magnitude. A clear rise in temperature for the year 2010 is observed in the case of NGFS-R and CRTUM, but ERA-40 fails to simulate this rise. To compare the ISM circulation feature between NGFS-R, JRA-55 and ERA-40 reanalysis for typical day, 30 June 2006 is chosen at random and plotted in Figure 9. It is clearly observed that there is agreement between major global scale circulation features; but there are small differences in synoptic scale details. These may be due to the difference in model resolution and physical parameterization schemes. Hence, these NGFS-R data can be utilized for summer monsoon studies.

High-resolution global analysis at T574L64 resolution (about ~27 km) was made for the years 2000 to 2011. Further, by taking into account similar operational products generated at NCMRWF, these high-resolution data are available for total 16 years. The quality of this product is found satisfactory. It simulated interannual variations in the Indian summer monsoon well. It also generated good-quality ocean surface winds as a co-product for use in ocean surface state models.

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Assessment of climate change impact on water diversion from the Bago River to the Moeyingyi wetland, Myanmar

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Originally built for flood control, the Moeyingyi wetland, Myanmar now provides valuable resources such as fishery, irrigation water and tourism, and is also home to many rare species and migratory birds. This is the only wetland in Myanmar listed as a Ramsar Site. Bias-corrected climate data from three general circulation models under two emission scenarios of IPCC Assessment Report 5 (AR5), namely RCP 4.5 and RCP 8.5 were used to forecast temperature and rainfall. Future climate scenarios were predicted for three future periods as 2020s (2021–30), 2030s (2031–40) and 2040s (2041–50). The Soil Water Assessment Tool (SWAT) was used for hydrological analysis to predict water availability. Analysis suggests that the discharge is expected to decrease during dry season, which can have a negative impact on the diversion of water from the Bago River to the Moeyingyi wetland. On the other hand, discharge is likely to increase during July and can further worsen the recurring floods. Similarly, inflow at the Moeyingyi wetland is expected to decrease in future. Hence, robust adaptation strategies should be formulated to cope with the negative impact of climate change.

Keywords: Climate change, hydrological analysis, water diversion, wetlands.

WETLANDS are important natural resources and are considered as natural heritages in Myanmar; they play a vital role in the economy of the country. Migratory birds are dependent upon these areas, especially on coastal and inland mangrove wetlands; therefore, they are of international importance[1]. In addition, wetlands act as natural barriers against sea water intrusion into the agricultural areas, preventing floods and coastal land from erosions.

The Moeyingyi wetland was constructed in 1978 and was originally built as a reservoir for flood control. This wetland is also used to supply water to the Bago–Sittaung canal during the dry season as a source of irrigation water for rice (*Oryza sativa* L.) farmers. In addition, it also serves as a habitat for various species and acts as a resting place for migratory birds. Thousands of tourists visit

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the site every year. Seeing the importance of the wetland ecosystem, in 2005 it was declared as a Ramsar Site. The Moeyingyi wetland provides many valuable resources such as fisheries and forest products; it is also a source of freshwater. In Myanmar, freshwater fish from this wetland has been the major source of protein for the people. A network of freshwater wetlands, rivers and adjacent irrigation canals is important for water supply, transport and as a habitat for freshwater fish. However, the characteristics of the Moeyingyi wetland have been changed due to human activities; thus, reducing their natural values.

Other than natural sources like rainfall and small streams, the Bago River is one of the major sources of water to the Moeyingyi wetland. Around 8.5 m^3/s of water is diverted to the Moeyingyi wetland through the Zangtu weir at the Bago River. Similarly, water is diverted during the monsoon season (May–October) to prevent flooding in Bago city situated on the banks of the Bago River. The Moeyingyi wetland is managed by the Forestry Department, Ministry of Environmental Conservation and Forestry, whereas the sluice gates are controlled by the Irrigation Department, Ministry of Agriculture and Irrigation. There are reports of conflicts between the Forestry Department and the Irrigation Department regarding maintenance of the water level of Moeyingyi wetland. The Forestry Department wants to maintain at least 7 m water level during March and April, whereas the Irrigation Department faces huge water demand during this period and is compelled to supply water for irrigation resulting in a decrease in water level to less than 6.4 m. Due to constant human interference, extraction of water for irrigation, climate variation and climate change, the Moeyingyi wetland faces serious threats to its ecosystem[2,3].

