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APPLICATION OF INUNDATION ANALYSIS MODEL IN NAGOYA CITY CONSIDERING SEA LEVEL RISE DUE TO GLOBAL WARMING

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Nagoya city is one of the largest city located at central zone of Japan. Main rivers such as Shounai River, Shin River, Hori River, and Yada River etc. are passes through densely populated city area and terminated into Pacific Ocean. A synthetic urban inundation model is applied for the simulation of inundation in the Nagoya city in various cases such as sea level rise by 0.5m, 0.95m, 1.5m, 2.0m with the design rainfall of 10 years return period. From this study, it is found that if the sea level rises more than 1m then severe inundation occurs in the densely populated city area between the Hori River and Nakagawa canal. Furthermore, the effect of sea level rise on the sewerage system is examined.

***Key Words*:** Inundation, Sea level rise, global warming, Numerical simulation

1. INTRODUCTION

Recently, in February 2007, IPCC published report warned that the sea level rises 18-58cm at the end of the century, which will be making coastal populations more vulnerable to flooding and more intense storms such as typhoons and hurricanes. In 1995, IPCC predicted sea level rise by 15-95cm and in 2001 8-88cm. A rise of sea level at the end of next century, caused by predicted greenhouse climate warming, would endanger human populations, cities, ports and wetlands in low lying coastal areas through inundation, erosion and salinization. Various studies utilizing tide-gauge data find an average global rate of sea level rise of 1-2 mm/year over the last 100 years. Due to rise of sea level, permanently inundated coastal zone would extend to a depth equivalent to the vertical rise in sea level. Major river deltas, coastal wetlands and coral islands would be most affected. IPCC recommends four major factors for sea level rise, which are thermal expansion of the ocean, mountain glaciers and small ice cap, Greenland ice sheet, Antarctic ice sheet. Future sea levels are predicted by using models representing relevant factors such as thermal expansion of the ocean, melting of mountain glaciers etc. Changes in the radioactive balance of the Earth due to an increase in GHGs (greenhouse gases) will alter atmospheric and oceanic temperatures and circulation of weather patterns. Global warming and climate change are the general terms for these changes. Since the industrial revolution, the atmospheric concentrations GHGs have been increasing dramatically. IPCC reported that global mean surface temperature has increase by 0.3 to 0.6^{o}c over the last 100 years (IPCC, 1996).

The urbanization trend increases in the coastal cities rapidly due to easy access and industrial development. Coastal cites have great concern on the sea level due to global warming.

In this study, the inundation scenario of Nagoya city caused by heavy rainfall with consideration of sea level rise due to global warming is analyzed by using numerical simulation model. The validity of the numerical simulation model applied here is explained in Takeda et al (2004) and pokharel et al. (2006). Inundation scenario in present sea level i.e. zero and the rise of sea level by 0.5m, 0.95m, 1.50m and 2.00m with the design rainfall of 10 years return period were considered in this analysis. The sea

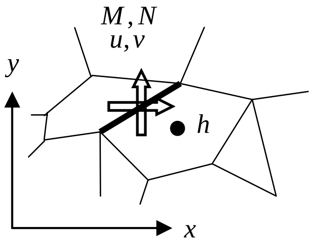


Fig. 1 Arrangement of Physical quantities

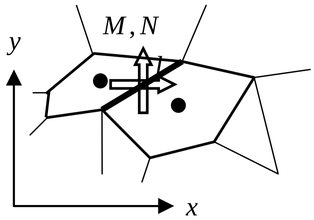


Fig.2 Control volume of momentum equation

level rise scenario of 1.50m and 2.00m is only for analysis. Analysis result is useful for the design of counter measure such as to increase the height of dyke in the Hori River, Nakagawa canal and planning and strengthening of drainage system.

2. NUMERICAL ANALYSIS MODEL

The inundation flow model applied here treats the flow dynamics in sea, river, urban area and sewer system simultaneously. The each model is shown below. In this analysis model, the water behavior in urban area which is rainfall, inflow into sewer system, pump out and discharge into river through water gate is treated.

