FUTURE INTENSIFICATION OF RAINFALL-RUNOFF AND INUNDATION IN PHO DAY RIVER BASIN

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Specialized in climate change studies and impacts of global warming on socio-economic, find the ways how society can adapt to and lessen the impacts of climate change, and how citizens can positively impact and protect the environment.

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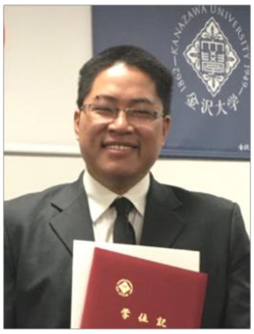

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Future Intensification of Rainfall-Runoff and Inundation in Pho Day River Basin

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Abstract

Vietnam has been considered as one of the most vulnerable countries in the world under global warming. The Intergovernmental Panel on Climate Change (IPCC) suggested the increasing trend in the total annual rainfall in Vietnam in the mid-21st century where 70% the amount of rainfall will be delivered by summer monsoon. The most problematic rainfall-related disasters in the northern mountainous region in Vietnam, flood and inundations, are also expected to become even more severe in the coming future. Recent years, Pho Day River basin have been undergoing the noticeably increasing trend of flood disasters. Since Pho Day River basin plays an important role for the development of the vast Bac Kan – Tuyen Quang – Vinh Phuc economic region, establishing the solid understanding of the current and future hydro-meteorological characteristics of the Pho Day watershed is very important to prepare the countermeasure for the coming severe variation in rainfall intensity and frequency. In this research, the rainfall-runoff and inundation characteristics of the Pho Day watershed has been investigated associated with the corresponded climate condition of the present (2000-2009) and future (2060-2069). The Rainfall-Runoff and Inundation (RRI) model was used for the simulation of watershed hydrological characteristics. The essential future precipitation inputs for RRI were achieved by using the Weather Research and Forecasting (WRF) model nested inside GFDL-CM3, and MIROC-5 models. Results of this study suggest the severe flood and inundation condition of the Pho Day watershed in the mid-21st century.

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1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) has forecasted the increasing trend of global surface temperature by 1-2°C at the end of 2050 and might rise to 2-5°C at the end of the century [2]. Global warming over the past several decades was accounted for various natural disaster throughout the world. In the recent publication IPCC's Fifth Assessment Report (AR5), climate change was proven the culprit behind the damages caused by harmful disasters in many region, the Southeast Asia (SEA) is known one of those heavily vulnerable region. Located in SEA, Vietnam has been considered as one the most affected countries in the world under climate change. Vietnam northern mountainous region is the poorest region of the country but highly susceptible to flood and inundation during the rainy season. Flood and inundation are the most destructive natural disasters that happened every year and resulted in great economic and social loss. Experts have forecasted the growing risks of these hazards in northern Vietnam in the mid-21 century and indicated the need of better awareness as well as the more effective flood risk and management [10].

Future changes in rainfall intensity accounts for the variations in flood runoff. This study focus on the flooding and inundation problems for one of the most important river basin the northern Vietnam. **Fig. 1(a)** shows the researching area with the location of Pho Day watershed placed in the center of the domain. This is one of the major river which running through the territory of five provinces. The Pho Day river basin plays the important role for the development of the region as it provides domestic and production water source for the vast populated-economic regions. Pho Day watershed was formed in the high mountain range in the Bac Kan province then flow southward with the lower river basin places on the flat plateau.

