

INUNDATION ANALYSIS MODEL ON CARTESIAN COORDINATE SYSTEM CONSIDERING INFLOW AND OUTFLOW INTO HOUSES

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ABSTRACT

Recently, large scale inundation which a lot of water flows into houses has occurred. The general inundation analysis model did not take into consideration inflow into houses. In urban inundation, evaluation and countermeasures for economic damage on houses are major issue. Therefore, it is considered the importance to develop an inundation analysis model considering inflow and outflow into houses in order to estimate the damage appropriately. In this study, based on the inundation analysis on the Cartesian coordinate system, the analysis model was developed with the hydraulic model considering inflow and the outflow into houses. The discharge between land and houses was analyzed by overflow formula. And the temporal change of water level in houses was analyzed by the continuity equation. In this analysis, the inundation situation due to flood of the Shonai River in Nagoya city, Japan was calculated and the difference of urban inundation analyzed with and without house inflow model was examined. From this study, the characteristics of the proposed analysis model were shown and the validity was confirmed from the viewpoint of mass conservation. In particular, the analysis result with the house inflow model was more slowly spread than the analysis result without the house inflow model. Moreover, as the application of the proposed analysis model, the effect of houses buildup on the inundation and economic damage of houses was examined.

Keywords: Inundation analysis model, House, Numerical simulation Economic damage

1. INTRODUCTION

Recently, the serious inundation disaster occurred due to river flood and heavy rain. For examples the serious water disaster occurred at Joso City due to the dike break of the Kinu River in 2015. Moreover, a large scale inundation occurred in Kurashiki City, Mabi cho which is the area between Takahashi River and Oda River in 2018. Many houses were submerged and the flood water flowed into houses.

An inundation analysis is used as an effective tool to examine the countermeasures for the water disaster. The development of the high accurate analysis model on the urban inundation has been studied. The various analysis model, road network model(SEKINE et al.(2018)), unstructured grid model(KAWAIKE et al.(2018a), AKOH et al.(2015)), are developed and applied to express the flow of the inundation water along road. On the other hand, inundation analysis model on the Cartesian coordinate system has a high accuracy because of setting of the about 25m analysis grid.

However, these analysis models are not considered inflow and outflow into houses. In the application of inundation analysis to the metropolitan region as Tokyo, Osaka, as there are big building closely and these building has the water stop board as the countermeasure of the inundation, it is thought that the ignoring of inflow into houses is not so big error in inundation simulation. But, basically, the phenomenon of inflow into houses should be considered in the inundation analysis.

The inundation analysis method with the building occupation ratio (the ratio of the building into the analysis grid) and the transmission factor is indicated in the inundation analysis manual as the method to consider the influence of the buildings. But the change of the water behavior in buildings is not expressed in the inundation analysis manual. Moreover, GIS and the related data are prepared in recent years, and the various data (the house shapes, division by analysis grid in house, the building classification and correspondence with the building and the analysis grid) can be used easily.

In this study, the inundation analysis model which considered inflow and outflow into houses is developed and the validity of this analysis model is examined from view point of the conservation law. Moreover, the application of the developed analysis model is examined. In the study of AKOH et al. (2015), KAWAIKE et al. (2018b), the similar study themes were discussed. The validity of the model is estimated quantitatively from comparison with the observed water level and the importance of considering of inflow into buildings is indicated. Though unstructured grid model is applied in these studies, the inundation analysis model on the Cartesian coordinate system is examined from the generality in this study. Modeling of the water behavior in the houses and the application of the proposed analysis model regards as the features of this study.

2. ANALYSIS MODEL

In this study, an integrated inundation analysis model which consist of river flow analysis and inundation analysis is used. The aim of this study is to examine the expanse of inundation water due to the dike break condition in flood. The shallow water equations (continuity equation (eq.(1)) and momentum equation (eq.(2) and eq.(3))) are used for the analysis of inundation situation. For the analysis of discharge due to dike break and overtopping, overflow formulation of eq.(6) and eq.(7) are used with the height of top of the dike, the water level of river and the water level of land. In this study, the treatment of the analysis model in inundation situation is the main research topic. Here, the inundation analysis method in land are indicated in detail.

