Application Of Integrated Urban Area Flood Estimation System

APPLICATION OF INTEGRATED URBAN AREA FLOOD ESTIMATION SYSTEM

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ABSTRACT**:** As frequency and intensity of torrential rain increases, water disaster caused by flood has become very serious. This appears remarkable especially in urban areas where population and industry have been heavily concentrating and underground facilities have been excessively developed. Under this undesirable trend, an integrated flood control system, by which the water disaster can be prevented or mitigated, is highly expected to be devised and installed. In order to achieve this goal, methods for understanding of hydraulic mechanism causing the water disaster as well as planning of measures against it have been proposed. Kajima Corporation and Chubu University jointly developed *Integrated Urban Area Flood Estimation System* to evaluate outflow and drainage in urban areas under torrential rain dynamically and precisely. It has been demonstrated that several damages of the water disaster in urban areas caused by torrential rain in the past can be appropriately simulated by our system. In this paper, it is considered how our system can be applied to assess effectiveness of measures installed against flood, such as sewer systems and reservoir facilities. For Tokai Heavy Rain, which caused one of the severest damages of the water disaster in the area of Nagoya City in the Chubu Region in Japan, numerical simulations using our system are conducted under several conditions regarding sewer systems and reservoir facilities. By comparison of their computed results, such as maximum inundation water depths and serious flooded areas, it is demonstrated how their effectiveness can be shown qualitatively.

KEYWORDS: numerical simulation, inundation, sewer system

1. INTRODUCTION

As frequency and intensity of torrential rain increases, water disaster caused by flood has become very serious. This appears remarkable especially in urban areas where population and industry have been heavily concentrating and underground facilities have been excessively developed. Under this undesirable trend, an integrated flood control system, by which the water disaster, due to not only river embankment breaks but also interior runoff, can be prevented or mitigated, is highly expected to be devised and installed. In order to achieve this goal, methods for understanding of hydraulic mechanism causing the water disaster as well as planning of measures against it have been proposed. Kajima Corporation and Chubu University jointly developed *Integrated Urban Area Flood Estimation System*, for instance, in Takeda et al., to evaluate outflow and drainage in urban areas under torrential rain dynamically and precisely. It has been demonstrated that several damages of the water disaster in urban areas caused by torrential rain in the past can be appropriately simulated by our system.

As urban facilities heavily affect behavior of inundation water, modeling of urban infrastructures, such as roads, buildings and sewer systems, must be meticulously considered in numerical simulations. Especially, as sewer systems have a function of outflow of rainwater and inundation water, a treatment of them in numerical simulations is very important.

Many studies on an inundation analysis model with sewer systems have been reported. On inundation analysis sufficiently taking sewer systems in urban areas due to interior runoff into consideration, detailed modeling and processing of both inundation and drainage have been examined by Kawaike et al., Sagara et al., Sekine et al. and so on.

In this paper, it is considered how our system can be applied to assess effectiveness of measures installed against flood, such as sewer systems and reservoir facilities. For Tokai Heavy Rain, which caused one of the severest damages of the water disaster in the area of Nagoya City in the Chubu Region in Japan, numerical simulations using our system are conducted under several conditions regarding sewer systems and reservoir facilities. This study has characteristics that a treated analysis region is relatively large and advanced modeling of sewer systems is examined in comparison with other studies. First, numerical simulations implementing a model considering a detailed manhole-sewer structure are conducted, and validity and numerical accuracy of the model is discussed. Second, in order to examine effects of reservoir facilities, numerical computations with and without them are conducted. By comparison of their computed results, such as maximum inundation water depths and serious flooded areas, it is demonstrated how their effectiveness can be shown qualitatively.

2. MODEL FORMULATIONS

The modeling of water behavior on overland, sewer pipe and manhole is described below. Its numerical treatment of other parts is fully presented in Matsuo et al.

