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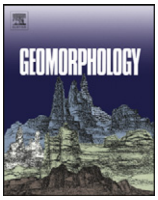

Review

Bedload transport in SE Asian streams—Uncertainties and implications for reservoir management

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ABSTRACT

This paper reviews the current state of knowledge regarding bedload transport in SE Asian streams and presents the results from a case study on bedload transport in a mountain stream in northern Thailand. Together, the review and new data help contextualize the paucity of work done in the region in the face of a rapid increase in development and reservoir building throughout SE Asia. Data from both the reviewed studies and the case study indicate that bedload transport in many SE Asian streams (e.g. catchment areas < 100 km^2) is often much higher than is commonly assumed for tropical streams (i.e., about 10% of the total sediment load). Estimated annual bedload proportion was 18% of the total annual sediment load in the 74-km^2 Mae Sa Catchment in northern Thailand. Bedload transport rates ranged from 0.001 to 1.1 kg s^{-1}; and measured total suspended solid (TSS) rates ranged from 0.01 to 39 kg s^{-1}, equivalent to TSS concentrations of 20 to 14,000 mg l^{-1} (associated with flows ranging from 0.4 to 30 m^3 s^{-1}). Event and annual loads of bedload and TSS were determined from rating curves based on automated measurements of discharge and turbidity (for TSS only). When taking uncertainty into account, the estimated range for the bedload proportion of total sediment load was 9–25% (equivalent to a yield of 81–279 Mg km^{-2}y^{-1}). The corresponding TSS yield estimate ranged from 649 to 1037 Mg km^{-2}; and the total sediment load is an estimated 730–1313 Mg km^{-2} y^{-1}. The proportion of bedload was lower than that reported in some other Asia streams, probably due to the occurrence of extended periods with high TSS that dampened the bedload signal, which was sand-dominated during the low-energy events that were sampled. Nevertheless, the bedload rate was generally higher than for most SE Asian locations, likely due to the occurrence of several road-related landslides the previous year. Although we were not able to measure bedload transport for high energy flows (discharges > 4.5 m^3 s^{-1}), we believe our upper estimates for bedload variables (25% of the total sediment load; and a yield of 279 Mg Km^{-2} y^{-1}) provide reasonable upper bounds. Finally, the bulk of bedload transport is episodic in nature, with a higher proportion moved during high energy tropical storms that occur late in the monsoon rainy season, as well as in response to both natural and anthropogenic landscape disturbances. The possibility that bedload proportion could exceed 20–40% for rivers and streams of various sizes reinforces the need for accurate estimates of both bedload and suspended solid loads prior to building dams in the region. Past examples of reservoir closure following rapid infilling possibly stem from underestimating sediment loads, particularly the bedload component, and failing to factor in the very high sediment loads associated with large storm events.

1. Introduction

Bedload and total suspended solids (TSS) comprise the total sediment load of rivers and streams. Whereas bedload is the portion of solid material transported by rolling, bounding, and sliding along the channel bed (saltation processes), TSS are carried in suspension in the water column (Gomez, 1991). Depending on the size of material and energy of the flowing water, solid material may interchange between bedload and TSS components on its journey through a river system (Church, 2006). The interplay of sediment size, discharge energy, antecedent storm history, channel bed conditions, channel obstructions, and storage causes bedload transport rates and residence time in any one stream system to vary across several orders of magnitude (Sidle, 1988; Hoey, 1992; Smith et al., 1993a; Habersack et al., 2001; Church and Hassan, 2002; Yu et al., 2009; Turowski et al., 2010).

Bedload and TSS transport, both natural processes, vary substantially across river catchments of differing geology, climate, vegetation, and land cover (Church, 2006; Hinderer, 2012). Anthropogenic activities

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producing landslides and accelerating erosion affect the generation and delivery of sediment into and through a stream system (Douglas, 1999; Sidle et al., 2006). Large episodic flushes of sediment may also be associated with extreme weather events or catastrophic events, such as dam breaks (Wasson, 2008; Korup, 2012). Discharge becomes an important controlling factor of bedload transport when sediment supply is not limited. Sediment transport is affected by the availability of transportable material, which is related to linkages between the channel and hillslope sources as well as the structure and stability of the stream channel bed or bank (Dietrich et al., 1989; Church et al., 1998; Buffington and Montgomery, 1999; Hassan and Church, 2000; Gomi and Sidle, 2003; Recking, 2012).

Sediments are vital in maintaining aquatic habitats such as pools and sand bars in river channels, flood plain soils, and wetlands; they also contribute to the formation of downstream deltas (Coleman and Wright, 1975; Smith et al., 1993b; Yarnell et al., 2006). Bedload and TSS estimates are essential components of catchment sediment budgets (Slaymaker, 2003; Parsons, 2011), and are therefore useful for managing river systems where sediment may interfere with ecological processes, flood control, water quality, or water storage (Nagle et al., 1999; Annandale, 2006). They are also paramount for the estimation of reservoir filling rates and dam lifetimes.

