Establishing flood damage functions for agricultural crops using estimated inundation depth and flood disaster statistics in data-scarce regions

Nhu Y Nguyen¹, Yutaka Ichikawa² and Hiroshi Ishidaira¹
¹Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Japan
²Graduate School of Engineering, Kyoto University, Japan

Abstract:
Flood damage functions form the core of flood risk assessment. This study proposes a method for establishing flood damage functions for agricultural crops in data-scarce regions. The method assumes that the flood damage ratio is a function of inundation depth only and utilizes inundation depth estimated from flood extent information and hydrodynamic simulations. The parameters of the damage functions are calibrated through the SCE-UA method (Shuffled Complex Evolution method developed at The University of Arizona) so that the calculated flood damages match observations compiled in flood disaster statistics. The established three functions show good agreement with actual agricultural damages caused by a rainfall event in 2010 and are validated against another rainfall event in 2009. The results indicate that the established damage functions are capable of estimating flood damage at the district scale, while damage estimations at finer spatial resolution differ between the functions, suggesting that detailed statistical data need to be incorporated to reduce the estimation uncertainty at fine scales.

KEYWORDS flood damage function; damage ratio; inundation depth; disaster statistics; SCE-UA method

INTRODUCTION

Flood damage occupies approximately one-third of the global economic losses caused by water-related disasters (Douben and Ratnayake, 2006) and thirty-five percent of all physical losses in the Asia–Pacific region over the past 40 years (Asian Development Bank, 2013). Therefore, many countries have made large investments in flood control measures; e.g., approximately 10 billion USD (about 1 trillion JPY) per year in Japan (Kazama et al., 2009) and 229 billion USD (5,725 trillion VND) over five years in Vietnam (Hanoi Department of Finance, 2012). These investments are beneficial for enhancing safe living environment. Flood risk, however, cannot be completely eliminated, and there remains a residual risk in spite of such investments (Kundzewicz et al., 2013). Hence, flood risk management becomes important as part of a comprehensive flood control, and a key aspect of flood risk management is to assess currently existing risks.

A flood damage function, which is the relationship between flood parameters and the degree of damage, is often used for monetary flood risk assessment. It provides the monetary value of flood damage or the percentage of damage accounting for total asset values (damage ratio) once flood parameters such as inundation depth are known. A flood damage function is typically specific to the target area, because the relationship between flood parameters and the degree of damage depends strongly on both geographical and social conditions such as land use, economic development and climatic conditions. National and local authorities in sufficiently gauged regions often prepare their own standard methodology for assessing flood risks including damage functions, as in the UK (Penning-Rowsell and Chatterton, 1977), Netherlands (Messner et al., 2007), EU (Meyer et al., 2009), and Japan (Kazama et al., 2009). However, the framework for flood risk assessment in developing countries with typically insufficient hydrometeorological measurements causing relatively low data availability is mostly under development, although many studies have been already conducted (Ganji et al., 2012; Chau et al., 2015; Domeneghetti et al., 2015).

This study proposes a new methodology to establish flood damage functions for agricultural crops using estimated inundation depth and flood disaster statistics in data-scarce regions, which are common in developing countries where agricultural flood damage has a considerable impact as agriculture is often their main industry. Agricultural flood damage consists of losses of agricultural products, farmhouses, and related infrastructure (Dutta et al., 2003). This study focuses on crop damage because it is dominant among the aforementioned damage types (Förster et al., 2008).

Crop flood damage is mainly controlled by hydrodynamic parameters such as water depth, inundation duration, and flow velocity (e.g., Merz et al., 2010; Förster et al., 2008). Among these parameters, this study considers inundation depth as the single variable in damage functions since inundation depth is the easiest parameter to obtain and can be estimated with relatively little uncertainty even in data-scarce regions, for example by using the method developed by the authors (Nguyen et al., 2016). The crop growth stage is not parameterized in the current study because this attempt to develop flood damage functions is in an early phase,
although the importance of crop growth stage is widely recognized (Citeau, 2003; Todorovic and Woolhiser, 1972), which will obviously narrow the range of applicability of the functions established by the proposed methodology. Furthermore, this study assumes that agricultural flood damage information is available to varying extents, even in data-scarce regions, because agriculture is usually a basic industrial sector and, accordingly, both its products and the damage caused by disasters are deemed essential components of industrial statistics in many countries. The basic idea of the methodology proposed in this study is to make the best possible use of flood damage statistics in the target area while its availability may vary from one case to another.

**METHODOLOGY**

The procedure for developing flood damage functions can be summarized under the following steps: estimating inundation depth using hydrodynamic simulations, identifying flood damage functions, and calibrating flood damage functions using estimated inundation depth and disaster statistics.

