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Modelling the Seasonal Response of Sediment Yield to Climate Change in the Laos-Vietnam Transnational Upper Ca River Watershed

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Abstract

Changes in stream sediment yield impact material fluxes, water quality, aquatic geochemistry, stream morphology, and aquatic habitats. Quantifying sediment yield is important for predicting watershed erosion and understanding sediment transport processes. In the context of a changing climate, this is important for the management and conservation of soil and water to cope with the effects of increasingly severe climate conditions that are likely to occur in the near future. This study aims to predict seasonal trends in sediment yield under climate change impacts in the Laos-Vietnam transnational Upper Ca River Watershed. The SWAT model was used for hydrological simulation, coupled with future climate projections under three IPCC emission scenarios, B1, B2, and A2. We found an increase in the seasonality of sediment yield due to increases in the seasonality of both rainfall and runoff. However, the increase of sediment yield in the wet season appeared more significant than its decrease in the dry season, due to more significant increases in rainfall as well as runoff in that season compared to decreases in these factors in the dry season. Consequently, annual sediment yield is predicted to increase, with a rate ranging from 12.1% to 16.5% by the end of this century, depending on emission scenario. The seasonal sensitivity of sediment yield to climate change found in this study is expected to be useful in collaborative management initiatives related to soil and water resources in the watershed.

Keywords: climate change; seasonality; sediment yield; SWAT model

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1. Introduction

Over the past several decades, climate change and its impact on the environment received increasing attention from researchers around the world. Many recent studies have focused on the potential effects of climate change on specific aspects of water resources, such as water quality, streamflow, and water demand. However, few studies have considered the potential impacts of climate change on watershed erosion, and the resulting sediment loads of streams and rivers. Erosion due to heavy rainfall and high surface runoff causes the loss of fertile soil, and degrades inherent soil structure. The sediment produced by erosion process is eventually transported into streams, resulting in serious silting in streams, rivers and reservoirs (Verstraeten and Poesen, 1999). Heavy metals and other non-point pollutants, pesticides, and chemical fertilizers can also be transported with sediments by becoming attached to soil particles (Sakata *et al.,* 2010). The resulting high sediment loads can impact the use of river water, especially for water supply. Changes in fluvial sediment loads impact channel morphology, material fluxes, water quality, aquatic geochemistry, and aquatic habitats. Therefore, quantifying sediment loads under present and future conditions is important both for understanding and predicting sediment transport processes as well as for watershed-scale management of sediment in order to maintain high water quality (Mukudan *et al.,* 2013).

Although climate change is a global issue, its impact varies from region to region and from country to country. It has been predicted that Southeast Asia is among the regions facing the most severe impacts (Pham *et al.,* 2012; Watson *et al.,* 2013). Despite this forecast, little research has been published on the potential impacts of climate change in this region. Research focusing on transnational watersheds is especially scarce due to the lack of collaboration and data sharing among riparian states. In this study, we focus on the impact of climate change on seasonal patterns of sediment yield in the upper part of the Ca River Watershed (UCRW) in mainland Southeast Asia, which is shared upstream by Laos and downstream by Vietnam and covers an area of 22,798 km^2 (Fig. 1). The watershed is a typical example in terms of having a seasonally unbalanced distribution of rainfall, with the wet season receiving more than 80% of the annual rainfall (about 1600mm/ year). This high amount of rainfall in the wet season leads to high rates of soil erosion and high sediment concentration in streams and rivers. In the present study, We predicted seasonal trend in sediment yields for three time periods, the 2030s (near future), the 2060s (middle future), and the 2090s (far future) under three IPCC emission scenarios, A2, B2, and B1, which respectively represent high, medium, and low levels of greenhouse gas (GHG) emissions. The Soil and Water Assessment Tool (SWAT) was employed for hydrological simulation. The results of this study are expected to be useful for the development of effective watershed management strategies, especially for initiatives aimed at soil and water resource conservation and management to cope with future climate change impacts.

2. Materials and Methods

2.1. Hydrological simulation and data

The SWAT model is a physically-based, semi-distributed hydrological model designed to simulate runoff, sediment, and agricultural chemical yields in large complex watersheds with varying climate, soils, and land use management conditions over long time periods (Neitsch *et al.,* 2011). In SWAT, a watershed is divided into multiple sub-watersheds that are then further subdivided into unique soil/land-use characteristics called hydrological response units (HRUs). SWAT calculates soil erosion and sediment yield within each HRU using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), which is shown as Equation (1).

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K \cdot C \cdot P \cdot LS \cdot CFRG \qquad (1)$$

where *sed* is the sediment yield in a given day (metric tons), Q_{surf} is the surface runoff volume (mm ha^{-1}), q_{peak} is the peak surface runoff rate (m^3 s^{-1}), $area_{hru}$ is the area of the HRU (ha), *K* is the Universal Soil Loss Equation (USLE) soil erodibility factor, *C* is the USLE cover and management factor, *P* is the USLE support practice factor, *LS* is the USLE topographic factor, and *CFRG* is the coarse fragment factor. These parameters are adjusted in the model calibration process.

