FATALITY ESTIMATION BY LIFE LOSS EVALUATION MODEL FOR THE LARGE-SCALE FLOODS UNDER FUTURE CLIMATE

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ABSTRACT

In recent years, large-scale floods frequently caused many fatalities in Japan. In Hokkaido, northern Japan, serious flood damage caused by hit of the three consecutive typhoons and approach of another typhoon in August 2016. After this, it became necessary to grasp accurate flood risk under future climate for considering climate change adaptation measures. The LIFESim model is used widely in Japan, which estimates numbers of fatalities based on water depth in flooded area. However, in the Netherlands, the life loss evaluation model has been used to grasp human damage in the national risk assessment project called Floris. This model considers not only flood depth but also water velocity and rise rate of water.

In this study, we simulated floods for heavy rainfall events over the Tokachi River basin in Hokkaido under past and future climate detected from large ensemble climate projection data (d4PDF). We estimated the fatality in the urban area of Obihiro city located in the center of the Tokachi River basin from the simulation results by LIFESim model and life loss evaluation model. Finally, this study elucidated the differences of fatality by each model.

Keywords: *climate change, large ensemble climate projection database, fatality estimation, LIFESim model, Life loss evaluation model*

1. INTRODUCTION

Recently, large-scale floods that caused death have occurred frequently in Japan. In response, the MLIT held a technical review committee about flood control plan, and began to consider new safety level that take climate change into account[1)].

In Hokkaido located in northern Japan, consecutive typhoons have caused severe flood damage in August 2016 (2016 flood). After 2016 flood, Flood Prevention Committee[2)] was established by Hokkaido Development Bureau (MLIT) and Hokkaido government. This committee reported that flood control measures with relevant risk assessment, based on scientific climate change projection. Climate change projection and impact assessment[3)4)5)6)] have been done by utilizing output rainfall of massive ensemble climate projection data "database for Policy Decision making for Future climate change (d4PDF)" [7)] in Hokkaido.

Estimated fatality caused by flood is a way to indicate risk assessment of large-scale flood. In Japan, the fatality estimation model, LIFESim model, developed by M.A. Aboelata and D.S. Bowles[8)] with support from the USACE and Australian National Committee on Large Dams (ANCOLD), and estimates fatality by water depth of flooded area. It is the same model adopted by the United States Army Corps of Engineers (USACE) [9)] to verify fatalities around New Orleans when Hurricane Katrina attacked in 2005. In Japan, Wakigawa et al.[10)] applied LIFESim model to Shinano River basin, afterwards Ikeuchi et al.[11)12)] applied it to Arakawa River basin. However, fluid force and velocity could be better taken into consideration in a model, since many rivers in Japan are characterized to be rapid stream. As a specific model, the Dutch model proposed by S.N. Jonkman[13)] was adopted as a basic model, which had been used for Dutch national risk assessment project "Flood Risks and

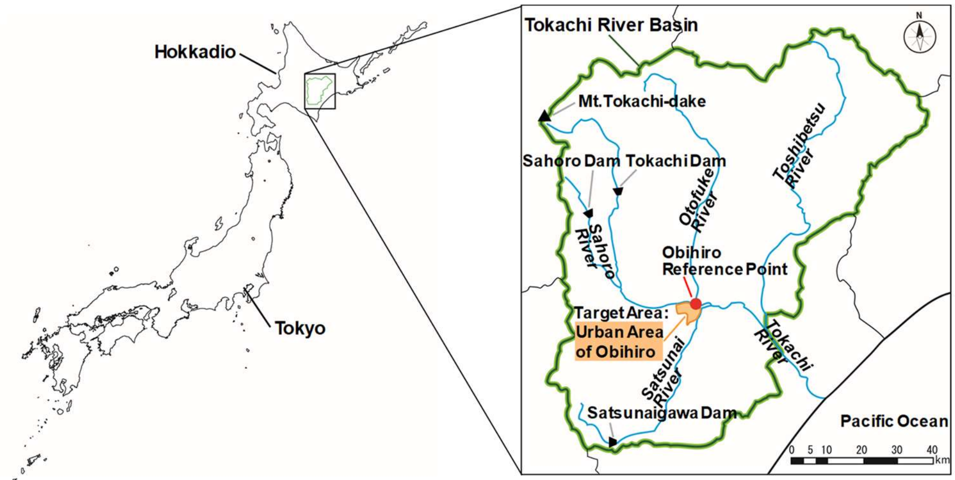


Figure 1. Outline of Tokachi River basin and target area.

Safety in the Netherlands (Floris)"[14], estimating fatality based on mortality function derived with information regarding historical flood events (hereinafter called LIFEEva model).