Climate change, once a topic of heated debate, is now a subject of near-unanimous agreement among scientists. Global climate change may alter hydrologic parameters upon which wetlands and the species that inhabit on them depend[4]. Hydrology is probably the most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes[5]. Climate change could have an effect both on the long-term water availability and short-term variability of water resources in many regions of the world[6]. Almost all parts of the world are now facing the negative impacts of climate change. However, the intensity and characteristics of the impact vary significantly from region to region. Some forms of climate change experienced by mankind in recent years include more frequent floods, stronger hurricanes, typhoons and other storms, as well as extended droughts and heat waves[7].

Although climate change is a global phenomenon, the impact is mostly faced by regional communities[8]. It is of utmost importance to assess the impact of climate change on hydrology at regional scale to better understand the potential change in water resources[6,8–11]. Previous studies in many Asian countries have concluded that climate change will negatively impact water resources[8,9,12,13]. Myanmar ranks one of the top countries vulnerable to the effect of climate change[14]. The country is experiencing an increase in temperature and a change in precipitation patterns over the past decade[2].

The objective of the present study was to assess the impact of climate change on the hydrology of the upper Bago River Basin (BRB) and the Moeyingyi wetland of Myanmar. The impact of climate change on river run-off was projected using three general circulation models (GCMs) and two emission scenarios for different future periods. Multiple GCMs were used in the study to reduce the uncertainty while projecting the climate change impact analysis, which has been widely adopted in other studies[8,11,13,15,16]. The result of this study would provide a change in the discharge of the Bago River due to climate change for diversion to the Moeyingyi wetland. The findings would help decision-makers devise necessary adaptation strategies for sustainable development of the water resources.

The study area comprises the Moeyingyi wetland and the nearby BRB. Figure 1 shows the overall study area with location of hydrological stations and canal system. The total area is 3170 sq. km, with an average annual temperature of 26°C. The average annual rainfall is about 3000 mm and almost 85% of it occurs during monsoon season.

The Moeyingyi wetland lies in the Bago and Waw townships of Bago district and covers an area of 103.6 sq. km. The wetland is surrounded by an embankment of average height 3.66 m, with the total storage capacity of 173 million cubic metres. There are three main sluice gates to supply water for irrigation: Moeyingyi (10 openings), Kapin (eight openings) and Zwebat (four openings). These sluice gates are controlled and managed by the Irrigation Department of Bago district to irrigate around 12,400 ha land through the Bago–Sittaung canal. Around 65 species of water birds, 60 species of terrestrial birds, 30 species of fishes and 29 species of reptiles and amphibians are commonly observed in the Moeyingyi wetland[3].

The upper BRB is jointly shared between Bago Township of Bago Division and Yangon Division of Myanmar and lies west of the Moeyingyi wetland. The northern part of the basin is at a higher altitude of up to 800 m amsl, whereas the lower southern part is relatively plain and fertile. The Bago River flows through Bago city and is flooded almost every year during the monsoon period. The average flow in the Bago River is 135 m^3/s, which can increase to 450 m^3/s during the rainy season. Water from the Bago River is diverted for irrigation and is used to maintain the water level of the Moeyingyi wetland during the dry season through a canal. The intake of the irrigation canal lies between Zangtu and Bago stations.

