ASSESSMENT OF FLOOD DAMAGE TO RESIDENTIAL HOUSES AND ANALYSIS OF EFFECTIVENESS OF FLOOD DAMAGE REDUCTION MEASURES

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Developing a quantitative flood damage estimation method is important to plan and implement effective adaptation and preventive measures for reducing flood damage to residential areas. We thus developed a flood damage assessment method by integrating hydrologic-hydraulic simulation model outputs and a flood damage model capable of considering house characteristics, and conducted the quantitative assessment of flood damage to houses and household contents, including the effectiveness analysis of flood damage reduction by the use of existing dams for flood control and elevating the plinth level of houses. We also developed average flood damage curves as a function of flood depth for the houses considering house types and also for household contents, using secondary data sources. Selecting the Solo River basin of Indonesia as the study area, we computed flood characteristics using a water and energy budget-based rainfall-runoff-inundation model and estimated flood damage using the developed flood damage curves based on house characteristics and the exposed property value. The findings show that the use of the dam for flood control in the basin can reduce the expected annual damage (i.e., the average total expected damage per year from all flood probabilities) to residential areas by 21%. Flood damage to households can be reduced by more than 45% by elevating the plinth level height.

Key Words : *flood damage, residential areas, adaptation, WEB-RRI model, Indonesia*

1. INTRODUCTION

Floods can cause significant damage to houses and household contents, infrastructure, crops, and human beings[1)]. Flood risk has been increasing worldwide due to climate and social changes[1),2)]; particularly, flood-prone areas in developing countries have become more vulnerable to floods because of limited implementation of preventive and adaptation measures. Therefore, understanding potential flood damage (FD) and risk and evaluating such measures for their FD reduction effect are crucial in an effort to their effective planning and implementation.

The quantitative analysis of FD is essential to quantify flood risk for better management of flood disasters in the future. In quantifying flood risk, flood damage curves (FDCs) developed based on actual or synthetic data are often used for estimating direct FD to residential areas[1),3)]. Numerous researchers have presented depth-damage curves for the estimation of household damage[1)-6)], and there are large differences between their damage curves. In addition, most previous studies assessed FD to residential areas based on land use classification or considering single-type houses[7)]. The house characteristics, such as house type, wall materials, and the height of the plinth level, were not well considered, because of the lack of detailed data. It is thus important to develop a more reliable FD assessment method capable of considering such characteristics and applicable to regions where data are not readily available. Furthermore, less attention has been paid on the quantitative evaluation of the effectiveness of flood damage reduction measures (FDRMs). It is crucial to evaluate the effectiveness of the use of existing dams for flood control and adaptation options for houses to reduce flood risk more effectively in the future.

To overcome the above-discussed issues, we aimed to develop more reliable FDCs for houses considering house types and also for household contents and quantitatively evaluate flood risk reduction measures, such as using existing dams for flood control and elevating the plinth level of houses, focusing on the Solo River basin of Indonesia. We presented a quantitative FD assessment method developed by integrating a FD estimation model with hydrologic-hydraulic model outputs. Average FDCs for houses and household contents were developed using secondary data sources to quantify damage.

2. MATERIALS AND METHODOLOGY

(1) Study area

Fig. 1 shows the location of the Solo River basin in Indonesia. The catchment area of the study basin is about 15,752 km^2, and the main Solo River is 600 km long. The Wonogiri dam with a water storage capacity of 730 × 10^6 m^3 is located in the upstream part of the basin and used for multiple purposes of irrigation, hydroelectric power generation, and flood control (flood storage capacity is 220 × 10^6 m^3). The catchment area of the Wonogiri dam is 1350 km^2.

(2) Development of methods

A FD assessment method was developed by integrating a FD model with simulation outputs obtained from the water and energy budget-based rainfall-runoff-inundation model (WEB-RRI)[8]. The methodology is described in detail in the following sections.

a) Flood inundation analysis

The WEB-RRI model developed by Rasmy et al.[8], which was developed by coupling water and energy budget processes, land-vegetation-atmosphere interactions, multi-layer soil moisture dynamics, and two-dimensional lateral water flows and flood inundation, was used to simulate inundation. The model calculates runoff and inundation processes interacting two-dimensional diffusive wave model for slopes and one-dimensional diffusive wave model for rivers. Inundation may occur when water overflows from the rivers or accumulation of water in the areas due to heavy rainfall. The WEB-RRI model was set up using a HydroSHEDS digital elevation model of 30-arc seconds. The river width and depth were approximately calculated using empirical equations[8], which were defined as the function of the upstream

