FINAL REPORT for APN PROJECT
Project Reference Number: ARCP2008-01CMY-ZIEGLER

Sediment Dynamics and Down-stream Linkages in Tropical Streams as Affected by Projected Land-Cover / Land-Use and Climatic Change

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Sediment Dynamics and Down-stream Linkages in Tropical Streams as Affected by Projected Land-Cover/Land-Use and Climatic Change

Project Reference Numbers: APN2006-06NMY-Ziegler, ARCP2007-01CMY-Ziegler, ARCP2007-01CMY-Ziegler, ARCP2008-01CMY-Ziegler

Final Report submitted to APN

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OVERVIEW OF PROJECT WORK AND OUTCOMES

Non-technical summary

Through field measurements and computer modeling this project attempted to understand how headwater streams in mainland SE Asia would be affected by plausible changes in both climate and land-cover/land-use. Fieldwork was conducted for several years in Thailand; two years in China. Analyses performed at these sites are some of the most comprehensive ever performed in the region. In collaboration with other international projects, the modeling component involved the prediction of land-cover/land-use change and climate change for the entire SE Asia region. Advances were also made on developing a model for simulating sediment and nutrient dynamics in headwater catchments; however, the end goal of predicting changes in sediment with a changing climate was not fully achieved. Collectively, the various phases of the project have led to nearly 30 publications in international journals. In addition, follow-on work has already been started on a few important issues in the region, for example (1) studying the the impact of uncontrolled expansion of rubber plantations in mainland SE Asia; and (2) determining the anthropogenic and natural controls on stream chemistry.

Objectives

The main objectives of the project were:

1. Determine the effect of projected land-cover/land-use on climate over the next 50 years for the Montane Mainland SE Asia (MMSEA) region.
2. Study the anthropogenic versus natural controls on stream discharge, geochemistry, and sediment-nutrient dynamics at a site in Thailand in attempt to predict how these variables might change in the future (as defined by Objective 1).
3. Develop the means of performing Objective 2 at sites in China, Vietnam, and India.

Amount received and number of years supported

The Grant awarded to this project was:
US$ 40,000 for year 1: APN2006-06NMY,
US$ 40,000 for year 2: ARCP2007-01CMY,
US$ 40,000 for year 3: ARCP2008-01CMY

Activity undertaken

At a regional level, we simulated changes in land-cover/land-use to the year 2050 with an agent-based model using expert predictions and publically-available socio-economic indicator data as input. For the same period we used a regional climate model to predict changes in climate to 2050 using the land-cover predictions. We did the following to understand discharge, sediment, and water chemistry dynamics in headwater streams: (1) established the Mae Sa Experimental Catchment in northern Thailand, which has supplied data continuously from 2006-pres; and (2) conducted measurements on the Longchuanjiang River in Yunnan Province, China. To understand the anthropogenic versus natural drivers of flooding events, we did the following: (1) performed a 100-year analysis of high and low flows on the Ping river in Thailand; (2) conducted paleoflood experiments on the Ping and Mekong rivers; and (3) studied the 2011 Chao Phraya flood. We also analyzed the hydro-geomorphological impacts of rapid intensification of agriculture systems in the region. This analysis involved performing two meta-analyses and conducting a field study on the impact of rubber expansion in China. Finally, modeling studies were performed to identify a reliable means of simulating present and future stream discharge and fluxes of suspended sediments and associated solid constituents (e.g., nutrients, contaminants).

Results

Agent-based computer simulations of future land-cover change in Montane Mainland Southeast Asia (MMSEA) predicted change in approximately 16% of the MMSEA landscape between 2001 and 2050. Roughly 9% of the current vegetation, which consists of native species of trees, shrubs, and grasses, was predicted to be replaced by tree plantations, tea, and other evergreen shrubs during the 50-year period. Regional climate simulations with the Reg3CM yielded different responses to different future land-cover/land-use scenarios. Simulations using the predicted 2050 land covers showed little change in the hydrometeorology of the region. However, important regional changes resulted from simulations using extreme deforestation scenarios (e.g., grassland and irrigated crop). These differences suggest that the effects of predicted land-cover/land-use change on climate in MMSEA are probably smaller than those caused by increasing CO_2 levels.

The intensification of agriculture systems away from small-holder swidden systems to large-scale cash-generating systems, including plantations, is of concern because many of the latter systems require irrigation, fertilizers, pesticides, and elaborate road networks for support. The expansion of road networks in the region is one of the greatest anthropogenic factors affecting river systems. Roads not only have the ability to change storm runoff dynamics, they represent important sources areas of sediment via erosion and mass wasting.

One significant change in land cover in MMSEA is the continued expansion of rubber, a tree plantation crop that may have important implications for local-to-regional scale hydrology because of potentially high water use in the dry season. Evidence points to the high water use of rubber during the monsoon dry season; however, this effect on catchment groundwater reserves is still unknown.

Great inter- and intra-annual variability in the dynamics of stream total suspended solids, macro nutrients (C, N, P), and various dissolved constituents (e.g., cations, anions) is affected by both natural and anthropogenic factors. For nearly all rivers and streams in the region, insufficient data are available to separate the differences of natural versus anthropogenic controlling factors. Flood events, in particular, are affected by multiple human activities and natural processes. With respect to the former, although the effects of land-cover change, characterized by forest removal, on flooding cannot be ascertained for large catchments, the influence of dam/reservoir management is an important factor regulating both high and low flows.

Paleo-evidence suggests that floods much larger than those witnessed in the last few hundred years are possible. Currently, must countries are not prepared for catestrophic floods because of the great number of people and businesses living/located on the flood plains of large rivers. Preparation for a changing climate, which may be marked by an acceleration in the hydrological cycle, should not rely solely on engineering works (more dams, higher dykes), it should also address vulnerability.

Finally, advances were made in modeling catchment runoff and suspended solid transport using artificial intelligence models that are not restricted by parameterization of myriad catchment physical processes and properties.

Relevance to the APN Goals, Science Agenda and to Policy Processes

The research increases understanding of how water resources in headwater streams in montane mainland SE Asia could be affected by plausible changes in both climate and land-cover/land-use. This information is important for developing sound mitigation strategies, as well as determining non-linear vulnerabilities of natural (e.g., aquatic life) and human systems (e.g., water quality degradation of municipal water). Our efforts include transferring knowledge generated in the study to appropriate local officials who make policy related to sustainability. The study also improved the existing monitoring capability of two rivers, thereby making them suitable sites for future research. The project also facilitated collaboration between researchers from several APN-approved countries.

Self evaluation

The project was highly successful in terms of improving our understanding of how anthropogenic versus natural factors affect stream water quantity and quality in the montane mainland SE Asian region. Results have lead to nearly 30 publications to date. Project data have been used in 15 student theses. The MSEC network is still fully operational; and it will continue to provide data for follow-on studies. Although the objective of simulating sediment changes to 2050 was not fully achieved, the work is still continuing. Establishing a viable collection site in China was accomplished. However, new projects were not implemented in Vietnam and India, largely because we failed to generate additional funding to support research in those countries.

Potential for further work

Follow-on work has already begun; and students from NUS and other universities (e.g., Kasesart, Hohenheim) are performing thesis research at the Thailand site. New grants have been received to investigate the following: (1) regional impact of rubber expansion in the regon; (2) anthropogenic causes of landslides in headwater catchments of Thailand; (3) anthropogenic versus natural controls on river chemistry; and (4) carbon fluxes to the ocean in SE Asia.

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TECHNICAL REPORT

Preface

This study represents an initial attempt to understand land-cover/land-use and climate impacts on fluvial systems in the Montane Mainland SE Asia region. The investigation combines regional computer model simulations and field work at several sites in Thailand and Yunnan province of China in attempt to understand how anticipated land-cover/land-use change will affect hydrological and geomorphological systems under a changing climate. In addition, insights were gained regarding anthropogenic versus natural variability in important hydro-geomorphological processes. The research has supported the publishing of nearly 30 journal articles.

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1. Introduction

Montane mainland Southeast Asia (MMSEA), a region of great biological and cultural diversity, has come under close scrutiny in the last several decades as a result of both real and perceived deforestation, land degradation, and most recently, the conversion of traditional agricultural practices to more permanent cash crop agriculture driven by regional and global markets (Fox et al., 2012). These human-induced changes have important implications for river ecology, natural resource management, and public health. As MMSEA is the headwater region for several major river systems including the Mekong, Chao Phraya, Irrawaddy, and Yangzte, hydrologic change and water resource degradation could have serious consequences for its hundreds of million inhabitants.

Significant decrease in rainfall during the height of the summer monsoon rainy season is thought to have already occurred over the Indochina peninsula as a result of extensive deforestation in lowland areas (Kanae et al. 2001). Werth and Avissar (2005) simulate significant local reductions in precipitation in Southeast Asia in response to deforestation. Schneck and Mosbrugger (2011) simulated remote as well as local changes in climate as a result of deforestation in Southeast Asia.

Looking ahead, the still largely forested MMSEA region is poised for additional rapid land-cover change, stimulated in part by agriculture intensification, emergence of lucrative plantation systems, and expansion of road systems. Land-cover/land-use (LCLU) changes in this region may impact rivers systems at several scales by increasing surface runoff and catchment erosion processes, thereby changing the flux of sediment and nutrients in stream systems, as well as causing on-site degradation. Changes in the frequency and patterns of rainfall, particularly large tropical storms, will also affect water quality and quantity in the region's river systems. When viewed in this context, understanding how land cover change and global climate change will affect fluvial systems is a high priority.

In 2006 a grant was received from the Asia Pacific Network (Japan) to investigate sediment dynamics in tropical streams as affected by potential changes in climate and land-cover/land-use change. The project immediately coordinated with (a) an on-going investigation of the role of land-cover change in altering regional hydrological processes under a changing climate (Jefferson Fox, PI); and (b) a third project looking at sediment and carbon fluxes in large Asian rivers, as related to climate and human impacts (Lu XiXi, PI). The goals of the collective effort were three fold:

1. Assess the extent that changes in land-cover/land-use will affect climate over the next 50 years for the Montane Mainland SE Asia (MMSEA) region.
2. Study the anthropogenic versus natural controls on stream discharge, geochemistry, and sediment-nutrient dynamics at a site in Thailand in attempt to predict how these variables might change in the future (as defined by Objective 1).
3. Develop the means of performing Objective 2 at sites in China, Vietnam, and India.

We anticipated the study would allow us to distinguish the degree that various types of anthropogenic change will affect hydrological and geomorphological response in river systems in the region. In particular, we were hoping to gain insight on extreme flows (e.g., droughts and floods), erosion, sediment delivery, water quality, and nutrient dynamics. This information is important for determining non-linear vulnerabilities of natural and human systems to anthropogenic changes in LCLU and climate.

During the course of the study, detailed sampling was conducted on the nested Ping and Mae Sa rivers, tributaries to the Chao Phraya in Thailand. Measurement sites were also established at two sites in Yunnan Province of China, the Nam Ken Catchment and on the Longchuanjiang river. Preliminary investigations were made at locations in India and Vietnam. This report provides a synthesis of results stemming from the Thailand, China, and regional analyses.

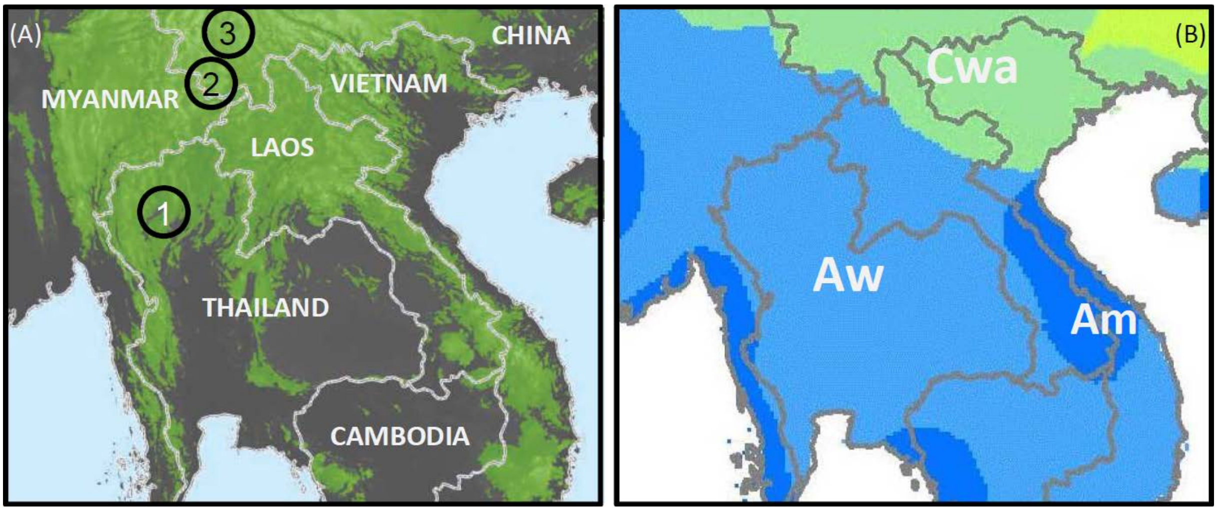

Figure 1. (A) Locations of research sites in Montane Mainland SE Asia (green shading): (1) Mae Sa Experimental Catchment (MSEC) within the Ping river basin; (2) Nam Ken Climatological Network, Xishuangbanna Prefecture, Yunnan Province, China; and (3) Longchuan gauging site in Nanhua county of Chuxiong Yi Autonomous Prefecture, Yunnan province. (B) Köppen climate classification of MMSEA region is predominantly: Tropical Monsoon (Aw); Tropical wet/dry (Am); or Humid subtropical (Cwa). All sites have distinct monsoon seasons.

2. Methods

A broad overview of the methods employed at important study sites is presented here. Additional details of specific methods are provided in cited works.

2.1 Montane Mainland Southeast Asia

2.1.1 Site description

Montane mainland Southeast Asia (MMSEA), 300 m asl and above, is a large ecologically vital region comprising about half of the land area of Cambodia, Laos, Myanmar, Thailand, Vietnam, and China's Yunnan Province (Figure 1). Large-scale climatic variability in the area is associated with the Indian Ocean and Pacific Ocean impact annual and seasonal rainfall patterns (Rasmussen and Carpenter, 1983, Chen and Chappell, 2009). The Southeast monsoon, extending from approximately late April or early May to October/November (Matsumoto, 1997, Cook and Buckley, 2009), occurs as warm air from the Indian Ocean moves northward with the Inter-Tropical Convergence Zone (ITCZ) towards Thailand. By July the ITCZ has moved to Southern China; thereby decreasing monthly rainfall. In August, the ITCZ moves southwards again over North Thailand; and peak rainfall occurs during this month or in September. The end of the monsoon period in October/November coincides with the moving of the ITCZ farther south. A dry winter season then extends until April/May of the following year.

