Journal of Climate Change, Vol. 9, No. 4 (2023), pp. 13-23.
DOI 10.3233/JCC230028

Assessment of Flood Economic Losses Under Climate Change: A Case Study in the Ngan Sau River Basin, Ha Tinh Province and Vietnam

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Received August 10, 2023; revised and accepted September 30, 2023

Abstract: The Ngan Sau River basin, which is situated in Ha Tinh Province of Vietnam, experiences flooding during the rainy season, resulting in significant loss of property and human life. This research aimed to investigate the impact of climate change and land-use variation on flood losses. The study began by simulating the heavy rainfall events in August 2007 using the Weather Research and Forecast model with an ensemble method. Future rainfall was examined through numerical simulation based on pseudo-global warming constructed using six CMIP5 models (MIROC-ESM, MRI-CGM3, GISS-E2-H, HadGEM2-ES, HadGEM2-ES, and CNRM-CM5), and the variation in land-use was obtained from local authorities. Inundations caused by rainfall in 2007 and rainfall in the future were determined by the rainfall-runoff-inundation model. Finally, based on flood maps, land-use, and flood depth-damage functions, the economic losses were computed. The results of the average flood economic loss were \$380 million in CTL, whereas the local authorities report an estimated loss of over \$300 million. Under the impact of climate change and land-use variation, economic losses ranged from \$380 million to \$526 million in six CMIP5 models. The result of INMCM4 showed the highest value of \$526 million, the results of MRI-CGM3, GISS-E2-H, HadGEM2-ES, and CNRM-CM5 fluctuated around \$500 million, and the MIROC-ESM recorded the lowest at \$380 million. The damage maps showed that the losses would be highest in urban areas, followed by forest areas, and lowest in agricultural areas. This information is essential for decision-makers to improve solutions for preventing economic losses caused by floods.

Keywords: Climate change; Rainfall-runoff-inundation; Flood economic losses.

Introduction

Flooding is a natural disaster that occurs frequently across the globe. It is predicted that flood risks will continue to rise in the future (Hirabayashi, 2013). When there is too much rainfall in a watershed system, flooding occurs when the amount of water flowing in a stream exceeds the channel capacity. This can be caused by either heavy or prolonged rainfall (Dingman, 1994). Most developing countries in the world were affected by floods, especially in their deltaic regions. Therefore, flood damage assessment in these countries is very important and necessary. From 1986 to 2015, there were over 470 natural disasters, with total economic losses estimated at approximately 126 billion USD worldwide (Munich, 2016a). For example, total losses from natural disasters increased up to USD 175 billion in 2016 when compared to the averages of previous decades (Munich, 2016b). The increase in intensities and frequency of extreme weather events may be due to climate change (IPCC, 2012). The International Red Cross Organization's report reveals that more than 66 million people worldwide are affected by flood damage, either directly or indirectly. Flooding results in billions of dollars in infrastructure losses and the loss of thousands of lives annually (Koirala, 2013). To calculate flood losses in affected areas, it is essential to estimate the inundation of flood areas in the short period after the disaster. In recent years, using general circulation models (GCMs) and regional climate models (RCMs) to assess the impacts of climate change on extreme weather events has become more popular (Booij, 2005; Charles et al., 2007; Chiew & McMahon, 2002). Combining hydrological models and GCM models can simulate current and future flood frequencies, especially in countries where meteorological data are scarce (Haarsma et al., 1993; Tomkratoke & Sirisup, 2015).

The variation in heavy rainfall events caused by global warming and the increase in flood economic losses have been studied in several studies. The overall cost of flood damage is mentioned in these studies. Döll et al. (2014) showed that flood damage will double in Europe by the end of the 21st century (Döll et al., 2014). In Asia, the frequency of floods is expected to increase. For example, in the Lower Brahmaputra River basin, some policy-level expectations for policymakers and government agencies have been established (Gain & Hoque, 2013).

Vietnam is one of the countries that has been strongly impacted by climate change. Floods are caused by factors such as heavy rainfall, typhoons, and sea level rise. In 2013, fourteen hurricanes, five tropical depressions, and three major storms made landfall directly in Vietnam. In 2020, natural disasters caused heavy losses in the Vietnam Central Region: 357 dead or missing, 876 injured, 511,172 submerged houses, and 3,429 collapsed houses. These storms and floods occurred consecutively and are considered the worst disasters to hit the Central region in the past 100 years. Storms with heavy rain also cause severe floods, leading to enormous destruction accounting for approximately 0.75% of Vietnam's GDP.

This study focusses on the flood economic losses in the Ngan Sau River basin, Ha Tinh Province, Vietnam, during the flood event in August 2007. To investigate the impact of climate change and land-use variation on these losses, we first created a flood map using meteorological data and the rainfall-runoff-inundation model (RRI). We then used a damage function to calculate the losses in the present and future. To prepare for potential climate changes in the future, we employed six CMIP5 GCM models. Based on these results, we were able to determine the impact of climate change and land-use on flood economic damage.

This paper's structure is as follows: Data and Methodology (section) presents the data and methodology. Models (section) shows the calculation results of flood damage. Finally, the conclusion summarises the whole study.

Data and Methodology

Methodology

We estimate damage in the future and different types of damage by combining scenarios for climate change projections and land-use change (Figure 1). The losses are based on land-use types and inundation depth. This approach is applied to a case study in the Ngan Sau River Basin, Ha Tinh Province, Vietnam.

