Geographically Weighted Regression Analysis Applied to the Establishment of Paddy Field Flooding Loss Functions

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***Abstract*—**Disasters due to typhoons and heavy rainfall occur frequently in Taiwan. With the increase of social and economic development density, flood damages are becoming more and more serious. Flood risk management has thus turned into a very important task. Flood damage assessment is the basis of flood risk management. The disaster damage estimation model is often divided into residential areas, industrial and commercial areas, agricultural areas and public facilities. Previous studies have mostly focused on residential, industrial and commercial areas. Agricultural losses are due to a large number of impact factors, and the relevant literature is insufficient.

The most common methods are the loss curves for unit area and the flood depth loss curves method. Although the loss curves for unit area method is relatively simple, the differences in loss caused by various flooding depths are not considered. The flooding depth loss curve method often needs to be established through questionnaires. However, questionnaire surveys have to consume lots of manpower and material resources. Both the two methods above do not take the growth period of crops into consideration.

When disasters occur in different growth periods of crops, the losses caused by the same flooding depth are different due to the various flooding tolerances of crops in each growth period. Due to the hydrological and geographical factors, such as climate, the growth period of rice transplanting is different due to dissimilar climatic conditions. The complexity of establishing a flooding loss curve for paddy field is thus obvious.

In addition, in case the analysis of the flooding loss data is based on the traditional global regression analysis approach, there usually exists a spatial autocorrelation of the residual term with no consideration of spatial variation. This result violates the assumption of linear regression. In view of this, this study is expected to use paddy field as the research object.

At first, paddy field loss factors considered in each literature are reviewed and studied. Relevant domestic factors are also collected and it then to establish a paddy field flooding loss estimation model, and then use the geographically weighted regression model for spatial analysis and spatial grouping comparison. The selection of the research site is to consider large-scale historical disaster events. The event is selected for analysis and assessment of the disaster area o of Typhoon Morakot in Kaohsiung City in 2008.

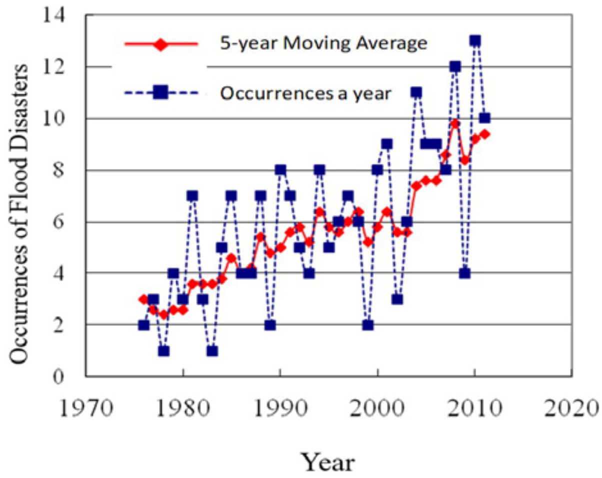
Keywords—Paddy field flooding loss function, Paddy field flooding loss curves for growth period, Geographically weighted regression analysis

I. INTRODUCTION

Due to global climate change and other factors in recent years, flooding disasters occur frequently and have been resulting in substantial economic losses, especially at the metropolitan area. According to statistics from the Ministry of the Interior in Taiwan, there were 270 natural disasters such as typhoons, floods and heavy rains between 1976 and 2010, with an average of 5.09 times per year (National Fire Agency, Ministry of Interior, 2011), making industry and commerce, housing, agriculture, fisheries, water conservancy, accommodation, transportation, electricity, telecommunications and other facilities as well as economic activities hit hard and also caused many casualties. In order to understand the flooding disaster situation in Taiwan, this study collects and organizes the data from the Fire Department of the Ministry of the Interior as shown in Figure 1, with the five-year moving average method. Figure 1 shows the occurrences of the average annual flood disaster in Taiwan from 1976 to 2011. There is an obvious growing trend in Figure 1. Due to the incessant disasters and serious economic losses in Taiwan in recent years, the risk management of floods has been playing a very important role in flood prevention.