(1) River

The continuity and momentum equation denoted below are used for analysis in rivers.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

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

where A : area of cross section, Q : discharge, q : lateral inflow discharge, u : water velocity $(= Q/A)$, h : water depth, θ : bed slope, R : hydraulics radius, x : axis of downstream, t : time.

(2) Urban Areas

The method with unstructured grid system of Inoue et al (1999) is used. Discharge flux (M, N) and water depth (h) are set at center of side and grid, respectively. The algebraic equations expanded by finite volume method are as follows

$$\frac{h^{n+3} - h^{n+1}}{2\Delta t} + \frac{1}{A}\sum_{l'=1}^{m}\left\{M_{l'}^{n+2}(\Delta y)_{l'} - N_{l'}^{n+2}(\Delta x)_{l'}\right\} = q \tag{3}$$

$$\frac{M_l^{n+2} - M_l^n}{2\Delta t} + M1 + M2 = -g\tilde{h}^{n+1}(\nabla H)_x - \frac{gn^2\frac{M_l^{n+2}+M_l^n}{2}\sqrt{(u_l^n)^2+(v_l^n)^2}}{(\tilde{h}^{n+1})^{4/3}} \tag{4}$$

$$\frac{N_l^{n+2} - N_l^n}{2\Delta t} + N1 + N2 = -g\tilde{h}^{n+1}(\nabla H)_y - \frac{gn^2\frac{N_l^{n+2}+N_l^n}{2}\sqrt{(u_l^n)^2+(v_l^n)^2}}{(\tilde{h}^{n+1})^{4/3}} \tag{5}$$

where, m : number of side surrounding the grid. A : area of grid, $M_{l'}, N_{l'}$: flux at the centre of side l' in x, y direction, respectively, $(\Delta x)_{l'}, (\Delta y)_{l'}$ are difference of x, y coordinate value at the both side of l' (l' means the side around grid), u_l, v_l : flow velocity of x, y coordinate at the centre of side l respectively, $(\nabla H)_x$, $(\nabla H)_y$: gradient of water surface in x, y coordinate at the centre of side l, $\tilde{h}$: water depth analyzed by h at the centre of side, $M1, M2$ or $N1, N2$: advection terms presented by below equations.

$$M1 + M2 = \frac{1}{A_{cv}}\sum_{l'=1}^{m'}\left\{(u_{l'}\tilde{M}_{l'})(\Delta y)_{l'} - (v_{l'}\tilde{M}_{l'})(\Delta x)_{l'}\right\} \tag{6}$$

$$N1 + N2 = \frac{1}{A_{cv}}\sum_{l'=1}^{m'}\left\{(u_{l'}\tilde{N}_{l'})(\Delta y)_{l'} - (v_{l'}\tilde{N}_{l'})(\Delta x)_{l'}\right\} \tag{7}$$

where, A_{cv} : area of control volume in Fig.2, m' : number of side surrounding the control volume, $\tilde{M}, \tilde{N}$: flux analyzed by M, N at the centre of grid. The analysis of equation (6) and equation (7) are used for flux calculation in upstream.

(3) Sea Areas

The plane 2D Model based on shallow water equation is used for analysis in sea area.

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0 \tag{8}$$

$$\frac{\partial M}{\partial t} + \frac{\partial uM}{\partial x} + \frac{\partial vM}{\partial y} = -gh\frac{\partial H}{\partial x} + \frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right) - \frac{\tau_{bx}}{\rho_w} + fN \tag{9}$$

$$\frac{\partial N}{\partial t} + \frac{\partial uN}{\partial x} + \frac{\partial vN}{\partial y} = -gh\frac{\partial H}{\partial y} + \frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right) - \frac{\tau_{by}}{\rho_w} - fM \tag{10}$$

where u, v : flow velocity in x, y direction respectively, h : water depth, M, N : discharge flux in x, y direction respectively $(M = uh, N = vh)$, H :

water level, τ_{bx}, τ_{by} : component of shear stress at water bottom in x and y direction respectively, g : gravity acceleration, $\varepsilon_x, \varepsilon_y$: eddy viscosity in x, y direction, respectively, f : Corriolis parameter, x, y : axis of plane, t : time.