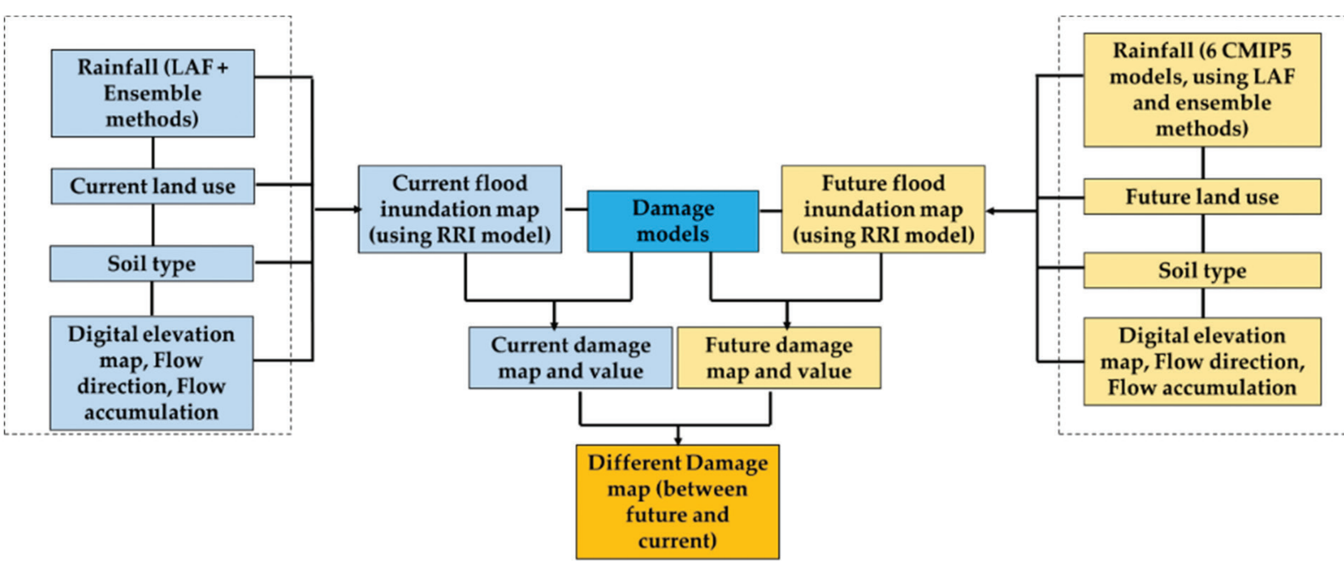

Figure 1: The methodology flowchart.

Catchment Overview

The Ngan Sau River is approximately 131 km long. The basin area is 3,214 km^2, with an average height of 360 m, an average slope of 28.2%, and a river density of 0.87 km/km^2. The annual average flow is 195 m^3/s, and the flow rate is 47 l/s. km^2. The rainy season is from September to November, with approximately 56-57% of the annual flow. Figure 2 shows the research area.

Models

Weather Research and Forecasting Model (WRF)

The WRF model version 3.6.1 was adopted for the control run (CTL) and pseudo global warming (PGW) simulations. A two-way nesting grid system was used, as shown in Figure 3. The coarsest domain, D01, had a 30 km horizontal resolution, and the higher resolution domain, D02, had a 6 km horizontal resolution.

To assess the effects of global warming in the future, simulations with coupled atmosphere-ocean global climate models (AOGCMs) are often used. However, the spatial resolution of the AOGCM is too coarse for investigating the detailed changes in extremely heavy rain events. Therefore, even if a heavy rainfall event is found in a future climate scenario as an AOGCM result, a detailed analysis is difficult. The pseudo-global warming (PGW) method (Sato et al., 2007) provides not only a higher resolution but also future variations based on reliable simulations using reanalysis data. Therefore, the PGW downscaling approach was applied to investigate the future variation in a heavy rain event. In this study, the heavy rainfall in August 2007 was selected. To assess future global warming, we use future climate projections by 6 CMIP5 GCM models (Taylor et al., 2012) with the RCP8.5 scenario and list them in Table 1.

The ensemble method was implemented for the reproductive simulation (hereafter, CTL) and each PGW simulation to reduce model uncertainties. For more details on this methodology, refer to Tran and Taniguchi (2016).

Rainfall-Runoff-Inundation Model (RRI)

The RRI model, a two-dimensional model (2D) that can simulate both rainfall-runoff and flood inundation processes (Sayama et al., 2012), is used to simulate flood events in the Ngan Sau River basin. Figure 4 shows the schematic diagram of the RRI model. The RRI model tracks the flow based on 2D diffusive wave equations regardless of topography. Vertical

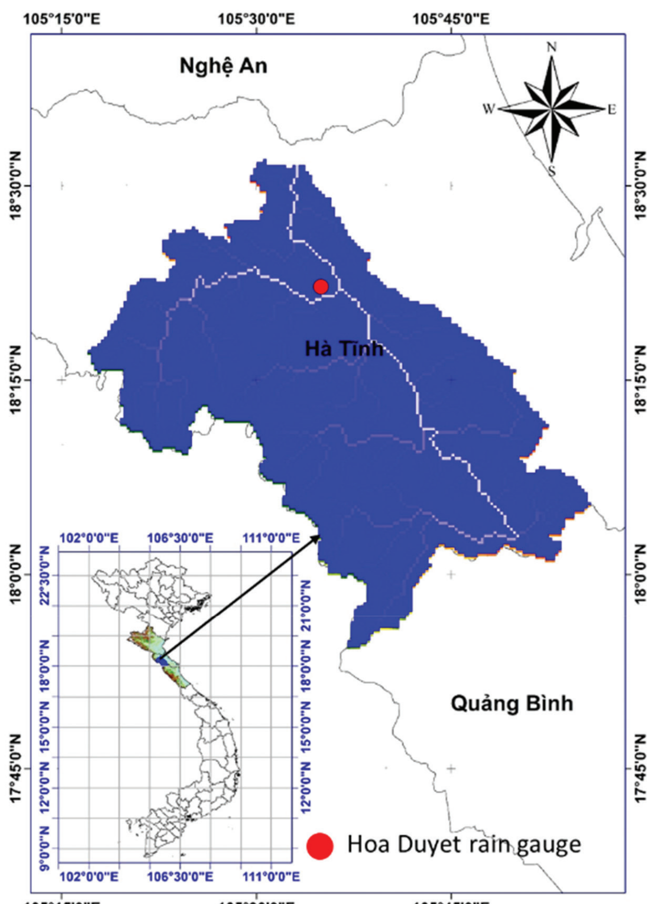

Figure 2: The location of the Ngan Sau river basin.