This study aims to differentiate between the estimated fatalities of flood by LIFESim model and LIFEEva model, based on run-off/flood analysis targeting the urban area of Obihiro city in Tokachi River basin, in order to do relevant risk assessment considering the influence of climate change. In addition, challenges and future direction are mentioned in terms of boundary conditions by setting mortality, for LIFEEva model estimates based on mortality function per hazard zone in flooded area.

2. TARGET AREA AND RAINFALL DATA

2.1 Target area

Tokachi River flows from Mount Tokachi-dake in Daisetsuzan National Park, along the west side of Tokachi Plain, and into Pacific Ocean. The length of the river channel is 156km and its basin area is 9,010km^2, which classifies it as a first-class river. There are multi-purpose dams to control flood, such as Tokachi Dam along the mainstream of the Tokachi River mainstream and Satsunaigawa Dam along the Satsunai River, tributary channel of the Tokachi River system. August 2016 flood caused huge damages such as traffic obstacles. around upstream of Tokachi River. The urban area of Obihiro is in the midstream, and about 340,000 people living within the basin.

This study focuses on urban area of Obihiro (Figure 1), where the capital city and the population is concentrated within the basin.

2.2 Rainfall data

This study utilized the output rainfall data from d4PDF which was dynamically downscaled from 20 km to 5 km horizontal resolution according to the study of T. Yamada et al.[3] and T. Hoshino et al.[4]. Further, we used the method of F. Uemura et al.[5] for the bias correction of rainfall data.

d4PDF is caluculated by historical climate simulation data (3,000 cases) of ensemble members, adding 50 perturbations to sea surface temperature data, based on the target period of 60 years between 1951 and 2010 (50 times 60 equals 3,000 cases), and by future climate simulation data (for 5,400 cases) of ensemble members, adding 15 perturbations to 6 sea surface temperature data, based on the target period of 60 years between 2051 and 2110 (15 times 6 times 60 equals 5,400 cases). Future climate simulation data is based on the worst scenario RCP8.5 indicated by IPCC AR5, which estimates 2K rise of average global temperature by 2040 compared to the period of the Industrial Revolution and 4K rise by 2100.

This study employed the historical climate simulation data (past simulation) and the future climate simulation data with 4K rise (future simulation) for the calculation of hydraulic quantities needed to estimate the fatality of the flood.

3. CALCULATION OF HYDRAULIC QUANTITIES OF FLOOD PLAIN TO ESTIMATE FATALITY BY FLOOD

3.1 Run-off data

3.1.1 Outline of run-off analysis model

This study applied the distributed two-cascade storage routing model called "Hoshi's model"[15] to analyze run-off, for actual flood in Hokkaido. The outline of the basic formula of the two-cascade storage and channel routing is as follows.

<Basic formula of two-cascade storage routing model>

$$\left\{\begin{array}{ll} s_1 = k_{11}q_1{}^{p1} + k_{12}\dfrac{d}{dt}(q_1{}^{p2}) & \dfrac{ds_1}{dt} = r - q_1 - b \\ b = k_{13}q_1 & \\ s_2 = k_{21}q_2 + k_{22}\dfrac{d}{dt}(q_2) & \dfrac{ds_2}{dt} = b - q_2 \\ q = q_1 + q_2 & \end{array}\right. \quad (1)$$

where, s_1: first storage tank (mm), s_2: second storage tank (mm), q_1: height of surface-subsurface run-off (mm/h), q_2: height of groundwater run-off (mm/h), q: total run-off height (mm/h), p_1, p_2: storage index (p_1=0.6, p_2=0.4648), r: rainfall intensity (mm/h), b: infiltration capacity from first to second storage (mm/h), k_{11}, k_{12}, k_{21}, k_{22}: storage coefficient, k_{13}: permeation coefficient.

<Basic formula of channel routing model>

$$\frac{dA}{dt} + \frac{dQ}{dx} = 0 \qquad Q = hBv \qquad v = \frac{1}{n}h^{\frac{2}{3}}i^{\frac{1}{2}} \quad (2)$$

$$\left\{\begin{array}{lll} k_{11} = c_{11}A^{0.24} & k_{12} = c_{12}k_{11}{}^{2}\bar{r}^{-0.2648} & k_{13} = c_{13} - 1 \\ k_{21} = \dfrac{c_1}{c_0}k_{13}\left[c_0 = \left({}^{\delta}/_{T_c}\right)^2\right] & k_{22} = \dfrac{1}{c_0}k_{13}\left[c_1 = {}^{\delta^2}/_{T_c}\right] & \\ c_{11} = \mathrm{X} \times f_c & f_c = \left({}^{n}/_{\sqrt{i}}\right)^{0.6} & \end{array}\right. \quad (3)$$

