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DEFINITION AND MEASUREMENT OF A HOUSEHOLD'S DAMAGE COST CAUSED BY AN INCREASE IN STORM SURGE FREQUENCY DUE TO SEA LEVEL RISE

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Abstract

Most of previous studies on the problem of sea level rise focused on prediction of sea level rise and measurement of physical damage costs, but did not consider uncertainty and psychological damage in connection with storm surge disasters. Moreover, the relationship between a household's damage cost due to sea level rise and benefit from countermeasures against sea level rise was not clear in those studies. The objectives of this study are to define and measure a household's damage cost and benefit considering uncertainty by applying the concept of equivalent variation to the expected utility level of a household and to clarify this relationship.

KEYWORDS: *sea level rise, household's damage cost, storm surge disaster*

1. Introduction

Recently, global warming is recognized as the great international environment problem that is becoming increasingly serious. Global warming is caused by an increase of man-made greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), resulting from deforestation in order to improve the quality of urban life and from consumption of fossil fuel such as petroleum and coal in large quantities. If the average temperature on earth rises due to an increase of greenhouse gases, then water bodies expand and glaciers melt, and as a result the average sea level on earth may rise. The Intergovernmental Panel on Climate Change (IPCC) has estimated that, if the concentration of CO_2 in the atmosphere will be double the pre-industrial level, the average

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temperature will rise 2.5°C by the year 2025 and the sea level will rise 65 cm (30-110 cm) by the year 2100 (IPCC WG I, 1990).

Because the Japanese economy is highly dependent upon the coastal area, sea level rise may have great impacts on the Japanese economy (Ito *et al.*, 1993; Nakatsuji *et al.*, 1993; Kitajima *et al.*, 1993). Matsui and Tateishi (1992) showed that a land area of 850 km^2, a population of 2 million people, and 54 trillion yen worth of property are presently under the influence of the sea at high tide in the coastal areas of Japan. They also estimated that a sea level rise of 1 m may cause 2,400 km^2, 4.1 million people, and property worth 109 trillion yen to be affected by the sea, and at high tide 8,900 km^2, 15.42 million people, and 378 trillion yen of property may be lost.

Countermeasures against sea level rise are classified by IPCC into three kinds: evacuation, adaptation, and protection (IPCC WG III, 1990). The evacuation policy relocates people to new places in order to evade disasters, the adaptation policy eliminates damages if disasters occur, and the protection policy focuses on avoiding disasters. The last policy may be thought as the most effective among these policies to be implemented in Japan. The total cost of upgrading coastal defense systems is estimated to 2 trillion yen for the dikes within the jurisdiction of the Ministry of Transport (Negi, 1992), and 6 trillion yen within that of the Ministry of Construction (Mimura *et al.*, 1992).

Most of the previous studies on the problem of sea level rise, as mentioned above, focused on the prediction of sea level rise itself and the measurement of physical damage costs, but did not consider psychological damages due to increased anxiety for the risk of storm surge disasters. The objectives of this study are to define and measure the household's damage cost with respect to this problem, to estimate the household's benefits from different countermeasures considering uncertainty, and to clarify the relationship between the household's damage cost and benefit.

2. Definition of a Household's Damage Cost and Benefit

2.1 Probability Density Function of Sea Level

Although many researchers are studying prediction of sea level rise, it may be difficult to predict with certainty environmental changes like sea level rise in the future because the mechanisms of the CO_2 built-up process in the atmosphere and the ocean are not well understood. Thus, the sea level rise in the future should be treated as a probabilistic variable.

Assuming that the probability density of high sea level (f) is a function of the high sea level (H) and the increase in mean sea level (L) as shown in Fig.1, the probability density function in the future (f_1) is described as

$$f_1 = f[H, L], \tag{1}$$

where

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H, L]dLdH = 1.$$

However, practically the function $f[H, L]$ can not be estimated as mentioned above. We set the probability density function for the present conditions (f_0) as

$$f_0 = f[H, 0], \ (L = 0), \tag{2}$$

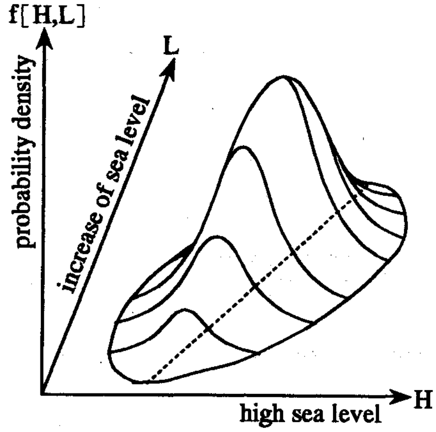

Figure 1. Probability density of high sea level considering sea level rise.