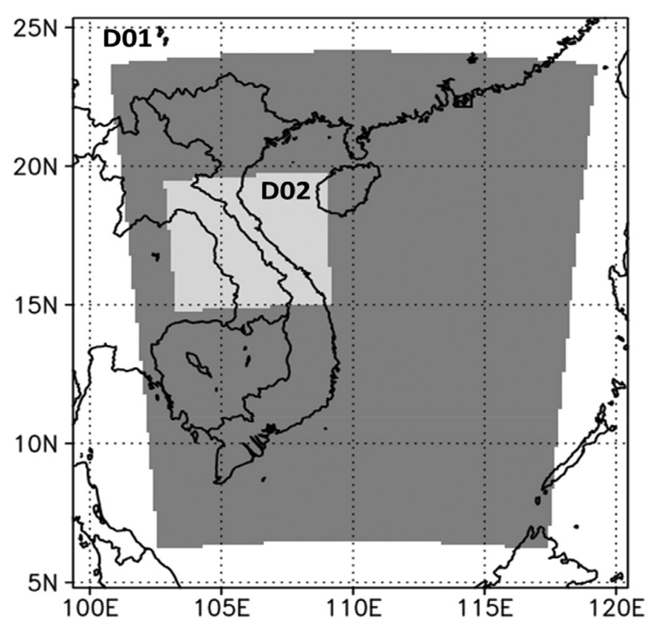

Figure 3: Target domains of downscaling in the Weather Research and Forecasting (WRF) model. The spatial resolutions are 30 km and 10 km for D01 and D02, respectively.

Table 1: List of the CMIP5 models used for analysis

CMIP5-RCP8.5_ID	*Institute*	*Country*
MIROC-ESM	Center for Climate System Research (the University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change	Japan
MRI-CGCM3	Meteorological Research Institute	Japan
INMCM4	Institute for Numerical Mathematics	Russia
GISS-E2-H	NASA/Goddard Institute for Space Studies	United States
CNRM_CM5	Meteo-France, Centre Nationale de Recherches Meteorologique	France
HadGEM2-ES	Hadley Center for Climate Prediction and Research, Met Office	United Kingdom

infiltration flow is estimated by using the Green-Ampt model (Kidwell et al., 1997; Sayama et al., 2015). The channel flow is calculated with a one-dimensional diffusive wave model, whose lateral inflow and outflow or overbank flow are estimated by coupling with the 2D land model. The flow interaction between the river channel and slope is determined at each time step based on different overflowing formulations, depending on water-level and levee-height conditions.

The river depths D (m) and widths W (m) were approximated by following equations (1) and (2):

$$W = C_W A^{S_W} \tag{1}$$

$$D = C_D A^{S_D} \tag{2}$$

where A is an upstream contributing area (km^2). C_W, S_W, C_D and S_D are geometric parameters. The parameters in equations (1) and (2) were estimated from regression analysis at several locations in the Ngan Sau River watershed based on Google Earth images and local technical reports. The obtained parameters were C_W = 6.25, S_W = 0.225, C_D = 3.75 and S_D = 0.175.

Data

Topographic Information

The USGS HydroSHEDS topography data were used in the RRI model. The dataset includes elevation, flow direction, and flow accumulation with 15 arc-second resolution (approximately 500 m). Figure 5 shows the topography input data.

Landuse

In this study, we used the High-Resolution Land Use and Land Cover (LULC) map of the central region of Vietnam provided by the Japan Aerospace Exploration Agency (JAXA). Original land cover data are too detailed to assign all different parameters; therefore, similar land cover types were merged into three categories: cropland, urban-built-up and forest, as shown in Figure 6.

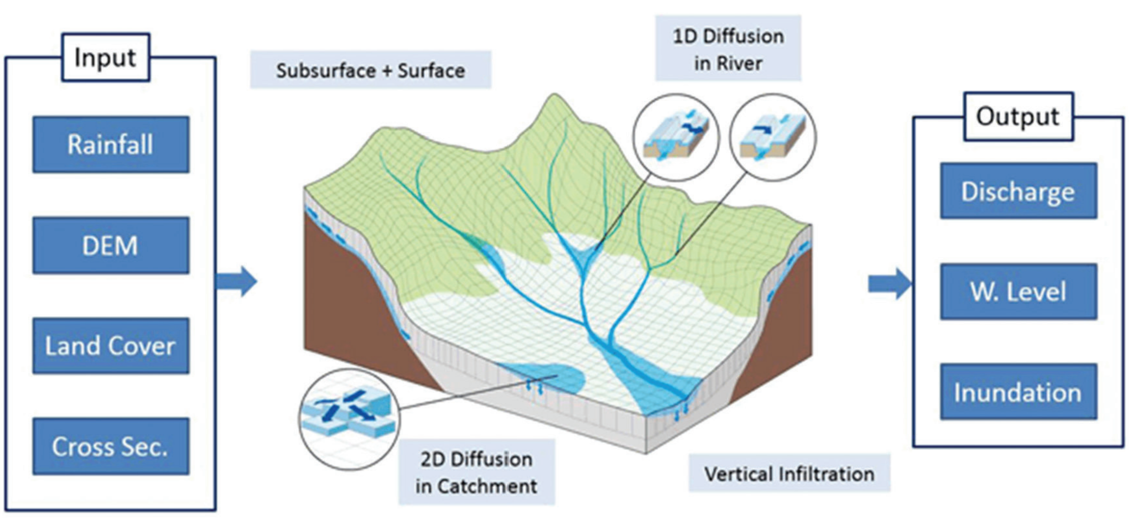

Figure 4: Schematic diagram of rainfall-runoff – inundation model.

To assess the variation in land-use in the Ngan Sau River basin, historical and future land-use data were investigated. For the historical period, the change in land-use data was obtained based on JAXA and the local authorities of Ha Tinh Province. Urban and agricultural areas will increase significantly in the future, whereas the forest area will decrease. Figure 7 shows the land-use map.