For sediment transport in the channel network, deposition and degradation are the two dominant processes that influence sediment yield at the watershed outlet. The sediment routing model (Arnold *et al.,* 1995) was used to simulate these processes. The amount of deposition and degradation is calculated based on the maximum concentration of sediment in the reach and the concentration of sediment in the reach at the beginning of the time step. The final amount of sediment

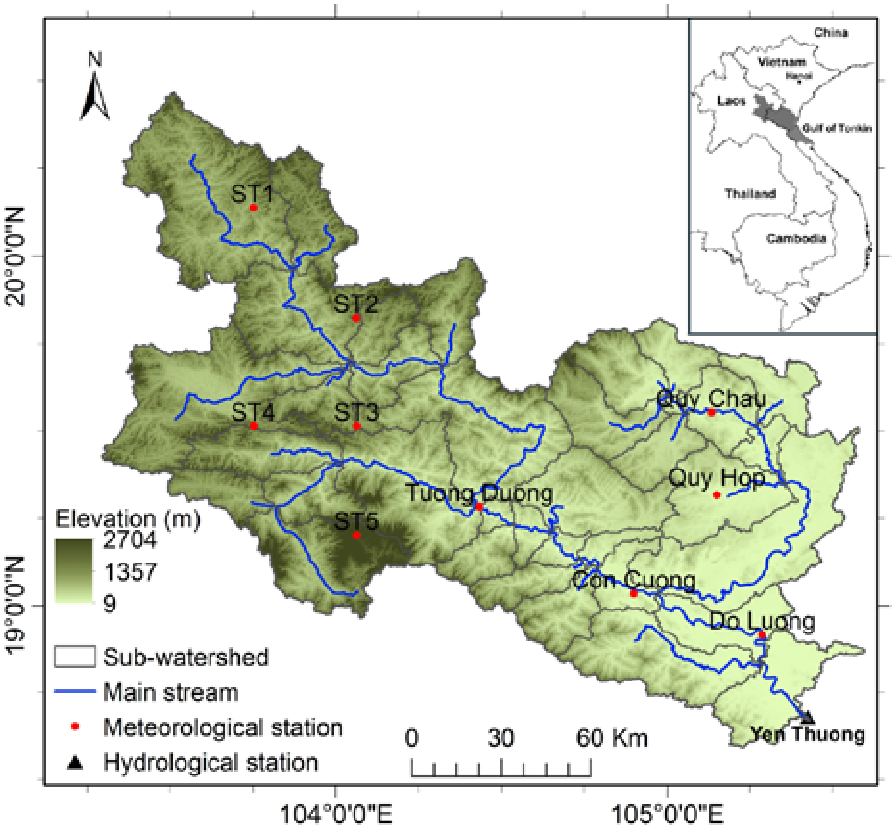


Figure 1. Geographic location of the entire Ca River Watershed (inset) and its upper part (UCRW)

in the reach is determined by Equation (2):

$$sed_{ch} = sed_{ch,ini} - sed_{dep} + sed_{re-entr} \quad (2)$$

where sed_{ch} is the amount of suspended sediment in the reach (metric tons), $sed_{ch,\,ini}$ is the initial amount of suspended sediment in the reach at the beginning of the time period (metric tons), sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), $sed_{re\text{-}entr}$ is the amount of sediment reentrained in the reach segment (metric tons). The amount of sediment transported out of the reach is calculated by Equation (3).

$$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \quad (3)$$

where sed_{out} is the amount of sediment transported out of the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3). V_{ch} is the volume of water in the reach segment (m^3). In this study, the term "sediment load" refers to the total amount of sediment, while the term "sediment yield" refers to the sediment load per unit of area (sediment yield = sediment load/area).

SWAT requires a very large amount of data, including weather variables, topography, soil properties, and land cover data. In this study, weather data on a daily basis were available for five observed stations i.e. Con Cuong, Do Luong, Quy Chau, Quy Hop, Tuong Duong. In addition, weather data at five points ST1-ST5 were obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (http://rda.ucar.edu/pub/cfsr.html). The location of these stations is shown in Fig. 1. Future climate data under three emission scenarios A2, B2 and B1 of the IPCC Fourth Assessment Report (AR4) were generated using MAGICC/SCENGEN model (Wigley, 2008), which contains 20 Global Climate Models (GCMs). Because the resultant data generated from MAGICC/SCENGEN have a coarse spatial resolution and a monthly basis, downscaling methods were used to downscale these data to at-site daily data, which can be used for hydrological simulation by SWAT. The downscaling process for climate stations in Vietnam can be referred to in MONRE (2012).

2.2. Model calibration and validation

Calibration and validation of the SWAT model were performed using observed stream discharge and sediment data collected from Yen Thuong hydrological station. For convenience, the total available historical data (1971-2010) was divided into two sets: 25 years (1971-1995) for calibration and 15 years (1996 - 2010) for validation. To evaluate the model predictions for both time periods, we used several different statistical indicators, including the coefficient of determination (R^2), Nash-Sutcliffe simulation efficiency (NSE), Percent Bias (PBIAS), and Root Mean Square Error - Observation Standard Deviation Ratio (RSR). A widely accepted guideline on these indicators was reported in Moriasi *et al.* (2006), according to which, for monthly time-step simulation, predictions of stream discharge and sediment can be judged as satisfactory if $NSE > 0.50$ and $RSR \leq 0.70$, and $PBIAS \leq \pm 25$ for stream discharge and $\leq \pm 55$ for sediment.