Typhoons and other types of climatic disturbances in the form of monsoon depressions influence rainfall activity in the catchment. Typhoons originating from the Western North Pacific Ocean or the South China Sea pass over northern Thailand, with peak activity occurring usually from September to October (Lim and Boochabun, 2012). ENSO (El Ninõ or La Niñã) events also influence wet season rainfall (Kripalani & Kulkarni, 2001, Singhrattna *et al.,* 2005a,b). El Ninõ and La Nino events are believed to correspond with dry and wet periods respectively; however, research has shown that this is not always the case (Kripalani & Kulkarni, 2007, Singhrattna et al., 2005a,b; Lim et al, forthcoming).

The region harbors a wealth of natural resources including globally important stocks of forest and biological diversity and the headwaters for several major river systems including the Mekong, Chao Praya, Irrawaddy, and Yuan-Hong. Much of MMSEA has only been reopened to outside influences within the last two decades, bringing profound and widespread changes to both its physical environment and to its local societies. Swidden agriculture (also called shifting cultivation), the dominant farming system in MMSEA where it has been practiced for at least a millennium, has greatly influenced land cover and land use throughout the region. However, swidden agriculture has been giving way to more intense types of cash crop systems, including plantations. The region is also affected by the expansion of road networks which are vital for development. In addition to the economic and social changes they produce, emerging road networks promote rapid LCLU change by providing access to formerly isolated areas and facilitating transport of timber and other products to market.

2.2.2 Simulated land-cover/land-use changes in MMSEA

The conversion of land use and its effects (CLUE-s) model (Verburg et al. 1999a, Verburg et al. 2002, Verburg 2006) was used to simulate land-cover change between 2001 and 2050. A 2001 land-cover map was developed to serve as the model baseline. We first acquired a 1-km resolution global land cover map from the USGS Land Processes Distributed Active Archive Center that was generated from 2000-2001 MODIS/Terra observations (Friedl *et al.* 2002) and was made available in the 17-class International Geosphere-Biosphere Programme (IGBP) global vegetation classification scheme. The land cover dataset was then clipped to the simulation model domain (Figure 2). The IGBP classification was then reclassified to the 20-class Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson *et al.* 1993) to support regional climate modeling of the study area (see below).

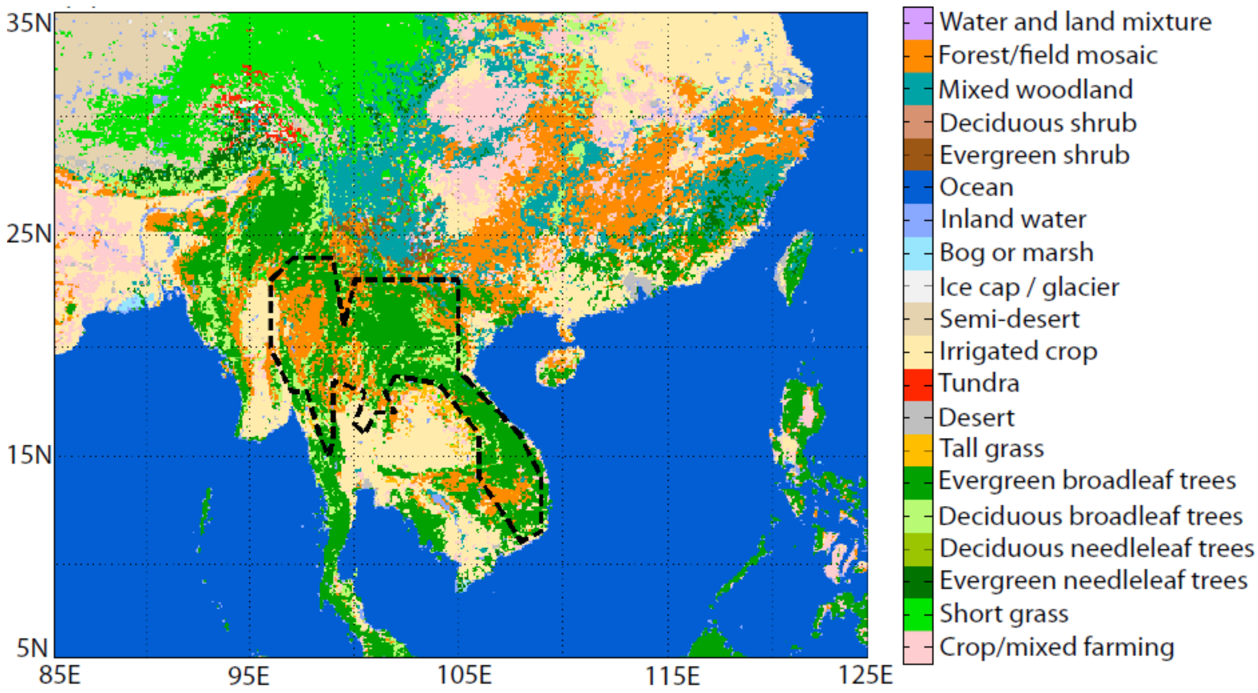

Figure 2. Domain and baseline land-cover for climate and land-cover/land-use change simulations. Montane Mainland SE Asia (outlined) refers to lands higher than 300m within the greater modeling domain, below 24ºN. The climate simulations used the entire domain , because the high elevation land mass are important for simulating climate on the SE Asia peninsula.

In recognizing the countries in MMSEA have unique social, political, and economic histories that influence land-cover change trajectories, we developed separate models for the portion of each, allowing independent simulation of land-cover changes (Fox et al., 2012). Model inputs included data related to (a) land-cover demands; (b) location suitability; and (c) conversion characteristics and restrictions. Land-cover demands refer to the aggregate area occupied by each land-cover type at an annual time step. These demands were based on country-specific expert predictions. Estimates were derived using a non-spatial, scenario-driven approach that involved consideration of four scenarios of change (Lebel et al., 2006): (i) Plantation economy scenario; (ii) Parks and conservation scenario; (iii) traditional agroecosystem scenario; and (iv) diverse agroecosystem scenario.

Land-cover spatial allocation is an automated, iterative process in CLUE-s that attempts to generate a spatial land cover pattern that best satisfies the annual land-cover demands (scenario-based) for a given simulation year. Up to 20,000 iterations are allowed for any given simulation year to reach a satisfactory solution. Land-cover demand values by themselves are non-spatial, and thus the spatial patterns are driven and shaped by the combination of land-cover location suitability at the grid cell level, allowable land-cover transitions and cover type elasticities, and geographic restrictions (as described above). We performed multiple 50-year land-cover simulation runs per country domain, tested sensitivity of input parameters, and evaluated resulting land-cover patterns against country domain scenario demands. In the end, we selected the simulation having overall land-cover patterns that most accurately reflected the plausible scenarios envisioned by the experts.

2.2.3 Climate simulations for MMSEA

The regional climate model (RegCM3) of the International Centre for Theoretical Physics is a primitive equation, hydrostatic, compressible, limited-area model that employs a sigma-pressure vertical coordinate system (Pal et al. 2007). RegCM3 includes the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993) soil-vegetation-atmosphere model, the non-local boundary layer scheme of Holtslag et al. (1990), the radiative transfer package of the Community Climate Model (CCM3; Kiehl et al. 1996), the ocean surface flux parameterization of Zeng et al. (1998), a simplified version of the explicit moisture scheme of Hsie et al. (1984), and a large-scale cloud and precipitation scheme that accounts for subgrid-scale cloud variability (Pal et al. 2000). We used the cumulus cloud scheme of Grell (1993). The model employs a mosaic-type parameterization of subgrid-scale heterogeneity in topography and land use (Giorgi et al. 2003).

The modeling experiment to investigate climatic effects of LCLU change in MMSEA included control simulations with a 2001 MMSEA baseline LCLU and sensitivity simulations with projected LCLU in MMSEA for year 2050 (Fox et al., 2012). Each set consists of multi-year simulations performed over the wet periods (between April 15 and October 30) of the years from 1998 to 2002. All analyses are based on the (5-year) averages of the simulation outputs. The model was run at two different spatial resolutions: 27.79 km for the atmosphere; 9.26 km for the land surface. Thus, one atmospheric grid is coupled to 9 land surface grids, thereby increasing the representativeness of the fine-scale land-surface parameterization. Spatially, 201x171 grid cells were defined for the atmosphere; 603x513 grid cells for the land surface. Eighteen sigma levels represented the atmosphere vertically.

For the baseline land-surface cover we replaced model default land cover (based on AVHRR 1992-93 observations) with MODIS 2001 observations, available in the International Geosphere-Biosphere Programme (IGBP) LCLU classification scheme, into the BATS classification scheme. This required up-scaling 0.00833-degree (~0.926 km) MODIS data to a 0.0833-degree (~9.26 km) resolution using the dominant cover approach (model default), then translating IGBP classes to BATS classes. In some cases AVHRR observations were needed to reassign the classes (e.g., to convert from the IGBP grass class to either the tall or short grass BATS classes). The resulting BATS LCLU map was used in the control simulation.

In the second set of simulations, land-cover was based on projected 2050 MMSEA LCLU map, determined by Fox et al. (2012) using an agent-based model. Using the same rules described above to obtain a baseline BATS LCLU map, their LCLU change simulations were based on historical LCLU transitions and expert knowledge of probable trajectories of change in the region (Fox et al., 2012). The simulations forecast a 16% change in baseline vegetation (summarized above). For the extreme scenario experiments, we replaced the MMSEA LCLU with two BATS classes, irrigated crop and short grass.

2.2 Ping river (Thailand)

2.2.1 Site description

Originating within the mountainous areas of Northern Thailand with steep hills rising to an elevation of 2000 metres with valleys below 500 metres, the Ping River drains an area of 6355 km^2 at the P1 gauging location in Chiang Mai (18◦47'09", 99◦00'29") (Figure 3). The width of the river at Chiang Mai is approximately 110m; and the floodplain extends about 15 km on either side of the river bank (Wood & Ziegler, 2008). The river basin is underlain by older paleozoic gneissic granites, Paleozoic sediments and volcanics, Mesozoic granitic rocks and Tertiary continental basin-fill sediments (Wood & Ziegler, 2008).

The catchment was previously covered by subtropical forests that have been slowly converted to agricultural lands in the recent past due to a host of economic, social and political drivers that have commonly been driving land-cover/land-use changes through montane mainland SE Asia (cf. Fox et al., 2012). The Indochina Peninsular saw the most dramatic forest loss from 1973 to 1985, with Thailand experiencing the highest rates of deforestation (Sen et al., 2004). Ongsomwang and Rattanasuwan (2009) found that forest cover in Thailand reduced from 53% to 32% from 1961 to 2005. Deforestation rates only stabilised after the logging ban in 1989. The current landscape in northern Thailand consists of a mosaic of fragmented forest covers interspersed with agricultural and peri-urban areas

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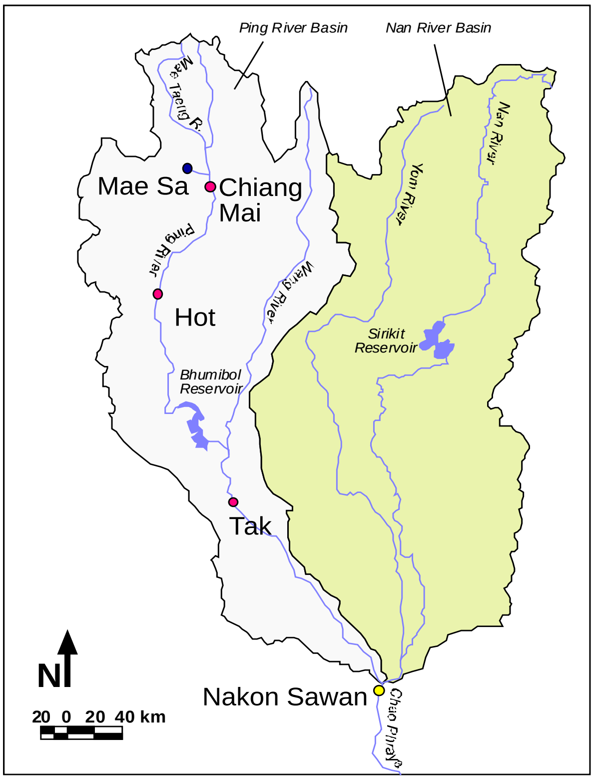

Figure 3. Ping River basin in northern Thailand is one of two large tributaries to the Chao Phraya river. River discharge is measured at the P1 station in Chiang Mai. The Mae Sa Experimental Catchment is a tributary to the Ping (Figure 4), located about 30 km NW of Chiang Mai. The Mae Sa and Ping Rivers are two of the primary research sites in this investigation.

2.2.2 Streamflow analyses

To better understand the anthropogenic versus natural drivers on high and low flows in the Ping river catchment we used examined daily streamflow data, collected between 1921 and 2009 at the P1 gauging station. The following variables were considered: annual peak discharge; annual minimum discharge; total annual discharge; wet-season and dry-season discharge. We also considered the following climate variables that modify or amplify river flows: total annual, wet-season, and dry season rainfall; one- and seven-day maximum rainfall depths; number of rain days in a year; duration of monsoon season; tropical storm frequency; occurrence of ENSO events. Finally the following anthropogenic activities related to stream discharge were considered: landcover/landuse change between 1973 and 2005; and development activity including urbanization, road building, and dam building.

Streamflow and climate data were obtained from the Royal Irrigation Department and the Thai Meteorological Department. The data span from 1921 to 2009 with the exception of length of monsoon season and tropical storm frequency, which are only available from 1951 to 2009. Discharge was collected using a water level recorder which provides continuous stage readings. The stage values were converted to daily discharge values using a rating curve that is updated every year. We analyzed the data with reference to the Thai water year, which starts from April and ends in March the following year. The wet season is defined as extending from April to November. This period covers the annual variability in the onset and withdrawal of the monsoon.

2.3 Mae Sa Experimental Catchment (Thailand)

2.3.1 Site description

In 2004 we initiated a hydro-climatic monitoring program in the 74.16 km_2 Mae Sa Experimental Catchment (MSEC), which is located in Chiang Mai province of northern Thailand (Figures 1,4). The Mae Sa River is a headwater tributary to the Ping River (Figure 3).