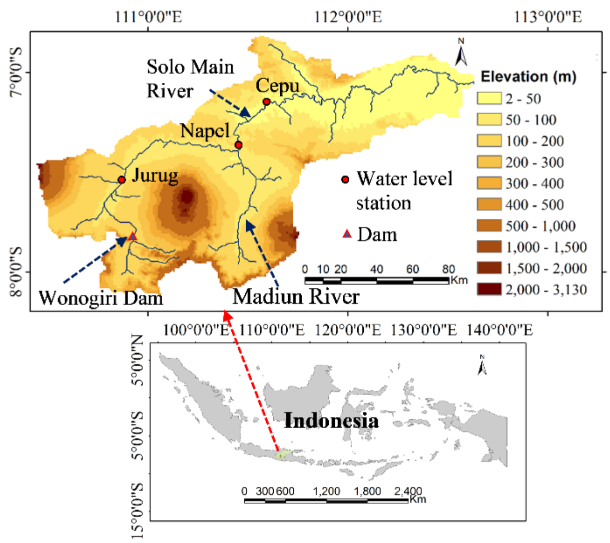

Fig. 1 Topographical features and location of study area.

catchment area. It was calibrated by comparing calculated and observed flood discharge for December 2007–January 2008 flood event and validated for the 2009 flood event. The calibration and validation were conducted using ground-observed precipitation and the observed outflow discharges from the Wonogiri dam were also defined as boundary conditions for the flood events of calibration and validation. The details on other input data required for WEB-RRI model and their sources can be found in Rasmy et al. [8].

To determine rainfall for floods of different return periods (RPs), we conducted frequency analysis using the 4-d annual maximum rainfall (basin-average) from 1976 to 2009 by employing the Gumbel distribution. The spatial and temporal rainfall patterns resulting in the flood event from December 2007–January 2008 was selected to determine rainfall for flood events of different RPs. After that, simulations were performed using the WEB-RRI model by applying determined rainfall for a flood of a specific RP to calculate flood inundation extent and depth.

b) Flood damage assessment method

We focused on FD to houses and household contents. Based on the 2021 census data, the major house types in the study area are masonry-walled (79%) and wooden-walled (21%) (houses with other wall types are negligible). The number of houses distributed in the area was estimated using the population and the average family size. The Worldpop 2007 population data were used for damage estimation for the December 2007–January 2008 flood to validate the method, and the Worldpop 2020 population was used for damage estimation for floods of different RPs (**Fig. 2**). The estimated population in the basin in 2007 and 2020 was 11.9 million and 12.2 million, respectively.

Since no FDCs for houses and household contents are available for the study basin, we first developed average FDCs for masonry- and wooden-walled houses and contents using secondary data sources.

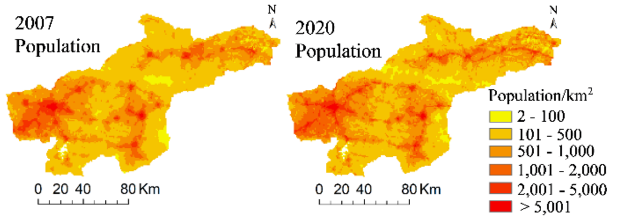

Fig. 2 Population distribution in 2007 and 2020 (Source: Worldpop population, https://www.worldpop.org/).

We compiled damage curves developed for Asian countries in previous research[1)-6),9)-14)] and used them to establish average FDCs. After the establishment of FDCs, we developed a FD assessment approach by integrating the WEB-RRI simulation model outputs and the FD estimation model. The FD to households in each grid were estimated as follows:

$$D_h(i,j) = DR_m(i,j) \times N_m(i,j) \times HV_m(i,j) + DR_w(i,j) \times N_w(i,j) \times HV_w(i,j) \quad (1a)$$

$$D_c(i,j) = DR_c(i,j) \times N_T(i,j) \times CV(i,j) \quad (1b)$$

where, *(i, j)* is any grid cell; D_h and D_c are the estimated damage value of houses and contents in each grid, respectively; DR_m and DR_w are the damage rate for masonry and wooden wall houses, respectively; N_m and N_w are the number of masonry and wooden wall houses, respectively; HV_m and HV_w are the unit price (total rebuilding/replacement value) of masonry and wooden wall houses, respectively; DR_c is the damage rate for contents; N_T (=$N_m + N_w$) is the total number of residential houses; and CV is the unit price of total replacement cost of household contents (inside house) per household.