Shear stress at bottom is presented by using of water density (ρ) and roughness coefficient of Manning (n).

$$\tau_{bx} = \rho g n^2 M \sqrt{u^2 + v^2} / h^{4/3} \qquad (11)$$

$$\tau_{by} = \rho g n^2 N \sqrt{u^2 + v^2} / h^{4/3} \qquad (12)$$

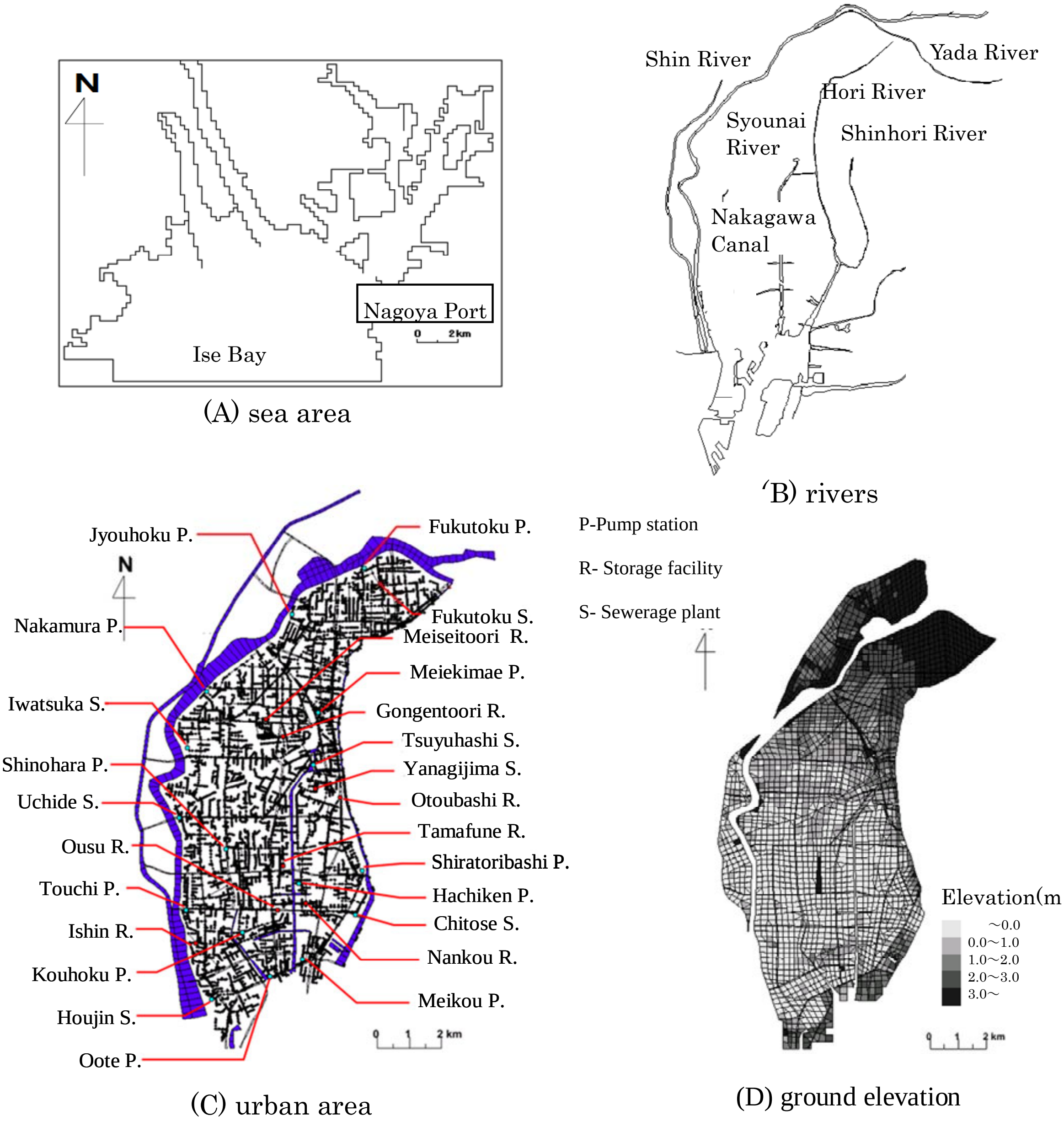
(4) Sewer System

This analysis model treats behavior of inundation water in sewer pipe and manhole. The model on sewer pipe flow used equation (1) and equation (2) as governing equation and slot model for pipe flow. Slot width is analyzed by $B = gA_S / C^2$ where, g is acceleration due to gravity, A_S is area of cross section and C is wave velocity.

