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Predicting future land cover change and its impact on streamflow and sediment load in a trans-boundary river basin

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Abstract. Sediment load can provide very important perspective on erosion of river basin. The changes of human-induced vegetation cover, such as deforestation or afforestation, affect sediment yield process of a catchment. We have already evaluated that climate change and land cover change changed the historical streamflow and sediment yield, and land cover change is the main factor in Red river basin. But future streamflow and sediment yield changes under potential future land cover change scenario still have not been evaluated. For this purpose, future scenario of land cover change is developed based on historical land cover changes and land change model (LCM). In addition, future leaf area index (LAI) is simulated by ecological model (Biome-BGC) based on future land cover scenario. Then future scenarios of land cover change and LAI are used to drive hydrological model and new sediment rating curve. The results of this research provide information that decision-makers need in order to promote water resources planning efforts. Besides that, this study also contributes a basic framework for assessing climate change impacts on streamflow and sediment yield that can be applied in the other basins around the world.

1 Introduction

Studies on hydrological processes in a changing environment have been the focus of hydrological science in the 21st century. The geographic extent of land cover change worldwide has undergone tremendous change in the past years. It has been pointed out land cover change is a major driving force in degradation of natural environment, such as more frequent incidents of local flooding, increasing soil erosion (García-Ruiz et al., 2008).

The research of the impact of land cover change on hydrological condition of the catchment area has therefore received increasing considerable attention from both field observations and model simulations (Brown et al., 2005). However, most studies have been performed on the impact of land cover change on streamflow (Zheng et al., 2009) or sediment yield itself (Leh et al., 2013), few researches were related to impact of land use change on both streamflow and sediment load (Tang et al., 2011; Dao and Suetsugi, 2014). Consequently, it is of great importance to predict future land cover change and its effects on combined streamflow and sediment flow in an effort to optimize the use of water resources and prevent reservoir siltation in Red river basin.

The overall objective of this study is to investigate changes in streamflow and sediment load response to future land cover change in the target river basin. For this purpose, future scenario of land cover change is developed based on historical land cover changes and land change model (LCM).

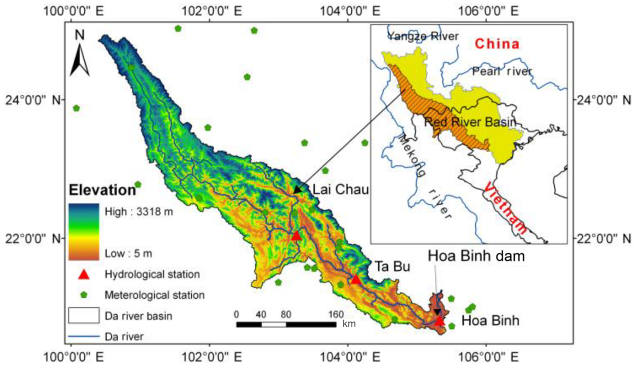

Figure 1. Location of DRB and the hydro-meteorological stations.

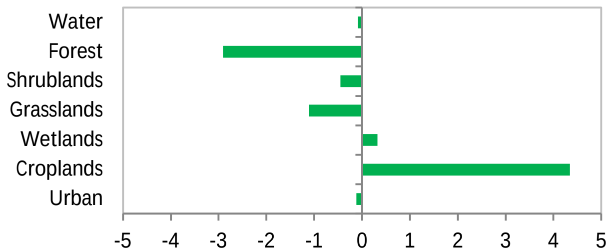

Figure 2. Net land cover changes between 2001 and 2008.

And future leaf area index (LAI) is simulated by ecological model based on the future land cover scenario. Then future land cover change scenario is used to drive a distributed hydrological model to forecast the impact of the predicted land use change on streamflow. And scenarios of future land cover change and LAI and new sediment rating curve model to assess the impact of the future land use change on sediment load into Hoabinh reservoir. A methodology is developed in which the land change model and ecological model are coupled with a calibrated a distributed hydrological model and sediment simulation model. This coupling is new and essential for evaluating effects of land cover change on streamflow and sediment load, required for providing information that decision-makers need in order to promote water resources planning efforts.