Rainfall and Flood Events

To ensure the precision of rainfall and flood simulations, we relied on rainfall from twenty-seven meteorological

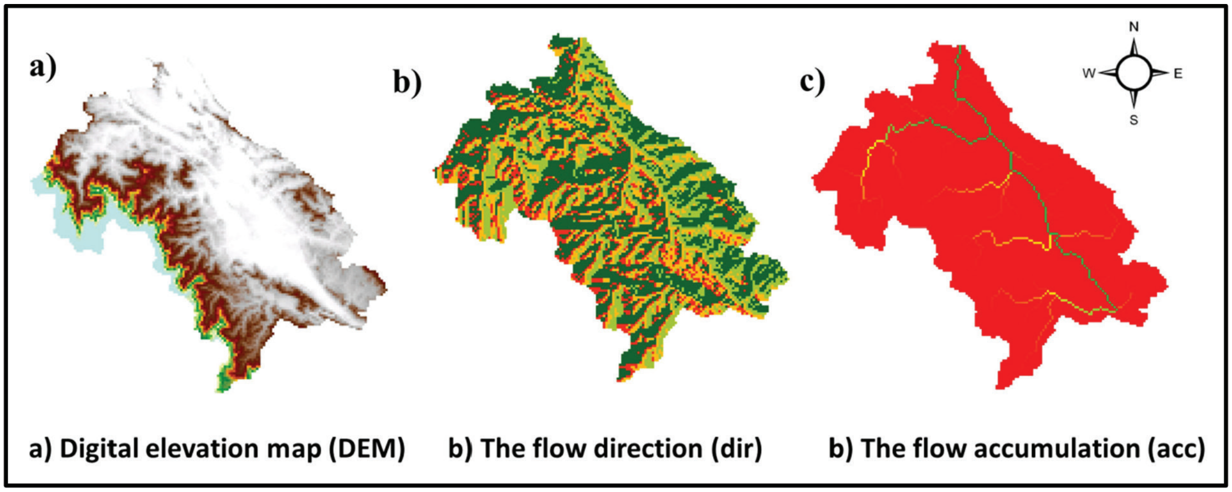

Figure 5: Topography input data.

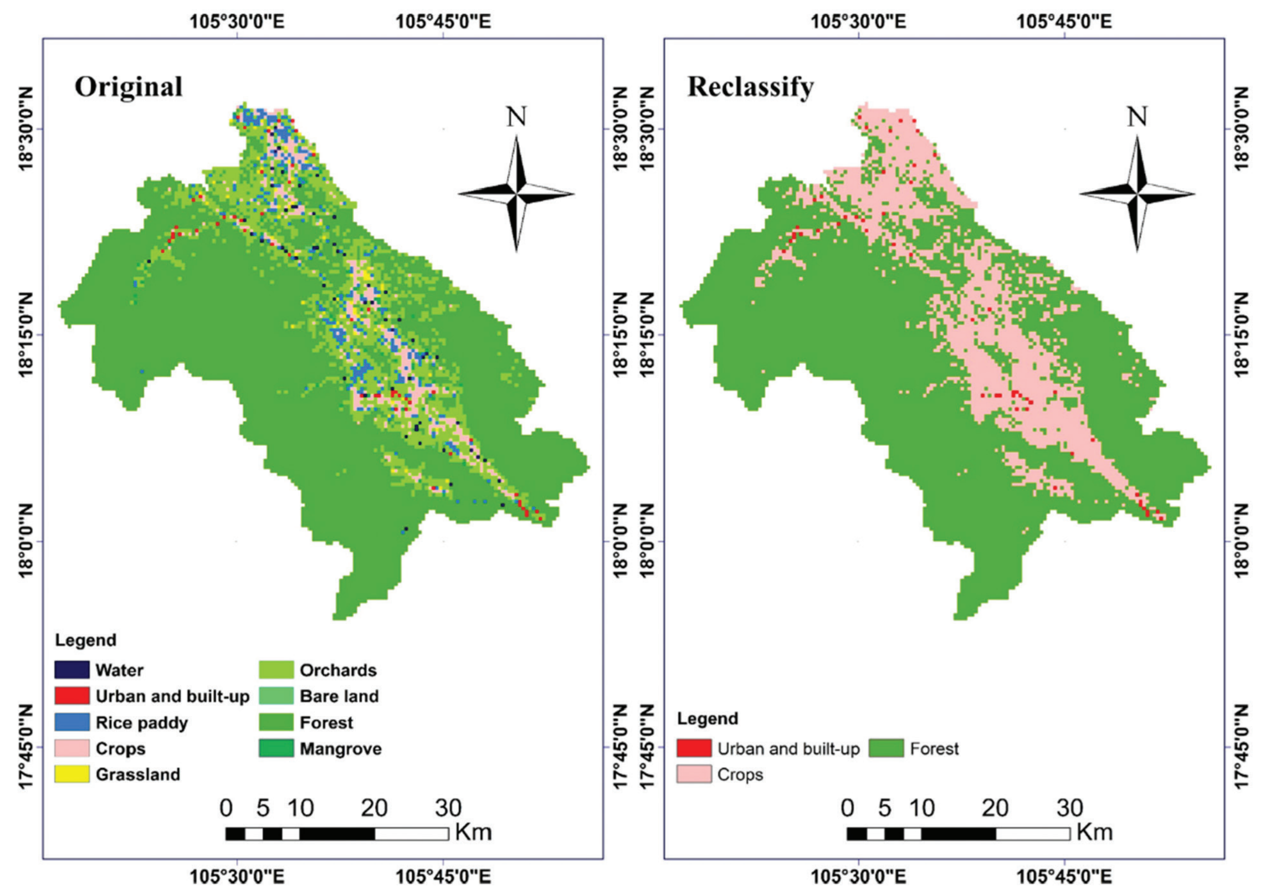

Figure 6: The original and reclassified land use of the Ngan Sau River basin, Ha Tinh Province, Vietnam.