The water level at manhole is computed by below continuity equation.

$$A_m \frac{\partial H}{\partial t} = \sum Q + Q_{in} - Q_{out} \qquad (13)$$

where A_m : area of manhole, H : water level of manhole, $\sum Q$: net inflow discharge from sewer pipe, Q_{in} : inflow discharge from overland($Q_{in} = \mu L h \sqrt{gh}$: μ is discharge coefficient, L is circumference of manhole, h is water depth), Q_{out} : outflow discharge of pump (Q_{out} is set by the maximum capacity of the pump and inflow discharge from the sewer system and overland).



(A) sea area

(B) rivers

(C) urban area

(D) ground elevation

Fig.3 Analysis regions

3.ANALYSIS REGION AND CONDITIONS

The analysis region includes Nagoya city, Nagoya port sea area, Rivers, and sewer system. **Fig. 3(A)** shows the sea area with Nagoya port, **Fig. 3(B)** shows the river system, **Fig. 3(C)** is the sewer system of the Nagoya city and the location of pumps and storage facilities, and **Fig. 3(D)** is the ground elevation of analysis region in Nagoya city. **Fig. 4** shows the design rainfall data of 10 years return period which is treated here for inundation analysis. **Fig. 5** shows tidal variation with time. In Nagoya city, most of the sewer drain out through pumping and discharge into river by pump station located as in the **Fig. 3(C)**. The sewer system design is mostly based on the rainfall of 10 years return period. The estuary gate of the Hori River remains open in normal situation. Due to influence of sea level rise the sea water enters into sewer system through water gate at the sewer disposal area and spread out from the manhole. The pump discharge is not directly related to sea level rise. In this study, the inundation occurred by spread out from the manhole as well as overflow from the dyke due to rise of sea level is mainly examined. It is considered that there is no water in the sewer system in the initial stage. Upstream normal discharge in the river is considered as upstream boundary condition. The maximum inundation occurred when peak of rainfall overlap with the peak of tidal water level at zero lag time.

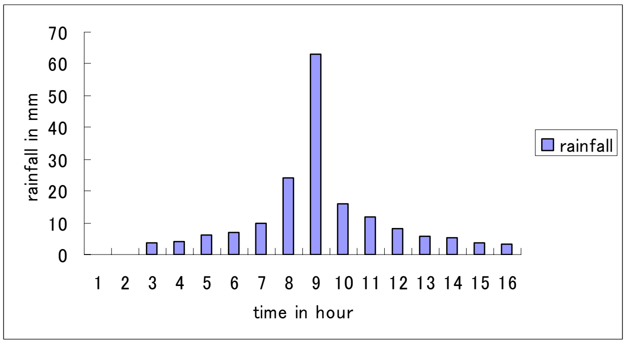


Fig. 4 Design rainfall of 10 years return period

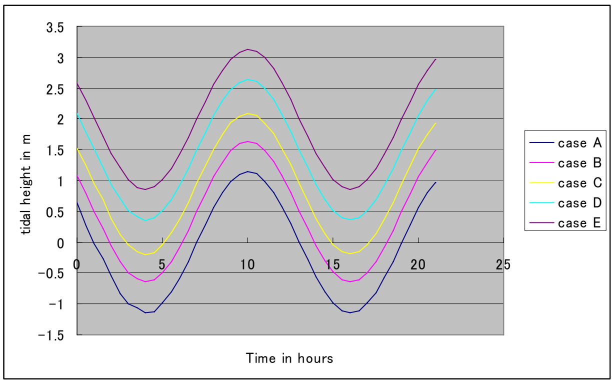


Fig. 5 Tidal variation

Simulation cases are shown below

1) Case A: Without considering global warming

Considering sea level rise due to global warming

2) Case B: Sea level rise 0.50m
3) Case C: Sea level rise 0.95m.
4) Case D: Sea level rise 1.5m
5) Case E: Sea level rise 2.0m

4. NUMERICAL ANALYSIS METHOD

Finite volume method is used as numerical simulation method. In the 1-D analysis for river and sewer pipe and 2-D analysis for sea region, forward deference scheme is used on time terms, DONOR scheme on advection terms and center scheme are used on other terms.