c) Flood damage reduction by adaptation options

We also evaluated FDRMs: the effective use of the existing Wonogiri dam for flood control and elevating the plinth level of houses to avoid inundation. Based on the existing standard flood control operation rule (SFCOR) of the dam, when the inflow discharge exceeds 400 m^3/s, the outflow release from the dam should be kept at 400 m^3/s until the reservoir water level reaches the design flood water level[15)]. The effectiveness of FD reduction by the use of the Wonogiri dam was evaluated by setting a discharge control rate based on SFCOR in the model simulation. The outflow rate from the dam was maintained to be 400 m^3/s when the inflow into the dam exceeded 400 m^3/s until the water storage volume reaches maximum flood storage capacity (220 × 10^6 m^3). When the inflow into the dam is below 400 m^3/s or when the flood storage capacity of the dam filled, the dam's outflow rate was set to be the same as its inflow rate.

Residents living in flood-prone areas can also contribute to FD reduction by implementing adaptation options for houses. Thus, we analyzed the FD reduction effect of elevating the plinth level of houses to different heights. The current average height of the plinth level from the ground is approximately 0.5 m. We estimated the reduction in FD to households by elevating the plinth level higher than the current level (i.e., rise to 0.8, 1.0, 1.2, and 1.5 m). To analyze FD reduction quantitatively, the expected annual damage (EAD), which is the average total expected damage per year from all flood probabilities, was calculated for each case by summing the areas under a damage-probability curve (DPC). The EAD was calculated by estimating the FD for different RPs.

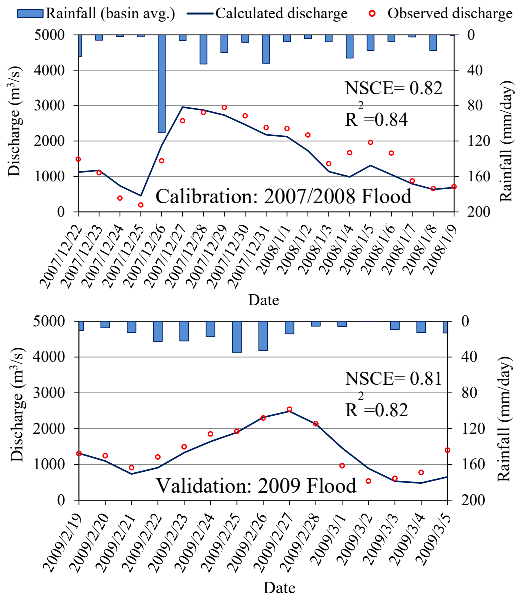

Fig. 3 Calculated and observed discharge at Cepu.

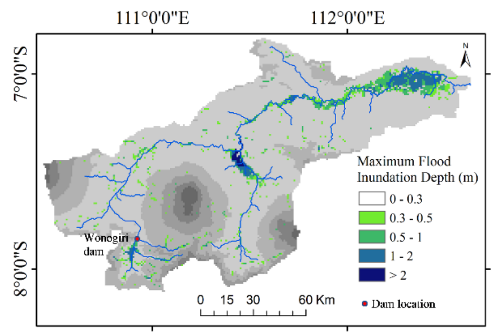

Fig. 4 Calculated maximum flood inundation depth during December 2007–January 2008 flood.

3. RESULTS AND DISCUSSION

(1) Flood inundation and hazard analysis

Fig. 3 compares the calculated discharge using the WEB-RRI model with the observed discharge at the Cepu station. It indicates that the calculated results reasonably agree with the observed discharge at Cepu, with high Nash-Sutcliffe efficiency and r-squared values. **Fig. 4** shows the calculated maximum flood inundation depth during December 2007–January 2008 flood. The estimated inundation extent with a flood depth greater than 0.3 m was 1122.3 km^2.

