Potential impact of climate change on inflows to the Batang Ai reservoir, Malaysia

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The authors describe a study to determine possible climate change impacts on river inflow at the Batang Ai hydro plant in Sarawak, Malaysia, which will help to assess future annual energy yields for the plant. Five models were used to simulate the daily precipitation over the catchment under two future scenarios. It was projected that for three months of the year, the catchment will receive less precipitation in future, but one month will be wetter under both future scenarios. The average annual precipitation is not likely to change, but seasonal precipitation is likely to shift, it was concluded.

Hydropower is a relatively low-cost source of renewable energy, which can be well integrated with intermittent sources, such as solar and wind power, to ensure grid system stability. Currently producing 16 per cent of global electricity, hydropower is the main source of sustainable and renewable energy. It is also noteworthy that from 1973 to 2011, global hydropower production increased by 175 per cent [Cole *et al*, 2014[1]].

View of Batang Ai hydro plant in Sarawak, showing the main dam, spillway, saddle dam, powerhouse, penstocks and reservoir.

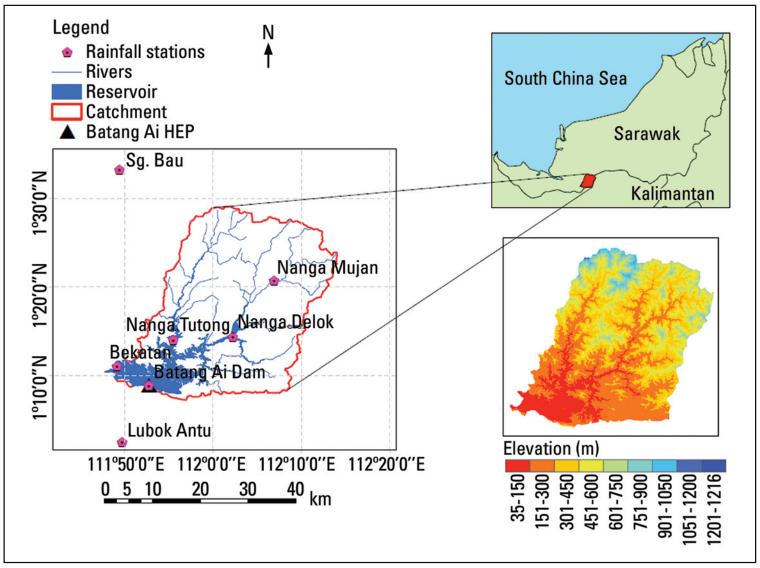

Fig. 1. Location of Batang Ai catchment, reservoir, main dam, rivers and selected rainfall stations in the study area.

Increased greenhouse gas emissions into the atmosphere and global warming are evidence of anthropogenic influence on the global climate system [Hassan *et al*, 2015[2]]. Between 1951 and 2010, emissions of greenhouse gases caused a global surface warming of 0.5 °C to 1.3 °C. Continued emissions will cause further warming and will modify the global climate system [IPCC, 2013[3]]. Studies assessing climate change impacts have indicated that the water resources systems of major water catchments will be affected [Chang and Jung, 2010[4]; Grillakis *et al*, 2011[5]; Hidalgo *et al*, 2013[6]; Khadka *et al*, 2014[7]; Kienzle *et al*, 2012[8]; Mahmood *et al*, 2016[9]; Zhang *et al*, 2014[10]]. In Malaysia, only a few studies have explored the potential climate change impact on water resources [Amin *et al*, 2016[11]; Mustafa *et al*, 2016[12]; Tan *et al*, 2014[13]] and these have revealed that there will be notable changes in river inflows during the 21st century.

Climate change and anthropogenic effects are considered as the two major drivers of changes in river inflows [Piao *et al*, 2007[14]]. Climate change results in changes in temperature as well as precipitation intensities and patterns, and significantly impacts on regional hydrological processes [Labat *et al*, 2004[15]]. In this study, the authors assessed the potential impacts of climate change on the river inflow at the Batang Ai hydro plant using general circulation models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5).

The objectives of the study described here were to:

- project future changes in precipitation over the Batang Ai catchment using the GCMs from the CMIP5;
- simulate river inflow for the baseline period and future scenarios; and,
- assess the impact of climate change on river inflows to the Batang Ai reservoir.

1. Project area and rainfall

1.1 Study area

Batang Ai was the first hydro plant to be built in Sarawak, and it is located in the southern part of the state. A project overview is shown in the photograph, and the location is shown in Fig. 1. The scheme was commissioned in 1985. It has a maximum installed capacity of 108 MW from four 27 MW vertical Francis units. The project has an 85 m-high concrete face rockfill main dam, as well as three saddle dams: Lima, with a height of 60 m; Sebangki, with a height of 30 m; and, Bekatan, with a height of 50 m. The main dam has a spillway structure equipped with seven radial gates (each 10.5 m wide and 5 m high) with a total discharge capacity of 2613 m^3/s. The project has a surface powerhouse connected through four steel penstocks, each 4 m in diameter and 300 m long. A catchment of 1200 km^2 drains into the reservoir, to provide water resources for the hydro plant. The catchment area comprises tropical rainforest, where precipitation in the form of rainfall drives the water resources system.

