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Assessment of future stream flow over the Sesan catchment of the Lower Mekong Basin in Vietnam

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Abstract:

This study used a regional climate model, driven at a resolution of 30 km, to derive climate estimates that were used as input to a hydrological model to determine stream flow in a changing climate. This regional climate model output was derived using the Weather Research and Forecasting model, which was used to downscale the general circulation model ECHAM5 T63 under the A2 greenhouse gas emission scenario for the future. Two river basins, Dakbla and Poko, over the Sesan catchment of the Lower Mekong region were considered for runoff modeling. A 10-year climatology of the recent past, 1991–2000, was used as the baseline for the present-day climate, and another 10-year climate over the period 2091–2100 was chosen for the future time slice. The results from the simulation of future stream flow indicate that, over both Dakbla and Poko river basins, the stream flow is likely to increase, especially during the peak rainfall season. The Dakbla River Basin shows a substantial increase in stream flow when compared with the Poko River Basin. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS downscaling; regional climate model; climate change; hydrological model; stream flow

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INTRODUCTION

There has always been uncertainty in understanding a system as complex as climate and equally climate change, but there is now stronger evidence that significant global warming is happening. Attributing the warming in the recent decades to human-induced activities, the Intergovernmental Panel on Climate Change (IPCC) has mentioned in its Fourth Assessment Report (2007) that 'It is *likely* that there has been a substantial anthropogenic contribution to surface temperature increases in every continent except Antarctica since the middle of the 20th century'. It has been noted that the global warming is likely to increase both the frequency and severity of weather events such as heat waves and heavy rainfall and could lead to large-scale effects such as melting of large ice sheets, with major impacts on low-lying regions throughout the world (IPCC, 2007). Because these projected climate changes will impact water resources, agriculture, bio-diversity and health, one of the key challenges of climate research is the application of climate models to quantify future climate change and its impacts on both the physical environment and the society through the employment of impact models (Hewitson and Crane, 1996). The general circulation models (GCMs), which are primary physically based tools giving information on global climate, provide reasonable simulation accuracy of climate in a global, hemispheric or a continental scale, but at a regional/sub-regional scale representation, the simulation accuracies are poor due to their coarse spatial resolution (Giorgi, 1990, Giorgi and Marinucci (1996a, 1996b)).

Regional climate is often affected by forcings and circulations that occur at a sub-grid scale of the GCM. Some of the regional and local scale climate forcings due to land-use characteristics, complex topography, land–ocean contrasts, aerosols, radiatively active gasses, snow, sea ice and ocean currents are not resolved well by GCMs. It is therefore obvious that the GCMs cannot explicitly capture the fine scale structure that characterizes climate variables in many regions of the world that is required to run impact models. This becomes particularly problematic for important climate variables such as precipitation that have high variability in space and time. Because of their coarse spatial resolutions and their inability to include mesoscale atmospheric features in their large-scale circulation, the GCMs do not simulate the precipitation fields with adequate fine scale details to be applied to impact models such as hydrological models. Hence, before the GCM output information of certain key variables such as rainfall can be used to drive the impact models at a regional or a local scale; there is an intermediate step that requires the 'downscaling' of this large-scale GCM information to regional scale information. For regions such as river basins, this is very crucial because many river basins and catchments around the world are too small in size compared with the size of a GCM grid.

Hay *et al.* (2002) used the output from regional climate model (RCM) RegCM2 driven at 52 km for the continental United States as input to a distributed hydrological model for one rainfall-dominated basin and three snowmelt-dominated basins along with the station data as the other input. They found that the RegCM2 output did not exhibit

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the day-to-day variability in rainfall and temperature; even after they were bias-corrected suggested that the systematic biases in the RCM need to be further evaluated, and improved methods were needed to remove bias to obtain a better day-to-day variability of climate variables for use in hydrological models. Another application of RCM output was mentioned in a study by Fowler and Kilsby (2007) for simulating river flows in northwest England. The output data from RCM HadRM3H were bias-corrected on observed mean statistics and used as input to hydrological models that were calibrated for eight catchments. The authors reported that the simulated daily flow distributions were reasonable and hence could be used with some confidence to examine future changes in flow regimes. Climate change inputs from different RCMs produced from the PRUDENCE experiment (Christensen and Christensen, 2007) were used in a study by Graham *et al.* (2007) to address how differences in the climate models affect estimates of projected hydrological change over the Baltic Basin, the Bothnian Bay Basin and the Rhine Basin. The application of delta factor method for assessing future changes was deemed robust, and the authors concluded that the hydrological simulations were more dependent on the choice of the GCM that was downscaled and not the RCM that was used to downscale the GCMs. Im *et al.* (2010) dynamically downscaled the GCM ECHO-G using RCM RegCM3 whose outputs were applied to determine the hydrological response over three Korean basins. The authors reported the usefulness of the application of RCM-derived information for use in impact assessments. Ma *et al.* (2010) studied the hydrological response to future climate change over Agano River Basin in Japan using the regional climate model output. After the performance of the hydrological model was checked using a 20-year hind cast for the period between 1980 and 1999, the model was found suitable for future climate change studies.