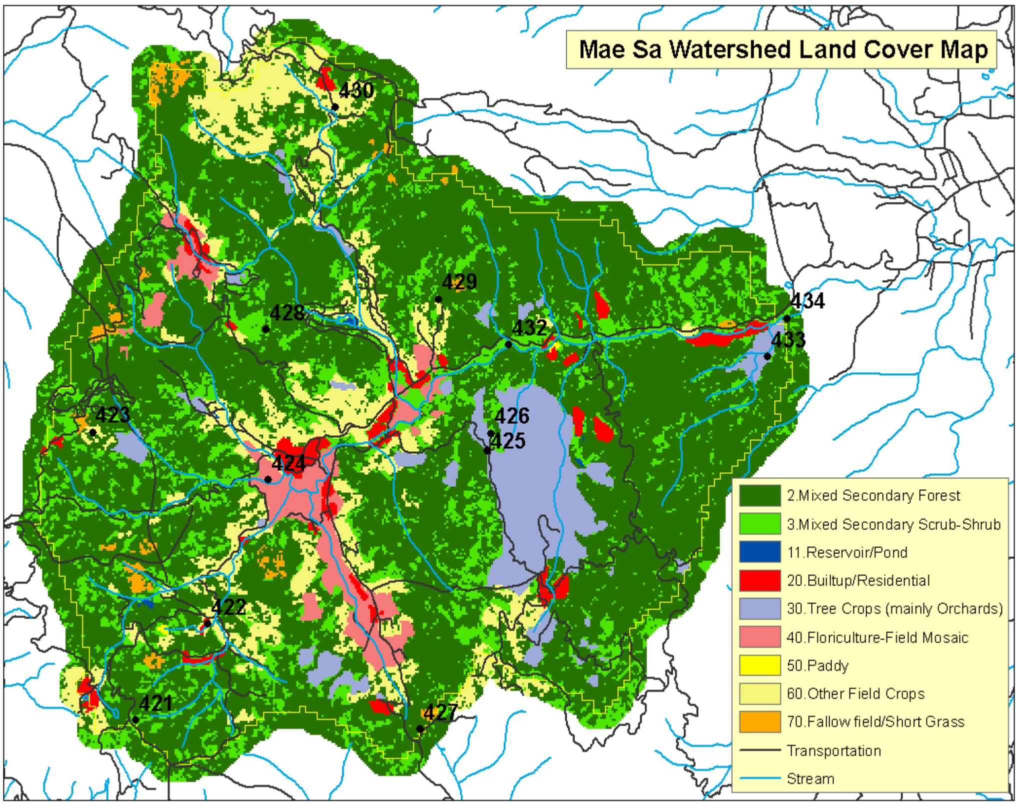

Fig. 4 Mae Sa Experimental Catchment (MSEC) study area in northern Thailand (see Figure 1,3). Streamflow is monitored at one location (434); energy flux variables for estimating evapotranspiration at three locations (421, 429, 433); soil moisture at six locations (421, 423, 425, 428, 429, 433); and rainfall at eleven locations (all but 425 and 434). Adapted from Ziegler et al (submitted).

Land-cover is representative of that now found elsewhere in developing upland areas surrounding major population centers in northern Thailand. Mixed secondary forest (62%) and scrubland (16%) comprise most of the catchment area (Figure 4). However, almost 20% is now dedicated to various types of agriculture, including tree crops, floriculture, and cultivated row crops such as cabbage. An increasing amount of agriculture land is being converted to greenhouse production systems, which provide high-value cash crops to lowland urban centers. In addition, approximately ten villages scattered throughout the basin play a complex role in terms of water management and agricultural impacts in the catchment.

Over the last decade much of the catchment has become peri-urbanized. Several tourist sites, including elephant trekking camps, resorts, and a botanical garden, are prominent points of interest in the catchment. Encroachment on the river bank and surrounding flood plane has occurred with land-use intensification. Mean rainfall in MSEC varies from 1500-2000 mm across an elevation range of 500-1300 m. Granite and gneiss are the dominant rock types in the catchment, which also contains a large vein of marble crossing the mid section, and pockets of fresh-water limestone. Soils orders include Ultisols, Alfisols, and Inceptisols. Stream water color varies from orange to reddish-brown during runoff events, owing to the transport of clay material that is associated with eroded iron-rich horizons of the tropical residual soils that dominate the region. Erosion rates as high as 80 Mg ha^{-1} y^{-1} have been reported for some steep cultivated fields.

2.3.2 River sampling

A hybrid approach using automated turbidity and manual sediment sampling was implemented to develop a continuous signal of total suspended solids (TSS) in the Mae Sa River. Minutely rainfall was recorded with tipping-bucket rain gages [Onset; 20-cm catch area] at 11 measurement locations in the basin. Each gage, initialized at 0.254 mm tip^{-1}, was dynamically calibrated to account for variable tipping rates associated with highly variable rainfall rates in the region. Stream stage was measured automatically in an unmodified cross-section of the main channel with a pressure transducer and data logger [Campbell Scientific; models CS 425 & CR10x] (Station 434; Figure 4). A stage-discharge rating curve was determined from 56 stage-velocity-profile measurements made during flow volumes ranging from 0.3–30 m^3 s^{-1}. The streambed profile was monitored continuously to correct for stage-discharge relationships variations related to changes in the stream bed.

Turbidity in fresh water is caused by the presence of suspended and dissolved matter, such as clay, silt, fine organic matter, and other microscopic organisms, organic acids, and dyes. Instruments capable of measuring turbidity are useful in providing proxy data for sediment concentrations. We used a factory-calibrated, self-cleaning [infrared, 90º optics] Analite (McVann Instruments, Australia) NEP-395 turbidity probe to register a continuous turbidity signal in nephelometric turbidity units (NTU). The probe was calibrated to a range of 0 to 3000 NTU; recalibration was performed annually. To facilitate graphing and non-linear curve fitting, zero values registered by the probe were set to 1 NTU. The probe was housed inside a perforated PVC pipe (7.6 cm diameter), which was suspended from a walking bridge (Figure 5). This cantilever system allowed the probe to "float" in the water column, approximately 10-20 cm below the water surface for all flow ranges. Turbidity readings were recorded by the data logger every 20-min and also at times when stream stage changed by a 0.5-cm increment (often minutely during runoff events). Each recorded value was the median of several readings taken over a period of about 45 seconds.

Total suspended solid samples were collected from the stream bank near the location of the turbidity probe in 20-l buckets during runoff events during the wet seasons of 2006, 2007, and 2008. Large samples were collected to ensure sample material for grain size determination. Additional samples were collected during baseflow conditions and/or at other arbitrary times. Sampling was geared toward collecting samples that corresponded to various stages of the rising and falling limbs of the storm hydrographs in anticipation that a hysteresis effect would exist in the Q-TSS relationship. We also used changes [e.g., increases/decreases of 50-100%] in the turbidity signal to determine sampling times.

Figure 5. River sampling in MSEC. (A) Collection of high concentration sediment with depth-integrated sampler; (B) Filtering samples through 0.7um filters; (C) wet sieving large fractions in 20-l samples; and (D) automated turbidity probe installed in cantilever suspended from the bridge (From Ziegler et al,. submitted).

The 2006 and 2007 TSS samples were partitioned into fine (<63 µm), medium (63-2000 µm) and coarse (> 2000 µm) grain size fractions by wet sieving 20-l grab samples (Figure 5). Three 250-ml sub-samples passing through the 63-µm sieve were individually filtered through 47-mm, pre-ashed, pre-weighed, 0.7-µm Whatman GF/F glass filters. All filtered and sieved samples were oven-dried at 105ºC to a constant mass before determining concentrations. The fine suspended solid fraction was calculated as the mean of three replicates. Thus, the $TSS_{<63\mu m}$ fraction is operationally defined as material between 0.7 and 63µm. Total suspended solid concentration was calculated as the sum of the concentrations of all fractions ($TSS = TSS_{<63\ \mu m} + TSS_{63\text{-}2000\ \mu m} + TSS_{>2000\ \mu m}$).

We also attempted to measure bedload using a Helley-Smith sampler during several low-energy events. Internal dimensions of the sampler intake were 7.62cm x 7.62cm. A standard 0.2-mm mesh collection bag with surface area = 1950 cm^2 was used. During each sampling interval, the sampler was placed on the sand bed at 1-m intervals across the stream for one minute. Thus, each sample was the aggregate of 5-7 sub-samples (more sub-samples were taken as the stream width increased during higher stages). For consistency, the same sampling locations, which were identified by a measuring tape spanning the river, were used for all measurements. This location was approximately 20-m up river from the TSS measurement location. Samples were dried to a constant mass at 50°C in the laboratory. Total mass of material for the entire cross section was computed by increasing the sample mass by the proportional difference between the cross-section width and the width of the sampler multiplied by the number of sub-samples. Bedload transport rate was then calculated by dividing by the total discharge during the collection of the sub-samples.

Analysis for total carbon and nitrogen concentration was conducted by dry combustion using a Thermo Flash EA 1112 Elemental Analyzer. Analysis standardization was based upon aspartic acid standards; this material was analyzed as an internal standard. Laboratory replicates, both between runs and during runs, quantified instrument drift. Organic/inorganic fractionation was performed by pre-treating several representative samples with 2-3 drops of concentrated HCl or H_3PO_4 (NRCS, 2004). Samples were then allowed to air dry in a fume hood until effervescence ceased. After effervescence, samples were re-dried in an oven at 105°C and the organic carbon fraction determined using the Thermo Flash EA 1112 Elemental Analyzer. Inorganic carbon content was then calculated by the difference between total carbon and the organic carbon fraction determined after the HCl/ H_3PO_4 treatment.

Correlative relationships between observed stream flow (Q), turbidity, and total suspended solids (TSS) and measured total suspended C and N were evaluated using both linear and non-linear regression analysis. The resulting relationships between discharge, turbidity and TSS were then used to estimate TSS, C and N flux rates. When modeling C and N flux rates from turbidity measurements, observed turbidity values measured over that time period were used. When modeling C and N flux rates based on TSS values, the input TSS data were synthetically generated using multiple regression analysis linking observed sediment loads with measured turbidity and water flux values (Ziegler et al, forthcoming).

2.4 The Longchuan river (China)

2.4.1 Site description

The Longchuan river was the site of monitoring stream discharge, and suspended sediment, and geochemistry in China. The river originates from Nanhua County and joins the lower Jinshajiang, a tributary of the upper Changjiang river (Figure 6). The river is 231-km in length and covers an area of 5560 km^2 (24°45′N - 26°15′N and 100°56′E - 102°02′E). The 1788 km^2 upper catchment (upper the Xiaohekou station) has a sub-tropic monsoon climate, characterized by annual mean temperature of 15.6 ºC; annual rainfall amount is 825 mm, with more than 80% of the annual total occurring in the rainy season from May to October. Elevation varies from 700 to 3000 m a.s.l. The area is dominated by purple soil, which is very susceptible to water erosion and weathering. However, erosion has been accelerated by growing populations and economic growth, which have contributed to deforestation (in earlier times), intensified agriculture activity, reservoir building, stone excavation and road construction. Also, there are several counties (Nanhua and Chuxiong) along the riverine network, where industrial and domestic wastes discharge directly to the upper River. Chuxiong County, adjacent to the sampling location, has large impacts on water quality.

2.4.2 River sampling

Daily water discharge and monthly precipitation from January 2007 to March 2009 were recorded at the Xiaohekou discharge gauging station located in the Chuxiong County (Figure 6). Water samples for chemical analysis were collected once a month (on 9-15th each month) over a 19-month period (September 2007 to March 2009) using the same mechanized pulley system employed by the station workers to determine the discharge rating curve. Mixed samples were collected in the center of the river from a water depth of 50 cm in acid-washed 5-L high density polyethylene (HDPE) containers. Total suspended solid (TSS) concentration was determined by filtering through pre-cleaned 0.45-µm pore size Whatman GF/F filters in a plastic tent. Filtrates, used in several geochemical analyses, were acidified to pH < 2 with high purity HNO_3 and preserved in high-density polyethylene bottles (marinate for 24 h in 1:10 HNO_3 acid solution beforehand) in the refrigerator for geochemical analyses in the laboratory.

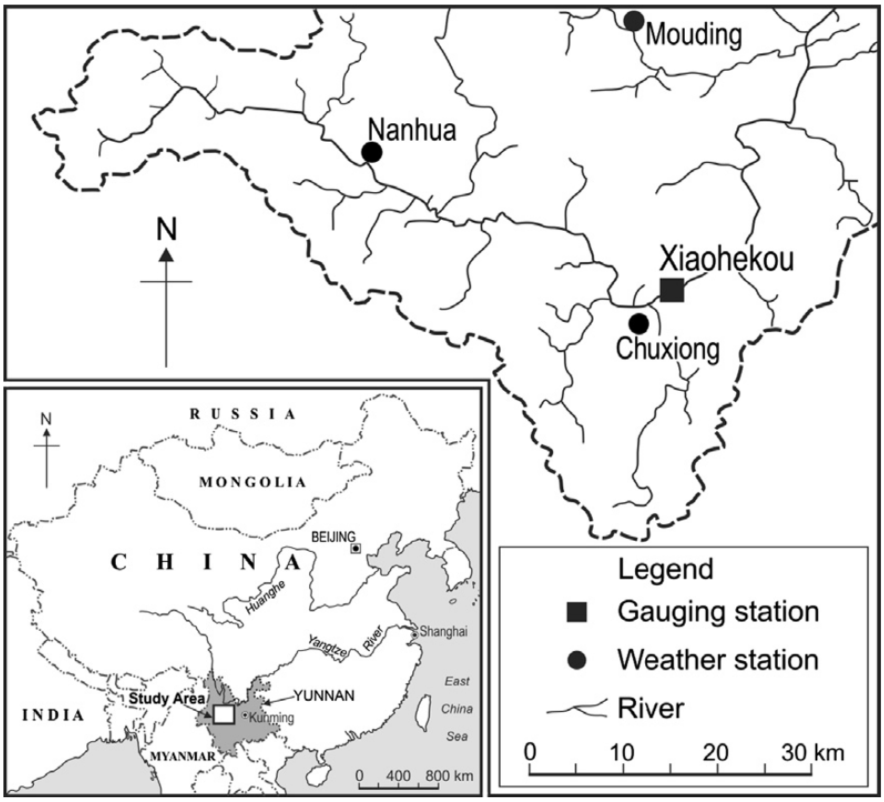

Figure 6. Location map of the Longchuan River with sampling sites and gauge stations, and other Changjiang's tributaries, China (From Li et al, forthcoming).