1.2 Data description

Daily rainfall records from seven gauging stations (as shown in Fig. 1) for the period of 1976–2005 were acquired for this study. Data from six of the stations were obtained from the Department of Irrigation and Drainage, Sarawak, and rainfall records for the dam were obtained from the Hydro Department of Sarawak Energy Berhad. There were some missing periods in the rainfall records, and to fill in missing information, the multilevel regression method was used. Five of the selected rainfall stations are within the catchment, and two of them (Lubok Antu and Sg. Bau) are located nearby. The two which are nearby have the longest rainfall records, and were used to fill in the data for the stations within the catchment.

For the climate change impact assessment, the precipitation ensembles for five GCMs from the CMIP5 have been selected in this study, as listed in Table 1. The precipitation time series for the controlled run (1976-2005) and future run (2016-2075) of each GCM were downloaded from the website of the Intergovernmental Panel on Climate Change (IPCC) World Data Center for Climate. Only one ensemble member, r1i1p1, was used in this study. These five models were considered satisfactory during a recent evaluation relating to Singapore (which is in the same region) by McSweeney *et al*. [2015[16]], and was therefore selected for this study. The mean ensemble of the five selected models (B5MMM) was also developed as the control, and for the future period to include in the study.

2. Methodology

2.1 Downscaling future precipitation

A weather generator approach was used to simulate future precipitation over each selected rainfall station. The weather generator, called WeaGETS, developed by Chen *et al* [2010[17]] was used in this study. The third order Markov chain was used for the precipitation occurrence and gamma distribution to generate the precipitation volume for the wet days. The historical daily precipitation for the period of 1976-2005 was used as input to the weather generator to obtain the future time series of daily precipitation. The detailed approach of this method is provided by Chen *et al*. [2010[17]]. The stochastically generated future precipitation at each rainfall station in the catchment was perturbed, using the quantile perturbation technique (a change factor technique) employing the controlled (historical) and future runs of all selected GCMS and their mean ensemble of B5MMM under both scenarios (RCP4.5 and RCP8.5). During this study, the 'climate perturbation tool' developed by Ntegeka *et al*. [2014[18]] was used for precipitation quantile perturbation of daily future precipitation at each station.

Table 1: Selected GCMs from CMIP5 used in the study

CMIP5 Model	Institute	Modelling group	Country
ACCESS1.0	CSIRO-BOM	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology, (BOM)	Australia
ACCESS1.3	CSIRO-BOM	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology, (BOM)	Australia
BCC-CSM1.1m	BCC	Beijing Climate Centre, China Meteorological Administration	China
BNU-ESM	BNU	College of Global Change and Earth System Science, Beijing Normal University	China
GFDL-ESM2M	NOAA-GFDL	Geophysical Fluid Dynamics Laboratory	USA

2.2 Hydrological modelling using HEC-HMS

A rainfall-runoff model was developed using the hydrological modelling system HEC-HMS, to simulate the river inflows at Batang Ai. HEC-HMS is a rainfall-runoff simulation software used for a wide range of watersheds from large river basins to small urban areas. The model is formulated by the US Army Corps of Engineers at the Hydrologic Engineering Center (HEC). A complete basin model setup for rainfall-runoff processes comprises a basin model, a meteorological model, control specification, and input time series [Center, 2015[19]]. The historical precipitation and future projected precipitation for each scenario was input to the model to generate river inflow at the Batang Ai hydro plant. The hydrological model was developed for the catchment and was calibrated with the observed inflow for the period 2004 to 2009. In this study, the basin model was developed using the Clark unit hydrograph method for transforming direct runoff, lag for channel routing, and the constant monthly base flow for the base flow method. The meteorological model was established using the Thiessen polygon gauge weight method for calculating precipitation. During the model calibration, the simulated monthly inflows were compared (as shown in Fig. 2) with the observed monthly inflow using the coefficient of determination (R^2), per cent deviation (D), and Nash-Sutcliffe efficiency (E). The model's performance parameters, R^2, D, and E, were calculated using the following equations:

$$R^2 = \frac{\Sigma(Q_{obs}-\overline{Q_{obs}})\times(Q_{sim}-\overline{Q_{sim}})}{\sqrt{\Sigma(Q_{obs}-\overline{Q_{obs}})^2\times(Q_{sim}-\overline{Q_{sim}})^2}}$$

