration T_2, by which the maximum value of Q_L at $x=L$, $Q_{L,\max,2}$ appears as

$$Q_{L,\max,2}=i_2BL \quad\cdots\cdots(35)$$

just at $t=T_2$ with no retardation. Then, the time of concentration, T_2, the sum of the inlet time t_{B2} and the flow-down period t_{LS2}, can be written by Eqs. (24) and (28) as follows.

$$T_2=t_{B2}+t_{LS2}=\frac{(n_{e1}B)^{3/5}}{(\sin\theta')^{3/10}i_2^{2/5}}+\frac{\kappa L^Z}{(i_2B)^{1-Z}}. \quad\cdots\cdots(36)$$

On the other hand, the rainfall of intensity i continues for the duration T which is expressed as

$$T=\frac{\{n_{e1}(B-\varDelta x')\}^{3/5}}{(\sin\theta')^{3/10}\,i^{2/5}}, \quad\cdots\cdots(37)$$

by transformation of Eq. (30).

Suppose

$$\left.\begin{array}{l} Q_{L,\max,1}\geqq Q_{L,\max,2},\\ \text{i.e. } B-\varDelta x'\geqq \frac{i_2}{i}B \end{array}\right\} \quad\cdots\cdots(38)$$

is the result of comparison between the two values of $Q_{L,\max}$ in Eqs. (32) and (35), and eliminating $(n_{e1}B)^{3/5}/(\sin\theta')^{3/10}$ from Eqs. (36) and (37) by considering the relation (38) yields

$$i_2T_2\leqq iT+\frac{\kappa(i_2L)^Z}{B^{1-Z}}. \quad\cdots\cdots(39)$$

Therefore, whenever the relation (39) is established, the maximum rate of run-off with retardation becomes larger than the one without retardation.

If the Talbot type intensity-duration formula,

$$i=\frac{a_1}{T+a_2}, \quad\cdots\cdots(40)$$

is adopted, in which $a_2=0$, the relation of $i_2T_2=iT$ satisfies the relation (39) and thereafter, the section of sewer designed for rainfall of same duration with the time of concentration would be insufficient. However, in case when a_2 is larger than 0, or the Sherman type,

$$i=\frac{a_3}{\sqrt{T}}, \quad\cdots\cdots(41)$$

is adopted, the relation $i_2T_2 > iT$ exists generally, so that $Q_{L,\max,1}$ for retardation does not always exceed $Q_{L,\max,2}$. Consequently, it is necessary to investigate the existence of the relation (39) together with the magnitude of second term of right side. It must be noted, however, that the relaiton (39) may also exist in such cases that the constant amount of rainfall is teken off as the lost, and that the larger roughness n_{e2}, estimated exactly against the less intensity i_2, would make the first term of the relation (39) larger as follows;

$$i_2T_2 \leqq iT\left(\frac{n_{e2}}{n_{e1}}\right)^{3/5}+\frac{\kappa(i_2L)^Z}{B^{1-Z}}. \quad\cdots\cdots(39')$$

7. The Equivalent Roughness in Compound Drainage Area

The above investigations are limited for only the storm run off in the upstream drainage area. In the case of designing lower part of sewer, they must also be applied similarly, but it seems difficult to formulate the complex phenomena due to the difference in characteristics of each drainage area and to the changed boundary condition by the flow from upstream side of the reach. However, if the compound drainage area, which contains the side gutters of the upstream end, the tributary and trunk sewer to some extent, is transformed into an equivalent drainage area having its own equivalent roughness, then, the above derived relationships are still applicable without modification and it may become quite easy to calculate the timely change of actual storm run-off at any important section in the sewer. Although the equivalent roughness of compound drainage area, also, should be estimated by the observations of inflow rate to the sewer or the run-off at the lower end of sewer, a method to estimate the compound value of equivalent roughness theoretically from the knowledge for the smallest area is stated as fol-lows.

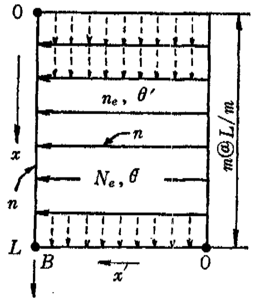

Fig. 9 Compound equivalent drainage area.

