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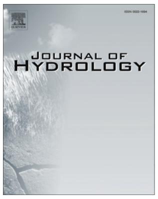

Turbidity-based sediment monitoring in northern Thailand: Hysteresis, variability, and uncertainty

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SUMMARY

Annual total suspended solid (TSS) loads in the Mae Sa Catchment in northern Thailand, determined with an automated, turbidity-based monitoring approach, were approximately 62,000, 33,000, and 14,000 Mg during the three years of observation. These loads were equivalent to basin yields of 839 (603–1170), 445 (217–462), and 192 (108–222) Mg km^{-2} for the 74.16-km^2 catchment during 2006, 2007, and 2008, respectively. The yearly uncertainty ranges indicate our loads may be underestimated by 38–43% or overestimated by 28–33%. In determining the annual loads, discharge (*Q*) and turbidity (*T*) values were compared against 333 hand-sampled total suspended solid concentrations (TSS) measured during 18 runoff events and other flow conditions across the three-year period. Annual rainfall varied from 1632 to 1934 mm; and catchment runoff coefficients (annual runoff/annual rainfall) ranged from 0.25 to 0.41. Measured TSS ranged from 8 to 15,900 mg l^{-1}; the low value was associated with dry-season base flow; the latter, a wet-season storm. Storm size and location played an important role in producing clockwise, anticlockwise, and complex hysteresis in the *Q*-TSS relationship. Turbidity alone was a good estimator for turbidity ranges of roughly 10–2800 NTU (or concentrations approximately 25–4000 mg l^{-1}). However, owing to hysteresis and high sediment concentrations that surpass the detection limits of the turbidity sensor during many annual storms, TSS was estimated best using a complex multiple regression equation based on high/low ranges of turbidity and *Q* as independent variables. Turbidity was not a good predictor of TSS fractions >2000 μm. Hysteresis in the monthly *Q*-TSS relationship was generally clockwise over the course of the monsoon season, but infrequent large dry-season storms disrupted the pattern in some years. The large decrease in annual loads during the study was believed to be related to depletion of fine sediment delivered to the stream by several landslides occurring the year prior to the study. The study indicated the importance of monitoring *Q* and turbidity at fine resolutions (e.g., sub-hourly) to capture the TSS dynamics and to make accurate load estimations in this flashy headwater stream where hysteresis in the *Q*-TSS signature varied at several time scales.

1. Introduction

Data describing sediment dynamics in river systems are useful for inferring both natural and anthropogenic degradation and andscape evolution processes within catchments, especially when complete sediment budgets cannot be derived (Walling, 1999). These data are increasingly important for headwater catchments of mainland SE Asia where rapid land-cover/land-use change is contributing to a growing number of water quantity/quality problems in downstream areas (Forsyth and Walker, 2008; Ziegler et al., 2009b). Recent flooding in many SE Asian countries reinforces the need to understand the dynamics of discharge and

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sediment in tributary streams of larger rivers supporting multi-purpose reservoirs (Wood and Ziegler, 2008; Ziegler et al., 2011). Related, the ongoing and proposed dam building on the main stems of rivers and tributaries threatens to change river flows, sediment dynamics, and aquatic ecosystem functioning (Kummu and Varis, 2007; Wang and Lu, 2008; Ziegler et al., 2013). Looking ahead, the potential for future changes in catchment erosion processes and sediment delivery in response to predicted changes in landcover/landuse and climate in the region necessitates improving our baseline knowledge of river sediment dynamics (Fox et al., 2012; Sen et al., 2012).

The hydro-geomorphological consequences of forest conversion, cultivation on sloping lands, and road building have received significant attention in many countries throughout SE Asia, including Thailand (cf., Ziegler and Giambelluca, 1997; Hill and Peart, 1998; Ziegler et al., 2004; Valentin et al., 2008). Large-scale forest conversion for agriculture and intensification of steep-slope cultivation systems have accelerated erosion and mass wasting in many areas (Hurni, 1982; Janeau et al., 2003; Turkelboom et al., 2008; Rijsdijk, 2012). Roads, in particular, contribute disproportionally to catchment sediment budgets either directly or by triggering mass wasting events (Ziegler et al., 2001b, 2004; Cuo et al., 2006; Sidle et al., 2006; Sidle and Ziegler, 2012). Dense networks of footpaths may also be responsible for substantial runoff and erosion (Ziegler et al., 2001a). Despite widespread recognition of the importance of these sediment sources, few studies set in SE Asia have investigated sediment delivery to stream networks in headwater catchments (e.g., Chappell et al., 2004; Sammori et al., 2004; Sayer et al., 2006; Ziegler et al., 2006; Valentin et al., 2008; Sidle and Ziegler, 2010; Rijsdijk, 2012; Orange et al., 2012). Increasingly, however, work has been concerned with sediment and carbon delivery from large rivers to deltas and the oceans (e.g., Nelson, 2001; van Maren, 2007; Aldrian et al., 2008).

