Received: 29 September 2023 | Revised: 15 February 2024 | Accepted: 14 May 2024

DOI: 10.1111/jfr3.13052

SPECIAL ISSUE ARTICLE

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management | WILEY

Assessment of future risk of agricultural crop production under climate and social changes scenarios: A case of the Solo River basin in Indonesia

Badri Bhakta Shrestha | **Mohamed Rasmy** | **Tomoki Ushiyama** | **Ralph Allen Acierto** | **Takatoshi Kawamoto** | **Masakazu Fujikane** | **Takafumi Shinya** | **Keijiro Kubota**

International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), Tsukuba, Japan

Correspondence
Badri Bhakta Shrestha, International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), Tsukuba, Japan.
Email: shrestha@icharm.org

Funding information
Advanced Studies of Climate Change Projection (SENTAN), Grant/Award Number: JPMXD0722678534; Ministry of Education, Culture, Sports, Science and Technology (MEXT)

Abstract

Understanding the impacts of climate change and conversion of paddy field areas in the future on agricultural production is an essential part of flood-risk management. However, the quantitative impact of flood on agricultural crops in the far-future under climate change, considering prospective changes in paddy area, is still not clearly understandable. This study thus focused on quantitative analysis of flood impact on rice crops under climate change using MRI-AGCM climate model outputs for the past (1979–2002) and far-future (2075–2098) periods for the Solo River basin in Indonesia. We developed a quantitative damage assessment method by coupling water and energy budget-based rainfall-runoff-inundation model outputs and a depth-duration-damage flood loss model. We also analyzed land-use and land cover changes to project future paddy areas. The future rice production in the study basin may decrease by 21% by 2048 and by 24.6% by 2076 compared with that in 2020, due to the conversion of paddy fields to other land cover classes. The average annual flood damage value of rice crops may increase in the future period (2075–2098) by 93.7% (average damage: 666.08 billion IDR) compared with that in the past period (1979–2002) (average damage: 343.7 billion IDR), due to climate change impacts alone.

KEYWORDS

agricultural crops, climate change impact, flood, land cover change, WEB-RRI

1 | INTRODUCTION

The exposed properties and agricultural lands are becoming more vulnerable to floods due to climate and social changes (Jongman et al., 2012; Shrestha et al., 2021). Flood inundation in paddy fields often causes huge losses in agriculture production, especially rice production, and adverse impacts on food security and rural livelihoods in many developing countries. Therefore, assessment of potential flood damage (FD) to rice crops in the future due to climate and social changes is crucial for preparing and implementing effective preventive and adaptation measures (Januriyadi et al., 2018; Yamamoto, Sayama, et al., 2021).

The frequency and intensity of floods are increasing in many river basins, which may increase further in the future due to climate change impact (Loo et al., 2015). Recent studies also found that precipitation is likely to increase in the future in different parts of the world (Budiyono et al., 2016; Chen et al., 2022; Toosi et al., 2020; Yamamoto, Sayama, et al., 2021). The increase in precipitation due to climate change significantly contributes to the increase in river discharge and intensity of flood hazards (Hanif et al., 2020; Iwami et al., 2017; Loo et al., 2015). As a result, FD to agricultural crops, as well as to other sectors, might be more severe in the future. Many areas are already at risk of flooding and have a great economic loss, and the risk level in those areas will further increase due to climate change (Chen et al., 2022). Previous studies also reported that future flood risk and damage are likely to increase due to climate change in most areas of the world (Alfieri et al., 2015; Januriyadi et al., 2018; Rojas et al., 2013; Tanaka et al., 2018; Wing et al., 2022; Wobus et al., 2017). Therefore, it is necessary to analyze future flood risk due to climate change impact in order to implement effective preventive and adaptation measures to reduce potential losses.

Flood risk is usually defined as the probability of a flood event and its negative consequences (Löschner et al., 2017; UNISDR, 2009), and the consequences expressed as FD are calculated as the product of the value of the exposed elements in the flood hazard areas and flood vulnerability (Löschner et al., 2017; Shrestha & Kawasaki, 2020). FD refers to a variety of losses in exposed elements caused by flooding. FD is typically categorized as direct damage, which occurs as a result of direct physical contact with flooding, and indirect damage, which is the losses or damage not directly due to flood exposure. Both direct and indirect damage in the agricultural sector can be further categorized as instantaneous damage, which occurs during or immediately after the flood and induced damage, which occurs not immediately after flooding (Brémond et al., 2013). Evaluating the complete damage due to flooding in the agriculture sector is challenging, particularly in the case of induced damage; thus, this study focused on direct instantaneous damage to rice crops caused by flooding.

Rice crops are primarily cultivated in low-lying or flat areas, particularly in Asian countries, because these areas have more water available for crop cultivation (Tsuboi, 2012). However, those areas are easily flooded during the rainy season, and rice crops are severely damaged when flooding occurs; thus, it is necessary to assess FD to rice crops in those areas, considering the effect of climate change for better management of rice crop cultivation. Many studies on FD to rice crops focused on development of damage curves (Dutta et al., 2003; Hendrawan & Komori, 2021; Nguyen et al., 2021; Samantaray et al., 2015; Shrestha et al., 2016, 2021; Win et al., 2020) or assessment of post-flood damage (Dutta et al., 2003; Nguyen et al., 2021; Shrestha et al., 2016; Win et al., 2020). Many others focused on the impact of climate change on rice crop production based on crop water demand and water availability (Huynh et al., 2020; Tsujimoto et al., 2022). Still others focused solely on the estimation of flooded paddy area (Huynh et al., 2020; Khiem et al., 2019). However, since the impact of climate change is highly uncertain, understanding the overall flood impact on rice crops under climate change is challenging. In addition, the degree of FD to rice crops due to the effect of climate change varies from place to place and in time. It is thus crucial to understand climate change impact on rice crops and quantitatively assess the damage or production loss under a changing climate, focusing on a river basin or at a local scale. The quantification of flood damage under climate change provides key information for decision-making and policy development in climate change adaptation planning and flood management to reduce the damage more effectively in the future.

In addition to considering climate change impact, it is also important to consider potential changes in paddy fields in assessing the rice crop damage and better preparation. The analysis of changes in paddy area and the projection of future land use are essential for our better understanding of environmental issues (Binutha & Somashekar, 2014), which will also provide more information for effective land-use planning and management and environmental risk reduction in the future (Lv, 2017). However, most previous studies assessed FD to rice crops only considering paddy areas exposed at present, and potential changes in the paddy area are often ignored. By monitoring the dynamics of land-use and land cover (LULC) changes using historical LULC maps or remotely sensed satellite-based images, we can analyze changes in patterns of LULC classes, including paddy fields (Shrestha, 2019; Yuliyanto et al., 2016). Potential LULC changes can be projected by analyzing trend changes in past years and by training the model using such historical changes. The LULC maps for historical years and their changes can be considered the key driving elements to predict potential LULC (Lv, 2017) and eventually predict changes in paddy area. A prospective decrease in paddy area may also result in a reduction in rice production and an increase in adverse impact on food security.

In this study, we aimed to investigate flood impact on agricultural crops and production quantitatively under climate change scenarios, focusing on the Solo River Basin (SRB) in Indonesia. We also analyzed and projected historical and future changes in LULC and investigated how changes in paddy area in the future may affect rice production and FD in the future. For analysis, we developed a quantitative flood loss assessment method for rice crops as a function of flood depth, duration, and the growth stage of rice crops by integrating the water and energy Budget-based Rainfall-Runoff-Inundation model (WEB-RRI Model) outputs and a FD estimation model. Flood hazards and rice crop damage were assessed under climate change scenario for the past climate period (1979–2002) as the base period and the far-future climate period (2075–2098). This study considered the worst-case scenario for the future, that is, high-emission scenario RCP8.5 in which emissions continue to increase throughout the 21st century, and focused far-future period considering the long-term adaptation planning. Recent study by Farid et al. (2023) also reported that the flood hazard in the study region will be more severe in far-future period than in the near-future period. Future FD to rice crops was assessed using current and projected paddy area. We also analyzed rice production losses due to changes in paddy area in the future.

2 | STUDY AREA

The SRB is located on Java Island in Indonesia (Figure 1). The catchment area of the study boundary is about 15,752 km^2, and the Solo River, which is the longest river on the Java Island, is approximately 600 km long. The Wonogiri multipurpose dam, with a reservoir capacity of 730 million m^3, is in the upper part of the basin. The estimated population for the study area based on the Worldpop population data for 2020 (https://hub.worldpop.org/) was approximately 12.24 million. The paddy field area in the study basin boundary, based on a 2006 LULC map produced by the Ministry of Environment and Forestry, Indonesia, was approximately 6098.74 km^2, which declined to 5687.02 km^2 in 2020.

The SRB is one of the country's important river basins in terms of agriculture production, dominated by rice cultivation. The SRB is also important in terms of economy and culture as Surakarta city is located in the study area. On the other hand, the SRB is flood-prone river basin and experiences frequent FD due to high variation in precipitation, rapid development and urbanization, and limited investment in disaster risk reduction measures. It is also expected that the frequency and magnitude of extreme precipitation in the study area are likely to increase in the future due to climate change (Iwami et al., 2017). The large areas in the basin are lowland areas (Figure 1) and paddy field areas located in such areas are mostly inundated during monsoon. To reduce FD in future, SRB needs a planning and implementation of effective flood prevention and adaptation measures, which will also support the economic and social growth at Java Island. Therefore, the assessment of FD to agricultural crops under climate change in this basin is essential to implement effective preventive and adaptation measures.

3 | DATA AND RESEARCH METHODOLOGY

The overall research methodology consisted of data preparation for global climate model (GCM), hydrologic-hydraulic model setup, flood hazard analysis, LULC change analysis, paddy area projection, and damage assessment including validation of results (Figure 2).

3.1 | GCM data preparation

The most widely used tools for projecting future climate changes are the outputs of GCMs. This study considered the worst climate change scenario for the future (i.e., RCP8.5 scenario) and used the outputs of atmospheric general circulation model (AGCM), called MRI-AGCM3.2S (Kitoh & Endo, 2016; Mizuta et al., 2012), which are produced by the Meteorological Research Institute (MRI) of Japan as the high-resolution climate model outputs (20 km grid size) in Climate Model Intercomparison Project-phase five. MRI-AGCM climate model outputs are widely used in East and Southeast Asian countries for climate change impact assessment (Chen et al., 2022; Ito et al., 2020; Mishra et al., 2018; Tanaka et al., 2018; Yamamoto, Sayama, et al., 2021). In SRB, floods usually occur between December and March. We thus defined the period from August 1 (beginning from the month with the least rainfall in the year) to the end of July as the hydrological year (e.g., the year 1979 refers to a period from 1979/08/01 to 1980/07/31). The climate model outputs of MRI-AGCM3.2S (past period: 1979–2002, far-future period: 2075–2098), which were dynamically downscaled to a 5 km domain using a regional climate model and statistically bias-corrected using long-term ground-observed rainfall data, were employed to simulate flood hazard conditions under climate change.