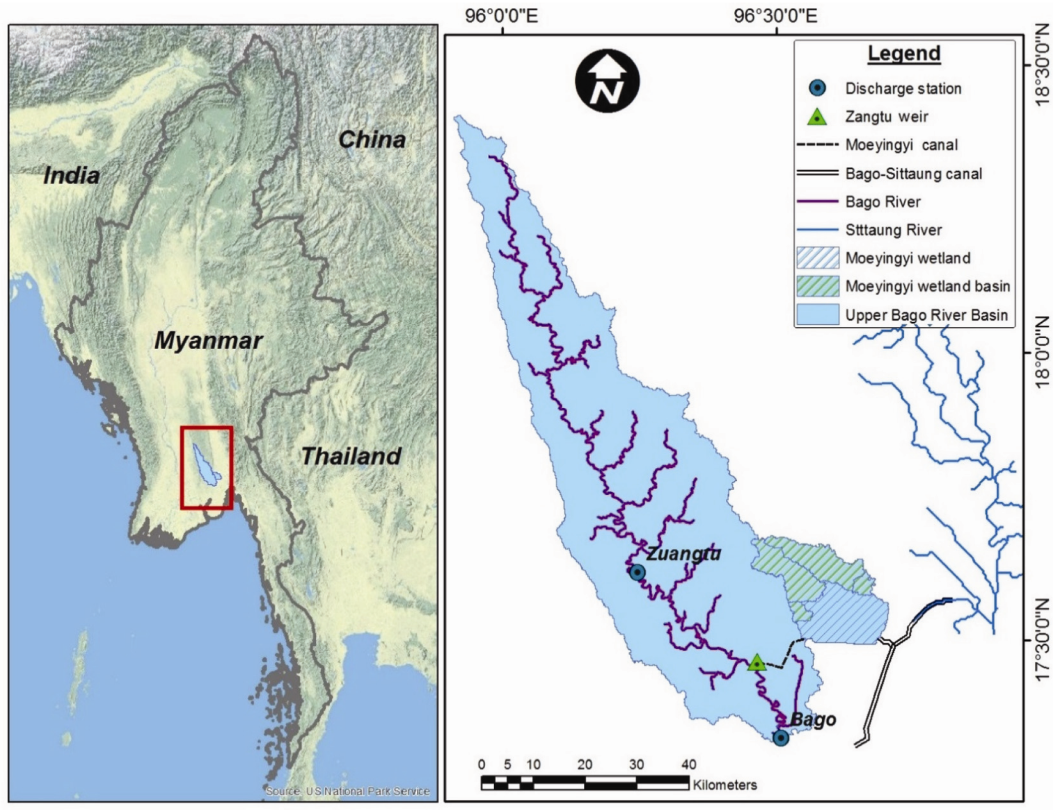

Figure 1. Location map of the study area in Myanmar.

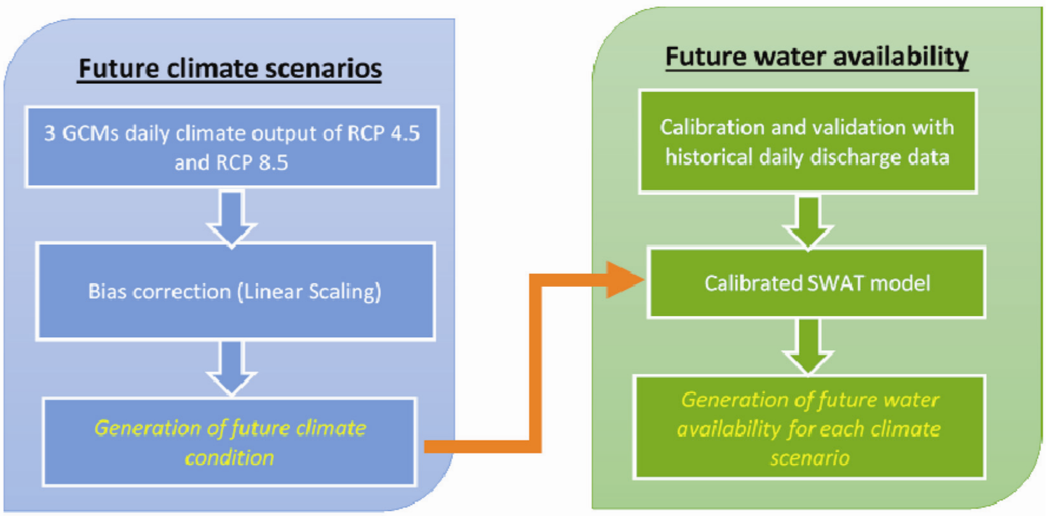

Figure 2. Research methodology for the study.

The study was conducted to evaluate the impact of future climate change on the BRB and the Moeyingyi wetland and its effect on water availability in the Moeyingyi wetland for the future period of 2050. The overall methodology used in the study is shown in Figure 2. Outputs from three GCMs, namely MIROC5, CSIRO and ECHAM for two representative concentration pathway (RCP) scenarios of RCP 4.5 and RCP 8.5 were used. The outputs from these GCMs were bias-corrected using linear scaling technique into local observed stations to project future climate scenarios in terms of rainfall and maximum and minimum temperature.

The hydrological model Soil and Water Assessment Tool (SWAT) was set-up and calibrated against the historical observed discharge at Bago and Zangtu stations. Projected future climate data were then used as input for SWAT model to determine the future water availability at the Bago River and the Moeyingyi wetland.

The climate change scenarios were generated from the output of GCMs based on IPCC Fifth Assessment Report (AR5). There are four types of RCPs: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 that represent different alternatives of global development. The RCPs were defined by their total radiative (cumulative measure of human emissions of greenhouse gases from all sources expressed in W/m^2) forcing in 2100 (ref. 17). The pathway of any single radiative forcing will be based on socio-economic and technological development in the future. These scenarios also include impact due to land-use changes.

