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Reducing the basin vulnerability by land management practices under past and future climate: a case study of the Nam Ou River Basin, Lao PDR

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Abstract

This research evaluates different land management practices for the Nam Ou River Basin in Northern Laos for reducing vulnerability of the basin due to erosion and sediment yield under existing and future climate conditions. We use climate projection data (precipitation and temperature) from three general circulation models (GCMs) for three greenhouse gas emission scenarios (GHGES), namely B1, A1B and A2 and three future periods, namely 2011–2030, 2046–2065 and 2080–2099. These large resolution GCM data are downscaled using the Long Ashton Research Station-Weather Generator (LARS-WG). The Soil and Water Assessment Tool (SWAT), which is a process based hydrological model, is used to simulate discharge and sediment yield and a threshold value of annual sediment yield is applied to identify vulnerable sub-basins. Results show that the change in the annual precipitation is expected to be between −7.60 to 2.64 % in 2011–2030, −8.98 to 11.85 % in 2046–2065, and −11.04 to 25.84 % in 2080–2099. In the meantime, the changes in mean monthly temperature vary from 0.3 to 1.3 °C in the 2011–2030, 1.3 to 2.9 °C in the 2046–2065 and 1.9 to 4.9 °C in the 2080–2099. Five sub-basins are identified vulnerable (critical) under the current climate. Our results show that terracing is the most effective land management practice to reduce sediment yield in these sub-basins followed by strip-cropping and filter strip. Appropriate land management practices applied under future climate scenarios show significant reduction in sediment yield (i.e. up to the tolerance limit) except for some sub-basins. In these exceptional sub-basins, designing an optimum combination of management practices is essential to reduce the vulnerability of the basin.

1 Introduction

Soil erosion is a complex process and one of the most serious problems that has always been a threat to the environment and the water resource system of an area (Yang et al., 2003; Feng et al., 2010). Soil erosion in any area is attributed to its precipitation

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levels, geology, climate, land cover, soil management practices, and seismology. The outcome of soil erosion and deposition is sediment yield. Sediment yield is defined as the amount of sediment load that is normalized for any drainage area. It is controlled by factors affecting the erosion and deposition of eroded soil particles. Types of vegetation, topography, land use, climate, catchment morphology, soil type and drainage characteristics are responsible factors for sediment yield (Walling, 1994; Hovius, 1998). A detailed theory of sediment yield helps in providing relevant information when formulating quantitative models for landscape evolution and sediment mass balance and for estimating the sediment load and erosion intensities in any basin (Walling, 1994).

Roberts (2001) estimated that 50 % of the total suspended sediment in the Lower Mekong River is contributed by China. According to You (1999), suspended sediment is transferred at about 85 Mtons yr^{-1} to the lower reaches of the river from China. Most of this sediment remains as bed load or as insets against rock cut banks in the mainstream of the Mekong (Gupta et al., 2002). Lu and Siew (2006) observed a decrease in sediment in the reaches over Vientiane but an increase at stations downstream in the post-dam period. In addition, the sloping land of Southeast Asia was found to be bio-geochemically active (Labat et al., 2004). The sloping lands of northern Thailand showed that soil losses measured in the cropping field (1 m × 1 m plots) increased from 0.6 to 3.3 kg m^{-2} yr^{-1} with a decreasing slope gradient (Janeau et al., 2003). The study on the changes in the annual runoff and sediment load of the Yan River, China over the last 60 years by Wang et al. (2013) showed the great variance in the amount of runoff and sediment load. It revealed the significant difference in the coefficients of variations than those in precipitation and temperature. Furthermore, a significant trend of linear decline was observed in both annual runoff and sediment load over the study period.

Many studies so far have focused on the potential effects of climate change on watershed hydrology, water quality and water demand (Christensen et al., 2004; Bates et al., 2008; Hoanh et al., 2010; Reungsang et al., 2010; Kingston et al., 2011). However, very limited research have been carried out on the potential impact of climate change on soil erosion (Yang et al., 2003; O'Neal et al., 2005; Zhang and Nearing,

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2005; Zhang, 2007; Nunes et al., 2009; Maeda et al., 2010). One of these studies was also carried out by Zhu et al. (2008), who demonstrated that the combination of future precipitation and temperature change will result in the variation of sediment flux in the Upper Yangtze River Basin, China. It was observed that wetter and warmer periods will result in a higher sediment flux in the river basin. Nunes and Nearing (2011) also researched the impact of climate change on soil erosion and found that there are few studies done at the watershed scale on the uncertainty of future climate and the linkage between land cover and soil erosion. Phan et al. (2011) stated that there was change in mean annual discharge from 1 to 3 %, and mean annual sediment yield from 1.2 to 4.7 % in the Song Cau Watershed of northern Vietnam under future climate conditions and different greenhouse gas emission scenarios (GHGES). Mullan (2013) performed six case studies in hills of Northern Ireland and revealed that the future climate projection in isolation shows decrease in soil erosion while the change in land use and sub-daily rainfall intensities result in increase in soil erosion. The preliminary study in eight large rivers of China showed that every 1 % change in precipitation has resulted in 1.3 % change in water discharge and 2 % change in sediment loads (Lu et al., 2013). In addition, it also indicated that every 1 % change in discharge caused by precipitation led to 1.6 % change in sediment loads. Gao et al. (2013) analyzed the impact of climate change and human activities on the long-term trends for discharge and sediment during the flood season in the Wei River basin, China.

The projection of future climate is more complex due to uncertainties associated with use of various general circulation models (GCMs), greenhouse gas emission scenarios (GHGES) and downscaling approaches used (Chen et al., 2011; Di Baldassarre et al., 2011). Uncertainty in future climate is especially linked to GCMs due to its limitation in topography representation and climatic processes (Minville et al., 2008). The hydrological models such as Soil and Water Assessment Tool (SWAT), Hydrologic Simulation Program – FORTRAN (HSPF) used for the impact assessment also have their own uncertainty related to model structure and parameterization. All these sources of uncertainty makes the assessment of climate change impacts on river discharge as

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well as sediment yield uncertain and complicated. Chen et al. (2011) in their study on a Canadian catchment showed that the selection of GCMs and downscaling techniques contribute the largest uncertainty in hydrological projections, followed by emission scenarios, hydrological model structure and parameterization. Similarly, Teng et al. (2012) also pointed out that the uncertainty from 15 GCM outputs is much higher than from 5 hydrological models used in the study. On two catchments of the Yangtze River and Yellow River Basins, Xu et al. (2011) showed that GCM structure is more prominent in producing uncertainties in hydrological projections. The study highlighted the significance of use of multi-model evaluations in the hydrological study of the river basins.

Various kinds of land management practices are available for controlling soil erosion in a river basin. To reduce the vulnerability of river basins in terms of sediment yield, land management practices such as vegetative filter strips, buffer strips, terracing, strip cropping, mulching, applying stone bunds and grassed waterways can be applied. Though these different land management practices have been proposed for reducing sediment yield in various watersheds, the proper control of soil erosion by these practices is site specific. Phomcha et al. (2011) identified critical watersheds and applied alternative management practices to reduce the soil erosion in the Lam Sonthi Watershed, Thailand. Similarly, the analysis of effectiveness of agricultural management practices has been carried out by many researchers with the aim of reducing the sediment load in different watersheds (Betrie et al., 2011; Wang et al., 2011; Zhang et al., 2011). An evaluation of management practices has also been performed for non-point source pollution reduction using Soil and Water Assessment Tool (Behera and Panda, 2006; Lee et al., 2010; Laurent and Ruelland, 2011; Giri et al., 2012).