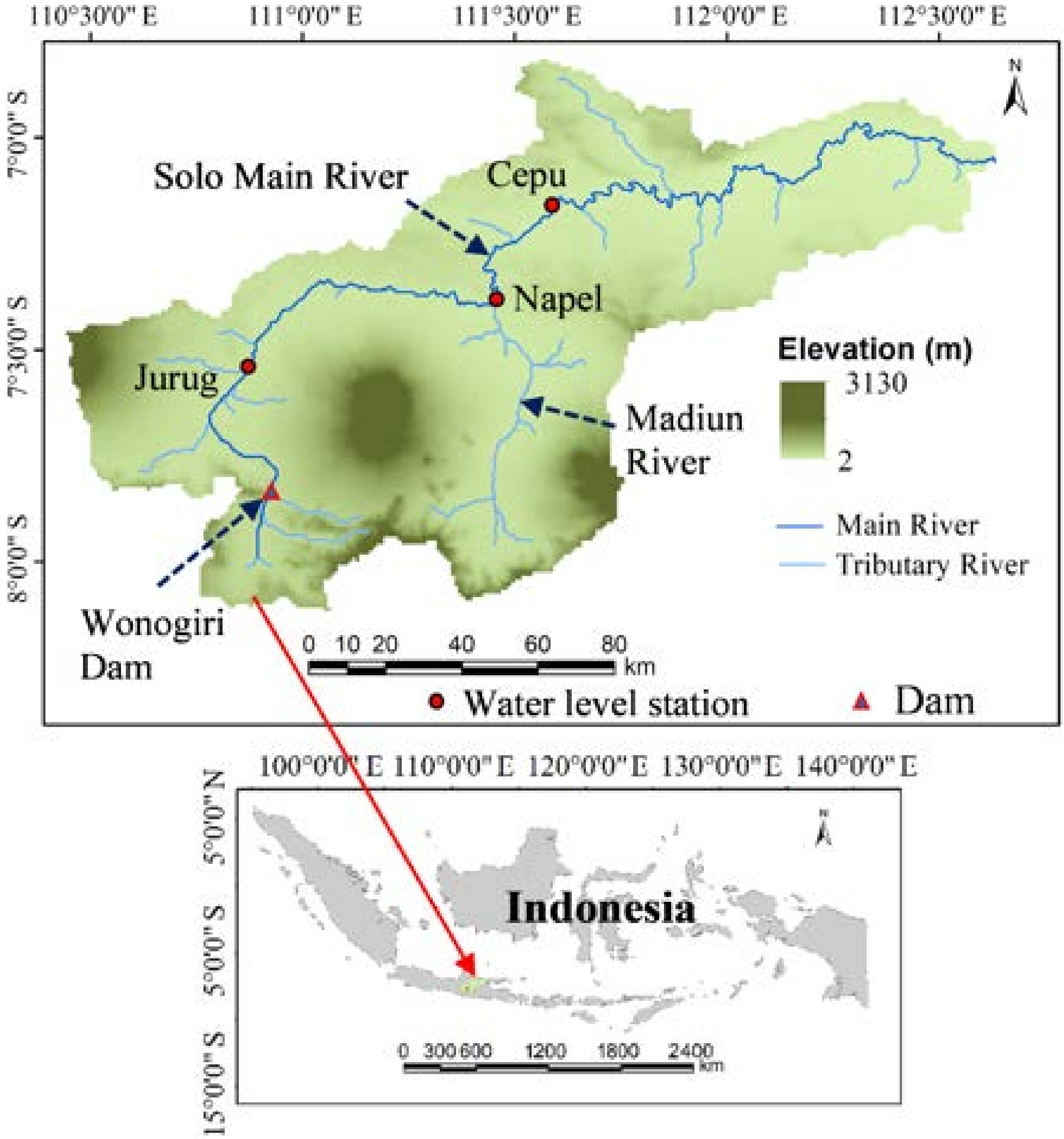


FIGURE 1 Location of the study area and the basin boundary.

3.2 | Flood hazard analysis using hydrologic-hydraulic model

Flood hazards were assessed using the WEB-RRI model, developed by Rasmy et al. (2019), which is an advanced hydrologic-hydraulic model that is coupled with the water and energy budget processes, land-vegetation-atmosphere interactions, multi-layer soil moisture dynamics, and 2D lateral water flows to improve interception, evapotranspiration, infiltration, runoff, and inundation processes. The details of the WEB-RRI model can be found in Rasmy et al. (2019). We used the digital elevation model (DEM) and flow direction and accumulation data (30 arc second) obtained from the USGS-HydroSHEDS to set up the model for the study area. The river depth and width were calculated approximately at each river cell using the empirical equations (Sayama et al., 2012). To calibrate and validate the WEB-RRI model parameters, ground-observed rainfall data obtained from the Ministry of Public Works and Housing, Indonesia, and other forcing inputs such as air temperature, specific humidity, wind speed, radiation, and surface pressure obtained from the Japan Meteorological Agency's Japanese 55-year ReAnalysis (JRA-55)

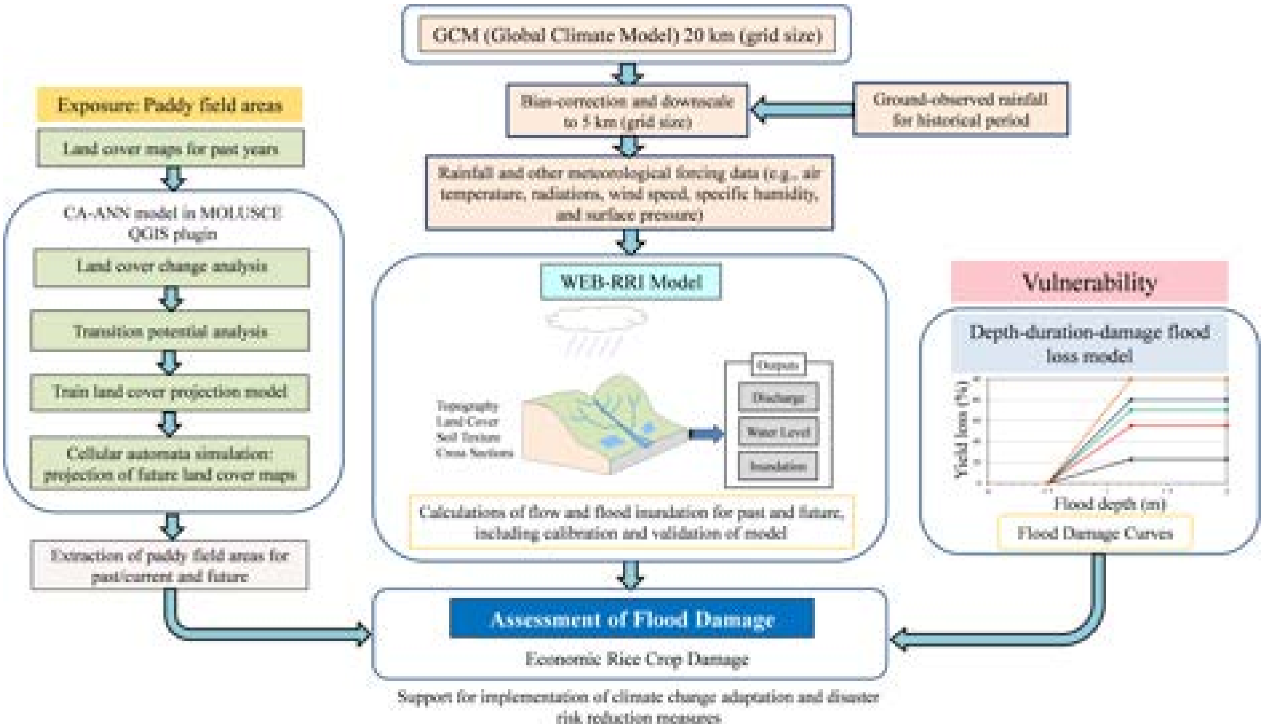


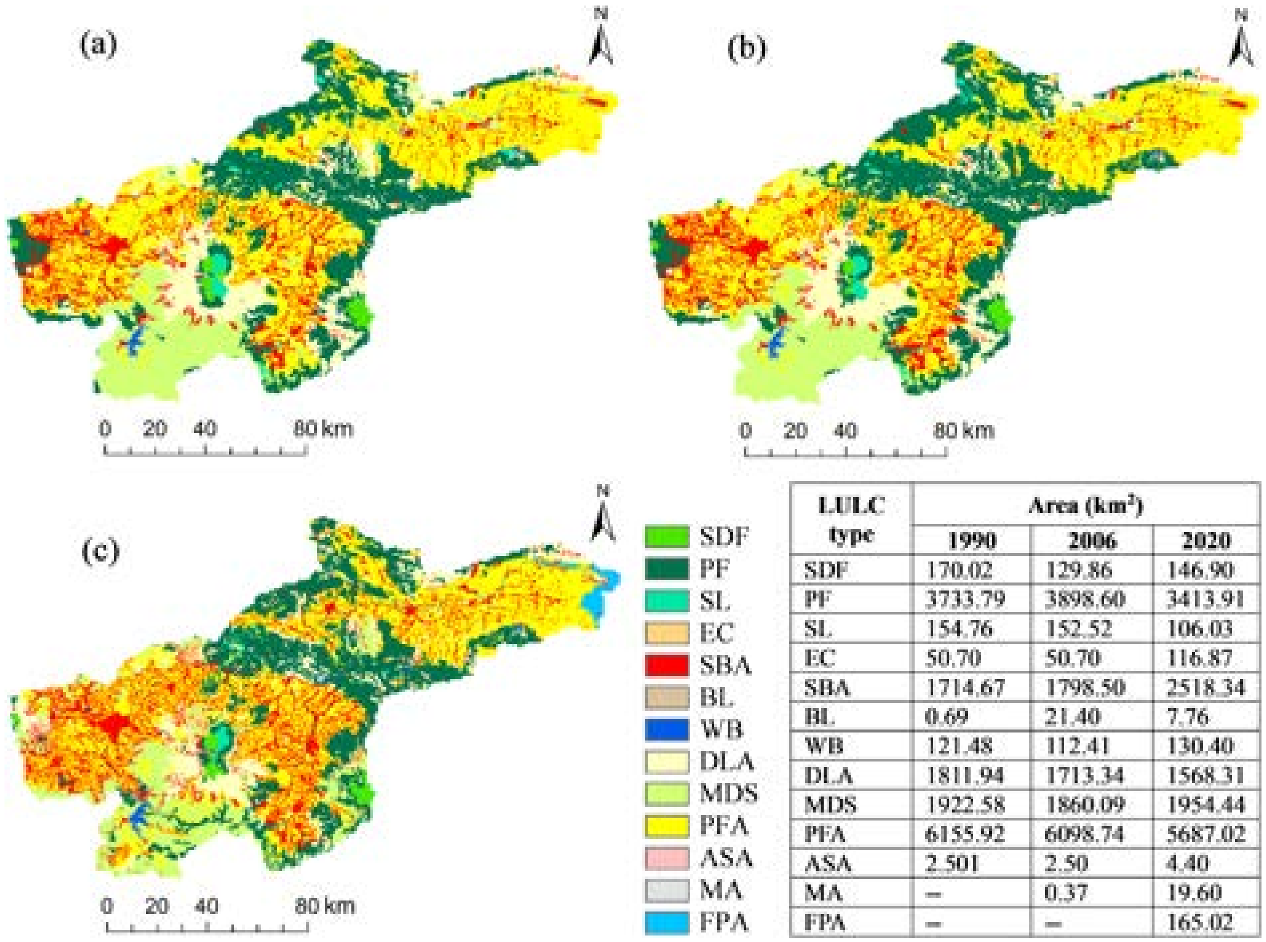
FIGURE 2 Overview of research methodology.

data were used. The release of water from the Wonogiri dam was also considered for the flood events of calibration and validation. The values of the WEB-RRI model parameters were calibrated and validated by comparing the calculated discharges of past flood events with their observed discharges. Then, flood hazards were simulated using a calibrated and validated WEB-RRI model using MRI-AGCM3.2S outputs for the past (1979–2002) and far-future (2075–2098) climate periods. The natural river flow conditions were considered in flood simulations for the past and far-future climate periods as water release from the existing dam is unknown in the future.

3.3 | Analysis of land-use and land cover changes and projection for future

To investigate LULC changes and project future paddy area, LULC maps published by the Ministry of Environment and Forestry (MoEF), Indonesia, were collected for the past years 1990, 2006, and 2020, which were prepared based on Landsat images. The collected LULC maps in vector format (shape file format) for these years were converted to raster format with 3 arc-second spatial resolution (approximately 90 m) in ArcGIS 10.8. Figure 3 shows the LULC maps for 1990, 2006, and 2020. The fishpond area (FPA) was not observed in the LULC maps for 1990 and 2006, and the mining area (MA) was also not observed for 1990. It was observed that the large paddy field area (PFA) converted to FPA from 2006 to 2020. The accuracy assessment of maps was conducted by the MoEF using reference data of actual situations (MoEF, 2023). We also assessed the accuracy of the collected LULC maps by checking random samples of land cover class with google earth images (see Data S1).