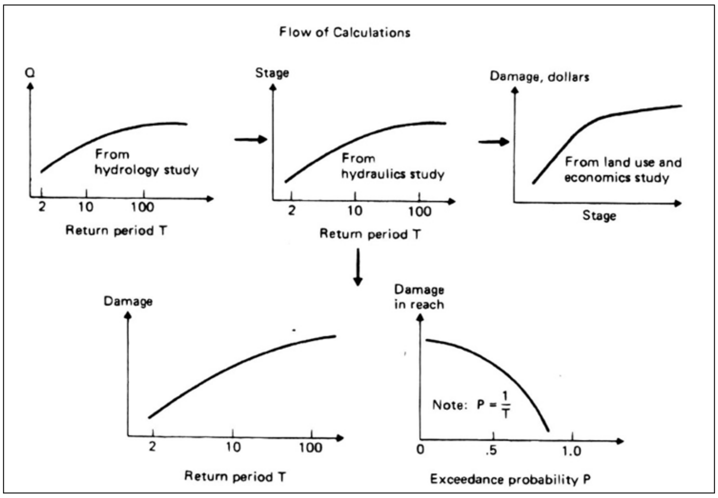
Grigg (1985) considers that a complete flood control system should include hydrological, hydraulic and damage assessment models (as shown in Figure 2). Hydrological models use meteorological and hydrological data with terrain and surface coverage at the area of interest to estimate different scenarios of various recurrence intervals (Fig. 2-a). The flooding coverage and flooding depth are then estimated by the hydraulic model (Fig. 2-b). Finally, the regional disaster assessment model is used to estimate the disasters of various scale events (Figure 2-c, d). After the analysis described above conducted on a certain area, the damage-frequency curves of the area can be established (shown in Figure 2-e). In case the damage-frequency curve is integrated, the expected annual damages (EAD) can be obtained and usually is used as a reference for decision-making with regional flood prevention planning. In order to effectively assess the risk of natural disasters, it is necessary to reasonably estimate regional losses at various disaster levels. The development of hydrological and hydraulic modeling in Taiwan is quite sound. The disaster assessment models have to express in terms of land use, social economy and facility form in various regions of a country. Therefore, the way in which the damage assessment model is established needs to consider the characteristics of the area of interest. The damage assessment model splits land use types into residential areas, industrial and commercial areas, agricultural areas and public facilities according to the differences in flooding potential. Since residential areas and industrial and commercial areas are closely related to residents, relevant basic information (such as socio-economic survey data) is relatively complete, the previous researches are mostly based on residential areas as well as industrial and commercial areas (TVA, 1969; FIA, 1970; Grigg & Helweg, 1975; Smith, 1994; Zhang et al., 2003; Gissing & Blong, 2004; Kang, 2005; Su, et al., 2005; Shaw, et al., 2007; Li, et al., 2008; Li & Yang, 2011). Losses in agricultural area have more influential factors than other sectors, and the related literature is thus inadequate. The assessment methods frequently adopted are the unit area loss curve method and the flooding depth loss curve method (Chen, 2003; Liu et al., 2009; Li & Liu, 2010; National Chiao Tung University, 2013). Although the unit area loss curve method is relatively simple, it seems not to consider the differences in damage caused by flooding depth. On the other hand, the flooding depth loss curve method (Chen, 1981; Ministry of Economic Affairs, Water Resources Agency, 2007) often needs to be established through questionnaires. However, the questionnaire survey method has to consume plenty of manpower and material resources. Both the above two methods do not take the various growth stages of crops into consideration. When disasters occur in different growth stages of the crops, the losses caused by the same flooding depth are different due to the different flooding tolerances of the crops at each growth stage.