The following shallow water equations are used in inundation analysis with consideration of the building occupation ratio (the ratio of building in analysis grid) and the transmission factor.

$$(1-\theta)\frac{\partial h}{\partial t} + \frac{\partial \lambda M}{\partial x} + \frac{\partial \lambda N}{\partial y} = q_r \quad (1)$$

$$\frac{\partial M}{\partial t} + \frac{\partial uM}{\partial x} + \frac{\partial vM}{\partial y} = -gh\frac{\partial(z_G+h)}{\partial x} + \frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial M}{\partial y}\right) - \frac{\tau_{bx}}{\rho} \quad (2)$$

$$\frac{\partial N}{\partial t} + \frac{\partial uN}{\partial x} + \frac{\partial vN}{\partial y} = -gh\frac{\partial(z_G+h)}{\partial y} + \frac{\partial}{\partial x}\left(\varepsilon_x\frac{\partial N}{\partial x}\right) + \frac{\partial}{\partial y}\left(\varepsilon_y\frac{\partial N}{\partial y}\right) - \frac{\tau_{by}}{\rho} \quad (3)$$

shear stress of bottom surface(ground) is expressed in the following formulation using the coefficient of roughness of the Manning (the value is set with the ratio of building in the analysis grid)

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

$$\tau_{by} = \rho g n^2 N \sqrt{u^2 + v^2} / h^{4/3} \quad (5)$$

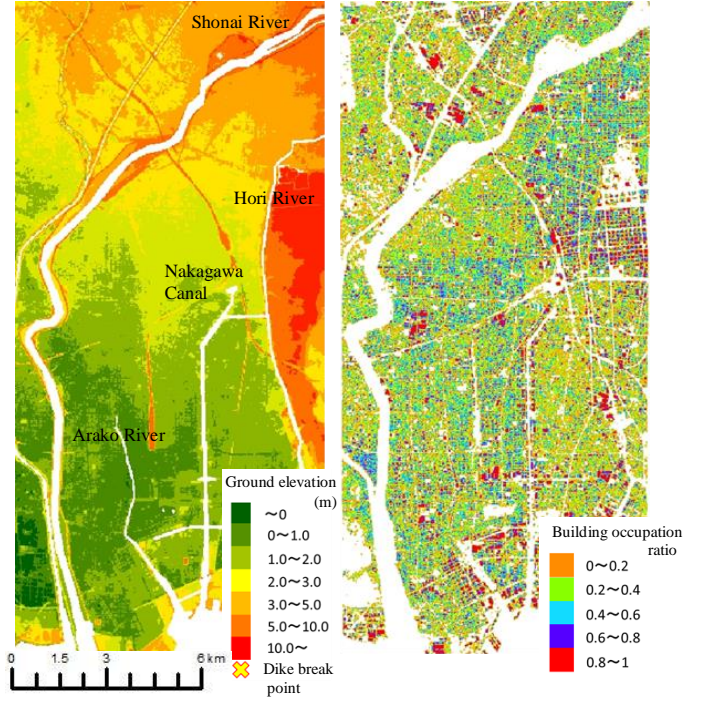


Figure 1 Analysis region

Figure 2 Building occupation ratio

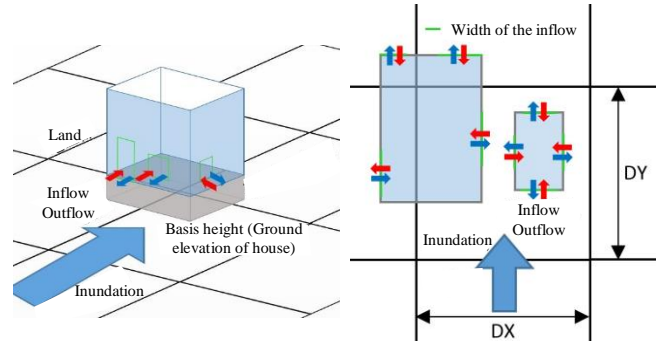


Figure 3 House inflow model

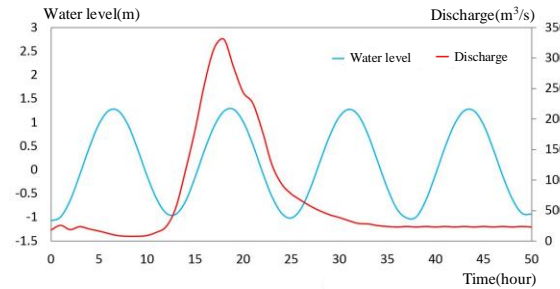


Figure 4 Boundary conditions

where, u, v are the water velocity(m/s) in x, y axis, respectively, h is the water depth (m) , M, N are the flux ($M = uh$, $N = vh$)(m²/s) in x, y axis respectively, q_r is the inflow discharge (m/s) with unit area from river, g is gravity acceleration (m/s²) , z_G is the ground elevation, τ_{bx}, τ_{by} are share stress of the ground in x, y axis respectively, ρ is the density of water (kg/m³), $\varepsilon_x, \varepsilon_y$ are the eddy viscosity coefficient(m²/s) in x, y axis respectively (the value assumed as 0), θ is the building occupation ratio (the ratio of building in analysis grid), $\lambda = 1 - \sqrt{\theta}$ is the transmission factor, x, y are the coordinate in the plane where plus value of x is east wise and plus value of y is north value.