3. Results and Discussion

3.1. Calibration and validation of hydrological simulation

Time-series comparisons of simulated and observed cumulative monthly data over the calibration and validation periods are shown for stream discharge in Fig. 2 and for sediment in Fig. 3. In general, the SWAT model accurately tracked the observed data for both sediment and stream discharge during both time periods, although some of the low flow months were overpredicted and most of the peak flow months were underpredicted. Regarding stream discharge, according to Luo *et al.* (2012), one explanation for the problem of underestimation in SWAT is the assumption behind the model that water entering deep aquifers is not included in the water budget, but is considered lost from the system. In addition, Beven (2006) argues that the setting of model parameters to obtain the highest NSE values may cause underestimation due to the parameter equifinality or over-parameterization problem. For sediment, according to Shrestha *et al.* (2013), the underprediction of peak sediment values can be due to an uncertainty in the soil erosion model used in SWAT. SWAT simulates soil erosion using MUSLE, which was originally designed to predict annual soil loss from agricultural fields. In addition, Babel *et al.* (2011) state that the topographic factor (LS) in MUSLE, which is normally derived from DEM (Digital Elevation Model, which contains information of the topography of an area), may not be accurate enough due to inaccuracies in DEM. Johnson *et al.* (1986) also reported that for sediment yield prediction, MUSLE tends to overpredict for small events and underpredict for large events. In the present study, the UCRW is located in a tropical climate zone with heavy storms and intense rainfall events in the flooding season, which have great potential to erode surface soil and to cause landslides and river bank erosion, but MUSLE is not capable of accounting for such factors.

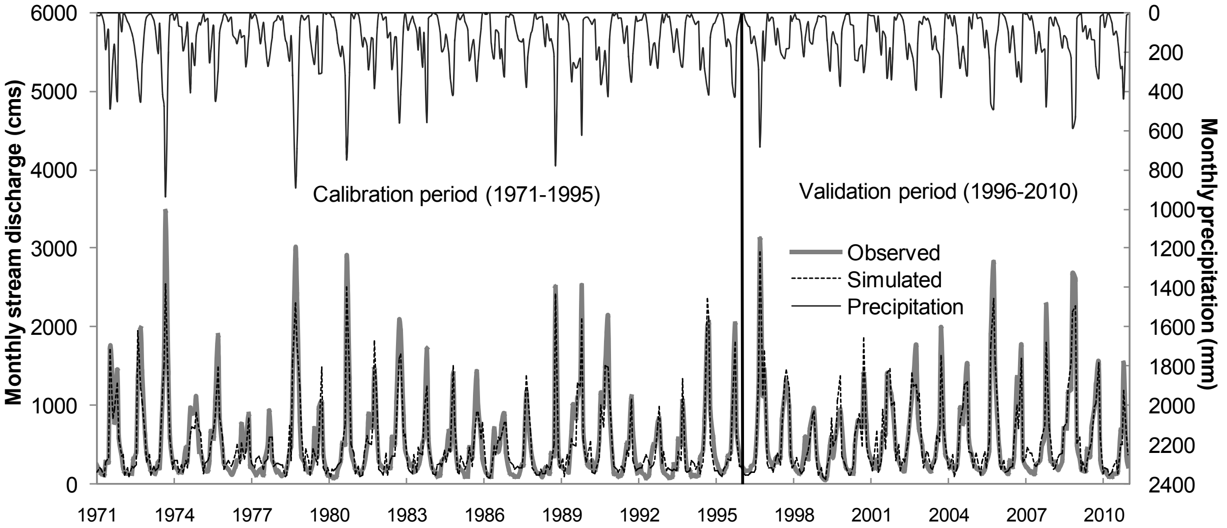


Figure 2. Simulated versus observed river discharge with reference to monthly precipitation during calibration and validation periods

Evaluation statistics for stream discharge and sediment simulation computed for both time periods are presented in Table 1. All of the NSE and R^2 values were higher than *0.8*, RSR values were below 0.4, and PBIAS values were below 5%. Based on the guidelines recommended by Moriasi *et al.* (2006), the performance of SWAT in this study met the criterion for “very good”. Although the model was found to underestimate most of the peak values both for stream discharge and for sediment load, on average, there was an overestimation bias for the validation period of stream discharge simulation as the PBIAS value was -1.44. For sediment simulation, an underestimation was found for both time periods. Considered overall, although the ability of SWAT to capture the peak values of stream discharge and sediment load during the wet season was not particularly good, the model was able to capture average system behavior well, which confirms that it is applicable to our study.

3.2. Impacts of climate change on stream discharge and sediment yield

Our climate change projection indicates that temperature and potential evapotranspiration (PET) will increase in all months of future years throughout the 21st century. In comparison with the baseline period (1980-1999), temperature increases range from 0.8 to 1.2 °C in the 2030s, 1.8 to 2.2 °C in the 2060s, and 2.8 to 3.4 °C in the 2090s depending on the scenario, while annual PET increases range from 5 to 7%, 10