where, Q : river discharge (m^3/s), v: velocity (m/s), h: water depth (m), B: river width (m), n: channel roughness (s/m$^{1/3}$), i: channel slope, k_{11}, k_{12}, k_{21}, k_{22}: storage coefficient, k_{13}: permeation coefficient, c_{11}, c_{12}, c_{13}: model constant (unknown constant), A: basin area (km^2), r: average rainfall intensity (mm/h), c_0, c_1: definite value, δ: damping coefficient (δ =2.1), T_c: constant for separation of groundwater runoff components, X: unknown constant, f_c: basin roughness.

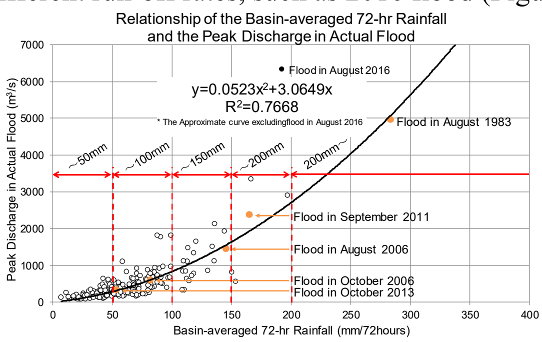
The distributed model is a 1km grid mesh. The drainage network is determined by the ground height of each grid cell based on the 10-m Digital Elevation Model (DEM) of the Geospatial Information Authority of Japan. The roughness coefficient for the routing drainage network is 0.030 for mountain channel according to the Technical Criteria for River Works[16)]. Equivalent roughness to calculate surface-subsurface run-off is determined in accordance with The Collection of Hydraulic Formula[17)] which is dependent on the land use in the area. The land use of each grid is based on National Land Numerical Information.

3.1.2 Setting model constant

We calculated the historical major floods to reproduce, and determined unknown constant X for run-off model constant. In order to grasp run-off features of Tokachi River basin, we examined the relationship of the basin-averaged 72-hr rainfall and the peak discharge of historical major floods (Figure 2). We selected significant and different scale events in August 1981, August 2006, October 2006, September 2011, and October 2013. After calibration for each of the five floods, the relational expression of unknown constant X and the basin-averaged 72-hr rainfall was obtained (Figure 3). By using this relational expression, we determined each unknown constant X from the basin-averaged 72-hr rainfall in each case (3,000 cases for past simulation and 5,400 cases for future simulation). When unknown constant X is evaluated, model constants c_{11}, k_{11} and k_{12} are calculated (hereinafter called functionalization of c_{11}).

3.1.3 Performance reproducibility

When the annual maximum rainfall of past simulation for 3,000 cases is applied, the peak discharge based on run-off analysis with the assumption of no flood control facility is quite identical to frequency distribution (Figure 4 and Table 1) of observed peak discharge (dam return discharge after completing Tokachi Dam in 1984) between 1961 and 2010, which indicates excellent reproducibility. However, this study employed an average value for model constant, which did not achieve the accurate reproducibility for floods with extremely different run-off rates, such as 2016 flood (Figure 2).



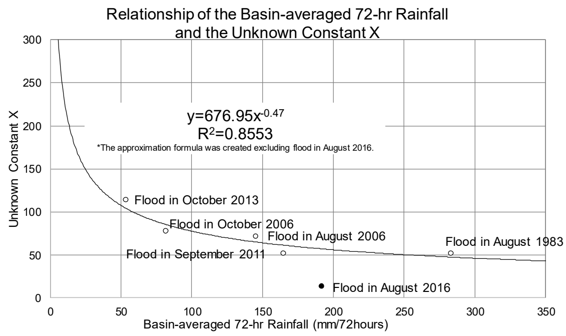
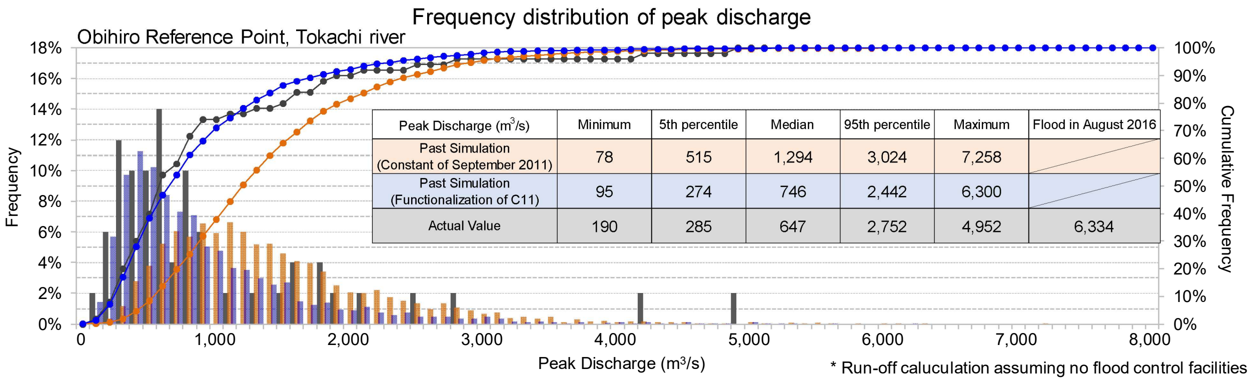