2.1 Urban area

The plane 2-dimensional model based on shallow water equations is used for inundation analysis in urban areas.

$$\frac{\partial h}{\partial t}+\frac{\partial M}{\partial x}+\frac{\partial N}{\partial y}=0 \qquad (2.1)$$

$$\frac{\partial M}{\partial t}+\frac{\partial uM}{\partial x}+\frac{\partial vM}{\partial y} = -gh\frac{\partial H}{\partial x}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right)-\frac{\tau_{bx}}{\rho} \qquad (2.2)$$

$$\frac{\partial N}{\partial t}+\frac{\partial uN}{\partial x}+\frac{\partial vN}{\partial y} = -gh\frac{\partial H}{\partial y}+\frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right)-\frac{\tau_{by}}{\rho} \qquad (2.3)$$

where u, v :flow velocity in x, y directions respectively, h :water depth, M, N :flux in x, y directions respectively $(M = uh, N = vh)$, H :water level, τ_{bx}, τ_{by} :component of shear stress at the bottom in x, y directions respectively, ρ :water density, g :acceleration due to gravity, $\varepsilon_x, \varepsilon_y$:eddy viscosity in x, y directions respectively, x, y :axis of plane, and t :time.

The shear stresses at the bottom are presented by using the roughness coefficient of Manning, n, as follows.

$$\tau_{bx} = \rho g n^2 M \sqrt{u^2 + v^2} \Big/ h^{4/3} \tag{2.4}$$

$$\tau_{by} = \rho g n^2 N \sqrt{u^2 + v^2} \Big/ h^{4/3} \tag{2.5}$$

2.2 Sewer system

For sewer systems, behavior of inundation water in sewer pipes and manholes is formulated. An interaction between overland and sewer systems on inundation water is taken into consideration in a manhole model.

The model on sewer pipe flow is based on Eq.(2.6) and Eq.(2.7) as governing equations for the slot model.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2.6}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\cos\theta\frac{\partial h}{\partial x} - g\sin\theta + \frac{gn^2 u|u|}{R^{4/3}} = 0 \tag{2.7}$$

where A :area of cross section, Q :discharge, q :lateral inflow discharge ↩ u :water velocity $(= Q/A)$, h :water depth, g :acceleration due to gravity, θ :bed slope, n :roughness coefficient of Manning, R :hydraulics radius, x :distance to downstream, and t :time.

A slot width, B, is calculated by the following equation.

$$B = gA_S / C^2 \tag{2.8}$$

where g :acceleration due to gravity, A_S :area of cross section, and C :wave velocity set to be 20m/s.

A water level at a manhole is computed by the continuity equation below.

$$A_m \frac{\partial H}{\partial t} = \sum Q + Q_{in} - Q_{out} \tag{2.9}$$

where A_m :area of manhole, H :water level at the manhole, $\sum Q$:net inflow discharge from sewer pipes, Q_{in} :inflow discharge from overland, and Q_{out} :outflow discharge of pumps.

2.3 Analysis model

Numerical simulations for inundation water behavior due to Tokai Heavy Rain in the area of Nagoya city are considered. Fig. 2.1 and Fig. 2.2 show the analysis region colored with yellow and its corresponding ground elevations, respectively. In Fig.2.1, the region contains the catchment area of Hori River.