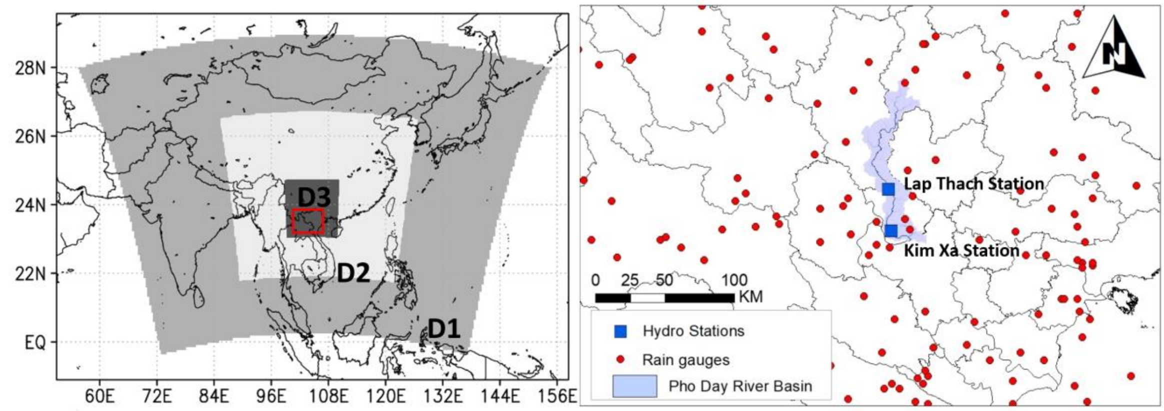


Fig.1 The target areas for WRF and ANN models, in which (a) The outermost 90 km resolution (D1), the middle 30 km resolution domains (D2) and the innermost 10 km resolution are shown in the grey, white, and dark grey colors, respectively, the red rectangular indicate the locations of the researching area; (b) Locations of Pho Day watershed and hydro-meteorological stations

The number of flood occurrence in Pho Day watershed has been rapidly increasing recently. In the theme of global warming, it is important to prepare the countermeasures and mitigation methods to cope with the potential risks. It is impossible to establish the action plan without the deep understanding of the characteristics of the flood in accordance with the present and future hydro-meteorological conditions. The traditional simulation method for inundation researches combines both rain-fall-runoff models for river discharge and hydraulic model for water propagation. However, this method not suitable for flat watershed with large inundation area as it requires significant calculation between the river and flood water. This study, therefore, used the Rainfall-Runoff Inundation (RRI) model, which is a fully coupled model of rainfall-runoff model and hydraulic inundation model [6]. Besides, the Weather Research and Forecast (WRF) model [7] was also employed to provide present and future input precipitation for RRI model.

2. RESEARCH DATA AỊ D MATERIALS

(1) In-situ daily observation data

The in-situ rainfall data collected by the Vietnam National Centre for Hydro-Meteorological Forecasting (NCHMF) at 56 rain gauges station from 2000-2009 provides a basis for this study. As river discharge data for verification of RRI simulation results, we used monitored data in July and August 2008 from Lap Thach and Kim Xa hydraulic stations which locate in major branches of Pho Day river system. Locations of hydro-meteorological stations are shown in **Fig. 1(b)**. Northern Vietnam climate is distinguished by the Southeast Asia monsoon system with the hot-rainy season from Jun to August (JJA) then the cold-dry season from December to February (DJF). In this study, we focused on the hydro-meteorological condition of Pho Day river system during JJA period.

(2) CMIP5 global warming experiments

For assessment of future global warming, this study based on the global warming experiments by the fifth phase of the Coupled Model Inter-comparison Project (CMIP5). Numerous experiments provided by CMIP5 represent for the state-of-the-art international assessment of climate science. The future climate projections in CMIP5 are based on different future greenhouse emission scenarios known as representative concentration pathways (RCPs). Herein, we examined the daily precipitation for mid-21st century from 2060 to 2069. In Vietnam, progress of climate change is taking place faster