Figure 2 (left). Relationship of the basin-averaged 72-hr rainfall and the peak discharge in actual flood.
Figure 3 (right). Relationship of the basin-averaged 72-hr rainfall and the unknown constant X.



Peak Discharge (m3/s)	Minimum	5th percentile	Median	95th percentile	Maximum	Flood in August 2016
Past Simulation (Constant of September 2011)	78	515	1,294	3,024	7,258	
Past Simulation (Functionalization of C11)	95	274	746	2,442	6,300	
Actual Value	190	285	647	2,752	4,952	6,334

Figure 4. Comparison of frequency distribution between the peak discharge of past simulation for 3,000 cases and observed peak discharge.

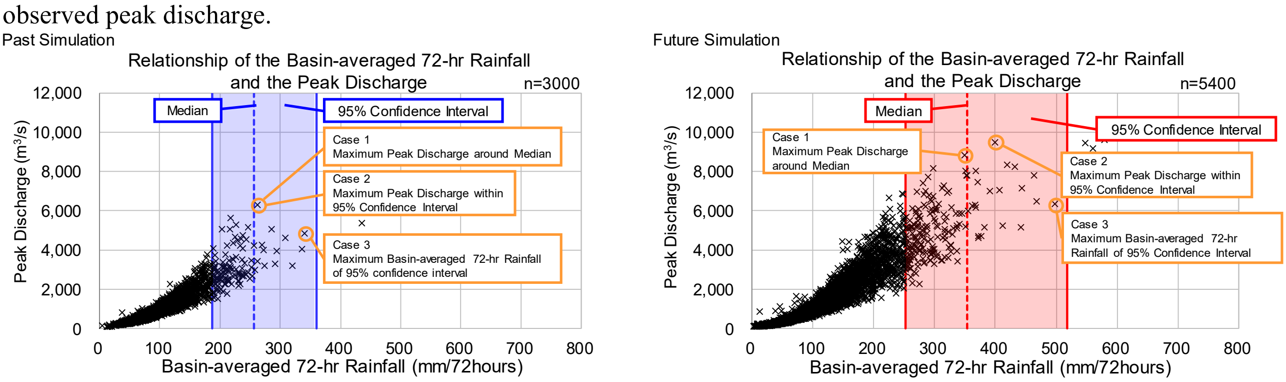


Figure 5. Possible peak discharge by 1/150 probability rainfall. (left: past simulation, right: future simulation)

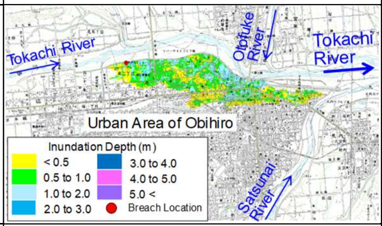
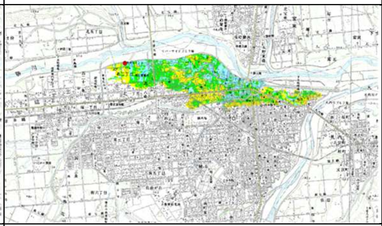
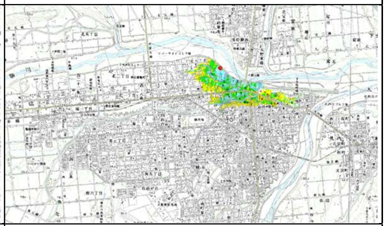
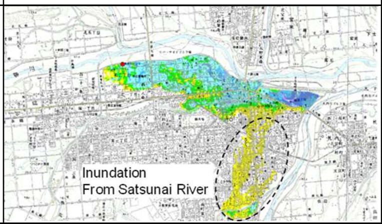
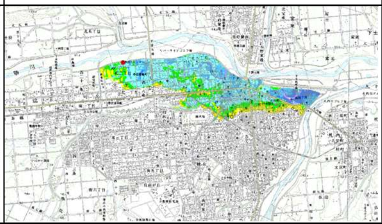
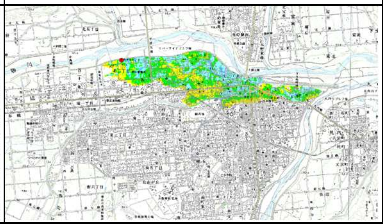
3.1.4 External force for flood analysis