5. RESULTS AND DISCUSSION

Fig. 6 shows the distribution of maximum inundation in Case B, C, D and E of Sea level rises scenarios and Case A without sea level rise scenario. Inundation scenario of Case B and C are more or less same with Case A. It means that the existing sewer system is effective to pump out the inundated water. However, in Case D and E severe inundation appears in urban area between the Hori River and Nakagawa canal.

Fig. 7 demonstrates the inundation volume with increase in time. Initially, in the Case A, B and C, there is no significantly inundation appears. The inundation volume increases slightly with increase in time and becomes maximum at 10 hours of computation period and then decreases. In Case D and Case E, inundation appears from the beginning due to rise of sea level. In Ease E, the inundation volume is significantly larger than the other case because overflow from the river.

Fig. 8 shows pump out discharge with time. The discharge scenario is more or less similar in Case A, B, and C. It means that there is no influence of sea level rise in Case B and C. In the Case D and E are different from case A which means the inundation due to sea and river level rise make increase pump out discharge before and after the peak of discharge.

Fig. 9 shows the typical inundation scenario in the sewer system in Case D at 0 hours i.e. initially, 5 hours, 10 hours, and 15 hours computation period. Red line in the figure shows the situation of sewer line filled with water whereas the black line shows the open channel flow. After the sewer is filled by water, sewer water spread out from the manhole and inundation occurred. In **Fig. 8**, the inundation appears from the beginning and it is due to the spread out from the manhole.