Bedload studies are time-consuming and labor-intensive; and measurements are potentially risky during large rainfall–runoff events, even in small streams (Garcia et al., 2000; Turowski et al., 2010). Because of these difficulties, bedload is often omitted from total sediment load estimates; or it is assumed to be a small percentage of the total load (e.g., Milliman and Meade, 1983; Nagle et al., 1999; Wang et al., 2011). Worldwide, the bedload proportion (BL_p) of the total sediment load is believed to be about 10 to 20% for rivers in general and 20 to >40% for mountain streams (Sidle, 1988; Turowski et al., 2010). In some environments, such as the arid regions and ephemeral streams, bedload rates may be exceptionally high, exceeding 50–70% of the total load (e.g., Laronne and Reid, 1993; Rovira et al., 2005). Only limited work has been conducted on bedload in tropical streams, but generally BL_p has often been considered to be quite low (e.g., ~10%; cf. Nagle et al., 1999).

Thailand, for example, has an extensive network of small-to-large reservoirs constructed on many river systems to provide water for agriculture, domestic, and commercial use. While suspended sediment rating curves are calculated routinely for several rivers and streams by the Thai Royal Irrigation Department, detailed studies of bedload processes have not been a priority (e.g., Ziegler et al., 2000). To date, there has only been one other published bedload study conducted in Thailand to guide decisions (Ziegler et al., 2000). In that study, the bedload proportion to the total load was 30%. The paucity of published bedload data in the SE Asia region is egregious given current plans of building a large number of dams in the coming decades (Wang et al., 2011; Ziegler et al., submitted for publication).

This paper reviews the available data for SE Asian streams and presents results from a bedload monitoring experiment conducted in the 74-km^2 Mae Sa catchment in northern Thailand. The Mae Sa River is a tributary into the Ping River, one of the largest rivers in northern Thailand, on which the multi-purpose Bhumipol dam is located. Although the research was conducted on a relatively small river, we believe our results, when combined with the regional bedload data from the reviewed case studies, will provide information to guide management decisions in river systems where bedload transport is very difficult to measure.

2. Part I: review of bedload studies in Southeast Asia

Review of the literature uncovered bedload information on a handful of SE Asian river and stream systems in Cambodia, southern China, Indonesia, Lao PDR, Malaysia (both Peninsular and insular), Papua New Guinea, the Philippines, Thailand, Timor Leste and Vietnam (Table 1). In the review we have included Hong Kong and Papua New Guinea to increase the data pool, even though they are not part of SE Asia by most political definitions. Most work has been done in Malaysia; and no information was found for Brunei, Myanmar or Singapore. The studies were inconsistent in scope and data collection protocol, as well as in the level of detail in the reporting of the results and associated errors.

Early work in the Cameron Highlands, Malaysia, Shallow (1956) determined bedload yields associated with different 'treatments' of steepland agriculture in three forested catchments varying in catchment areas: Sungai (Malay for river; abbreviated as Sg.) Telom (77.7 km^2); Sg. Kial (21.4 km^2); and Sg. Bertam (75.2 km^2). Bedload was measured with box traps embedded into the stream channel. Differences in bedload yields ranging from 25.7 to 70.1 Mg km^{-2} y^{-1} did not appear to be related to the intensity of agriculture. The catchment with the greatest degree of forest conversion (36% reduction in forest in Bertam) had a bedload yield intermediate of the other two catchments with higher forest cover (70 and 94%). The bedload proportion to the total load was higher in catchments with the least amount of forest disturbance.

In a long-term experiment, Kasran (1996) determined bedload yield in the small logged Jengka Experimental Basin at Pahang in Peninsular Malaysia from 1980 to 1989. The forested catchment had an area of 0.28 km^2 and a mean slope of 28%. Bedload was measured in 4 × 3 m sediment traps at six month intervals. Annual bedload yield increased modestly from 10 to 19 Mg km^{-2} y^{-1} during the pre-logging phase to 14–30 Mg km^{-2} y^{-1} following logging. Although bedload yield was higher in the post-logging phase, its proportion to the total sediment load decreased from 60% to 45%, indicating that an increase in logging-associated TSS overwhelmed the proportion of the naturally higher bedload.

Lai (1993) investigated the impacts of logging by comparing bedload yields in four catchments on the western flank of the Main Range in Peninsular Malaysia (1988–1989): Sg. Lawing (4.7 km^2); Sg. Chongkak (12.7 km^2); Sg. Batangsi (19.8 km^2); and Sg. Lui (68.1 km^2). The catchments were moderately steep, with slopes ranging from 34 to 40%. Channel bed material ranged in size from sand to boulders. Bedload transport was determined from rating curves established from measurements made with a Helley–Smith sampler. Very high bedload yields of 1264 Mg km^{-2} y^{-1} were calculated for the Sg. Batangsi catchment, where commercial logging generated stream sediment inputs from both steep logged hillslopes and the logging road network. The bedload proportion was 31% of the total sediment yield. In the unlogged, forested Lawing catchment, bedload yield was 125 Mg km^{-2} y^{-1}, an order of magnitude lower, but BL_p was 70%. Following commercial logging in Sg. Lawing in 1993, bedload yield increased by more than three times the unlogged condition (Lai et al., 1995). Bedload yield was relatively high (333–619 Mg km^{-2} y^{-1}) in Sg. Chongkak, where logging had ended a year before the study was initiated in 1988; and BL_p constituted 20% (note that Chappell et al. (2005) reported a much lower value: <1%, which is <2 Mg km^{-2} y^{-1}). In the largest catchment (Sg. Lui; 68 km^2), bedload yield was the lowest of the four rivers investigated (22 Mg km^{-2} y^{-1}), perhaps because logging had ceased a decade prior to measurement. The lower yield may also be a characteristic of this lower gradient river system with enhanced storage opportunities—features that often differentiate larger verses smaller catchments. Lai (1993) noted high bedload rates occurred during high rainfall periods, indicating the importance of stream energy on bedload transport in this particular system where transportable material was not limited. He also called attention to the role of road construction and logging in elevating sediment yields in some of the catchments.