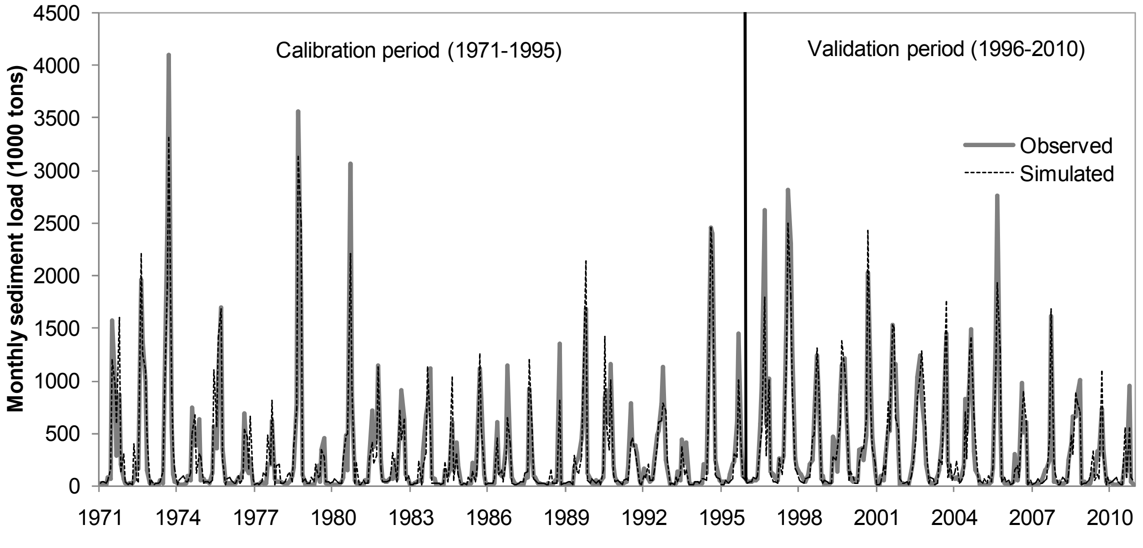


Figure 3. Simulated versus observed sediment load during calibration and validation periods

Table 1. Model performance evaluation statistics

Simulation period	Evaluation statistic			
	NSE	R^2	RSR	PBIAS (%)
Discharge calibration	0.86	0.87	0.37	3.17
Discharge validation	0.89	0.89	0.32	-1.44
Sediment calibration	0.89	0.88	0.34	0.90
Sediment validation	0.87	0.87	0.35	4.14

to 14%, and 14 to 20% in the same periods, respectively. PET increases in both the dry and the wet season, but the increase in the dry season is more significant than that in the wet season (Fig. 4). Changes in precipitation are complicated, varying by emission scenario, weather station, and month (Fig. 7a). However, a general trend can be drawn. Precipitation is likely to increase in the wet season and to decrease in the dry season, but the increase in the wet season is more significant than the decrease in the dry season, leading to an increase in annual precipitation. On a basin average, annual precipitation is projected to increase

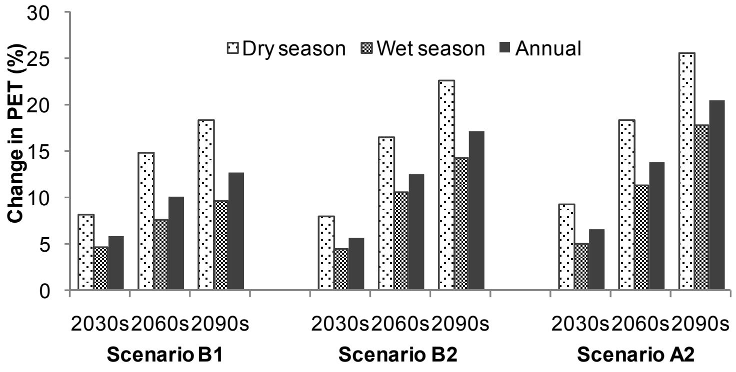
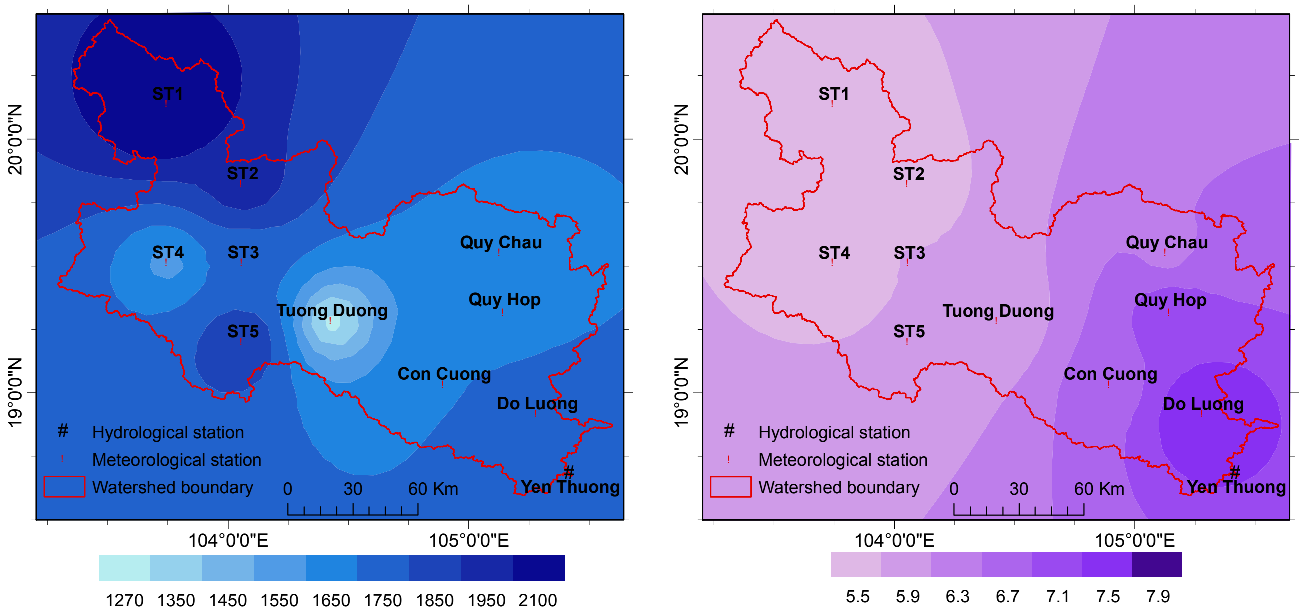


Figure 4. Predicted change in PET



a) Average annual precipitation of the baseline period (1980-1999)

b) Increase in annual precipitation in the 2090s according to scenario A2 (%)

Figure 5. Spatial patterns of precipitation in the baseline period and projected increases in precipitation in the 2090s compared to the baseline period.