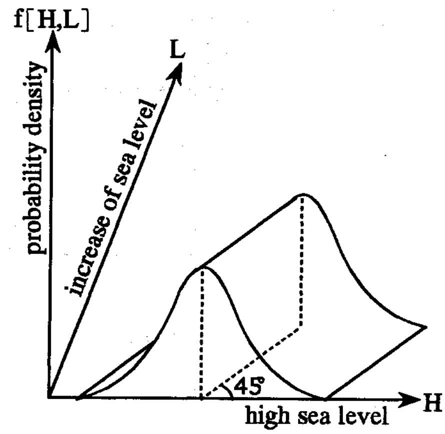

Figure 2. Probability density of high sea level assumed here.

where

$$\int_{-\infty}^{\infty} f[H,0]dH = 1,$$

and estimate the function $f[H,0]$ from observed data on high sea levels, and construct the function $f[H,L]$ by sliding the function $f[H,0]$ from $L = 0$ to L =(value estimated of the increase in mean sea level) along the 45° line in the $L - H$ space as shown in Fig.2.

2.2 Household's Utility Level

Although a household's utility level (U) must be defined practically as being a function of many types of socio-economic and individual conditions, we assume U to be a function of the income (Ω) and the damage cost (P), where P is determined by the high sea level (H) and the dike height (C), that is, $P = P[H,C]$ for simplicity. The household's utility function (U) is described by

$$U = U[H,\Omega,C], \tag{3}$$

and the utility level may change as the sea level changes as shown in Fig.3. The utility level decreases as high sea level increases. It decreases drastically beyond the boundary sea level (H_d) at which overflow occurs, and then it reaches a certain lowest level corresponding to death.

2.3 Household's Expected Utility Level

By using the household's utility function (U) and the probability density function of high sea level (f), the household's expected utility function (EU) can be defined as a function of the income (Ω) and the dike height (C);

$$EU[\Omega,C] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H,L]U[H,\Omega,C]dLdH, \tag{4}$$

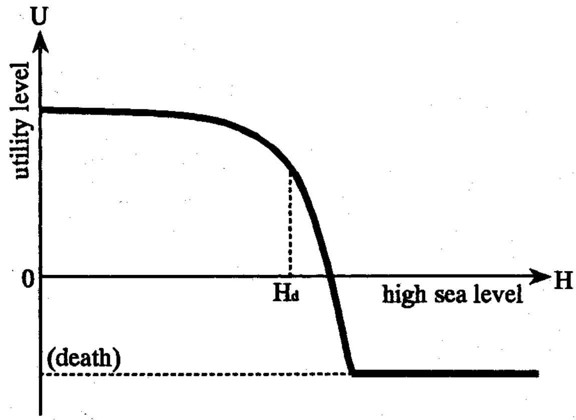

Figure 3. Household's utility level depending on high sea level.

which is the integral of the product $f \times U$ with respect to the high sea level (H) and the increase in mean sea level (L).

Now, we define three expected utility levels: level at the present conditions (without any countermeasures), level without any countermeasures in the future, and level with some countermeasures in the future.

a) Expected utility level at the present conditions: (EU_0^a)

$$EU_0[\Omega, C^a] = \int_{-\infty}^{\infty} f[H,0]U[H,\Omega,C^a]dH, \tag{5}$$

b) Expected utility level without any countermeasures in the future: (EU_1^a)

$$EU_1[\Omega, C^a] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H,L]U[H,\Omega,C^a]dLdH, \tag{6}$$

c) Expected utility level with some countermeasures in the future: (EU_1^b)

$$EU_1[\Omega, C^b] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H,L]U[H,\Omega,C^b]dLdH, \tag{7}$$

where superscripts (a) and (b) indicate, respectively, the case without and with countermeasures against sea level rise; subscripts (0) and (1) indicate, respectively, the case at present and in the future.

The difference ($C^b - C^a$) represents the up-grading level of the dike height as a countermeasure against sea level rise, and it decreases the probability of high sea level. Because the probability of high sea level in the future is greater than that at present, $EU_1^a < EU_0^a$. Concerning EU_1^b and EU_0^a, their relationship depends on the effect of the countermeasures; $EU_1^b > EU_0^a$ if the effect is great, or $EU_1^b < EU_0^a$ if the effect is small.