In this study, inflow and outflow of the inundation water are considered at each house. The settlement in the house (the inner structure) is omitted and the inflow and outflow of the water is considered at the door and the window in the outer wall of the house. the discharge is calculated using the following overflow formula.

$$h_2 / h_1 \leq 2/3 \quad Q_e = \mu L h_1 \sqrt{2g h_1} \quad (6)$$

$$h_2 / h_1 > 2/3 \quad Q_e = \mu' L h_2 \sqrt{2g (h_1 - h_2)} \quad (7)$$

where, the water depth is analyzed by $h = H - z_h$ and $h = H_h - z_h$, the big one is h_1 and the small one is h_2 in two analysis results. Here, H is the water level, $H_h = h_h + z_h$ is the water level of the house (h_h is water depth of the house and z_h is the ground level of the house). L is the inflow length of the house, μ is 0.35 and μ' is 0.91. The change of water depth in the house is analyzed by the following continuous equation.

$$A_h \frac{\partial h_h}{\partial t} = \sum Q_e \quad (8)$$

where, A_h is the plane area of house, h_h is the water depth in the house, $\sum Q_e$ is the inflow discharge in the house.

This analysis model has the staggered grid as the arrangement of unknown values. The explicit finite difference method was applied as the numerical analysis method. The donor scheme which is considered the upwind method is used for the analysis of the advection terms of the momentum equations and central difference method was also applied to the pressure terms and the viscosity terms.

The distribution of the ground elevation with 25m grid is shown in Figure 1 and the building occupation ratio (the ratio of building in the analysis grid) is shown in Figure 2. The Hori River, the Arako River and the Nakagawa Canal were treated as no calculation area. The outline of the house inflow model is indicated in Figure 3. The height of the ground level of the house was calculated from ground elevation data every 5m. The inflow width of the house was made to consider the sum between the width of the door and the width of the window. The inflow width of the building is calculated by the following equation.

$$L_0 = 0.8 + \sqrt{A_h} \times 1/7 \quad (9)$$

Moreover, the width L which divided by $L_0 \times S_{IJ} / S$. Where, S is the circumference of the house, S_{IJ} is the circumference of the house in the analysis grid of (I,J).