This study is to use paddy rice as the research object. At first, through literature review, the factors for paddy rice loss considered are investigated. It is then to collect relevant factors in Taiwan and establish a paddy rice flooding loss estimation model. Spatially weighted regression model is then adopted for spatial analysis and space grouping comparison. The selection of the study site is to consider large-scale historical disaster events. It is to analyze and evaluate the disaster area at Kaohsiung area in which is more severely affected by Typhoon Morakot in 2009. The results of this study can be used as references for agricultural agencies in the flood prevention planning.



Note: Data from National Fire Agency, Ministry of Interior (2011) and complied by this study.

Fig.1. Statistics of flood disaster events in Taiwan from 1976 to 2010



Note: Grigg (1985)

Fig. 2. Framework for a complete flood Assessment system

There are two ways to establish the flooding depth loss curve method (Kang et al., 2005). One is established through the flood damage field questionnaire investigation after the disaster events (TVA, 1969; FIA, 1970; Grigg & Helweg, 1975; Smith et al., 1994); the other is synthetic curve approach (Chang, 2000; Chang & Su, 2001; Kang et al., 2005). The questionnaire approach (TVA, 1969; FIA, 1970; Grigg &

Helweg, 1975; Smith et al., 1994; Su et al., 2005) is to investigate the flood damage data after the disaster event, and then statistical regression is applied for the analysis. The analysis methods generally have the following two approaches: (1) Regression analysis directly from the original questionnaire survey data: the original questionnaire survey data are plotted on the flooding depth-loss map, and then the data points are subjected to regression analysis. The data points of this method are usually quite scattered spatially (Figure 2-15, 2-16). Sometimes the regression analysis is imposed to establish the flood depth loss curve, and the result is quite unacceptable, and it cannot even pass the statistical tests (Gissing & Blong, 2004). (2) Regression analysis after grouping is performed according to the flooding depth. In view of the direct regression analysis method from the original questionnaire survey data, they may not be able to pass statistical tests due to the scattered distribution of the original data. The flooding depth ranges are grouped, and the median, mean or quartile (25%, 50%, 75%) values of the flooding losses of each group were taken for regression analysis. (Taipei Municipal Government Works Bureau Maintenance Engineering Office, 2004; Ministry of Economic Affairs, Water Resources Bureau, 2001; Kang, 2005; Zhang, 2008). Because this method is to group the original data, and then take the median, mean or quartile of flooding loss of each group, the number of data points is less than the direct regression analysis method of the original data. This then leads to a higher coefficient of correlation (R). The regression line thus generated is the median, mean or quartile regression result of flooding loss of each group. It can be seen that the trends of each group for the median, mean or quartile regression of the flooding losses. The limitation of such use of grouping is that the variability of the original data cannot be explained. The method of establishing the flooding depth loss curve by questionnaire approach can thorough be divided into two types: direct regression analysis and grouping regression analysis. However, both methods need field questionnaire investigation followed after flood event. They both need questionnaire investigation data to establish the flooding depth loss curve, which is the limitation of the application of the questionnaire approach.

The synthetic curve approach collects relevant data on property items, possession rates, and placement heights for each household in floodplains of interest, and also investigates the possible losses caused by flooding of each property object to estimate the flooding loss at each depth. The synthetic curve approach (Smith, 1994; Zhang, 2000; Zhang & Su, 2001; Su et al., 2005) is to simulate the possible losses caused by flooding to construct flooding water depth-loss curve (Smith, 1994; USACE, 1996; Zhang, 2000; Zhang & Su, 2001; Dutta et al., 2003; Kang et al., 2005; Su et al., 2005). Since the concept of this approach is to investigate property items and assess the value of the damage that may be caused by flooding, some scholars refer to this estimated loss value as possible flood damage (Smith, 1994).