The main objectives of the present study were to identify the critical sub-basins under past and future climate based on the amount of sediment yield in the Nam Ou River Basin, Lao PDR and to reduce the vulnerability of these identified sub-basins by applying suitable land management practices. The Nam Ou River Basin has been categorized as highly vulnerable to soil erosion (Fuchs, 2004). The sediment generation in the Nam Ou River Basin is considered to be higher than most basins in the Mekong region. Under a 20 year development plan, the water resources of the Nam Ou River Basin are going to be used extensively for electricity generation (Hoanh et al., 2010). The previous study carried out in this basin showed that there is a definite impact of climate change on the sediment yield of the basin in the future, but the change is not always unidirectional when different general circulation models (GCMs) and GHGES are considered (Shrestha et al., 2013). The study also demonstrated the necessity of the management of high sediment yield, the increase in which is due to both human interference and climate change. Hence, this study was conducted to observe the vulnerability of the basin in terms of sediment yield and to evaluate relevant land management practices to assess their impact in reducing the sediment yield of the critical sub-basins.

2 Study area and data

2.1 Study area

The Nam Ou River Basin, located in the northern part of the People's Democratic Republic of Laos, is a part of the Mekong River Basin (Fig. 1). The Nam Ou River is the longest river in the northern region of the Lao PDR. The river originates at the Ban Lantoug Gnai village near the Laos–China border and flows towards the south. Its total length is 390 km to the point of confluence with the Mekong River. The Nam Ou River is situated between latitudes 21°17′17″–22°30′40′ N and longitudes 101°45′47″–103°11′57″ E. Its total drainage area is approximately 26 180 km^2. The topography of the Nam Ou River Basin is mostly mountainous, with sharp relief. The elevation ranges from 263 to 2035 m above mean sea level. The geology of the basin is mostly red continental sandstone and clay with middle limestone. The main land cover of the basin is wood and shrubland, covering about 62 % of its total area.

The climate of the Nam Ou River Basin is dominated by a subtropical monsoon. The annual mean temperature of the basin ranges from 20 to 26 °C. This basin has two distinct seasons: a wet season (May to October) and a dry season (November to April). The annual rainfall of the basin is about 1700 mm, 80 % of which occurs during the wet season.

The Nam Ou River is one of the major tributaries of the Mekong, and has great potential for developing hydroelectric power that can be exported to neighboring countries like China. Under 20 year-plan for hydropower development by the Mekong River Commission (MRC), about 4661 MW of electricity is expected to be generated from the tributaries of Laos. In Nam Ou alone, 21 % of the above mentioned electricity generation is planned to be developed. In order to fulfill the plan, 7 cascades of dams (with a total live storage capacity of 1659.4 MCM) have been planned in the Nam Ou River. Apart from this, the increment of irrigation area by 44.4 % has also been planned in the basin (Hoanh et al., 2010).

Most people in the Nam Ou River Basin depend largely on subsistence-agriculture. They exchange their products by means of fluvial navigation from Pak Ou to Ban Hatsa, in the Phongsaly province. Currently, road network has been improved, which has a positive impact on rural development. However, people still preserve their traditional modes of earning a livelihood.

2.2 Data

2.2.1 Observed data

The input data sets used in this study were obtained from the Mekong River Commission (MRC) at the Secretariat of Phnom Penh, Cambodia. A 250 m resolution Digital Elevation Model (DEM) created based on interpolated topographical maps, was used in this study. A land use map (Fig. 2) for the year 2000, and a soil map with resolution 250 m were also obtained from MRC. Land use was assumed to remain the same in the future periods in this study.

The observed daily precipitation data was obtained from eleven different stations for the period of 1980–2003. The stations are Dien Bien, Lai Chau, Luang Prabang, Muong

Namtha, Muong Ngoy, Muong Te, Oudomxay, PhongSaly, Quynh Nhai, Tuan Giao, and Xieng Ngeun. The observed precipitation at the stations was interpolated and aggregated to the sub-basin using the MQUAD program in the Decision Support Framework (DSF) of the MRC (Shrestha et al., 2013). This MQUAD program functions on the basis of a multi-quadratic analysis developed by Hardy (1971). Using this methodology, the precipitation for the 19 sub-basins of the study area was obtained for 1980–2003.

Climate data such as maximum and minimum temperature, wind speed, humidity and solar radiation were obtained from three meteorological stations (Luang Prabang, Oudomxay and Phongsaly) for the period of 1992–2003. The daily maximum and minimum temperatures for 1980–1991 were obtained from the 0.5° gridded global daily temperature data from the Santa Clara University (SCU) (http://www.engr.scu.edu/~emaurer/global_data/), available for 1950–1999. The relationship between observed maximum and minimum temperature was established using the SCU data for 1992–1999. An R^2 value equaling 0.8 was obtained. This relationship was then used to derive temperatures for 1980–1991. In this way, the maximum and minimum temperature data for 1980–2003 was obtained.

The daily discharge data for period 1992–2003 and suspended sediment concentration data for period 1996–2002 were obtained at Muong Ngoy gauging station. The sediment data was very scattered within the period, providing data between 6 and 56 measurements per year.

2.2.2 GCM data

The analysis based on 15 GCMs (that are available in the Long Ashton Research Station-Weather Generator, LARS-WG) showed a wide range of uncertainty in the projection of both mean precipitation and temperature (Maharjan, 2012). The probability density functions (PDFs) became flatter for the future periods compared to the baseline period showing increased climate variability with time. Among 15 GCMs, the analysis highlighted three GCMs which projected extremely high, average and extremely low change in future precipitation from the baseline period (Table 1). These three GCMs

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are used in this study for the assessment of impact of climate change on the future projection of sediment yield. These GCMs are IPCM4 from the Institute Pierre Simon Laplace, France (predicting minimum change); MIHR from the National Institute for Environmental Studies, Japan (predicting average change); and HADCM3 from the UK Meteorological Office, UK (predicting maximum change). All three GHGES B1, A1B and A2 for three future periods 2011–2030 (2020s), 2046–2065 (2055s), and 2080–2099 (2090s) are available in LARS–WG for HADCM3 and IPCM4 but A2 scenarios is not available for MIHR (Table 2). The B1, A1B and A2 represent low, medium and high emissions of greenhouse gases respectively, with respect to the prescribed concentrations in Special Report Emission Scenarios. B1 is an optimistic emission scenario whereas A2 is a pessimistic one. A1B lies between these two. Among the 15 GCMs analyzed (Maharjan, 2012), the highest increase in median value of annual precipitation is predicted by HADCM3 for 2090s under A2 and the lowest decrease by IPCM4 for 2020s under the same GHGES of A2. During 2090s, the uncertainty in the projection of annual precipitation was higher compared to 2020s and 2055s.

3 Methods

3.1 Future climate projection

The Long Ashton Research Station-Weather Generator (LARS-WG), a stochastic weather generator model developed by Mikhail Semenov, was used to project future climate. LARS-WG is capable of simulating daily series weather records of a single site (Racsko et al., 1991). It can be used to extend weather data from unobserved locations in order to generate time series data for agricultural and hydrological risks. It is an inexpensive tool which can yield daily site specific climate scenarios, useful for climate change assessment. LARS-WG approximates the probability distribution of the dry and wet series, maximum and minimum temperatures, daily precipitation, solar radiation etc. by using the Semi-Empirical Distribution (SED) function (Semenov et al., 2010).

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SED is a cumulative probability distribution function. LARS-WG uses daily observed climatic parameters for a particular area in order to calculate probability distributions of weather variables and the correlation between them (Semenov et al., 2010). The same set of parameters is then used to generate synthetic weather time series of any length by a random selection of appropriate distributions.