*Estimating inundation depth using hydrodynamic simulations*

Inundation depth is a primary variable controlling flood damage. This study utilizes a method for estimating inundation depth from flood extent information and hydrodynamic simulations proposed by the authors (Nguyen et al., 2016). The method was developed for data-scarce regions assuming that hydro-meteorological variables, including inundation depth, are rarely observed. The datasets needed for inundation depth estimation in the abovementioned method are the floodplain topography and flood extent boundary, which, in most cases, can be extracted from satellite images even for data-scarce regions. The most likely estimation of inundation depth is determined so that the estimated wetted area of inundation matches the one calculated from the flood extent boundary information as closely as possible.

*Identifying flood damage functions*

This study assumes that the flood damage ratio is determined by inundation depth only. Accordingly, a flood damage function provides the relationship between inundation depth and damage ratio, and must comply with the following requirements:

- the damage ratio is defined as the dependent variable in a closed interval [0, 1];
- the damage ratio is 0 when inundation depth is zero and increases monotonically, either in a continuous or intermittent manner, approaching 1, as inundation depth becomes larger;
- the depth–damage relationship is plausible.

Any function can be a candidate for the damage function as long as it satisfies the above requirements. For example, the application of the flood damage function shown below uses three typical, but different, functions that were found through a literature survey: (1) quadratic function (Merz et al., 2010), (2) exponential function (Notaro et al., 2014) and (3) S-shape function (Totschnig et al., 2011). All are considered appropriate for providing the damage ratio of flood-affected crops and are simple enough to match uncertainties in other factors related to damage assessment such as estimated inundation depth and flood disaster statistics that are used to calibrate function parameters.

*Calibrating flood damage functions using estimated inundation depth and disaster statistics*

The parameters of the flood damage functions are calibrated using the SCE-UA method (Shuffled Complex Evolution method developed at The University of Arizona (Duan et al., 1992, 1994), which is an optimization method developed and used mainly for calibrating hydrological models. This study employs it to optimize the parameters in damage functions, so that the damage calculated by the functions agrees with the flood disaster statistics.

The estimated inundation depth is converted into the damage ratio through the damage function for each computational cell used in the hydrodynamic simulations, and the damage ratio is multiplied by the exposed property (e.g., crop yield) existing in the corresponding cell to obtain its flood damage. The cell-wise damages are added up to assess the damage of the unit (e.g., administrative region) used in the flood disaster statistics for the study area. The SCE-UA method is used to find the parameter value set of the damage function that provides the best fit for the unit-wise damage. A property map needs to be prepared for this purpose from land use patterns and other relevant information (e.g., crop productivity).

**APPLICATION AND DISCUSSION**

*Study area and flood event*

The proposed methodology was applied to the seven districts in the Nghe An and Ha Tinh provinces, Vietnam (Figure 1(a)) to develop flood damage functions for winter rice, a primary crop in this area. The districts are located in the Ca River Basin of the central region of Vietnam, where the main industry is agriculture. A significant portion of the districts are flood-prone and often suffer enormous flood damage. The heavy rainfall during October 14–19, 2009 led to flooding in Nghe An and Ha Tinh provinces with inundation depths of up to 3–5 m and lasted 7–10 days. A record-breaking weekly rainfall of 1,127.6 mm was observed at the Hon Ngú meteorological station. Inundation extended to 182 of 243 communes, among which 105 communes were completely isolated. In Vietnam, local governments survey affected areas and classify them into three different categories based on the degree of damage (devastated, severely damaged and partially damaged) to sum up flood damages from lower order administrative units to district/province level (General Statistics Office of Vietnam, 1996). The total economic losses exceeded 1,700 and 6,000 trillion VND (68 and 240 million USD), in which agricultural damage accounted for 21% and 30% in Nghe An and Ha Tinh, respectively. This considerable agricultural damage resulted from that the devastating rainfall that happened during the harvesting period of winter crops. This study focuses on this disaster to establish flood damage functions for winter rice, usually planted from May to July and harvested in the early winter from October to November in central Vietnam (Agriculture and Rural Information of Vietnam, 2013).
A land use map and flood disaster statistics compiled at the district level was provided by the local committee (People’s Committee of Nghe An Province, 2011; People’s Committee of Ha Tinh Province, 2011). The land use map was used to estimate the spatial distribution of the exposed winter rice crop yield in combination with productivity and market price (Department of Agriculture and Rural Development of Nghe An, Ha Tinh, 2011; Department of Agriculture and Rural Development of Quang Tri, 2014). The average for productivity of 4,518 kg ha\(^{-1}\) in Nghe An and 4,186 kg ha\(^{-1}\) in Ha Tinh and the market price of 6.5 thousand VND kg\(^{-1}\) are considered as representative values. The exposed crop yield was calculated as the product of average productivity, average price, and paddy area.

