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Sediment load monitoring in the Mae Sa catchment in northern Thailand

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Abstract This paper describes the development of an automated system to monitor total suspended solids (TSS) in the main channel of the Mae Sa River in northern Thailand. Logged discharge (Q) and turbidity (NTU) values were compared with hand-sampled TSS concentrations that were determined during six runoff events (n = 85 samples) and 13 other baseflow periods. Measured TSS values ranged from 10 to 7600 mg L^{-1}, reflecting variable conditions between dry-season baseflow and wet-season stormflow. Because of hysteresis effects in the TSS *versus* discharge relationship, and high sediment concentrations that surpass the detection limits of the turbidity sensor during some storms, TSS was predicted best using multiple regression with both Q and NTU as independent variables. The estimated annual TSS load for 2006 is about 79 822 t, which is equivalent to a basin yield of 1076 t km^{-2} for the 74-km^2 catchment.

Key words total suspended solids; sediment sampling; turbidity monitoring; suspended sediment yield; erosion in the tropics; land-cover change

INTRODUCTION

Data describing the movement of sediment into and through river systems is important for understanding both natural degradation processes and the environmental impacts of anthropogenic activity. These data are increasingly important for headwater catchments of mainland SE Asia owing to: (a) the rapid land-cover/land-use change that has been taking place in most highland regions; (b) the growing number of reported water quantity/quality problems in downstream areas; and (c) the likelihood of changes in the hydrological cycle related to predicted climate change (Ziegler *et al*., 2009). Despite the importance of such data, only a few analyses of sediment dynamics/loads have been published for catchments in the region (e.g. Alford, 1992; Nishimura *et al*., 1997; Wood & Ziegler, 2008). In this study we use automated stream discharge and turbidity measurements to estimate the annual TSS load in a headwater catchment in northern Thailand (Fig. 1).

STUDY AREA

The Mae Sa River is a headwater tributary of the Ping River, which flows into the Chao Phraya River, Thailand’s largest river (Fig. 1). Land use is representative of that now found in developing upland areas surrounding population centres in northern Thailand: e.g. forest reserves in mixed secondary forest, fruit orchards, cultivated slopes, recreation sites, and greenhouse agriculture. Rainfall ranges from 1200 to 2000 mm, with 80% of the total falling in the May–October monsoon rain season (Ziegler, unpublished data). Elevation varies from about 500 to 1400 m. Stream water colour is typically 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.

METHODS

Flow depth was measured automatically at station 434 in the main channel with a pressure transducer and data logger (Fig. 2). A rating curve was established based on 37 stage-velocity-profile measurements made during discharges ranging from 0.3 to 30 m^3 s^{-1}. The streambed profile

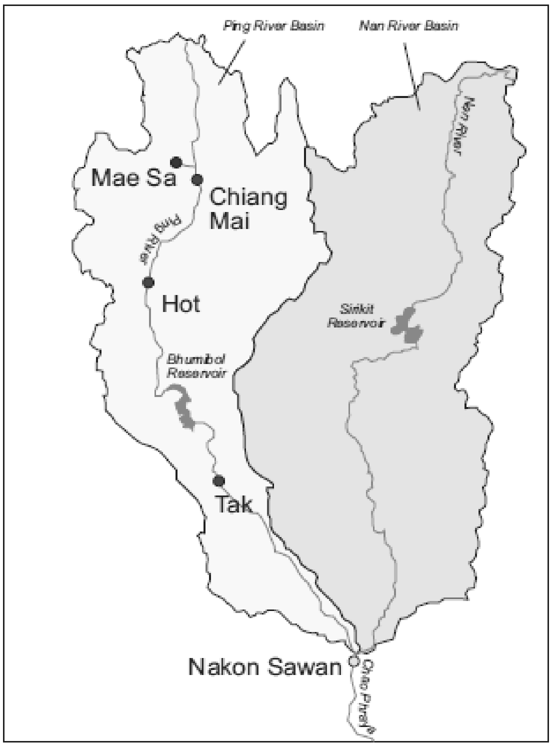

Fig. 1 The Mae Sa River in northern Thailand.