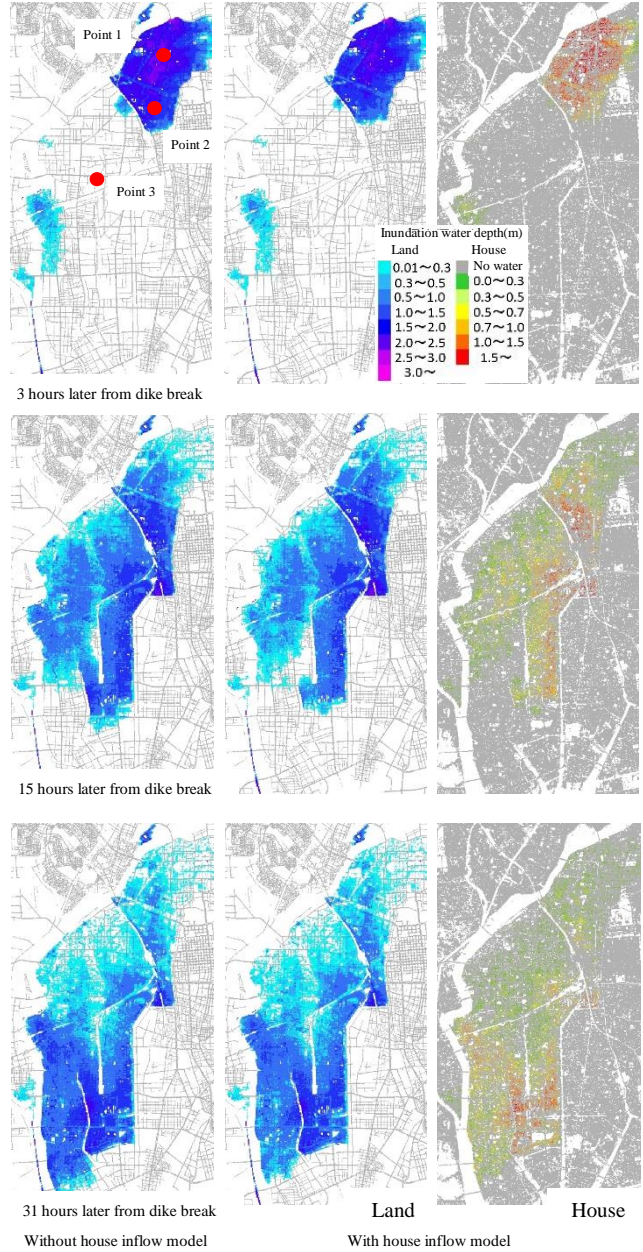


Figure 5 Distribution of inundation water depth

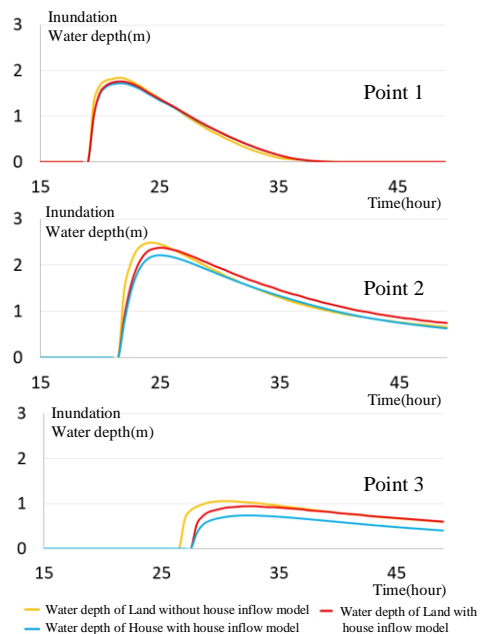


Figure 6 Inundation water depth

The area of the house, the ground elevation of the house and the circumference of the house are made based on houses data and ground elevation data of the Geographical survey institute, Japan by using GIS. The elevation of houses was calculated as mean value using the spatial combination function of GIS with house information and 5m mesh ground elevation data. The houses data of Geographical Survey Institute has the kind, the area and the circumference of the house. The house information was divided using the clip function and the intersecting function as the information of each analysis grid. Moreover, analysis grid(I,J) which related the building part was obtained from position information of the median point of the building parts.

3. THE ANALYSIS CONDITION AND THE EXAMINATION OF THE VALIDITY WITH THE VIEW POINT OF THE MASS CONSERVATION

(1) Analysis conditions

The discharge hydrograph with $4400\text{m}^3/\text{s}$ of planned high water discharge as peak value is set at the upstream point of the Shonai River. The temporal change of the water level of spring tide is set at the downstream point of the Shonai River. These boundary conditions are shown in Figure 4. A left side dike is broken at the 17km point from the mouth of the river with 100m as dike break width. The break time is 19 hours later and total analysis time is 50 hours.