In a similar study, this paper describes a study that assesses hydrological responses over a couple of river basins in one of the most climate-vulnerable regions, the Mekong River Basin in Southeast Asia. This study uses the output of an RCM as the input to the chosen hydrological model.

MODELS AND METHODOLOGY

This section describes the Sesan catchment, which is the study region, a small part of the Lower Mekong Basin. The hydrological model and the regional climate model that were used for this study and the modeling experimental approaches are also described.

Sesan catchment

The catchment considered in this study is the Sesan catchment, lying over the central highland region of Vietnam between 107°19′E and 108°38′E and 13°33′N and 15°15′N. Together with SrePok and Sekong rivers, the catchment forms the main river system of sub-area 7 (SA7) of Lower Mekong Basin. Detailed information about the SA7 region is available from the Mekong River Commission website at

http://www.laoiwrm.com/BDPatlas/BDPatlas_6-10 (final June 2006)/SA7/SA7_Main.htm.

The Sesan River Basin has a catchment area of 9030 km^2, which consists of two sub-catchments, called Poko and Dakbla, formed by the discharge stations located at the ending point of each sub-catchment (Figure 1). There are six rainfall stations inside and outside the study catchment with three stations for each sub-basin (Poko and Dakbla). This is also indicated in Figure 1. The shaded region in the diagram in the left is magnified for clarity in the right, which shows the two sub-basins considered in this study.

The climate of this region follows the pattern of central highlands in Asia with an average temperature of 21–25 °C around the year, a high total rainfall of about 1600–3000 mm/annum. Rainfall in this region is influenced by the South West monsoon season that usually starts in May and ends in September/late October.

Hydrological model (SWAT) and the experimental design

Soil and Water Assessment Tool (SWAT) is a river basin scale model, developed at the United State Department of Agriculture – Agriculture Research Service in early 1990s (Arnold *et al.*, 1998). SWAT is a physically based model that is designated to work for

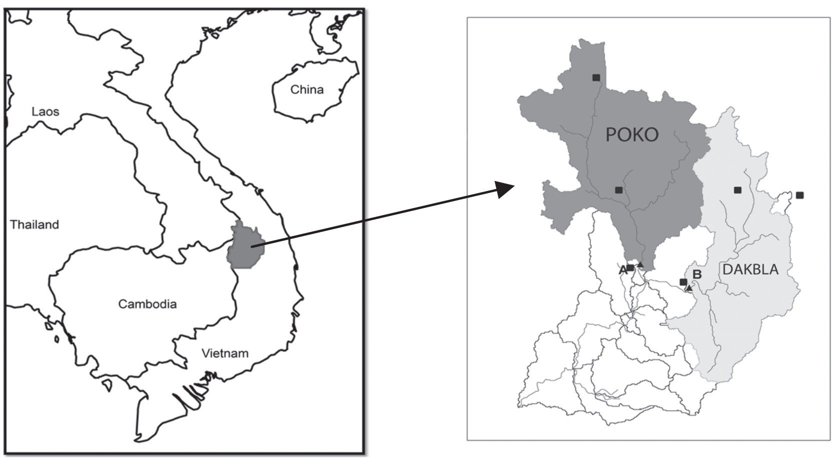

Figure 1. The study domain and the river basins. [Inset: map of Vietnam showing the location of the catchment (shaded)]

large river basins and catchments and uses readily available inputs. It is widely used to study the impacts of land management practices on water, sediment and agriculture chemical yields with varying soil, land use and water management conditions. A suite of information about the model and its varied applications are available at the SWAT website: http://swatmodel.tamu.edu/.

In this study, the main objective was to quantify the impacts of climate change to hydrological stream flow over a long period of time. SWAT was chosen as the hydrological model to which the precipitation output of a regional climate model was applied as input to simulate stream flow. The SWAT version 2005 was coupled to an ArcGIS interface (ArcSWAT) making the input and calibration steps more convenient. The input for ArcSWAT included a spatial reference map such as the digital elevation model (DEM) with a resolution of 250 m × 250 m, a land-use map and a soil map (converted to raster format with same resolution) and meteorological data (precipitation and temperature time series of all stations in daily format). The DEM was obtained from Department of Survey and Mapping of Vietnam. The land-use map was taken from the Forest Investigation and Planning Institute, of Vietnam for the year 2000. The soil map was obtained through the Ministry of Agriculture and Rural Development of Vietnam categorized by the Food and Agriculture Organization. The DEM, land use and soil map for SWAT are shown in Figure 2.