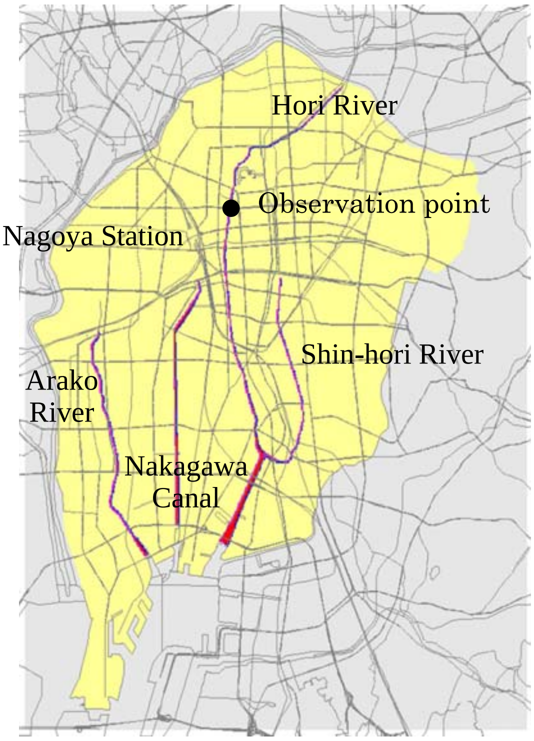

Figure 2.1 Analysis region

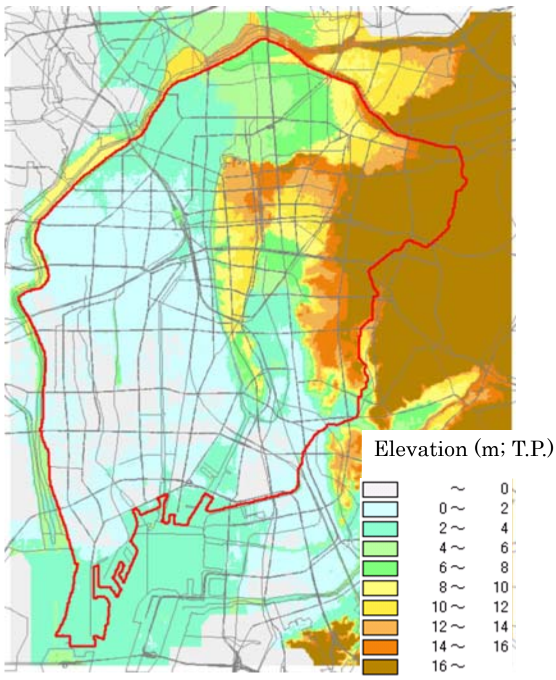

Figure 2.2 Ground elevations

Table 2.1 Analysis conditions

Grids	30m by 30m (Number of grids: 640 by 490)
River and canal	Hori River, Shin-Hori River, Arako River, Nakagawa Canal
Roughness coefficients	Overland: 0.067, Sewer Pipes: 0.013, Rivers: 0.030
Rainfall	Observed data per 10min
Downstream of river	Observed water elevation data
Time increment	0.1sec

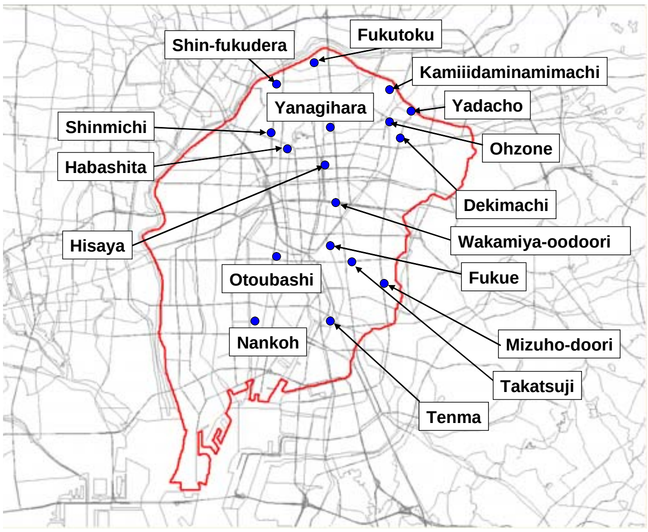

Figure 2.3 Location of reservoirs

Table 2.2 Volume of reservoirs

Name of reservoir	Volume (m^3)
Fukutoku	7,500
Shin-fukudera	1,500
Kamiiidaminamimachi	420
Yadacho	560
Ohzone	34,000
Yanagihara	280
Shinmichi	1,000
Dekimachi	480
Habashita	600
Hisaya	2,000
Wakamiya-oodoori	19,000
Fukue	22,000
Otoubashi	2,500
Takatsuji	30,000
Mizuho-doori	4,600
Nankoh	20,000
Tenma	1,000

A summary of analysis conditions is shown in Table 2.1. The total duration of the numerical simulations is 29 hours, from 2:00am of 11th to 7:00am of 12th in September, 2000. The data regarding the sewer systems are generated based on the ledger. The numbers of manholes and pipes are about 20,000 and 21,000, respectively. In addition, all the reservoir facilities that exist in the analysis region are considered. Fig. 2.3 and Table 2.2 show their locations and capacities, respectively.