To analyze LULC changes and project future paddy area, we used a QGIS plugin called Modules of Land Use Change Evaluation (MOLUSCE) in QGIS 2.8.3. The MOLUSCE, which can estimate potential LULC changes, calculate transition probability, and project LULC maps, is available for free and widely used by numerous researchers for LULC projections (Abbas et al., 2021; Baig et al., 2022; Dawid & Bielecka, 2022; Kafy et al., 2021; Kamaraj & Rangarajan, 2022; Muhammad et al., 2022; Pandi et al., 2022; Perović et al., 2018). The MOLUSCE is built with the cellular automata (CA) model, including a transition probability matrix (Tadese et al., 2021). Jayasinghe et al. (2020) reported that the MOLUSCE can be implemented with acceptable accuracy with limited data requirements. Because the cellular automata-artificial neural network (CA-ANN) model in the MOLUSCE has been reported as a reliable tool for predicting LULC changes in the future (Kamaraj & Rangarajan, 2022) and also has been widely used for LULC projections (Abbas et al., 2021; Baig et al., 2022; Dawid & Bielecka, 2022; Kafy et al., 2021; Kamaraj & Rangarajan, 2022;



LULC type	Area (km^2)		
	1990	2006	2020
SDF	170.02	129.86	146.90
PF	3733.79	3898.60	3413.91
SL	154.76	152.52	106.03
EC	50.70	50.70	116.87
SBA	1714.67	1798.50	2518.34
BL	0.69	21.40	7.76
WB	121.48	112.41	130.40
DLA	1811.94	1713.34	1568.31
MDS	1922.58	1860.09	1954.44
PFA	6155.92	6098.74	5687.02
ASA	2.501	2.50	4.40
MA	–	0.37	19.60
FPA	–	–	165.02

FIGURE 3 Land cover maps: (a) 1990, (b) 2006, and (c) 2020 (Source: Ministry of Environment and Forestry, Indonesia) (ASA, Airport/seaport areas; BL, bareland; DLA, dryland agriculture; EC, estate croplands; FPA, fishponds areas; MA, mining areas; MDS, mixed dryland and shrub; PF, plantation forest; PFA, paddy field areas; SBA, settlement and built-up areas; SDF, secondary dryland forest; SL, shrubland; WB, water bodies).

Muhammad et al., 2022; Pandi et al., 2022; Perović et al., 2018), we used the CA-ANN model for predicting LULC changes in the future.

To train and validate the LULC change model, the transition matrix and change map of the LULC maps between 1990 and 2006 were generated in the MOLUSCE. Then, the modeling of potential transitions was performed using the transition map of 1990–2006 and the static variables based on the ANN (multi-layer perceptron) method and trained the ANN model. The static variables, such as DEM, slope, aspect, distance from the river, distance from the road, and distance from the main city or settlement areas, were considered in the potential transition modeling to train the ANN model. Then, CA simulations were conducted to project the LULC map for 2022. The projected LULC map for 2022 was compared with an actual LULC map for 2020 to evaluate the performance of the trained ANN model, assuming that there are negligible changes in LULC classes between 2020 and 2022. After validating the trained model with satisfactory performance based on kappa value and overall accuracy, future LULC maps (years: 2048 and 2076) were projected using the transition maps from 2006 to 2020. The MOLUSCE projects future maps at intervals of the period of transition maps. The projections of future LULC maps are based on the learning process using historical maps and static variables, and the restricted or protected areas by local governments were not considered due to limited information and data.

3.4 | Flood damage assessment

First, FD was assessed for past flood events and validated the results by comparing the calculated results with reported data. Then, FD was assessed under climate change scenarios for the past period (1979–2002) and the far-future period (2075–2098).

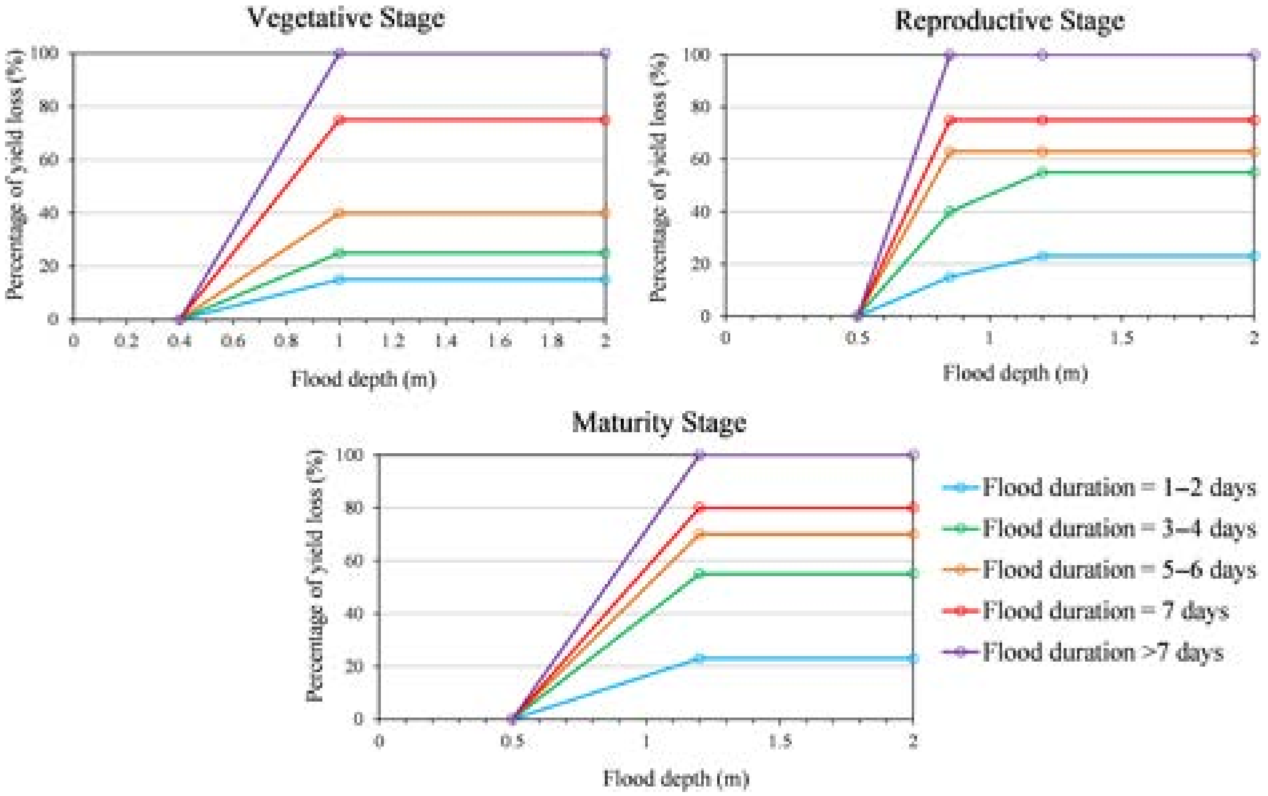


FIGURE 4 Flood damage curves for rice crops (modified/redrawn by authors) (Shrestha et al., 2016).

3.4.1 | Assessment of rice crop damage and validation

Because no FD curves are available for rice crops for the study areas, FD curves for rice crops presented in Shrestha et al. (2016) were employed, as there are similarities in the major types of rice grown in Southeast Asian countries (GRiSP, 2013). The yield loss caused by flooding was quantified using depth-duration-damage curves for rice crops presented in Figure 4, which was adapted from Shrestha et al. (2016) while adjusting the minimum damage threshold value during the process of validation. When flooding occurs during the early growth stage of rice plants, that is, from newly planted or vegetative stages, at which no rice production is expected, farmers normally replant rice crops. In such a case, the monetary value of FD to rice crops was estimated as losses of the cost of input. However, when flooding occurs during the reproductive and maturity stages, during which rice production is usually expected, there is no time for replanting rice crops (Shrestha et al., 2016). In these cases, the monetary value of FD to rice crops was estimated as the volume of production losses.

The method of rice crop damage assessment was validated for the December 2007 to January 2008 flood event. FD to rice crops for this flood event was assessed based on the 2006 paddy area map. After validating the results, we assessed the FD to rice crops for the past and future periods. We analyzed FD to rice crops in the future period, considering climate change impact and potential changes in future paddy area. We used the 2020 paddy area map as the base map for the past period and the 2020 paddy area map and the projected future paddy area maps (2048 and 2076) for the future period. FD to rice crops for the future period was estimated based on current price and rice yield conditions, and implementation of preventive measures in the future were not considered. The rice crop damage was estimated for both past and future periods using the following values: a farm gate price of 4650 IDR/kg (Thom, 2014), a cost of input of 1,970,414 IDR/ha (Zakaria et al., 2004), and a rice yield of 5230 kg/ha (Panuju et al., 2013).

Figure 5 shows the generalized cropping calendar for the study area based on cropping patterns and scheduled for the same basin presented in DSRI (2001). In the study area, farmers usually start rice plantation in early October in the upstream parts of the basin (orange colored area in Figure 5), while in early December in the downstream parts of the basin (green-colored areas in Figure 5). Based on the duration of each growth stage of rice plants (Shrestha et al., 2016) and cropping calendar (Figure 5), the rice plants during the 2007/2008 flood event were at the maturity and vegetative stages in the

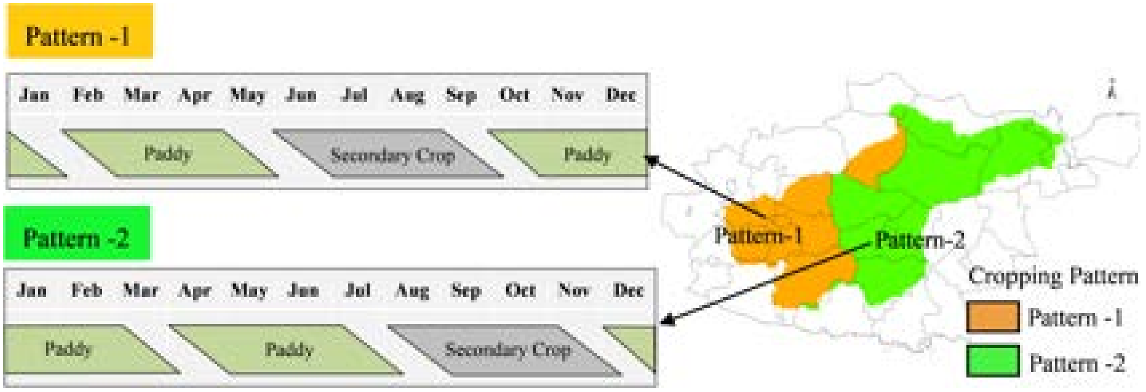


FIGURE 5 Generalized cropping patterns and calendar for study area (Source: DSRI, 2001).

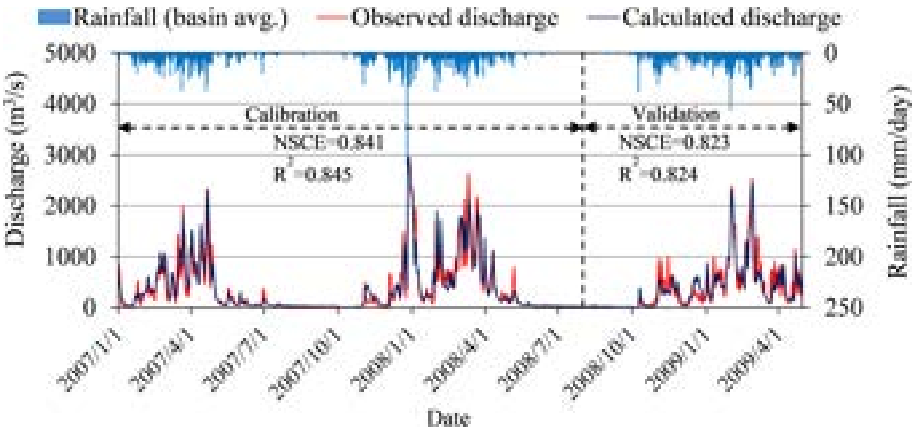


FIGURE 6 Comparison of calculated discharge using WEB-RRI model with observed daily discharge at Cepu station for flood events in 2007–2009.

upstream and downstream parts, respectively. The possible growth stage of rice crops during the flooding time for both the past and future periods was identified on the basis of the cropping calendar published in DSRI (2001) (i.e., the identified growth stage of rice crops (IGS) based on the cropping calendar and the timing of flooding). Based on identified possible growth stage, FD was assessed for the past and future periods under climate change impact. Since the cropping pattern and calendar may change in the future depending on policies of local governments, we thus also assessed FD to rice crops with scenarios of different growth stages of rice plants during a flood event for our better understanding (i.e., assumed if flooding occurred or will occur during the vegetative stage or reproductive stage or maturity stage of the rice crops in both the past and future periods).