Model calibration. A period of 5 years from 1995 to 2000 was used to calibrate the SWAT model for stream flow with the first year 1995 as a warm up period using the observed station data. The validation of the model was carried out for the period 1991–1995 to check if the calibration holds good for a different period. Observed discharge data from the station Kon Tum (on the Dakbla River) and the station Trung Nghia (on the Poko River) were used to calibrate the model separately. The precipitation data on a daily scale were used from 1991 to 2000 from the stations inside and outside catchment (Figure 1) for the calibration and verification processes of the SWAT model.

The coefficient of determination R^2 and the Nash–Sutcliffe index (*NE*) were used as statistical indices to assess the goodness of fit of the model. The coefficient of determination R^2 is a measure of how well future outcomes are predicted by the model. It should be noted that Nash–Sutcliffe efficiencies can also be used to quantitatively describe the accuracy of model outputs other than discharge. This method can be used to describe the predicative accuracy of other models as long as there is observed data to compare the model results with. The *NE* index is defined by

$$NE = 1 \frac{\sum_{i=1}^{N} (O_i - S_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2}$$

and the coefficient of determination R^2 is defined by

$$R^2 = \left\{ \frac{N \sum_{i=1}^{N} S_i O_i - \sum_{i=1}^{N} S_i \sum_{i=1}^{N} O_1}{\sqrt{N \sum_{i=1}^{N} S_1^2 - \left(\sum_{i=1}^{N} S_i \right)^2} \sqrt{N \sum_{i=1}^{N} O_i^2 \left(\sum_{i=1}^{N} O_i \right)^2}} \right\}$$

where, O and S are the observed and simulated flow and N, is the period of time steps.

Sensitivity analysis was performed for the SWAT model, which demonstrates the impact a change to an individual input parameter has on the objective function value. The method in ArcSWAT combines Latin hypercube and one-factor-at-a-time sampling. The calibration and validation (Figures 3 and 4) of the model for the Dakbla and Poko basins were performed both on a

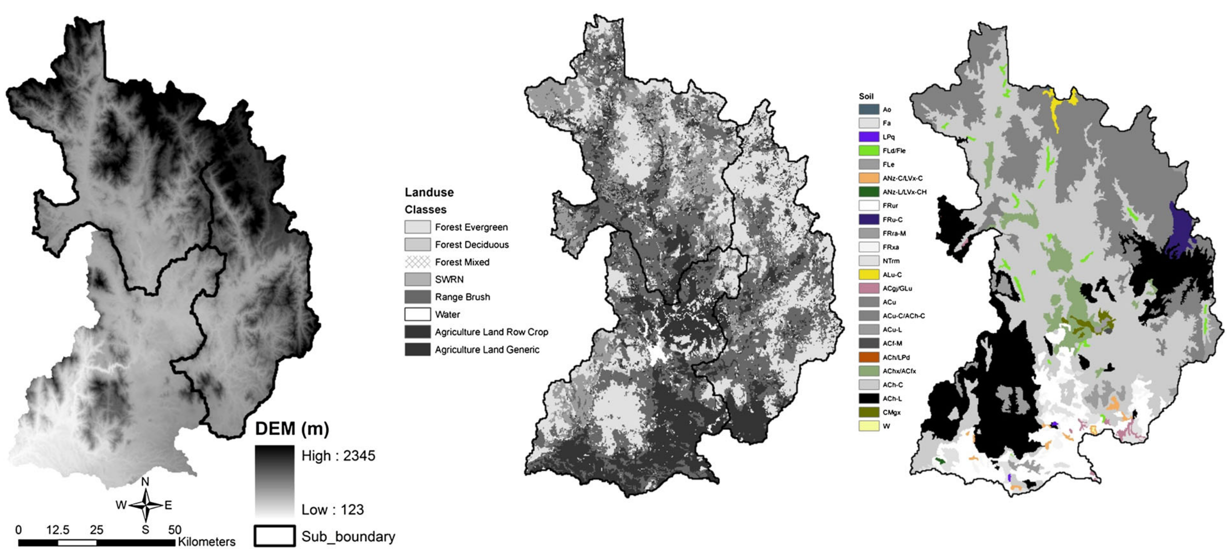

Figure 2. ArcSWAT inputs over the Sesan catchment: from left: digital elevation model (DEM), land-use map and soil map