3. COMPUTATIONAL RESULTS

3.1 Effects of manhole-sewer structure on water transport

Generally, sewer pipes are connected with others at a manhole, but various kinds of manhole-sewer structures exist, some of which are very complicated. Fig. 3.1 shows two types of typical manhole-sewer structures. Type 1 is very simple, in which all the water in upper pipes goes down to lower main pipes. On the other hand, Type 2 is a little complicated, in which only the water above some specified level in upper pipes overflows down to lower main pipes. In order to observe effects of considering the manhole-sewer structure of Type 2, numerical simulations under the two conditions, in which some of them are Type 1 and the others are Type 2 as they are in reality, and all of them are assumed to be Type 1, respectively, are conducted. The numerical simulations are referred to CASE I and CASE II, respectively, as is shown in Table 3.1.

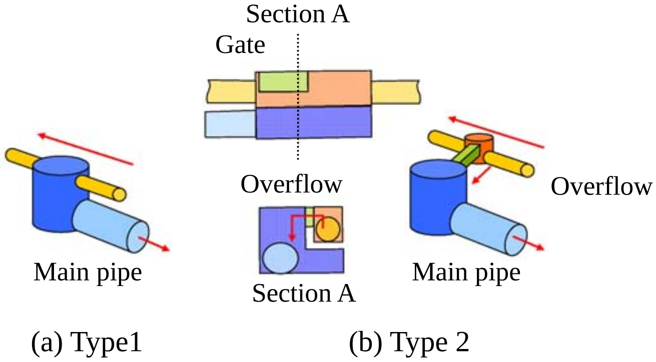

Figure 3.1 Manhole-sewer structure on water transport

Table 3.1 Computational conditions

	Manhole-sewer structure on water transport
CASE I	Some are Type 1, others are Type 2 as in reality
CASE II	Type 1 only

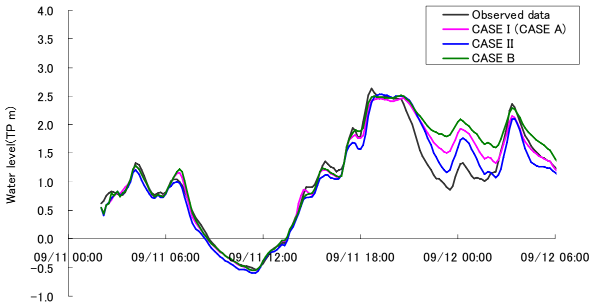

Figure 3.2 Water level at the observation point in Hori River

Fig. 3.2 shows the water levels at the observation point in Hori River, which is located at the black dot in Fig. 2.1. By comparison of the computed results of CASE I and CASE II with the observed data, CASE I shows better agreement with the observed data, in the beginning phase, in the phase when the water level is going up, and in the very end phase. However, after the time of 7:20pm of 11th when the peak of the observed water level is attained, the difference between the results of CASE I and the observed data is larger than that between the results of CASE II and the observed ones.

Fig. 3.3 and Fig. 3.4 show the computed results of maximum inundation water depths for CASE I and CASE II, respectively. The difference between the results of CASE I and CASE II seems very slight, but it is observed that the area circled with the blue line in Fig. 3.3 is inundated, which can be hardly seen in Fig. 3.4. As it is surveyed that this area was actually inundated at the time of Tokai Heavy Rain, it is likely that the analysis model for CASE I is more reasonable than that for CASE II.

As the behavior of the inundation water is much more focused and discussed than that of the water levels, it is supposed that the analysis model for CASE I is a prototype throughout this paper.

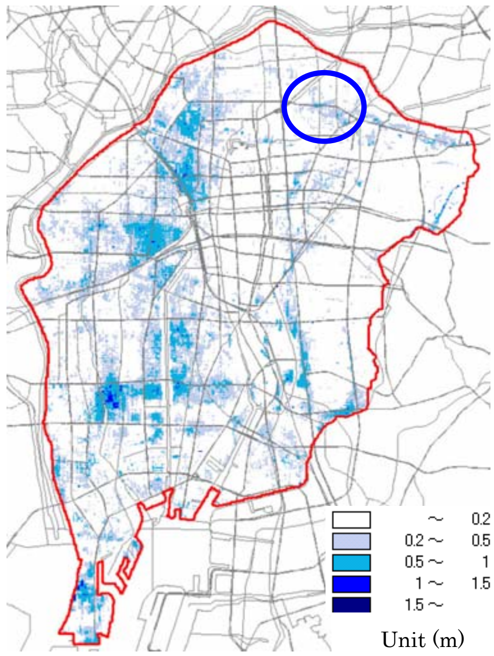

Figure 3.3 Maximum inundation water depths (CASE I / CASE A)