Determination of pH was performed in situ using an Orion 230A pH/Temp meter, which was calibrated each sampling occasion using pH-7 and pH-10 buffer solutions. Major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and dissolved silica were determined for each of the three replicates by inductively coupled plasma-optical emission spectroscopy. Anions Cl^- and SO_4^{2-} were determined by ion chromatography; HCO_3^- was titrated using 0.025 mol/l hydrochloric acid on the sampling day. Analysis precision was better than ±5%

Dissolved organic carbon (DOC) was measured using a total organic carbon (TOC) analyser (phoenix8000, Tekmar) in the Ailaoshan Forest Ecological Research Station (ASSFERS), Chinese Academy of Sciences. Particulate organic carbon (POC), particulate nitrogen (PN), and C/N ratio were analyzed using a CHN analyzer in the Key Laboratory of Tropic Forest Ecology, Chinese Academy of Sciences. Duplicate samples were run, and the precision was within 5% for C and N. Dissolved inorganic carbon (DIC) was recalculated from HCO_3^- concentration because of the river waters with pH ranging from 7.2 to 8.4, measured using acid titration reported by Li et al. (2011).

Nitrogen and P variables were determined using the ultraviolet-visible spectrophotometric method described by Grasshholf et al (1983) and *Water and Wastewater Monitoring Analysis Methods, China* (CSEPB, 2002). Dissolved nitrogen (DN) was measured with potassium peroxodisulphate oxidation-colorimetry; total phosphorus (TP) and dissolved phosphorus (DP) with ammonium molybdophosphate colorimetry; ammonium-N (NH_4-N) and Nitrate-N (NO_3-N) with Nessler reagent method and UV spectrophotometry. The detection limits for the analysis of NO_3-N, NH_4-N, DN, DP and TP were 0.08 mg/l, 0.02 mg/l, 0.05 mg/l, 0.01 mg/l and 0.01 mg/l, respectively.

2.5 Nam Ken catchment (China)

2.5.1 Site description

The Nam Ken catchment (69 km^2) is located in the Chinese prefecture of Xishuangbanna (22°N, 101°E), next to the Myanmar border (Figure 1). The catchment is within the upper Mekong River basin. Elevation ranges from 800 m to over 2000 m AMSL, and mean annual precipitation and temperature are 1380 mm and 20°C, respectively. Nam Ken is characterized by a monsoon-dominated climate, where most of the precipitation falls between May and October. During the dry season monthly precipitation usually is below 50 mm and often absent. Rubber was introduced at low elevation areas in the late 1970s. With the development of lower temperature resistant clones, rubber has been planted up to 1100m AMSL, covering by 2005 about 16% of the total basin area. Rubber expansion has occurred largely at the expense of swiddening and forest.

2.5.2 Hydro-climatology monitoring

A hydro-meteorological data acquisition network was established from 2004 to 2007. It consisted of two micrometeorological (MET) stations located in rubber and on a tea plantation; and two soil moisture/precipitation (SM/RF) stations (one in mixed grassland and young rubber, and one in secondary forest) (Figure 7). Both MET stations measured hourly four radiation components (incoming shortwave and long wave radiation, reflected shortwave radiation and emitted long wave radiation), wind speed, air temperature, relative humidity, and precipitation above the canopy. Soil heat flux was measured at the soil surface together with soil moisture. Additional soil moisture measurements were taken at 1 and 2 m depth. From the ratio of incoming and reflected shortwave radiation surface (canopy) albedo was derived. Daily albedo values are calculated by averaging the hourly radiation from 10:00 to 14:00 local time and range from 0.12 to 0.25 for the rubber and tea plantation, respectively. The two SM/RF stations recorded hourly soil moisture at three different depths (surface, 1, and 2 m) and precipitation above the canopy.

Figure 7. Instrumentation and various land covers investigated in Nam Ken Catchment: (a) micrometeorological station within a mature rubber plantation; (b) micrometeorological station within a new tea plantation; (c) soil moisture station in a secondary forest; (d) soil moisture station within a mixed grassland and young rubber plantation (From Guardiola-Claramonte et al., 2006).

3. Results and Discussion

3.1 Impacts of land-cover/land-use change on climate

Results of the CLUE-s model simulations of land-cover change in Montane Mainland Southeast Asia predicted that change would occur in approximately 16% of the MMSEA landscape between 2001 and 2050 (Figure 8; Fox et al., 2012). The greatest change (23%) was predicted for Yunnan Province, China; the least, Myanmar (10%). Change for Cambodia, Laos, Thailand and Vietnam ranged from 14-23%. Roughly 9% of the current vegetation, which consists of native species of trees, shrubs, and grasses, was predicted to be replaced by tree plantations, tea, and other evergreen shrubs during the 50-year period. Importantly, 4% of this change was predicted to be the expansion of rubber, a tree plantation crop that may have important implications for local-to-regional scale hydrology because of potentially high water use in the dry season (Ziegler et al., 2009a).

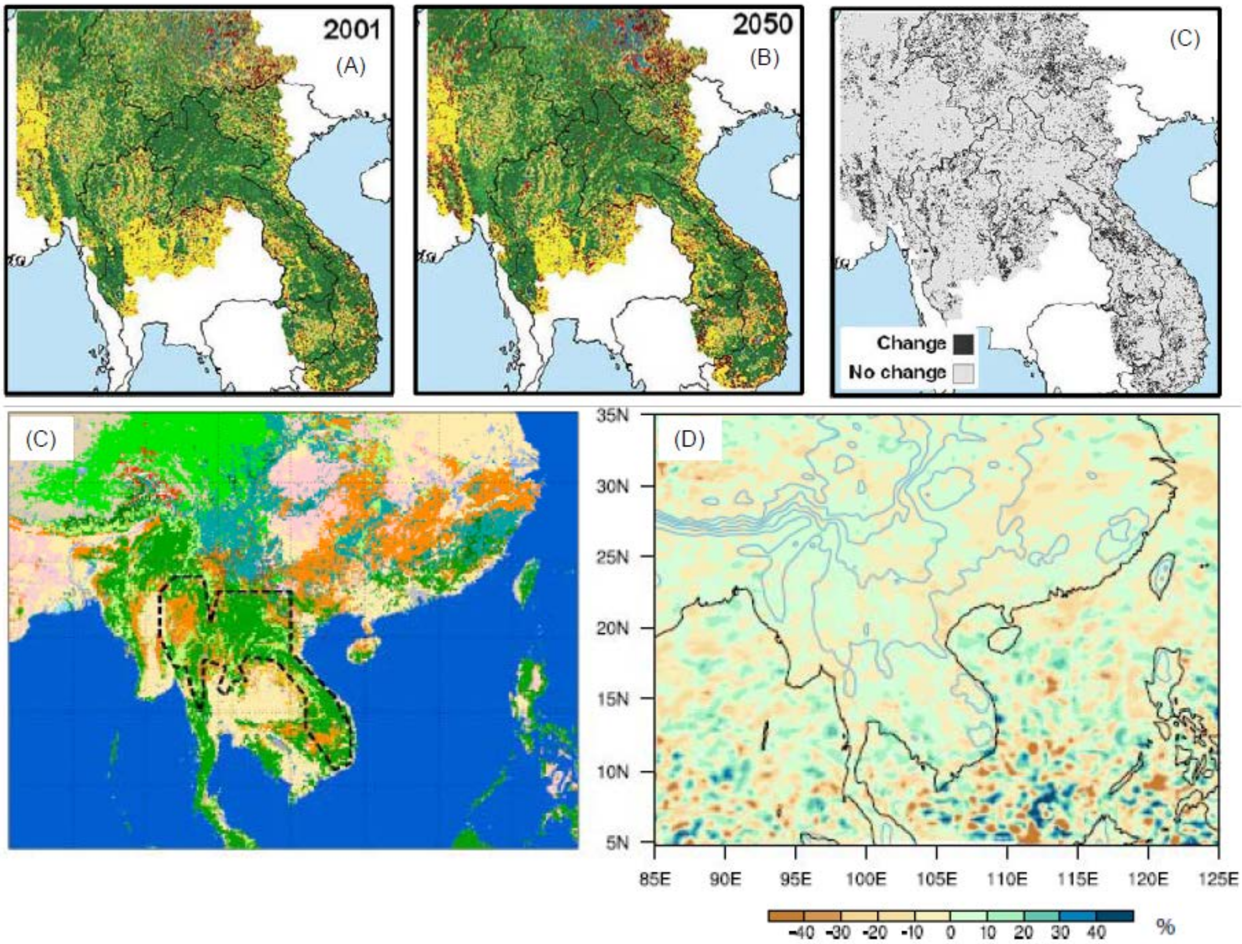

Figure 8. (A) Baseline land-cover map for year 2001; (B) CLUE-s land-cover simulation output map for 2050; (C) map highlighting areas of change/no change in LCLU for 2001–2050 simulation periods; (D) maps (at 9.26 km resolution) of projected 2050 land cover (used in climate simulations); and (E) relative change (%) in monsoon (June-August) precipitation caused by the predicted 2050 land-cover change (panel D). Most areas for large predicted precipitation change occur in the South China Sea and over the Indian Ocean. Simulated precipitation changes over land-areas of mainland SE Asia are generally only ±10% (Adapted from Fox et al., 2012; Sen et al., forthcoming).

In the climate simulations, Reg3CM climate simulations yield different responses to different LCLU scenarios. When LCLU was replaced with the results from the CLUE-s simulation (Fox et al 2012), results showed little change in the hydrometeorology of the region (Figure 8). However, when present LCLU was replaced with “irrigated crop”, precipitation slightly increased in the Indochina Peninsula, substantially decreased in southeastern China, and increased significantly in the South China Sea. When present LCLU was replaced with “short grass”, precipitation substantially decreased in MMSEA, but changed little elsewhere. These results suggest that the effects of increasing CO_2 will probably have a greater impact on precipitation than the predicted 16.4% changes in land cover in the region. The analysis demonstrates that much of the uncertainty regarding the hydrological impacts of tropical deforestation stems from a failure to develop and use realistic LCLU projections in climate simulations. The results clearly demonstrate the need to integrate realistic LCLUC simulations based on expert opinion with climate change simulations.

3.2 Hydrological Impacts of rubber

We investigated the hydrologic implications of land use conversion from native vegetation to rubber in the 69-km^2 Nam Ken experimental catchment. Observations show that root water uptake of rubber during the dry season is controlled by day-length, whereas water demand of native vegetation starts with the arrival of the first monsoon rainfall. The different dynamics of root water uptake in rubber result in distinct depletion of soil moisture in deeper layers (Figure 9). Traditional evapotranspiration and soil moisture models are unable to simulate this specific behavior (Guardiola-Claramonte et al., 2008).

We developed a new method for estimating the water losses to the atmosphere through rubber evapotranspiration (ET). The method is based on the premise that rubber ET is energy-limited during the wet season, but during the dry season water consumption is mostly governed by environmental variables that directly affect rubber phenology, namely, vapour pressure deficit, temperature and photoperiodicity. When the new ET model was introduced into a hillslope-based hydrologic model to predict the basin-scale hydrologic consequences of rubber replacing native vegetation, simulations suggested greater annual catchment water losses through ET from rubber dominated landscapes compared to traditional vegetation cover. This additional water use reduces discharge from the basin, or its storage. These reductions could in some cases contribute to water shortages in the dry season (Guardiola-Claramonte et al., 2010).

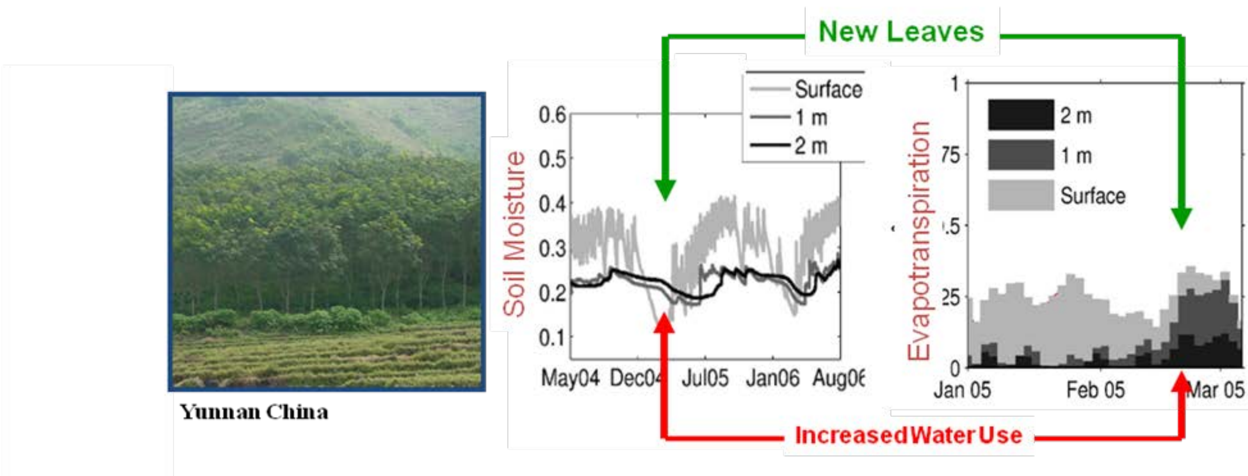

Figure 9. Observations showed a distinct increase in water use (inferred from drop in soil moisture) corresponding with the flushing of new leafs in the dry season. (After Guardiola-Claramonte et al., 2006; 2008).

3.3 Environmental consequences of agriculture intensification

During field investigations we observed rapid conversion away from swidden agriculture to more intensified systems, including semi-permanent and permanent cash cropping systems, monoculture plantations, and greenhouse complexes. Teaming with other researchers working on this issue, and drawing from prior works in Myanmar, Thailand, and Vietnam (Sidle et al., 2007; Ziegler et al., 2006, 2007a,b), we assessed the hydro-geomorphological impacts of the demise in swidden agriculture (Ziegler et al., 2009b; Brunn et al, 2009; Ziegler et al, 2012).