Although questionnaire approach and synthetic curve approach are different in the way of establishing the curves, the common concept for the two approaches is to assume that flooding loss of a household unit is a function of the flooding depth. It was found that flooding damage investigation and related researches usually give small number of data about high flooding depths, and it is then difficult to establish the flooding depth loss curve of a complete depth range. The analysis results therefore could not be applied to the events of high recurrence interval. By the way, the cost of manpower, material resources and time required for the field survey of the questionnaires are high. In view of the above, this study follows the concept of synthetic curve approach and uses paddy rice as the research object to establish the flooding water depth-loss curve with consideration of growth stage.

The flooding depth loss curve method with empirical approaches has not considered the loss caused by flood flow rate, flooding duration, sediment deposition carried by floods and other factors, so some scholars have proposed that other flood damage impact factors should be considered, such as flood early-warning, flooding duration and flood velocity. It is recommended to use the flood depth-loss curve as a basis to perform weighted correction of the estimated flooding loss (McBean et al., 1988). The factors currently considered by scholars in constructing the flooding loss function in agriculture can be divided into flooding depth, duration, velocity, deposit and salinity (as shown in Table 1).

Because flooding in Taiwan is mostly caused by inland water, its damage situation is less affected by flow velocity, deposit and salinity. Relatively speaking, the flooding depth and duration have a greater impact on crops. The data of flooding duration are not easy to obtained, so they are not to be considered in this study. In addition, the growth stage of crops is also an important factor. Most of the literatures are describing the season of the crops analyzed, rather than discussing the differences in the flooding loss of the same crop at different times. When flood disasters occur in different growing stages of crops, the losses caused by the same flooding depth are different due to the various flooding tolerances of crops in each stage. Due to the hydrological and geographical factors, the growth period of paddy rice transplanting is different due to distinctive climatic conditions, and thus causing high complexity in establishing flooding loss assessment model for paddy rice

In the crop classification of the loss estimation model in agriculture, some of the researches analyzed the crops in a comprehensive way, and some analyzed the differences separately for the losses of the crops. The Water Resources Planning and Research Institute (2007) used the results of the flood analysis of the Erlin Creek Drainage System in Changhua County to match the field investigation flooding losses. The study split the losses into crop losses, facility and industrial-commercial losses, losses of aquaculture fishing ponds, and losses of public facilities. Crop losses include paddy fields and upland fields. The flooding loss curves differ due to different crops. Dutta et al. (2003) used crop classification of census data to classify crops into eight categories: beans, Chinese cabbage, dried crop, melons, paddy, vegetable with root, sweet potato, and green leave vegetable. The relationship between the depth of flooding and damage percentage under the three flooding depths of 0~0.5m, 0.5-1m and >1m. National Chiao Tung University (2013) proposed the damage area-flooding loss curve for rice, fruit trees, corn, sweet potatoes and stem vegetable due to the relationship between damage area and amount of damage. Since paddy rice is an important crop in Taiwan and the proportion of the area is quite high, this study selected paddy rice as the research object.

In the establishment of the model, if the damage data analysis is based on the traditional global regression analysis method, the spatial autocorrelation of the residual term often exists because the spatial variation is not considered. This result violates the assumption of linear regression. This study intends to establish a model with a geographically weighted regression model, and it is necessary to conduct spatial group comparison.

Tab.1. Influential factors for flooding losses in agriculture

Depth	Blanc et al. (2008); Brémond (2011); CA30 (2009); Deleuze et al. (1991); Devaux-Ros (2000); Dunderdale and Morris (1997a); Du Plessis and Viljoen (1997); Dutta et al. (2003); Erdlenbruch et al. (2007); Förster et al. (2008); Goulter and Morgan (1983); Hoes and Schuurmans (2006); Jonkman et al. (2008); Lacewell and Eidman (1972); Lacewell et al. (2006); McDonald (1970); Morris and Hess (1988); Penning-Rowsell et al. (2005); SIEE et al. (2003); USACE (1985)
Duration	Agenais (2010); Brémond (2011); CA30 (2009); Consuegra Zammit (1992); Deleuze et al. (1991); Du Plessis and Viljoen (1997); Duthion (1982); Dutta et al. (2003); Förster et al. (2008); Goulter and Morgan (1983); Morris and Hess (1988); Penning-Rowsell et al. (2005); Pierson et al. (1994); Poirée and Ollier (1973); USACE (1985)
Velocity	Agenais (2010); Brémond (2011); CA30 (2009); Devaux-Ros (2000); SIEE et al. (2003); USACE (1985)
Deposit	Pierson et al. (1994); USACE (1985)
Salinity	Agenais (2010)