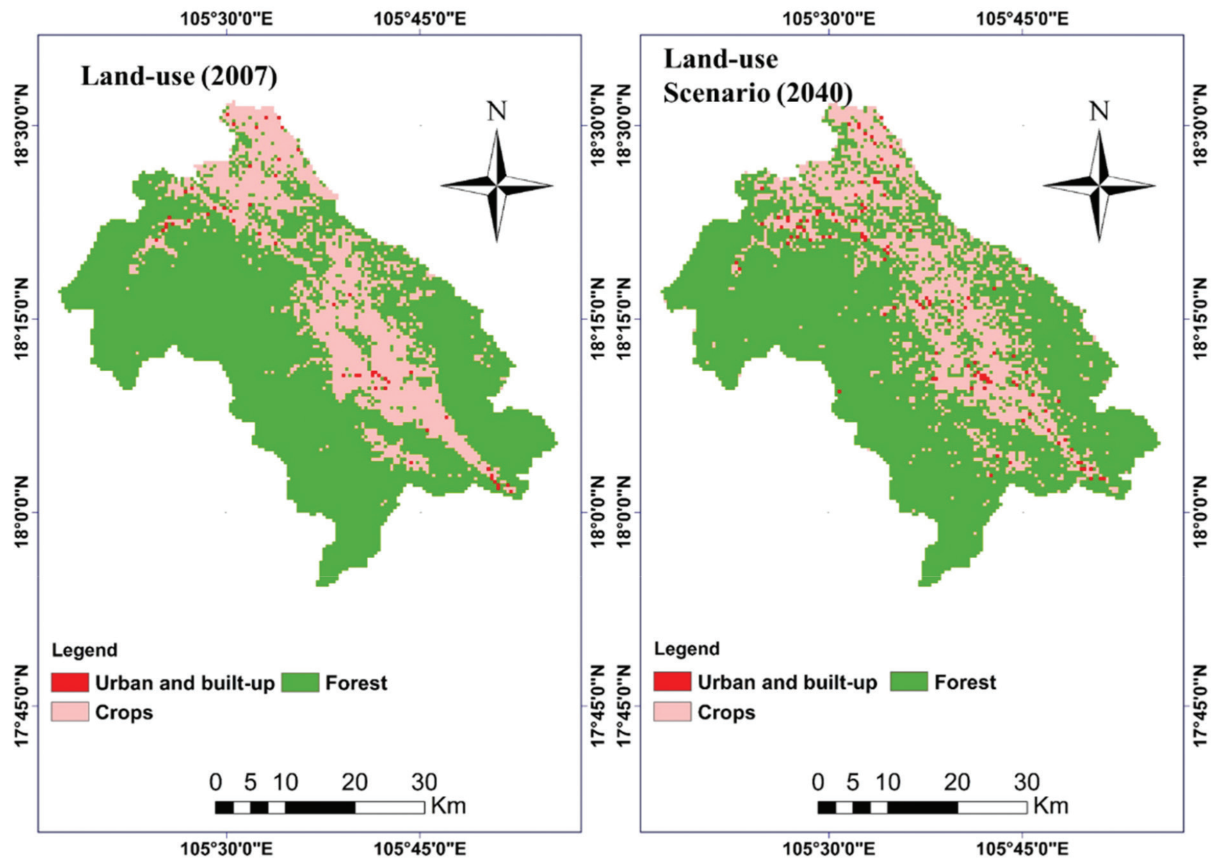

Figure 7: The variation of land-use in the Ngan Sau River basin.

stations, and the flows from August 16 to October 03, 2005, for the calibration and from August 03 to 20, 2007, for validation, were collected at the Hoa Duyet hydrological station.

Economic Flood Damage

Several studies have assessed flood economic losses from the local (Bouwer et al., 2010) to regional scales (Te Linde et al., 2011). However, these evaluations are currently limited in evaluating the impacts of flooding due to the absence of a comprehensive global database of flood damage functions that can translate floodwater levels into direct economic losses. Variations from local-to-regional damage models are available, especially for Europe and the US. Nevertheless, for most other regions, little information can be found on the relationship between the occurrence of the physical event and the resulting economic impacts.

Damage functions for floods consist of tangible flood damage, namely, damage to infrastructure, houses, transport, agriculture, and forests. Due to the lack of a flood damage function, in this research, the flood depth-damage functions are based on the Joint Research Centre (JRC) Technical Report for Vietnam (Jan Huizinga & Szewczyk, 2017), as shown in Figure 8.

Urban Damage Function

The urban land losses are represented by three types of land-use: houses, transport, and infrastructure. Kok et al. (2005) developed the standard method to calculate flood losses for various land-use.

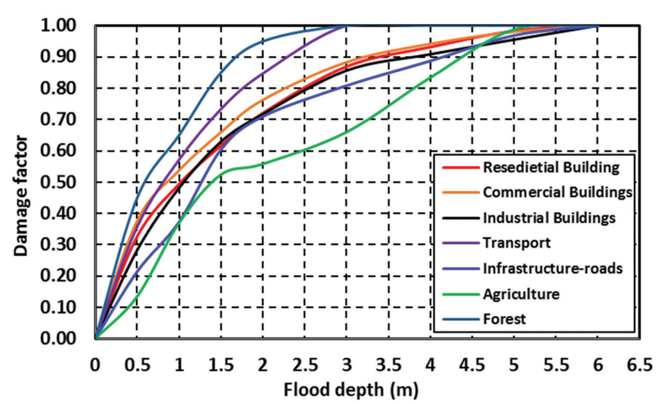

Figure 8: The damage function is utilised for computing the damages inflicted in the Ngan Sau River basin. The inundation depth and damage factor are represented by the horizontal and vertical axes, respectively.

The equation that estimates losses in each grid within an urban area is provided below

$$D_i = f_i \times c_i \times A_u \times P_i \quad (3)$$

i is the type of land-use in an urban area (house, transport, and infrastructure).

D_i is the damage of land-use i in an urban area (USD).

c_i is the percentage of land-use i in the urban area.

A_u is the area of the urban land (m^2).

f_i is the damage factor of land-use i.

P_i is the average price per 1 m^2 for land-use i.

Total economic losses in the urban area can be calculated as the summation of each component.

$$D_{\text{urban}} = D_{\text{house}} + D_{\text{infrastructure}} + D_{\text{transport}} \quad (4)$$

Agricultural Damage Function

It is assumed that all areas of rice cultivation are uniform, and therefore, the loss curve will be applied to the entire region. An equation is used to estimate the agricultural product damage in each grid.

$$D_{\text{agriculture}} = f_{\text{agriculture}} \times c_{\text{agriculture}} \times A_{\text{agriculture}} \times Y \times P_{\text{agriculture}} \quad (5)$$

$D_{agriculture}$ is agricultural damage (USD). $c_{agriculture}$ is the percentage of cultivated land over total agricultural land, $A_{agriculture}$ is the area of total agricultural land (ha), $f_{agriculture}$ is the damage factor of agricultural land, Y is the yield of rice (ton/ha), and $P_{agriculture}$ is the average price per 1-unit weight of the crop.