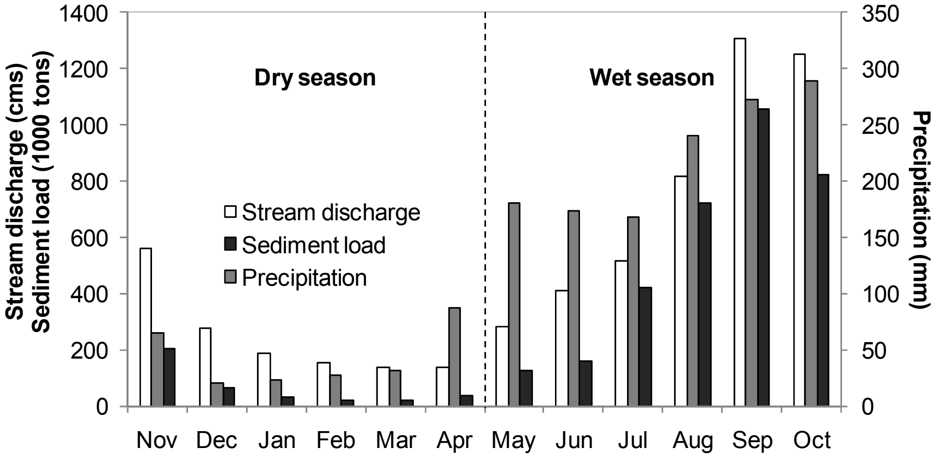


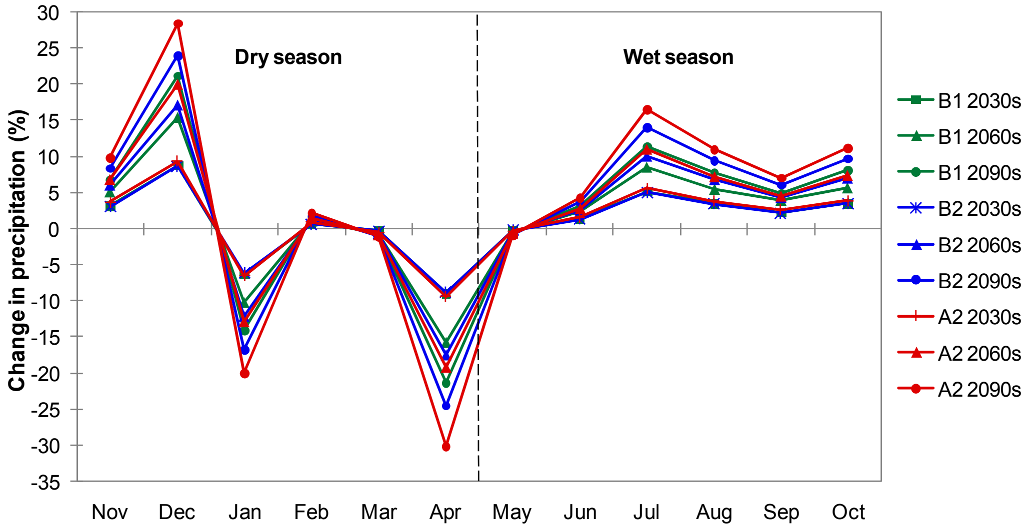
Figure 6. Average monthly precipitation, river discharge and sediment load of the baseline period

by 2.0 to 2.3% in the 2030s, by 3.3 to 4.3% in the 2060s, and by 4.5 to 6.7 % in the 2090s, depending on the emission scenario. Fig. 5a shows the spatial pattern of precipitation for the baseline period, and Fig. 5b shows the pattern for the projected increase in annual precipitation in the 2090s under the high emission scenario (scenario A2).

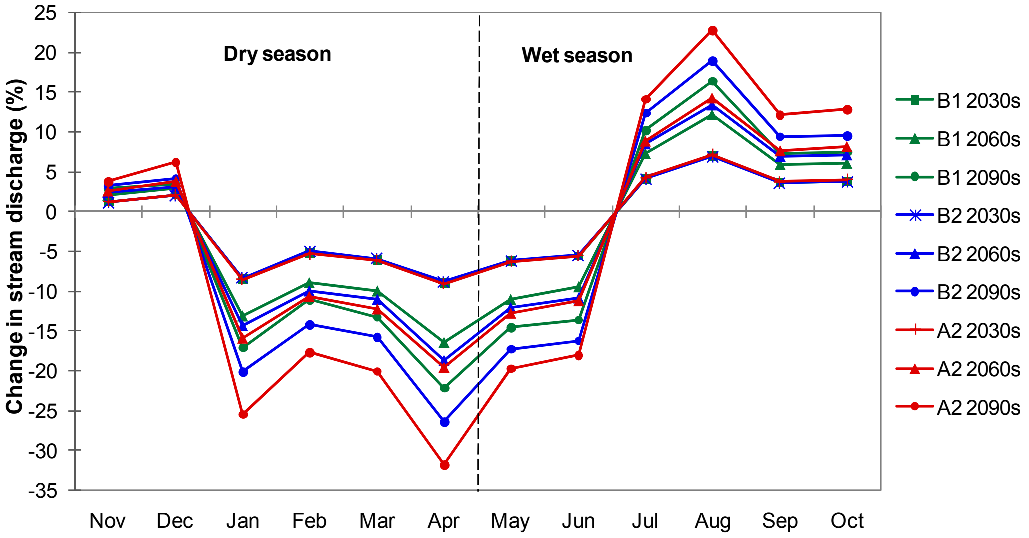
Fig. 6 shows the average data of precipitation, stream discharge, and sediment load for the baseline period (1980-1999). The difference between the wet season and the dry season is obvious. On average, precipitation in the wet season accounts for 84% of annual precipitation. Meanwhile, sediment load in the wet season accounts for 89% of annual sediment load, and stream discharge in the wet season is approximately 3 times higher than in the dry season.