Lai and Detphachanh (2006) studied bedload yield in the 2.6-km^2 Sungai Pansun catchment in Selangor, Peninsular Malaysia, for a year extending from 1997 to 1998 (Table 1). y^{-1} and 11.4 Mg km^{-2} y^{-1}, respectively. The weir pool estimates were considered superior because they captured the entire sediment cumulative load. The BL_p was an estimated 33%. Two major storm events contributed 45% of the annual bedload yield. Furthermore, large events exhausted the supply of bedload material. Bedload transport (BL_i; kg s^{-1}) had the following relationship with discharge (Q_i; m^3 s^{-1}):

$$BL_i = 0.0017Q_i^{1.0013}. \tag{1}$$

The authors postulated that bedload yield was low because the study was conducted in a dry year with reduced stream flow energy. They expected that under normal conditions, not only would the total yield increase, but bedload would possibly contribute to a greater proportion of the total sediment load. This would obviously require the suspended solid load to not increase proportionally.

Also in Selangor, Peninsular Malaysia, Yusop et al. (2006) monitored the bedload yield in two steep catchments, C1 and C2, at Bukit Tarek from 1991 to 1994 (Table 1). Both experimental catchments are similar in size, but had differing slopes, 33 versus 45% at C1 and C2, respectively. Vegetation consisted of secondary forest that had regenerated 25–30 years following the cessation of logging operations in the early 1960s. The channel bed was composed of sandy clay material and bedload material was generally sand-sized or smaller. Bedload measurements were determined by measuring sediment accumulation behind weirs. Both catchments had relatively low mean bedload yields: 13 and 14 Mg km^{-2} y^{-1}, for C1 and C2 respectively. However, annual variability was high, ranging from 6 to 28 Mg km^{-2} y^{-1} at C1 and 10–20 Mg km^{-2} y^{-1} at C2. This great variation was indicative of the strong influence of episodic storm events on bedload transport as well as the potential for storage behind accumulations of woody debris. Unfortunately, they were unable to quantify TSS in the study, thus there is no estimate of BL_p for these disturbed catchments.

Geoffrey and Yusop (2005) performed a brief study in 2004–2005 on the bedload transport in the small (<1 km^2) regenerated forest catchment of Sg. Kebow in Sarawak, Malaysia. Bedload measurements were made with a Helley–Smith sampler during the six wettest (on average) months of the year (Oct 2004–March 2005). Bedload yield of 1.8 Mg km^{-2} y^{-1} was determined from the following equation estimating total bedload (BL_T, Mg) from river discharge during a sampling period (Q; m^3 s^{-1}):

$$BL_T = 0.0005\,Q^{0.5895}. \tag{2}$$

The highest estimated monthly bedload yield was recorded in December, the month with the highest stream flow. Thus, the high values were a result of determining bedload transport from Eq. (2). The authors reported that large episodic events had a strong influence on the bedload transport at the site.

In comparison with Eqs. (1) and (2), Sirdari (2013) developed the following bedload rating equations for the Kurau, Lui, and Semenyih rivers in Malaysia:

$$BL_i = 0.164\,Q_i^{1.314}. \tag{3}$$

New data were collected with a Helley–Smith sampler on six sand-gravel bed reaches of the Kurau River during flows ranging from 0.55 to 12.79 m^3 s^{-1}. The data were then combined with those determined on the Lui and Semnyih Rivers by Ariffin (2004) to create the equation. Chang and Ab. Ghani (2011) report a similar equation for the Sg. Kumlin:

$$BL_i = 0.171\,Q_i^{0.82}. \tag{4}$$

In general, most recent work in Malaysia has involved short-term bedload data collection to develop transport equations to study the impacts of river sand-mining or reservoir sedimentation (e.g., Yahaya, 1999; Ab. Ghani et al., 2003; Chang, 2006; Chang et al., 2007; Azamathulla et al., 2009; Sinnakaudan et al., 2010; Ab. Ghani et al., 2011; Talib et al., 2012).