S. Masuya et al.[7] calculated 1/150 probability rainfall of Obihiro reference point along Tokachi River while considering uncertainty. As a result, the median of past simulation was 256mm/72h, and 95% confidence interval was 188-360mm/72h. The median of future simulation was 353mm/72h, and 95% confidence interval was 252-517mm/72h. Figure 5 shows the relationship of the basin-averaged 72-hr rainfall and the peak discharge of the run-off analysis of past simulation for 3,000 cases and future simulation for 5,400 cases. This study employed different scenario cases for flood analysis using the discharges of 1/150 probability rainfall of 95% confidence interval at the Obihiro reference point along Tokachi River in both historical and future simulations. The simulation was performed for cases with maximum peak discharge around the median (Case 1), maximum peak discharge within 95% confidence interval (Case 2), and maximum basin-averaged 72-hr rainfall of 95% confidence interval (Case 3). However, existing flood control facility is taken into account actual flood analysis.

3.2 Calculation of hydraulic quantities of flood plain

Among the dikes in target urban area of Obihiro, we focused on one location, with maximum damage amount, and with dike failure in the calculated flood analysis in case of dike failure. Furthermore, we calculated hydraulic quantities, such as flood depth and flow velocity, that are prerequisites to estimate fatality. The flood analysis in this study is based on the integrated model that calculates water level with the one-dimensional unsteady flow, and flood flow tracking analysis with the two-dimensional unsteady flow. Flood volume from the river is calculated by side overflow formula of Kuriki et.al., which updated the front overflow formula of Honma[18].
These maps are based on the latest LP elevation data and has calculation resolution of 25m. Breaching width is calculated by relational expression of river width, indicated in Flood Assumption Area Map Manual[18]. In this model, it is assumed that the dikes start to breach when the water level reaches H.W.L. The breach width is calculated from river width by relational expression indicated in Flood Assumption Area Map Manual. The breach width is half of them for first hour and the whole of them after that.
Table 1 shows the contour maps of flooded area and flood depth as results of the flood analysis. In comparison with the cases of the past and future simulations, the expansion of flooded area increased by 1.58 times in Case 1, 1.32 times in Case 2, and 2.74 times in Case 3.
However, for the Case 3 of the past simulation, water depth did not reach the critical water level for breaching in the urban area of Obihiro. Therefore, Case 3 shows the result in the case of breaching at the other break point, and flood discharge is significantly lower than in other cases. That is the reason why the flooded area of the Case 3 in past simulation is smaller than other cases.

Table 1. Contour map of flooded area and flood depth per case.

<table>
<tr><th></th><th>Case 1: Maximum Peak Discharge Around Median</th><th>Case 2: Maximum Peak Discharge Within 95% Confidence interval</th><th>Case3: Maximum Rainfall of 95% Confidence Interval</th></tr>
<tr><td>Past Simulation</td><td>
</td><td></td><td></td></tr>
<tr><td>Flooded Area</td><td>600ha</td><td>600ha</td><td>230ha</td></tr>
<tr><td>Future Simulation</td><td>
</td><td></td><td></td></tr>
<tr><td>Flooded Area</td><td>950ha</td><td>790ha</td><td>630ha</td></tr>
<tr><td>Rate of Change</td><td>1.58times</td><td>1.32times</td><td>2.74times</td></tr>
</table>

4. FATALITY ESTIMATION

4.1 Outline of fatality estimation model

4.1.1 LIFESim model

The LIFESim model (Figure 6) estimates fatality, classifying danger based on flood depth, and then multiplying mortality per classification by population of flood area. The model assumes that if the victims are under the age of 65, they can evacuate vertically to the roof of the house or building. On the other hand, it's assumed that if the victims are over 65, they can evacuate vertically to the top floor of the house or building.

4.1.2 LIFEEva model

LIFEEva model (Figure 7) estimates fatality by mortality function derived from the flood damage data worldwide, classifying in 3 categories by flood depth, the product of flood depth and flow velocity (hereinafter called fluid force $v \cdot h$), flow velocity, and rise rate of water:

1. The breach zone (Zone 1): High flow velocities occur around the breach. House and building can collapse.
2. The zone with rapidly rising water (Zone 2): Due to the rapid rising of the water, people cannot evacuate shelter, higher floors of buildings, or higher places.
3. The remaining zone (Zone 3): In this zone, the flood conditions are more slow-onset, offering better possibilities to find shelter.