Fig. 9 illustrates schematically the rectangular drainage area of width B, length L and slope $\sin\theta$ which consists of the equal end areas of width L/m, length B and slope $\sin\theta'$, where m is the number of the smallest areas. Therefore, this drainage area contains the side gutters or tibutary sewers, length B, of m in number. In order to transform the area into the equivalent one, it may be sufficient for the problem of designing sewer section to satisfy the condition giving the same rate of maximum inflow at the same time after rainfall begins both from the compound equivalent area and from the tributary sewers. Under this condition, the maximum rate of run-off at the section $x=L$ in **Fig. 9** can be calculated taking account of the single drainage area regardless of the boundary condition at $x=0$.

For simplicity, if the run-off without retardation is considered to know the maximum rate of inflow, $q_{B,\max}$ becomes iB constantly. When the equivalent roughness in the individual small drainage area is n_e, $q_{B,\max}$ flows into the sewer in **Fig. 9** through the individual area and the tributary sewers at the time,

$$t_{L/m}+t_{BS}=\frac{(n_eL/m)^{3/5}}{(\sin\theta')^{3/10}\,i^{2/5}}+\frac{\kappa B^Z}{(iL/m)^{1-Z}} \quad\cdots\cdots(42)$$

after rainfall begins. Eq. (42) is easily produced from Eq. (36), and $t_{L/m}$ denotes the inlet time in the small drainage area and t_{BS} the flow-down period in the tributary sewer. On the other hand, symbolizing the equivalent roughness of newly compounded drainage area as N_e, the corresponding time to Eq. (42) is only the inlet time, which is written from Eq. (24) as

$$t_B=\frac{(N_eB)^{3/5}}{(\sin\theta)^{3/10}\,i^{2/5}}. \quad\cdots\cdots(43)$$

The times given in Eqs. (42) and (43) both signify the rainfall duration of intensity i, just after which q_B at $x'=B$ becomes steady and maximum. Therefore, equating these two and using Eq. (15),

$$N_e^{3/5}=\left(\frac{\sin\theta}{\sin\theta'}\right)^{3/10} n_e^{3/5}\frac{(L/m)^{3/5}}{B^{3/5}} + \frac{(\sin\theta)^{(3-5Z)/10}\, n^Z (iB)^{(5Z-3)/5}}{\kappa_0^{2Z/3}(L/m)^{1-Z}} \cdots\cdots(44)$$

is obtained. From Eq. (44), the compound value of roughness N_e can be calculated knowing the values of n_e in small drainage area and n, κ_0 and Z in the tributary sewers. If the equivalent drainage area is intended to expand more wider, the several units of the similar area as in **Fig. 9** are compounded in the same manner and the calculation is to be repeated using Eq. (44), while n_e and n are replaced by N_e, once obtained, and the Manning's roughness of sewer with length L in **Fig. 9**, respectively.

To study the characters of Eq. (44), simplifications are possible by considering $\sin\theta \cong \sin\theta'$ and $(3-5Z)/5$ or $(3-5Z)/10 \cong 0$ because $Z \cong 0.7$ referring to **Fig. 4**, and symbolizing the $mB/LB=m/L$ as l_d which signifies the line density of sewers in the unit area of drainage. Then Eq. (44) is written as follows,

$$N_e^{3/5}=\left(\frac{n_e}{Bl_d}\right)^{3/5}+\frac{n^Z l_d^{1-Z}}{\kappa_0^{2Z/3}}. \cdots\cdots\cdots\cdots\cdots\cdots(45)$$

Bl_d in Eq. (45) is the ratio of total length of the tributary sewers contained in the compound area under consideration, mB, to the one of sewer in question, L. If Bl_d is larger than unity, the value of the first term may decrease gradually every time the drainage area is compounded. On the contrary, it may become larger when Bl_d is smaller than unity. The second term is considered to give less influence against the value of N_e because l_d, the dimensisn of which is l/m, is never valued so large. In the street area, in which side gutters or sewers are fully equipped and Bl_d may happen to be larger than unity, however, the equivalent roughness N_e in the finally compounded large area may be very small value which is affected mainly by the second term. Whereas, the value of N_e in the suburban undeveloped district containing few drainage canals will be quite large ruled only by the first term as $Bl_d \ll 1$.

