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Future climate change impact assessment of watershed scale hydrologic processes in Peninsular Malaysia by a regional climate model coupled with a physically-based hydrology modelo

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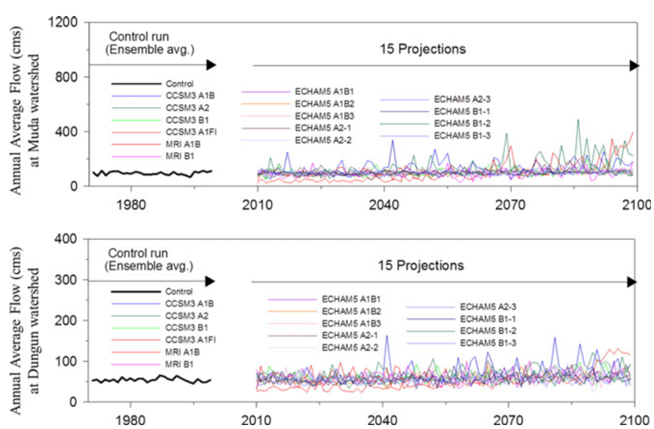
HIGHLIGHTS

- Water balances and flooding conditions in 21st century over Muda and Dungun watersheds in Malaysia
- Coupled regional climate and hydrology model was simulated for 90 years for each of the 15 realizations at hourly scale
- Significant increase in mean monthly flows are observed during monsoon seasons after 2040
- Flood frequency curves vary through time
- Overall increasing trend of the flood frequencies in the second half of the 21st century

GRAPHICAL ABSTRACT



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ABSTRACT

Impacts of climate change on the hydrologic processes under future climate change conditions were assessed over Muda and Dungun watersheds of Peninsular Malaysia by means of a coupled regional climate and physically-based hydrology model utilizing an ensemble of future climate change projections. An ensemble of 15 different future climate realizations from coarse resolution global climate models' (GCMs) projections for the 21st century was dynamically downscaled to 6 km resolution over Peninsular Malaysia by a regional climate model, which was then coupled with the watershed hydrology model WEHY through the atmospheric boundary layer over Muda and Dungun watersheds. Hydrologic simulations were carried out at hourly increments and at hillslope-scale in order to assess the impacts of climate change on the water balances and flooding conditions in the 21st century. The coupled regional climate and hydrology model was simulated for a duration of 90 years for each of the 15 realizations. It is demonstrated that the increase in mean monthly flows due to the impact of expected climate change during 2040–2100 is statistically significant from April to May and from July to October at Muda watershed. Also, the increase in mean monthly flows is shown to be significant in November during 2030–2070 and from November to December during 2070–2100 at Dungun watershed. In other words, the

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impact of the expected climate change will be significant during the northeast and southwest monsoon seasons at Muda watershed and during the northeast monsoon season at Dungun watershed. Furthermore, the flood frequency analyses for both watersheds indicated an overall increasing trend in the second half of the 21st century.

1. Introduction

Global climate change is nowadays a key issue in water management all over the world. As reported by Intergovernmental Panel on Climate Change (IPCC, 2013), precipitation regimes are changing under changing climate. Precipitation peaks are also getting more intense in many regions of the world. These changes in precipitation are leading to changes in flow discharge. Therefore, climate change impacts on hydrologic processes have to be taken into account for a robust and resilient water management approach under the changing climate.

Climate change assessment has also been an important topic in Peninsular Malaysia recently. However, investigations of the climate change impacts on the hydrologic processes in Peninsular Malaysia are limited. Historical trends in rainfall and rainfall-related extremes, such as maximum daily rainfall, number of rainy days, average rainfall intensity, heavy rainfall days, extreme rainfall days, and precipitation concentration index for historical 40 years (1971–2010) in the east coast of Peninsular Malaysia were analyzed using the rainfall records from 54 stations by Mayowa et al. (2015). Ercan et al. (2013) estimated the spatial variation of the sea level change along the Malaysian coastlines by assimilating the global mean sea level projections from the coupled Atmospheric and Oceanic GCM (AOGCM) simulations to the satellite altimeter observations. Shaaban et al. (2011) assessed the effects of future climate change on Peninsular Malaysia's water resources during the 2025–2034 and 2041–2050 periods in comparison with the historical period of 1984–1993 based upon one realization of future climate change projection from one global climate model (the Coupled General Circulation Model of the Canadian Center for Climate Modeling and Analysis, CGCM1). This was due to the limited availability of the GCM projection data for the 21st century, and limited computer resources at the time of that study. Shaaban et al. (2011) found that the overall mean monthly streamflow increases significantly during the future period in Kelantan and Pahang watersheds. Moreover, in the future, high flow conditions will increase in the Kelantan, Terengganu, Pahang, and Perak River watersheds during the wet months, whereas monthly flows will be significantly lower in the Selangor and Klang watersheds during the dry months.