This study examines the potential effect of climate change under RCPs 4.5 and 8.5 scenarios on the discharge of the Bago River. Under the RCP 4.5 scenario, the population will decrease and proper land rules and regulations will be created to preserve the environment. In contrast, under RCP 8.5, people will focus more on economic development rather than environmental preservation[18].

Data from three GCMs, namely MIROC5, CSIRO and ECHAM were analysed to find the future climate scenarios for the period of 2021–30 (2020s), 2031–40 (2030s) and 2041–50 (2040s). The GCMs were selected by evaluating their historical run with the observed meteorological station based on four indicators: coefficient of determination (R^2), root mean square error (RMSE), mean and standard deviation. These data were bias-corrected using linear scaling bias correction method[10,16]. The bias correction helps increase the R^2 value while decreasing RMSE. In addition, the mean and standard deviation of the model would be close to those of observed precipitation and temperature.

The SWAT is a semi-distributed hydrological model widely used by the scientific community to simulate hydrological processes[16,19–22]. It can be used in modelling ungagged basins and the input data can be altered to simulate the changes such as land-use change, climate change or land management practices[23]. SWAT divides the basin into a number of sub-basins, which are further sub-divided into hydrological response units (HRUs) based on the topography, land use and soil type.

The observed rainfall and maximum and minimum temperature from three stations, Bago, Zangtu and Tharayawady, were collected on daily time-step from the Department of Meteorology and Hydrology, Myanmar for the period 1991–2008. Two stations, Bago and Zangtu, lie within the BRB. There are no weather stations within or near the Moeyingyi wetland. Other climate data required for SWAT such as relative humidity, wind speed and solar radiation were simulated within each sub-basin based on topography, rainfall and temperature[23]. The SWAT model was verified based on the observed discharge of the Bago River. The daily discharge of the Bago River was collected from two stations, Bago and Zangtu, for the period 1994–2008.

The digital elevation model (DEM) used here was of 90 m resolution collected from SRTM (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1). Land-use map and its properties were collected from the European space agency (ESA) website (http://due.esrin.esa.int/globcover/), which has a resolution of 300 m. Among 22 land-cover types identified by ESA, 7 were found in the study area. The data show that forest covers 46% and 10% is covered by agricultural area. The soil map and soil properties required for the SWAT model were collected from digital soil map of the world (DSMW) of 1 : 5,000,000 scale (http://data.fao.org/map?entryId=446ed430-8383-11db-b9b2-000d939bc5d8). Two types of soil are present in the study area: Nitosols (Ne) covering 62% of the area and Eutric Gleysols (Ge) covering 38% of the total area.

The SWAT is a process-based model and its parameters must be within a realistic uncertainty range[24]. Local sensitivity analysis was performed by changing the parameter value one at a time to find out the most sensitive parameters[24]. Two separate models were created for the upper BRB and the Moeyingyi wetland. A total of 22 parameters were selected to calibrate the model. The upper BRB model was calibrated against the observed discharge at two stations: Zangtu and Bago, which is the basin outlet. The observed discharge data from 1994 to 2003 and 2004 to 2008 were used for calibration and validation of the model. Data for three years, i.e. 1991–93 were used as a warm-up period for the model.

The model performance was checked using statistical indicators such as Nash–Sutcliffe Simulation efficiency (NSE), percentage bias (PBIAS), coefficient of determination (R^2)[16,20,21,25–27]. The optimum value indicating the perfect match between the observed and simulated discharge for NSE and R^2 is 1, whereas PBIAS is 0. The model performance is acceptable if NSE is greater than 0.5 and PBIAS lies in the range ± 25 (refs 26, 27).

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q_i')^2}{\sum_{i=1}^{n}(Q_i - \bar{Q}_i)^2}, \tag{1}$$

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(Q_i - Q_i') * 100}{\sum_{i=1}^{n}(Q_i)}, \tag{2}$$

$$R^2 = \frac{n\sum Q_i Q_i' - \sum Q_i \sum Q_i'}{(\sqrt{n(\sum Q_i^2) - (\sum Q_i)^2}) \times (\sqrt{n(\sum Q_i'^2) - (\sum Q_i')^2})}, \tag{3}$$

where Q_i is the measured daily discharge, Q_i' the simulated daily discharge, $\bar{Q}_i$ the average daily discharge for the observed period, $\bar{Q}_i'$ the average daily discharge for the simulated period and n is the total number of daily discharge.