$$D(\%) = 100\times\frac{\Sigma(Q_{sim}-Q_{obs})}{\Sigma Q_{obs}}$$

$$E = 1-\frac{\Sigma(Q_{sim}-Q_{obs})^2}{\Sigma(Q_{obs}-\overline{Q_{obs}})^2}$$

The value of R^2 close to 1, value of D close to 0 per cent and the value of E close to 1 implies good calibration. During this study, the coefficient of determination (R^2) was found to be 0.68, the per cent deviation (D) as 5.61 per cent, and the Nash-Sutcliffe efficiency (E), 0.61. These results were considered satisfactory and complement previous studies such as those by Meenu *et al* [2013[20]], Verma *et al* [2010[21]], Yimer *et al* [2009[22]] and Garcia *et al* [2008[23]]. All these studies used HEC-HMS to simulate river inflow for the climate change studies, with E ranging from 0.48 to 0.83 and R^2 from 0.63 to 0.84.

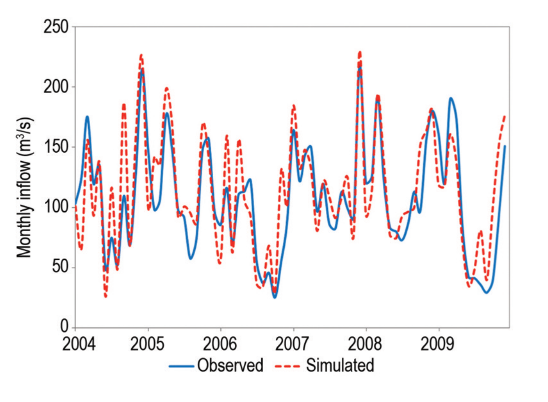

Fig. 2. Comparison of observed and simulated monthly inflows at Batang Ai during the model calibration.

Table 2: Potential changes in the river inflows at Batang Ai dam

Inflow	Historical	RCP4.5		RCP8.5	
		2030s	2060s	2030s	2060s
	m^3/s				
Q_{95}	8	29	26	29	25
Q_{50}	108	111	110	114	110
Q_5	294	262	267	276	272

3. Results and discussion

3.1 Future changes in precipitation

Daily precipitation time series were generated at all stations in the catchment for the two future periods of 2016–2045 and 2046–2075, and were compared with the baseline period (1976–2005). The precipitation was generated for all selected models under RCP4.5 and RCP8.5 and percentage change with respect to the baseline period were plotted as shown in Fig. 3. It was noted that all the models projected noteworthy changes in monthly precipitation. ACEESS1.3, BNU-ESM and GFDL-ESM2M showed the most robust changes in monthly precipitation especially during 2060s under both RCP4.5 and RCP8.5.

For B5MMM, it was projected that between August and October, the catchment will receive less precipitation in the future. However, July will be wetter compared with the baseline period under both future scenarios. The annual precipitation will not change in future, but a seasonal precipitation shift is projected under both RCPs.

3.2 Future changes in river inflows

To model the potential impact of climate change on river inflow, the projected precipitation for the mean ensemble of B5MMM was selected to simulate the river inflow at Batang Ai for the two selected future periods. Fig. 4 shows the comparison of monthly inflows for the baseline period with the projected future monthly inflows at Batang Ai during the 2030s and 2060s. The monthly inflow was projected to increase during April, July, August, November and December, as shown in Fig. 4. However, September will be drier in future (in the 2030s and 2060s) as compared with the baseline period (1976–2005) under both RCPs.

The flow indicators such as low flow (Q_{95}), median flow (Q_{50}), and high flow (Q_5) were also computed for the two future periods and were compared with the baseline period. Q_{95}, Q_{50} and Q_5 are the inflow values available up to 95 per cent, 50 per cent and 5 per cent of the time duration, respectively. All these flow parameters were derived from the flow duration curves and are as shown in Table 2. Q_{95} was projected to increase in future, Q_{50} will also be slightly increased and Q_5 was projected to decrease in future under both scenarios, as shown in Table 2. The same projection is shown in Fig. 5 for