Prediction of changes in monthly precipitation, stream discharge, and sediment load for the three time stages (2030s, 2060s, and 2090s) relative to the average data of the baseline period (Fig. 6) is presented in Fig. 7. The overall trend is that the behavior of scenarios B1, B2, and A2 is fairly similar for the prediction of monthly data until the near future period (2030s), as the lines B1 2030s, B2 2030s, and A2 2030s almost coincide. The difference in behavior increases slightly in the middle future period (2060s). From then on, the A2 scenario simulation predicts the largest changes, followed by the B2, and then the B1 scenario. This is consistent with the characteristics of the emission scenarios, which evolve similarly until the middle of the 21st century, when A2 becomes more negative due to the continuous increase in population growth and, therefore, the increase in GHG emissions. In contrast, B1 becomes less negative due to the slowing of population growth, with a corresponding reduction in GHG emissions (IPCC, 2000). The same behavior has also been reported in several very recent studies using IPCC AR3 or IPCC AR4 models on a regional scale (Liu *et al.,* 2012; Ribalaygua *et al.,* 2013).

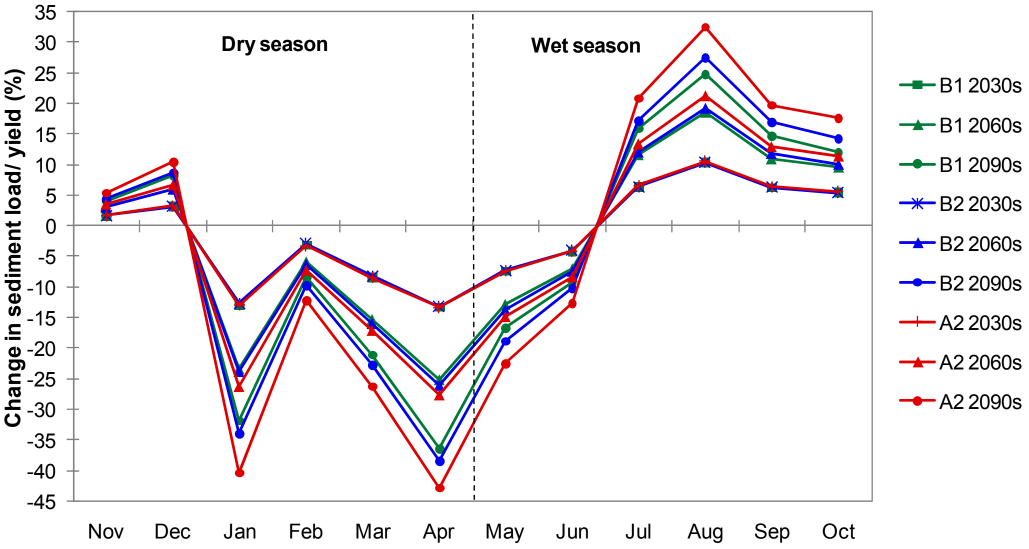
Precipitation is predicted to increase for February, and for all months from June to December, and to decrease for January, March, April, and May. The trend for change in stream discharge, however, is more obvious. Discharge is projected to decrease for the first six months of the year, from January to June, and to increase for the last six months, from July to December. The magnitude of changes varies depending on the month and scenario. The increase in discharge for all months from July to December can be explained by the large increases in precipitation for these months. Similarly, the decrease in discharge in January, March, April, and May corresponds to the decrease in precipitation in these months (Fig. 7a). It is noticeable that discharge decreases in February and June, despite the increase in precipitation in these months. In February, the increase of about 1% in a small precipitation amount (about 20mm) cannot compensate for the increase in PET driven by the temperature rise, resulting in a discharge decrease. June is one of the hottest months in the studied watershed, with an average maximum temperature of about 38°C, and an average PET of more than 100 mm. As the increase in PET in this month is predicted to be more significant than the increase in precipitation, the stream discharge decreases. The differences in the trends in precipitation change and discharge change in June may also be due to the time-lag between the precipitation events and the stream discharges. In addition to evaporation, saturation is also an important factor. When it rains, it takes time for the ground to become saturated, but once it has become saturated, any additional stormwater then runs over the land into streams. However, the increase in temperature in the month of June can cause an increase in the ground infiltration rate,



a) Change in precipitation



b) Change in stream discharge



c) Change in sediment load

Figure 7. Change in monthly precipitation, stream discharge, and sediment load

resulting in a decrease in the amount of water running into streams.