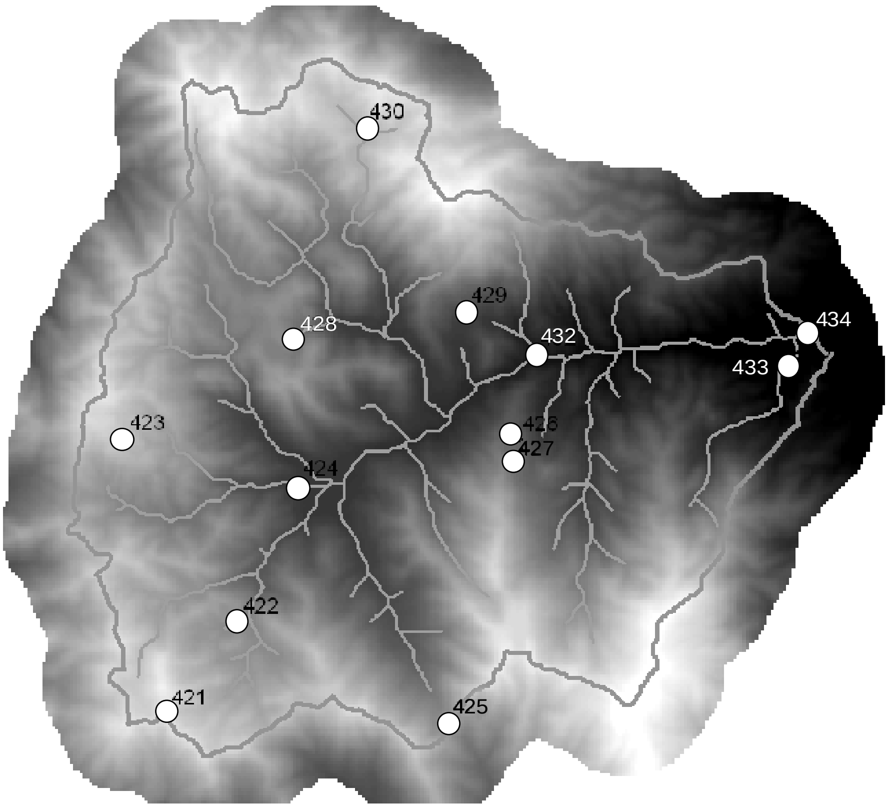

Fig. 2 The location of hydro-meteorological measurement instruments in the 74.16 km^2 Mae Sa Catchment. Streamflow and turbidity has been monitored at one location (434); energy flux variables for estimating evapotranspiration at three locations (421, 429, 433); soil moisture at six locations (421, 423, 425, 428, 429, 433); and rainfall at all locations but Stations 427 and 434.

was monitored continuously to correct for stage–discharge changes that were related to an unstable stream bed.

A self-cleaning NEP-395 turbidity probe was used to provide a continuous turbidity signal ranging from 0 to 3000 nephelometric turbidity units (NTU). The probe was housed inside a perforated PVC pipe (7.6 cm diameter) that was suspended from a footbridge in a manner that allowed the probe to "float" in the water column, approximately 10–20 cm below the surface for all flow ranges. Discharge and turbidity readings were logged at least every hour and at times when stage changed by a 0.5-cm increment. Turbidity readings were calibrated against hand samples, to facilitate the synthesis of a continuous TSS signal. Manual samples were taken during dry-season baseflow conditions and storm runoff events.

The fine (63–2000 µm) and coarse (>2000 µm) sand fractions of the suspended load were determined by wet sieving 20-L water samples that were collected by hand near the turbidity probe. For the silt-clay fraction (operationally defined as 0.7–63 µm), three 150–500 ml sub-samples screened through a 63-µm sieve were individually filtered through 47-mm, pre-ashed, pre-weighed, 0.7-µm Whatman GF/F glass filters. All samples were oven dried to a constant mass. The total suspended solids concentration was calculated as the sum of all three fractions.