4 | RESULTS

4.1 | Validation of flood hazards and damage

Figure 6 compares calculated discharges using the WEB-RRI model with observed discharges at the Cepu station for the past 2007/2008 and 2009 floods. The calculated discharges from the model match the observations well, as indicated by the high Nash–Sutcliffe coefficient efficiency (NSCE) and R^2 (coefficient of determination) values. Figure 7a,b shows the calculated flood inundation depth and duration during the 2007/2008 flood event. The results of the flood hazard assessment found that low land areas farthest downstream of the basin were largely inundated with a flood inundation depth of greater than 1 m. The flood duration in the basin ranged mostly from 1 to 2 weeks. Figure 7c shows the estimated FD to rice crops during the same flood event in 2007/2008. Table 1 compares the calculated results of FD to rice crops with reported data for 2007/2008 flood. The root mean square error (RMSE) and mean absolute percentage error (MAPE) values between reported and calculated damage values were 4.2 billion IDR and 4.5%, respectively, which indicated good agreement between calculated and reported damage value (MAPE < 10% indicates highly accurate (Vivas et al., 2020)). While the RMSE and MAPE values between reported and calculated damaged paddy field areas were 12,694 ha and 20.9%, respectively, the RMSE value indicated some discrepancy between reported and calculated damaged paddy field areas, but the MAPE value indicated that the discrepancy between reported and

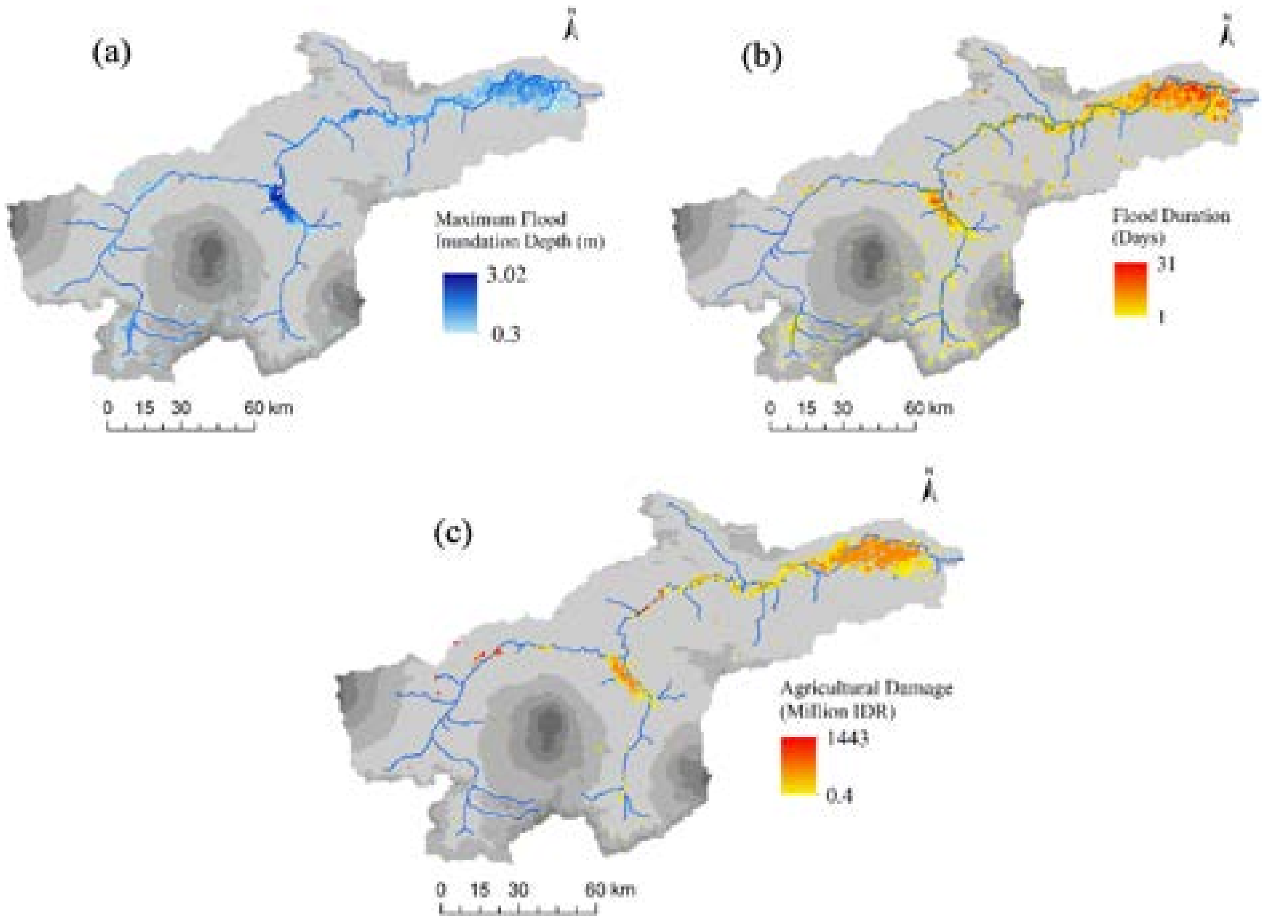


FIGURE 7 (a) Maximum flood inundation depth and flood extent areas, (b) flood duration, and (c) calculated agricultural damage (rice crops), during 2007/2008 flood.

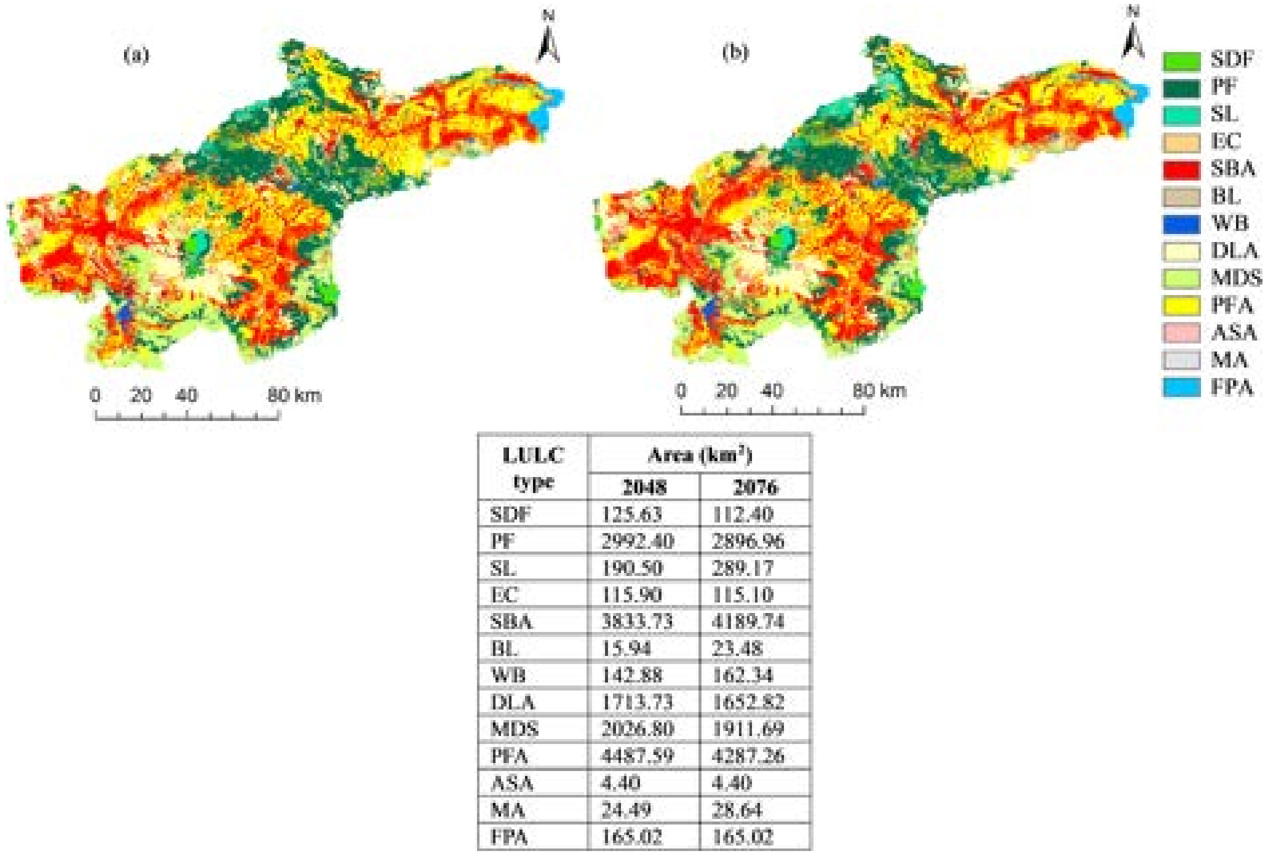
TABLE 1 Comparison of calculated results of rice crop damage for the 2007/2008 flood event with reported data.

Rice crop damage	Calculated results	Reported data	Root means square error (RMSE)	Mean absolute percentage error (MAPE)	Sources for reported data
Value of Rice crop damage (billion IDR)	89.1	93.3	4.2	4.5%	Hidayat et al. (2008)
Affected paddy area with rice crop damage (ha)	73,324	60,630	12,694	20.9%	DFCP (2010)

calculated damaged paddy field areas was reasonably acceptable (10%–20% MAPE: good agreement; 20%–50% MAPE: reasonably acceptable (Vivas et al., 2020)).

4.2 | Dynamic changes in land cover and projection for future

The trained MOLUSCE model was validated by comparing the projected LULC map for 2022 with an available LULC map for 2020, and the model performance was in an acceptable range with 76% overall accuracy and 0.68 kappa values. An overall accuracy value higher than 70% or a kappa value higher than 0.6 represents substantial agreement (Lukas et al., 2023; Nath et al., 2020; Pandey et al., 2023). Figure 8 shows the projected LULC maps (2048 and 2076). Figure 9 shows dynamic changes in LULC area from past to future, and Figure 10 shows the loss and gain in area for each LULC class. In the historical period, the LULC area changed more significantly in the period from 2006 to 2020 than in the period from 1990 to 2006 and may change more significantly in the future due to social disturbances; particularly, the paddy field area (PFA), plantation forest (PF), and settlement and built-up area (SBA) may significantly change in the future (Figures 9 and 10). The PFA and PF are decreasing



LULC type	Area (km²)	
	2048	2076
SDF	125.63	112.40
PF	2992.40	2896.96
SL	190.50	289.17
EC	115.90	115.10
SBA	3833.73	4189.74
BL	15.94	23.48
WB	142.88	162.34
DLA	1713.73	1652.82
MDS	2026.80	1911.69
PFA	4487.59	4287.26
ASA	4.40	4.40
MA	24.49	28.64
FPA	165.02	165.02

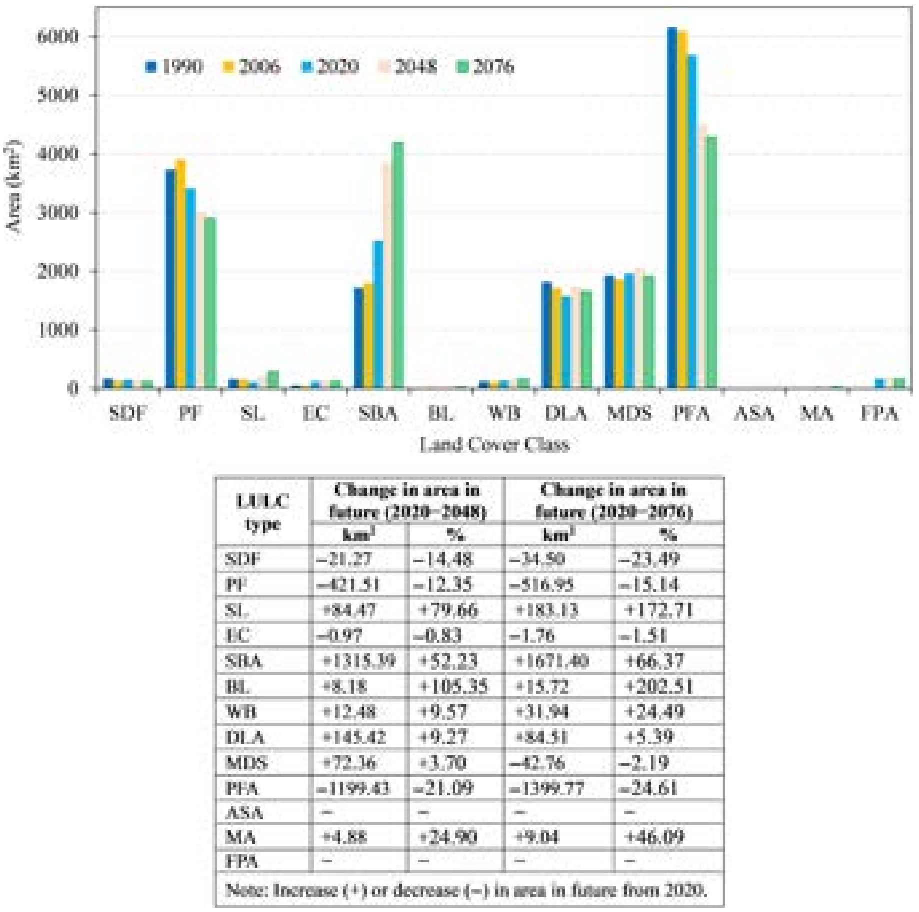
FIGURE 8 Projected land cover maps for future: (a) 2048 and (b) 2076 (ASA, Airport/seaport areas; BL, bareland; DLA, dryland agriculture; EC, estate croplands; FPA, fishponds areas; MA, mining areas; MDS, mixed dryland and shrub; PF, plantation forest; PFA, paddy field areas; SBA, settlement and built-up areas; SDF, secondary dryland forest; SL, shrubland; WB, water bodies) (since the FPA was not observed in the LULC maps for 1990 and 2006, the FPA in the future was assumed same as that in 2020. The airport and seaport area in the future was also assumed same as that in 2020).

in trend, while the SBAs are increasing in trend. The PFA and PF may decrease significantly in the future. The PFA may decrease in future by 21.09% by 2048 and 24.61% by 2076 compared with that in 2020. The PF may also decrease by 12.35% by 2048 and 15.14% by 2076, whereas the SBA may increase in future by 52.23% by 2048 and 66.37% by 2076. The loss in PFA might be mainly converted to expand SBA (e.g., more than 1024 km^2 by 2048 and 1290 km^2 by 2076), while the loss in PF might be converted to PFA, SBA, dryland agriculture, and shrubland in the future.