Monthly sediment load change (and as a result, sediment yield change) ranges from a 40.3% decrease to a 32.6% increase depending on the specific month, emission scenario, and period of time. The trend of changes in monthly sediment yield (Fig. 7c) is consistent with that of changes in monthly stream discharge (Fig. 7b), although the rates of changes are different between these two variables. This is because sediment yield at the outlet of a watershed is primary influenced by streamflow (Equation (3)). Interestingly, in general, the monthly changes in sediment yield are greater than the corresponding changes in discharge. This indicates that the impact of climate changes on sediment yield is greater than on streamflow. In a study conducted at Nam Ou Basin (Laos), which is located near the UCRW, Shrestha *et al.* (2013) reported a similar finding. One explanation for this is that sediment yield increases more than linearly with an increase in streamflow (Naik and Jay, 2011).

From a seasonal point of view, in the dry season, there are four months in which sediment yield decreases and two months in which it increases. On the other hand, sediment yield increases for four of the six months of the wet season, and decreases for the other two months. Besides the effects of surface runoff, decrease in sediment yield during the dry season and early wet season (May and June) may also be related to changes in antecedent soil water content during rainfall events under future climate conditions. Even when an increase in rainfall was predicted (in February and June), increases in PET (Fig. 4) appeared to cause a reduction in soil water content which may result in increased saturation deficit. This means that more rainfall is required to bring the soil to saturation and generate the same amount of runoff as under the current conditions. The importance of antecedent soil water content on erosion (and consequently, sediment yield) in saturation excess dominated landscapes has been previously reported (Mukudan *et al.,* 2013). In addition, increased temperature and increased rainfall in the dry months may also accelerate plant growth, which results in increased biological cover, and as a result, less erosion. However, in the late wet season and early dry season (November and December), this is not the case, because the mean monthly sediment cycle follows an increasing trend in both precipitation and discharge (Figs. 7a and 7b). This may be due to more intense rainfall in this period and the steep topography of the watershed. It should be noted that the UCRW is dominated by numerous high and steep hills, which are sensitive to rainfall-induced erosion. In fact, approximately 70% of the watershed area has a slope of above 15 degrees, and more than 20% of it has a slope of above 30 degrees, with a long slope length (Fig. 8). The role of hillslope in causing erosion is represented by the topographic factor *LS* in Equation (1). The topographic factor *LS* ($LS=L_{hill}/22.1)^{m}(65.41\cdot\sin^{2}(\alpha_{hill}+4.56\cdot\sin\alpha_{hill}+0.065)$ is a function of the land slope length (L_{hill}), the angle of slope (α_{hill}), and the exponential term *m.* The exponential term ($m=0.6\cdot(1-exp\,[-35.835\cdot tan\ \alpha_{hill}\,])$) also depends on the angle of slope (i.e. $tan\ \alpha_{hill}$). Thus, the greater the slope length (L_{hill}) and the slope angle (α_{hill}) are, the greater the topographic factor (*LS*) will be. In other words, the longer and steeper the slope of the surface, the higher the risk of erosion. In fact, in this study we found that in the upstream sub-watersheds, such as Numbers 8, 24, and 25 (Fig. 8), where the topography is dominated by excessively steep slopes, erosion rates were up to more than 50 tons/ha/year in the baseline period. Meanwhile, in the downstream sub-watersheds, such as Numbers 36, 37, and 39, where the topography is mostly flat, erosion rates were mostly below 3 tons/ha/year. Hillslope and intense rainfall also accelerate the sediment transport process and bring more eroded soil into streams. The effect of climate-change-induced intense rainfall on hillslope erosion and sediment transport has also been reported previously (Mukudan *et al.,* 2013). Furthermore, Zhu *et al.* (2008) also found that an increase in sediment yield is likely to occur in wetter and warmer climates, when higher transport capacity is accompanied by higher erosion rates.

Projected future seasonal and annual changes in sediment load at the watershed outlet have been computed from monthly changes and are presented in Fig. 9, and corresponding net sediment yields are presented in Fig. 10. Overall, dry season sediment load is likely to decrease, while wet season sediment load is projected to increase. This trend is obvious for all three scenarios. There is a similarity among the three scenarios until the period of the 2030s, with a prediction for dry season sediment load to decrease by around 1.7%, and wet season sediment load to increase by approximately 6.0%. From the 2030s on, the magnitude of differences between the three scenarios increases. Sediment load/yield is likely to change the most quickly under scenario A2, faster than under scenario B2, and considerably faster than under scenario B1. This pattern reflects that found in the monthly changes previously discussed (Fig. 7). Annual sediment load increases both because sediment load in the wet season is much higher than that in the dry season (3.3 million tons compared to 0.39 million tons, computed as the average of the baseline period), and because the increase in wet season sediment load is more significant than the decrease in dry season sediment load. Under