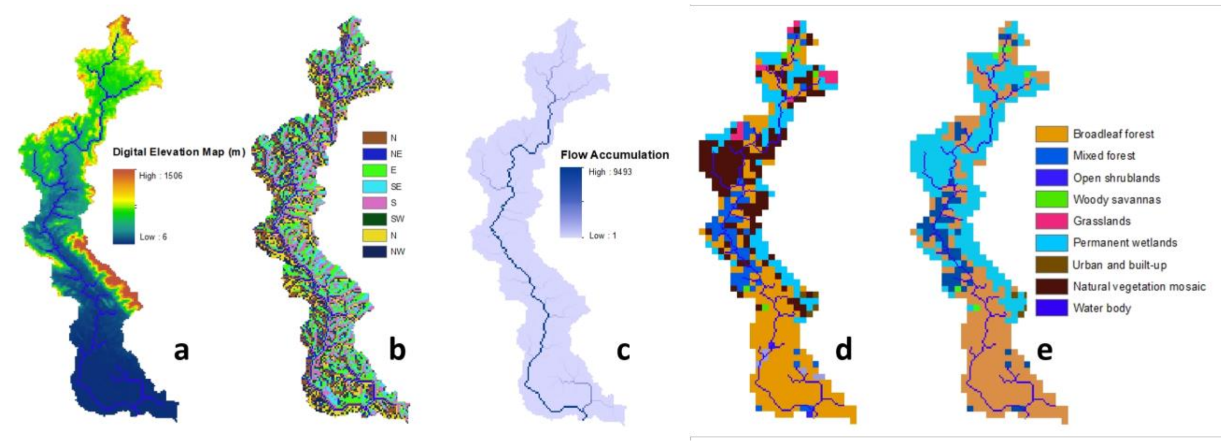


Fig.2 Topography and land use inputs for RRI model

than expected. Recently, Vietnam government has updated the high emission scenario RCP8.5 in the national strategy on climate change to propose the action plan for extreme weather events under the worst case scenario [3]. In RCP8.5, the radiative forcing of the Earth become 8.5 W/m^2 larger than before the industrial revolution. In this study, we used the output of two Atmosphere Ocean General Circulation Model (AOGCM) projections from NOAA Geophysical Fluid Dynamics Laboratory Climate Model version 3 (GFDL-CM3) [1] and a new version of Model for Interdisciplinary Research on Climate (MIROC-5) [12] for preparation of the future conditions.

(3) Initial and boundary conditions for numerical weather simulation

This study uses Japanese 25-year reanalysis (JRA-25) product by The Japan Meteorological Agency (JMA) for reproducing the present climate conditions which are also the base state for future (pseudo global warming) conditions. The global spectral resolution of JRA-25 kept at T106 with 40 vertical layers where 0.4 hPa was set for the height of the top level. Since the JRA-25 only provide the assimilation data from January 1979 to December 2004, the reanalysis product from the JMA Climate Data Assimilation System (JCDAS) has been used for the period from January 2005. JCDAS deploys the similar system as JRA-25 which guarantee the homogeneous in quality and accuracy in the application of both datasets. The current climate conditions were obtained by performing dynamical downscaling to the 2000-2009 data. Simulation results for climate condition (or control simulation) is called CTL.

For land-surface boundary conditions for WRF model, we used the NCEP Final Operational Global Analysis data (NCEP FNL)[4]. For the lower boundary condition over the ocean, the NOAA Optimum Interpolation 1/4 Degree Daily Sea Surface Temperature Analysis (NOAA OI SST) [5] was used.

(4) Topography and global land cover data

Input data for RRI model was taken from the hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS). Topography inputs of 15-arc second resolution (approximately 500m) for digital elevation model, flow accumulation, and flow direction was used for RRI model (**Fig.2(a,b,c)**). Regarding the RRI requirement of land cover data, we used the Moderate Resolution Imaging Spectroradiometer (MODIS) based product of 0.5 km resolution (**Fig.2(d,e)**).

3. METHODS

(1) Design of numerical simulation

a) The Weather Research and Forecasting model

Downscaling of present and future climate condition was implemented using the WRF model version 3.6. A two-level, two-way nesting system for WRF downscaling is shown in **Fig.1(a)**, where

D1 and D2 represented for the 30km and 10km grid spacing resolution, respectively. The Pho Day watershed locates in the Northern Vietnam where placed the center of the D2 domain. The WRF Double-Moment 5-class scheme (WDM5) microphysics and Grell-Devenyi cumulus parameterization schemes were used to calculate precipitation in the model. Planetary boundary layer parameterization is used from the Mellor-Yamada Nakanishi and Niino Level 2.5 PBL (MYNN2). The used parameterization for the surface layer and land surface are taken from Nakanishi and Niino PBL's surface layer scheme and Noah land surface model, respectively. The new Rapid Radiative Transfer Model (RRTMG) schemes are selected for long wave radiation and shortwave radiation conditions.