4.3 | Flood hazard and damage assessment under climate change scenarios

4.3.1 | Flood hazard conditions under climate change

Figure 11 shows the calculated flood inundation area and peak inundation volume (flood depth > 0.5 m) for the past period (1979–2002) and the future period (2075–2098), calculated using MRI-AGCM3.2S climate model outputs. The figures show that the flood inundation area and the peak inundation volume will increase in the future period due to climate change. The median and average values of flood inundation area and peak inundation volume for the future period are comparatively higher than those for the past period. The flood hazard will be more severe in the future. The first quartile values of the calculated flood inundation area and peak inundation volume for the future period under RCP8.5 are higher than the third quartile values for the past period. The calculated average inundation area for the past period was approximately 408.96 km^2 (24-year average), while it was approximately 802.32 km^2 for the future period (an increase of 96% compared to the past period). Similarly, the calculated average peak inundation volume for the past period was approximately 325.66 million m^3 (24-year average), while it was approximately 657.86 million m^3 for the future period (an increase of 102% compared to the past period). The results indicate that the flood inundation area and the flood peak volume will be



LULC type	Change in area in future (2020–2048)		Change in area in future (2020–2076)	
	km²	%	km²	%
SDF	−21.27	−14.48	−34.50	−23.49
PF	−421.51	−12.35	−516.95	−15.14
SL	+84.47	+79.66	+183.13	+172.71
EC	−0.97	−0.83	−1.76	−1.51
SBA	+1315.39	+52.23	+1671.40	+66.37
BL	+8.18	+105.35	+15.72	+202.51
WB	+12.48	+9.57	+31.94	+24.49
DLA	+145.42	+9.27	+84.51	+5.39
MDS	+72.36	+3.70	−42.76	−2.19
PFA	−1199.43	−21.09	−1399.77	−24.61
ASA	–	–	–	–
MA	+4.88	+24.90	+9.04	+46.09
FPA	–	–	–	–

Note: Increase (+) or decrease (−) in area in future from 2020.

FIGURE 9 Dynamic changes of land cover classes from past to future (ASA, airport/seaport areas; BL, bareland; DLA, dryland agriculture; EC, estate croplands; FPA, fishponds areas; MA, mining areas; MDS, mixed dryland and shrub; PF, plantation forest; PFA, paddy field areas; SBA, settlement and built-up areas; SDF, secondary dryland forest; SL, shrubland; WB, water bodies).

larger in the future period compared with those in the past period.

4.3.2 | Agricultural crop losses under climate and social changes

Figure 12 shows the estimated paddy area and rice production for the current year (2020 PFA) and the future years (2048 PFA and 2076 PFA). The figure also shows the losses due to a reduction in paddy area in the future. The estimated rice production for the current year based on 2020 PFA was 2.974 million tons, which will decline to 2.347 million tons based on 2048 PFA (21.1% reduction) and to 2.242 million tons based on 2076 PFA (24.6% reduction), due to a decrease in PFA in the future. The estimated amount of rice production losses in the future due to a decrease in PFA was 2916.9 and 3404.1 billion IDR based on 2048 PFA and 2076 PFA, respectively.

Figure 13 compares the calculated damaged paddy area and estimated value of rice crop damage between the past period (1979–2002) with 2020 PFA and the future period (2075–2098) for the cases of 2020, 2048, and 2076 PFAs. The results show that the FD to rice crops may increase in the future due to climate change impact. The first and third quartile values of calculated damaged agricultural area and estimated damage value of rice crops for the future period for all three cases of paddy area (2020, 2048, and 2076 PFAs) are comparatively higher than those for the past period (2020 PFA). The plus signs in the figure are the average value of the calculation periods (i.e., the average of years 1979–2002 for the past and the average of years 2075–2098 for the future). The results indicate that the increase in average damage paddy area and value in the future were 89.8% and 93.7% (Table 2), respectively, due to climate change impact alone, if there are no changes in PFA in the future. In the cases of both climate change impact and changes in PFA in the future, the increase in average damage paddy area and value were 52.2% and 61.2%, respectively, for the case of 2048 PFA, and 40.2% and 50.7% for the case of 2076 PFA (Table 2). The results clearly indicated that the estimated values of the damaged paddy area and economic loss in the future were comparatively higher due to climate change impact than those for the past period, even if the PFA decreases in the future. Figure 14 shows the spatial distribution of average damage value for the past and future periods. FD to rice crops will be more severe in the paddy areas located the farthest downstream of the basin and immediately upstream of the confluence of

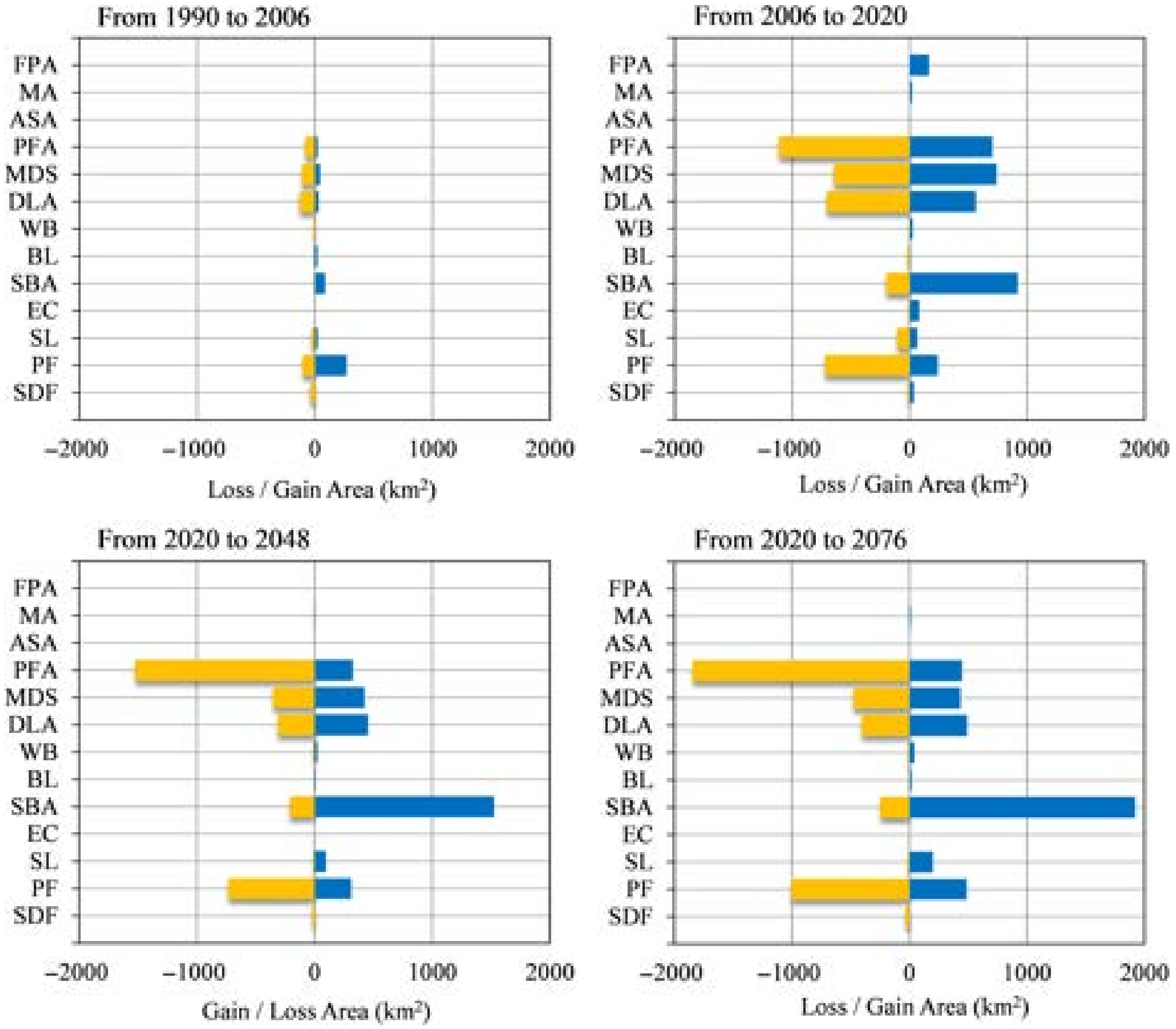


FIGURE 10 Loss and gain in areas for each land cover class for past and future periods (Past: 1990–2006, 2006–2020; Future: 2020–2048, 2020–2076) (ASA, Airport/seaport areas; BL, bareland; DLA, dryland agriculture; EC, estate croplands; FPA, fishponds areas; MA, mining areas; MDS, mixed dryland and shrub; PF, plantation forest; PFA, paddy field areas; SBA, settlement and built-up areas; SDF, secondary dryland forest; SL, Shrubland; WB, water bodies).

the Madiun River, where the flood depth and duration were greater and longer.

For our better understanding, FD to rice crops was also assessed with different scenarios of the rice crop growth stages, and the calculated average annual damage values of rice crops per year for the past and future periods for each growth stage scenario are presented in Figure 15. The average rice crop damage value for the future period in the cases of all growth stage scenarios was comparatively higher than that for the past period. The calculated value of rice crop damage in the case of the vegetative stage is less compared to the values in the other growth stage cases because the damage value of rice crops in the vegetative stage was estimated as losses of the cost of input, while FD to rice crops in the other growth stages was estimated as losses in the volume of rice production. The figure shows that FD to rice crops can be more severe in the case of the maturity stage of rice plants. The calculated rice crop damage in the cases of the reproductive and maturity stages of rice crops in the past period was more than 8% higher than the IGS case and more than 20% higher in the future period (in all PFA cases).