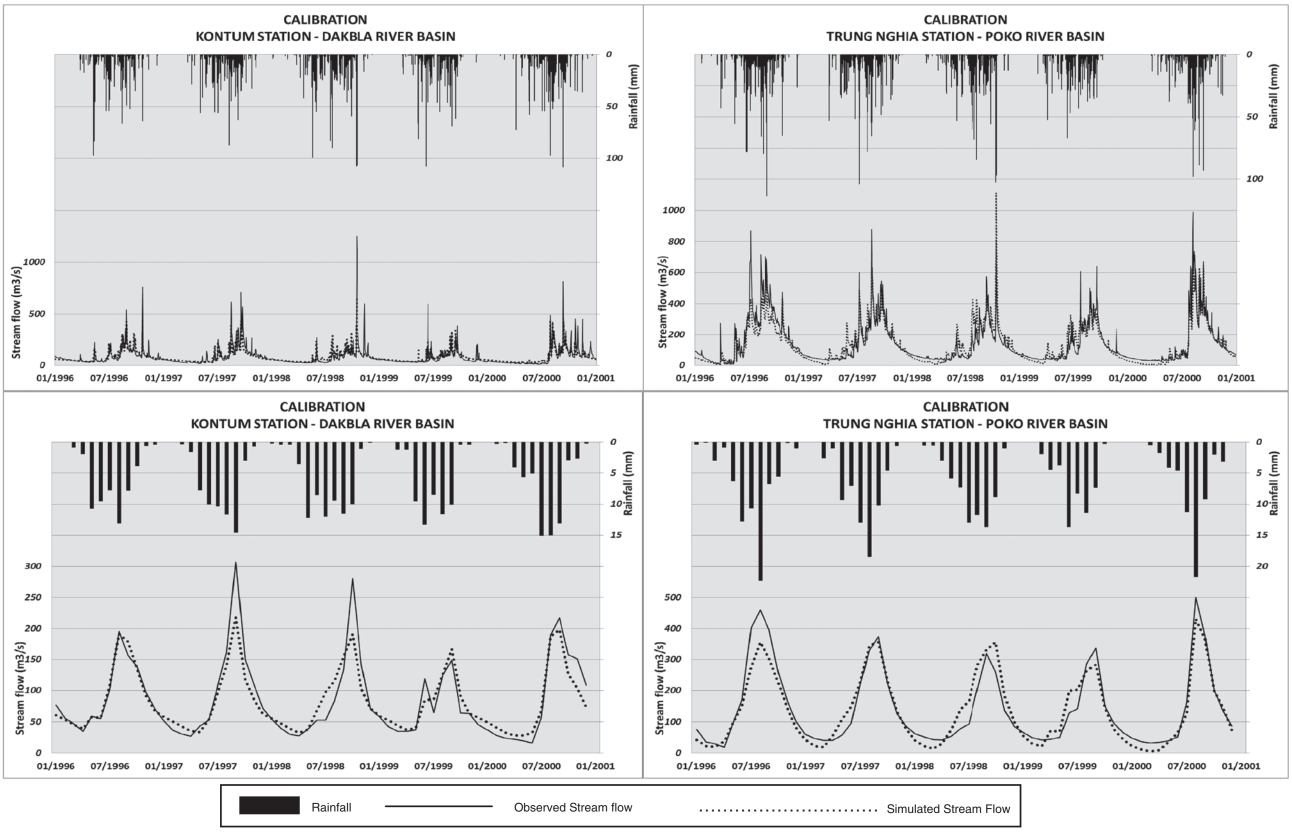

Figure 3. Calibration of the model: Dakbla (left) and Poko (right) river basins on the daily (top) and monthly (bottom) scales