Compared to the LIFESim model, the LIFEEva model takes into consideration other factors such as the fluid force $v \cdot h$, flow velocity, and rise rate of water level are taken into consideration to calculate mortality, however, the age of victims is not taken into account. The following LIFEEva model formulas show how to calculate mortality per zone.

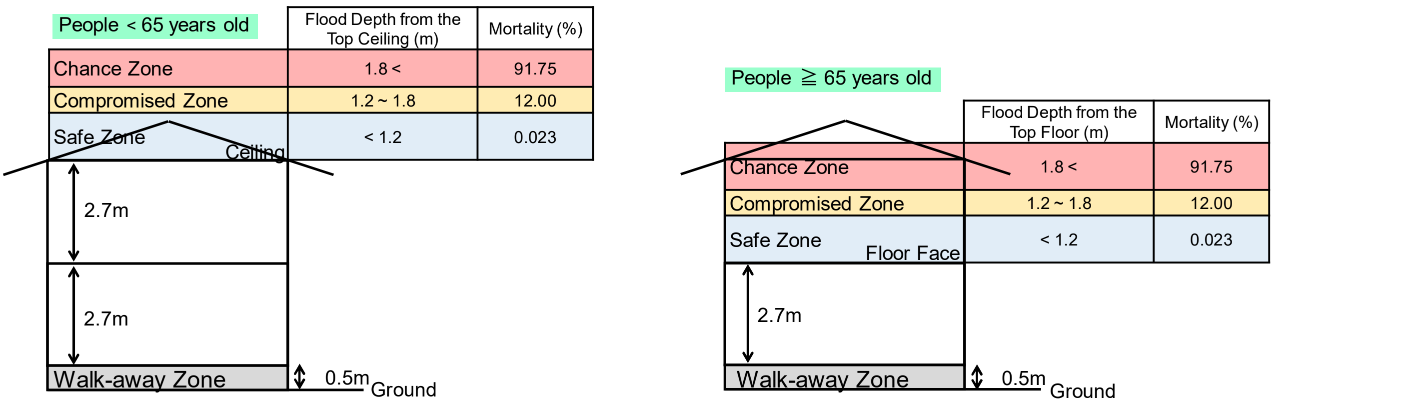
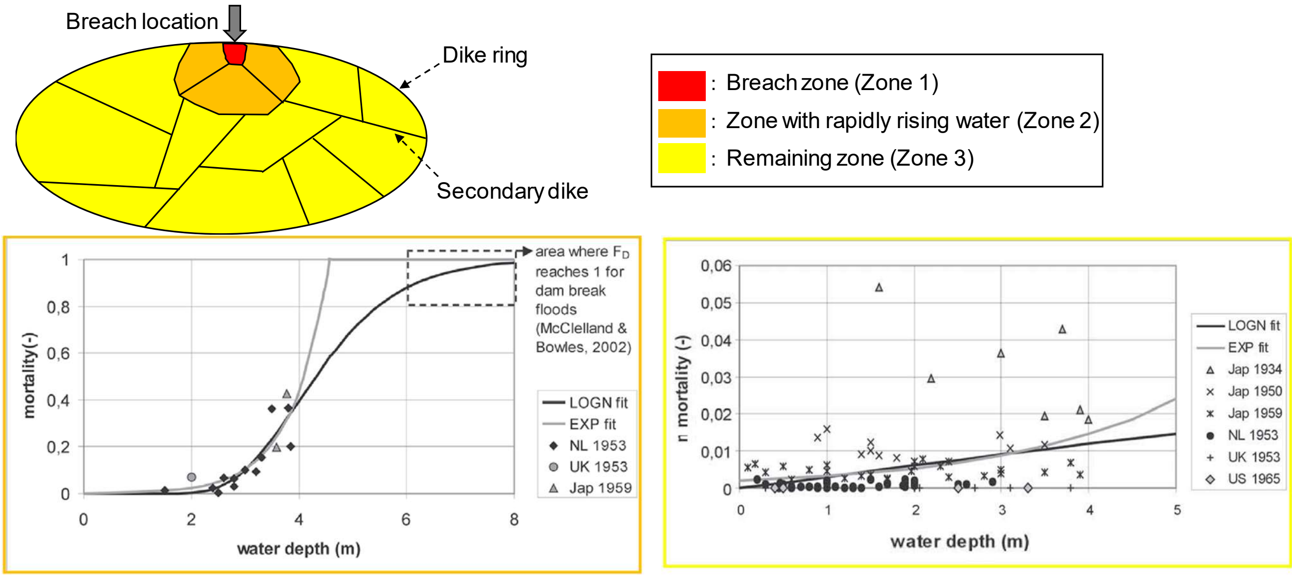


Figure 6. Outline of fatality estimation by LIFESim model (based on reference[9)11)12)]).



a) Mortality function of the Zone 2 b) Mortality function of the Zone 3

Figure 7. Outline of mortality estimation method by LIFEEva model[13].