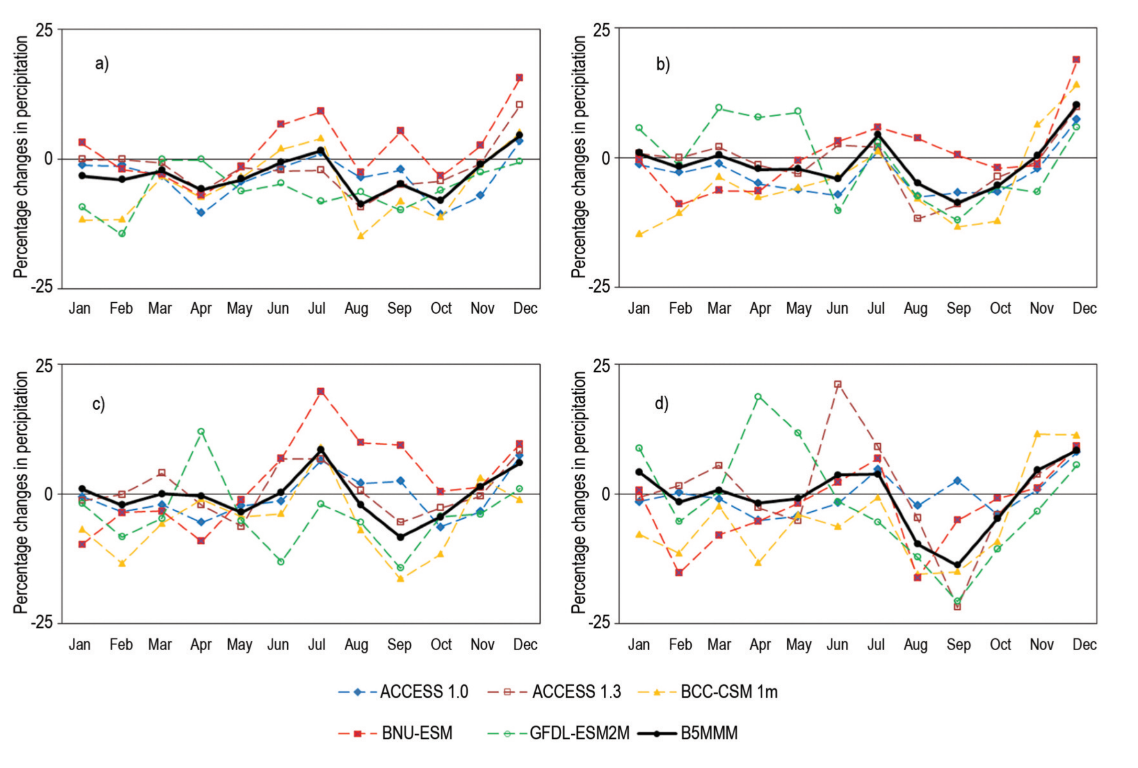

Fig. 3. Percentage changes in monthly precipitation over the Batang Ai catchment under the selected GCMs and their mean during 2030s and 2060s: (a) under RCP4.5 during 2030s; (b) under RCP8.5 during 2030s; (c) under RCP4.5 during 2060s; and, (d) under RCP8.5 during 2060s.

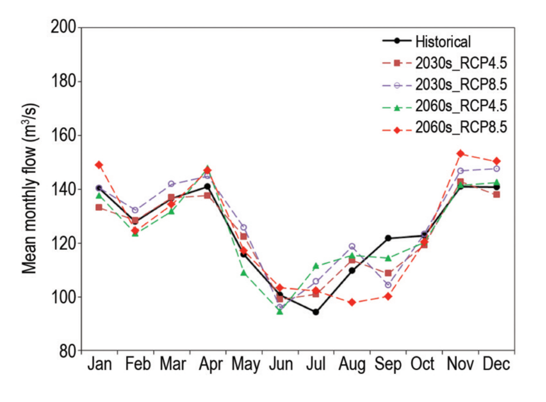

Fig. 4. Comparison of mean monthly inflow at Batang Ai dam under both scenarios during the 2030s and 2060s with a baseline period of 1976-2005.

comparison of flow duration curves. It can be seen in the comparison of flow duration curves that the lowest inflows will be improved under future scenarios, as a result of the increase in projected future precipitation during July.

Overall, it was concluded that river flow duration at the Batang Ai hydro plant will improve under both future climate scenarios, which will help the plant to supply consistent power to the grid system. Batang Ai will be operated in the upper band of the operating range closer to full supply level in future, and the reduction in the high flow (Q_5) modelled under future scenarios will reduce the risk of downstream flooding during such events ◊

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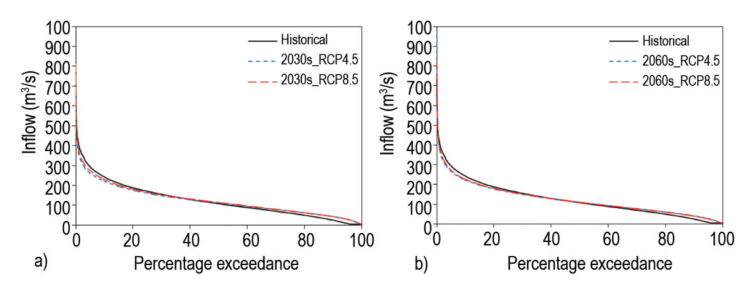

Fig 5. Comparison of flow duration curves for historical and projected inflow under RCP4.5 and RCP8.5: (a) projection for 2030s; and, (b) projection for 2060s.

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