3.3.1 Hydro-geomorphological effects

The hydrological and geomorphological impacts of traditional swidden cultivation in Montane Mainland Southeast Asia were often small when compared with intensified replacement agricultural systems (Ziegler et al., 2009b). The negative impacts associated with intensified systems include changes in streamflow response, increased surface erosion, a higher probability of landslides, and the declination in stream water quality. Unlike the case for traditional swiddening, these impacts result because of several factors: (1) large portions of upland catchments are cultivated simultaneously; (2) accelerated hydraulic and tillage erosion occurs on plots that are cultivated repetitively with limited or no fallowing to allow recovery of key soil properties, including infiltration; (3) concentrated overland flow and erosion sources are often directly connected with the stream network; (4) root strength is reduced on permanently converted hillslopes; (5) surface and ground water extraction is frequently used for irrigation; and (6) and pesticides and herbicides are used. Furthermore, the commercial success of these systems relies on the existence of dense networks of roads, which are linear landscape features renowned for disrupting hydrological and geomorphological systems (Sidle and Ziegler, 2012).

3.3.1 Changes in Carbon stocks

Time-averaged aboveground carbon stocks decline by about 90% if the long fallow periods of traditional swidden cultivation are reduced to 4 years and by about 60% if swidden cultivation is converted to oil palm plantations (Bruun et al., 2009). Stocks of soil organic carbon (SOC) in tree plantations are 0–40% lower than stocks in swidden cultivation, with the largest losses found in mechanically established oil palm plantations. Impacts of tree plantations on soil quality are to a large extent determined by management. Conversion of swiddening to continuous annual cropping systems brings about substantial losses of time-averaged above-ground carbon stocks, reductions of SOC stocks and generally leads to declining soil quality.

Meta-analysis of over 250 studies reporting above- and below-ground carbon estimates for different land-use types indicates great uncertainty in the net total ecosystem carbon changes that can be expected from many transitions, including the replacement of various types of swidden agriculture with oil palm, rubber, or some other types of agroforestry systems. These transitions are underway throughout Southeast Asia, and are at the heart of REDD+ debates. Exceptions of unambiguous carbon outcomes are the abandonment of any type of agriculture to allow forest generation (a certain positive carbon outcome) and expansion of agriculture into mature forest (a certain negative carbon outcome). With respect to swiddening, our meta-analysis supports a reassessment of policies that encourage land-cover conversion away from these [especially long-fallow] systems to other more cash-crop-oriented systems producing ambiguous carbon stock changes – including oil palm and rubber. In some instances, lengthening fallow periods of an existing swidden system may produce substantial carbon benefits, as would conversion from intensely cultivated lands to high-biomass plantations and some other types of agroforestry.

3.4 Sediment and nutrient dynamics in Mae Sa River

Annual total suspended solid (TSS) loads in the Mae Sa River in northern Thailand were 62,000, 33,000, and 14,000 Mg during the three years of observation. Annual rainfall varied from 1632 to 1934mm; and catchment runoff coefficients (Q/rainfall) ranged from 0.25 to 0.41. Measured total suspended solid values ranged from about 5-16000 mg l^{-1}; the former was associated with dry-season base flow; the latter, a wet-season storm. Storm size and location played a role in producing clockwise, anticlockwise, and complex hysteresis effects in the Q-TSS relationship. Owing to hysteresis and high sediment concentrations that surpass the detection limits of the turbidity sensor during many annual storms, TSS was predicted best using a complex multiple regression equation based on high/low ranges of turbidity and Q as independent variables.

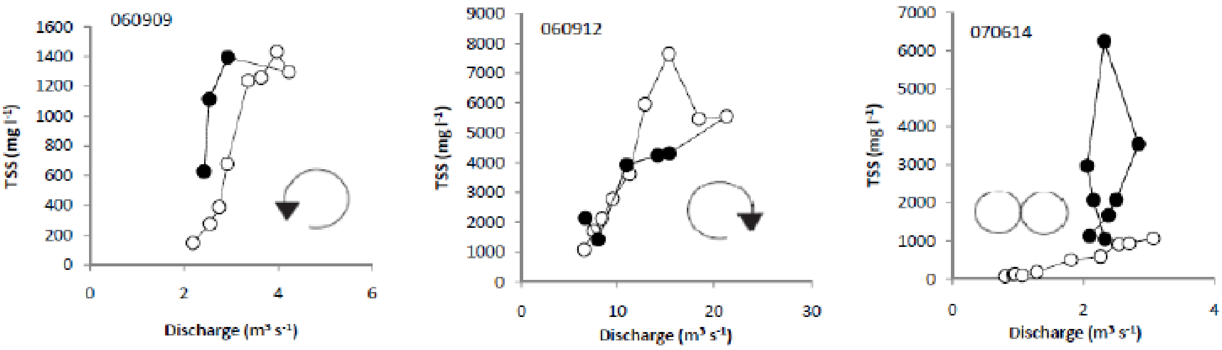

Figure 10. Various types of hysteresis in the discharge-TSS (total suspended solids) relationship were observed: anti-clockwise, clockwise, and figure eight, respectively (left to right). Labels refer to sampling dates (From Ziegler et al., submitted).

An estimated 65%, 34%, and 1% of the material transported was <63 µm, 63-2000 µm, and > 2000 µm, respectively, but inter-storm variability was high. Estimated annual TSS loads for the three years were equivalent to basin yields of 839, 445, and 192 Mg ha^{-1} for the 74.16-km^2 catchment. The high variability in sediment loads and yield is in part related to the depletion of fine sand and smaller sediment fractions over time following several road-related landslides in 2005 (Figure 11). The decrease was also attributed simply to a decrease in the transport of eroded material into and through the stream during the latter two drier years. Hysteresis in the monthly Q-TSS relationship was generally clockwise over the course of the monsoon season. Some high loads in the dry season were caused by large early storms flushing sediment stored within or near the channel, as well as bank erosion and construction in the channel. A novel means of improving turbidity-based sediment concentration estimates based on unique turbidity/sediment relationships associated with spatial differences of storm rainfall is proposed.

Only a handful of steam bedload experiments have been performed in SE Asia, most in Malaysia. To our knowledge, the experiments at Mae Sa represent the only published combined TSS and bedload data for a stream in Thailand. Estimated bedload for 15 low-energy events (i.e., Q < 7 m^3 s^{-1}) typically comprised 5-15% of the total load. The mean flow-weighted bedload contribution was 12% for the 15 low-energy events. Unfortunately, we were not able to perform reliable annual bedload calculations for the large river, because our sampling strategy (Helley-Smith sampler) could not be used during large runoff events.

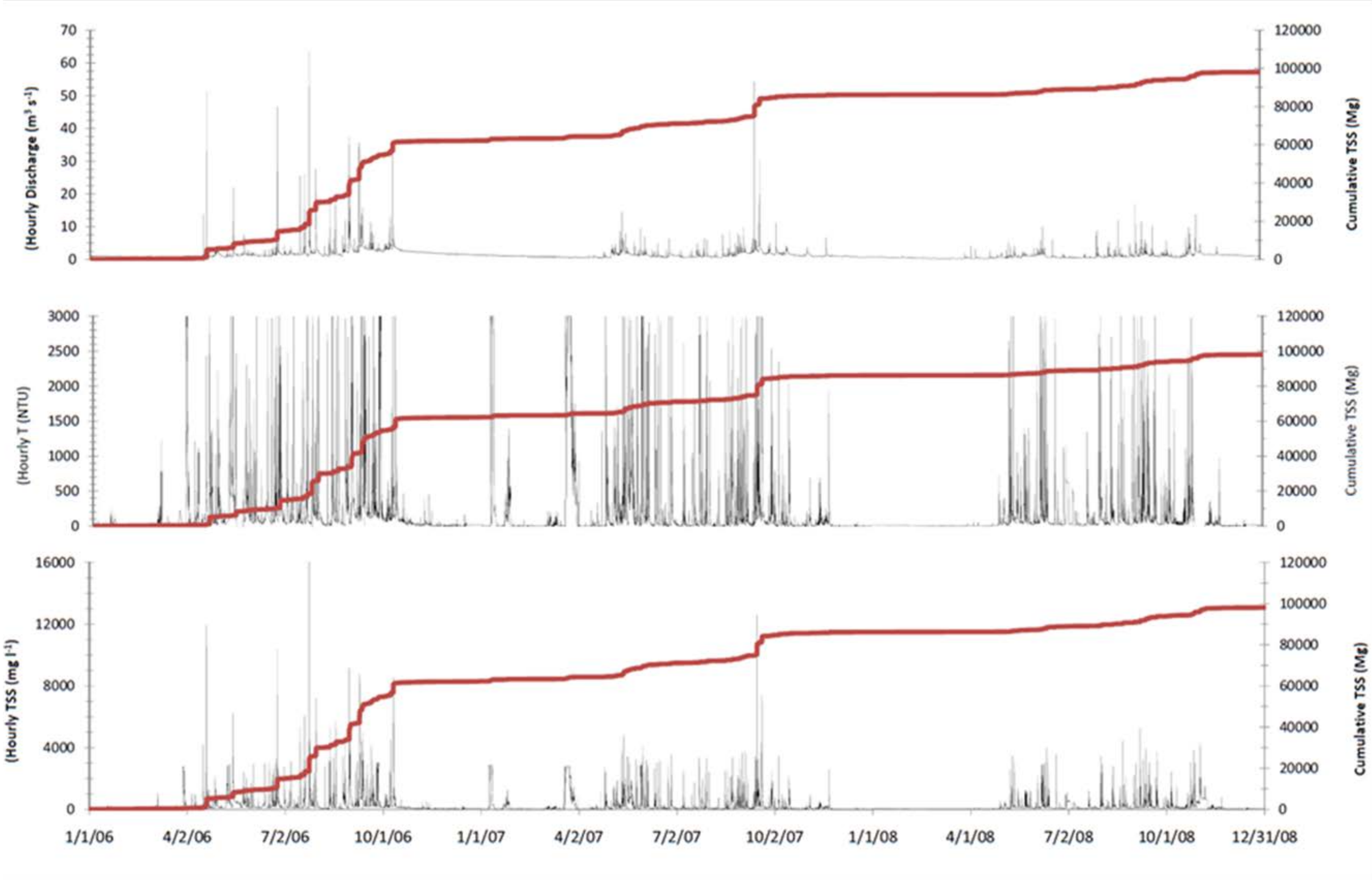

Figure 11. Cumulative total suspended solid (TSS) loads (thick red line), hourly discharge, turbidity, and total suspended solids (TSS) for the three-year period 2006-2008 in Mae Sa catchment. Substantially more TSS was transported in 2005, in part because of higher rainfall and runoff, but also because of the availability of a higher supply of stream sediment resulting from several road-related landslides in the prior year (from Ziegler et al., submitted).

An attempt was made to use multiple geochemical tracers to partition basin stream sediment in the Mae Sa catchment (Ang, 2012). Sediment signatures in nine observed events were distinct for upper and lower catchment sources. Using a mixing model approach employing 12 geochemical tracers we determined that approximately equal portions came from upper and lower basin sources. This result is in contrast to reported cases of accelerated erosion related to agriculture on steep slopes in the upper basin. Variation of sediment signatures over time during the collection campaign suggested changes in sediment provenance, as related to the spatial distribution of rainfall during storms. Active sources of sediment entering the stream included recreation areas, construction sites, and roads. With respect to the latter, road-related landslides occurring in 2005 is believed to nearly triple the annual sediment yield in the river during the following year (Figure 11). Fieldwork at elephant camps revealed the trails leading to grazing/bedding areas located a few km from the camps were chronic sources of overland flow, erosion, and on-site degradation to native vegetation (Sidle and Ziegler, 2009; Song, 2012).

We also documented strong pulse hysteretic behavior, whereby peak fluxes of particulate C and N are delayed relative to stream flow peaks. This behavior makes modeling annual particulate carbon and nitrogen fluxes difficult. While stream flow volume is not a good predictor of particulate C and N concentrations, stream turbidity is a reasonable proxy (e.g., r^2=0.64 for carbon; Figure 12). Total suspended sediment, when known, provides a modest improvement in C and N flux estimates (r^2=0.70). Modeling results indicate MSEC produces some of the highest particulate carbon and nitrogen yields on the south Asia continent; and those yields vary dramatically year to year (8-26 Mg C km^{-2}; 0.7-2.3 Mg N km^{-2} yr^{-1}). The large particulate size fraction (>0.63 um) contributes nearly 30% of the total particulate C and 20% of the particulate N, a much higher fraction than observed in larger rivers. This trend likely reflects debris delivered by overland flow; it also indicates significant carbon transformation during down-river transport. These observations highlight the inner- and inter-annual complexity of C and N particulate flux for smaller streams. Finally, automated turbidity measurements were shown to be highly useful for modeling C and N fluxes in this flashy stream, where hysteresis was prevalent for most variables.

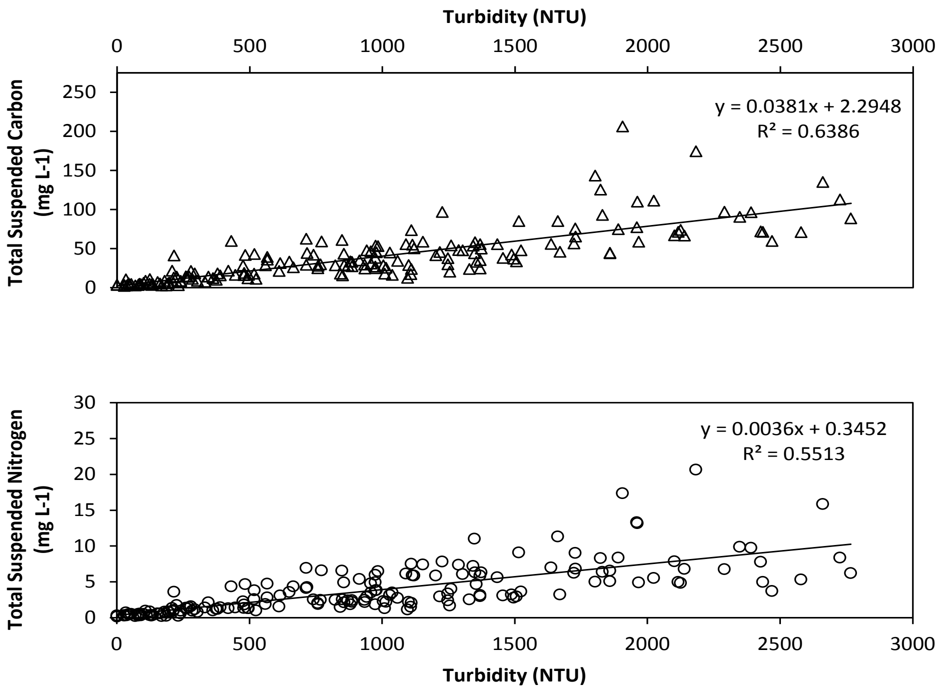

Figure 12. Linear regression provided a reasonable prediction of total suspended carbon and nitrogen from automated turbidity measurements (From Benner et al., submitted).