2 Study Area and Data Description

2.1 Study Area Description

The Da River Basin (DRB) located in humid region is the biggest branch of the Red River which gets its name from the reddish-brown color caused by its high sediment load rich in iron dioxide. The DRB drains 55 000 km^2, originates in Yunnan Province, China (Fig. 1). The river cross sections are narrow, with a steep slope of 0.37. The annual mean runoff is about 1168 m^3 s^{-1} from 1988 to 2004 at Laichau station, associated with the total annual sediment load about 40.1×10^6 t yr^{-1}. The Da River basin is characterized by a tropical monsoonal. Summer season is warm and humid, whereas the winter season is cool and dry (Le et al., 2007; Dang et al., 2010). The annual mean rainfall is about 1320 mm for the Da River basin, 85 % of which falls during wet rainy season. The HoaBinh reservoir, located on the downstream of Laichau station, is one of the largest ($V = 9.5$ km^3) and highest (120 m) dams in South-East Asia. It was completely finished in 1993, with the main purpose of flood control, irrigation and hydropower generation (Le et al., 2007).

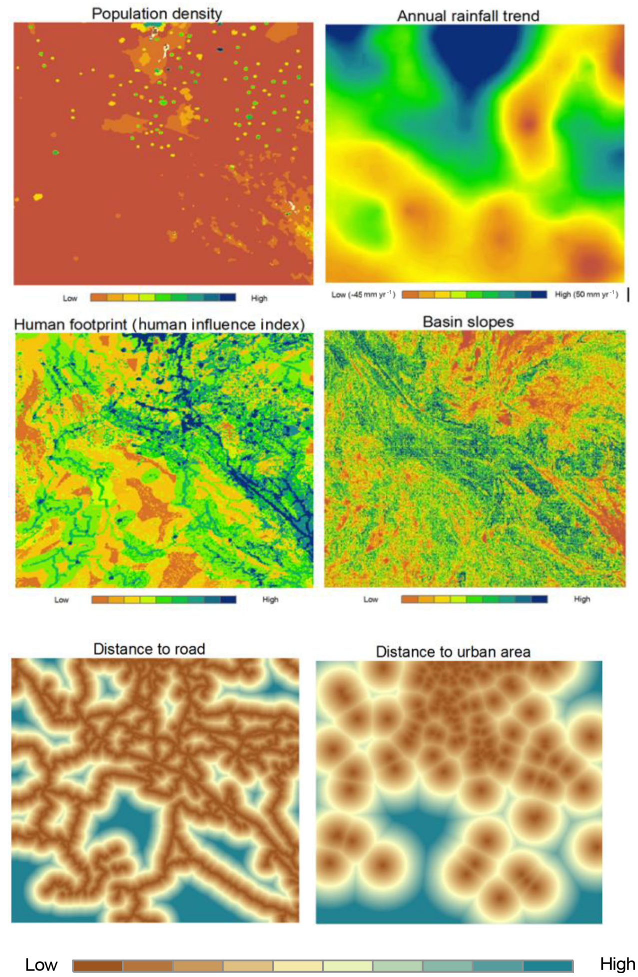

Figure 3. Selected drive factors for LCM.

2.2 Dataset Description

Daily streamflow data and Monthly suspended sediment concentration (SSC) data at Laichau (LC) and Tabu (TB) stations in DRB (Fig. 1) were used in hydrological simulation. Daily meteorological data of 14th stations well distributed are obtained from the China Meteorological Data Sharing Service Center, which has been checked by the primary quality control. All datasets above covering 1991–2000 were used as inputs for hydrological simulation and sediment load calcula-

Table 1. Dataset summary for different models in the study.