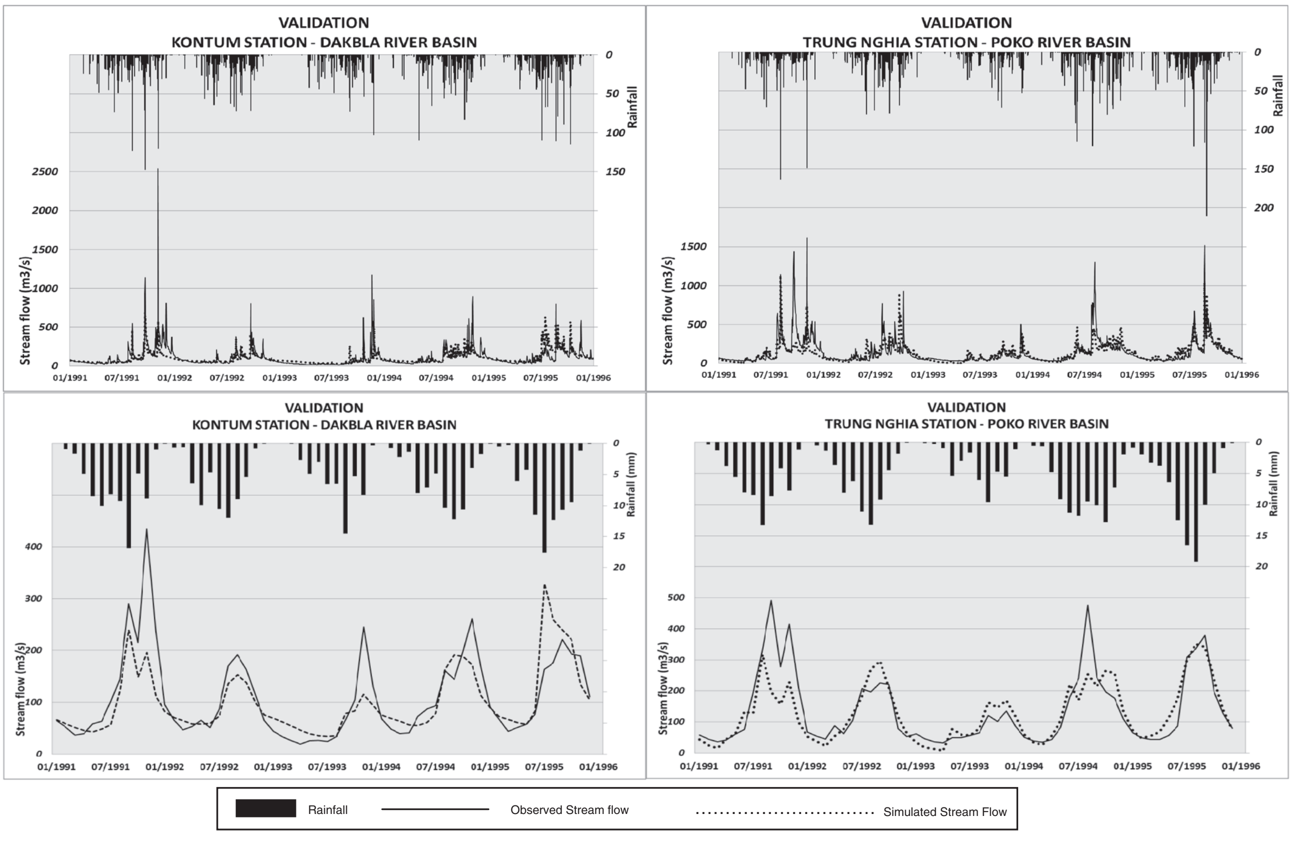

Figure 4. Validation of the model: Dakbla (left) and Poko (right) river basins on the daily (top) and monthly (bottom) scales

monthly and a daily scale. The statistical indices show that the values of validation indices were higher on a monthly scale than on a daily scale because the values for the daily validation were affected by the day-to-day variability on the daily scale. The statistical indices showed a value of 0.7 for the monthly value of R^2 and *NE*, which suggested that the model was well calibrated and the results of validation were acceptable. These indices suggested that the SWAT model showed highly reasonable performance.

Regional climate model (WRF) and experimental design

Developed at the National Center for Atmospheric Research (NCAR) in the USA, the Weather Research and Forecasting (WRF) model is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. The WRF software has a modular, hierarchical design that provides good portability and efficiency across a range of foreseeable parallel computer architectures. The model incorporates advanced numeric and data-assimilation techniques, a multiple nesting capability and numerous state-of-the-art physics options. Other than applications of weather forecasting, the model has found wide applications in climate research.

In this study, RCM WRF was run over a part of the Lower Mekong Region (Figure 1) at a horizontal resolution of 30 km centered over the Sesan catchment area. The model was driven by both National Center for Environmental Prediction (NCEP)/NCAR reanalysis and the GCM ECHAM5 T63, developed at the Max Planck Institute, Germany. As for the physics options, the Kain–Fritsch scheme was used for the cumulus convection scheme, the Yonsei University scheme for the planetary boundary layer, Thomson scheme for the explicit moisture physics and Rapid Radiative Transfer Model GCM applications (RRTMG) http://rtweb.aer.com/rrtm_frame.html, for both long and short wave radiations along with the NOAH land surface scheme for implementation of surface hydrology. The physics options were chosen from different parameterization sensitivity studies that best represented the climate of the region. Because the focus of this paper is more on the hydrology, these results are not being discussed in detail. A detailed description of the numerous physics options of the WRF model can be obtained from the documentation available at the WRF website: http://wrf-model.org/index.php.