b) High-frequency-anomaly PGW

Downscaling simulations for present and future climate condition were prepared with pseudo global warming forcing. The lateral boundary conditions for future were constructed by adding projected changes in AOGCM simulations to reanalysis climate. In this study, the high-frequency anomaly pseudo global warming (HF-PGW) methods were applied to prepare the initial forcing with future high-frequency anomalies [8]. The future inter-annual variability and diurnal cycle can differ from the present climate. At first, six-hourly AOGCM and reanalysis dataset (RD) were divided into climatological monthly mean plus the short perturbation terms:

$$AOGCM_P = \overline{AOGCM}_P + AOGCM'_P \quad (1)$$

$$AOGCM_F = \overline{AOGCM}_F + AOGCM'_F \quad (2)$$

$$RD_P = \overline{RD}_P + RD'_P \quad (3)$$

The subscript P and F represent the present (2000-2009) and the future (2060-2069), respectively. Then the bias-corrected six-hourly AOGCM data for the future period,$AOGCM *_F$, was calculated by adding the climatology variation between future and present ($\overline{AOGCM}_F - \overline{AOGCM}_P$) and short term perturbation $\overline{AOGCM}_F{}'$ to climatological mean reanalysis:

$$AOGCM *_F = \overline{RD}_P + \overline{AOGCM}_F - \overline{AOGCM}_P + AOGCM'_F \quad (4)$$

The inter-annual variation and diurnal circle were both included in HF-PGW conditions which are expected to greatly reduce the bias in AOGCM outputs.

(2) RRI model

RRI model has been used to simultaneously simulate the conditions of rainfall-runoff and flood inundation for the research domain[2)]. In RRI model, both slope and river are assumed within the same grid cell. The river channel is considered as a single line on the overlying slope cells. The 2-dimension diffusive wave model was adopted to calculate the flow over slope grid cells, while the 1-dimension diffusive wave model was applied for the main channel flow. For better representation the rainfall-runoff-inundation processes of Pho Day watershed, the surface/subsurface condition parameterization was enabled with vertical Green-Ampt model infiltration flow. Since the original MODIS product includes 16 types of land use which is too detailed to designate all the parameters, similar land cover types were combined into four major categories and also overlaid with river floodplain region (**Fig. 2(e)**). Human management activities to control and regulate the river channel was considered by dam model. Evaporation parameter in RRI model was disable due to the lack of detailed monitored evaporation data. Simulation result of RRI for 2009 was used for model verification.

4. SIMULATIOI̥ RESULT OF HISTORICAL FLOOD II̥ UI̥ DATIOI̥

In this section, we verify the accuracy of rainfall downscaling by WRF from 2002-2009 by using the observation data (OBS) from 56 rain gauges. The RRI simulation results has also been examined for the 2008 flood event at Lap Thach and Kim Xa hydro stations.

(1) Reproducibility of WRF model

Fig.3 compares the JJA rainfall averaged for 56 rain gauges and corresponding CTL grids from

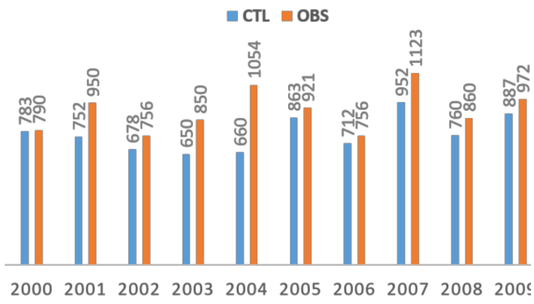


Fig.3 JJA rainfall averaged for 56 observation sites and corresponding grids in CTL from 2000 to 2009

2002 to 2009. It can be seen from the results that JJA rainfall reproduced by CTL varied from 73.5% to 92.2% of observation data and consistently underestimated. Average spatial correlation coefficient for 10 years (2000-2009) calculated between CTL and OBS was 0.77, indicates the relatively good agreement between simulation results and observation. Regarding the temporal variation of rainfall, correlation coefficients between CTL and OBS averaged for JJA periods in 10 years in 56 observation sites range from 0.52 to 0.89 with an average of 0.7 (details not shown). Verification result indicates the WRF model can be used for rainfall downscaling in Pho Day watershed with reasonable accuracy.