5 | DISCUSSION

Flood hazard areas and the quantitative estimation of FD to rice crops under the RCP8.5 scenario for the future, that is, the scenario of no climate change mitigation,

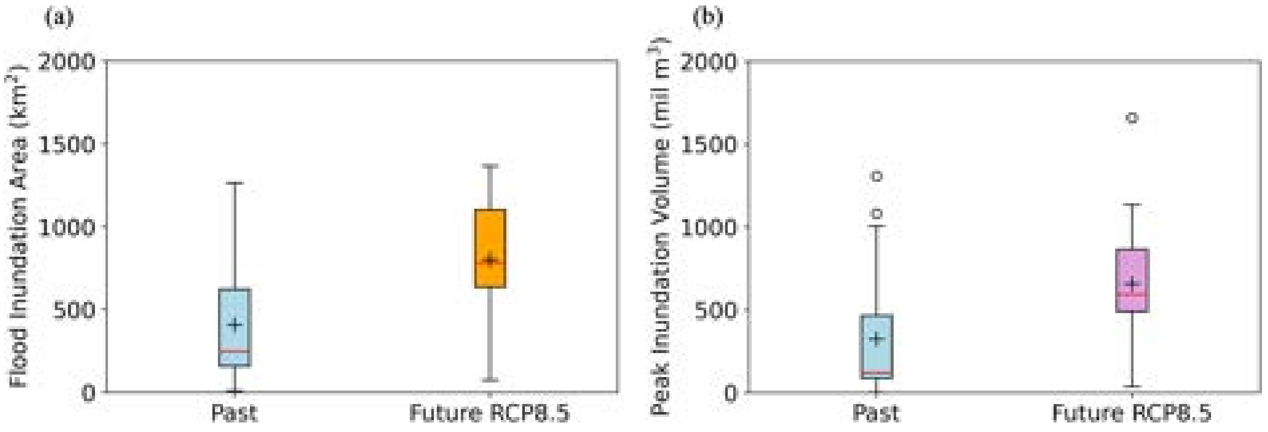


FIGURE 11 (a) Calculated flood inundation area and (b) peak volume of flood for past period (1979–2002) and future period (2075–2098) using MRI-AGCM3.2S climate model outputs (plus mark: Average value).

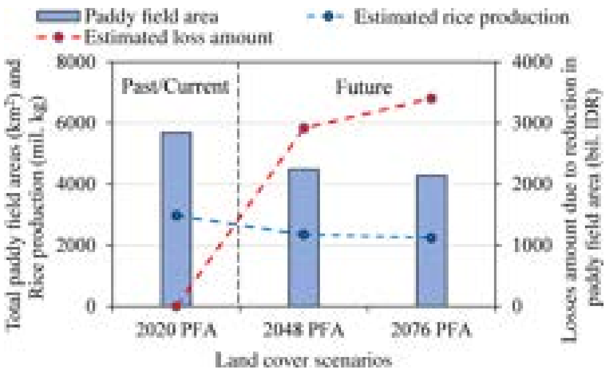


FIGURE 12 Estimated paddy areas, rice production, and losses amount in agriculture sector due to reduction in paddy field areas in the future.

were presented in this paper. The results from this study clearly indicated that flood inundation area in the study basin will increase in the future period (2075–2098) compared to the past period (1979–2002). More areas will be flooded with higher flood depths in the future. The increase in flood hazard area due to climate change has been reported for areas in Indonesia (Farid et al., 2023; Muis et al., 2015; Yamamoto, Kazama, et al., 2021) and for other river basins in Southeast Asia (Perera et al., 2017; Try et al., 2020). The peak of flood inundation volume for the future period in the study area was comparatively higher than that for the past period, which indicated that FD to agricultural products will be more significant in the future.

This study also clearly indicated that there will be losses in rice production or rice crops in the future due to both decreases in future PFA and the effect of climate change. The PFA in the study basin is decreasing in trend, which may cause a significant reduction in rice production in the area and adverse impacts on food security and rural livelihoods. Rice production in the future in the study area may decrease by more than 21% due to the conversion of PFA to SBA and other LULC classes, which indicates the urgent necessity of land-use planning for agriculture.

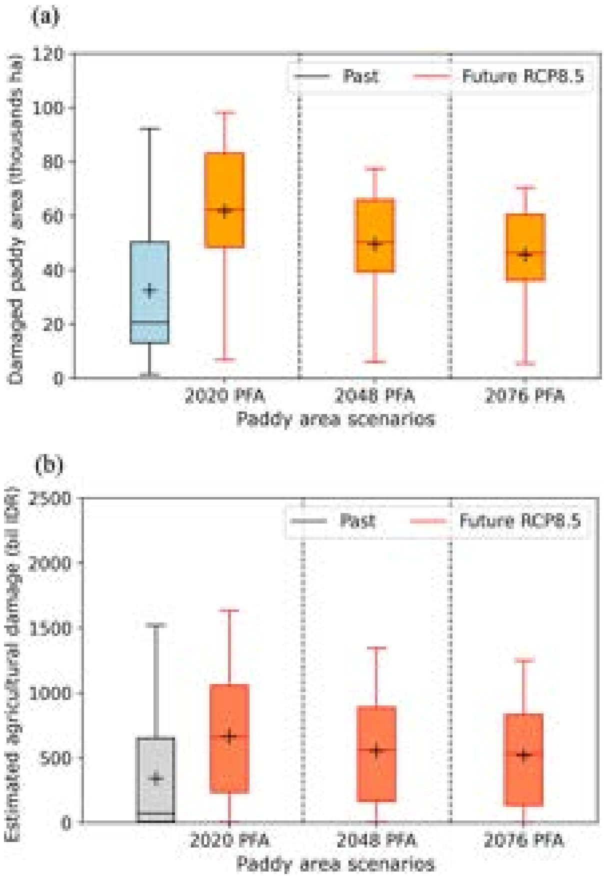


FIGURE 13 (a) Calculated damage paddy areas and (b) estimated value of rice crop damage for the past climate period (1979–2002) using 2020 paddy field areas and future climate period (2075–2098) using 2020, 2048, and 2076 paddy field areas.

TABLE 2 Calculated average damaged paddy area and value for past and future periods and percentage change in future.

	Past period (1979–2002)	Future period (2075–2098)		
	Using 2020 PFA	Using 2020 PFA	Using 2048 PFA	Using 2076 PFA
Average damaged paddy area per year (ha)	32,547.3	61,799.3 (89.8% increase)	49,536.2 (52.2% increase)	45,629.8 (40.2% increase)
Average damaged value per year (billion IDR)	343.7	666.08 (93.7% increase)	554.2 (61.2% increase)	518.2 (50.7% increase)

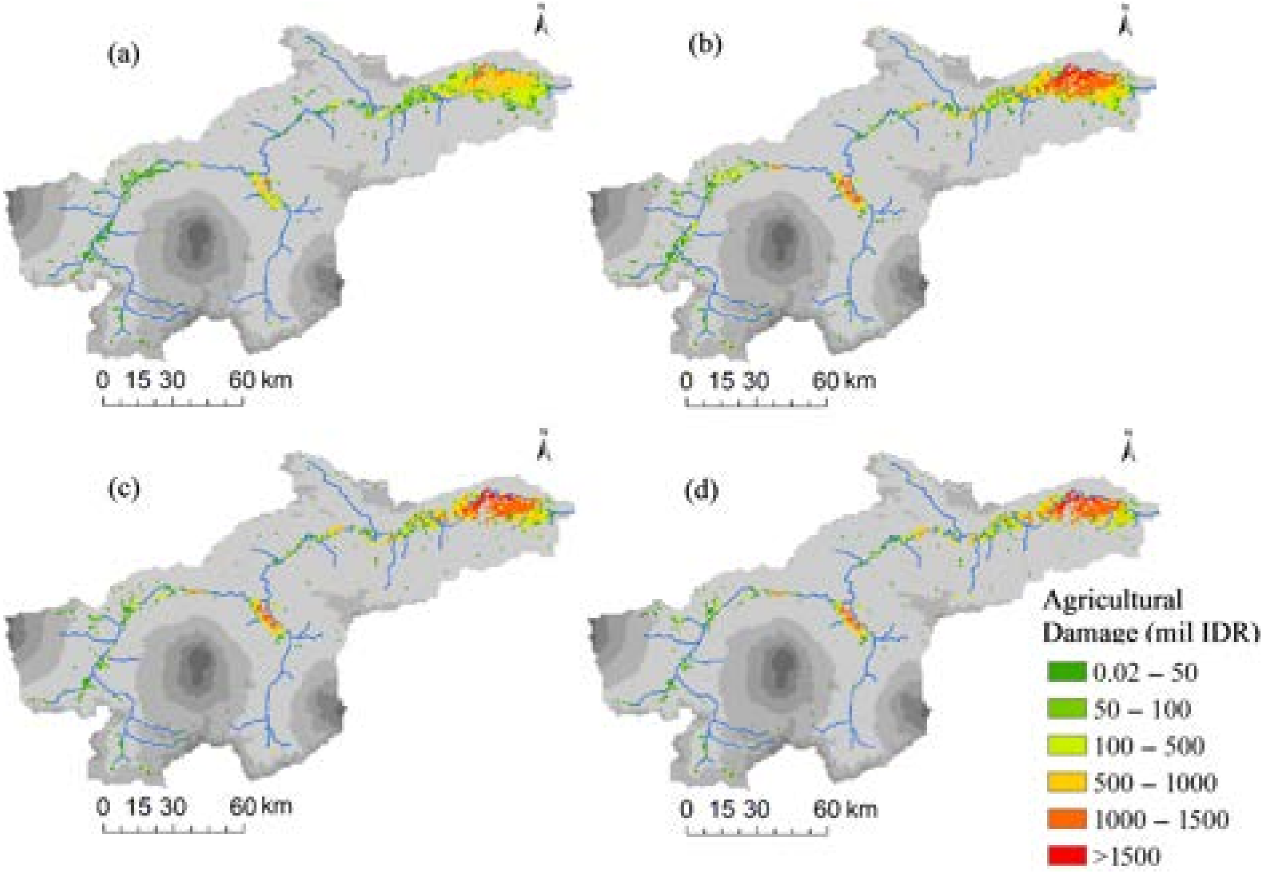


FIGURE 14 Spatial distribution of calculated average damage value for past and future climate periods: (a) past period using 2020 paddy field areas, (b) future period using 2020 paddy field areas, (c) future period using 2048 paddy field areas, and (d) future period using 2076 paddy field areas.

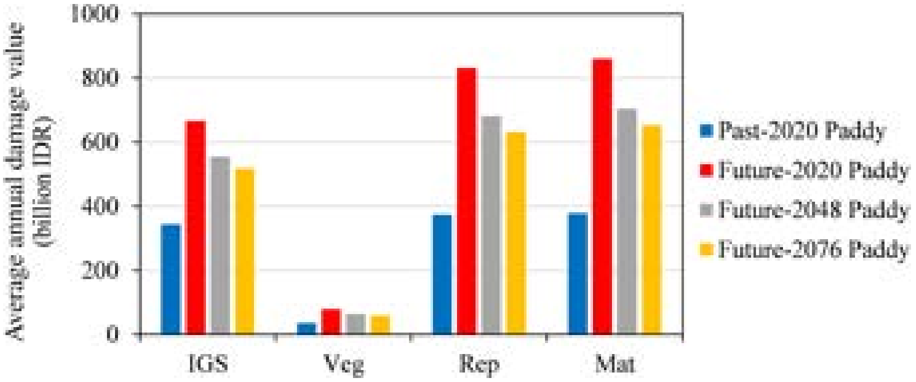


FIGURE 15 Calculated average annual damage values of rice crops per year for past and future periods for different growth stage scenarios (IGS, the identified growth stage of rice crops based on the cropping calendar and the timing of flooding; Mat, maturity stage; Rep, reproductive stage; Veg, vegetative stage).

FD to rice crops in the study basin will increase in the future period (2075–2098) compared to the past period (1979–2002), if climate change mitigation and adaptation measures are not put into action. Our study showed that the average annual damage value of rice crops (per year) for the study area may increase in the future period by 93.7% due to climate change impacts alone, if there are no changes in PFA in the future. The average annual damage value of rice crops (per year) may increase in the future by more than 50%, if both climate change effects and changes in future PFA are considered. This reduction in percentage increase is due to a decrease in PFA in the future. Januriyadi et al. (2018) also reported that the mean value of expected annual damage of agricultural, housing, and manufacturing and service sectors in the Jakarta area of Indonesia may increase by 72%–127% only due to climate change alone during the future period (2051–2100). The study by Bouwer et al. (2010) showed that climate change may lead to an increase in expected losses by 46%–201% by 2040 in a Dutch Polder area, if no mitigation measures are put into action to reduce the losses. Yamamoto, Sayama, et al. (2021) reported that the expected annual flood damage to general property and agriculture in Japan may increase in the future (in the late 21st century) by more than 57% under the RCP8.5 scenario. Syldon et al. (2024) reported that rice crop damage value may increase by more than 4 times in the far-future period in the region of Bhutan.