Forest Damage Function

The forest losses depend on inundation depth, the development stage, and the duration of flooding. The loss curve for the forest system is used from JRC. The losses at each grid are computed using equation (6)

$$D_{\text{forest}} = D_{\text{forest}} \times c_{\text{forest}} \times A_{\text{forest}} \times P_{\text{forest}} \quad (6)$$

D_{forest} is the forest damage (USD), c_{forest} is the percentage of trees covered over total forestland, A_{forest} is the area of total forestland (ha), f_{forest} is the damage factor of forestland, and P_{forest} is the average price per 1 ha of harvest forest.

The yields and price coefficients are listed in Table 2. These coefficients were collected in Ha Tinh Province of Vietnam.

Table 2: The coefficient, yields, and price of each land-use in the Ngan Sau River basin

1. Urban-build up			
Parameters	*Houses*	*Roads*	*Infrastructures*
% of Urban land	20%	13%	23%
Price (USD/m^2)	95	30	120
2. Agriculture			
Price (USD/ton)	*Rice yield (ton/ha)*		*$c_{agriculture}$ (%)*
267	2.7		70
3. Mix-forest			
Price (USD/ha)		*c_{forest} (%)*	
5,000		45	

Results

Future Rainfall And Floods

Results of Heavy Rain Under Climate Change

The results of the ensemble mean spatial distribution in total rainfall in CTL runs and the difference in total rainfall between 6 PGW experiments and CTL runs are shown in Figure 9. Distributions of the total rainfall and its variation in the MIROC-ESM and HadGEM2-ES indicate that the heavy rain in some models shifted to the southwest of Vietnam, Laos, and Thailand. At the same time, heavy rain may occur over short periods and larger areas in future climate conditions.

Flood Simulation Results

The Hoa Duyet hydrological station on the Ngan Sau River demonstrated a strong correlation between observations and simulations during both the calibration and validation periods, as indicated by Nash–Sutcliffe efficiency values of 0.61 and 0.82, respectively. The simulation results are shown in Figure 10.

Figure 11 indicates the spatial distribution of the maximum inundation depth in the Ngan Sau River basin simulated by the CTL run and 6 PGW experiments. The simulation results of flood depth from the MIROC-ESM and HadGEM2-ES would decrease in the future. Other PGW experiments show an increasing tendency in flood depth compared to CTL runs. From the maximum inundation map, land-use and damage function, using equations (3) to (6), the loss in each grid and the damage map were generated.

Climate Change Impacts on Economic Flood Damage

Figure 12 shows that the average economic flood loss is approximately \$380 million in the CTL run, whereas the losses from the report of local authorities are over

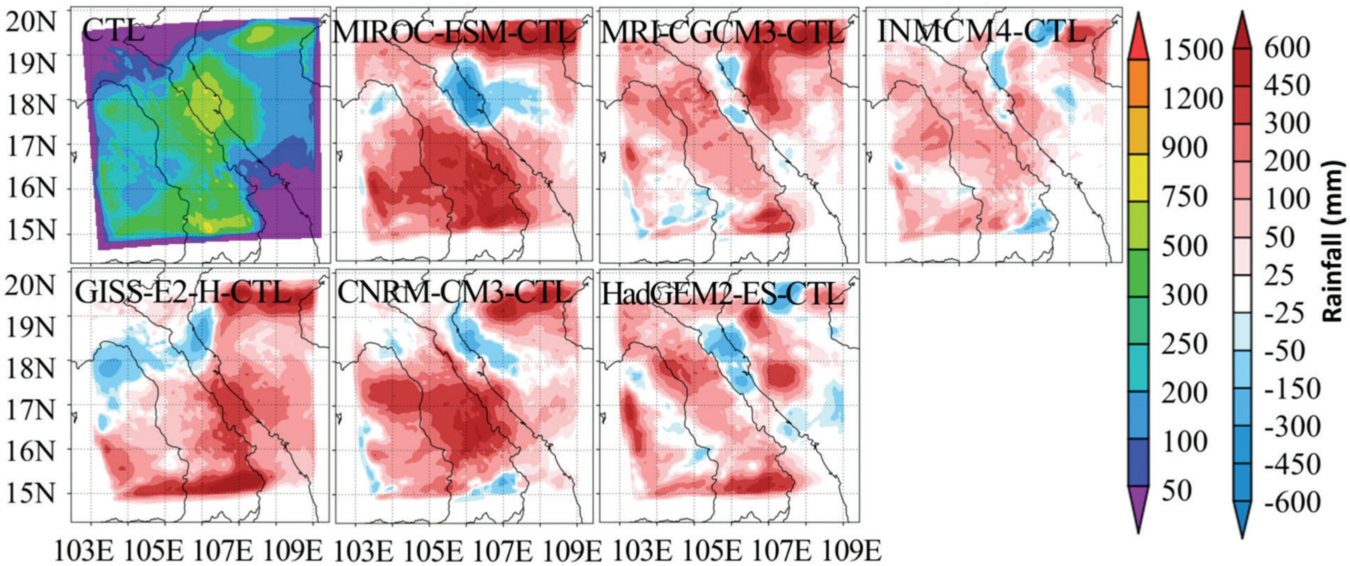

Figure 9: The spatial distribution of CTL runs and difference in maximum total rainfall between PGWs experiments and CTL runs. The colour bars represent the maximum total and different rainfall between PGWs and CTL runs.