(2) Simulation of RRI models for historical flood events

Observation rainfall data in July-August 2008 was fed into RRI model to examine the accuracy of the model to represent the flood events. Comparison of river discharge between RRI simulated results (RRI-CTL) and observation data was shown in **Fig.4**. The Nash-Sutcliffe efficiency coefficient (NSE) was used to quantitatively describe the predictive power of RRI model outputs for river discharge. NSE indexes in Lap Thach and Kim Xa stations are calculated 0.71 and 0.74, respectively. NSE results showed the good match between simulated results and OBS in the decreasing trend of river discharge at the end of the rainy season. Since the NSE index in sensitive to extreme value, the high NSE results also suggested that extreme discharge periods were relatively well predicted. Simulation results slightly overestimated the peaks of river discharge in both Lap Thach and Kim Xa stations. However, peaks of large and small floods are correctly reproduced for each stations in RRI simulation. Verification results show the good applicability of adopting RRI model to further investigation of the future hydrological condition of Pho Day river system.

5. FUTURE FLOOD FORECASTIỊ G

(1) Future trend in rainfall intensity

WRF daily rainfall outputs during JJA for 10-years periods of CTL (2000-2009), GFDL-CM3 and MIROC-5 (2060-2069) was used as inputs for RRI model to examine the variation of rainfall distribution over the Pho Day river basin. Spatial distribution of 10-years average JJA rainfall clearly shows the future higher intensity of rainfall throughout the watershed (**Fig.5**). Average JJA rainfall

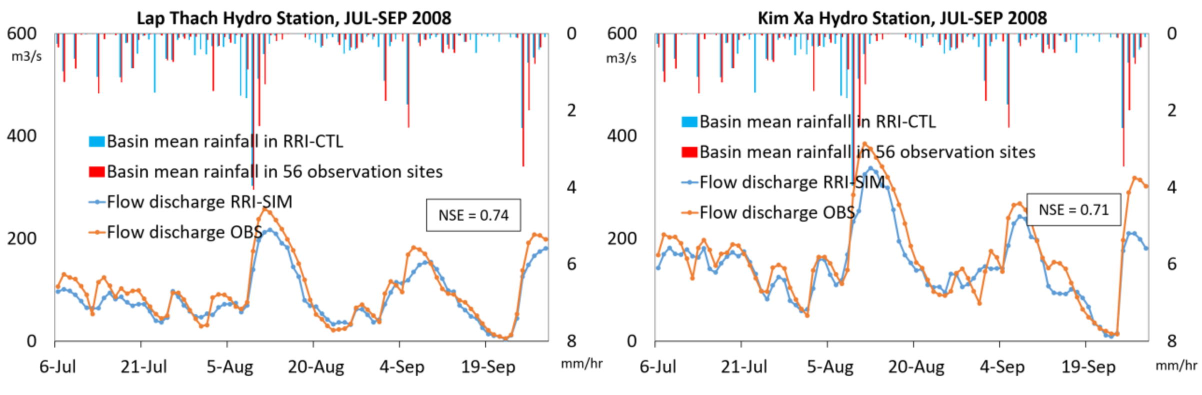


Fig .4 Basin mean precipitation and river discharge by RRI model and observation data in Lap Thach and Kim Xa stations during JJA in 2008