3.5 Geochemistry of the Longchuan River in China

The contents of particulate organic carbon (POC), total organic carbon (TOC) and total suspended sediment in the Longchuan river changed synchronously with water discharge, whereas the contents of dissolved organic carbon had a small variation. Total suspended solids (TSS) was 2.7 x 10^5 Mg y^{-1} in 2008. The POC concentration in the suspended sediment decreased non-linearly with increasing TSS concentration. Higher molar C/N ratio of particulate organic matter (average 77) revealed that POC was dominated by terrestrially derived organic matter in the high flows and urban wastewaters in the low flows. The specific fluxes of total organic carbon and dissolved inorganic carbon (DIC) were 5.6 and 6 Mg km^{-2} y^{-1} respectively, with more than 90% in the high flow period. A high carbon yield in the catchment of the upper Yangtze was due to human-induced land use alterations and urban wastes. Consistent with most rivers in the monsoon climate regions, the dissolved organic carbon–POC ratio of the export flux was low (0.41) (Figure 13). Twenty-two percent of the annual POC yield (4 Mg km^{-2} y^{-1}) was from autochthonous production; and 78% was from allochthonous production. The annual sediment load and hence the organic carbon flux have been affected by environmental alterations of physical, chemical and hydrological conditions in the past 50 years, demonstrating the impacts of human disturbances on the global and local carbon cycling.

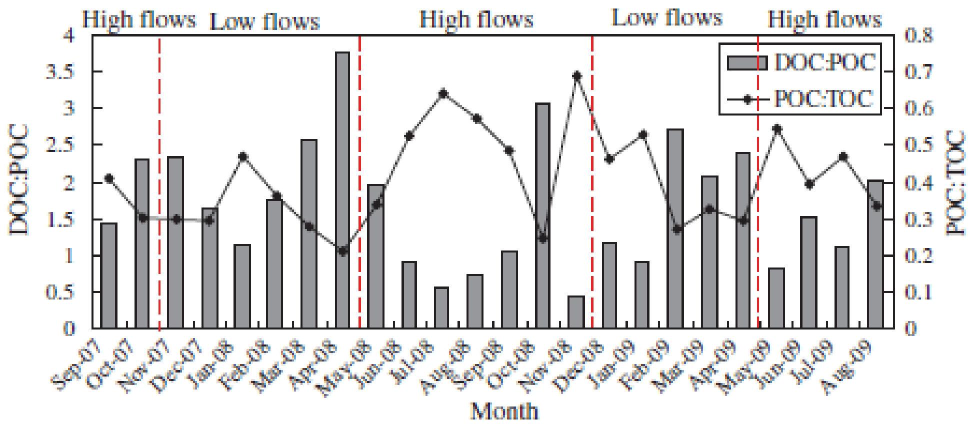

Figure 13: Seasonal changes DOC, POC, and TOC relationships. TOC was largely regulated by POC in the high flow period but by DOC in the low flow period, which was consistent with higher POC/TOC ratio occurred in the high flow period but higher DOC/TOC ratio in the low flow period (From Lu et al., 2012).

Particulate N (PN), dissolved P (DP), particle associated P (PAP) and total P (TP) exhibited great seasonality, as affected by water discharge. Dissolved N and PAP were the major forms of N and P, respectively. The concentrations of total nitrogen (TN), NH_4-N and TP were much higher than water drinking levels and the levels in Changjiang River and its tributaries. Annual nutrient fluxes were largely controlled by runoff with the yields of 428 kg km^{-2} y^{-1} for TN and 604 kg km^{-2} y^{-1} for TP, respectively. The Longchuanjiang produced much lower yields of TN, DN, NO_3-N and DP, but much higher yields of NH_4-N, PN, PAP and TP than the Chanjiang River and its tributaries. This was due in part to the mixing of eroded soils with high concentration of phosphorous during storm events. The atomic ratio of DN:DP was high (41-362), similar to previous studies on the Changjiang River, indicating that P was the potential limitation for phytoplankton growth. As dam building in the upper catchment can drastically decrease PAP and consequently enhance the atomic ratio of TN:TP, P may be a limiting factor for phytoplankton production in the fluvial system in the future.

Sampling undertaken to understand monthly variations in major elements and solute fluxes as related to rock weathering and associated CO_2 consumption rates showed that solute concentrations were 5 times the global median of 65 mg l^{-1}. Total cationic exchange capacity (Tz+) ranged from 2.4 to 6.1 meq l^{-1}; and the mean (4.4 meq l^{-1}) was significantly higher than that of the global river waters. Calcium and bicarbonate dominated the annual ionic composition, accounting for more than 70% of the solute flux that exceeded 71 $\times 10^6$ kg y^{-1}. Lower concentrations of most measured elements during the monsoon high flow period could be explained by dilution effects from precipitation. Three major reservoirs contributed to the dissolved load: carbonates, silicates and anthropogenic inputs—the majority comes from riverine cations from carbonates (>80%). The chemical weathering rate (26.1 Mg km^{-2} y^{-1}), with respective carbonate and silicate weathering rates of 20.3 Mg km^{-2} y^{-1} (8.46 mm ky^{-1}) and 5.75 Mg km^{-2} y^{-1} (2.13 mm ky^{-1}), was comparable to the average for global rivers, but higher than that for the Changjiang River in China.

Partial pressure of CO_2 (pCO_2) levels ranged from 230 to 8300 μatm with an average of 1230 μatm, with obvious daily and seasonal variations. More than 92% of the samples were supersaturated with CO_2 in contrast to the atmospheric equilibrium (380 μatm). The pCO_2 values in the river water in the wet season were relatively low, except in the flooding event in November, due to a dilution effect by heavy rainfall. In contrast, the pCO_2 levels in the dry season were much higher, due to lower pH resulted from anthropogenic activities. Net CO_2 degassing and pCO_2 were strongly correlated with dissolved nitrogen, but weakly with water temperature, dissolved inorganic carbon and water discharge, and uncorrelated with particulate nutrients and biogenic elements. The estimated water-to-air CO_2 degassing flux in the Longchuan river was about 27 mol m^{-2} y^{-1}, with the upper limit of 50 mol m^{-2} y^{-1}. Our study also indicated that among the carbon remobilized from land to water, around 7% (2800 Mg C y^{-1}) of the total carbon was emitted to the atmosphere; 42% (17,000 Mg C y^{-1}) deposited in the river-reservoirs system; and 51% (21,000 Mg C y^{-1}) exported further downstream (Figure 14).

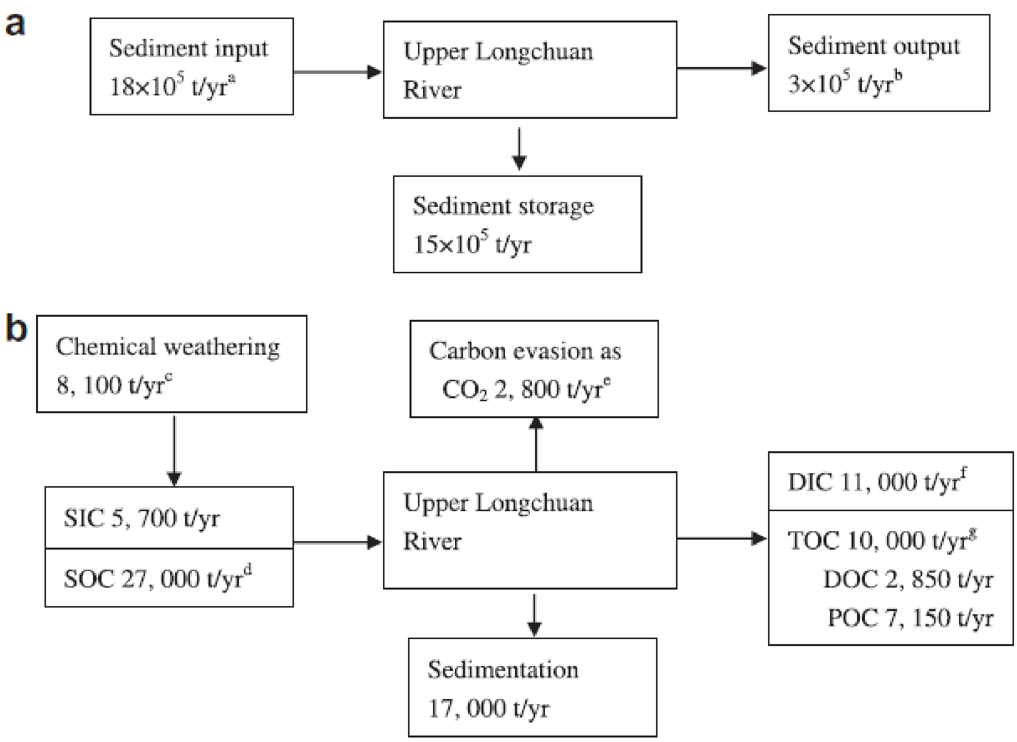

Figure 14. Sediment (a) and carbon (b) budgets for the upper Longchuang River (Li et al, forthcoming). SOC and SIC, refer to soil organic and inorganic carbon.

3.6 Natural versus anthropogenic controls on floods

Analysis of the 89-year Ping river streamflow record (1921-2009) showed that peak flows have not increased significantly since 1921 (Figure 15). However, minimum flows showed a very significant downward trend over the study period (α = 0.01). Both total discharge and wet season discharge show significant downward trends (α = 0.05). All flow variables appear to be more variable now than 90 years ago. As expected, both annual peak and minimum flows are correlated with annual and wet season rainfall totals. Rainfall has not changed over the 89-year period, but increases were observed in maximum one-day values and number of rain days per year (α = 0.05). Minimum flow was also sensitive to the length of the monsoon season and number of rainy days in the previous monsoon season.

Minimum flows are affected more by anthropogenic activities and show a major decline from the mid-1950s. Peak flow activity is driven predominantly by climate phenomena, such as tropical storm activity and monsoon anomalies, but the relationship between peak flows and ENSO phenomena is unclear. In general, annual discharge variables did not correspond unequivocally with El Ninõ or La Ninã events. The plausible intensification of the hydrological cycle that may accompany global warming is of concern because of the potential to affect and tropical storm activity and monsoon anomalies, phenomena that are linked with very high flows in this river. The obvious effect of human activities such as reservoir management on low flows calls for careful management to prevent droughts.

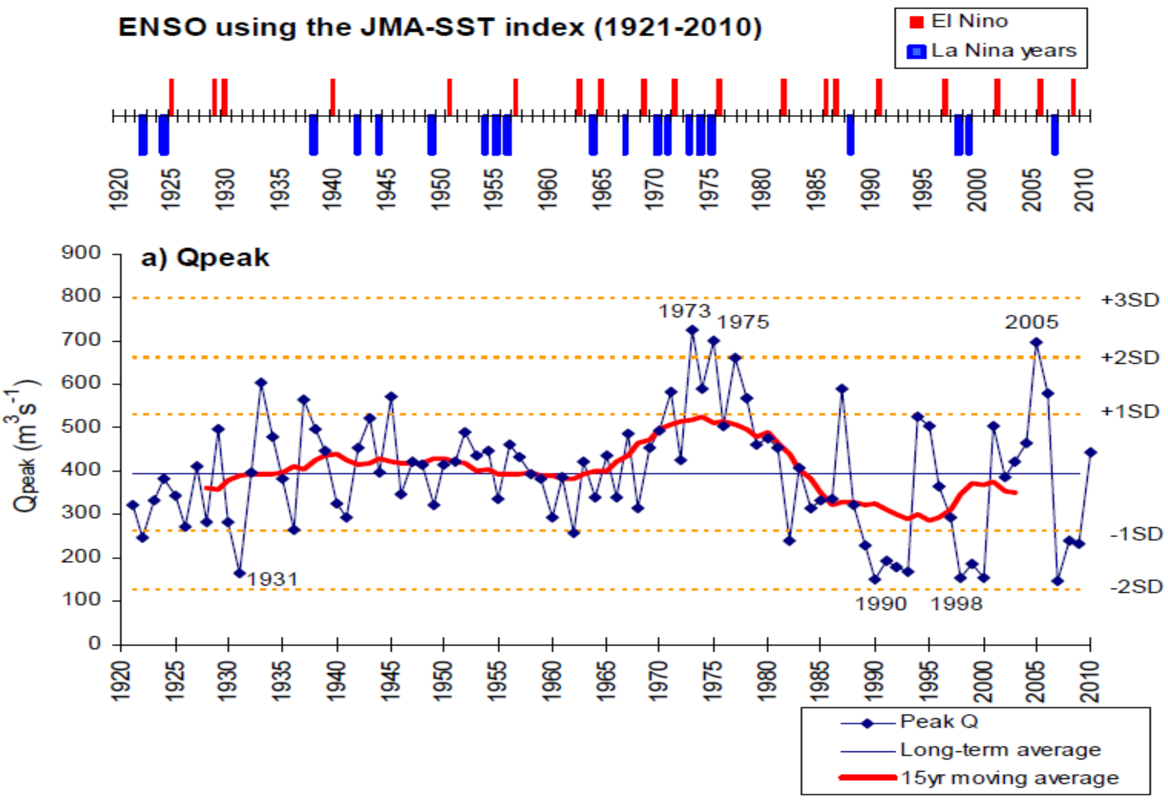

Figure 15. Episodic variation in peak flows on the Ping River. Episodes are approximately 15-20 years in length; and high flows are not simply explained by presence of an El Nino or La Nina event, at time scales of approximately 100 years (From Lim et al, forthcoming).

The 2011 Bangkok flood provided an opportunity to assess anthropogenic versus natural controls on flooding on a continental river (Ziegler et al., 2012a,b). The flood highlighted the difficulty of managing surface water in tropical monsoon areas where several months of ample rainfall are followed by long dry periods. Dual-purpose reservoirs provide two competing functions: (1) maximizing water storage for irrigation and commercial use in the dry season; and (2) minimizing flood risk late in the wet season. Uncharacteristically high rainfall (Figure 16), and questionable reservoir management decisions, were factors exacerbating the estimated US$45 billion in flood damages in Bangkok and surrounding areas. The fundamental cause of the catastrophe was arguably the failure to prepare for a recurrent hazard—major floods have occurred on the Chao Phraya River in each of the last four decades.