One of the advantages of the method using compound equivalent roughness is that the effect of storage in gentle slope sewer, as assumed in the detention formula of Eq. (6), is capable of being quantitatively accounted in evaluation of N_e by taking the value of n in sewer equivalent to non-uniform flow. Moreover, if the sewerage system is constituted of circular pipes, the approximate formula of calculating N_e, Eq. (45), can be written as follows,

$$N_e^{3/5}=\left(\frac{n_e}{B\,l_d}\right)^{3/5}+\frac{n^Z l_d^{1-Z}}{\kappa'^{0.476}D^{-0.095}}, \cdots\cdots\cdots\cdots(46)$$

where D is the diameter of the tributary sewer, κ' the proportionality constant in the relation,

$$\kappa_0=D'D^{1-2Z_0}, \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots(13')$$

which is derived from Eq. (13) and **Fig. 4**, and also the actual value of $Z_0=0.6$ introduces $Z=3/(0.6\times 2+3)=0.714$ for circular section. As seen from Eq. (46), the compound value of the equivalent roughness can be determined by the arrangement of sewers only, except for the given factors in the upper end drainage area and the roughness of sewer, and is almost independent of sewer diameter. Therefore, the run-off analysis is performed quickly without assuming the pipe section, which is finally determined direct from the calculated rate of storm run-off.

However, the above procedure is based upon the knowledge of equivalent roughness in the upper end drainage area, to the last, so that the actual data of the rainfall and run-off must be collected and checked to clarify the hydraulic characteristics of the equivalent roughness, which the author will intend to study in various kinds of drainage area, hereafter.

8. Summary

In this paper, the basic considerations on the drainage of the storm run-off in the sewerage system were made hydraulically. From the investigation of the existing methods for storm run-off calculation, it is evident that the formulas of "practice first" have been used without sufficient considerations based on hydraulic background. Even the tendency of selecting a formula to use simply by reason of economy is seen. These conventional methods are quite doubtful in view of the present situation of sewerage works which must be promoted as quickly in Japan. From such standpoint, the author intended to make the hydraulic design of storm drainage in sewerage system reasonable as possible; that is, paying attention to the fact that drainage system in the street area may be regarded as the open channel with lateral inflow of rain water, the approximate method of hydraulic calculation using characteristic curves was studied for practical application, and by this method, the various factors concerning the process of run-off estimation were signified hydraulically. The results of the present research will be summarized as follows.

At first, with some comments on the empirical formula and the rational formula as the representatives of the storm run-off calculation, it was pointed out that the proprieties of these formulas had been usually discussed only about the calculated results, without satisfactory investigation of the hydraulic significance of the formulas, and moreover, the correct computation of the storm run-off would be made by the rational method if the time of concentration was estimated reasonably. The existing procedure of the rational method can be explained by the method of characteristics, that is, the advancing rate of the characteristic curve is taken equal to the flow velocity U in sewer and this velocity is often taken as constant, which means no consideration on the equation of motion of unsteady flow in sewer. Therefore, it may be regarded nothing but the increasing of convenience for design to take a rainfall of the same duration with the time of concentration or flow-down period of rain water.

The section of sewer may be designed as the open channel referring to its character of flow capacity. The approximate calculation method of unsteady flow in uniform channels with lateral inflow has been already modified for the practical procedure introducing the equivalent roughness of equivalent drainage area and the logarithmic representation of the standard characteristic curves, which were briefly described again in this paper. In sewers, the relationship between its sectional area A of flow and the hydraulic radius R satisfactorily leads to the exponential formula of A and flow rate Q from Manning's resistance law, hence the graphic representation of the standard characteristic curves and the evaluation of flow rate can be made quite easily using the logarithmic paper. Moreover, for the sewerage system of the street area, each drainage unit is nearly rectangular in shape and so the arrangement of sewers makes easier transformation of the drainage area to the equivalent one. One of the important purpose of the equivalent roughness procedure is to treat the storm run-off problem unifying the indistinct factors included in the rational method. The storm run-off phenomena of the upper end drainage area and its connecting sewer were studied by this procedure, especially for the maximum rate of run-off at the downstream end of sewer and the corresponding time to its appearance. From these results of study, the hydraulic significances of the various factors contained in the rational method could be made clear, and the basic course to revise the usual procedure was given.

The maximum run-off rate at the downstream end of the sewer is obtained, in the first place, assuming the rainfall, duration of which is equal to the sum of the inlet time and the flow-down period in the sewer. As for the correct meanings of these times, however, the inlet time must be the time required for the standard characteristic curve from the start to the sewer, and the flow-down period the shortest time in which the standard characteristic curve covers the distance of the sewer reach, besides, the former must be related to the width of the drainage area B and the equivalent roughness n_e.

In case so-called retardation occurs in a drainage area of large roughness, maximum storm run-off reduces its rate proportionally with the equivalent roughness. Therefore, it may be concluded that the run-off coefficient defined under consideration of the rain water detention in the drainage area has the same meaning with the equivalent roughness. However, the run-off coefficient is usually determined with no regards to the slope of the area and there remains a question about its physical treatment.