The RCM WRF model was run for the period 1991–2000 using the NCEP/NCAR analysis to assess its performance of the present-day climate. Later, the model was run using the GCM ECHAM5 T63 over the same period forced under the 20th century experiment (20C3M) to assess the model's performance on the 10-year climatology of the present-day climate. It would have been ideal to have run the climate simulations for a 30-year period, usually considered as for climatological baseline periods, but due to high computational demand at 30-km resolution and time, the runs were restricted to a 10-year period. The future climate simulation spanned the period 2091–2100 driven by the GCM ECHAM5 T63 under the IPCC SRES A2 emission scenario. This period has been considered in this study as the emission scenario shows clear signal of change towards the end of the century. For simplicity in reading, the simulations of NCEP/NCAR driven RCM WRF and GCM ECHAM5 T63 driven RCM WRF are being referred to as WRF-NCEP and WRF-ECHAM5, respectively. All climate simulations used the updating of sea surface temperatures, which is recommended for long-term climate simulations.

RESULTS AND DISCUSSIONS

Before analyzing how well the SWAT model responded to the simulation of stream flow when driven by RCM input, it is important to test whether the RCM-generated rainfall reproduced the observed annual cycle of rainfall over the region. This is significant because the RCM needs to represent the basic state of climate over the region, as any lead or lag in the seasonal rainfall will affect the seasonal simulation of stream flow. Firstly, the annual cycles of the observed rainfall at the station Dakto (located within the Poko River Basin) and at the station Kontum (located within the Dakbla River Basin) were compared with the popular 0.5° gridded observational dataset of the Climatic Research Unit (CRU TS 3.0) of the University of East Anglia, UK. The climatological period over 1991–2000 was chosen for evaluation, and the data for these two stations Dakto and Kontum were derived using bilinear interpolation of the closest grid points located near those stations.

The annual cycles of rainfall were also compared with the RCM-generated rainfall of WRF-NCEP and that of WRF-ECHAM5. The annual cycle simulated by WRF-ECHAM5 is significant to show the reliability of the downscaled GCM in representing the present-day climate as the RCM needs to be driven only by the same GCM to study future climate. These different annual cycles are shown in Figure 5 (left and right panels).

It is seen that when compared with the station data, the CRU dataset does not capture the seasonal cycle accurately as the peak rainfall season over the summer spans the months of June through August/September. Over both stations, both WRF-NCEP and WRF-ECHAM5 show reasonably simulated annual cycles compared with the station data, although WRF-NCEP shows slight underestimation and WRF-ECHAM5 exhibits marginal overestimation, especially during the peak rainfall season. With the use of these RCM-derived rainfall estimates (WRF-NCEP and WRF-ECHAM5), the stream flow over the chosen river basins were simulated [Figure 6 (left and right panels)]. For the Poko River Basin, the WRF-ECHAM5 shows a better representation of the stream flow over the present-day climate than does WRF-NCEP when compared with the observed station stream flow as the reference. For the Dakbla River Basin,

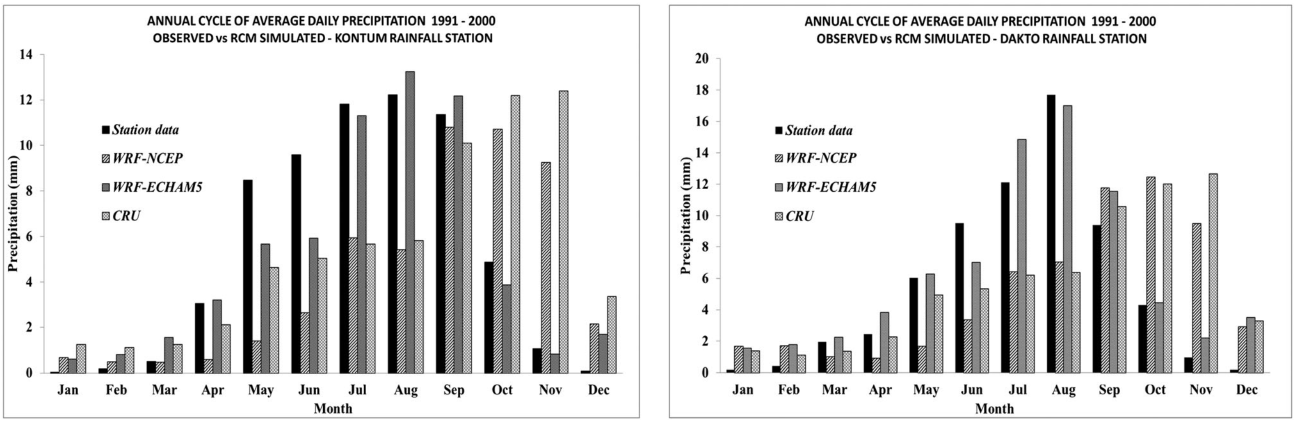

Figure 5. Climatological annual cycles of rainfall. Kontum observed station – Dakbla River Basin (left), Dakto observed station – Poko River Basin (right). WRF-NCEP, Weather Research and Forecasting-National Center for Environmental Prediction; CRU, Climatic Research Unit