Table 1 Discharge and sediment variables for six measured storms.

Event	n	D (hours)	Q_I ($m^3 s^{-1}$)	Q_P ($m^3 s^{-1}$)	TSS_{max} (mg L^{-1})	NTU_{max} (NTU)
060724	12	21	0.8	2.6	2252	1791
060728	12	4	1.9	2.2	1177	2850
060808	16	15	1.4	6.0	3391	3000
060908	20	23	2.3	6.7	2365	2124
060909	11	11	2.1	4.9	1434	1424
060912	14	9	6.8	29.9	7658	3000

n is sample number during event; D is duration from the storm onset until return to baseflow; Q_I is initial discharge; Q_p is peak discharge; TSS_{max} is maximum recorded suspended solids concentration, NTU_{max} is maximum recorded turbidity.

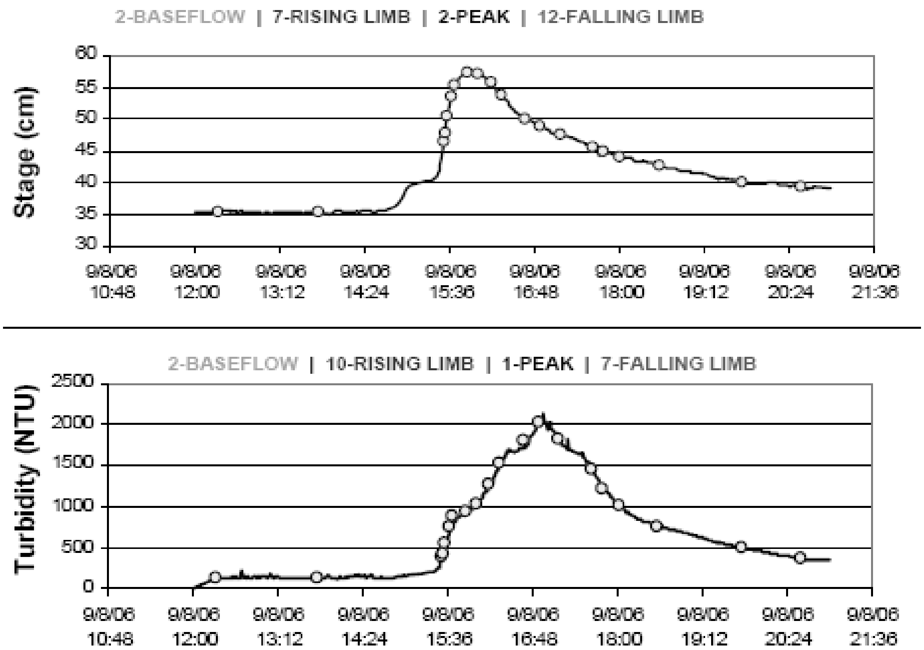

Fig. 3 An example of storm-based sampling for the 8 September 2006 event. Dots represent sampling times with respect to recorded stage or turbidity.

RESULTS

Water sampling for TSS determination was performed mostly during the 2006 wet season (24 July–31 October 2006) when 85 samples associated with six storms were collected (Table 1). Samples were collected during a range of flow conditions, including base flows, rising limbs, peaks, and falling limbs of individual storms (Fig. 3). The minimum and maximum discharges during which water samples were collected were 0.6 and 29.7 $m^3 s^{-1}$ (Table 1). Another 13 samples were collected during base-flow conditions during the dry season. Mean daily discharge for 2006 was about 2 $m^3 s^{-1}$; total rainfall was 1934 mm for the year.