Note: The table is compiled by this study and part of the content is except from Bremond et al. (2013).

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II. THE PURPOSE OF THE STUDY

This study uses paddy rice as the research object. The paper reviews the rice loss factors in each literature, collects the relevant domestic factors, establishes the rice flood loss estimation model, and then uses the geographically weighted regression model to carry out spatial analysis and comparison. The selection of the study area is to consider the place with a large-scale historical disaster event. The flooding event of Typhoon Morakot in Kaohsiung City in 2008 was selected for analysis and assessment.

III. RESEARCH FRAMEWORK

This study takes the disaster-stricken area of Typhoon Morakot in Kaohsiung City in 2008 as the research area. The research framework is shown in Figure 3. First, it is to collect and review relevant literatures, and analyze the flooding loss patterns and factors of paddy rice. It is then to assemble flooding data for the Kaohsiung area of Typhoon Morakot event in 2008, including natural disaster relief data, cadastral maps and flooding simulation maps of Typhoon Morakot. After correlation (JOIN) analysis for the natural disaster relief data and the cadastral map is performed, the natural disaster relief distribution map can be then obtained. The overlay analysis of the natural disaster relief distribution map layer and the flooding simulation map can be adopted to derive the flooding depth and loss data of each disaster point. Based on this data, a paddy rice flood loss estimation model is established, and then a spatially weighted regression model is used for spatial analysis. Finally, the results are investigated and discussed.

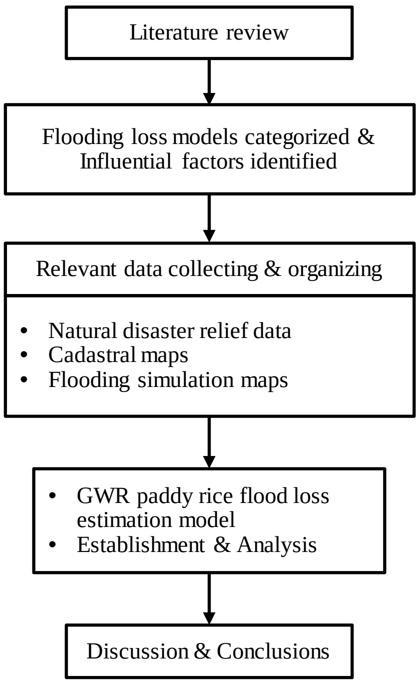

Fig. 3. Framework for a complete flood assessment system

IV. METHODOLOGY

This study reviews the literature, compares the flooding loss factors for paddy rice. It is then to collect relevant factors in Taiwan and establish the model for estimating the flooding loss for paddy rice. Spatial analysis with a geographically weighted regression model is conducted with the flooding loss model established. The relevant implementation framework is as follows:

(1) Collection of flooding losses and related data

A. Collection of simulation maps for flooding events

Flooding simulation maps for flooding events in the study areas were collected. This study takes flood events brought by Typhoon Morakot in Kaohsiung. Overlay analysis is performing by combining the verified flooding simulation maps and the cadastral maps together to scrutinize and identify the flooding depth of each cadastral number as the basis for the model construction.

B. Collecting and organizing of disaster data in agriculture

In addition to the annual report of the Council of Agriculture in Taiwan, this study also collects the natural disaster relief data. The data fields of the relief data include: location, land number, area, crop variety, approved area, approved damage rate, approved rescue unit value and relief amount (as shown in Table 2). The relief data are then joined with the cadastral maps as a natural disaster relief layer (as shown in Figures 4 to 5). The data joined are of a higher resolution and can be used as the basis for data analysis.