Fig. 5 compares the calculated results of flood inundation areas with and without considering the use

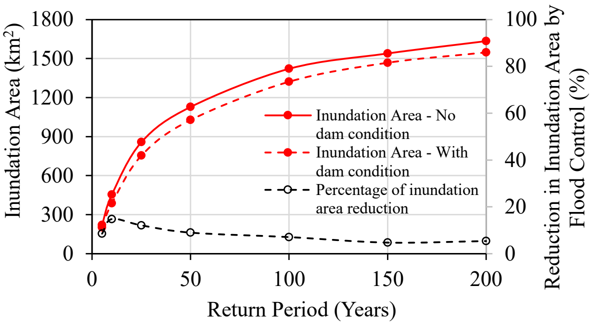

Fig. 5 Calculated inundation areas (with a flood depth > 0.3 m) with and without use of the Wonogiri dam for flood control, and reduction in inundation areas by the dam.

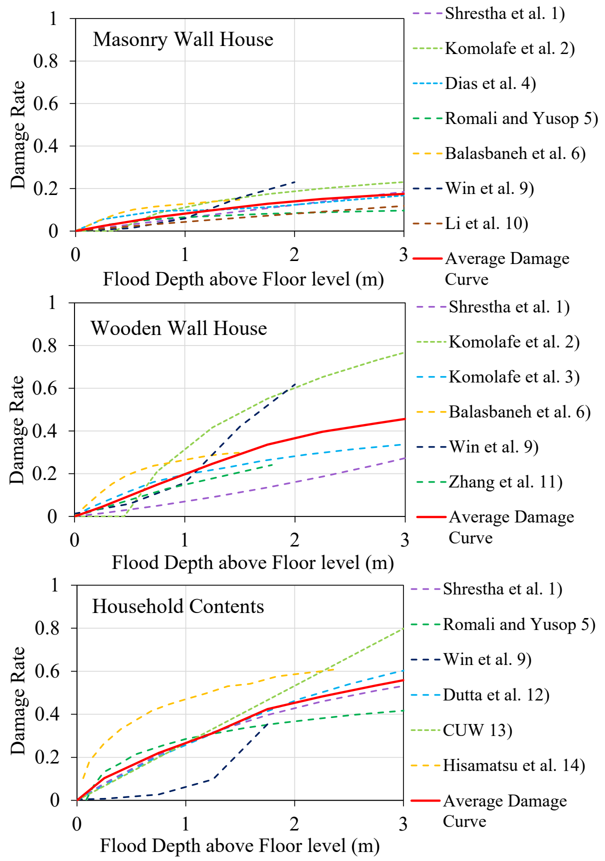

Fig. 6 Developed average flood damage curves for masonry and wooden wall houses and household contents using secondary data sources.

of the Wonogiri dam for flood control and the estimated reduction in inundation area due to the dam's contribution to flood control. The results indicate that the inundation area can be reduced by 8–15% using the dam for flood control when the flood scale is ≤ a 50-year flood, while 5–7% when ≥ a 100-year flood. The results show that even though the Wonogiri dam is located in the most upstream part of the Solo River basin, the inundation area can be reduced to some extent using the dam for flood control.

(2) Flood damage assessment

Fig. 6 shows the average FDCs developed for masonry-walled houses, wooden-walled houses, and household contents using secondary data sources. FD to houses and contents was assessed using these average FDCs. The average exposed value (rebuilding value) of residential houses per house was approximately 106.64 million IDR for masonry-walled house and 90 million IDR for wooden-walled house. The average replacement value of household contents per household was 32.37 million IDR[16].

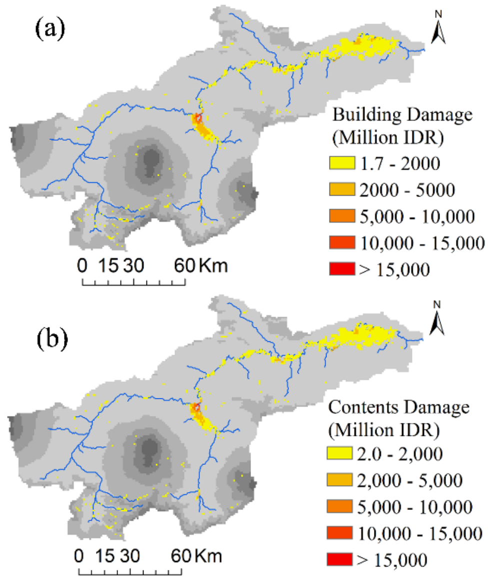

Fig. 7 Calculated (a) houses (buildings) damage and (b) contents damage, during December 2007–January 2008 flood.