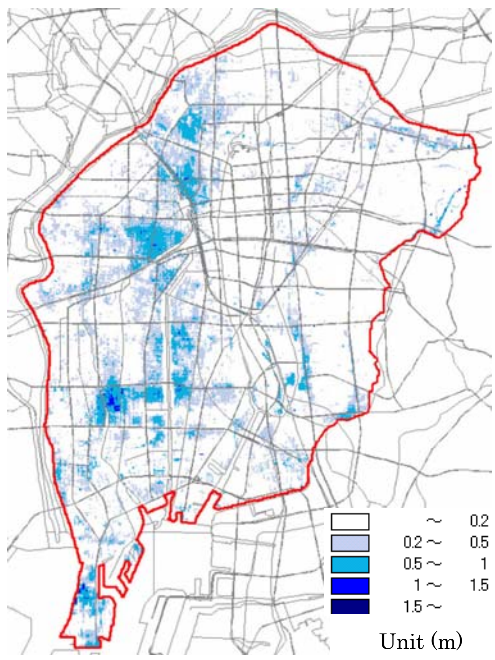

Figure 3.4 Maximum inundation water depths (CASE II)

3.2 Effects of reservoir facilities

In urban areas, reservoir facilities are properly installed as hardware measures against interior runoff. In our numerical simulations, the reservoir facilities are sufficiently considered, as is shown in Fig. 2.3 and Table 2.2. In order to assess the effects of the reservoir facilities, the numerical simulations under the two conditions, in which all of the reservoir facilities are considered, exactly the same as CASE I, and none of them are considered, respectively, are conducted. The numerical simulations are referred to CASE A and CASE B, respectively, as is shown in Table 3.2.

Table 3.2 Computational conditions

	Reservoir facilities
CASE A	Considered, the same as CASE I
CASE B	Not considered at all

Fig. 3.5 shows the computed results of maximum inundation water depths for CASE B. By comparison of Fig. 3.3 and Fig. 3.5, almost no difference among their results can be observed. This means that these reservoir facilities might have slight influence on the inundation water depths in the catchment area.

Fig. 3.6 shows the difference between the results of the maximum inundation water depths for CASE A and CASE B, which is calculated by subtracting the results of CASE A from those of CASE B. In Fig. 3.6, a grid colored with blue or red means that one has a positive or a negative value, respectively. Line A denotes the railroad on the embankment. From Fig. 3.6, it is observed that the northern part in the analysis region, especially in the area circled with the blue line, gets remarkable effects of the reservoir facilities. In the circled area, Fukutoku Reservoir is installed, as is shown in Fig. 2.3, and it is supposed that it gives good effects on the inundation there. It is also noted that few differences of the maximum inundation water depths can be seen in the area west to Line A. In addition, several areas colored with red and pink are found, which implies that maximum inundation water depths might increase with the reservoir facilities being installed at that area. It is inferred that this might be caused by the phenomena that due to the existence of the reservoir facilities, water gathers into pipes connected to them and their surrounding areas so rapidly that the inundation water depths increase. However, as it is also possible that these phenomena are caused by numerical oscillations during one-dimensional pipe computations with the slot model, further discussions must be required.

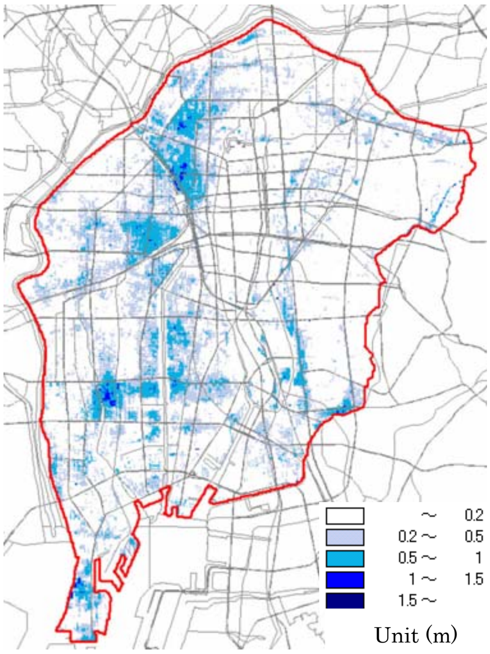

Figure 3.5 Maximum inundation water depths (CASE B)