Tab.2. Examples of natural disaster relief data

Year	County	District	Section	Subsection	Land No.	Area (ha)	Loss (10^3NY$)
98	屏東縣	高樹鄉	高樹段	0	1410007	0.31	9.3
98	屏東縣	高樹鄉	大路關段	舊大路關小段	1200002	0.28	8.4
98	屏東縣	高樹鄉	大路關段	舊大路關小段	1200003	0.03	0.9
98	屏東縣	高樹鄉	大路關段	舊大路關小段	1180099	0.17	5.1
98	屏東縣	高樹鄉	田子段	0	4120001	0.04	1.2
98	屏東縣	高樹鄉	田子段	0	4130016	0.33	9.9
98	屏東縣	高樹鄉	大路關段	舊大路關小段	3180000	0.25	7.5
98	屏東縣	高樹鄉	舊寮段	0	1491452	0.34	10.2

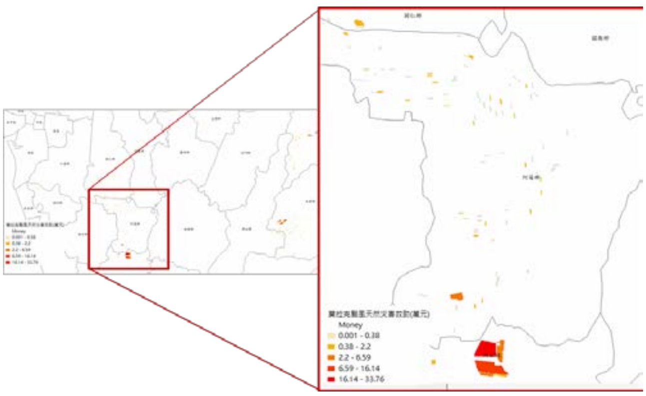

Figure 4: Paddy rice relief distribution for natural disaster by Typhoon Morakot

Data analysis of geographically weighted regression model

After the flooding depth loss curves for the study area are established, the flooding loss function is obtained by the global regression analysis method- Ordinary Least Squares approach(OLS). This study refers to the model of relevant literature and selects the linear model. The model is as follows: :

$$y = \beta_0 + \beta_1 x_1 + \ldots + \beta_n x_n + \varepsilon \quad (1)$$

y in Equation (1) is flooding loss (in unit of NT$). x_i's are independent variables, in which i=1 for flooding depth (cm), and i>1 for the factors identified from relevant researches. β_0, β_1,..., β_n are coefficients of OLS regression and ε is residual.

After the regression model is established, the Moran's I value is used to detect whether there is spatial autocorrelation in the residual term. The method of detection is: it is positive correlation if the Moran's I value is greater than 0. The larger the value, the greater the correlation of the spatial distribution. It is then shown that there is an obvious aggregate distribution in space. On the other hand, if the Moran's I value is less than 0, it is correlated in a negative way. The smaller the value, the smaller the spatial distribution correlation. Smaller values mean that the spatial distribution appears to be randomly distributed (Chen, 2001).

If there is spatial autocorrelation in the residual term, the geographic weighted regression model (GWR) (Brunsdon et al., 1996, 1998a, 1998b, Fotheringham et al., 1996, 1997a, 1997b, 1998, 2000, 2002, Platt, 2004) can be used for correction. Equation (1) is then modified as follows:

$$Y_i = \beta_0(u_i, v_i) + \beta_1(u_i, v_i) \cdot X_1 + \ldots + \beta_n(u_i, v_i) \cdot X_n + \varepsilon_i \quad (2)$$

Y_i is the value of flooding loss taken natural logarithm at location i. X_i's are independent variables, in which i=1 for reciprocal of flooding depth and i>1 for the factors identified from relevant researches as in Equation (1). (u_i, v_i) is the coordinates for location i. $\beta_i(u_i, v_i)$'s are coefficients of OLS regression and ε_i's are residuals.