Fig. 7 shows the calculated FD to houses and contents during the December 2007–January 2008 flood. The estimated damages to houses and household contents were 955.7 and 841.3 billion IDR, respectively (total household damage: 1797 billion IDR). The reported total losses of properties and crops due to the same flood event was reported to be 2000 billion IDR[17]. The estimated number of inundated houses was 162,505, whereas the reported value was 165,117[18]. FD to residential areas was severe in the areas furthest downstream of the basin and immediately upstream of the confluence with the Madiun River, where the flood depth was higher. More than 64,000 houses were inundated over 1 m deep.

The calculated damage values of houses and contents for 100-year flood without adaptation measures were 1616.9 and 1407.0 billion IDR (107.9 and 93.9 million USD), respectively. The total damage value of houses and contents (201.8 million USD) for the study area for 100-year flood is comparatively less than the total losses reported for 100-year flood for highly urbanized and populated Jakarta area in Indonesia (1768 million USD) by Budiyono et al.[7]. The higher damage in Jakarta is mainly due to higher exposures and their exposed value in flood prone areas.

(3) Evaluation of flood damage reduction

Fig. 8 (a) compares the DPCs for houses without and with considering the use of the Wonogiri dam for flood control. **Figs. 8 (b)** and **(c)** show the DPCs with elevating the plinth level of houses to different

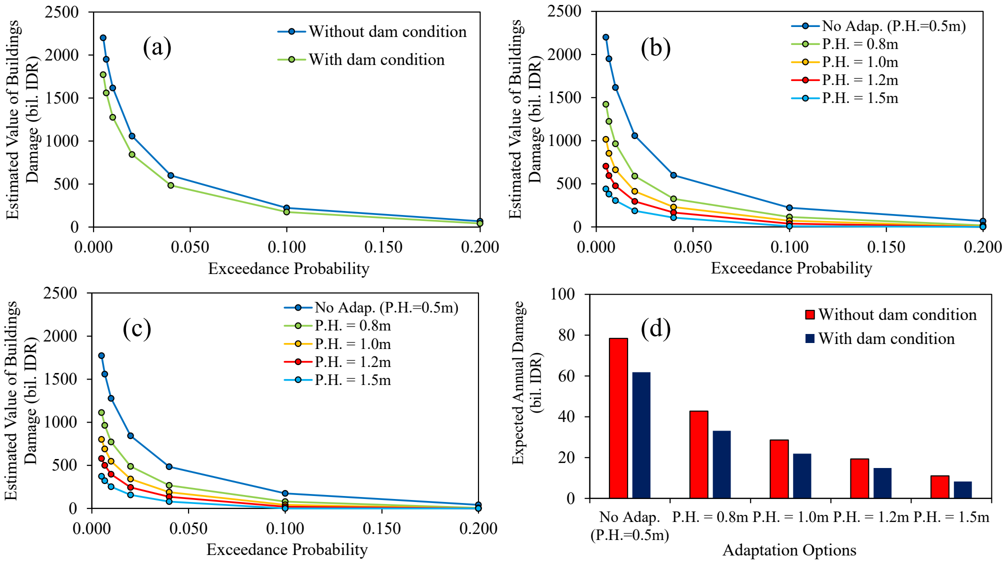

Fig. 8 Houses (buildings) damage: damage-probability curves (a) with and without dam conditions, (b) with elevating the plinth level of houses at different levels and without dam condition case, and (c) with elevating the plinth level of houses at different levels and with dam condition case, and (d) estimated expected annual damage (P.H. = plinth height).