2.4 A Household's Damage Cost due to Sea Level Rise

By applying the concept of equivalent variation to the expected utility level of a household, we may define the household's damage cost due to sea level rise under uncertainty (Morisugi *et al.*, 1985a, 1985b, 1992, 1993). The damage cost can be the minimum compensation which household needs in the case without sea level rise (at present) while maintaining the welfare level (EU_1) in the case with sea level rise (in the future). Adopting this compensation strategy to obtain a fixed amount which does not depend on the sea level (Morisugi *et al.*, 1992) defines two kinds of household's damage costs as follows.

a) Household's damage cost without any countermeasures: (X)

$$EU_1[\Omega, C^{\mathrm{a}}] = EU_0[\Omega + X, C^{\mathrm{a}}], \tag{8}$$

b) Household's damage cost with some countermeasures: (Y)

$$EU_1[\Omega, C^{\mathrm{b}}] = EU_0[\Omega + Y, C^{\mathrm{a}}], \tag{9}$$

where X is negative because $EU_1^{\mathrm{a}} < EU_0^{\mathrm{a}}$; Y is positive in the case of $EU_1^{\mathrm{b}} > EU_0^{\mathrm{a}}$ or negative in the case of $EU_1^{\mathrm{b}} < EU_0^{\mathrm{a}}$; the conditions of $EU_1^{\mathrm{b}} > EU_0^{\mathrm{a}}$ or $EU_1^{\mathrm{b}} < EU_0^{\mathrm{a}}$ are discussed above; $X < Y$ because $EU_1^{\mathrm{a}} < EU_1^{\mathrm{b}}$.

2.5 A Household's Benefit from Countermeasures against Sea Level Rise

Similar to the definition of the household's damage cost, applying the concept of equivalent variation, we can define the household's benefit from countermeasures. The benefit is the minimum compensation which a household needs in the case without any countermeasures while maintaining the welfare level (EU_1^{b}) in the case with some countermeasures. The benefit (Z) is defined as

$$EU_1[\Omega, C^{\mathrm{b}}] = EU_1[\Omega + Z, C^{\mathrm{a}}], \tag{10}$$

where Z is positive because $EU_1^{\mathrm{a}} < EU_1^{\mathrm{b}}$.

2.6 Relationship between a Household's Damage Cost and Benefit

We adopt a linear function to describe the influence of the income (Ω) on the household's utility function (U):

$$U[H, \Omega, C] = U'[H, C] + v[H, C]\Omega. \tag{11}$$

Then, the expected utility level (EU) is also a linear function of the income (Ω):

$$\begin{aligned} EU[\Omega, C] &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H, L]U[H, \Omega, C]dLdH, \\ &= V[C]\Omega + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H, L]U'[H, C]dLdH, \end{aligned} \tag{12}$$

where

$$V[C] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f[H, L]v[H, C]dLdH.$$

By applying equation (12) in equations (8), (9) and (10), the household's damage cost without any countermeasures (X) and with some countermeasures (Y) and the household's benefit with countermeasures (Z) are described as following equations:

$$X = \frac{EU_1[\Omega, C^{\mathrm{a}}] - EU_0[\Omega, C^{\mathrm{a}}]}{V_0[C^{\mathrm{a}}]}, \tag{13}$$

$$Y = \frac{EU_1[\Omega, C^{\mathrm{b}}] - EU_0[\Omega, C^{\mathrm{a}}]}{V_0[C^{\mathrm{a}}]}, \tag{14}$$

$$Z = \frac{EU_1[\Omega, C^{\mathrm{b}}] - EU_1[\Omega, C^{\mathrm{a}}]}{V_1[C^{\mathrm{a}}]}. \tag{15}$$

From equations (13), (14), and (15), the difference ($Y-X$) can be derived yielding the following equation:

$$Y - X = \frac{V_0[C^{\mathrm{a}}]}{V_1[C^{\mathrm{a}}]} Z. \tag{16}$$

Equation (16) implies that the difference between the damage cost without any countermeasures (X) and that with some countermeasures (Y) are not always equal to the benefit of countermeasures (Z). This fact comes from the difference in measurement basis; that is, the values of (X) and (Y) are based on the conditions at present and derived by considering both the conditions at present and in the future, but the value of (Z) is based on the conditions in the future and derived from conditions in the future only.