(2) The validity of the analysis model with the view of the mass conservation

The state of the inundation in land and houses due to dike break in flooding considered the inflow and outflow into the house are shown in Figure 5. Moreover, the temporal change of the water depth in the land and the house at the point in Figure 5 are indicated in Figure 6. Though the water depth in the house changes like the water depth in the land, the water depth of the land became small and the spreading time becomes late by consideration of the inflow and the outflow in house. The inundated water volume which obtained at the end time of analysis and inundation area with maximum inundation water depth are shown in Figure 7. From this figure, the inundation area of the land become small in overall by considering inflow and outflow into houses, and the water volume of house is about 20 % of total water volume. However, the error for 5 % of the total water volume occurred and the conservation law is not satisfied. It was considered that much water flowed in the land from the river because the inflow and the outflow into a house are considered. The inundation water volume and inundation area which did not consider the inflow and the outflow to a house the around dike break point area (the area which is radius 1km from the dike break point) is shown in Figure 8. It is found that the inundation water volume of two models are equal from Figure 8. Therefore, the validity of the analysis model is indicated from the view point of the conservation law.

4. UTILIZATION OF PROPOSED ANALYSIS MODEL

(1) The consideration of basic height of the house and the rising

The feature of the analysis model presented here is to treat the water behavior in each house. In this paper, the height of the ground elevation of the house assumes to be called as the basic height. The analysis result of inundation under the condition that 0.5m was added to the basic height is examined. The inflow and outflow into a house aren't considered around the dike break point like as 3.(2). Figure 9 shows the temporal change of the inundation water depth and Figure 10 shows the water volume change. It is found that the inundation in the house becomes small by the condition of the rising of the basic height and the inundation in the land spreads more than the results without the rising from the Figure 9. Moreover, it is found that the inundation water volume in the land increase and water volume in the house decrease after 27 hours of analysis time by consideration of the rising of the basic height from Figure 10. It is thought that the inundation water which flowed into a house flows to the land easily because the ground elevation of the house was raised.

The ground elevation of houses was raised 0.5m. Moreover, houses of 20%,40%,60%,80% were selected using random number and the ground elevation of the selected houses was raised more 0.5 m. Further, the ground elevation of all house in the black broken line of Figure 9 was raised 0.5 m. The temporal change of the water volume is indicated in Figure 11. It is found that the inundation water volume in the house decreases so that the percentage of the house of rising of the basic height increases from Figure 11. Moreover, the temporal change of water volume is big compared with other cases in the case of rising of the ground elevation of the house in the black broken line. As the ground elevation of the house in the black broken area was raised, the inundation water did not flow into house and the water pass the target area (the black broken line area). And the inundation water flow into the house outside of the black broken line area.

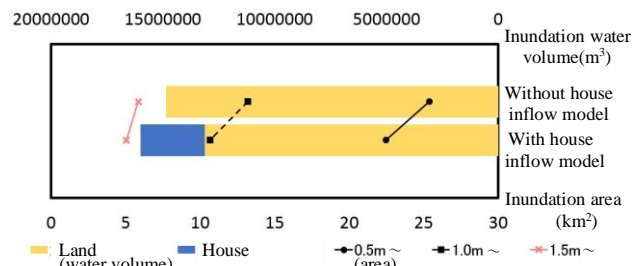


Figure 7 Inundation water volume and inundation area

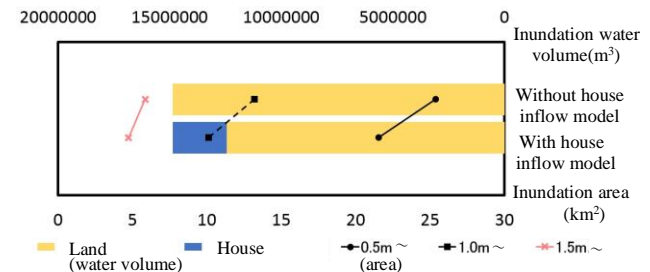


Figure 8 Inundation water volume and inundation area (without house inflow model around the dike break point)