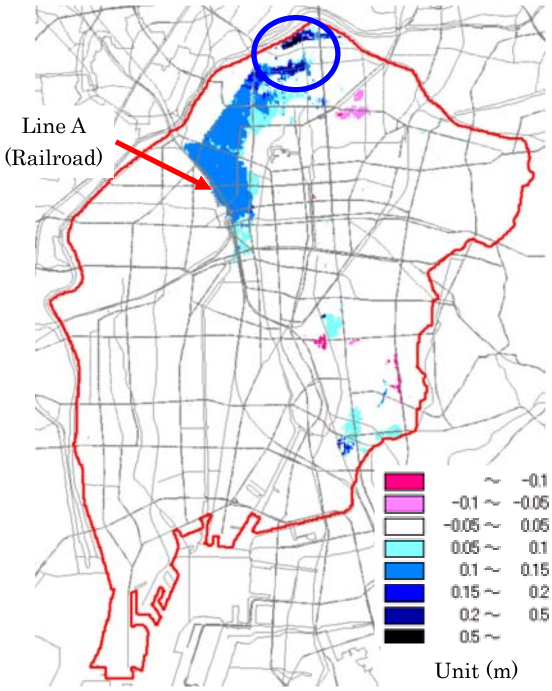

Figure 3.6 Difference of maximum inundation water depths (CASE B – CASE A)

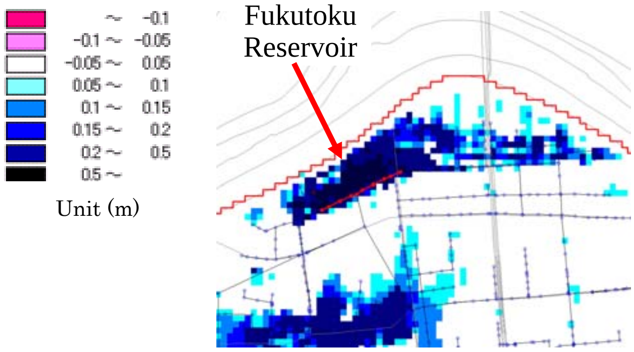

Figure 3.7 Difference of maximum inundation water depths (CASE B – CASE A)