FD and risk in the future can be reduced and managed through mitigation and adaptation strategies. A combination of climate change mitigation and adaptation measures can be more effective in reducing the FD in future (Yamamoto, Sayama, et al., 2021). The finding of this study can be useful for implementing the local level adaptation measures, such as land-use regulation, implementation of flood-protection measures, and adequate drainage capacity, to further reduce the losses in the future. Furthermore, FD to rice crops can be reduced by altering the cropping calendar or using submergence-tolerant rice varieties in flood-prone areas during the monsoon. Changes in FD to rice crops in the future will also depend on the timing of flooding or the growth stage of rice crops during flooding (Merz et al., 2010) and how local farmers adapt or plan a cropping calendar. The results of rice crop damage with various possible growth stage scenarios indicated that the rice crop damage value could be higher if flooding occurs during the maturity stage than if it does during the other growth stages. The presented results of rice crop damage with different scenarios of rice crop growth stages could help local farmers establish a cropping calendar that helps them avoid flooding or minimizes damage.

The results of FD assessment in this study can be useful to understand future flood hazards and damage conditions and help implement mitigation and adaptation actions to climate change as well as to plan land-use regulations. The results of FD assessment can provide information on flood hazards and damage that could help policymakers and decision-makers establish the policies and strategies required for disaster risk reduction activities. In this study, FD to rice crops for the future period was estimated based on the current farm gate value of rice product, because of the limited availability of data and information on the future conditions of the study area. This study considered the impact of climate change on flood runoff or inundation to assess agricultural damage. However, LULC changes may also impact on catchment hydrology and contribute to runoff change. Therefore, it is recommended that the impact of LULC changes or the combined effect of LULC changes and climate change on runoff and inundation should also be investigated in further studies, although previous studies have reported that the impact of LULC changes on hydrological response is relatively less in large catchments than in small catchments (Aragaw et al., 2021: Kayitesi et al., 2022). Additionally, this study used MRI-AGCM climate model outputs for far-future; however, it is also recommended that more ensemble data and other GCM model experiment outputs be used to evaluate uncertainty in further research for better understanding of the impacts of climate change. We also recommend further study to investigate climate change impact on agricultural damage for near-future term.

6 | CONCLUSIONS

We quantitatively analyzed potential FD to rice crops under climate change impact, considering changes in the PFA in the future in the SRB in Indonesia. We also analyzed possible changes in PFA in the future and reduction in rice production due to a decrease in PFA in the future. We employed MRI-AGCM3.2S climate model outputs for assessing climate change impact on rice crops for the past (1979–2002) and far-future (2075–2098) climate periods.

This study revealed that both climate change and reduction in future PFAs will severely impact rice production in the study area. Large paddy areas will be frequently flooded with greater flood inundation volume in the future in the study area due to climate change impact if no mitigation and adaptation measures are taken into action, which will result in significant losses or damage in the agriculture sector, affecting the livelihoods of the people living in flood-prone areas. The findings of this study indicated that more frequent floods with increased risks to rice crops are expected in the future due to climate change impact. With increase in inundation area and volume under the RCP8.5 scenario, FD to rice crops will also increase significantly in the future period, particularly in PFA located in lowland areas. The increase in average rice crop damage value per year in the far-future period is expected to be more than 93% higher than that in the past period. The findings also indicated that the PFA will decrease in the future, which may also lead to a significant reduction in rice production in the future (decline by more than 21%). The estimated results of rice production based on the current and projected future PFAs clearly show that rice production may decrease significantly in the future due to the conversion of PFA to other LULC classes, affecting food security and increasing the impact on the livelihoods of the people living in the area.

With the increase in flood characteristics and decrease in PFA, rice production is expected to decline significantly in the future. The estimation of FD in monetary values for the future period, considering changes in PFA for the future, contributes to understanding how climate change and changes in PFA will impact rice production, helping society to further implement adaptation measures to reduce the damage more effectively. To reduce the losses in rice production or rice crop damage in future, adaptation measures at the local level, together with land-use regulations, should be planned and implemented in the study area. The estimation of rice crop damage with different scenarios of growth stages also indicates that we can consider changing the rice cropping patterns and the use of flood submergence-tolerant rice varieties in flood-prone area to reduce the damage in future.

ACKNOWLEDGMENTS

This research was supported by program for the Advanced Studies of Climate Change Projection (SENTAN) (Grant Number JPMXD0722678534) funded by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The authors would like to thank the Research and Development Center for Water Resources, the Ministry of Public Works and Housing, Indonesia, for providing rainfall and discharge data, and the Directorate of Forest Resources Inventory and Monitoring and the Directorate General of Forestry Planning and Environmental Administration, the Ministry of Environment and Forestry, Indonesia, for providing land cover map data for the study area.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The sources data that support the findings of this study are available from the related organizations and the sources mentioned in this article.

ORCID

Badri Bhakta Shrestha https://orcid.org/0000-0002-1250-1596

REFERENCES

Abbas, Z., Yang, G., Zhong, Y., & Zhao, Y. (2021). Spatiotemporal change analysis and future scenario of LULC using the CA-ANN approach: A case study of the Greater Bay Area, China. *Land*, *10*, 584. https://doi.org/10.3390/land10060584

Alfieri, L., Feyen, L., Dottori, F., & Bianchi, A. (2015). Ensemble flood risk assessment in Europe under high end climate scenarios. *Global Environmental Change*, *35*, 199–212. https://doi.org/10.1016/j.gloenvcha.2015.09.004

Aragaw, H. M., Goel, M. K., & Mishra, S. K. (2021). Hydrological responses to human-induced land use/land cover changes in the Gidabo River basin, Ethiopia. *Hydrological Sciences Journal*, *66*(4), 640–655. https://doi.org/10.1080/02626667.2021.1890328

Baig, M. F., Mustafa, M. R. U., Baig, I., Takaijudin, H. B., & Zeshan, M. T. (2022). Assessment of land use land cover changes and future predictions using CA-ANN simulation for Selangor, Malaysia. *Water*, *14*, 402. https://doi.org/10.3390/w14030402

Binutha, R., & Somashekar, R. K. (2014). Future prediction of land cover in Devikulam taluk, Kerala. *International Journal of Science and Nature*, *5*(4), 677–683.

Bouwer, L. M., Bubeck, P., & Aerts, J. C. J. H. (2010). Changes in future flood risk due to climate and development in a Dutch polder area. *Global Environmental Change*, *20*, 463–471. https://doi.org/10.1016/j.gloenvcha.2010.04.002

Brémond, P., Grelot, F., & Agenais, A.-L. (2013). Economic evaluation of flood damage to agriculture – Review and analysis of existing methods. *Natural Hazards and Earth System Sciences*, *13*, 2493–2512. https://doi.org/10.5194/nhess-13-2493-2013

Budiyono, Y., Aerts, J. C. J. H., Tollenaar, D., & Ward, P. J. (2016). River flood risk in Jakarta under scenarios of future change. *Natural Hazards and Earth System Sciences*, *16*, 757–774. https://doi.org/10.5194/nhess-16-757-2016

Chen, Y.-J., Lin, H.-J., Liou, J.-J., Cheng, C.-T., & Chen, Y.-M. (2022). Assessment of flood risk under climate change RCP8.5 scenarios in Taiwan. *Water*, *14*, 207. https://doi.org/10.3390/w14020207

Dawid, W., & Bielecka, E. (2022). GIS-based land cover analysis and prediction based on open-source software and data. *Quaestiones Geographicae*, *41*(3), 75–86. https://doi.org/10.2478/quageo-2022-0026

Department of Settlement and Regional Infrastructure (DSRI). (2001). *Comprehensive development and management plan study for Bengawan Solo River basin under lower Solo River improvement project. Project report of Bengawan Solo River basin development project*. Department of Settlement and Regional Infrastructure, Directorate General of Water Resources, Indonesia.

Directorate of Food Crop Protection (DFCP). (2010). *Indonesia broad flood damage in rice plant: Solo River basin*. Flood Damage Data Published by the Directorate of Food Crop Protection.

Dutta, D., Herath, S., & Musiake, K. (2003). A mathematical model for flood loss estimation. *Journal of Hydrology*, *277*, 24–49. https://doi.org/10.1016/S0022-1694(03)00084-2

Farid, M., Sihombing, Y. I., Kuntoto, A. A., Adityawan, M. B., Syuhada, M. M., Januriyadi, N. F., Moe, I. R., & Nurhakim, A. (2023). Development of flood hazard index under climate change scenarios in Java Island. *Progress in Disaster Science*, *20*, 100302. https://doi.org/10.1016/j.pdisas.2023.100302

Global Rice Science Partnership (GRiSP). (2013). *Rice almanac* (4th ed., p. 283). International Rice Research Institute.

Hanif, A., Dhanasekar, A., Keene, A., Li, H., & Carlson, K. (2020). Flood risk assessment methodology for planning under climate change scenarios and the corresponding change in land cover. *Journal of Water and Climate Change*, *11*(4), 1370–1382. https://doi.org/10.2166/wcc.2019.016

Hendrawan, V. S. A., & Komori, D. (2021). Developing flood vulnerability curve for rice crop using remote sensing and hydrodynamic modeling. *International Journal of Disaster Risk Reduction*, *54*, 102058. https://doi.org/10.1016/j.ijdrr.2021.102058

Hidayat, F., Sungguh, H. M., & Harianto. (2008). *Impact of climate change on floods in Bengawan solo and Brantas River basins, Indonesia*. Proceeding of the 11th international Riversymposium September 1–4, 2008 Brisbane, Australia.

Huynh, H. T. L., Thi, L. N., & Hoang, N. D. (2020). Assessing the impact of climate change on agriculture in Quang Nam Province, Viet Nam using modeling approach. *International Journal of Climate Change Strategies and Management*, *12*(5), 757–771. https://doi.org/10.1108/IJCCSM-03-2020-0027

Ito, R., Nakaegawa, T., & Takayabu, I. (2020). Comparison of regional characteristics of land precipitation climatology projected by an MRI-AGCM multi-cumulus scheme and multi-SST ensemble with CMIP5 multi-model ensemble projections. *Progress in Earth and Planetary Science*, *7*, 77. https://doi.org/10.1186/s40645-020-00394-4

Iwami, Y., Hasegawa, A., Miyamoto, M., Kudo, S., Yusuke, Y., Ushiyama, T., & Koike, T. (2017). Comparative study on climate change impact on precipitation and floods in Asian river basins. *Hydrological Research Letters*, *11*(1), 24–30. https://doi.org/10.3178/hrl.11.24

Januriyadi, N. F., Kazama, S., Moe, I. R., & Kure, S. (2018). Evaluation of future flood risk in Asian megacities: A case study of Jakarta. *Hydrological Research Letters*, *12*(3), 14–22. https://doi.org/10.3178/hrl.12.14

Jayasinghe, P., Kantakumar, L. N., Raghavan, V., & Yonezawa, G. (2020). *Comparative evaluation of urban growth models*. GEOINFORUM-2020, 15–16. http://www.jsgi-map.org/geoinforum2020/08.pdf

Jongman, B., Kreibich, H., Apel, H., Barredo, J. I., Bates, P. D., Feyen, L., Gericke, A., Neal, J., Aerts, J. C. J. H., & Ward, P. J. (2012). Comparative flood damage model assessment: Towards a European approach. *Natural Hazards and Earth System Sciences*, *12*, 3733–3752. https://doi.org/10.5194/nhess-12-3733-2012

Kafy, A.-A., Naim, M. N. H., Subramanyam, G., Faisal, A.-A., Ahmed, N. U., Rakib, A. A., Kona, M. A., & Sattar, G. S. (2021). Cellular automata approach in dynamic modelling of land cover changes using RapidEye images in Dhaka, Bangladesh. *Environmental Challenges*, *4*, 100084. https://doi.org/10.1016/j.envc.2021.100084

Kamaraj, M., & Rangarajan, S. (2022). Predicting the future land use and land cover changes for Bhavani basin, Tamil Nadu, India, using QGIS MOLUSCE plugin. *Environmental Science and Pollution Research*, *29*, 86337–86348. https://doi.org/10.1007/s11356-021-17904-6

Kayitesi, N. M., Guzha, A. C., & Mariethoz, G. (2022). Impacts of land use land cover change and climate change on river hydromorphology – A review of research studies in tropical regions. *Journal of Hydrology*, *615*, 128702. https://doi.org/10.1016/j.jhydrol.2022.128702

Khiem, M. V., Hoang, T. T., Quy, P. T. D., Linh, H. T. M., Toan, H. C., Long, P. T., & Hang, N. T. T. (2019). Flooding impacts on rice cultivation area under climate change in Tra Vinh province. *Journal of Climate Change Science*, *9*, 68–76.