Maximum measured suspended solid concentrations (TSS_{max}) for the six monitored storms ranged from about 1200 to 7600 g m^{-3}, Table 1). TSS_{max} often exceeded maximum recorded turbidity values (T_{max}) because the probe had a limit of 3000 NTU. Turbidity reached the maximum during 2 of 6 monitored events (Table 1). The maximum measured suspended solids concentration (>7600 mg L^{-1}) was measured on the rising limb (at 20 $m^3 s^{-1}$) of the 12 September 2006 storm event, which had the largest peak of any monitored event (Table 1).

Comparison of observed TSS concentrations and corresponding Q and turbidity values shows great variation in the relationships between these variables during the six storms (Fig. 4). The high variability portends the difficulty in developing robust rating curves for predicting TSS from Q or turbidity alone. However, because discharge shows a greater spread for low-to-medium flows (<10 m^3) and turbidity had the greatest uncertainty for high values of TSS (>2000 mg L^{-1}), multiple regression using both Q and NTU may provide better TSS predictions for the range of flow conditions at the site.

Owing to substantial TSS–Q hysteresis effects, turbidity was a better predictor of TSS than discharge, for all but one event, the largest one on 12 September 2006 where the maximum TSS exceeded 7500 mg L^{-1} (Table 2). For three of the events, nonlinear regression using turbidity only produced r^2 values of 0.95 or greater (Table 2). For the entire data set (83 event values and 15 dry season base-flow values) both Q and NTU produced similar fits of TSS using regression analysis:

$$TSS = 254.389Q \quad r^2 = 0.86 \tag{8}$$

$$TSS = 1.38NTU \quad r^2 = 0.86 \tag{9}$$

Multiple regression using either discharge or turbidity as independent variables, however, produced a better fit than either Q or NTU alone (Fig. 5).

$$TSS = 139.5Q + 0.77NTU \quad R^2 = 0.96 \tag{10}$$

Most improvement occurred in the 2000–6000 mg L^{-1} range (Fig. 5).

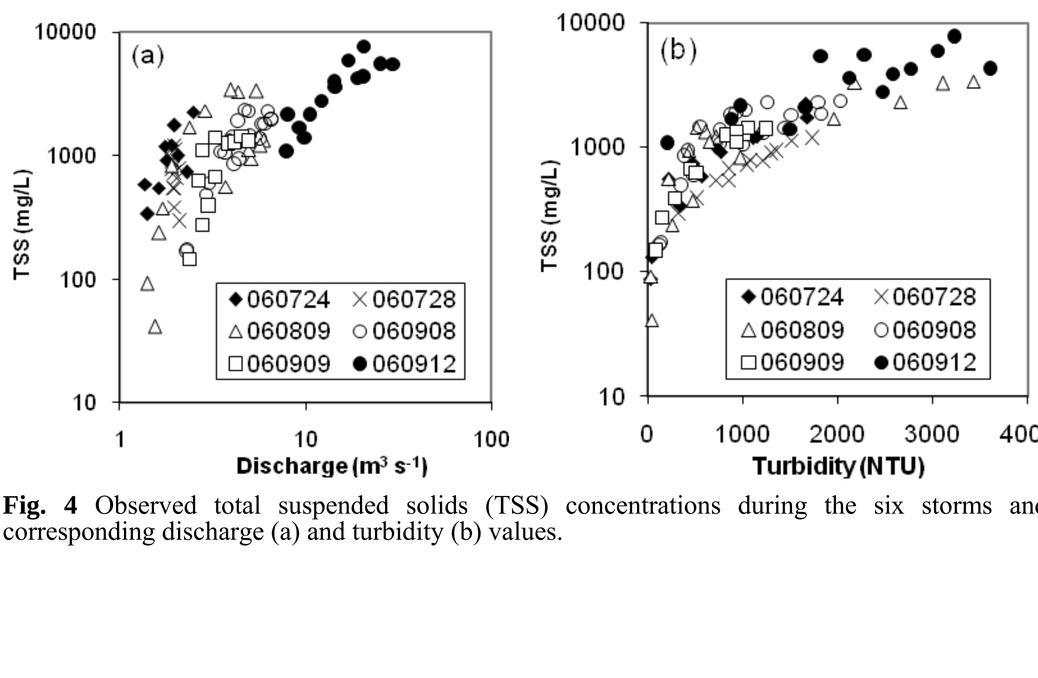

Fig. 4 Observed total suspended solids (TSS) concentrations during the six storms and their corresponding discharge (a) and turbidity (b) values.