3. Case Study

3.1 Fundamental Assumptions

In this case study, we try to measure the household's damage cost due to sea level rise and the household's benefit from countermeasures against sea level rise considering uncertainty by using the measurement method developed above. Although any area in Japan may experience a storm surge disaster, it is difficult to estimate the household's utility function and the probability density function of high sea level that are valid for each region of Japan. Here, we estimate these functions by using data from Ise Bay, and assume that the estimated functions can be applied all over Japan. Thus, we assume that Ise Bay is a representative region in Japan.

Now we introduce three assumptions:

a) the probability density function of high sea level (f) shown in Fig.2 is applicable, and three values (0.3 m, 0.5 m, 1.0 m) estimated for the increase in mean sea level is studied.
b) there are only two (ordinary and disastrous) conditions, and the boundary sea level (H_d) between them is 4.5 m.
c) the up-grading level of dike height (ΔC) as a countermeasure against sea level rise is equal to the increase in mean sea level.

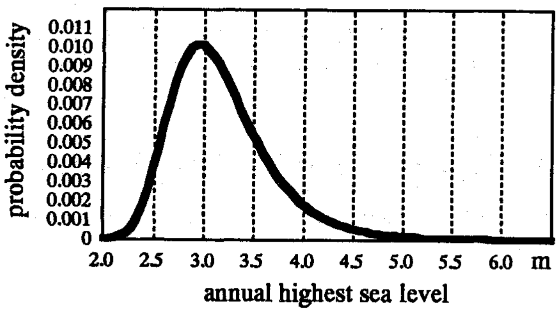

Figure 4. Estimated probability density function for high sea level.

3.2 Probability Density Function of Sea Level

Because the probability density function needed here is for the annual highest sea level, the probability density function for high sea level (f) is assumed to follow a first double-exponential distribution (Gumbel distribution) in the asymptotic distribution of extreme values:

$$f[H,L] = \omega J \exp[-J], \tag{17}$$

where

$$J = \exp[-\omega(H + L - \eta)],$$

$$\sigma^2 = \frac{\pi^2}{6\omega^2},$$

$$\mu = \eta + \frac{\gamma}{\omega}, \ (\gamma = 0.577),$$

and σ^2 is the variance; μ is the expectation; η is the mode.

We assumed $L = 0$, and got the values $\sigma^2 = 0.2136$ and $\mu = 3.0766$ by using data on the annual highest sea level in the Nagoya Port during 45 years (1949-93). The probability density function for high sea level is shown in Fig.4.

3.3 Household's Utility Function

The household's utility function (U) has been expressed in terms of the following linear function, and estimated by using household data derived from an interview survey designed within the framework of the contingent valuation method (Morisugi and Iwase, 1985):

$$U_j = \alpha_1\Omega + \alpha_2 LA + \alpha_3 FS + \alpha_4 CT + \alpha_5 PS + \alpha_6 SG + \alpha_7 FL + \alpha_8, \tag{18}$$

where Ω is the income; LA is the land area of residence; FS is the floor space of residence; CT is the commuting time; PS is the convenience of public service ($PS = 1$: convenient or $PS = 0$: not convenient); SG is the availability of sewerage system and manufactured gas service ($SG = 1$: equipped or $SG = 0$: not equipped); FL is an index for flooding by storm surge ($FL = 1$: flood or $FL = 0$: not flood); subscript (j) indicates the condition ($j = o$: ordinary or $j = d$: disastrous); $\alpha_1 = 0.054$; $\alpha_2 = 0.029$; $\alpha_3 = 0.048$; $\alpha_4 = -0.077$; $\alpha_5 = 2.417$; $\alpha_6 = 1.434$; $\alpha_7 = -30.058$; $\alpha_8 = 22.55$. Now the seventh term ($\alpha_7 FL$) of equation (18) is introduced in order to consider the psychological damage by flood directly (or sea level rise indirectly) in the household's utility.

In this case, the difference between the damage cost without any countermeasures (X) and that with some countermeasures (Y) is equal to the benefit by countermeasures (Z) because $V_0[C^{a}]$ and $V_1[C^{a}]$ in equation (16) are equal to α_1; that is, $Y - X = Z$ because $V_0[C^{a}] = V_1[C^{a}] = \alpha_1$.