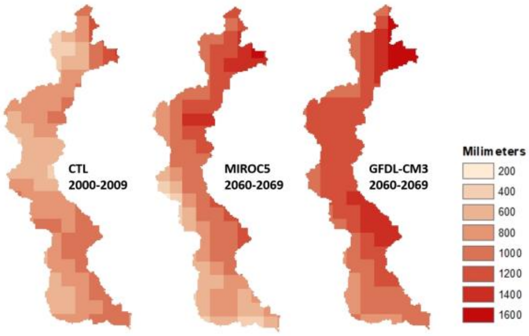
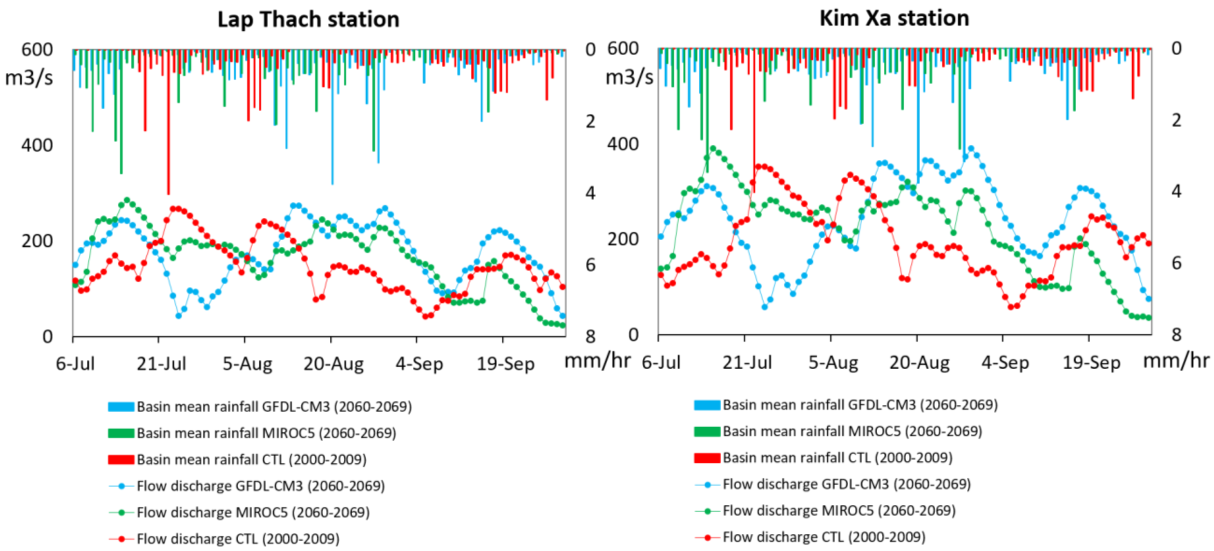


Fig.5 Spatial distribution of 10-years average JJA rainfall

indicated by CTL, MIROC-5, and GFDL-CM3 were 621 mm, 678 mm, and 821 mm, respectively. While GFDL-CM3 predicted small rainfall variation (9.1% increment), there was a significant gap between MIROC5 and CTL (32.2% increment). Rainfall forecasted by MIROC5 was 19.5% greater than GFDL-CM3. Tran and Taniguchi (2013) used 19 CMIP5 models ensemble and found the same increasing trend of rainfall over the northern of Vietnam at the second half of 21st century [11]. The same results also found by experts of MONRE [9]. Future scenario forecasted by both GFDL-CM3 and MIROC-5 indicated the similar rainfall distribution patterns with present where the major amount of JJA rainfall concentrated on the upper river basin, especially the far north and eastern corner. The featured distribution of rainfall pattern in Pho Day watershed results from its typical topographic condition.

(2) Future trend of flood and river runoff

Future precipitation was predicted to increase during mid-21st century. Increasing river discharge is found in **Fig.6**. RRI simulated river runoff in CTL (2000-2009) were comparable with GFDL-CM3 and MIROC-5 (2060-2069) in the middle period of the rainy season with no significant difference in average river discharge. Differences caused by higher rainfall intensity in the future scenario was found mostly in the latter half of the rainy season when future river discharge was projected larger than CTL. In the late JJA period, GFDL-CM3 model showed average river discharge will significantly increase, almost double as in CTL in both Lap Thach and Kim Xa station. Meanwhile, MIROC-5 exhibited lower average river discharge than GFDL-CM3 as expected while future precipitation in GFDL-CM3 is projected much higher than in MIROC-5. Future river discharge in MIROC-5 is slightly larger than in CTL at during the peak runoff period and equal to CTL at the end of rainy season. In Kim Xa station which locates in the largest branch of Pho Day watershed, MIROC-5 shows clear higher average discharge than in CTL. In Lap Thach station, MIROC-5 exhibited higher