Due to scarcity of discharge data at the Moeyingyi wetland outlet, calibration of the model was not possible.

However, Heuvelmans *et al.*[28] found that transfer of parameters of the semi-distributed SWAT model to a neighbouring catchment with similar topography, soil and land use yields reasonably good model performance. Hence, model parameters from the neighbouring BRB were transferred to the Moeyingyi wetland model, as both share similar topography, soil and land use.

The average temperature of the basin was calculated by averaging bias-corrected maximum and minimum temperature using Thiessen polygon method. A continuous increase in annual mean temperature was observed under both the scenarios. Figure 3 shows the relative increase in temperature of the basin predicted by the three GCMs and their average ensemble under RCPs 4.5 and 8.5. The largest increase in temperature is predicted in 2040s, where ECHAM model shows the highest increase in temperature up to 2.7°C. A large uncertainty is observed while predicting the future temperature, but all the GCMs and both the scenarios predict a continuous increase in temperature of the basin. This indicates that evapotranspiration will increase in the future.

Precipitation was also calculated by Thiessenpolygon method. Figure 4 shows the relative annual precipitation changes under RCP 4.5 and RCP 8.5. Under both the scenarios, annual precipitation will likely decrease by 2020s. The largest decrease (up to 350 mm) is observed under RCP 4.5. A large uncertainty is observed while predicting the future precipitation. MIROC 5 shows a decrease in the annual precipitation for both scenarios, whereas ECHAM shows an increase in annual precipitation. The average ensemble of these GCMs shows that precipitation will decrease in the near future, whereas it will gradually increase for the period of 2040s.

Under RCP 4.5, a decrease in precipitation is noticed in May, June, August and September, whereas an increase is observed during April, July and November. The highest increase in precipitation (up to 300 mm) is predicted during April for the period of 2040s compared with the base period. For all time-periods, precipitation for the month of July increases with the highest value up to 65 mm for the period of 2040s. Similar pattern of changes is observed under RCP 8.5. Here the largest decrease is for May where the precipitation will decrease up to 113 mm for the period of 2020s. In general, precipitation will decrease during the monsoon period, except for July.

The daily simulated discharge values were compared with the observed discharge to calibrate the SWAT model at two points. Figures 5 and 6 show a graphical comparison between the observed and simulated discharge for calibration and validation period at Zangtu and Bago stations respectively. Table 1 shows the performance of the SWAT model at Zangtu and Bago stations. The model performed better at Bago than at Zangtu station. The NSE and R^2 values at Zangtu station showed satisfactory results and were above 0.50. In contrast, the NSE and R^2 values were above 0.70 during the calibration and above

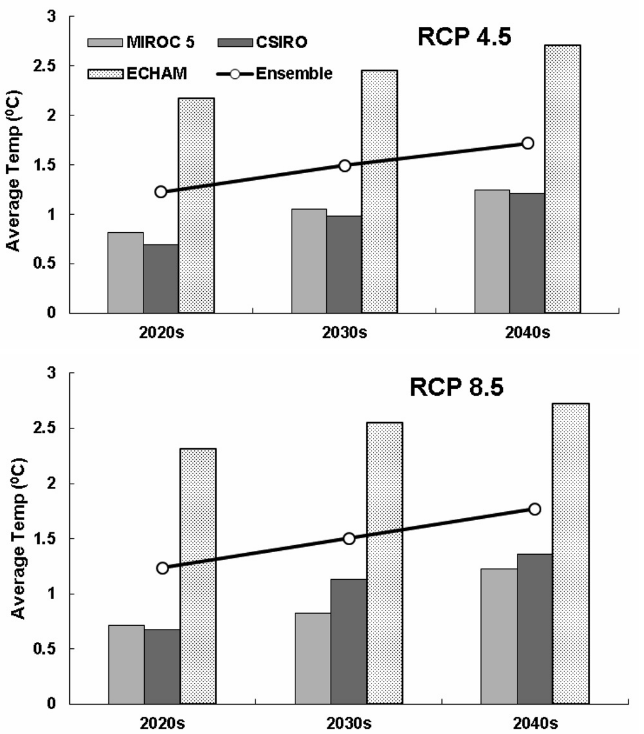

Figure 3. Relative change in average temperature for different future periods under RCPs 4.5 and 8.5.