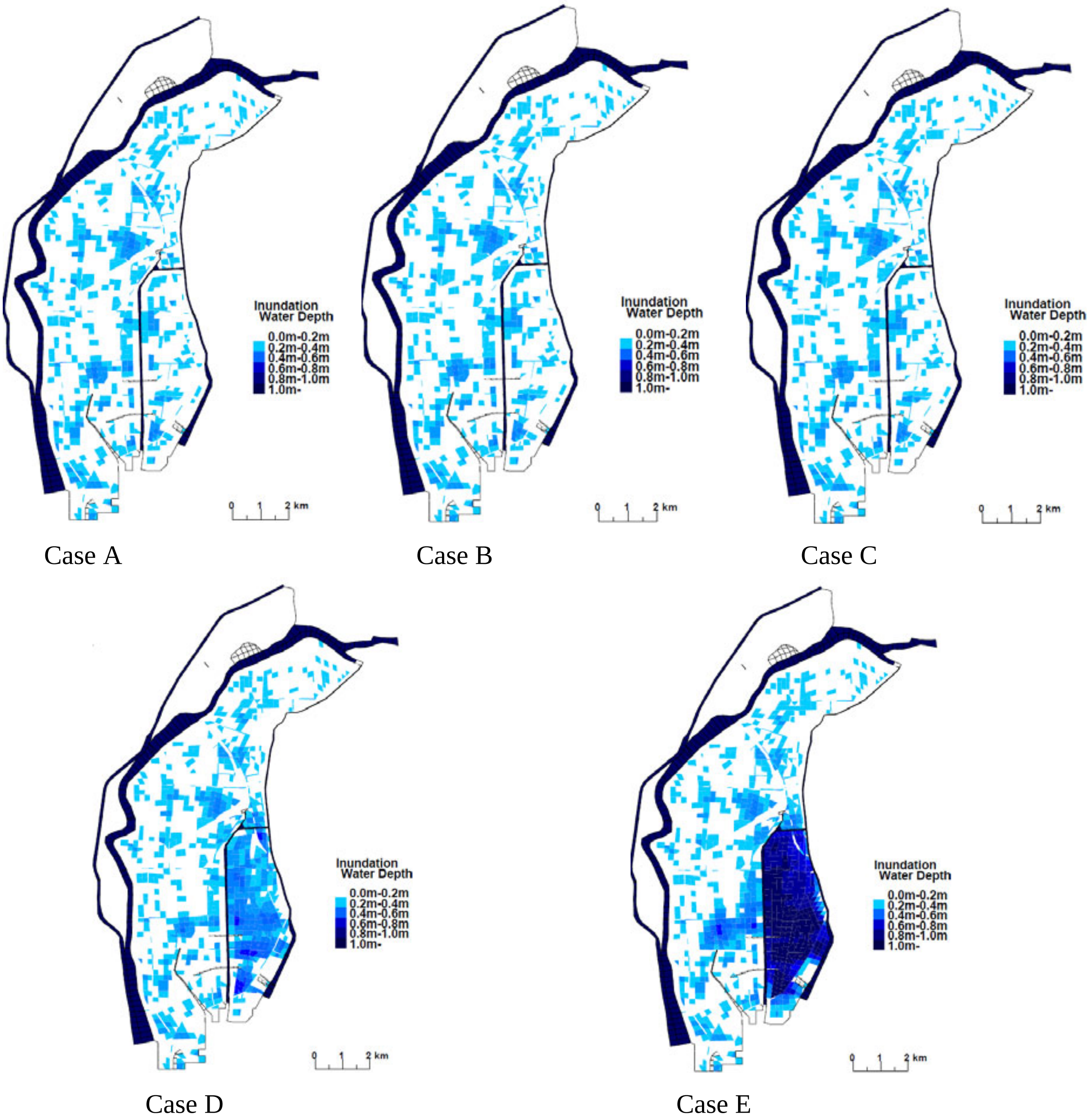


Fig. 6 Distribution of maximum inundation depth considering sea level rise due to global warming and design rainfall of 10 years return period