### Estimating inundation depth

A point-based elevation dataset with approximately 250-m resolution, provided by the Department of Survey and Mapping Vietnam (DOSM), was converted into a raster-type dataset with 50-m resolution, and a flood extent map, provided by Operational Satellite Applications Programme of the United Nations Institute for Training and Research (UNITAR-UNOSAT, 2015), was used for flood extent information.

Figure 1(b) depicts the inundation depth estimated using the flood extent information and hydrodynamic simulations. The simulation cell size was 50 m. The estimated inundation water level showed good agreement with observations despite a limited number of comparisons. The difference in water level between the observation (4.78 m) and estimation (4.84 m) at Linh Cam gauge was 0.06 m and the estimated water level was 3.29 m at Cho Trang – Ben Thuy gauge, 0.17 m higher than the observed value of 3.12 m. The estimated inundation depth ranged from 0.0 m for a high elevation area to 5.8 m for a small region of very low elevation, with an average inundation depth of 3.5 m. The characteristics of the inundation depth distribution for each districts are summarized in Table I. Details of the inundation depth esti-

![Figure 1. (a) Study area and (b) estimated inundation depth for the seven districts in the Ca River Basin](image-url)

Table I. Inundation depth distribution for seven districts in the Ca River Basin

| District (km\(^2\)) | Inundated area (ha) |
|---------------------|---------------------|
|                     | ≤ 1 m | 1-2 m | 2-3 m | > 3 m |
| Huong Son (1,096)   | 143   | 321   | 607   | 150   |
| Huong Khe (1,256)   | 64    | 287   | 412   | 296   |
| Loc Ha (115)        | 64    | 717   | 1,320 | 99    |
| Nghi Xuan (201)     | 79    | 681   | 1,403 | 126   |
| Hung Nguyen (164)   | 209   | 1,847 | 2,102 | 531   |
| Nam Dan (293)       | 460   | 787   | 1,321 | 335   |
| Vinh (68)           | 10    | 289   | 584   | 0     |
Establishing flood damage functions

This study considers the three following functions as candidates for flood damage functions:

- Quadratic function: $y = ax^2 + (1 - a)x$ \hspace{1cm} (0 \leq a \leq 1) \hspace{1cm} (1)
- Exponential function: $y = \frac{1}{(a - 1)(a^x - 1)}$ \hspace{1cm} (a > 1) \hspace{1cm} (2)
- S-shape function: $y = \frac{h^b}{a + h^b}$ \hspace{1cm} (a > 0, b > 1) \hspace{1cm} (3)

in which $y$ is damage ratio, $x = h/h_{max}$, where $h$ is the water depth, $h_{max}$ is the water depth at which the damage ratio becomes 1, and $a$ and $b$ are constants. $h_{max}, a$ and $b$ are treated as parameters to be calibrated by the SCE-UA method. The quadratic and exponential functions have a parameter $h_{max}$, which limits the damage ratio to 1. For a cell in which the simulated water depth is equal to or larger than $h_{max}$, the damage ratio is calculated to be 1.

Figure 2 compares damage observation and estimation for each district based on the three functions with calibrated parameters given in Figure 3. The root mean square error (RMSE) was used as the optimizing index in the SCE-UA method. The three functions provided similar and almost satisfactory performance with regard to RMSE, ranging from 7,000 to 8,000 million VND. Among the three functions, the exponential function performed best, with differences to the quadratic and S-shape functions not significant.

The calibrated functions, as shown in Figure 3, were similar, especially for inundation depths of less than 2.5 m. For shallow inundation depths (less than 1 m), all functions showed a slow increase in damage ratios, which were small (up to 0.1), suggesting that no significant damage occurred. For medium inundation depths (1 to 2.5 m), the damage functions showed rapid increases, with approximately 60% of crops being damaged by 2.5-m inundation. The damage ratios for deep inundation (more than 2.5 m) were different among the three functions. The rate of increase in the damage ratio remained high with the quadratic and exponential functions, while the S-shape function had a long tail, approaching 1 only slowly.

Validating the flood damage functions

The three damage functions were applied to five districts (Dong Ha, Gio Linh, Cam Lo, Trieu Phong and Hai Lang) in the Thach Han River Basin, Quang Tri Province, Vietnam, for validation (Figure 4(a)). Approximately 63% of the basin is used for agricultural purposes (Quang Tri Statistical Office, 2009). The topographical and meteorological features are similar to those of the Ca River Basin because both are located in the central Vietnam. Note that the validation area does not cover the entirety of the five districts because of the limited availability of flood extent information. In particular, a considerable portion of the paddy fields in the Gio Linh and Hai Lang districts are not included in the investigated area, although observed crop damages used for validation extend to the entire area of the five districts mentioned above.