In general, the estimation of the mode parameters is based on the OLS approach, and the parameters of the linear regression model can be obtained by the following equation:

$$\beta = (X^T X)^{-1} X^T Y \quad (3)$$

In the GWR mode, the regression coefficients of each location can be derived by the following Equation (4):

$$\boldsymbol{\beta} = (\mathbf{X}^T \mathbf{W} \mathbf{X})^{-1} \mathbf{X}^T \mathbf{W} \mathbf{Y} \quad (4)$$

X is the matrix ($n \times 1$) of the independent observations, and it is

$$\mathbf{X} = \begin{bmatrix} x_1(u_1, v_1) \\ x_1(u_2, v_2) \\ \\ x_1(u_n, v_n) \\ \end{bmatrix}$$

$\boldsymbol{\beta}$ is the matrix ($n \times 2$) of the coefficients of regression, and it is

$$\boldsymbol{\beta} = \begin{bmatrix} \beta_0(u_1, v_1) & \beta_1(u_1, v_1) \\ \beta_0(u_2, v_2) & \beta_1(u_2, v_2) \\ . & . \\ . & . \\ \beta_0(u_n, v_n) & \beta_1(u_n, v_n) \end{bmatrix}.$$

$\boldsymbol{W}$ is the matrix ($n \times n$) of spatially weighting coefficients, and it is

$$\boldsymbol{W} = \begin{bmatrix} w_{i1}(u_i, v_i) & 0 & ... & ... & 0 \\ 0 & w_{i2}(u_2, v_2) & ... & ... & 0 \\ . & . & & & . \\ . & . & & & . \\ 0 & 0 & ... & ... & w_{in}(u_n, v_n) \end{bmatrix}.$$

The weighting for each observation data is

$$w_{ij}(u_i, v_i) = \exp(-d_{ij} / h)^2 \quad (5)$$

d_{ij} is the distance between observation locations i and j , and h is a constant value for bandwidth.

The results of the GWR parameter estimation can explain the change of the region. Through the establishment of this model, the problem that the parameters are constant in the region may be corrected. If the regression coefficients are significantly varied spatially, then it is to observe what factors are causing the spatial unsteady state. At the final stage, the factors causing the spatial unsteady state are included in the global regression analysis to correct the results of the global regression analysis.

V. Results and Discussion

When flooding disasters occur in different growing seasons of crops, the losses caused by the same flooding depth are different due to the various flooding tolerances of crops in each growth stage. Due to the hydrological and geographical factors, the growing season of paddy rice is different due to different climatic conditions over the world. It is obvious that complexity comes for the establishment of a flooding loss model for paddy rice.

The predicted variable selected in this study is the amount of flooding loss, the independent variables are the flooding area and the flooding depth. The global regression analysis shows that the area flooded is a significant factor, and the influence of flooding depth on flooding loss is not significant. This result is consistent with the conclusions obtained during the expert interview. In the interview of the expert, the study found that with the roots of the herbaceous plants being flooded for more than 2 hours, the herbaceous plants are almost completely impaired. It is concluded that the inundation or flooding duration for herbaceous plants is more important when compared with the depth of flooding.

In statistics, Moran's I is a measure of spatial autocorrelation. Spatial autocorrelation is characterized by a correlation in a signal or an observation among nearby locations in space. Spatial autocorrelation is more complex than one-dimensional autocorrelation because spatial correlation is multi-dimensional (i.e. 2 or 3 dimensions of space) and multi-directional.

In this study, it is found that the regression coefficient values have spatial autocorrelation with Moran's I measure. Therefore, the geographically weighted regression model not only increases the model coefficient of determination (R2) from 0.867 to 0.989, but also improves the problem of the residual from global regression model on spatial autocorrelation.

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