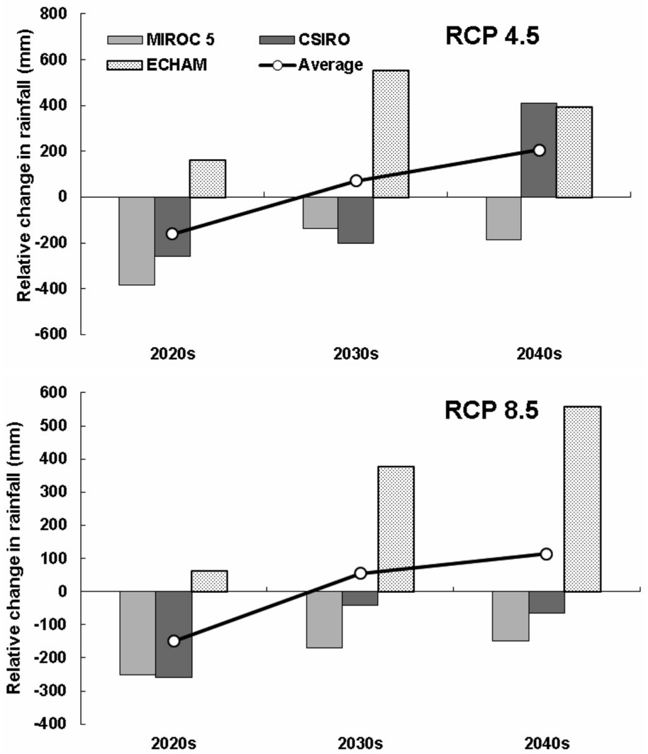

Figure 4. Relative change in rainfall for different future periods under RCPs 4.5 and 8.5.

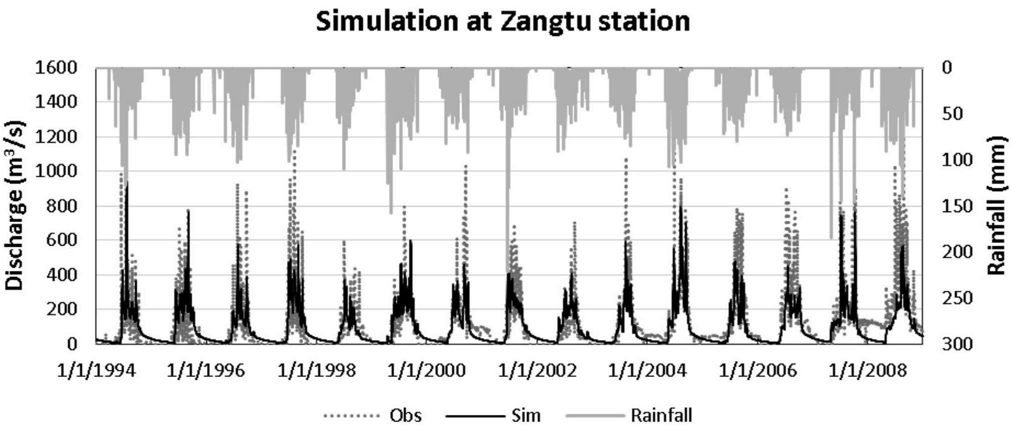

Figure 5. Comparison of the observed and simulated daily discharge during calibration at Zangtu station.

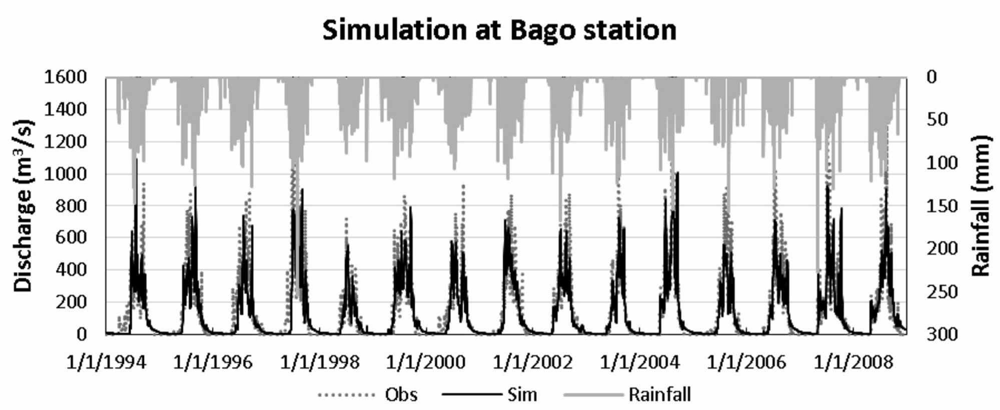

Figure 6. Comparision of observed and simulated daily discharge during calibration at Bago station.