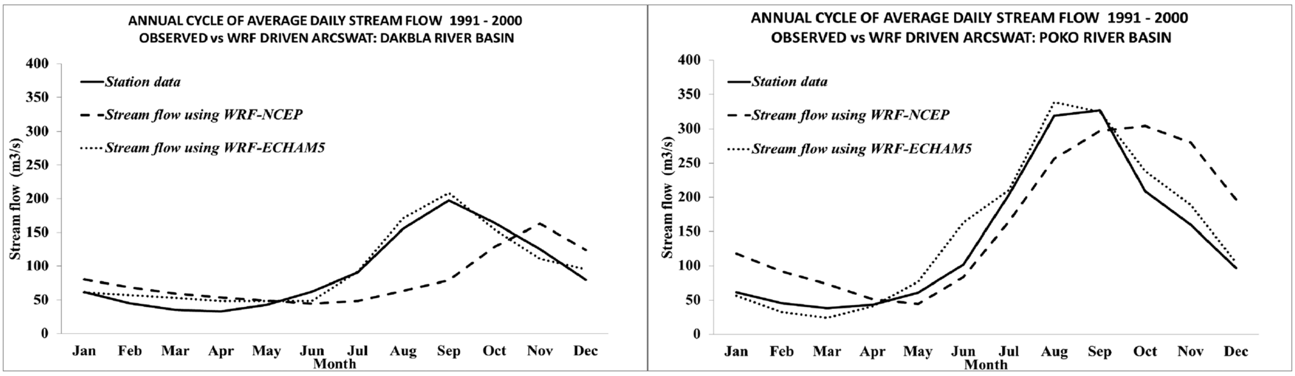

Figure 6. Climatological Annual Cycles of Stream flow. Kontum observed station – Dakbla River Basin (left), Trung Nghia observed station – Poko River Basin (right). WRF-NCEP, Weather Research and Forecasting-National Center for Environmental Prediction

the signature of the stream flow produced by WRF-NCEP is closer to the observed station stream flow than WRF-ECHAM5. The use of CRU data and its under-representation of the mean state of climate suggest the use of other gridded observations, specifically at higher resolutions as they might capture the mean state of climate better. The use of satellite gridded observations could also supplement the data inadequacies. However, these are beyond the scope of this present work but possible future study. It is also likely that even the 30-km resolution of WRF may be still inadequate to study the hydrological responses and even higher resolution of about 10 km could be implemented. The uncertainties in doing such high resolution simulations are also higher, but probable use of ensemble approach could constrain the uncertainties.

For the assessment of future stream flow, the delta factor approach was undertaken where the climate change factor was derived using the estimates of the future climates and present-day climates of the WRF-ECHAM5 simulations. This factor is the difference between the future and the present-day rainfall estimates. This method is usually practiced by impact modelers as the difference between the future and present-day model output cancels the biases in the model output and yields the clear signal of climate change. Because the best available record of rainfall is the station data, the change factor is being added to the station data time series, which in turn represents the changed future conditions of rainfall. The change factor that added station rainfall was then used as the input to the SWAT model to simulate future stream flow. Such an application of delta factor for climate change studies have been described by Sushama *et al.* (2006) and Andersson *et al.* (2006). A student *t*-test was performed to ensure that the climate signal is true and not a noise (not shown). This method entails that a credible estimate of future stream flow could be obtained. Figure 7 shows the stream flow thus derived over the two river basins, Poko and Dakbla. For clarity in comparison, the present-day stream flow (shown as 'baseline') is overlaid on the future estimated stream flow that used the WRF-ECHAM5 change factor, as discussed previously. Results show that, over both Dakbla and Poko river basins, the future stream flow is expected to increase, especially during the peak rainfall season and, at the same time, decrease during the dry season, making it difficult for irrigation purposes. The Dakbla River Basin shows a pronounced increase when compared with Poko River Basin (Table I).