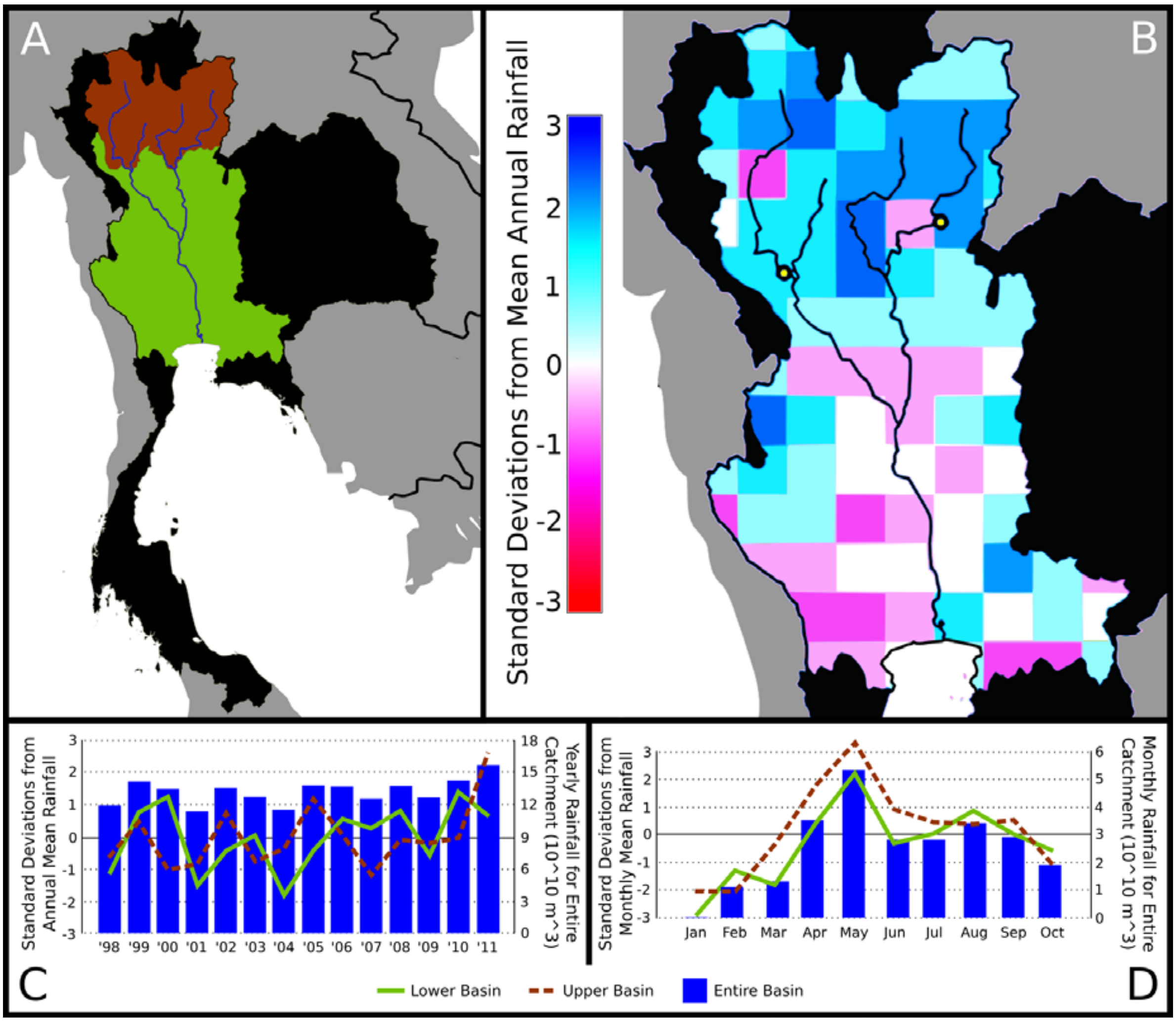

Figure 16. (A) Map of Thailand showing the Chao Phraya River sub-catchments that contributed to the large-scale flooding in late 2011. The blue lines represent the Chao Phraya River and four main upland tributaries. The brown and green areas correspond to the upper and lower sub-basin considered in this rainfall analysis. (BD) Map of the 2011 Jan-Oct rainfall anomaly in Thailand. The aggregated anomaly in the northern region upstream of the Bhumipol and Sirikit dams (circles) was 1.6 standard deviations above the mean (From Ziegler et al., 2012a). (C) January-October (yearly) rainfall for the entire Chao Phraya catchment (blue bars). Annual rainfall anomalies (represented as standard deviations from the mean rainfall), determined from the 14-year NASA TRMM satellite archive for the upper (brown line) and lower (green line) sub-catchments. Rainfall in 2011 was 10% higher than the second highest year on record. (D) 2011 monthly rainfall for the entire catchment (bars); and upper basin and lower basin monthly rainfall anomalies. The highest rainfall anomalies occurred in May when the total depth comprised 24% of the January-October total.

3.7 Hydrological modeling

Hydrological monitoring over the last eight years provided sufficient data to begin building models that realistically describe streamflow and sediment dynamics in the Mae Sa river. We attempted to identify the most appropriate models for predicting streamflow and the transport of TSS and various particulate constituents. Several processed based models were considered: DHSVM, SWAT, IHACRES (Cuo et al., 2010, Tan 2012; Bannswath, forthcoming). Analysis simulations using DHSVM determined that the most sensitive soil parameters were porosity, lateral saturated hydraulic conductivity, and the exponential decrease rate of lateral saturated hydraulic conductivity with soil depth. The most sensitive vegetation parameters were leaf area index, vegetation height, vapour pressure deficit, minimum stomatal resistance (for both grassland and forest scenarios), hemisphere fractional coverage, overstory fractional coverage, and trunk space (for the forest scenario only). Parameter sensitivity was also found to be basin-specific, with tropical catchments being greatly influenced by soil properties. Increases and decreases in parameter values resulted in opposite and unequal changes in bias and root mean square error (RMSE), indicating the non-linearity of physical processes represented in the hydrological model.

Owing to the great sensitivity of process-based models to parameterization, we turned attention to empirical data-driven artificial intelligence (AI) techniques that avoided the process complexities of physical models. Support Vector Machines performed best (Anver and Ziegler, 2012). In simulations of Mae Sa streamflow, the best AI models for forecasting have a Nash-Sutcliffe Model Efficiency of 0.88 for the multi-year dry season time series; 0.91 for the wet season (Figure 17). In comparison, the simpler physical IHACRES model performed poorly, as it draws on a much smaller input data set than AI models. Highly adaptable general purpose AI models are easily ported to different time resolutions, data limitations, and different catchment scales, providing a powerful alternative to physically based models requiring more strenuous parameterization. They also model complex systems without requiring potentially unrealistic assumptions about underlying processes.

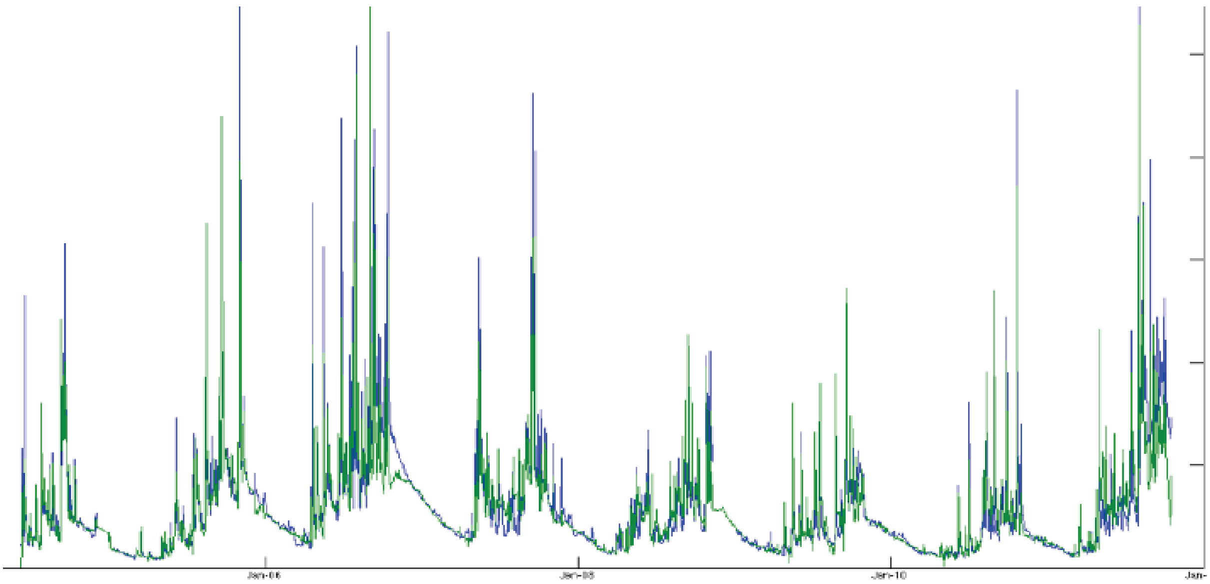

Figure 17. Observed daily and predicted stream flow in the Mae Sa River (Thailand) for the period 2006-2010. Streamflow is predicted with a support vector machine using the spatial distribution of rainfall (measured at 11 locations), and stream flow from the previous time stamp. Model efficiency was 0.83 for the 8 year simulation.

3.8 Paleoflood investigations

Paleoflood investigations suggest that recent floods on the Chao Phraya River (2011) and the Ping River (2005) are not anomalously high. In one study, we investigated the chronology of floodplain areas along the Mekong River near Chiang Saen, Thailand (Wood and Ziegler, 2008). Radiocarbon data indicates an average vertical-accretion rate at that site ≥ 6.7 cm/year for silt laid down episodically in a few large floods over a period of about 85 years. Satellite-imaged channel patterns suggest two types of channel avulsion have occurred: (1) Alternating and mid-channel sand-and-gravel bars (> 1-km long, > 200-m wide), dividing the channel, evolve into vegetated islands and vertically accrete silt. In flood, a preferred channel, or a previously abandoned channel becomes the main channel. Minor channels between the island and adjacent floodplain are silted up and merge with the floodplain. (2) Along this reach of the river, the 2-to-5-km-wide floodplain is bordered by saprolite-mantled bedrock hills with accurate cuts (wavelength ≈ 5 km). Meander-point bar patterns of similar wavelength occur on the floodplain, indicating channel avulsion has also occurred by meander loop cutoff. At some time prior to the AD 14th Century the channel apparently changed from a meandering channel to a straight, somewhat braided channel.

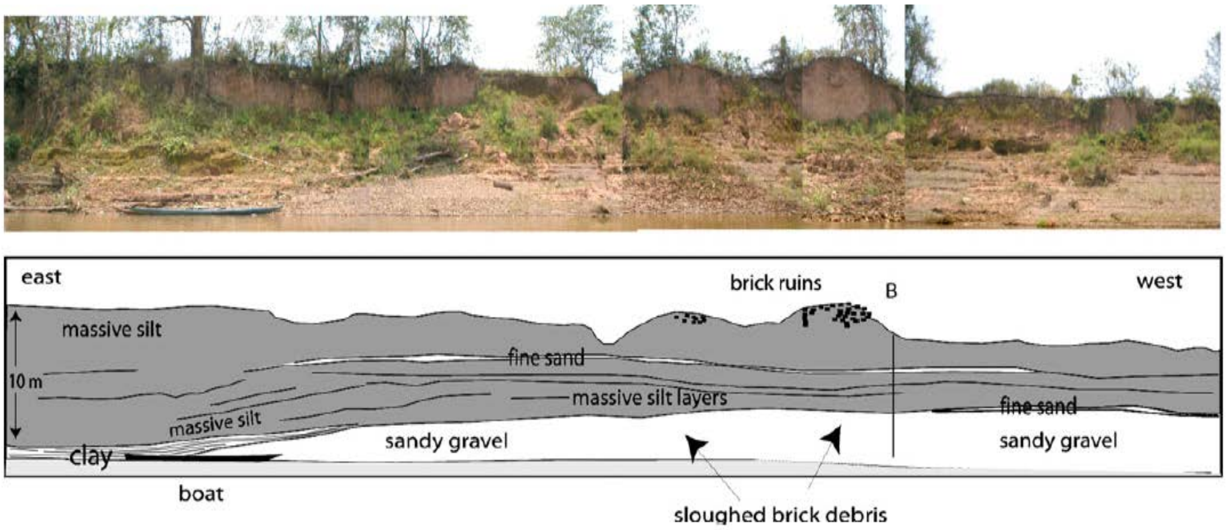

Figure 18. Cross section view of the floodplain stratigraphy of the Ping River near Chiang Khong Thailand. Alternating layers of silt and sand deposits indicate the occurrence of several large floods, some of which lead to the abandonment of large cities and cause avulsions on some river stretches (From Wood et al., 2008).

We also investigated the historical interaction between the Ping River and Wiang Kum Kam, a former Lannathai capital, located near Chiang Mai Thailand (Ng, 2012). We challenged prior assessments that an elongated mound on the floodplain in Wiang Kum Kam was an old levee system of the paleo-Ping River channel. We determined that the mound was a man-made dyke, constructed after 1411 AD to alleviate effects of persisting floods. One distinct layer in the floodplain stratigraphy consisted of a 30 cm of coarse sand overlain by 10-15 cm of fine-silty sand. Radiocarbon dating of charcoal found in this layer suggests that the sediments were deposited by a large flood ca 1477 AD to 1512 AD. Comparisons with deposits of 2005 and 2011 Ping River floods revealed that this flood event was a high-energy, destructive event that likely caused an avulsion on the Ping River and the eventual abandonment of Wiang Kum Kam. In comparison, the largest floods we have observed within the last 100 years are small compared with those in the past.

4.0 Conclusions

The study has provided insight on land use and climatic impacts on fluvial systems in Montane Mainland SE Asia; and it has increased our understanding of the following: (1) negative consequences of on-going land-cover/land use changes in the region; (2) how anticipated land-cover/land-use change will affect climate regional in the future; (3) what are some important natural and anthropogenic factors affecting the fluxes and dynamics of stream flow, sediment, and nutrients in SE Asian rivers. The following conclusions were reached:

1. Important land-cover/land-use changes anticipated during the first half of the 21st century center on the intensification of agriculture systems, including the replacement of traditional swiddening systems with cash-crop systems and plantations. The imprint this change will have on rainfall and other climate variables in the MMSEA region is simulated to be small, compared with the changes caused by CO_2 forcing alone.