Table 1. Performance of the SWAT model at Zangtu and Bago stations

		Zangtu			Bago		
Period	Time span	R^2	NSE	PBIAS	R^2	NSE	PBIAS
Calibration	1994–2003	0.53	0.50	–16.63	70.00	0.69	5.40
Validation	2004–2008	0.56	0.50	29.49	0.82	0.81	4.54

0.80 during the validation at Bago station. For all cases, PBIAS was within the ±25% range, except at Zangtu station during validation.

The impact of climate change on the Bago River and the Moeyingyi wetland was analysed using two emission scenarios in decadal time-frame. The period 1994–2008 was considered as the base period for the Bago River and change in the future discharge was calculated as the relative change in discharge at two points: Zangtu and Bago stations. Land-use change and its effect on the discharge have not been considered during the study period.

Figure 7 shows the relative change in discharge at Zangtu and Bago stations. In the box and whisker plots, the height of each box represents 50% of the respective distribution (interquartile range) of the data. The length of error bars denotes the maximum and minimum (range) values of the datasets. The uncertainty of climate projection is measured by the interquartile range and ranges, and the middle line represents medium[13]. The discharge in the river will decrease under RCP 4.5 in both the stations. Under RCP 8.5, however, the discharge will increase for the period of 2040s. The simulation projected an average change in discharge of –7% (–38% to 29%), –7% (–32% to 42%) and –1% (–29% to 126%) in the 2020s, 2030s and 2040s respectively, for Zangtu station. Similarly, an average change in discharge of –6% (–45% to 62%), –5% (–36% to 61%) and 0.1% (–31 to 166%) in the 2020s, 2030s and 2040s respectively is observed for Bago station.

Figure 8 shows the relative change in monthly mean discharge at Zangtu and Bago stations under two scenarios. Both show similar change in trends. The discharge at

Zangtu station is likely to decrease during monsoon season. The maximum decrease of up to 25 m^3/s is predicted for August under RCP 4.5. At Bago station, similar pattern is observed. The discharge will likely increase during April and lies in the 27–80 m^3/s range during the period of 2040s under RCP 4.5. On the other hand, a discharge of up to 130 m^3/s will increase during April for the period 2020s under RCP 8.5. The maximum decrease (up to 30–56 m^3/s) is observed in October. Similarly, the discharge is expected to decrease during the dry season which could have a negative impact on the diversion of water from the Bago River to the Moeyingyi wetland. On the other hand, discharge is likely to increase during monsoon season for the period of 2040s in Bago city and this could further worsen the recurring floods. The change in discharge is driven by both an increase in temperature and change in precipitation.

Climate change impact analysis shows a decrease in inflow at the Moeyingyi wetland in future periods. Inflow at the wetland can decrease up to 18% for the period of 2020s compared with the base period (Figure 9). This can have serious consequences for both agriculture and wetland biodiversity. The inflow is expected to decrease during the dry season and increase during the wet season. The highest decrease in the inflow can be observed during May and October, whereas inflow will increase for June and July.

In this study, the impact of climate change on water availability of the upper BRB and Moeyingyi wetland has been investigated. Two emission scenarios and three GCM outputs were used to predict the future climate data, which were used in the SWAT model to predict future discharge in the Bago River. Three future periods of up to 2050 as 2020s, 2030s and 2040s were considered for the study. The bias-corrected data of temperature show that the basin average temperature increases continuously throughout the study period, reaching up to 1.2–2.7°C, indicating an increase in evapotranspiration. It is also observed that the overall precipitation will decrease during the near future and will rise in the middle of the 21st century. The monthly analysis of precipitation also shows a decrease during the monsoon period, except in July when precipitation will increase.

With increasing temperature and decreasing precipitation, a decrease in mean annual discharge will be evident at both Zangtu and Bago stations, indicating a decrease in water availability in the BRB. The projected monthly changes in discharge reveal that will decrease during May and October. These can have a serious consequences on water diversion to the Moeyingyi wetland. On the other hand, an increase in discharge during the monsoon season can worsen the regular floods in Bago city. Similarly, a large increase in discharge is predicted during April due to an increase in precipitation. Overall, the inflow at Moeyingyi wetland is expected to decrease in the future.