Table 2 Best-fit regression relationships for total suspended solids (TSS) *versus* turbidity (T) or discharge (Q) for each set of storm and baseflow measurements.

Event	Best-fit equation	r^2 value	
060724	$TSS = 6.5621NTU^{0.7507}$	0.95	(1)
060728	$TSS = 1.7776\ NTU^{0.8679}$	0.97	(2)
060808	$TSS = 3.1757NTU^{0.8703}$	0.89	(3)
060908	$TSS = 2.6798NTU^{0.9107}$	0.85	(4)
060909	$TSS = 3.4687NTU^{0.8542}$	0.98	(5)
060912	$TSS = 114.25Q^{1.249}$	0.79	(6)
Baseflow	$TSS = 15.849\ NTU^{0.4688}$	0.82	(7)

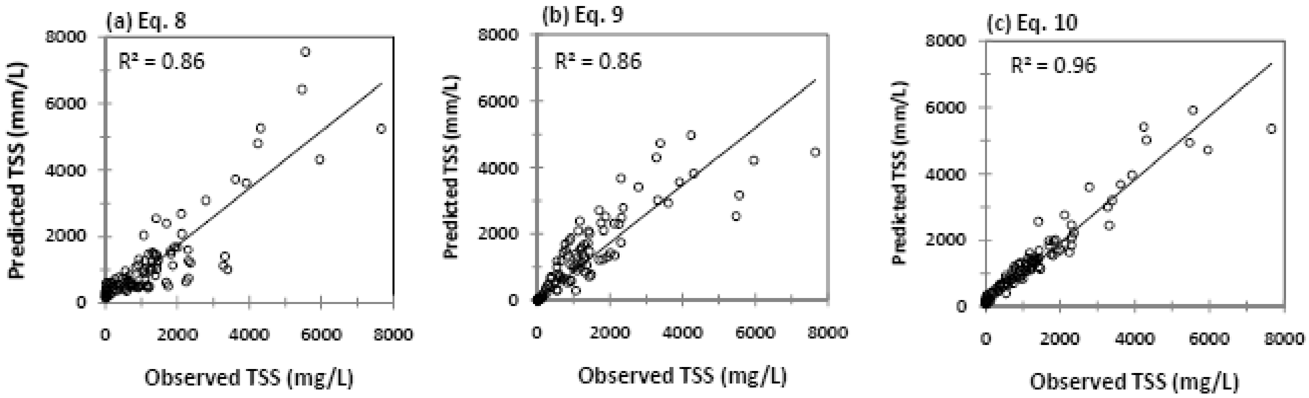

Fig. 5 Comparison of observed total suspended solids (TSS) concentrations with those predicted via regression using (a) discharge; (b) turbidity, and (c) discharge and turbidity.