Elsewhere in SE Asia, bedload rates have been determined for a few locations in Java, Indonesia (Table 1). Bruijnzeel (1983) reported a yield of 44 Mg km^{-2} y^{-1} for the 0.187-km^2 Mondo River catchment, which had been converted to forest plantation. The BL_p was only 13%, largely because of a high TSS yield (209-313 Mg km^{-2} y^{-1}). Rijsdijk (2012) provide data for the upper and lower sections of three river systems in the Konto basin of Java: Coban, Manting, and Sayang rivers. In all cases, the upper catchments were less disturbed than their lower counter parts which had higher estimated bedload yields. Mean bedload yield increased from <1 to 66 Mg km^{-2} y^{-1} from the forested (88% forest cover), 11.7-km^2 upper Coban Rondo catchment to a lower site, which drained a 21.62-km^2 area. Swidden agriculture was an important land cover in the lower catchment. The BL_p values were very low for both locations: 1.8 versus 6.7%. The Manting upper and lower catchment areas were very similar (3.88 to 4.6 km^2), but had very different yields (means = 0.5 versus 4 Mg km^{-2} y^{-1}). Values of BL_p were similar (0.5 versus 3.6%). Sayang showed a 60% increase in bedload yield between upper (3.41 km^2) and lower catchment (12.33 km^2) sites (means = 46 versus 74 Mg km^{-2} y^{-1}). In this case, however, BL_p reduced from 11.9% in the upper catchment to 6.3% downstream.

The Management of Soil Erosion Consortium (MSEC) project included bedload experiments in their study of 27 experimental catchments located in Indonesia, Lao PDR, the Philippines, Thailand, and Vietnam (Table 1). Annual bedload was measured behind weirs draining sub-catchments ranging in size from less than 1 to more than 250-km^2 (Table 1). Catchment treatments included traditional versus improved farming methods. Technical difficulties limited the results that could be derived from many of the catchments (summarized by Valentin et al. (2008)). However, some data are reported on the project homepage (http://msec.iwmi.org/) and in various project reports or follow-on works (Maglinao and Valentin, n.a.). Collectively, the MSEC data suggest bedload yields across the region are high (44 to 869 Mg km^{-2} y^{-1}) for these agriculture-dominated catchments. In the 0.67-km^2 Huay Pano catchment (Lao PDR), bedload yield ranged from 69 to 117 Mg km^{-2} y^{-1}; and BL_p ranged from 35 to 59%. In contrast, bedload yields in the 0.96-km^2 Dong Cao catchment (Vietnam) were higher (99–322 Mg km^{-2} y^{-1}), but BL_p was lower (23%). Limited data at the 0.92-km^2 Huai Ma Nai site in Thailand indicate very high bedload yields: 95–869 Mg km^{-2} y^{-1}. Bedload yields reported for four small (<0.12 km^2) sub-catchments of mixed agriculture at Huai Ma Nai ranging from 32 to 129 Mg km^{-2} y^{-1} for the rainy season of 2003 (Bricquet et al., 2004). The BL_p for two of the sites was over 60%; but it was only 20% for a third subcatchment. At the 1.39-km^2 Babon study catchment in Indonesia, bedload yields ranged from 158 to 174 Mg km^{-2} y^{-1}, occupying 29–88% of the estimated total loads. Bedload yield at the 0.91-km^2 Mapawa catchment in the Philippines was higher (301–517 Mg km^{-2} y^{-1}), but BL_p could not be quantified because of difficulties in measuring suspended sediment.

Data for Cambodia, Hong Kong, Papua New Guinea, Timor Leste, and Vietnam are few and of unknown quality (Table 1). For example, very low bedload yields of 0.06 and 0.7 Mg km^{-2} y^{-1} were reported for the Stung Sen and the Stung Ksach Toch rivers in Cambodia (Douglas, 1999; Carbonnel and Guiscafre, 1965). The bedload yield (112 Mg km^{-2} y^{-1}) for the Fly River in Papua New Guinea is based on Walsh and Ridd's (2008) estimation that fine sediment comprises 90% of total sediment load, 1118 Mg km^{-2} y^{-1} (from Harris et al. (1993)). The only data for Timor Leste are estimates of the bedload proportion of the total sediment load—up to 50% in the Laclo and Caraulun rivers (Alongi et al., 2009). Douglas (1999) provides limited bedload information for the Sesan River at Kontum (2910-km^2) and Trung Nhia (3139-km^2) in Vietnam. The proportion of bedload to the total load was an estimated 5–64%—and a value of 20% was assumed to be the mean. In a small (<1-km^2) urban basin in Hong Kong, Peart and Fok (2006) found annual sediment yields ranging from 0.4 to 3.9 Mg km^{-2} y^{-1} with a mean bedload yield of 1.3 Mg km^{-2} y^{-1}during a 15-year study conducted between 1989

Table 1
Summary of studies conducted in SE Asia region reporting data for which bedload yield (BL_{yield}), suspended sediment yield (TSS_{yield}), and the fraction of the total load that is bedload (BL_p).