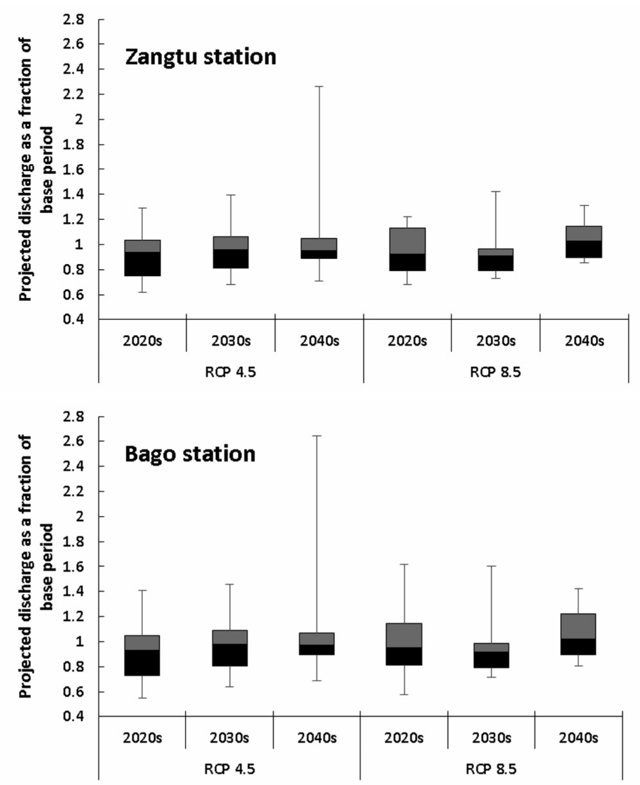

Figure 7. Box and whisker plots of projected discharge under RCPs 4.5 and 8.5 as a fraction of discharge of the base period for Zangtu and Bago stations.

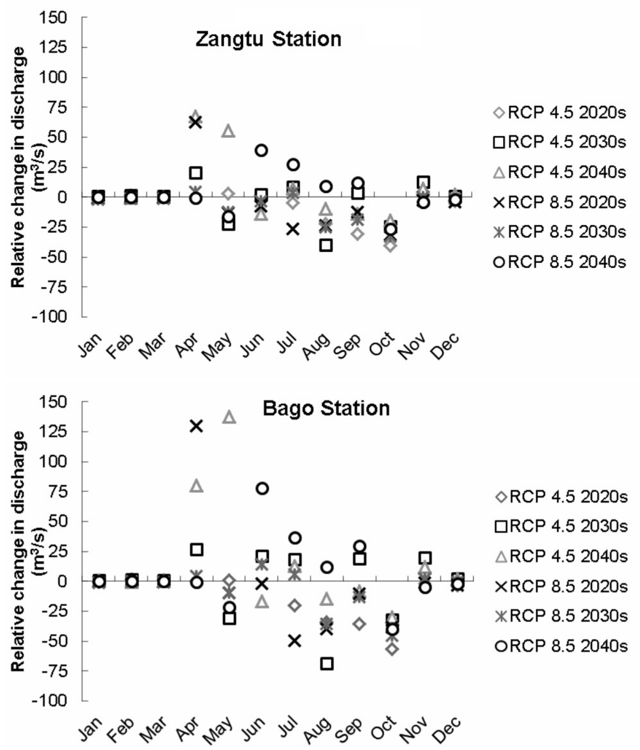

Figure 8. Relative change in monthly discharge of Zangtu and Bago stations.

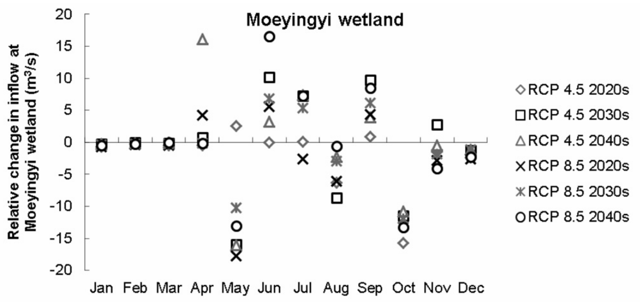

Figure 9. Relative change in monthly inflow at the Moeyingyi wetland.

Water availability at the Moeyingyi wetland may decrease in future as a result of decrease in discharge at the Bago River for diversion as well as a decrease in inflow at the Moeyingyi wetland during dry season. This will have a negative impact on the irrigation water management and ecosystem of the wetland. Proper adaptation measures should therefore be formulated and implemented to minimize the impact of climate change.

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