2. The ongoing demise of swidden agriculture is alarming because in some cases these systems may be the most efficient in terms of protecting livelihoods and causing minimal disturbance on the environment. With respect to the latter, the commonly held belief that swidden systems are more destructive than permanent systems is not always justified. Unlike traditional systems, many intense systems require fertilizers, pesticides, irrigation, and an extensive road network for transporting crops to the markets.

3. The proliferation of rubber from Yunnan throughout the region is of concern because of the rapid rate of expansion and the potentially high water use of the trees during the dry season. Also of concern is the encroachment of large-scale plantations on small-holder farming systems through unjust means or exploitation. Although not studied in detail, this concern applies to other plantation crops such as oil palm. Currently, there is insufficient evidence to support the notion that rubber and oil palm plantations always sequesters more carbon than more traditional tree-based agroforestry systems—thus they should not automatically qualify for REDD+ funding.

4. Mulit-year monitoring and sampling in the Mae Sa Experimental Catchment demonstrated great variability in total suspended solid loads (TSS). Annual differences in rainfall contributed to TSS differences by either amplifying or reducing erosion processes, including slope wash, mass wasting, and channel bank erosion. Major anthropogenic factors included road building, landscaping, river channel alteration, and agriculture. Importantly, mass wasting events related to road-building and the occurrence of large storms, introduce large quantities of course sediments to stream systems. This material often resides in the stream for several years, thereby affecting annual variations in sediment yields.

5. Attempts at bed load sampling demonstrated the difficulty of measuring this variable in all but very small streams. As the filling of reservoirs with course river bedload is key factor limiting the life span of a dam, the inability to measure bedload accurately is a major limitation when developing climate change mitigation programs for the future.

6. Two-year sampling showed distinct differences in stream chemistry in the Longchuan river, compared with its parent river, the Chiangjiang, and other tributaries. Differences were related to both anthropogenic factors (e.g, land-use) and natural factors (e.g., geology). Chemical weathering rate was an estimated 26 Mg km^2 y^{-1}, resulting CO_2 consumption rate of 377×10^3 mol km^2 y^{-1}. Annual yields of total nitrogen and total phosphorus were 550 and 610 kg km^2 y^{-1}; the high concentrations of phosphorus indicate potential P limitation for phytoplankton growth. Specific fluxes of total organic carbon and dissolved inorganic carbon were 5.6 Mg km^2 y^{-1} and 6

Mg km^2 y^{-1}, respectively, with more than 90% occurring in the high flow period. Roughly 22 and 78% of the measured particulate organic carbon (4 Mg km^2 y^{-1}) was from autochthonous versus allochthonous production.

7. The abundance of large floods in the MMSEA region over the last decade are not necessarily a harbinger of climate change nor an indicator of the effects of land-cover change on fluvial systems. Several large flows on the Ping river in the last century frequently occur in response to large late-season tropical storms, sometimes occurring in conjuction with monsoon anomalies. At this spatial scale the effects of land-cover change are not noticeable. At this temporal scale, the influence of regional-to-global climate phenomena, particularly ENSO, is not apparent.

8. The perception of increased flooding is tied to increasing monetary losses, as well as the number of people affected. These impacts are in part driven by the increasing number of people and businesses living and located on flood plains. The current attitude of fighting flooding impacts via engineering works is potentially flawed because it fails to address the underlying issue of vulnerability to very large floods. Pale-evidence suggests floods much larger than have been witnessed in Thailand recently have occurred in the past. Given the current situation of millions of people living in flood prone areas, future floods of these magnitudes would be devastating.

5.0 Future Directions

Immediate follow-on works should focus on the relative roles of anthropogenic versus natural factors on river hydrological, geochemical, ecological, and geomorphological systems. Too few reliable data have been collected in the past; and much of what has is not available for the science community. During the course of the project we have identified several areas where new research is needed: (1) developing new ways of measuring rainfall accurately across MMSEA and predicting the timing and pathways of tropical storms; (2) develop a means to estimate accurately bedload transport accurately in large rivers that are dammed; (3) determining the greater impacts of reservoir building on large rivers (e.g., loss of biodiversity, effects on public health, effects on carbon storage); (4) identifying management strategies that will minimize the transport of sediment and other contaminants from road networks and agriculture systems, both of which are intensifying; and (5) investigating the recurrence intervals for large paleofloods in an effort to understand how climate change may affect river flows in the future.

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Appendix 1

Conferences/Symposia/Workshops

The following conference presentations benefitting from APN funding

1. Ziegler, AD, JC Chuah. The role of water use and management in the dynamics of water-borne pathogens in SE Asia – NUS Geography's research directions. International workshop 9-15 September 2012, Karlsruhe Institute of Technology, Karlsruhe Germany.
2. Song, SHM, XQS Ng, AD Ziegler. Toward Better Management of Elephant Trail Degradation. Poster # HS16-A033, AOGS - AGU (WPGM) Joint Assembly, Singapore, 13-17 Aug 2012.
3. Ang, ZJ, P Olin, S Benner, SH Wood, RA Sutherland, AD Ziegler. Geochemical Partitioning of Total Suspended Solids in a Tropical Catchment. Paper #HHS22-A007, AOGS-AGU (WPGM) Joint Assembly, Singapore, 13-17 Aug 2012.
4. Ziegler, AD, NRA Jachowski, HS Lim, RJ Wasson. Floods, False Hopes, and the Future. Paper # HS22-A008, AOGS - AGU (WPGM) Joint Assembly, Singapore, 13-17 Aug 2012.
5. Ng, XQS, SH Wood, AD Ziegler. Rivers in Thai History - Implications for Management. Paper # HS22-A009, AOGS - AGU (WPGM) Joint Assembly, Singapore, 13-17 Aug 2012.
6. Anver, MS, AD Ziegler. Artificial Intelligence Approaches for Streamflow Modelling. Paper # HHS16-A033, AOGS - AGU (WPGM) Joint Assembly, Singapore, 13-17 Aug 2012.
7. Slaets J, P Schmitter, A Bürger, AD Ziegler, T Hilger, G Dercon , N. Huu Thanh, N Lam, T Duc Vien, G Cadisch. Tracing carbon fluxes with turbidity sensors: a time saving alternative for better understanding nutrient flows at the landscape level. Int Symposium on Soil Organic Matter 2011: Organic matter dynamics - from soils to oceans". It is in Leuven, Belgium from 11-14 July 2011.
8. Ziegler AD. 2010. Implications of Rapid Land-cover/Land-use Change in Montane Mainland SE Asia, 2012. Sustainable Land Use and Rural Development in Mountainous Regions of Southeast Asia, 21-23 July 2010 Hanoi.
9. Giambelluca, TW, R Mudd, AD Ziegler, M Huang, W Liu, M Nullet, Q Chen, J Fox. 2010. Preliminary estimates of evapotranspiration for a rubber plantation in Nong Khai, northeastern Thailand. Hydrology delivers Earth System Science to Society. GSWP/GLASS AsiaFlux/FLUXNET LandFlux-Val. 22-25 June 2010. Tokyo.
10. Ziegler AD. 2010. Tillage erosion in developing countries in Asia. Vignettes: Key Concepts in Geomorphology. http://serc.carleton.edu/vignettes/collection/42228.html
11. Ziegler, AD. Sediment and nutrient dynamics in a SE Asian headwater catchment. 6Th Annual General Meeting of AOGS, Singapore, 11-5 August 2009.
12. Quek, SL, YC Wang, AD Ziegler. Seasonal variation in soil moisture in a tropical catchment in northern Thailand. 6Th Annual General Meeting of AOGS, Singapore, 11-5 August 2009
13. Dan, N.P., Liem, TT, AD Ziegler, LD. Hiep. 2008. Assessment of change of land use on solid TOC into the Hau River. In proceeding "1st International Conference on Environment and Natural Resources, Ho Chi Minh City, Vietnam, March 17th-18th.
14. Dan, N.P., Liem, TT, AD Ziegler, LD. Hiep. Assessment of change of land use on solid TOC into the Hau River Regional Conference on Global Environment, Feb 2-3, 2009, Manila, Philippines.
15. Guardiola-Claramonte, M, PA Troch, AD Ziegler, TW Giambelluca, JB Vogler, MA Nullet. 2006. The effects of introducing non-native vegetation on hydrological partitioning in a tropical catchment. 93rd ESA annual meeting, Milwaukee WI, 8 Aug 2008.
16. Ziegler, AD., C Tantasarin, S Benner, Lu Xixi, T Giambelluca, D Higgitt. 2007. Sediment and Nutrient Fluxes in a Tropical Headwater Stream in Northern Thailand. International Association of Geomorphologists, Koto Kinabalu, Sabah, Malaysia, 25-29 June 2007.
17. Benner, SG, AD Ziegler, C Tantasarin, Lu Xixi, T Giambelluca. 2006. Quantifying Stream Flux of Carbon Nitrogen and Phosphorus in a Tropical Watershed, Mae Sa Thailand. AGU Fall Meeting, Dec 2007, San Francisco.

Appendix 2

Funding sources outside the APN
Aspects of the project were supported in part by the following grants (US dollars)

- Fox, JM (PI, E/W Center, Hawaii), TW Giambelluca (Co-PI, UHM), Qi Chen (Co-PI , UHM), AD Ziegler (Co-PI, UHM). The expansion of rubber and its implications for water and carbon dynamics in Montane Mainland Southeast Asia. 2008-2012. NASA project #NNX08AL90G ($960,000): Laos, Thailand, Cambodia.
- Ziegler AD (PI). 2009-2012. Landslide initiation mechanisms and fate of sediment in a headwater catchment in Thailand. NUS FASS Start-up grant (R-109-000-092-133) ($20,000): Thailand.
- Ziegler AD (PI), Lu XiXi (NUS). 2011-2012. FASS Faculty Research Support Scheme. Singapore Ministry of Education (MOE) Academic Research Fund (AcRF) Tier 1 (c-109-000-222-091) (S$6400): Singapore.
- Lu Xi Xi (PI, Singapore), M Bird (Scotland), A Chen (Taiwan), D Higgitt (Singapore), M Kummu (Finland), R Robinson (UK), J Sarkkula (Lao PDR), AD Ziegler (NUS/UHM). 2008-2010. Sediment and carbon fluxes in large Asian rivers: Climate and human impacts. Ministry of Education (MOE) Academic Research Fund (AcRF), Singapore ($200,000): South and SE Asia.
- Lu Xi Xi (PI, Singapore), M Bird (Scotland), A Chen (Taiwan), D Higgitt (Singapore), M Kummu (Finland), R Robinson (UK), J Sarkkula (Lao PDR), AD Ziegler (UHM). 2008-2010. Sediment and carbon fluxes in large Asian rivers: Climate and human impacts. National University of Singapore Bridge Funding, Singapore ($24,500): Red, Mekong, and Chao Phraya Rivers.

Appendix 3

List of Young Scientists

The following students used data from the project for their theses:

1. Jakkrit Chainet. 2007. Application of Rutter Model on Interception Process of Different Land use at Mae Sa Watershed, Chiang Mai Province. Department of Conservation, Faculty of Forestry, Kasetsart University. Catchment, Thailand.
2. Panidtha Saard. 2007. Determination of Soil Water Characteristic Curve in Mae-Sa Watershed, Chiang Mai Province. Masters thesis, Conservation Dept., Kasetsart University.
3. Maite Guardiola-Claramonte. 2009. Modeling water use by rubber in SE Asia. PhD dissertation, Hydrology Dept., University of Arizona.
4. Natalie Wood. 2009. Sediment and carbon export from a tropical catchment. Honors Thesis, Geography, University of Manchester.
5. Quek See Leng. 2010. Masters Thesis Seasonal changes in soil moisture variability in tropical landscapes. Geography, National University Singapore. Geography, National University of Singapore.
6. Angus Sham. 2010. Honors Thesis (ISM): Influence of land-cover changes on saturated hydraulic conductivity in three forest land-covers in northern Thailand. Geography, National University of Singapore.
7. Alvin Yeo. 2010. Honors Thesis (ISM): Variation in soil physical characteristics in three forest soils in Mae Sa. Geography, National University of Singapore.
8. He Min. 2010. MA Thesis: Ion Geochemistry of the dissolved loads in the Longchuanjian River, upper Yangtze Catchment, China. Masters thesis. Kunming University of Science and Technology.
9. Song Si Hui Mandy. 2012. Honors Thesis: Biophysical impacts of elephant trampling in Mae Sa catchment of northern Thailand. Geography, National University of Singapore.
10. Ng Xiao Qian Serene. 2012. Honors Thesis: Flooding effects on the location of Wat Wian Khum Kam, Chiang Mai, northern Thailand. Geography, National University of Singapore.
11. Ang Zuo Jin. 2012: Honors Thesis. Sediment Fingerprinting as a tool to identify temporal and spatial variations in sediment sources in Mae Sa catchment of northern Thailand. Geography, National University of Singapore.
12. Kelvin Ho. Current. Honors Thesis: Role of grain size and organic matter in affecting sediment-turbidity hysteresis patterns in a Thai river. Geography, National University of Singapore.
13. Kitson Tan. Current. Honors Thesis: Stream chemistry and hydrograph separation in Mae Sa River. Geography, National University of Singapore.
14. Chatchai Tantasarin. Current. Automated extraction of hillslope hydrologic response units for a physically based hydrological modeling. Asian Institute of Technology.

Appendix 4

Glossary of Terms

BATS	Biosphere-Atmosphere Transfer Scheme
CLUE-S	The conversion of land use and its effects model
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
ENSO	El Nino Southern Oscillation
ET	Evapo-transpiration
IGBP	International Geosphere-Biosphere Programme
ITCZ	Inter-Tropical Convergence Zone
LCLU	Land-cover/land-use
MMSEA	Montane Mainland SE Asia
MSEC	Mae Sa Experimental Catchment (in northern Thailand)
NTU	Nephelometric turbidity units
PAP	Particulate associate phosphorus
PN	Particulate nitrogen
POC	Particulate organic carbon
Q	Discharge
REDD+	REDD+ (Reducing Emissions from Deforestation and Forest Degradation "plus" conservation, the sustainable management of forests and enhancement of forest carbon stocks)
Reg3CM	Regional climate model 3
SOC	Soil organic carbon
SIC	Soil inorganic carbon
TOC	Total organic carbon
TSS	Total suspended solids
USGS	US Geological Survey