Reference[a]	Area km^2	BL_{yield} Mg $km^{-2}y^{-1}$	TSS_{yield} Mg km^{-2} y^{-1}	BL_p %	Site note	Type[b]	Time	Note
Stung Sen at K. Chamlang (Cambodia)[1]	16200	0.062	0.61	9	Various states for forest, savanna, and wetlands	Lake	1962–1963	Bedload determined as sand transport
Stung Ksach Toch (Cambodia)[1]	30	0.70	-	-	Various states for forest, savanna, and wetlands	Weir	1962–1963	Bedload determined as sand transport; TTS is basin degradation rate
Shek Kong, Kam Tin basin (Hong Kong)[2]	1	1.3	-	-	Woodlands and shrublands	Weir	1989–2003	Geology: intrusive granodiorite
Sg. Ikan (Malaysia)[3]	9.2	<1	-	-	Rainforest and agriculture	–	–	–
Mondo River, Java (Indonesia)[4]	0.187	44	209-313	13	Agricultural land use	calc	1977	Metamorphic rocks, phyllites, graywackes, shales, marls, volcanic breccias
Upper Coban Rondo, Java (Indonesia)[5]	11.7	0.4–0.9	23–48	1.8	88% forested	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Lower Coban Rondo, Java (Indonesia)[5]	21.62	54–78	523–1332	6.7	Forests (49%) and agriculture	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Upper Manting, Java (Indonesia)[5]	3.88	0.4–0.5	77–113	0.5	82% forest	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Lower Manting, Java (Indonesia)[5]	4.6	4.0	81–548	3.6	Forest (69%) and agriculture	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Upper Sayang, Java (Indonesia)[5]	3.41	43–49	340–715	11.9	Forest (60%) and agriculture	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Lower Sayang, Java (Indonesia)[5]	12.33	35–74	621–1179	6.3	Forest (35%) and agriculture	Trap	1988–89	Volcanic geomorphology: soils: Andosols, Cambisols and Luvisols
Babon, Java (Indonesia)[6]	1.39	158–174	22–433	29–88	Agroforestry and lowland rice	Weir	2001–2002	Geology: andesite and basaltic rocks
Huay Pano (Lao PDR)[6]	0.67	69–117	81–126	35–59	Trad. agriculture & trial practices	Weir	2001–2002	Geology: Shale, schist, mudstone, sandstone
Huay Pano sub-catchments (Lao PDR)[7]	0.57–0.73	11–474	1–99	19–98	Trad. agriculture & trial practices	Weir	ca 2000–2002	Geology: shale, schist, mudstone, sandstone
Sg. Telom (Cameron Highlands, Malaysia)[8]	77.7	25.7	50	34	Forest (94%) and agriculture	Trap	pre 1960	Regional geology: slate, phyllite, schist and granite
Sg. Kial (Cameron Highlands, Malaysia)[8]	21.4	70.1	265	21	Forest (70%) and agriculture	Trap	pre 1960	Regional geology: slate, phyllite, schist and granite
Sg. Bertam (Cameron Highlands, Malaysia)[8]	75.2	35.7	250	12	Forest (64%) and agriculture	Trap	Pre 1960	Regional geology: slate, phyllite, schist and granite
Sg. Lawing, Main Range (Malaysia)[9]	4.7	125	54	70	Steep rainforest (unlogged)	HS	1988–89	Geology: medium granite; steep, channel gradient = 0.17; bedload: sand–boulder
Sg. Lawing, Main Range (Malaysia)[9]	4.7	414	1129	27	Logging began at start of the year	HS	1993	Geology: medium granite; steep, channel gradient = 0.17; bedload: sand–boulder
Sg. Chongkak, Main Range (Malaysia)[9]	12.7	334–619	1335–2476	20	Logging ceased in April 1987	HS	1987–88	Geology: granodiorite granite; steep, channel gradient = 0.11; bedload: sand–boulder
Sg. Batangsi, Main Range `(Malaysia)[9]	19.8	1264	2826	31	Steep rainforest; logging	HS	1987–89	Geology: coarse grainite; steep, mean main channel slope = 0.05; bedload: sand–boulder