Models	Spatial dataset	Point dataset
Hydrological model	Elevation, land cover, soil map	Rainfall, streamflow
New sediment rating curve		Streamflow, LAI, SSC
Land change model	Elevation, land cover, population density, road, river network, slope, human footprint, rainfall trend	No need
Ecological model	Elevation, land cover, soil map	Rainfall, maximum and minimum temperature

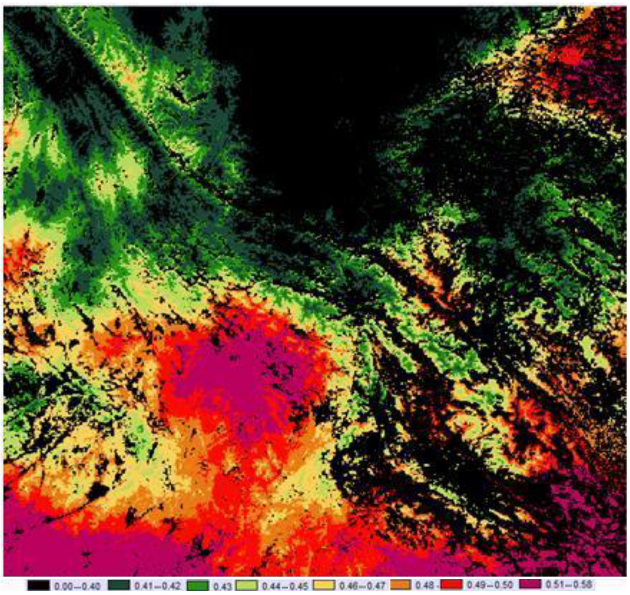

Figure 4. Potential map for transition from forest to croplands.

Table 2. Difference between the reference map of 2011 and the simulated map 2011.

Land cover type	Reference 2011 (pix)	Simulated 2011 (pix)	Error percent (%)	Kappa index
Water	869	842	−3.1	
Forest	184 701	177 657	−3.8	
Shrublands	60 433	69 411	14.8	
Grasslands	10 743	9126	−15.0	0.94
Wetlands	825	896	8.6	
Croplands	58 871	58 403	−0.8	
Urban	1618	1725	6.6	

tion. A series of geographical datasets (e.g., DEM, LAI, land cover type) were also employed in ecological simulation, hydrological simulation and land change prediction, summarized in this study (Table 1).

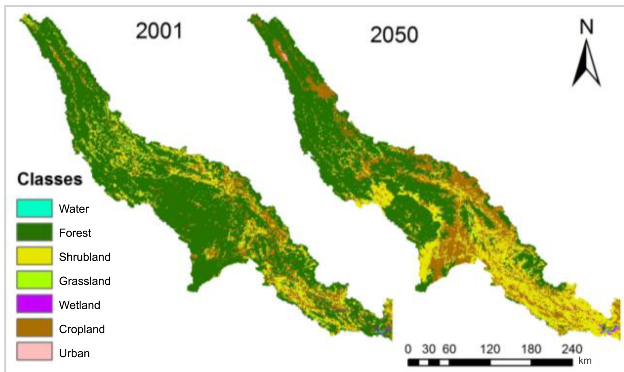

Figure 5. Land cover map of 2001 (basin line) and 2050 (predicted).

3 Methodology

In this study, a group of models coupled in a "one-way" manner framework were applied. Firstly, the Land Change Modeler (LCM) was used to predict future the land cover change in the year of 2050. LCM is a powerful tool to predict future land cover change scenarios and was widely applied (Wilson and Weng, 2011). More technical details of this model could be found in the reference (Clark Labs, 2009). Then, Biome-BGC was also applied to calculate the potential LAI under future land cover changes. In our previous work, we have already described it in detailed and validated this model well in DRB (Wang and Ishidaira, 2013). So in this research this validated Biome-BGC model would be applied to predict future LAI under future land cover scenario directly.

Finally, future land cover and LAI obtained above were used to drive hydrological and sediment simulation model. The hydrological model "Blockwise use of TOPMODEL with Muskingum–Cunge routing" (BTOPMC), a grid-based distributed hydrological model developed by University of Yamanashi, Japan (Takeuchi et al., 1999; Ao et al., 2003), was applied in river flow simulation. And sediment simulation model considering vegetation cover (LAI) which has already been developed and could give better agreement simu-

Table 3. Future land cover changes of 2050 created through neural networks compared with the baseline map of 2001 image in DRB (area percent: %).