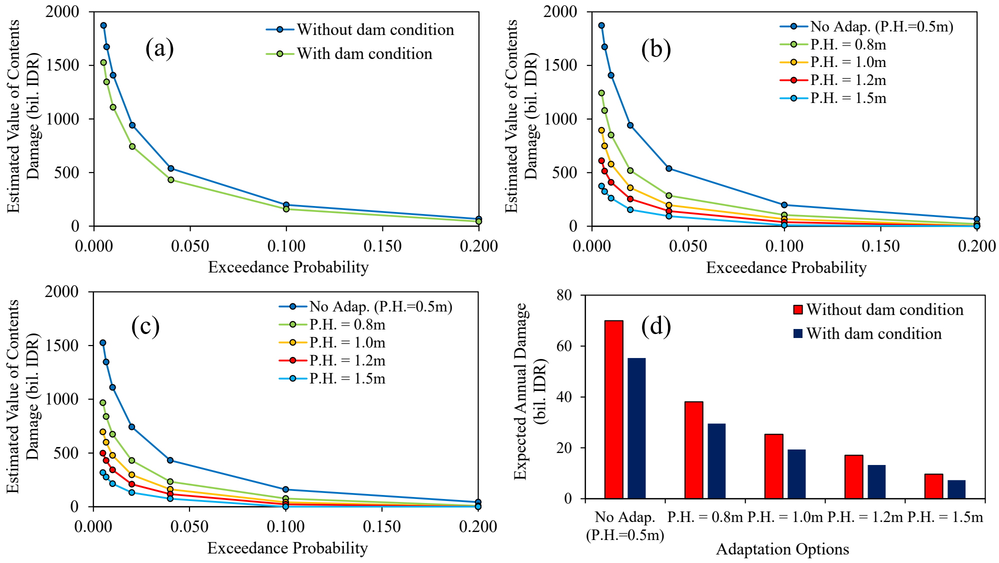

Fig. 9 Contents damage: damage-probability curves (a) with and without dam conditions, (b) with elevating the plinth level of houses at different levels and without dam condition case, and (c) with elevating the plinth level of houses at different levels and with dam condition case, and (d) estimated expected annual damage (P.H. = plinth height).

heights and without and with considering the use of the dam for flood control. The estimated EADs of building damage for different cases are presented in **Fig. 8 (d)**. Similar results of DPCs and estimated EADs for household contents are presented in **Fig. 9**. The estimated EAD of both house and contents damage without adaptation measure for the study area was 148.38 billion IDR per year (9.9 million USD per year). Budiyono et al.[7] estimated total EAD based on land use classification for Jakarta at 333 million USD per year, which can be increased in future due to climate change as reported in Januriyadi et al.[19]. Yamamoto et al.[20] estimated the EAD value of direct FD to general properties and agriculture in the late 20th century for Japan at 3259 billion JPY per year (23,376 million USD per year). The estimated EAD value from one location to another greatly varies as exposures and exposed values vary widely depending on the location and size of the study area. The reduction in EAD of houses and household contents by the use of the Wonogiri dam for flood control is 21.2% and 20.9%, respectively. The effective use of the Wonogiri dam for flood control in the study basin can reduce the FD to residential areas to some extent. Januriyadi et al.[19] showed that recharge and retention ponds can reduce FD by 33.2% in Jakarta, Indonesia. The reduction in EAD of houses and household contents only by elevating the plinth level of houses to 0.8 m is 45.4% and 45.5%, respectively (no dam consideration) and greater than 63% (for both cases of houses and contents damage) when the plinth height is ≥ 1 m (**Figs. 8 (d) and 9 (d)**). The results indicate that elevating the plinth level of the houses can significantly reduce FD to houses and contents.

Yamamoto et al.[20] also reported that by changing the buildings to piloti buildings can reduce FD by 18%. The FD can be further reduced by elevating the plinth level even higher or by combining plinth elevation with the effective use of the dam for flood control.

We presented the quantitative evaluation of FD reduction by effectively using an existing dam for flood control and elevating the plinth level of houses. The results can help residents plan and implement better FDRMs for houses and household contents, such as considering an optimal plinth height to avoid inundation when constructing new houses in flood-prone areas. The construction of new structural measures for reducing FD might be challenging in many developing countries as it requires a huge amount of financial resources[1]. Therefore, the effective use of dams and other existing structures and the application of guidelines for FDRMs for new houses should be included in the list of strategies to reduce FD to households.

4. CONCLUSION

We developed a FD assessment method for the residential sector by integrating hydrologic-hydraulic model outputs and a FD model, aiming to apply it to flood-prone areas where damage data are not readily available. We also quantitatively evaluated the FD reduction effect of using an existing dam for flood control and adaptation measures of houses.

The findings indicate that FD to residential areas can be significantly reduced by elevating the plinth level of houses. The FD can be further reduced by combining house adaptation measures with the use of existing dams for flood control. The results of this study can be useful for planning and implementing adaptation and preventive measures. The developed average FDCs, which relate FD to houses or contents with flood depth, estimate FD in monetary value. The developed average FDCs can be applied to other areas where data are not readily available.

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