The results of analysis for the case of retardation was also useful to discuss the standard of selection of rainfall duration for design. It would be possible theoretically that the maximum rate of storm run-off at the sewer end could be the larger value, compared with the conventionally calculated value, according to the type of intensity-duration curve even if the retardation occured due to heavier rainfall in shorter duration. This is considered as the blind side in the conventional procedure of the rational method and, hereafter, must be noted for practical design.

To make up a few numbers of the drainage area into one large equivalent area including the tributary sewers may be quite effective for the run-off estimation in the trunk sewer. The quantitative relationship between the compound value of the equivalent roughness and the one for individual elementary area was derived, by which the character of the equivalent roughness could be explained in connection with the width of drainage area and the line density of sewer and it would take very small value in the street area with fully equipped sewers but larger in the suburban undeveloped district. Moreover, if the circular sewers are to be laid for whole sewerage system, the compound equivalent roughness can be determined approximately without assuming the diameters which will be designed directly after run-off calculation.

In the present investigation, the hydraulic performance of the equivalent roughness compared with the experiments in actual sewerage system is not yet studied. But theresults of application of the similar procedure[9] for the run-off analysis has already comfirmed that the equivalent roughness is quite useful to explain the run-off mechanism. The author is now intending to study the problems of the practical method to evaluate the roughness from run-off observation and also the relation between the reasonable arrangement of sewers and the equivalent roughness.

Acknowledgements

The author is indebted to Dr. Tojiro Isihara and Dr. Takeshi Goda, Professors of Kyoto University, for their kind encouragements. The present research is a part of the hydraulic study on the water collection and distribution in the water works and sewerage financially supported by the Ministry of Education.

Bibliography

1) J.E. McKee : Loss of Sanitary Sewage through Storm Overflows, Jour. of Boston Soc. Civil Engrs., Vol. 34, p.55 (1947).
2) C.L. Palmer : The Pollutional Effects of Storm-Water Overflows from Combined Sewers, Sewage and Industrial Wastes, Vol. 22, p.154 (1950).
3) T.R. Camp : Overflows of Sanitary Sewage from Combined Sewerage System, Sewage and Industrial Wastes, Vol. 31, p. 381 (1959).
4) T. Ishihara and A. Kanamaru : On the Application of the Unit Hydrograph Method to Run-off Analysis for Rivers in Japan, Bulletin of Disaster Prevention Research Institute, Kyoto Univ., No. 19, p. 1 (1958).
5) T. Ishihara and T. Takasao : Fundamental Researches on the Unit Hydrograph Method and Its Application, Trans. J.S.C.E., No. 60, Extra Paper 3-3 (1959).
6) Y. Ishihara : On an Electronic Analog Computer for Run-off, Trans. J.S.C.E., No. 60, p. 37 (1959).
7) Y. Iwagaki and T. Sueishi : On the Unsteady Flow in Open Channels with Uniform Lateral Inflow, —Hydraulic Studies on the Run-Off Phenomena of Rain Water, 1st Report—, Proc. J.S.C.E., Vol. 39, p. 575 (1954).
8) Y. Iwagaki and T. Sueishi : Approximate Method for Calculation of Unsteady Flow in Open Channels with Lateral Inflow, Proc. of the 4th Japan National Congress for App. Mech., 1954, p. 235 (1955).
9) T. Sueishi : On the Run-Off Analysis by the Method of Characteristics, —Hydraulic Studies on the Run-Off Phenomena of Rain Water, 2nd Report—, Trans. J.S.C.E., No. 29, p. 74 (1955).
10) A. Kanamaru : On the Simplification of the Natural Shape of Hill Side for Run-off Estimation, Trans. J.S.C.E., No. 73, p. 7 (1961).
11) T. Ishihara and T. Takasao : A Study on the Subsurface Runoff and Its Effects on Runoff Process, Trans. J.S.C.E., No. 79, p. 15 (1962).
12) A.S.C.E. Manuals of Engineering Practice—No. 28, Hydrology Handbook, p. 101 (1949).
13) G.M. Fair and J.C. Geyer : Water Supply and Wastes Water Disposal, John Wiley & Sons, Inc., p. 169 (1954).
14) Above appeared 12), p. 92.
15) M. Itakura : Studies on the Rational Method and "Detentions of Flow-Outs", Trans. J.S.C.E., No. 28, p. 1 (1955).
16) A.L. Tholin and C.J. Keifer : The Hydrology of Urban Runoff, Proc. A.S.C.E., Vol. 85, SA 2, p. 47 (1959).
17) Above appeared 13), p. 429.

(Received July 18, 1962)