3.4 Measurement of a Household's Damage Cost and Benefit

By applying equation (18) to equation (2), and then to equations (13), (14), and (15), the following equations are derived:

$$X = \frac{\alpha_7}{\alpha_1}(F - E), \tag{19}$$

$$Y = \frac{\alpha_7}{\alpha_1}(G - E), \tag{20}$$

$$Z = \frac{\alpha_7}{\alpha_1}(G - F), \tag{21}$$

where

$$E = \int_{Hd}^{\infty} f[H, 0]dH, \tag{22}$$

$$F = \int_{Hd}^{\infty} \int_{-\infty}^{\infty} f[H, L]dLdH, \tag{23}$$

$$G = \int_{Hd+\Delta C}^{\infty} \int_{-\infty}^{\infty} f[H, L]dLdH, \tag{24}$$

and E, F, and G mean, respectively, the probability of storm surge at present, for the case without any countermeasures in the future, and for the case with some countermeasures in the future, as indicated in Table 1. Now, as mentioned above, $Y - X = Z$ from equations (19), (20), and (21).

The annual damage cost and benefit of a household is indicated in Table 2. By applying these values to all households who live in an area that may experience a storm surge disaster, the total annual damage cost and benefit in Japan can be derived. The number of such households has been estimated by Mimura *et al.* (1992); 4.10, 4.53, and 5.14 million households will be influenced by a disaster, respectively, in the case of 0.3 m, 0.5 m, and 1.0 m sea level rise. Tab.3 indicates values on the total annual damage cost and benefit. By using an annual interest rate of 5%, the damage cost and benefit calculated in the stock values are, respectively, about 7 ($\simeq 0.360/0.05$) and 10 ($\simeq 0.501/0.05$) trillion yen in the case with a 0.5-m sea level rise. This cost is almost the same as the cost of 3.5-m up-grading of the dike height all over Japan, where the cost means, as mentioned before, 6 trillion yen within the jurisdiction of the Ministry of Construction. Thus, the benefit of countermeasures may exceed the project costs.

Table 1. Probabibility of storm surge.

Sea Level Rise	E	F	G
0.0 m	0.0123	-	-
0.3 m	-	0.0192	0.0084
0.5 m	-	0.0266	0.0067
1.0 m	-	0.0644	0.0042

Table 2. Household's damage cost and benefit.

Sea Level Rise	Damage Cost without Countermeasures	Damage Cost with Countermeasures	Benefit by Countermeasures
0.3 m	38.352	-21.746	60.098
0.5 m	79.497	-31.136	110.633
1.0 m	289.872	-45.011	334.883

[unit: thousand yen per year]

Table 3. Total damage cost and benefit in Japan

Sea Level Rise	Damage Cost without Countermeasures	Damage Cost with Countermeasures	Benefit by Countermeasures
0.3 m	157.242	-89.158	246.400
0.5 m	360.123	-140.104	501.167
1.0 m	1,489.943	-231.355	1,721.298

[unit: billion yen per year]

4. Summary and Conclusions

In order to consider uncertainty concerning the increase in storm surge frequency when estimating a household's damage cost due to sea level rise, this study has introduced increase of sea level as a variable in the probability density function of high sea level, and defined a household's expected utility level by using a household's utility level including anxiety caused by sea level rise and the probability of high sea level. Then, by adopting the concept of equivalent variation to the expected utility, the household's damage cost by sea level rise and the benefit by countermeasures against sea level rise have been defined with respect to uncertainty.

The relationship between the household's damage cost and benefit has been clarified; that is, the difference between the damage cost without any countermeasures and that with some countermeasures is not always equal to the benefit by countermeasures. This relationship depends on the form of the household's utility function. If the marginal utility on the income is constant as in this case study, the difference of these damage costs is equal to the benefit.

As a result of the case study, where the utility function and the probability density function are estimated by using data from Ise Bay, 0.5 m of sea level rise may bring annually about 360 billion yen of damage costs in the case without any countermeasures, and countermeasures against sea level rise may derive annually about 500 billion yen of benefit all over Japan. By using an annual interest rate of 5%, the damage cost and benefit are, respectively, about 7 and 10 trillion yen in the stock value, where the benefit must exceed the project cost of dike up-grading according to a 0.5-m sea level rise.

On measuring the damage cost and the benefit, this study has adopted a method which needs to directly estimate the household's utility function. There should be other methods, for example, which can measure the benefit by using the consumer surplus model constructed by developing the benefit definition equation in this study within the framework of general equilibrium theory (Ohno, 1992). The damage cost and the benefit measured by this consumer surplus model do not only include direct effects but also any repercussion effects.

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