Sg. Lui, Main Range (Malaysia)[9]	68.1	22	90	20	80% forest; logging ceased in 1978	HS	1987–89	Mean main channel slope = 0.02; bedload: sand to boulder bedload
Bukit Tarek catchment C1 (Malaysia)[10]	0.33	6–28	–	–	25 + year forest regrowth	Trap	1991–1994	Geology: quartzite; sandy-clay channel bed; sand-dominated bedload
Bukit Tarek catchment C2 (Malaysia)[10]	0.34	10–20	–	–	25 + year forest regrowth	Trap	1991–1994	Geology: quartzite; sandy-clay channel bed; sand-dominated bedload
Sg. Kebow (Sarawak, Malaysia)[11]	0.6	1.80	–	–	Secondary regenerated forest	HS	10/04–3/05	Geology: sandstone, shale, limestone, mudstone
Jengka Exp. Basin, Pahang (Malaysia)[12]	0.28	10–19	4–22	60	Rainforest (pre-logging)	Trap	1980–1986	Geology: Triassic sedimentary rocks with shale and sandstone
Jengka Exp. Basin, Pahang (Malaysia)[12]	0.28	14–30	23–38	45	Rainforest (post-logging)	Trap	1987–1989	Geology: Triassic sedimentary rocks with shale and sandstone
Berembum subcatchments (Malaysia)[13]	0.04-0.29	2-242	7-27	20–90	Undisturbed forests	–	1980-1985	Granitic rocks; soil textures range from coarse to sandy clay
Ulu Langat Forest Reserve (Malyasia)[14]	2.6	1–2	10	17	Hill forest in a reserve	HS	1997–1998	Geology: orthoquartzitic sedimentary rocks; and argillaceous and calcareous shales.
Sg. Pansun, Main Range (Malaysia)[15]	2.6	4.6-11.4	22	33	Forested catchment	Trap/HS	09/97–06/98	Geology: granite, quartzite, schist; mean main channel slope = 0.29; bedload: gravel
Fly River (Papua New Guinea)[16]	184000	112	1006	10	30% forested; great mining effects	Est	NA	Varied lithology including volcanics, clastics, limestones, and sediments
Mapawa (The Philippines)[6]	0.91	301–517	–	–	Tree plantations, grass, crops	Weir	2001–2002	Predominantly of an argillaceous and carbonate rocks
Huai Yai (Thailand); 4 small weirs[17]	0.032–0.118	10–1620	70–520	13.3–75.7	Mixed Agriculture	Weir	2001–2002	Geology: siltstone, sandstone, limestone, shale, and phyllite
Mae Thang Reservoir survey (Thailand)[17]	121	2013	3087	39	Mixed agriculture	Res	2001–2002	Geology: siltstone, sandstone, limestone, shale, and phyllite
Huai Ma Nai (Thailand)[6]	0.92	95–869	147–466	39–65	Mixed agriculture	Weir	2001–2002	Geology: siltstone, sandstone, limestone, shale, and phyllite
Huai Ma Nai sub-catchments (Thailand)[18]	0.032–0.118	32–129	22–128	20–68	Mixed agriculture	Weir	2003	Geology: siltstone, sandstone, limestone, shale, and phyllite
Pang Khum (Thailand)[19]	0.94	28	65	30	Mixed forest and agriculture;	Weir	1998–99	Geology: granite; relatively flat main channel; stone bedload material
Huay Ma Feung (Rayong, Thailand)[20]	1.12	8395	2099	80	Undergoing road construction	Weir	1982–1983	Geology: schist, gneiss, sandstone
Mae Sa (Thailand)[21]	74	81–279	649–1037	18(9–25)	Mixed forest and agriculture;	HS	2005	Geology: granite, schist, limestone, marble; sand bedload material
Laclo & Caraulun Rivers (Timor Leste)[22]	580–1386	360-3988	3240–3988	10-50	Degraded catchments	Est	2006–2008	Highly erosive environment with landslides and river incision
Dong Cao (Vietnam): small weirs[23]	0.037–0.108	35–669	–	–	Agriculture and treatments	Weir	1999–2002	Geology: schist; soil: ultisols
Dong Cao (Vietnam): small weirs[24]	0.037–0.108	<20-1200	–	–	Agriculture and treatments	Weir	2000–2005	Geology: schist; soil: ultisols
Dong Cao (Vietnam): main weir[6,24]	0.96	99-322	330	23	Agriculture and treatments	Weir	2000–2005	Geology: schist; soil: ultisols
Sesan River (Vietnam)[25]	2910–3139	–	–	5-64	60% forested	HS	1994–1995	Diverse geology and soils

(continued on next page)

Table 1 (*continued*)

Reference[a]	Area km^2	BL_{yield} Mg $\text{km}^{-2}\text{y}^{-1}$	$\text{TSS}_{\text{yield}}$ Mg km^{-2} y^{-1}	BL_p %	Site note	Type[b]	Time	Note
Other Regional data								
East Tributary, Ngarradj Creek (Australia)[26]	10	58	60	49	Undisturbed catchment	HS	1998	Geology: quartz sandstone; bed sediments include a variety of sands and pebbles
Upper Swift Creek, Ngarradj[27] Creek (Australia)	19	53	–	–	Mining affected	HS	1998–2002	Geology: quartz sandstone; bed sediments include a variety of sands and pebbles
Swift Creek, Ngarradj Creek (Australia)[27]	44	37	–	–	Mining affected	HS	1998–2002	Geology: quartz sandstone; bed sediments include a variety of sands and pebbles
Magela Creek (N Territory, Australia)[28]	600	9	12	49	Mixed include barren lands, savannahs, and forest	HS	1980–1989	Drains plateau of resistant quartzose sandstone
Bhramaputra River (Bangladesh)[29]	583000	413	397	51	Variable (large catchment)	Est	Long-term	Sand-bottom river
Ganges (Bangladesh)[29]	1060000	270	260	51	Variable (large catchment)	Est	Long-term	Sand-bottom river
Yangtze River at xDatong (China)[30]	1705400	5	238	2	Variable (large catchment)	Est	50+ years	
Jinsha River (China)[31]	485000	16–56	196–666	8	Area affected by mass wasting	Mixed	1958–1984	Steep terrain in three provinces: Tibet, Yunnan and Sichuan
Marsyandi River (Nepal)[32]	4800	1083	5563	16–35	Erosive environment, landslides	Hydro/sd	Unsure	Geology: Greater Himalayan metasedimentary marbles and gneisses
Kali Gandaki River (Nepal)[33]	46300	216–680	475–1134	25–45	Erosive environment, landslides	Hydro	2006–2012	Geology: gneisses and metasediments
Reservoirs in Taiwan[34]	15–763	–	–	0–74	Various	Res	10–30 years	Estimated from 150 suspended sediment stations (see note Turowski et al., 2010)
Choshui river (Taiwan)[35]	3155	913–2107	4916–6109	13–30	Affected by typhoons, earthquakes	Res	2003	High relief, steep gradients, frequent tectonic activity