3.2 Assessment of sediment yield

3.2.1 Modeling rainfall-runoff and sediment yield

Soil and Water Assessment Tool (SWAT) is a process based semi-distributed model, capable of predicting various impacts of land management practices on water and sediments and the impact of chemical yields from agricultural land (Neitsch et al., 2009). Being a continuous hydrological model, SWAT requires information on weather, topography, vegetation, soil properties and other land management practices. SWAT divides a watershed into different sub-basins and Hydrological Response Units (HRUs). HRUs are lumped areas within a sub-basin, comprising unique soil type, land use and slope. The model predicts the hydrological state in each HRU using the water balance equation. The equation includes precipitation, runoff, evapotranspiration, percolation and return flow components. SWAT has been used and validated for modeling sediment yield and conservation practices in various river basins (Van Liew et al., 2007; Ullrich et al., 2009; Setegn et al., 2010; Qui et al., 2012).

In this study, the SCS-curve number method (SCS, 1972) was used to estimate surface runoff, which is a function of the permeability of soil, the soil's water content and land use. SWAT calculates the peak runoff rate (the maximum rate of runoff that occurs with a certain rainfall event) using the modified rational method. The Penman–Monteith method is used for estimating evapotranspiration. SWAT estimates erosion and sediment yield for each HRU with the Modified Universal Soil Loss Equation (MUSLE) given in Eq. (1) by Williams (1975). MUSLE is a modified version of the Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978). The MUSLE equation

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is

$$\text{Sed} = 11.8(q_{\text{peak}} \cdot Q_{\text{surf}} \cdot A_{\text{hru}})^{0.56} K_{\text{USLE}} \cdot C_{\text{USLE}} \cdot P_{\text{USLE}} \cdot \text{LS}_{\text{USLE}} \cdot \text{CFRG} \quad (1)$$

where, Sed is the sediment yield (metric tons d^{-1}), Q_{surf} is the surface runoff volume (mm ha^{-1} d^{-1}), q_{peak} is the peak runoff rate (m^3 s^{-1}), A_{hru} is the area of an HRU (ha), K_{USLE} is the USLE erodibility factor, C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor and CFRG is the coarse fragment factor.

Manning's equation was used to calculate flow rate and velocity. The variable storage coefficient method (Williams, 1969) performs flood routing in this study. Sediment Routing is controlled by the processes of deposition and degradation (Arnold et al., 1995). The sediment quantity in the channel's network depends on the initial sediment concentration and the maximum concentration in the reach. Hence, the final quantity of sediment in the reach is calculated using Eq. (2):

$$\text{Sed}_{\text{ch}} = \text{Sed}_{\text{ch},i} - \text{Sed}_{\text{dep}} + \text{Sed}_{\text{deg}} \quad (2)$$

where, Sed_{ch} is the quantity of suspended sediment (metric tons) in the reach, $\text{Sed}_{\text{ch},i}$ is the quantity of suspended sediment (metric tons) in the reach at the beginning of the period, Sed_{dep} is the quantity of sediment (metric tons) deposited in the reach segment, and Sed_{deg} is the quantity of sediment (metric tons) re-entrained in the reach segment.

Equation (3) determines the quantity of sediment transported out from the reach:

$$\text{Sed}_{\text{out}} = \text{Sed}_{\text{ch}} \times \frac{V_{\text{out}}}{V_{\text{ch}}} \quad (3)$$

where, Sed_{out} is the quantity of sediment (metric tons) transported out of the reach, Sed_{ch} is the quantity of suspended sediment (metric tons) in the reach, V_{out} is the volume of outflow (m^3 H_2O) during the time step, and V_{ch} is the volume of water (m^3 H_2O) in the reach segment.

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SWAT is capable of simulating various land management operations such as terracing, strip cropping, vegetative filter strips, stone bunds, reforestation, converting cropland to grassland and vice versa.

3.2.2 Calibrated SWAT model

The SWAT model for the Nam Ou River Basin was set up and calibrated by Shrestha et al. (2013) for both discharge and sediment but validated for discharge only. The discharge was calibrated for the period of 1992–1999 and validated for 2000–2003. The warm-up period of two years was retained in order to minimize the error from the estimation of initial state variables (Zhang et al., 2007). The sediment was calibrated for the period of 1996–2002. The SWAT Cup software was used for auto calibration. The calibration of sediment was carried out after the discharge was calibrated such that the parameter influencing only sediment was calibrated at the later step. The performance of the model was evaluated using the coefficient of determinant (R^2), the Nash–Sutcliffe coefficient (NS) by Nash and Sutcliffe (1970), and Percent Bias (PBIAS).

The model performance for discharge calibration gives $R^2 = 0.64$, NS = 0.64 and PBIAS = 5.12 % and validation gives $R^2 = 0.74$, NS = 0.72 and PBIAS = −14.25 %. The performance of the calibration for discharge was reasonable. Though the model could capture the runoff volume well, it was unable to capture peak discharge, except for 1998 and 1999. The error in peak discharge can be attributed to observed precipitation and discharge data during high flows. Rossi et al. (2009) discussed in his study in Lower Mekong River Basin about the possible error accumulation during the measurement in gauging station in high flow season. This can lead to less reliability in the observed data for model validation, mainly along the study area in the Mekong's tributaries.

The calibration result for sediment yield showed R^2 and NS to be less than 0.6. However, the PBIAS value was 4.18 %, which shows that the observed and simulated sediment loads have good balance in terms of volume. The poor performance of calibration for sediment yield might be attributed to missing data and fewer records. Other reasons may be inaccuracy in the derivation of the topographic (LS) factor (Babel et al., 2011), and uncertainty in the SWAT model while predicting sediment using MUSLE. According to the Sediment Parameter and Calibration Guidance for HSPF, sediment calibration always involves many steps, in estimating a model's parameters, in finding adjusted values for better simulation results of sediment sources in a watershed, and in calculating sediment delivery ratios. Calibration parameters for sediment erosion are more sensitive than other hydrological variables. These parameters for sediment are not distinctly differentiated as the parameters affecting sediment yield from those controlling sediment loss due to a storm. Bieger et al. (2012) mentioned in their study that lower R^2 values for sediment calibration might be due to inadequate input data, insufficient representation of the spatial variability of rainfall, uncertainties prevailing in the model's structure as well as in observed sediment data. Similarly, Jain et al. (2010) also pointed out that the possible human errors in the collection of observed rainfall, runoff and sediment yield data might be responsible for poor calibration results of sediment yield. In the present study, validation of sediment loss was not carried out due to data limitations.

3.2.3 Classification of critical sub-basins

Critical sub-basins are generally identified on the basis of their average annual sediment yield in the basin. The threshold criteria for classifying critical areas of basins in terms of sediment yield varies from basin to basin and also depends on the purpose of classification. Considering the sediment yield index, Chakraborti (1991) defined the ranges of sediment yield as very low, low, moderate, high and very high. With the similar approach, the threshold of sediment yield is defined as 0–2 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (slight), 2–6 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (moderate), 6–10 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (high), 10–20 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (very high) and $>20\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ (severe) for the classification of the Nam Ou River Basin. The areas falling under high, very high and severe zones were categorized as critical sub-basins in terms of sediment yield. The critical sub-basins were then assessed with different land management practices to reduce the vulnerability of the basin in terms of sediment yield.

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3.3 The evaluation of land management practices

Different land management practices were evaluated with the aim of reducing the already high sediment yield in the critical sub-basins. The assessment of these management practices was based on the parameters that are sensitive to sediment yield in the basin. Since most of the sub-basins in the Nam Ou River Basin have high slope and longer slope length, terracing was selected as one of the land management practices. Similarly, the USLE support practice factor (P_{USLE}) is also sensitive to sediment yield. Initially the P_{USLE} factor was considered to be 1 for all the sub-basins, under the assumption that there is no land management practice in the fields in these regions. That is, the management practices were chosen in such a way that the P_{USLE} factor would be reduced.