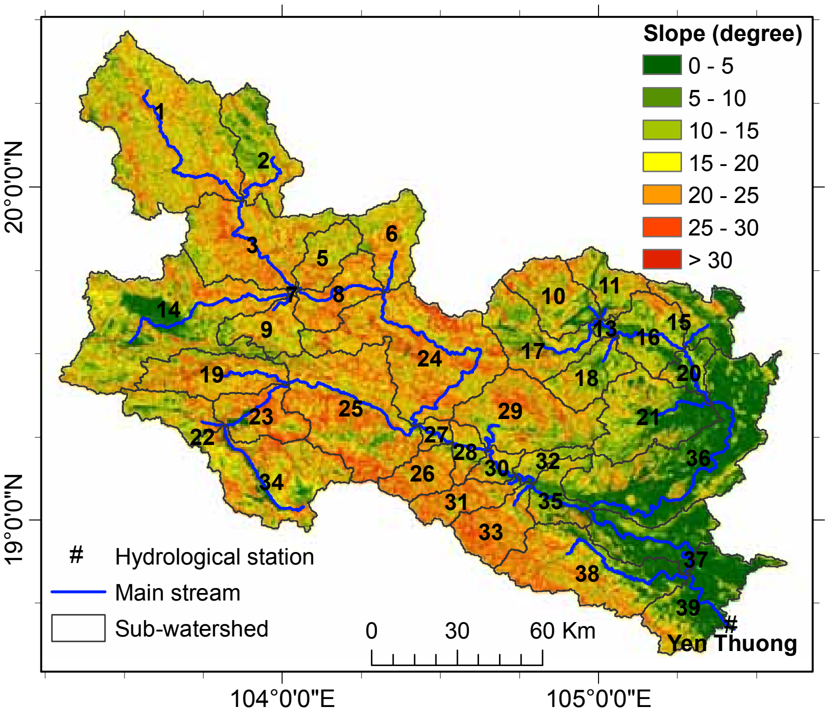


Figure 8. Slope map of the UCRW

the high emission scenario (A2), the annual sediment load may increase by 16.5% in the 2090s, meaning that each year in this period 4.3 million tons of suspended sediment will be transported out of the watershed. On a basin average, this amount is equal to a yield of approximately 190 tons/ km2/ year (Fig. 10).

4. Conclusion

Climate change is very likely to affect sediment generation and transportation processes, and resulting sediment yields in rivers. This study used the SWAT model coupled with downscaled future climate data to investigate the seasonal sensitivity of sediment yield to climate change in the Laos-Vietnam transnational Upper Ca River Watershed in Southeast Asia. It found that, although the ability of SWAT to capture the peak values of stream discharge and sediment yield during the wet season was not particularly high, the model was able to capture the average system behavior well, and that the model was applicable to our study. Impacts of climate change on stream discharge as well as sediment yield projected under three emission scenarios, B1, B2, and A2, are similar until the near future period (2030s). From then on,

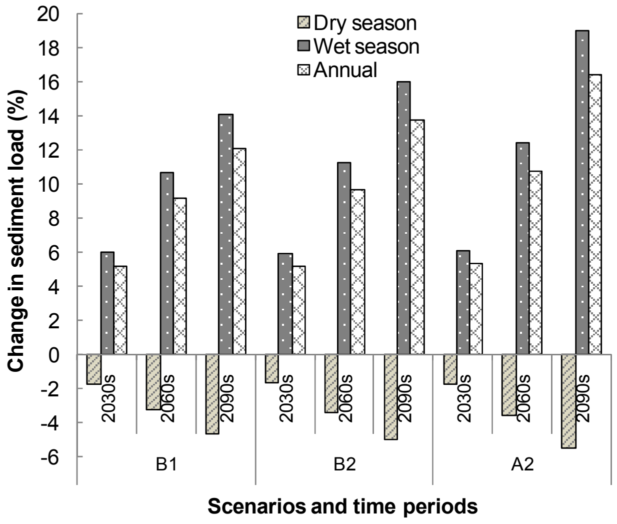


Figure 9. Seasonal change in sediment load at the watershed outlet.

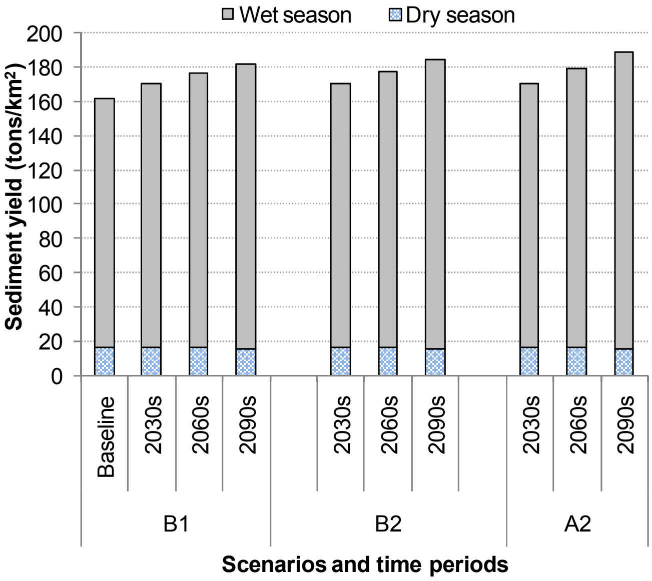


Figure 10. Prediction of seasonal sediment yield at the watershed outlet, calculated as the quotient of sediment load and the watershed area.

scenario A2 resulted in the largest changes, followed by scenario B2, and then B1. The differences between the scenarios become larger with time. As this study used the average values of 20 GCMs, the uncertainty of each GCM was not assessed.

The results of this study indicate that the trend of changes in sediment yield does not necessarily follow the trend of precipitation changes, but generally follows the trend of changes in stream discharge caused by the combined effects of increased temperature and PET as well as changes in precipitation. Sediment yield was found to increase significantly in the warmer and wetter climate of the wet season, when higher sediment transport capacity accompanied by the higher erosion rate caused by an increase in rainfall amount and intensity. Although sediment yield is likely to decrease in the dry season, its increase in the wet season appears to be more significant, both in terms of percentage and amount, resulting in a significant annual increase.

The results of this study should be useful to development planners, decision makers, and other stakeholders when planning and implementing appropriate soil and water management strategies, especially strategies for coping with future climate change impacts in the watershed. In addition, as the watershed is shared by two nations Laos and Vietnam, more collaborative studies on sediment sources, causes, and the relationship between sediment transport and climate change in the watershed should be conducted in order to develop better management plans for the watershed.

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