Modeling interactions between the atmosphere and land surface hydrologic processes in heterogeneous domains are among the key problems in atmospheric and hydrologic sciences (Kavvas et al., 2013). Realistic estimation of the land surface fluxes, such as evapotranspiration rates, requires the coupled modeling of land surface hydrologic processes with atmospheric processes (Kavvas et al., 1998; Ament and Simmer, 2006; Kavvas et al., 2013). Within this context, a physically-based hydrology model, Watershed Environmental Hydrology Model (WEHY; Kavvas et al., 2004; Chen et al., 2004a, 2004b), and a regional climate model, MM5 (Fifth Generation Penn State/NCAR Mesoscale Model), were coupled in this study so that the interactions between the atmosphere and land surface hydrologic processes could be modeled more realistically. Furthermore, the upscaled hydrologic conservation equations utilized in WEHY model enable the estimation of the model parameters that are capable of describing the heterogeneity within the natural watersheds by taking into account areal averages, variances, and covariances of the original point-scale parameters (Kavvas et al., 2004; Chen et al., 2004a). Details of the coupling methodology and its applications to reconstruction of historical precipitation and runoff conditions in ungauged and sparsely gauged watersheds in California were reported in Kavvas et al. (2013) and Kure et al. (2013), respectively.

Estimating the uncertainties in climate projections is a critical issue in climate change assessment studies. According to Hawkins and Sutton (2009), uncertainty in climate projections arises from three sources: the internal variability of the climate system (natural fluctuations that arise in the absence of any radiative forcing of the planet), model uncertainty (uncertainty due to different response of climate models in response to the same radiative forcing), and scenario uncertainty (uncertainty in future emissions of greenhouse gases). To quantify these uncertainties, the ensemble approach, which uses multiple future projections from multiple GCMs based on multiple scenarios, is generally employed as followed in this study.

Within the above framework, the aim of this study is to assess watershed-scale hydrologic processes in Peninsular Malaysia under future climate change conditions by means of the ensemble approach. Three different GCMs are utilized in order to account for the model uncertainty in climate change simulations. These models are the fifth-generation global climate model ECHAM5 (Roeckner et al., 2006) from German Max-Planck Institute (MPI), the Coupled Ocean-Atmosphere General Circulation Model version 2.3.2 CGCM2.3.2 (Yukimoto et al., 2001) from Japanese Meteorological Research Institute (MRI), and the third-generation community climate model CCSM3 (Collins et al., 2006) from the University Corporation for Atmospheric Research (UCAR) in the United States. Meanwhile, the complete spectrum of future greenhouse emission scenarios from the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000), from the best possible scenario, SRES B1, to the worst case scenario SRES A1FI, while also including the scenarios SRES A1B (most likely), and SRES A2 (second worst) are covered in order to account for the uncertainty in the future greenhouse emissions. Finally, in order to account for the internal variability on the future climate projection simulations of the earth as a nonlinear system, 15 different climate projection realizations from 3 GCMs under 4 different emission scenarios are utilized. To assess watershed-scale hydrologic processes in Peninsular Malaysia based on 15 climate projection realizations, this study utilizes a coupled model of a regional climate model and a physically-based hydrology model. The findings of this study can be helpful in the identification and quantification of the potential hazards due to the potential future extreme events, such as floods that may occur in the study areas due to climate change.

2. Methodology

A physically-based hydrology model, Watershed Environmental Hydrology Model (WEHY; Kavvas et al., 2004; Chen et al., 2004a, 2004b), and a regional climate model, MM5 (Fifth Generation Penn State/NCAR Mesoscale Model), were coupled in this study in order to model the interactions between the atmosphere and land surface hydrologic processes more realistically. An ensemble of 15 different future climate realizations of coarse resolution climate data from GCM projections was dynamically downscaled to 6 km resolution over Peninsular Malaysia by the regional climate model component. Then by means of the downscaled climate data as input, hydrologic simulations were carried out over Muda and Dungun watersheds of Peninsular Malaysia at hourly increments and at hillslope-scale in order to assess the impacts of climate change on the water balances and flooding conditions at these watersheds during the 21st century. An ensemble of 15 projections were simulated to address the uncertainties in the future climate projections, including the internal variability of the climate system, the climate model uncertainty, and the emission scenario uncertainty. The coupled regional climate and hydrology model was run for a duration of 90 years