Six different cases of land management practices were analyzed in this study. In Case 0 (C0), the basin was assumed to remain in the past land use condition and no management practices have been applied.

In Case 1 (C1), vegetative filter strip is applied in those areas of the basin which yielded higher sediment yield, based on the defined threshold values. The vegetative filter strips were placed on those areas which are wood and shrubland as wells as croplands. The effect of the filter strip is to filter the runoff and trap the sediment in a given plot (Bracmort et al., 2006).

In Case 2 (C2), contour strip cropping was applied in the wood and shrubland areas of the critical sub-basins. This scenario is based on the principle that contour strip cropping will help in increasing surface roughness and that will, in turn, reduce sediment yield. In this study, sugarcane is considered as an alternative crop, grown alternatively with the existing crops or any other vegetation. The cover and management factor for sugarcane lies between 0.13–0.4. For this study, 0.15 was taken as STRIP_C (cover factor for the stripped cropped field value). STRIP_P (the USLE support factor for the stripped cropped field) was chosen considering that the practice would be contour strip

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cropping. The selection of the STRIP_P value was carried out on the basis of the HRU's slope (Table 3).

In Case 3 (C3), strip cropping in a form of contour farm terraced field was applied in HRUs. This case is evaluated to analyze the effect of strip cropping in the terraced field conditions with different P_{USLE} factor from Case 2.

In Case 4 (C4) and Case 5 (C5), terracing was simulated with USLE topographic factor ($\mathrm{LS}_{\mathrm{USLE}}$) reduced by 25 and 50 % respectively in order to reduce the sediment yield in the sub-basins. Terracing is generally effective for steep slope areas. It reduces the slope length as well as the slope of the HRUs. The appropriate parameters for representing the effects of terracing are the slope length factor (TERR_SL), the USLE Support Practice factor (TERR_P), and the curve number (TERR_CN). Table 3 gives the detail about the values used for TERR_P and TERR_SL.

4 Results and discussion

4.1 Past climate and projections of future climate

Figures 3 and 4 showed the averaged monthly precipitation and temperature respectively for the baseline period and the future periods under different GCMs and GHGES. The high range of change in precipitation is observed in the latter part of the century. It illustrates that the change in precipitation is not unidirectional under different GHGES and GCMs. The wide variation of change in annual precipitation in both magnitude and direction between GCMs has also been described by Kingston et al. (2011). He also observed the extensive seasonal variation in precipitation between different GCMs. Figure 3 depicts that the change in precipitation during 2020s is comparatively lower than during 2055s and 2090s. The annual precipitation projection from three GCMs indicates the change of −7.6 to 2.64 % in the 2020s, −8.98 to 11.85 % in the 2055s, and −11.04 to 25.84 % in the 2090s. A wide variation in precipitation is observed in 2090s under all three GCMs. Among the three GCMs, HADCM3 predicted higher precipitation

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than MIHR and IPCM4. The intra-annual changes are also observed in the projection of precipitation. For example, under IPCM4, the precipitation decreases from January to July and increases from August to December.

Moreover, the results revealed an increase in monthly temperature under different GHGES and future climate (Fig. 4). The changes in mean monthly temperature vary from 0.3 to 1.3 °C in the 2020s, 1.3 to 2.9 °C in the 2055s and 1.9 to 4.9 °C in the 2090s. The temperature in the 2020s does not vary significantly from the 1990s but potential change is observed during the 2090s period under different GCMs and GHGES. All three GCMs projected higher temperature under A2 scenario and lower temperature under B1.

The result of climate projection from this study is comparable with that from Shrestha et al. (2013), which revealed that the trend of projection of both precipitation and temperature is analogous under different GCMs and GHGES. In his study, the CGCM3 projected relatively higher precipitation and temperature in the early and mid-centuries than under other GCMs and RCMs used in his study.

4.2 The impact of climate change on sediment yield

The percentage change in the annual mean sediment yield with respect to the baseline period is presented in Table 4. The highest change in sediment yield is expected in 2090s under HADCM3 with 85.87 % under A2, followed by 52.90 % under B1 and 52.53 % under A1B scenario. Figure 5 shows the monthly sediment yield in the baseline and future periods. IPCM4 predicted the lowest change in sediment yield of −26.38 % in 2090s under A1B scenario. The decrease in sediment yield is observed under IPCM4 in the future climate conditions under all GHGES except under A1B in 2055s. This decrement in the sediment yield corresponds to lower amount of precipitation in the future periods under IPCM4. Mostly in the wet seasons, the quantity of sediment yield is low under IPCM4. In addition, projections under A2 show higher sediment yield than under B1 and A1B. The sediment yield in 2020s is relatively higher in the wet season (May to October) under HADCM3 and MIHR. During 2055s and 2090s, the sediment

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yield is observed to be higher in the wet seasons compared to dry seasons. Study by Shrestha et al. (2013) in the same river basin found that monthly changes in sediment yield range from −81.8 to 242.5 % for 2011–2040 and −87.8 to 207.3 % for 2041–2070 with different GCMs. The sediment yield is observed to be more with the increase in temperature. Similar result has also been found in our research. The temperature under HADCM3 increased significantly in 2090s; and the sediment yield also increased substantially in that period. This signifies that increase in temperature could result in increasing sediment yield. Li et al. (2011) indicated that increasing temperature might exacerbate the soil erosion rate, resulting in increase sediment flux due to its influence on vegetation and weathering. Zhu et al. (2008) also outlined that soil erosion rate and sediment transport capacity may be controlled by changes in precipitation and temperature.

Similar to the projected temperature and precipitation (based on 15 GCMs and three GHGES), the projected sediment yield also showed increased uncertainty for the future periods (Maharjan, 2012). Most of the GCMs showed wide range of increase in sediment yield during 2090s for all three scenarios. In addition to uncertainty due to future climate projection, the uncertainty due to model parameterization in SWAT may also be responsible for larger uncertainty in projection of future sediment yield in the study basin. However, the effect of the possible uncertainties in model parameterization on the future sediment yield has not been analyzed in this study. But it is expected that the uncertainty due to model parameterization in SWAT would impart less uncertainty than the GCMs projections in the future sediment yield projections (Kingston et al., 2011).

4.3 Identification of critical sub-basins

4.3.1 Critical sub-basins under baseline period

Critical sub-basins were identified on the basis of the threshold value of sediment yield, as defined in Sect. 3.2.3 of this paper. During the baseline period, five sub-basins (ID 1, 2, 3, 4 and 10) out of 19 fell in the category of high and very high risk zones under

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C0, and were therefore categorized as critical sub-basins (Fig. 6a). However, none of the sub-basins fell under severe zone in the baseline period. Table 5 presented that the sub-basin IDs 1, 4 and 10 yielded 15.34, 13.35 and 11.52 $t\,ha^{-1}\,yr^{-1}$ of sediment, directing them to the very high risk zone. At the same time, sub-basins IDs 2 and 3 fell under the category of high risk zone with the sediment yield of 7.19 and 7.48 $t\,ha^{-1}\,yr^{-1}$.

4.3.2 Critical sub-basins under future climatic conditions

Figures 7–9 show the identified critical sub-basins based on the amount of sediment yield in the future under three GCMs and GHGES. It clearly depicts that HADCM3 and MIHR resulted in relatively higher sediment yield than under IPCM4. This explains that the IPCM4, being the GCM which predicts decreasing amount of precipitation and increasing temperature, resulted in low sediment yield. It shows that the sediment yield is reduced with lesser precipitation and higher temperature in the future. The result illustrates that highest number of critical sub-basins is observed under HADCM3 in comparison to MIHR and IPCM4 in the future climatic conditions. It is also expected that there will be higher number of vulnerable sub-basins in 2090s period irrespective of the GHGES. During 2090s, 11 sub-basins were in the category of critical sub-basins under HADCM3 and A2 scenario whereas this number reduced to 3 under IPCM4. None of the sub-basins fall under severe zone as projected by IPCM4 in the future periods, which explains that the vulnerability of the basin is less under this GCM. Similarly, MIHR which projected average change in future climate contributed to relatively lesser number of vulnerable sub-basins than HADCM3 but higher number than IPCM4.