<The Breach Zone: Zone 1>

$$v \cdot h \geq 7\ \mathrm{m}^2/\mathrm{s} \ \text{ and } \ v \geq 2\ \mathrm{m/s}$$
$$F_D(h) = 1 \tag{4}$$

<The Zone with Rapidly Rising Water: Zone 2>

$$(h \geq 2.1\mathrm{m} \ \text{ and } \ w \geq 0.5\ \mathrm{m/hr}) \text{ and } (v \cdot h < 7\ \mathrm{m}^2/\mathrm{s} \ \text{ or } \ v < 2\ \mathrm{m/s})$$
$$F_D = \Phi\left(\frac{\ln(h) - \mu}{\sigma}\right) \qquad \mu = 1.46, \sigma = 0.28 \tag{5}$$

<The Remaining Zone: Zone 3>

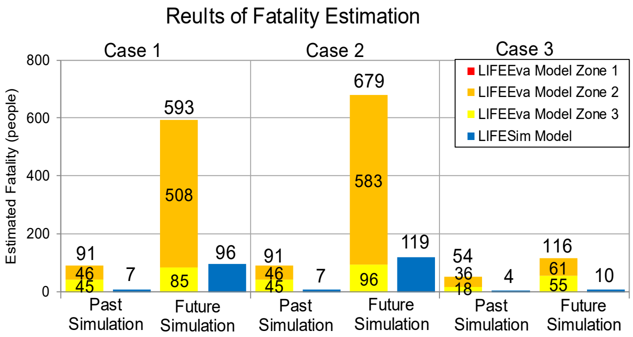
$$(w < 0.5\ \mathrm{m/hr} \text{ or } (w \geq 0.5\ \mathrm{m/hr} \text{ and } \ h < 2.1\mathrm{m})) \text{ and } (v \cdot h < 7\ \mathrm{m}^2/\mathrm{s} \ \text{ or } \ v < 2\ \mathrm{m/s})$$
$$F_D = \Phi\left(\frac{\ln(h) - \mu}{\sigma}\right) \qquad \mu = 7.6, \sigma = 2.75 \tag{6}$$

where, v: flow velocity (m/s), h: flood depth (m), w: rise rate of water (m/hr), F_D: mortality, Φ: cumulative probability density function of standard normal distribution, μ : average value of h , σ : standard deviation of h.

The Zone 1 is based on the assumption that an inhabitant dies when houses collapse according to collapse criteria of masonry, concrete and brick houses. The Zone 2 focuses on the rising rate of water since the rapid rise will cause the people in lower floors to be locked in their house, or there will be insufficient amount of time to evacuate to a higher place or a shelter. On the other hand, the Zone 3 has higher possibility to evacuate horizontally. Therefore, the curve of mortality function is less steep in relation to increasing flood depth, compared to the Zone 2.
In the Netherlands, there is an updated LIFEEva model by B. Maaskant[19]. However, we selected the Dutch-based LIFEEva model that is used for the national project.
In order to estimate the worst case, the evacuation rate is set to 0% for estimating fatality, and the source of population per age per mesh is National Census in 2016 (Ministry of Internal Affairs and Communication).

4.2 Results of fatality estimation

The results of comparison between LIFESim model and LIFEEva model are indicated in Figure 8. LIFESim model showed higher estimated fatality than LIFEEva model in every case. Estimated fatality of future climate simulation increased by 5.9 to 12.5 times compared to past simulation, depending on the model used.
Estimated fatality per zone by LIFEEva model (Figure 8) shows that there is no area categorized in the Zone 1, and majority is categorized in the Zone 2. Thus, the Zone 1 is classified by the collapse criteria of masonry, concrete and brick houses, and the boundary conditions of fluid force, $v \cdot h \geq 7\mathrm{m}^2/\mathrm{s}$ and $v \geq 2\mathrm{m/s}$. Existing research of the case in Japan by Sato et.al.[20] states that a wooden house collapses or outflows when fluid force $v^2 \cdot h$ exceeds $2.5\mathrm{m}^3/\mathrm{s}^2$. The collapse standard of LIFEEva model is set at higher boundary condition, therefore there is a possibility that the collapsed houses are not properly evaluated by LIFEEva model since majority of houses in Japan is made of wood (Figure 9).