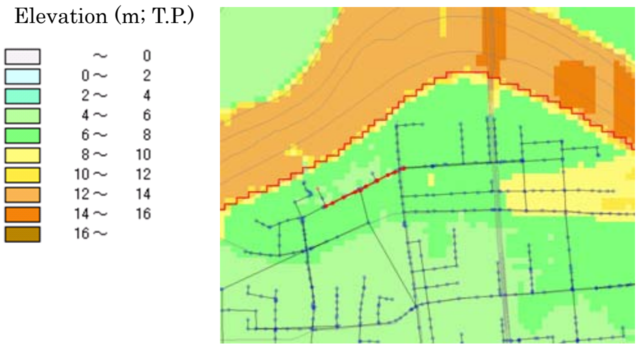

Figure 3.8 Ground elevations

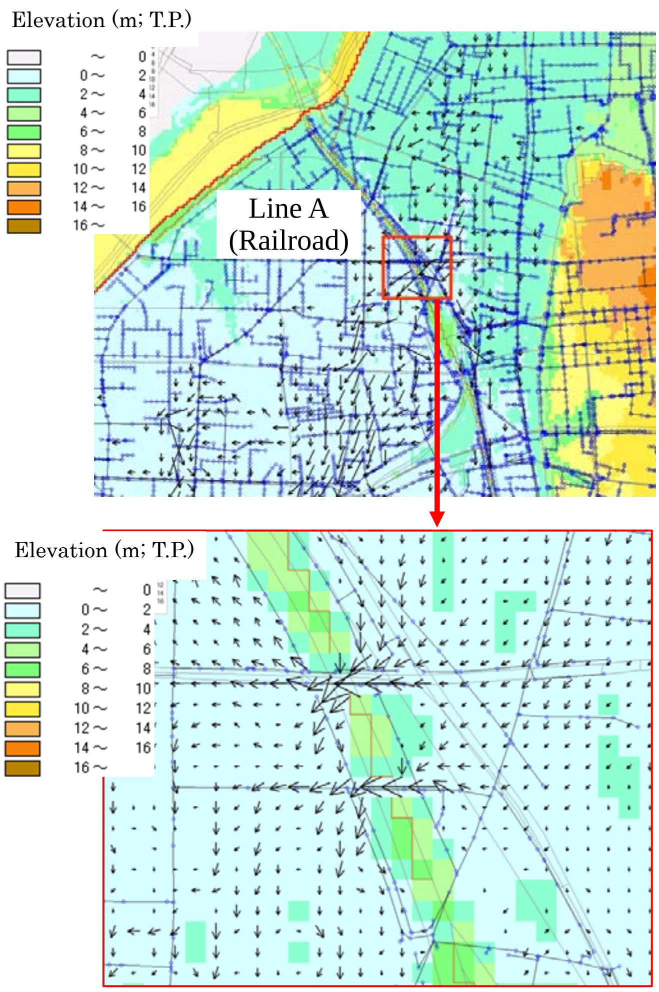

Figure 3.9 Discharge flux near Nagoya Station

Fig. 3.7 and Fig. 3.8 show the difference of the maximum inundation water depths and the ground elevations enlarged near Fukutoku Reservoir, respectively. The red lines and dots correspond to the sewer pipes and the manholes, respectively, with which Fukutoku Reservoir is properly modeled. From Fig. 3.7, it is obvious that there are huge differences in the area along the red lines and dots.

Fig. 3.9 shows the distribution of the discharge flux near Nagoya Station, in which its enlarged one is also shown. From Fig. 3.9, it is observed that the inundation water flows towards the west along the roads as well as through the pipes. As there are only a few routes and large amount of water cannot go from the east to the west crossing the embankment of Line A, it is natural that most of the inundation water remains in the east. Therefore, it is expected that the inundation water depths in the west of the embankment might be almost the same, regardless of the existence of the reservoir facilities.

In Fig. 3.2, the results for CASE A, exactly the same as CASE I, and CASE B, are also depicted. The water levels for CASE B are higher than those for CASE A, which must be reasonable, as the volume of the inundated water flowing into Hori River generally tends to increase without the reservoir facilities. Conversely, it is interpreted that the installment of the reservoir facilities reduces the water levels in Hori River. In rivers crossing through urban areas with relatively low ground elevations, it is highly expected that increase of water levels in the rivers causes deterioration of discharge ability in their surrounding catchment areas. Thus, it is noted that the effects of the reservoir facilities can be steadily evaluated by the numerical simulations using our system. Finally, as the effects of the reservoir facilities cannot be clearly seen, its reason might be that the total amount of the volume of the rainfall for Tokai Heavy Rain exceeded that of the sum of all the reservoir facilities.

4. CONCLUSIONS

The main findings in this paper can be summarized as follows:

1) It is examined how the manhole-sewer structure affects the inundation water depths. Assuming the two types of the manhole-sewer structure, Type 1 and Type 2, which are simple and complicated, respectively, the two sets of the numerical simulations, CASE I and CASE II, in which some are Type 1 and the others are Type 2 as in reality, and all are Type 1, respectively, are conducted. By comparison of their results, it is observed that Type 2 has the effects of keeping inundation water in overland and delaying its discharge into the rivers. All in all, CASE I shows better agreement than CASE II with respect to the water levels in Hori River and the inundation water depths in the region, though the decrease after the peak of the water levels at the observation point in Hori River is reproduced by CASE II better than CASE I. As a result, it is decided that CASE I is more appropriate than CASE II.
2) It is examined how the reservoir facilities affect the inundation water depths. The numerical simulations with and without them are conducted. By comparison of their results, sufficient effects of them are observed in the northern part of the analysis region near Fukutoku Reservoir. This seems very reasonable, as the influence of the sewer systems in that part is evident. It is also shown that the reservoir facilities in the catchment of Hori River have the effects mainly on the inundation water depths in the east of the railroad embankment. As the effects of the reservoir facilities might be less remarkable than expected, it can be considered that the total amount of the volume of the rainfall for Tokai Heavy Rain exceeded that of the sum of all the reservoir facilities.

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