4.4 Effectiveness of land management practices

4.4.1 The baseline period

The sub-basins in the study area vary from gentle slopes to very steep slopes and most of them have high slope length. Most of the critical sub-basins largely have steep

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slopes and sandy clay loam soil. The annual sediment yield in the critical sub-basins after the application of the land management practices in the critical areas (Fig. 6b) is presented in Table 5. The sediment yields in the critical sub-basins 2, 3, 4 and 10 were reduced sufficiently so that it fell under slight and moderate zone after the application of land management practices. For sub-basin 1, only terracing (C4 and C5) could reduce the sediment yield below 6 $t\,ha^{-1}\,yr^{-1}$, making it less vulnerable. It was found that land management practices C4 (Terracing with reduced LS_{USLE} by 25 %) and C5 (Terracing with reduced LS_{USLE} by 50 %) have significant effect in reducing sediment yield in the critical sub-basins. All the critical sub-basins show moderate reduction in sediment yield after the application of these management practices. Strip cropping under the contour farm terraced condition (C3) attribute to more sediment yield reduction after C4 and C5. The application of vegetative filter strips (C1) and contour strip cropping (C2) is also capable in reducing the sediment yield in the four sub-basins below the moderate level. The result clearly illustrates that terracing in the HRUs is an effective management strategy to reduce sediment yield in all the critical sub-basins. The notable reduction of sediment yield due to terracing can be attributed to the shortening of slope length in the sub-basins.

Figure 10 shows the reduction in sediment yield (%) under various management practices during the baseline period (1981–2000). The sediment yield reduction in sub-basins 2, 4 and 10 is more significant than in the sub-basins 1 and 3. Terracing (C5) reduces sediment yield in sub-basins 1, 2, 3, 4, and 10 by 66, 95, 37, 96 and 99 % respectively. For sub-basin 3, strip cropping in the contour terraced condition (C3) seems to be more effective. In this study, it was also found that the sediment yield in the dry season does not reduce much whereas the sediment yield in the wet season shows greater reduction.

4.4.2 The future periods

The study shows that the sediment yield under future climatic conditions is likely to be severe in some sub-basins under HADCM3 and MIHR (Figs. 7 and 8), because

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of which reducing the sediment yield to the acceptable range may prove to be very difficult. Table 6 presented the sediment yield in the basin under the existing land management practice (C0) along with the respective percentage of sediment yield reduction under different land management practices (C1 to C5) in the future climate. The result indicates that terracing (C4 and C5) reduces the sediment yield to a greater extent than strip cropping (C2 and C3) and filter strips (C1). C4 and C5 have same effectiveness in reducing the sediment yield in the basin. For example, in 2090s period, the sediment yield of the basin was 8.79 Mtons which is reduced by 21.39 % under C4 and C5 but only by 14.56 % under C1. The highest sediment yield of 10.69 Mtons is observed under HADCM3 and A2 scenario in 2090s period, which was reduced by 7.02, 8.51, 10.85, 11.60 and 11.69 % under C1, C2, C3, C4 and C5 respectively. The table also illustrates that the reduction in sediment yield is low under A2 compared to A1B and B1. While the projection of sediment yield is higher in the future climate under different GHGES, the land management practices adopted singly does not reduce the yield to the acceptable threshold in some sub-basins. Therefore, it might be necessary to apply a combination of appropriate land management practices in the vulnerable sub-basins to curtail the sediment yield up to the moderate range.

5 Conclusions

This study identifies the critical sub-basins in the Nam Ou River Basin, which yield more sediment annually than the value defined as threshold. Different land management practices were assessed in order to reduce the sediment yield in the critical sub-basins. The LARS-WG method was used to downscale future precipitation and temperature. The SWAT model was used to simulate discharge and sediment yield in the basin. The calibration and validation of the SWAT model demonstrates that SWAT can be used to simulate discharge and sediment yield in the basin.

Results of downscaling precipitation show that the change in precipitation is not unidirectional under different GCMs. Temperature are projected to increase in future

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periods for the selected GCMs and GHGES. The increase in precipitation and temperature will lead to an increase in the sediment yield of the basin. The critical sub-basins were identified on the basis of sediment yield in each sub-basin. The number of critical sub-basins is more in the future periods than in the baseline period, which can be attributed to the increase in the sediment yield in the overall basin in general. Different land management practices were applied in the critical sub-basins in order to reduce the sediment yield from those basins. The study shows that terracing is the best land management practice for reducing sediment yield, followed by strip cropping and filter strips. The terracing operation applied by reducing the topography factor by 25 and 50 % did not show significant differences in the result among them. The results also suggest that a combination of the land management practices might help in obtaining better results in sediment yield reduction.

However, the land management practices recommended in this study are based on the percentage of sediment reduction observed in the sub basin level. The assessment of the effectiveness of this land management practices in the practical implementation is beyond the scope of this paper. But this study may potentially help in building sustainable land management strategies for land development planners and decision makers, as well as in planning and implementing these strategies for a basin-wide sediment management.

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Table 1. Analysis of GCMs for selection on the basis of future precipitation projections.

GHGES	Period	GCMs showing extreme cases for precipitation from future projection analysis		
		Minimum change from baseline	Average change from baseline	Maximum change from baseline
B1	2020s	IPCM4	n/a	FGOALS
	2055s	IPCM4	n/a	GFCM21
	2090s	IPCM4	n/a	HADCM3
A1B	2020s	IPCM4	MIHR	CGMR
	2055s	NCPCM	MIHR	NCCCSM
	2090s	IPCM4	CNCM3	HADCM3
A2	2020s	NCPCM	GFCM21	HADCM3
	2055s	BCM2	MIHR	HADCM3
	2090s	IPCM4	MIHR	HADCM3

Note: Global Climate Models: BCM2 developed by Bjerknes Center for Climate Research, Norway; CGMR by Canadian Centre for Climate Modelling and Analysis, Canada; CNCM3 by Centre National de RecherchesMeteorologiques, France; FGOALS developed by Institute of Atmospheric Physics, China; GFCM21 by Geophysical Fluid Dynamics Laboratory, USA; HADCM3 by UK Meteorological Office, UK; IPCM4 by Institute Pierre Simon Laplace, France; MIHR by National Institute for Environmental Studies, Japan; NCPCM and NCCCSM by National Center for Atmospheric Research Research, USA.

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Table 2. GCMs selected for this research.

No.	Research centre	Country	GCM	Model acronym	Grid resolution	Emission scenarios
1.	Institute Pierre Simon Laplace	France	IPSL-CM4	IPCM4	2.5° × 3.75°	A1B, A2, B1
2.	National Institute for Environmental Studies	Japan	MRI-CGCM2.3.2	MIHR	2.8° × 2.8°	A1B, B1
3.	UK Meteorological Office	UK	HadCM3	HADCM3	2.5° × 3.75°	A1B, A2, B1

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Table 3. Different land management practices cases analyzed in this research.