Kitoh, A., & Endo, H. (2016). Changes in precipitation extremes projected by a 20-km mesh global atmospheric model. *Weather and Climate Extremes*, *11*, 41–52. https://doi.org/10.1016/j.wace.2015.09.001

Loo, Y. Y., Billa, L., & Singh, A. (2015). Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers*, *6*, 817–823. https://doi.org/10.1016/j.gsf.2014.02.009

Löschner, L., Herrnegger, M., Apperl, B., Senoner, T., Seher, W., & Nachtnebel, H. P. (2017). Flood risk, climate change and settlement development: A micro-scale assessment of Austrian municipalities. *Regional Environmental Change*, *17*, 311–322. https://doi.org/10.1007/s10113-016-1009-0

Lukas, P., Melesse, A. M., & Kenea, T. T. (2023). Prediction of future land use/land cover changes using a coupled CA-ANN model in the upper Omo–Gibe River basin, Ethiopia. *Remote Sensing*, *15*, 1148. https://doi.org/10.3390/rs15041148

Lv, J. (2017). *Using historical remote sensing image to predict future land use in Panjin City, China*. AIP Conference Proceedings, 1864, 020175. https://doi.org/10.1063/1.4992992

Merz, B., Kreibich, H., Schwarze, R., & Thieken, A. (2010). Assessment of economic flood damage. *Natural Hazards and Earth System Sciences*, *10*, 1697–1724. https://doi.org/10.5194/nhess-10-1697-2010

Ministry of Environment and Forestry (MoEF). (2023). *Method of land cover mapping*. Ministry of Environment and Forestry, Indonesia. https://nfms.menlhk.go.id/metode

Mishra, B. K., Emam, A. R., Masago, Y., Kumar, P., Regmi, R. K., & Fukushi, K. (2018). Assessment of future flood inundations under climate and land use change scenarios in the Ciliwung River basin, Jakarta. *Journal of Flood Risk Management*, *11*, S1105–S1115. https://doi.org/10.1111/jfr3.12311

Mizuta, R., Yoshimura, H., Murakami, H., Matsueda, M., Endo, H., Ose, T., Kamiguchi, K., Hosaka, M., Sugi, M., Yukimoto, S., Kusunoki, S., & Kitoh, A. (2012). Climate simulations using MRI-AGCM3.2 with 20-km grid. *Journal of the Meteorological Society of Japan*, *90A*, 233–258. https://doi.org/10.2151/jmsj.2012-A12

Muhammad, R., Zhang, W., Abbas, Z., Guo, F., & Gwiazdzinski, L. (2022). Spatiotemporal change analysis and prediction of future land use and land cover changes using QGIS MOLUSCE plugin and remote sensing big data: A case study of Linyi, China. *Land*, *11*, 419. https://doi.org/10.3390/land11030419

Muis, S., Güneralp, B., Jongman, B., Aerts, J. C. J. H., & Ward, P. J. (2015). Flood risk and adaptation strategies under climate change and urban expansion: A probabilistic analysis using global data. *Science of the Total Environment*, *538*, 445–457. https://doi.org/10.1016/j.scitotenv.2015.08.068

Nath, B., Wang, Z., Ge, Y., Islam, K., Singh, R. P., & Niu, Z. (2020). Land use and land cover change modeling and future potential landscape risk assessment using Markov-CA model and analytical hierarchy process. *ISPRS International Journal of Geo-Information*, *9*, 134. https://doi.org/10.3390/ijgi9020134

Nguyen, N. Y., Kha, D. D., & Ichikawa, Y. (2021). Developing a multivariable lookup table function for estimating flood damages of rice crop in Vietnam using a secondary research approach. *International Journal of Disaster Risk Reduction*, *58*, 102208. https://doi.org/10.1016/j.ijdrr.2021.102208

Pandey, S., Kumari, N., & Al Nawajish, S. (2023). Land use land cover (LULC) and surface water quality assessment in and around selected dams of Jharkhand using water quality index (WQI) and geographic information system (GIS). *Journal of the Geological Society of India*, *99*, 205–218. https://doi.org/10.1007/s12594-023-2288-y

Pandi, D., Kothandaraman, S., Kumarasamy, M. V., & Kuppusamy, M. (2022). Assessment of land use and land cover dynamics using geospatial techniques. *Polish Journal of Environmental Studies*, *31*(3), 2779–2786. https://doi.org/10.15244/pjoes/141810

Panuju, D. R., Mizuno, K., & Trisasongko, B. H. (2013). The dynamics of rice production in Indonesia 1961–2009. *Journal of the Saudi Society of Agricultural Sciences*, *12*, 27–37. https://doi.org/10.1016/j.jssas.2012.05.002

Perera, E. D. P., Sayama, T., Magome, J., Hasegawa, A., & Iwami, Y. (2017). RCP8.5-based future flood hazard analysis for the lower Mekong River basin. *Hydrology*, *4*(4), 55. https://doi.org/10.3390/hydrology4040055

Perović, V., Jakšić, D., Jaramaz, D., Koković, N., Čakmak, D., Mitrović, M., & Pavlović, P. (2018). Spatio-temporal analysis of land use/land cover change and its effects on soil erosion (case study in the Oplenac wine-producing area, Serbia). *Environmental Monitoring and Assessment*, *190*, 675. https://doi.org/10.1007/s10661-018-7025-4

Rasmy, M., Sayama, T., & Koike, T. (2019). Development of water and energy budget-based rainfall-runoff-inundation model (WEB-RRI) and its verification in the Kalu and Mundeni River basins, Sri Lanka. *Journal of Hydrology*, *579*, 124163. https://doi.org/10.1016/j.jhydrol.2019.124163

Rojas, R., Feyen, L., & Watkiss, P. (2013). Climate change and river floods in the European Union: Socio-economic consequences and the costs and benefits of adaptation. *Global Environmental Change*, *23*, 1737–1751. https://doi.org/10.1016/j.gloenvcha.2013.08.006

Samantaray, D., Chatterjee, C., Singh, R., Gupta, P. K., & Panigrahy, S. (2015). Flood risk modeling for optimal rice planning for delta region of Mahanadi river basin in India. *Natural Hazards*, *76*, 347–372. https://doi.org/10.1007/s11069-014-1493-9

Sayama, T., Ozawa, G., Kawakami, T., Nabesaka, S., & Fukami, K. (2012). Rainfall-runoff-inundation analysis of the 2010 Pakistan flood in the Kabul River basin. *Hydrological Sciences Journal*, *57*, 298–312. https://doi.org/10.1080/02626667.2011.644245

Shrestha, B. B. (2019). Approach for analysis of land-cover changes and their impact on flooding regime. *Quaternary*, *2*, 27. https://doi.org/10.3390/quat2030027

Shrestha, B. B., & Kawasaki, A. (2020). Quantitative assessment of flood risk with evaluation of the effectiveness of dam operation for flood control: A case of the Bago River basin of Myanmar. *International Journal of Disaster Risk Reduction*, *50*, 101707. https://doi.org/10.1016/j.ijdrr.2020.101707

Shrestha, B. B., Kawasaki, A., & Zin, W. W. (2021). Development of flood damage functions for agricultural crops and their applicability in regions of Asia. *Journal of Hydrology: Regional Studies*, *36*, 100872. https://doi.org/10.1016/j.ejrh.2021.100872

Shrestha, B. B., Okazumi, T., Miyamoto, M., & Sawano, H. (2016). Flood damage assessment in the Pampanga River basin of The Philippines. *Journal of Flood Risk Management*, *9*(4), 355–369. https://doi.org/10.1111/jfr3.12174

Syldon, P., Shrestha, B. B., Miyamoto, M., Tamakawa, K., & Nakamura, S. (2024). Assessing the impact of climate change on flood inundation and agriculture in the Himalayan mountainous region of Bhutan. *Journal of Hydrology: Regional Studies*, *52*, 101687. https://doi.org/10.1016/j.ejrh.2024.101687

Tadese, S., Soromessa, T., & Bekele, T. (2021). Analysis of the current and future prediction of land use/land cover change using remote sensing and the CA-Markov model in Majang Forest biosphere reserves of Gambella, southwestern Ethiopia. *The Scientific World Journal*, *2021*, 6685045. https://doi.org/10.1155/2021/6685045

Tanaka, T., Tachikawa, Y., Ichikawa, Y., & Yorozu, K. (2018). Flood risk curve development with probabilistic rainfall modelling and large ensemble climate simulation data: A case study for the Yodo River basin. *Hydrological Research Letters*, *12*(4), 28–33. https://doi.org/10.3178/hrl.12.28

Thom, W. (2014). *Indonesia Grain and Feed Annual: Indonesia grain and feed annual report 2014*. GAIN Report Number ID1407.

Toosi, A. S., Doulabian, S., Tousi, E. G., Calbimonte, G. H., & Alaghmand, S. (2020). Large-scale flood hazard assessment under climate change: A case study. *Ecological Engineering*, *147*, 105765. https://doi.org/10.1016/j.ecoleng.2020.105765

Try, S., Tanaka, S., Tanaka, T., Sayama, T., Lee, G., & Oeurng, C. (2020). Assessing the effects of climate change on flood inundation in the lower Mekong Basin using high-resolution AGCM outputs. *Progress in Earth and Planetary Science*, *7*, 34. https://doi.org/10.1186/s40645-020-00353-z

Tsuboi, T. (2012). *Upland rice cultivation guide*. Japan International Cooperation Agency. https://www.jica.go.jp/Resource/activities/issues/agricul/approach/ku57pq00002m21du-att/handbook_02.pdf

Tsujimoto, K., Kuriya, N., Ohta, T., Homma, K., & Im, M. S. (2022). Quantifying the GCM-related uncertainty for climate change impact assessment of rainfed rice production in Cambodia by a combined hydrologic – Rice growth model. *Ecological Modeling*, *464*, 109815. https://doi.org/10.1016/j.ecolmodel.2021.109815

UNISDR—United Nations International Strategy for Disaster Reduction. (2009). *UNISDR terminology on disaster risk reduction*. United Nations.

Vivas, E., Allende-Cid, H., & Salas, R. (2020). A systematic review of statistical and mahine learning methods for electrical power forecasting with reported MAPE score. *Entropy*, *22*, 1412. https://doi.org/10.3390/e22121412

Win, S., Zin, W. W., & Kawasaki, A. (2020). Development of flood damage estimation model for agriculture – Case study in the Bago floodplain, Myanmar. *Journal of Disaster Research*, *15*(3), 242–255. https://doi.org/10.20965/jdr.2020.p0242

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., & Kousky, C. (2022). Ineauitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, *12*, 156–162. https://doi.org/10.1038/s41558-021-01265-6

Wobus, C., Gutmann, E., Jones, R., Rissing, M., Mizukami, N., Lorie, M., Mahoney, H., Wood, A. W., Mills, D., & Martinich, J. (2017). Climate change impacts on flood risk and asset damages within mapped 100-year floodplains of the contiguous United States. *Natural Hazards and Earth System Sciences*, *17*, 2199–2211. https://doi.org/10.5194/nhess-17-2199-2017

Yamamoto, K., Sayama, T., & Apip. (2021). Impact of climate change on flood inundation in a tropical river basin in Indonesia. *Progress in Earth and Planetary Science*, *8*, 5. https://doi.org/10.1186/s40645-020-00386-4

Yamamoto, T., Kazama, S., Touge, Y., Yanagihara, H., Tada, T., Yamashita, T., & Takizawa, H. (2021). Evaluation of flood damage reduction throughout Japan from adaptation measures taken under a range of emissions mitigation scenarios. *Climate Change*, *165*, 60. https://doi.org/10.1007/s10584-021-03081-5

Yuliyanto, F., Prasasti, I., Pasaribu, J. M., Fitriana, H. L., Zylshal, Z., Haryani, N. S., & Sofan, P. (2016). The dynamics of land use/land cover change modeling and their implication for the flood damage assessment in the Tondano watershed, North Sulawesi, Indonesia. *Modeling Earth Systems and Environment*, *2*, 47. https://doi.org/10.1007/s40808-016-0100-3

Zakaria, A., Aring, H. L. D., & Indriani, Y. (2004). *The impact of irrigation development on rice production in Lampung Province*. Research Report, University of Lampung.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Shrestha, B. B., Rasmy, M., Ushiyama, T., Acierto, R. A., Kawamoto, T., Fujikane, M., Shinya, T., & Kubota, K. (2025). Assessment of future risk of agricultural crop production under climate and social changes scenarios: A case of the Solo River basin in Indonesia. *Journal of Flood Risk Management*, *18*(1), e13052. https://doi.org/10.1111/jfr3.13052