However, much more work is required to improve the confidence in these results. As mentioned before, a higher resolution simulation of the RCM may be required to obtain more credible estimates of future precipitation. Because this result has been obtained only from one run of the RCM, it would be better to obtain an ensemble estimate of future change in climate by downscaling more

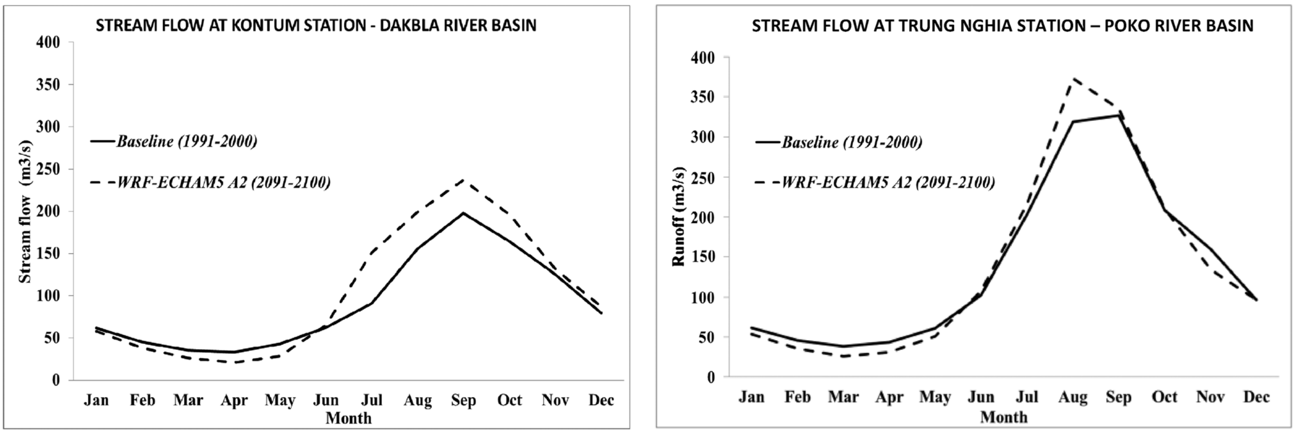

Figure 7. Future stream flow (compared with baseline stream flow). Kontum observed station – Dakbla River Basin (left), Trung Nghia observed station – Poko River Basin (right). WRF, Weather Research and Forecasting

Table I. Statistical indices of model calibration and validation: R^2 and *NE*

River basin	Calibration				Validation			
	Daily		Monthly		Daily		Monthly	
	R^2	*NE*	R^2	*NE*	R^2	*NE*	R^2	*NE*
Dakbla	0.71	0.68	0.94	0.86	0.47	0.46	0.59	0.58
Poko	0.83	0.82	0.90	0.89	0.56	0.55	0.68	0.67

GCMs or by using perturbed initial conditions to the RCM to derive multiple estimates of climate.

SUMMARY AND CONCLUSIONS

This study applied climate change simulations derived using a regional climate model to assess the future climate stream flow conditions over two river basins of the Lower Mekong region in Vietnam. The study employed the RCM WRF for generating the climate scenario whose outputs were used as inputs to the SWAT model to derive stream flow. The GCM ECHAM5 T63 under the A2 IPCC emission scenario was downscaled. The SWAT model was calibrated for the period 1995–2000 and validated over the period 1991–1995, all considered over years of the recent past. The future climate was considered over the period 2091–2100. Overall, a 10-year climatology was considered. The calibration and validation of the SWAT model showed that the model was suitable for climate study applications. The RCM-generated output of rainfall showed a reasonable annual cycle although with biases. The stream flow generated using the RCM inputs were also reasonable over the two river basins chosen for study, Poko and Dakbla. The results from the simulation of future stream flow indicate that, over both Dakbla and Poko river basins, the stream flow is likely to increase, especially during the peak rainfall season. The Dakbla River Basin shows a substantial increase in stream flow when compared with the Poko River Basin. The dry season also shows a decrease in stream flow, which could be a problem for adequate irrigation purposes.

Although the results of this study are encouraging to extend the scope of the research into a wider context, the uncertainties associated with RCM, hydrological model and GCM need further evaluation. Because these results have been derived using one RCM forced by one GCM under one scenario, the uncertainties are likely to have been underestimated and are not robust enough for adaptive measures as such. This paper deals with a single realization of the model chain. The objective is merely to interpret the changes in future climate and not to confirm changes in future climate. The results of this study, which have immense scope to develop, need to be taken as initial outcome. Nevertheless, this study lends room to apply multi-model ensembles to place more confidence on the outcomes of future changes. Further research work is expected to follow such an ensemble approach that might constrain the uncertainties and be more suitable for impact assessments and any adaptive measures thereof. This initial work, hence, could be a beginning of a detailed research program over the study region and could perhaps give the policy makers some idea of future change to devise adaptation plans suitably.

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