Cases	Variable Name	Description of Variable	Value
C1: Vegetative filter strips	FILTER_RATIO	Ratio of field area to filter strip area ($ha^2\ ha^{-2}$)	50
	FILTER_CON	Fraction of HRU which drains to the most concentrated ten percents of the filters strip area ($ha^2\ ha^{-2}$)	0.5
	FILTER_CH	Fraction of the flow within the most concentrated ten percents of the filters strip which is fully channelized	0
C2: Strip copping contour field condition	STRIP_C	USLE cropping factor for strip cropped field	0.15 (sugarcane)
	STRIP_P	USLE support practice factor for strip cropped field under contour field condition	slope 0–10 % = 0.50 slope 10–20 % = 0.70 slope 20–30 % = 0.90 slope > 30 % = 0.90
C3: Strip copping terraced field condition	STRIP_C	USLE cropping factor for strip cropped field	0.15 (sugarcane)
	STRIP_P	USLE support practice factor for strip cropped field under terraced condition	slope 0–10 % = 0.25 slope 10–20 % = 0.35 slope 20–30 % = 0.45 slope > 30 % = 0.50
C4: Terracing by reducing LSUSLE factor by 25 %	TERR_P	USLE support practice factor adjusted for terraces	slope 0–10 % = 0.10 slope 10–20 % = 0.14 slope 20–30 % = 0.18 slope > 30 % = 0.18
	TERR_SL	Averaged slope length in HRUs	slope 0–10 % = 40 m slope 10–20 % = 8 m slope 20–30 % = 5 m slope > 30 % = 5 m
C5: Terracing by reducing LSUSLE factor by 50 %	TERR_P	USLE support practice factor adjusted for terraces	slope 0–10 % = 0.10 slope 10–20 % = 0.14 slope 20–30 % = 0.18 slope > 30 % = 0.18
	TERR_SL	Averaged slope length in HRUs	slope 0–10 % = 15 m slope 10–20 % = 5 m slope 20–30 % = 5 m slope > 30 % = 5 m

Note: *P* factor (USLE support practice factor) is calculated based on the slope of HRUs and the farmed condition (Haan et al., 1994).

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Table 4. Percentage change in annual sediment yield under different GCMs and GHGES B1, A1B and A2 during future periods with respect to baseline period of 1981–2000.

	B1			A1B			A2		
GCMs	2020s	2055s	2090s	2020s	2055s	2090s	2020s	2055s	2090s
HADCM3	4.28	17.37	52.90	1.49	38.52	52.53	9.30	28.22	85.87
MIHR	1.86	9.67	11.86	−1.06	9.84	6.17	n/a	n/a	n/a
IPCM4	−8.20	−24.50	−19.53	−18.65	0.23	−26.38	−13.54	−19.16	−15.22

Table 5. Sediment yield in the critical sub-basins under different land management practices during the baseline period 1981–2000.

Sub-basin	Sediment yield under different cases of land management practices ($t\,ha^{-1}\,yr^{-1}$)					
	C0	C1	C2	C3	C4	C5
1	15.34	8.28	8.16	6.55	5.21	5.19
4	13.35	1.82	4.41	2.34	0.60	0.58
10	11.52	5.61	0.50	0.26	0.06	0.06
2	7.19	2.28	2.11	1.15	0.37	0.35
3	7.48	3.80	3.74	3.07	4.69	4.68

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Table 6. Sediment yield (in Mtons yr^{-1}) under land management practice case C0 in the future periods under different GCMs and GHGES along with the respective percentage reduction in the sediment yield under different land management practices (C1 to C5).

GCMs	GHGES	Sediment yield (Mtons yr^{-1})	Percentage reduction in sediment yield under different land management practices				
		C0	C1	C2	C3	C4	C5
		2011–2030					
HADCM3	B1	6.00	17.50	18.83	22.67	23.83	23.83
	A1B	5.84	17.12	18.32	21.92	23.12	23.12
	A2	6.28	16.72	17.52	21.18	22.13	22.13
MIHR	B1	5.86	17.24	18.09	21.84	22.87	22.87
	A1B	5.69	17.40	18.80	22.50	23.55	23.55
IPCM4	B1	5.28	16.48	17.23	20.45	21.21	21.40
	A1B	4.68	15.81	16.24	19.23	19.66	19.87
	A2	4.97	18.31	18.91	22.13	22.74	22.74
		2046–2065					
HADCM3	B1	6.75	15.70	16.30	20.00	21.19	21.19
	A1B	7.97	15.06	15.68	19.57	20.83	20.83
	A2	7.37	15.47	16.01	19.95	21.30	21.30
MIHR	B1	6.31	15.69	16.80	20.60	20.92	22.35
	A1B	6.32	14.24	15.19	18.67	18.67	15.82
IPCM4	B1	4.34	15.21	15.44	18.43	19.12	19.12
	A1B	5.76	15.63	15.80	19.44	18.92	20.31
	A2	4.65	14.62	14.84	17.85	18.71	18.71
		2080–2099					
HADCM3	B1	8.79	14.56	15.59	19.68	21.39	21.39
	A1B	8.77	12.54	14.03	18.24	19.84	19.95
	A2	10.69	7.02	8.51	10.85	11.60	11.69
MIHR	B1	6.43	15.71	16.33	19.75	20.84	20.84
	A1B	6.10	12.95	13.77	17.05	18.20	18.20
IPCM4	B1	4.63	14.04	14.25	17.06	17.71	17.71
	A1B	4.23	12.06	12.77	15.37	16.08	16.08
	A2	4.87	11.29	11.91	14.58	15.20	15.40

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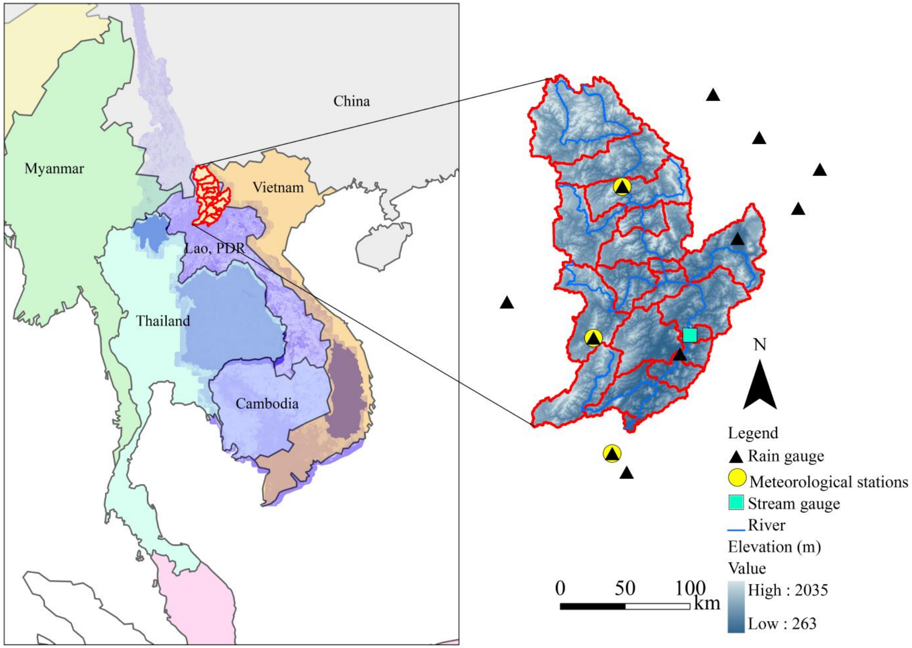

Figure 1. Location of study area.