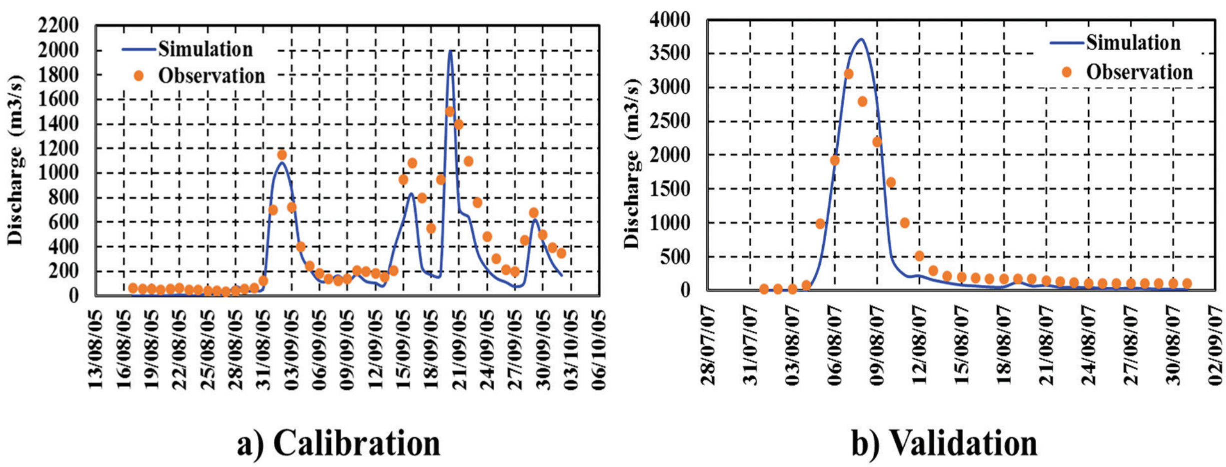

Figure 10: Comparison of observed and simulated results of river discharges in the calibration process for the (a) 2005 flooding event and validation process for (b) the 2007 flooding event at the Hoa Duyet hydro-meteorological station, Ngan Sau River basin, Vietnam

$300 million. The maximum economic loss varies from $380 million to $526 million, as per 6 PGW models. In the future, the simulation results of MIROC-ESM, HadGEM2-ES, and GISS-E2-H will decrease slightly due to the shift in heavy rainfall (Figure 8). However, damage to MRI-CGCM3, INMCM4, and CNRM-CM5 indicates an increase in the future.

Figure 13 displays the cumulative distribution curves of damage in the 6 PGWs and CTL run. An assumption of a normal distribution was used to describe the damage cumulative distribution curves. Focussing on the damage level of $400 million, the results of CTL and MRI-CGCM3 indicate that the probability is approximately 50% with similar heavy rainfall in 2007, whereas the possibilities of the CNRM-CM3 and INMCM4 models are 70% and 80%, respectively. As such, the combined use of the PGW method and ensemble simulation is helpful in estimating the probability of damage under specific meteorological conditions.

Spatial Distribution of Economic Flood Losses Under Global Warming Conditions

The spatial distribution of the CTL run and different maximum economic flood losses between PGWs and CTL are shown in Figure 14. The urban areas showed the highest damage from $10 million to $20 million in

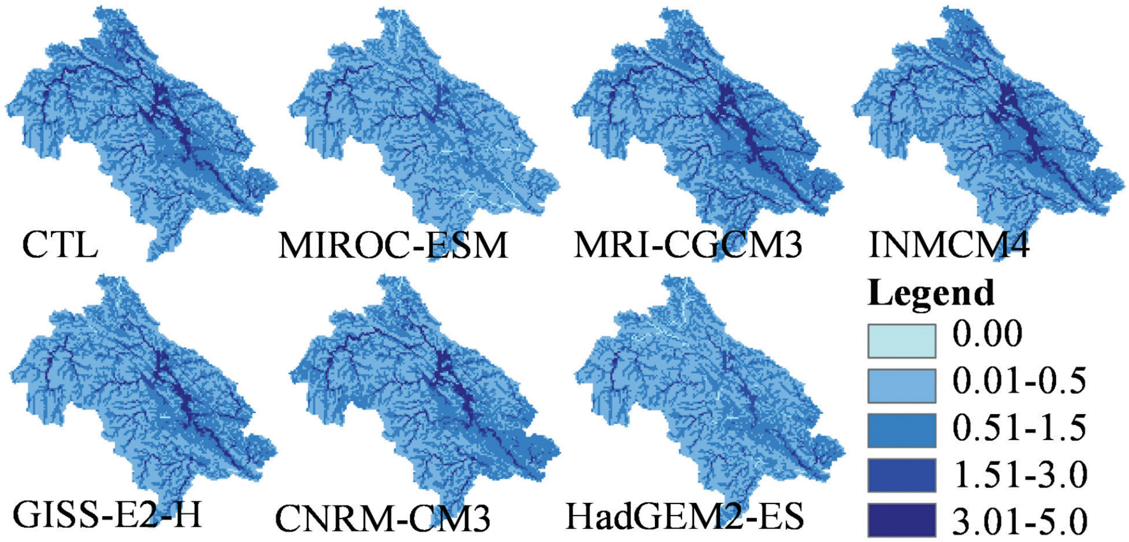

Figure 11: The spatial distribution of max inundation depth in the Ngan Sau River basin simulated by CTL run and 6 PGW experiments.

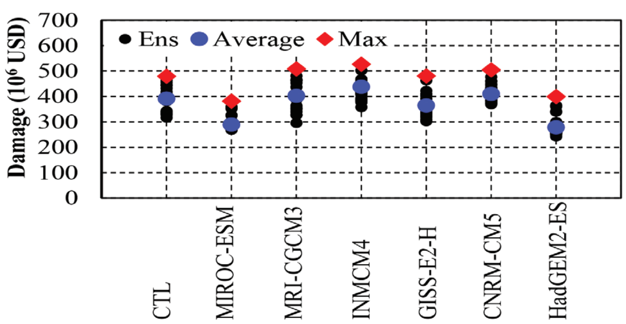

Figure 12: Economic flood losses of each simulation, ensemble mean, and maximum ensemble result under climate change.