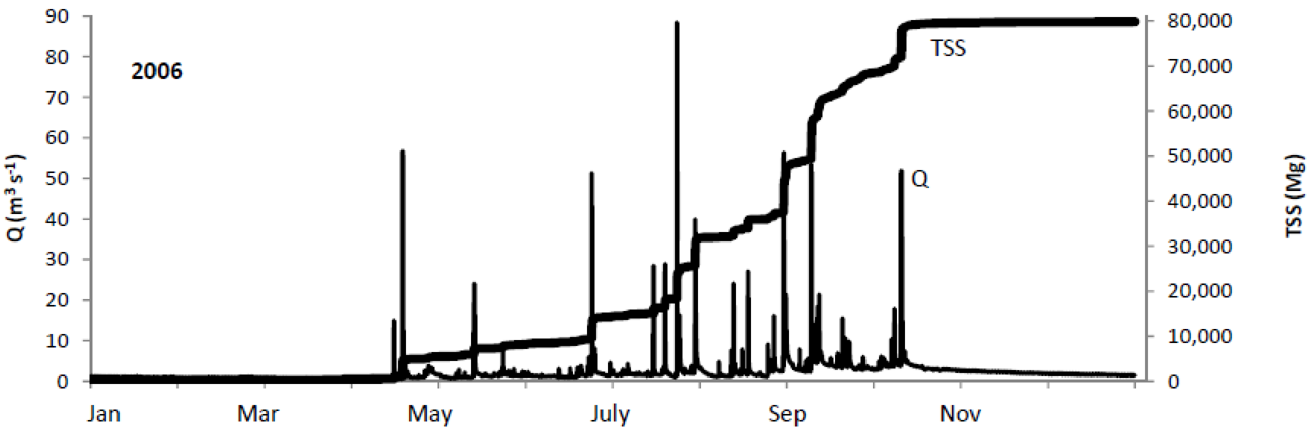

Fig. 6 Mean hourly discharge (Q) and cumulative TSS load (74 032 t) for the year 2006.

The estimated 2006 TSS time series was determined from logged, hourly Q and NTU measurements using a modification of equation (10) (Fig. 6). If hourly values of Q or NTU were missing, Equation (8) or (9) was substituted. Furthermore, restrictions were used to force the TSS estimations to fall within the range of observed values (10–7600 mg L^{-1}) to account for errors at both low and high ends of the range – particularly the high end after the detection limit of the turbidity sensor was surpassed. The final complex equation was used to determine the TSS load was the following:

$$
\text{TSS (mg L}^{-1}\text{)} \left\{ \begin{array}{ll} 10 & \text{NTU} \leq 10 \\ \text{equation (8)} & \text{hourly NTU missing} \\ \text{equation (9)} & 10 \leq \text{NTU} < 100\text{; hourly Q missing} \\ \text{equation (10)} & \text{NTU} > 1000\text{; TSS} \leq 7600 \\ 7600 & \text{TSS} > 7600 \end{array} \right. \qquad (11)
$$

The estimated annual TSS load was 79 822 t, which is equivalent to a specific annual sediment yield of 1076 t km^{-2} from the 74.16 km^2 basin. This is a very high value compared with the 44–256 t km^{-2} specific sediment yields that have been reported for larger rivers draining the Thai uplands (e.g. Jirasuktaveenkul *et al*., 1987; Alford, 1992; Nishimura *et al*., 1997; Wood & Ziegler, 2008). However, the yield is not consistent with the high specific suspended sediment yields associated with other rivers in the region (Gupta, 1996).

SUMMARY AND CONCLUSIONS

Discharge alone was not a reliable predictor of TSS because of marked hysteresis in the TSS–Q relationship during some events. Alternatively, turbidity failed to provide an adequate predictor of TSS for NTU values near or above the instrument detection limit of 3000 NTU. Improvement in the turbidity monitoring capability would require a field-based instrument that could record values of NTU exceeding 7600. Ideally, a second turbidity probe calibrated to capture the low-end values would also be installed. The limitations of the logged Q and NTU data were sometimes mutually exclusive, thus multiple regression using both variables provided the best model fit for TSS. Although the small data set of 98 values from six storms and a small number of dry season samples were sufficient to develop a multiple regression equation with a R^2 value of 0.96, additional sampling of a wider diversity of storms, particularly those with high TSS concentrations, may be useful for better understanding sediment dynamics during individual storms. Finally, the high annual TSS load of 79 822 t (1076 t km^{-2}) is likely to reflect the substantial disturbance throughout the basin, including year-round irrigated agriculture, road building, construction, and elephant camps.

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