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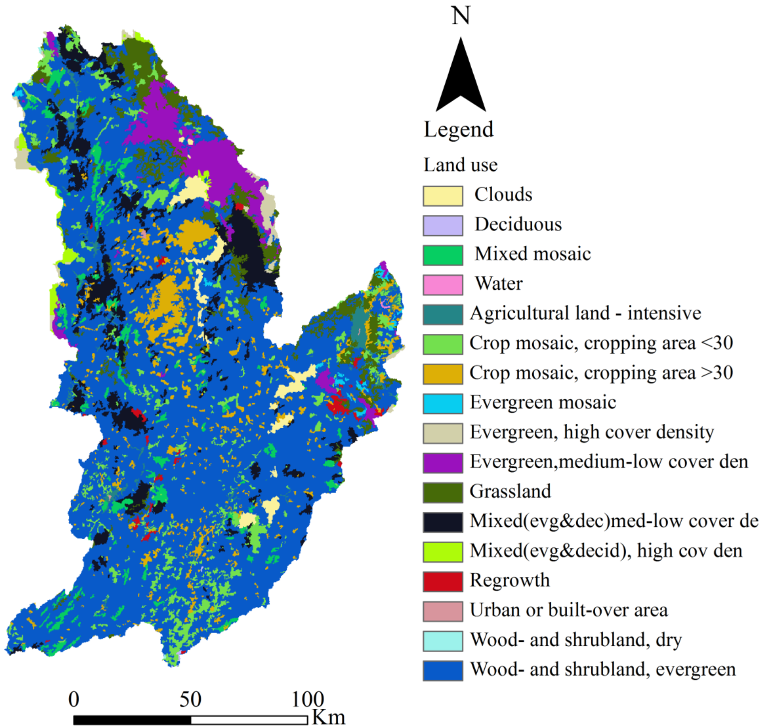

Figure 2. Existing land use.

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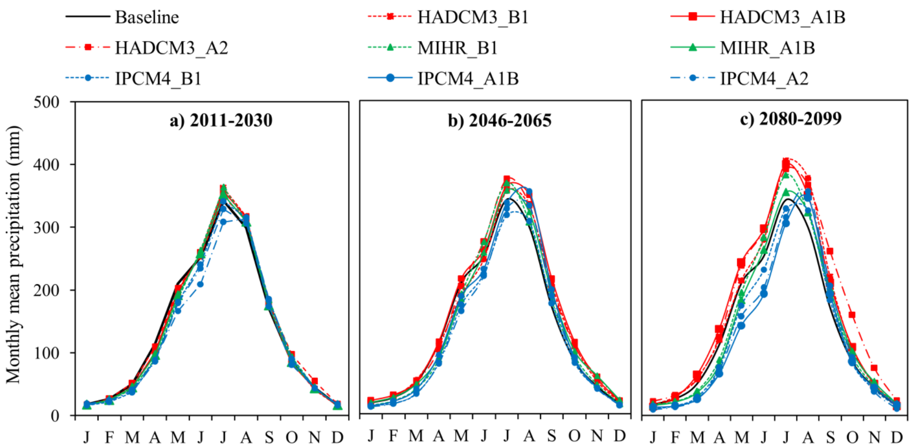

Figure 3. Comparison of mean monthly precipitation during the baseline period (1981–2000) and the future periods for B1, A1B and A2 scenarios.

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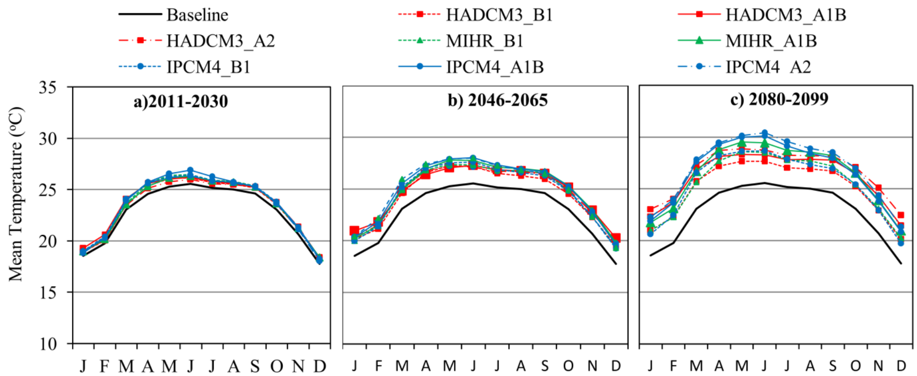

Figure 4. Comparison of mean monthly temperature during the baseline period (1981–2000) and the future periods for B1, A1B and A2 scenarios.

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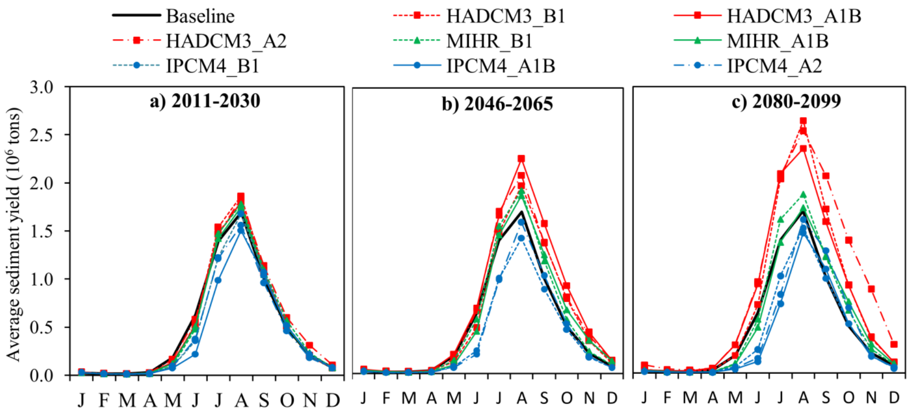

Figure 5. Average monthly sediment yield during the baseline and the future periods under different GCMs and GHGES.

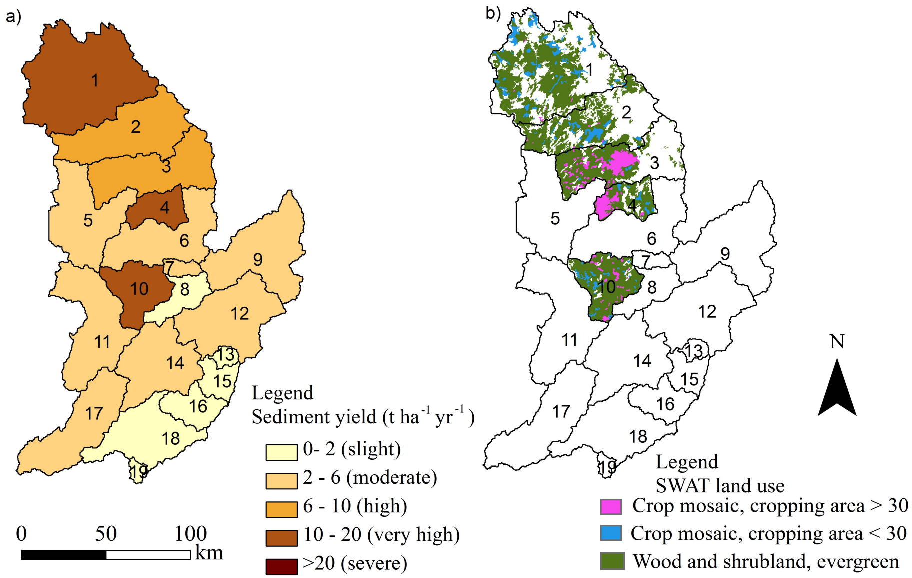

Figure 6. (a) Classification of sub-basins into five different categories based on the sediment yield during the baseline period in the Nam Ou River Basin. **(b)** Areas under the critical sub-basins during the baseline period where land management practices are applied.