During flooding of the Thach Han River from September 27 to October 1, 2009, the highest water levels ever were recorded at the Sepok River; large areas along the river channels were inundated. Widespread heavy rain, with total amounts of 739 mm at Hai Tan, 694 mm at Hai Son, and 655 mm at Thach Han, led to deep inundation and partial failure of the dike system, including damage to the Southern Thach Han irrigation system in 10 locations. The peak water level in the irrigation system was 18.3 m, which is comparable to the highest water level (18.5 m) of the historical 1999 flood event. Flooding resulted in severe damage to the winter rice crop, which was about to be harvested. The overall damage in the province amounted to approximately 2,500 trillion VND (100 billion USD), 60% of which was attributed to the agricultural sector.

To estimate inundation depth for this flood, flood extent information captured by ALOS PALSAR on September 30, 2009, which was the peak time of the flood, and a point-based elevation dataset by the Department of Survey and Mapping Vietnam (DOSM, 2015) were collected. Figure 4(b) shows the estimated inundation depth across the districts, ranging from 0.01 to 7.1 m. The estimated water level at the outlet (Figure 4(a)) is 3.471 m, which is slightly higher than the river water level of 3.468 m interpolated from
The estimated inundation depth was used to check the validity of the established damage functions in combination with the productivity of 5,060 kg ha$^{-1}$ and the market price of 4.74 thousand VND kg$^{-1}$ in Quang Tri. Figure 5 compares the estimated district damages with observations (People’s Committee of Quang Tri Province, 2009). All three functions performed relatively well with RMSEs around 4,800 million VND. It should be noted, however, that the investigated area does not cover all paddy fields in the Gio Linh and Hai Lang districts and accordingly, the estimated damage cannot be directly compared to the observations for these two districts, while most of the paddies in Dong Ha, Trieu Phong, and Cam Lo are located in the investigated area.

Compensating possible deficits in damage estimation for Gio Linh and Hai Lang is difficult because the inundation situation in these districts is unknown. However, a simple estimation using the area ratio of the paddy fields was applied. Approximately 70% of the paddy fields in Gio Linh and 50% in Hai Lang are located outside of the investigated area. According to these percentages, the estimated damages are approximately 33,000 and 26,000 million VND for Gio Linh and Hai Lang, respectively. The estimate for Hai Lang is comparable to the observation (21,000 million VND), but the estimate for Gio Linh is significantly larger than the observation (14,000 million VND). This discrepancy might be caused by differences in the flooding severity between paddies inside and outside of the investigated area and a nonlinearity of the damage–depth relationship.

The three other districts, Dong Ha, Cam Lo, and Trieu Phong, show good overall agreement between estimated damages and observations, although Dong Ha is characterized by a large overestimation of 50% of the observation. The estimation for Trieu Phong is almost perfect, with only 250 million VND difference between the estimation based on the quadratic function and observation.

**Discussion**

The damage in each district estimated by the three functions did not differ significantly from each other, indicating that the aggregated damage at the district level was not sensitive to the damage functions if they are properly calibrated. The proposed methodology appears to be robust for establishing damage functions with a goal of estimating district-scale flood damage.

The quadratic and exponential functions include a parameter $h_{\text{max}}$, at which a crop is supposed to be completely destroyed. For both functions, $h_{\text{max}}$ was calibrated to be
Agricultural crops in data-scarce regions based on estimated inundation depth and flood disaster statistics is proposed. The method assumes that inundation depth is the single variable in the damage functions and uses inundation depth estimated from flood extent information and hydrodynamic simulations. Flood damage statistics are used to calibrate the parameters of the damage functions through the SCE-UA method.

The proposed method was applied to develop damage functions for winter rice in the central part of Vietnam and shows good performance both in terms of calibration and validation. The calibrated damage functions are highly non-linear. The proposed method is capable of providing reliable damage estimations at the district scale, but has considerable uncertainty at finer scales, depending on the functions used for damage estimation. Incorporating detailed statistical data for flood damage may be helpful to reduce the uncertainty even if it is not available for the whole area but only for a part of the area. Furthermore, the damage functions developed for winter rice are valid at most for the harvesting period in central Vietnam and may not be universally used for different periods and locations, because agricultural crop damage caused by floods are highly dependent on growth stage, as well as geographical characteristics of the target area. The established damage functions were calibrated (and validated) for the harvesting periods, during which crops are susceptible to inundation. Accordingly, the functions are likely to overestimate crop damages if they are applied to floods that occur at different growth stages even in the same area. A simple solution to overcome this limitation is to prepare damage functions for different growth stages or possibly to develop a comprehensive damage function that is applicable to any growth stage by integrating damage functions for different periods.

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