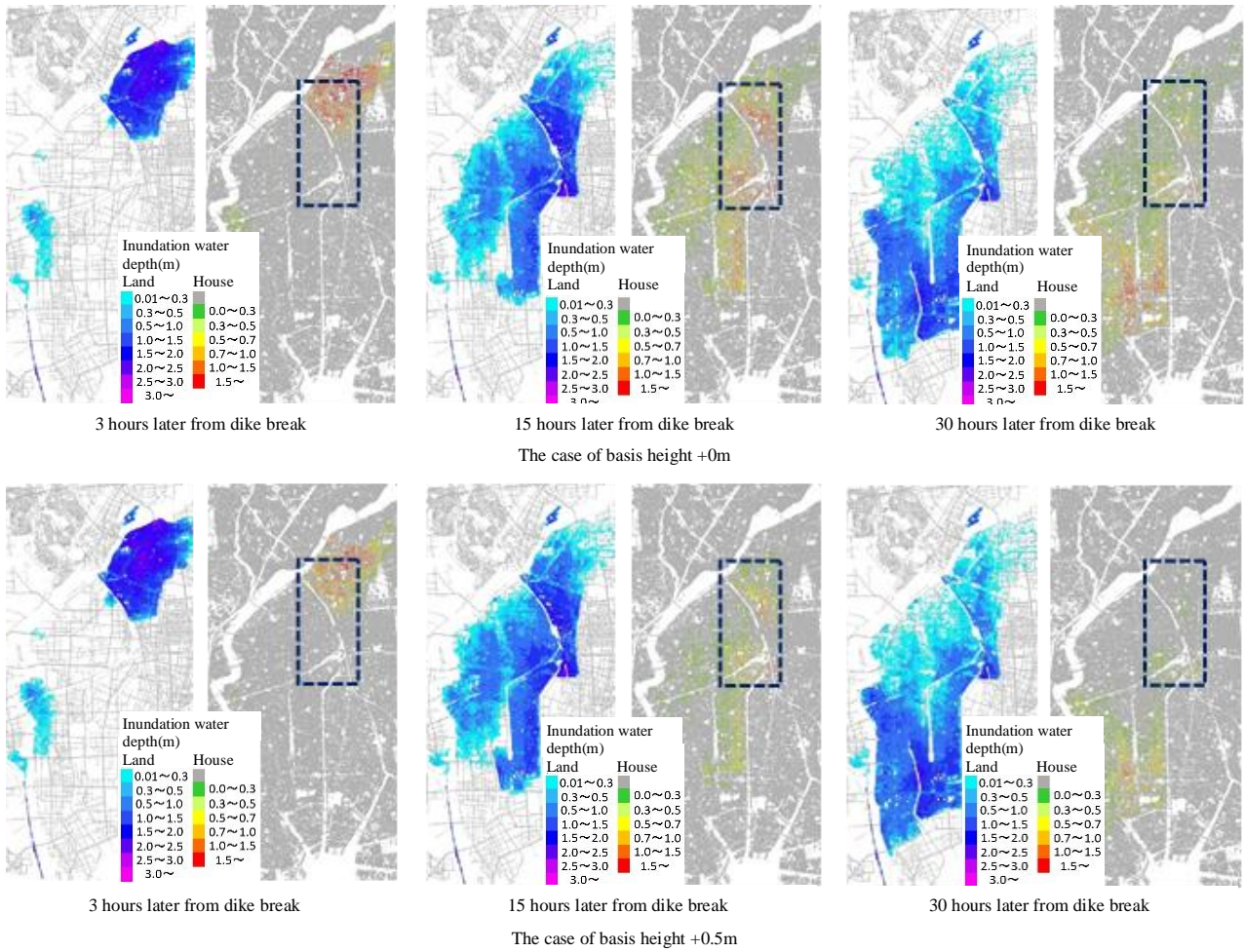


Figure 9 Distribution of the inundation water depth in land and houses

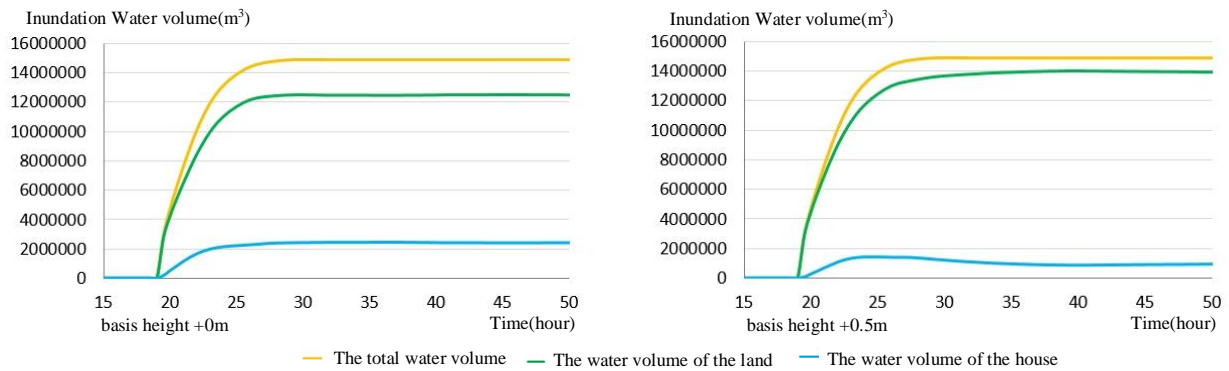


Figure 10 Temporal change of the inundation water volume

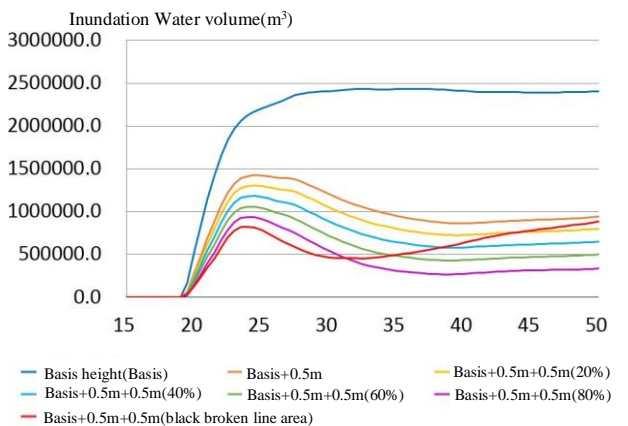


Figure 11 Temporal change of the inundation water volume in house

Table 1 Economic damage in house

Basis height(Basis)	593
Basis+0.5m	500
Basis+0.5m+0.5m(20%)	461
Basis+0.5m+0.5m(40%)	420
Basis+0.5m+0.5m(60%)	379
Basis+0.5m+0.5m(80%)	338
Basis+0.5m +0.5m(Black broken line area)	418

×100000000YEN

(2) The evaluation of the economic damage of houses

To express the inundation of the house is effective for the examination of the economic damage of houses. The economic damage of houses was calculated by flood control economic research manual(Ministry of Land, Infrastructure, Transport and Tourism(2005)). The information on the inundation of the house is effective for the analysis of the economic damage with the inundation above the floor level, but it can't be used for inundation below the floor level. Therefore, the inundation water depth below the floor level was calculated to pull the height of the ground elevation of the house from the water level of the land. The value of the house economic damage is shown in Table 1. It was shown that the amount of economic damage with the rising of the basis height of the house is about 10,000,000,000 yen less expensive than the condition without rising of the basis height. Moreover, the amount of economic damage is small by the condition with a lot of percentages of rising of the basic height. Though the number of houses in the area of black broken line is 20% in all houses, the amount of economic damage is almost the same to the economic damage in the case considered the rising of the basis height of 40%.

5. CONCLUSION

In this study, the house inflow model which considered inflow and outflow into houses is installed to the urban inundation analysis model due to the dike break condition in flood. As the results, the inundation water depth with the house inflow model is smaller than the inundation water depth without the house inflow model. The analysis result with the house inflow model was later more than the analysis results without the house inflow model in terms of the expanse of the inundation. Moreover, it is shown that the inflow discharge from the river is changed due to the modeling of the inundation analysis near the dike break point. The validity of the analysis model proposed here is shown from view point of the mass conservation. The effect of the basic height of the house, rising of the basic height and the economic damage of the house were estimated as the utilization of the proposed analysis model. The inflow of water to the house becomes small by the consideration of the basic height of the house and the inundation water flowed widely to the land. The amount of economic damage with the house inflow model was calculated, and the effect of the rising of the basis height of the house was shown.

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