[a] References are (1) Carbonnel and Guiscafre (1965) and Douglas (1999); (2) Peart and Jayawardena (1994); Peart and Fok (2006); (3) Kasran et al. (1996) cited by Geoffrey and Yusop (2005) and Chew (1999); (4) Bruijnzeel (1983); (5) Rijsdijk (2012); (6) MSEC experiments summarized by Valentin et al. (2008) and msec.iwmi.org/res/tools/database/bedload.htm; (7) Maglinao and Valentin, n.a.; (8) Shallow (1956) cited by Geoffrey and Yusop (2005), Lai (1993), and Choy (2002); (9) Lai (1993) & Lai et al. (1995); (10) Yusop et al. (2006); (11) extrapolated to one year using data of Geoffrey and Yusop (2005); (12) Kasran (1996); (13) Abdul Rahim et al. (1985) cited in Kasran (1996); Kasran (1988); (14) Detphachanh (2000); (15) Lai and Detphachanh (2006); (16) Estimated based on Walsh and Ridd (2008) comment about 90% of total load of 100,000,000 Mg/y being fine sediment; (17) Janeau et al. (2003); (18) Bricquet et al. (2004); (19) Ziegler et al. (2000); (20) Henderson and Witthawatchutikul (1984); (21) this study; (22) estimate by Alongi et al. (2009); (23) Toan et al. (2003); (24) Orange et al. (2012); (25) IMH (1998) cited by Douglas (1999); (26) Saynor et al. (2006); (27) Erskine et al. (2011); (28) Roberts (1991) and Erskine and Saynor (2000); (29) Turowski et al. (2010), Milliman and Farnswarth (2011); (30) based on the estimate of Hu et al. (2009) that only 2% of the total load is bedload; (31) Liu et al. (2011); (32) Values from Shrestha and Wannick (1989) suggest BLp value of 16%; the analysis of Pratt-Sitaula et al. (2007) suggest 35%; (33) Struck et al. (2013) and pers. comm (2013); (34) Dadson (2003a) reported in Turowski et al. (2010); (35) based on weir accumulation rates stated by Yeh et al. (2010) at Chi–Chi weir and Dadson et al. (2003b) estimate that bedload in Taiwan Rivers is 30% of the total load.

[b] HS refers to a Helly–Smith sampler measuring sediment trapped behind a weir; trap refers to collection in traps excavated into the channel; Res refers to data estimated from reservoir sediments; sd refers to sedimentary deposits; hydro refers to determined hydropowerstation; mixed refers to various methods such as back calculation or modeling.

and 2003 (also see Peart and Jayawardena (1994)). The great variability in annual load was related largely to the occurrence/absence of large storms that could mobilize large loads.

In Thailand, Ziegler et al. (2000) determined stream sediment contributions from roads, paths, and agriculture lands in the 0.94-km^2 Pang Khum Experimental Watershed (Table 1). Sediment, largely sand and small stones, trapped behind the weir at the catchment outlet was measured irregularly over a one-year period. Road sediment input to the stream was only slightly higher than that from agricultural lands (30–41 versus 25–40 Mg), but corresponding erosion rates were substantially greater (65–88 versus 0.02–0.04 Mg km^{-2} y^{-1}). The bedload proportion of total sediment was 30%. In contrast, 80% of the road-generated material entering the Huay Ma Fueng stream in Rayong Province was bedload (Henderson and Witthawatchutikul, 1984). The study in Pang Khum indicated that sediment budgeting approaches are needed to uncover important sediment sources that occupy small percentages of the total basin area (e.g., roads, landslides). Subsequent observations (unpublished) showed the importance of singular large events on bedload transport, as the capacity of the weir to trap bedload could be exceeded during one high flow event, but not likely during several months of low flows.

In brief, the bedload studies reviewed show that the bedload proportion to total sediment loads was frequently >10%—and often ≥30%. In addition, bedload transport was typically episodic, with high proportions being mobilized by infrequent large storms. The results of many studies had great uncertainty related to the difficulty in measuring bedload, as well as the short duration of the studies. In general, the amount of fieldwork dedicated to quantifying bedload is limited.

3. Part II: case study

3.1. Study area

In 2005 we conducted a bedload study in the 74-km^2 Mae Sa River Catchment in Chiang Mai Province of northern Thailand (Fig. 1). The Mae Sa River is a headwater tributary to the Ping River, which joins the Nan River to form the Chao Phraya, Thailand's largest river. Before the confluence, the Ping River enters the Bhumibol Reservoir in Tak Province (Fig. 1). Located almost 500 km north of Bangkok, the reservoir was built for water storage, hydroelectric power production, flood control, fisheries and saltwater intrusion management (cf. Tebakari et al., 2012).

Lithology in the Mae Sa catchment is variable. Milled granite and gneiss (both ortho- and para-gneiss) are the dominant rocks, but phyllite, limestone, and marble are also present. Soils are mostly ultisols, alfisols, and inceptisols that overlie a variably deep (1–20 m) weathered zone of iron-rich, orange-colored saprolite. Rainfall ranges from 1200 to 2000 mm, of which 80% of the total falls in the May–October monsoon rain season (Ziegler et al., 2011). Annual catchment runoff is approximately 20–30% of the annual rainfall total. Mean hillslope gradient, calculated from a 30-m DEM, is 0.28 (15.4°); the maximum is 1.54 (57°).