Only a handful of published studies report sediment loads for rivers in Thailand (Table 1). Data for several river systems have been collected for decades by the Thai Royal Irrigation Department (RID; www.rid.com). However, data for most of these rivers are available for only a few years (Table 1). The typical protocol is to sample the rivers several times during the year, with intensified sampling done during the monsoon period to develop a sediment rating curve based on discharge. For most rivers, this curve is based on fewer than 50 samples, which do not necessarily sample the largest flows. Thus, there is an unquantified uncertainty related to TSS estimates in the country, despite the professional manner in which they are consistently determined.

What is known generally is that annual catchment sediment yields vary among large Thai rivers, probably in response to differences in relief and geology, and in particular, in response to dynamic rainfall and land use variables (Table 1). Furthermore, substantial portions of annual river sediment loads are transported during large events, often occurring late in the monsoon rain season (e.g., Alford, 1992; Wood and Ziegler, 2008; Lim et al., 2012). Both the paucity and uncertainty of available data may stem, in part, from the difficulty in implementing intensive sediment monitoring programs, particularly on streams where large inter- and intra-storm variation hinders the development of reliable sediment rating curves based on discharge measurements. It also reflects limited resources—a problem in all countries.

Research worldwide has shown that rating curves are often not accurate for predicting sediment concentrations, particularly when there is a substantial hysteresis effect in the discharge–sediment relationship (Olive and Rieger, 1985; Williams, 1989; Brasington and Richards, 2000; Lefrancois et al., 2007; Stubblefield et al., 2007; Rodriguez-Blanco et al., 2010). Some of the difficulty involves collecting sufficient samples at fine time scales to make an accurate prediction. The advancement in automated turbidity-based systems provides a means of monitoring (by proxy) river sediment concentrations efficiently, and therefore, provides a means for estimating sediment loads more accurately, provided a reasonable mathematical relationship exists between turbidity and total suspended sediment concentrations (Gippel, 1995; Lewis, 1996). As such systems are automated, measurements can be made at very fine resolutions (e.g., minutely if needed).

In this study we implemented an automated turbidity monitoring approach to explore sediment dynamics and estimate total suspended solid loads in the Mae Sa River in northern Thailand. The objective was to develop a cost-effective protocol that could be used to provide reliable estimates of sediment loads in streams that may have complex discharge–sediment relationships. The sub-objectives were fourfold: (1) investigate how TSS is related to turbidity and discharge; (2) develop techniques to construct a complete suspended sediment time series from incomplete datasets of discharge and turbidity—and additionally address the limitations posed by the inability to measure turbidity values greater than 3000 NTU (the maximum limit of the sensor); (3) explore yearly sediment dynamics, with respect to management, rainfall variability, and sediment response hysteresis; and (4) estimate the uncertainty in the prediction of sediment loads. The study is part of a larger effort to understand the potential effects of changes in both climate and land-cover/land-use in the future (APN, 2012).

2. Study Area

The Mae Sa or Sa River (Mae is river in Thai language) is a headwater tributary to the Ping River that flows into the Chao Phraya River, which drains to the ocean (Fig. 1). In 2004, we initiated a hydro-climatic monitoring program in the 74.16 km^2 Mae Sa catchment to explore the impacts of climate and land-cover/land-use change on hydro-geomorphological processes (Fig. 1). The program involved establishing three water/energy flux climate stations, 11 rain gauges, six soil moisture measurement stations, and a stream discharge monitoring station in a natural stream channel at the catchment outlet. The density of the rain monitoring gages (1 per 6.7 km^2) is one of the highest for a monitored catchment in the region. The Mae Sa is not dammed; and flow is not regulated, although flows are affected by water extraction for irrigation and domestic use.

Land-cover in Mae Sa catchment is representative of that now found elsewhere in developing upland areas surrounding major population centers in northern Thailand. The major land cover in the catchment is still forest, but of various degrees of disturbance (62%, Fig. 1). More than 20% of catchment area 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 has been converted to greenhouse production systems (7% of the total land), which provide high-value cash crops to lowland urban centers. Approximately ten villages are scattered throughout the basin; and urbanized or per-urbanized (e.g., contains hybrid landscapes with fragmented urban and rural characteristics) surface occupy about 8% of the total catchment land area. Some of these villages historically participated in opium cultivation (Crooker, 2005). Several tourist sites, including elephant trekking camps, resorts, and a botanical garden, are prominent points of interest within the peri-urban landscape (e.g., Sidle and Ziegler, 2010). Encroachment on the river bank and surrounding floodplain has occurred with recent land-use intensification. Thus, the various land-used activities of these villagers, as well as resort owners, play a complex role in terms of water management and agricultural impacts in the catchment (cf. Neef et al., 2005).

Mean annual rainfall in Mae Sa catchment varies from 1200 to 2000 mm across an elevation range of 500–1300 m (Fig. 2).