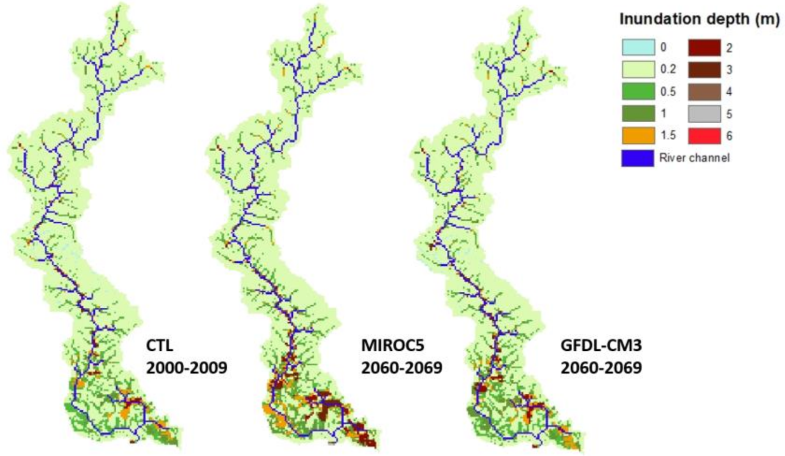


Fig.7 Maximum level of inundation depth in Pho Day watershed during JJA

discharge at late July-early August and similar to CTL at the end of JJA. After JJA ends, river discharge tends to reduce in both three cases. When MIROC5 and GFDL-CM3 forecast the future river discharge after rainy season significantly reduced, CTL indicate that discharge had not changed much.

Fig.7 illustrates the maximum inundation depth by CTL and future projections. The distribution map for maximum depth was prepared by selecting the highest value of depth for every grid in the Pho Day watershed during a 10-year period. Variation of maximum inundation depth represents the changes in the worse situation might happen. Both GFDL-CM3 and MIROC-5 show the huge difference in maximum inundation level than in CTL. The worst CTL situation indicates the inundation level of about 0.5 to 1.5 meters depth at the areas far from the river channel; closer to the river channel, the influence level becomes greater of 1.5 to 2 meters depth and up to 3-4 meters at some few locations (excluding river channel). Projection by GFDL-CM3 and MIROC-5 both indicate the more severe inundation in the lower river basin, about 0.5-1 meters higher than in CTL. Extreme flood (inundation depth > 3 meters) occur in more locations with extended inundation radius. Closer to main river channels at the downstream, the common inundation depth caused by the worst future flood situation in GFDL-CM3 and MIROC-5 are 1-3 meters, much higher than CTL. Compare between GFDL-CM3 and MIROC-5, the worst inundation situation in GFDL-CM3 was more intense for the most locations. Increase in the mean JJA rainfall and river discharge is larger in GFDL-CM3 than in MIROC-5. However, the maximum inundation depth is larger in MIROC-5. These result suggests the amplitude of climate variability in MIROC-5 is stronger than in GFDL-CM3. Since the comparison between CTL and future river runoff only exhibits the clear differences on from late July/early August, it is projected that the severe future flood conditions tend to occur in the late JJA period.

6. COỊ CLUSIOỊ

In this study, the present and future rain-fall-runoff and inundation conditions of Pho Day river basin during JJA were examined using the combination of WRF and RRI models. While simulation results of WRF for the present precipitation showed reasonable accuracy for temporal and spatial distribution, reproductive RRI results for Pho Day river discharge came relatively close to OBS. Generally, both WRF and RRI models are capable of deploying further assessment on the future river basin condition.

The future downscaling results by GFDM-CM3 and MIROC-5, indicated heavier rainfall conditions in the mid-21st century and consequently cause more severe inundation conditions. At the first half of JJA, there is no significant difference in average river runoff conditions between CTL and future projections, heavy rainfall and inundation were expected to increase in the second half of JJA. In both GFDL-CM3 and MIROC-5, the impacted areas due to flood will increase in both spatial and temporal extent, intensity, and density. MIROC-5 model forecasted the extreme flood might occur in late JJA. Future inundation condition will affect mostly the agricultural and residential areas in the lower Pho Day river basin. This study suggests further assessments on the impacts of the future flood to agriculture and environment as well as the needs of study on an adaptive management plan.

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