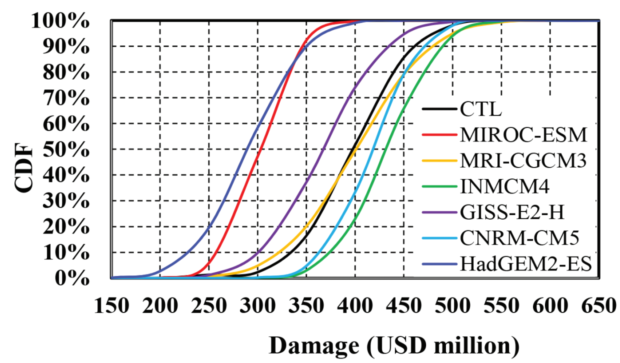

Figure 13: Damage cumulative distribution curves of six PGWs and CTL runs under climate change.

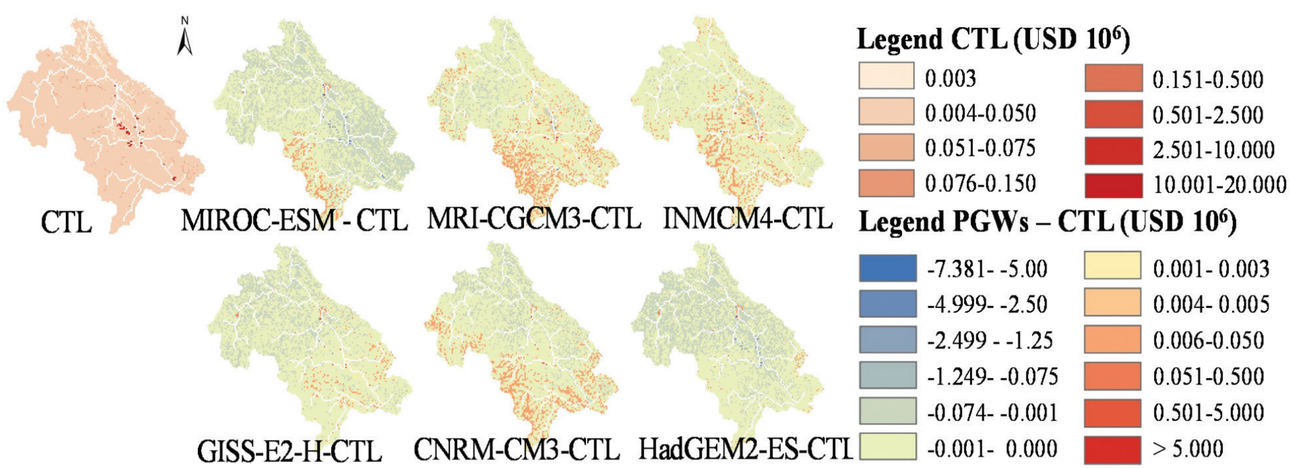

Figure 14: The spatial distribution of CTL runs and different maximum economic flood losses between PGWs and CTL in the Ngan Sau River (the unit is presented in $ million/grid).

the CTL run. The rice fields have the most undersized damage per grid smaller than $0.003 million. According to the simulation results of damage for urban areas, only two models (MIROC-ESM and HadGEM2-ES) do not show an increase, and the other four models (CNRM-CM5, MRI-CGCM3, GISS-E2-H, INMCM4) show slight increases. However, in cropland and mixed forest areas, the losses seem to decrease in the future. Therefore, the research suggests that the effects of climate change may not significantly impact flood damage, and the increased damage in this basin is mainly caused by land-use change. The research results would help local governments to better understand the impact of climate change and land-use on flood damage and make better decisions in risk management and planning appropriate land-use for the basin.

It seems that using the depth damage curve from the Joint Research Center (JRC) of the European Commission for Vietnam is a feasible method to create a damage map. However, it is crucial to verify the quality of the resulting spatial data since it has not yet been confirmed. If the basin lacks data, we can use the damage curves combined with inundation depth and land-use for estimating flood losses. It is crucial to validate the accuracy of the curves to ensure the damage reliability. To improve the accuracy of the damage map, it is recommended to update additional data such as the inundation depth and type of land-use in the research areas. Gathering these data is important, and it is also necessary to develop compatible curves of the water depth-damage for these new datasets.

Conclusions

This research aimed to investigate the impact of climate change and land-use variation on flood losses. The findings suggest the following:

Recent simulations indicate a rise in economic flood losses in the CNRM_CM5 and INMCM4 models. However, the damage caused by the MIROC-ESM, HadGEM2-ES, and GISS-E2-H models is projected to decrease because of shifting heavy rainfall in the future. The ensemble simulation produces cumulative distribution curves that aid in assessing various damage levels and determining disaster prevention targets.

According to the economic damage map data, it is crucial to prioritise reducing consequences in urban areas because urban areas face the most damage due to their high vulnerability. These settlements are often situated in heavily inundated areas, exacerbating the situation. Therefore, focusing on flood management strategies that prioritise urban areas is essential. This information can be useful in identifying vulnerable regions within the target area and can provide essential knowledge for regional planning.

Cumulative distribution curves of economic flood damage showed apparent differences between current and future losses. Heavy rainfall similar to the rainfall event in August 2007 can produce extreme flood losses that would not be expected in the current climate.

In addition to some useful results found from this research, it also has certain limitations:

It should be noted that the study only examines a restricted number of land-use types. As a result, the economic losses caused by flooding might be underestimated since other land-use, such as industry, commerce, tourism areas, and temples, are not considered. Therefore, the damage map created by this study may not offer a complete depiction of the actual situation.

It may be helpful to consider additional variables such as water velocity, duration of the flood, and wind speeds beyond the water depths provided by the RRI model to create a more precise damage map. This would lead to a more accurate definition of the damage.

The flood depth-damage functions in this study come from the Joint Research Center (JRC) for Vietnam. Therefore, in some cases, these functions cannot accurately reflect the relationship between flood depth and economic damage for research areas. Therefore, additional studies should be conducted to accurately investigate the flood damage caused by climate change and land-use variation.

Acknowledgements

The author would like to thank the Joint Research Centre and the European Commission's Science for supplying the Vietnam flood damage curves. The author pays appreciation to the Vietnam National Hydrometeorology Centre and the local authorities of Ha Tinh Province for providing us with a database. Finally, the author extend thanks to the anonymous reviewers for their valuable suggestions.

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