Land cover	Baseline 2001 (%)	Predicted 2050 (%)	Changes (%)
Water	0.06	0.05	−0.01
Forest	70.91	49.57	−21.34
Shrublands	15.5	25.47	9.97
Grasslands	0.72	0.16	−0.56
Wetlands	0.19	0.34	0.15
Croplands	12.57	24.27	11.7
Urban	0.06	0.14	0.08

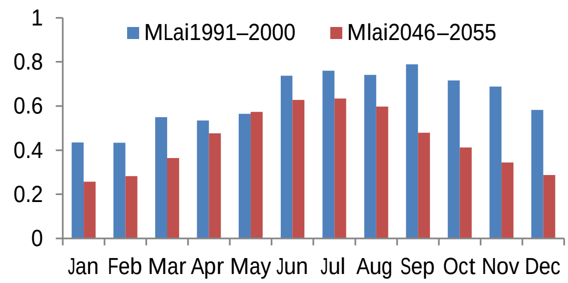

Figure 6. Comparison between current average LAI ($M_{\mathrm{lai}1991-2000}$) and future average LAI ($M_{\mathrm{lai}2046-2055}$).

lation result in several Asian basins (Wang et al., 2013; Wang and Ishidaira, 2013), was used to simulate SSC in DRB.

4 Results

4.1 Future land cover and LAI prediction

Land cover changes between year of 2001 and 2008 were calculated firstly by land change modeller, which showed that cropland increased and forest decreased obviously. So the increase in cropland mainly came from forest changes (Fig. 2). In addition, six driving factors (Fig. 3) which may affect land cover changes and land cover changes obtained above were introduced to build up potential land cover transition maps by multi-layer perceptron neural network method. For example, transition possibilities map from forest to croplands in Fig. 4 shows that there is a high possibility in the bottom and center of our basin.

Land cover map of 2011 simulated by LCM based on potential land cover transition maps showed an agreement spatially with actual land cover map of 2011. Additionally, high kappa index (Jensen, 1996) and low mean error between simulated and observed land cover maps in 2011 was calculated (Table 2), which indicated that simulated map had a good match with the reference one. So LCM was proved to have the ability to simulate land cover changes well, then we apply it to predict future land cover map of 2050 (Fig. 5 and Table 3). Comparison of the land cover maps for 2001 and 2050 reveals that that forest area would have an obvious decrease of about 26 % and croplands have an increase of 11.7 % in 2050 compared with 2001.

Finally, Biome-BGC model which has already been validated well in DRB (Wang and Ishidaira, 2013) was driven by future land cover of 2050 to predict future LAI in the period of 2046 to 2055. Results (Fig. 6) showed that future LAI would decrease especially for dry season due to deforestation.

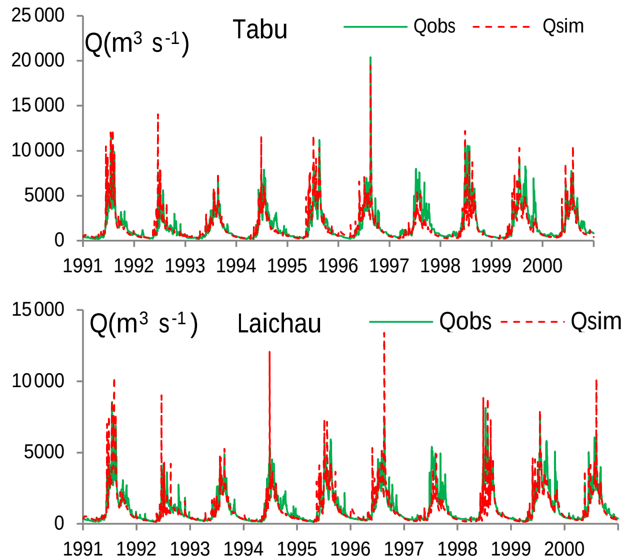

Figure 7. Comparison of observed and simulated daily streamflow in the DRB (calibration period: 1991–1995, validation period: 1996–2000).

Table 4. Evaluation of model simulation during the baseline period for the catchments controlled by Laichau and Tabu stations in the DRB.