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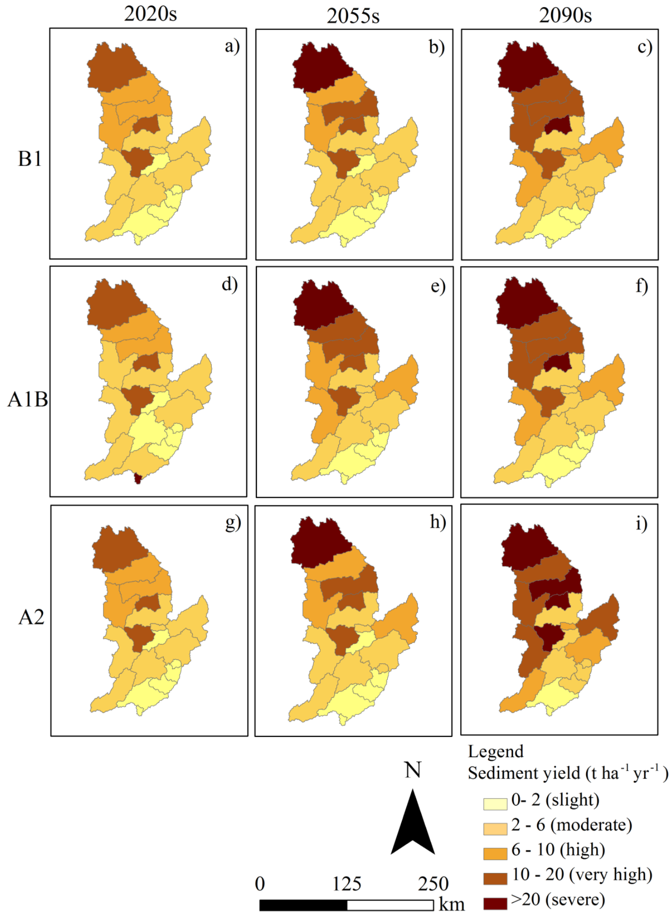

Figure 7. Sediment yield in the study basin with existing land management practice (C0) under HADCM3 for B1 **(a–c)**, A1B **(d–f)**, and A2 **(g–i)** scenarios for future periods.

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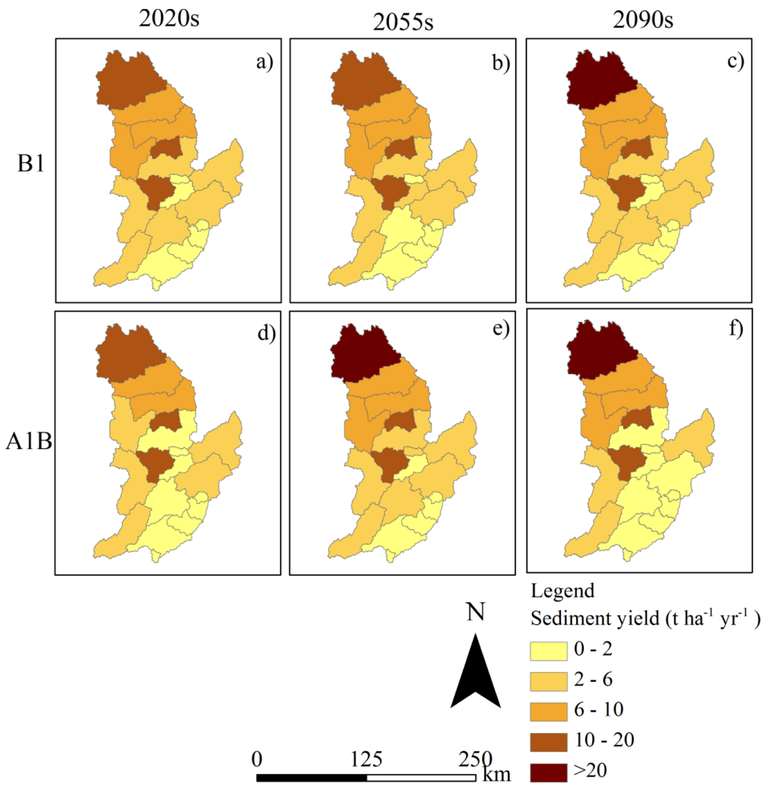

Figure 8. Sediment yield in the study basin with existing land management practice (C0) under MIHR for B1 **(a–c)**, A1B **(d–f)**, and A2 **(g–i)** scenarios for future periods.

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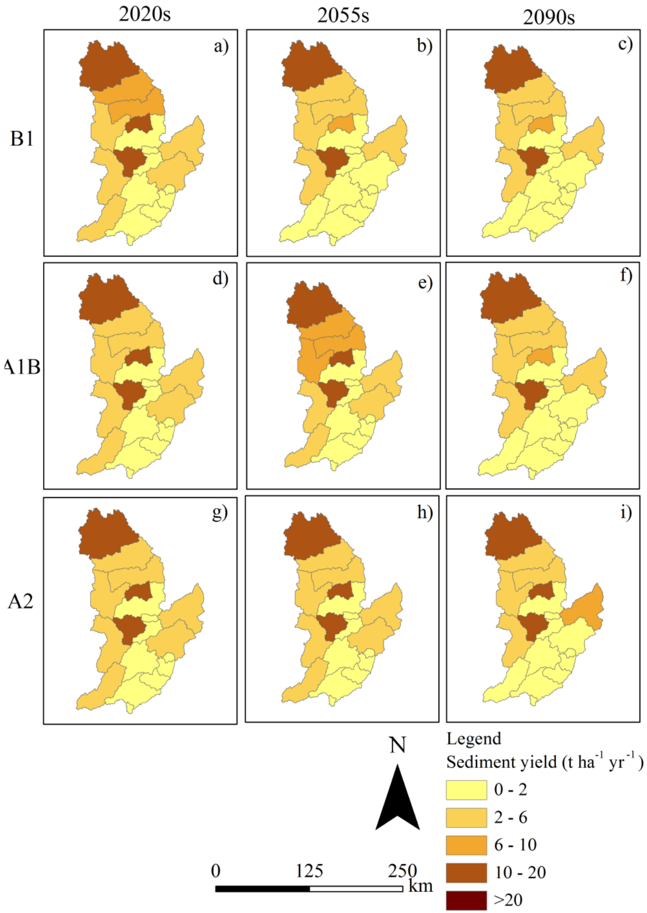

Figure 9. Sediment yield in the study basin with existing land management practice (C0) under IPCM4 for B1 **(a–c)**, A1B **(d–f)**, and A2 **(g–i)** scenarios for future periods.

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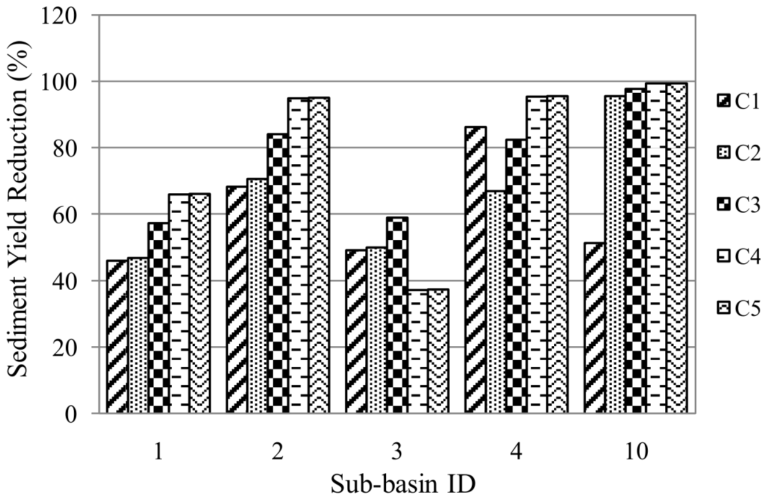

Figure 10. Percentage of sediment yield reduction in the existing land management practice (C0) when land management practices (C1 to C5) are assessed in the critical sub-basins.

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