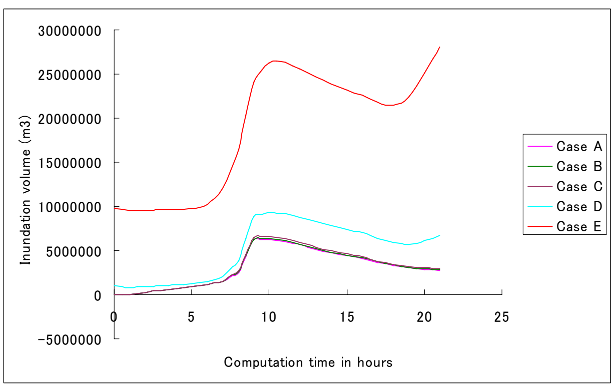


Fig 7 Inundation volume with computation time in hours

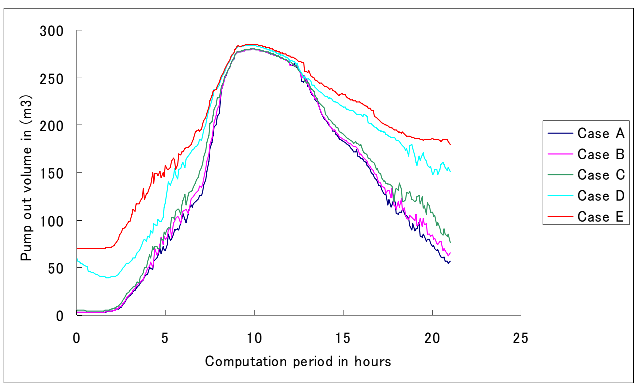


Fig 8 pump out volume computation with time in hours

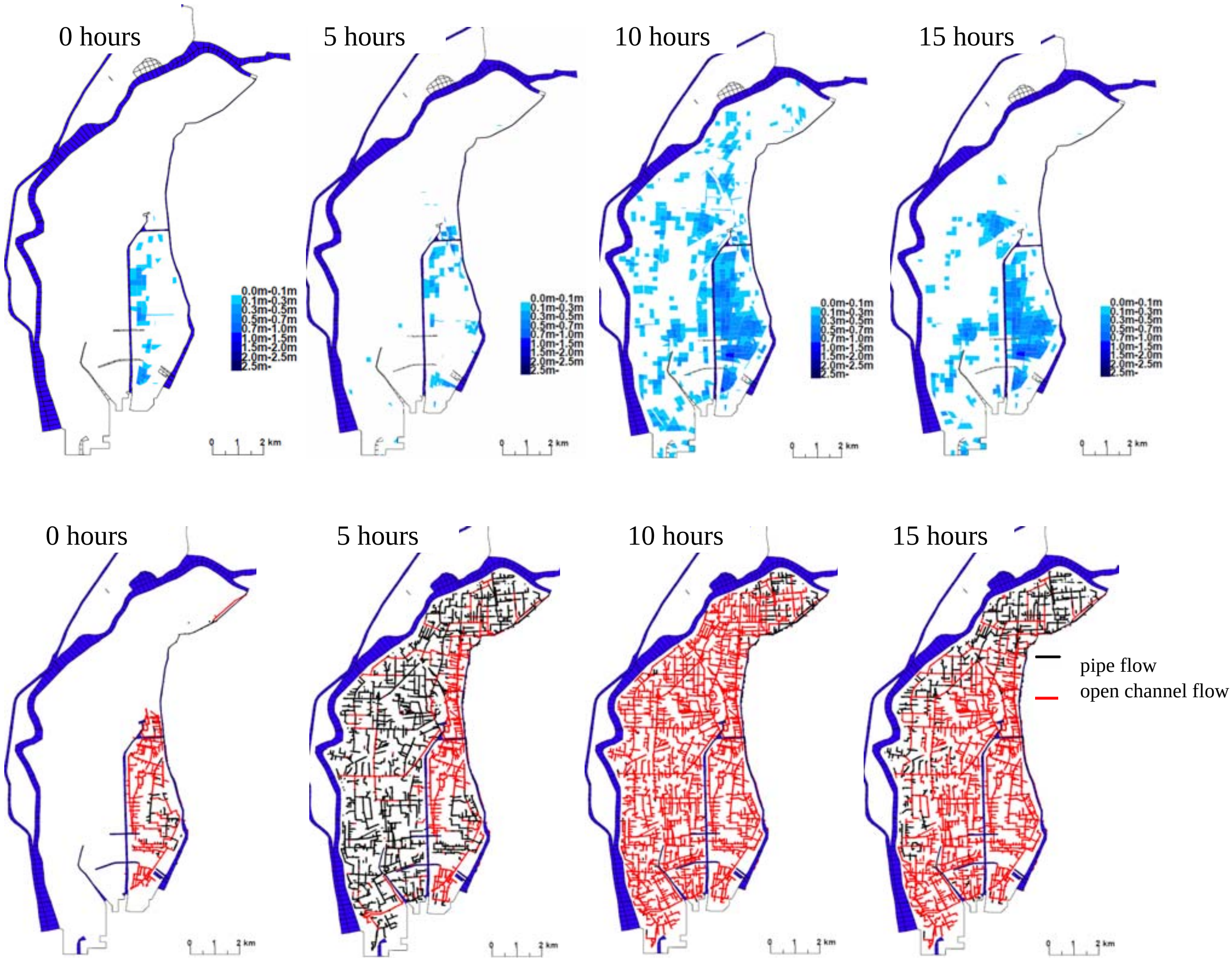


Fig 9 Inundation and corresponding sewer system simulation in Case D at computation period 0 hours 5 hours, 10 hours,15 hours considering design rainfall of 10 years return period

6. CONCLUSION

Following conclusions are drawn from this study:

(1) Severe inundation appears in the densely populated city area between the Hori River and Nakagawa canal if the sea level rise is considered as 1.5m or above.

(2) Inundation in the case of sea level rise by 0.50m, 0.95m and 1.50m is mainly due to spread out from the manhole. Whereas in the case of sea level rise by 2.00m, inundation is due to spread out as well as overflow from the river.

(3) Existing sewer system is efficient to drain out inundation water in the case of considering sea level rise by 0.50m and 0.95m.

(4) Analysis result is useful for the design of counter measure such as to increasing of the height of the dyke in the Hori River, nakagawa canal and increasing of the pumping facility, and planning for strengthening of drainage system.

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