	Laichau		Tabu	
	Calibration	Validation	Calibration	Validation
NSE	0.75	0.70	0.70	0.60
R^2	0.83	0.77	0.76	0.72
MAE (mm)	0.74	0.80	0.77	0.91
PBIAS (%)	6.2	7.2	7.0	7.8

4.2 Hydrological and sediment simulation

As shown in Tables 4 and 5, all statistics indicated that BTOPMC hydrological model and sediment simulation model could give a better simulation results in river flow and SSC, and simulated hydrograph also has a good match with the observed (Fig. 7). Results above comprehensively explained that BTOPMC and sediment model can simulate streamflow and SSC accurately.

Table 5. Performance of sediment simulation model for Laichau.

Catchment	R^2	MAE (g m^{-3})	PBIAS (%)
Laichau	0.894	3.23	0.524

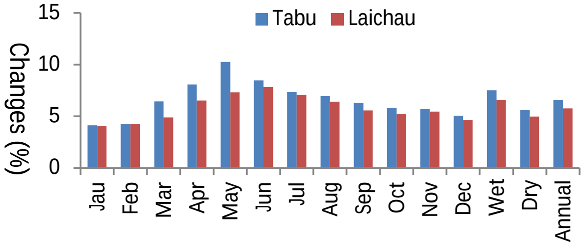

Figure 8. Changes in streamflow under land cover change in 2050 at Laichau and Tabu station.

4.3 Future land cover change impacts

Predicted land cover map, LAI data and fixing the climatic conditions were used to drive the validated hydrological and sediment simulation models to investigate future land cover change impacts on streamflow and sediment load. Changes in streamflow in upstream and downstream are illustrated in Fig. 8, which indicate that land cover change affect streamflow stronger in the downstream of DRB. As shown in Fig. 9, the effects of future land cover change would increase sediment load by 9.6 %, while the change rates in streamflow were within 5.7 %. Sediment load was found more sensitive to land cover change than streamflow. As for seasonally variations of stream flow and sediment load caused by land cover changes, changes in streamflow and sediment load were more pronounced during the wet season.

Other factors such as model parameters may lead to not realistic results in our study. To reduce uncertainty in model simulation, more field observations should be done.

5 Conclusions

In this study, one framework to evaluate future land cover change effects on streamflow and sediment load was developed and successfully applied in Da River Basin. Generally, the streamflow and sediment yield will increase in 2050s under land cover change. Streamflow and sediment load increase in 2050s emphasize the importance of building adaptation to land cover changes to avoid flood and soil erosion. The results obtained in this study could be useful for the appropriate utilization of water resources, flood control, soil conservation and ecological protection in this region by enhancing the understanding of the impact of land cover change scenarios on streamflow and sediment yield.

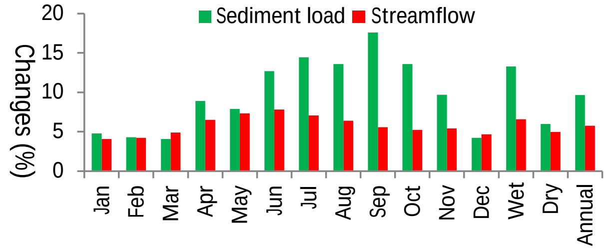

Figure 9. Changes in streamflow and sediment load under land cover changes in 2050 at Laichau station.

Data availability. 1. Daily meteorological and hydrological data from 1991 to 2000 were obtained from the hydrological stations and precipitation stations from China Meteorological Data Sharing Service Center and Vietnam Academy of Science and Technology which is considered confidential.

2. Digital elevation data (GTOPO30) is obtained from the flowing URL: https://lta.cr.usgs.gov/GTOPO30 (last access: 16 May 2017)
3. Soil type data is obtained from the flowing URL: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12 (last access: 15 December 2017)
4. Land cover data from 2001 to 2011 is obtained from the flowing URL: https://modis-land.gsfc.nasa.gov/ (last access: 10 June 2017)
5. Global roads dataset and global Human Footprint (HF) are obtained from the flowing URL: http://sedac.ciesin.columbia.edu/ (last access: 15 June 2017)
6. Monthly TRMM satellite rainfall data (TRMM_3A12) are obtained from the flowing URL: https://pmm.nasa.gov/data-access/downloads/trmm (last access: 15 May 2017).

Competing interests. The authors declare that they have no conflict of interest.

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