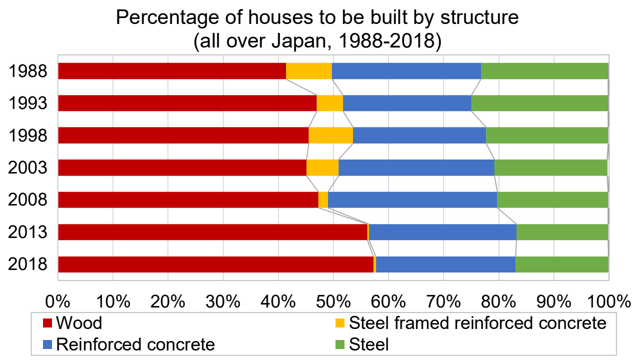
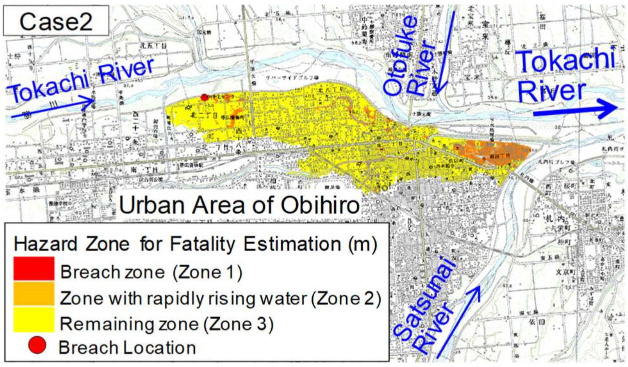


Figure 8 (left). Results of fatality estimation.
Figure 9 (right). Percentage of housing to be built by structure in Japan. (based on reference[21)])



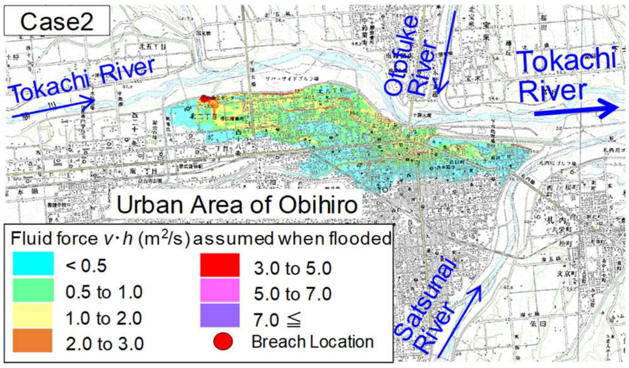


Figure 10 (left). Future simulation Case 2: Mortality zone map.
Figure 11 (right). Future simulation Case 2: Maximum fluid force $v \cdot h$ distribution.

The estimated fatality by LIFEEva model was the highest in future simulation Case 2, and its mortality area distribution map (Figure 10) shows that there is no area categorized in the Zone 1, indicated by fluid force $v \cdot h$ (Figure 11), a part of downstream under the block is categorized in the Zone 2, and most part of flooded area in the block is categorized in the Zone 3. The reason why the estimated fatality of the Zone 2 is higher than the Zone 3 is that the Zone 2 is about 1 order higher than the Zone 3 in terms of mortality at the same flood depth. The Zone 2 is considered to be a place where water rising rate increases due to flood flow from breaching point, which has been stored at downstream. LIFESim model does not estimate such a damage caused by rising rate of water, which made a big difference from the estimated fatality by LIFEEva model.

5. CONCLUSIONS

This study calculated the estimated fatality in the urban area of Obihiro in Tokachi River basin by applying both the LIFESim model and the LIFEEva model, compared the results of these models, and provided discussions, in order to examine the relevant risk assessment of climate change. Our result provides as follows:

1) Estimated fatality of future climate simulation increased by 5.9 to 12.5 times compared to past simulation, depending on a model used.
2) Estimated fatality by LIFEEva model was higher than LIFESim model, due to consideration of rising rate of water level.
3) It should be noted that damage by rapidly rising water has to be taken into account in the downstream area, where the urban area of Obihiro is located since floodwater is initially stored before the breaching occurs, then later causing the rapid increase of water level as it flows.

Based on the results, LIFEEva model needs to be improved to be able to apply to the features of Japan. For example, boundary conditions should be set according to the collapse standard for houses in existing domestic research, in order to properly evaluate areas of the Zone 1 by LIFEEva model. In addition, data needs to be collected from other basins with different features, to see if there are any differences in estimated fatality.

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