Much of the main stream is located on relatively flat valley floors, separated by a series of large waterfalls over bedrock (cascades). The river generally flows in a singular channel that is confined by the steep mountain topography. In some valley locations, the channel meanders on a wide riparian plain and the network is affected by agriculture—previously rice cultivation and now commercial agriculture. The channel gradient for the entire catchment is 0.11, with short sections varying from nearly flat to >1. Stream bed material in the main channel depends on location, relative to gradient. Most steep sections are composed of large stones and boulders on bedrock, while other sections are sand-dominated, but overlay larger material, including bedrock. The tributaries draining the surrounding mountain slopes often have steep, narrow channels (<1 m) and the stream beds are composed of large stones and boulders. In areas where the main channel flows through relatively flat valleys the surface bed material is largely sand.

Land use in the catchment includes forest reserves, cultivated hill slopes including plantations, rapidly-expanding greenhouse agriculture, and urbanized areas (Fig. 1). Much of the forested land is protected as a national park. The catchment is also an important recreational/tourist area that features several venues surrounding the stream, including two elephant camps, a botanical park, several resorts/spas, and various ecotourism activities (Sidle and Ziegler, 2010). An extensive paved and unpaved road system exists within the basin, linking numerous villages and agriculture sites. These roads are important sources of

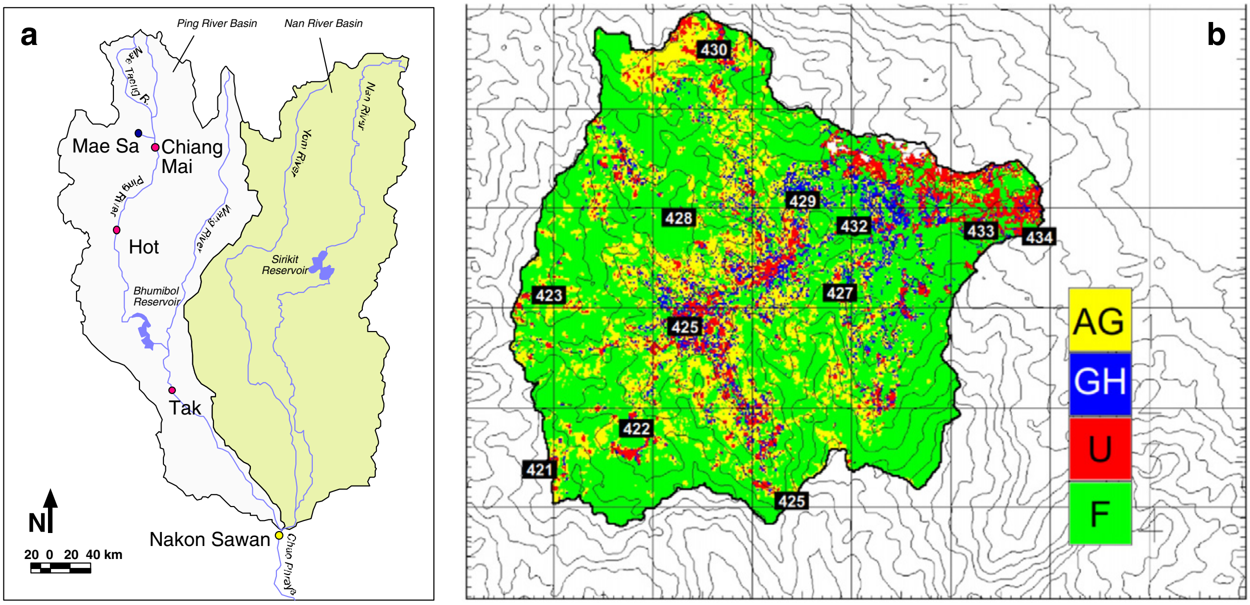

Fig. 1. (a) Location of Mae Sa study area in northern Thailand in relationship to other major rivers. (b) Major land covers in the catchment include forest of various degrees of disturbance (F, 62%); hillslope and plantation agriculture (AG, 23%), (peri)urbanized areas (UR, 8%), and greenhouse agriculture (GH, 7%). Grid cell dimensions are 2 × 2 km. Numbers refer to the location of hydro-meteorological measurement instruments in the catchment. Streamflow variables were monitored at location 434. Rainfall is measured at all other number stations (black numbered rectangles).

coarse sediment entering the stream during infrequent mass wasting events (Ziegler et al., 2011).

Local officials believe there has been a significant increase in sediment transport in the Mae Sa river over the last couple of decades. Stream water color 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. Additionally, distinct sediment deposits (bars, overbank deposits) appear in the lower gradient reaches of the river. Recently, several water quality studies conducted in sub-catchments indicate increased chemical and sediment loadings (Ciglasch et al., 2005, 2006; Kahl et al., 2008; Sidle and Ziegler, 2010). Erosion rates as high as 80 Mg ha^{-1} y^{-1} have been reported for some steep cultivated fields (Ongprasert, 1995). Suspended sediment delivery rates were estimated in a preliminary investigation (Ziegler et al., 2011): 1075 Mg km^{-2} y^{-1} for year 2006. This yield has since been revised to 839 Mg km^{-2} y^{-1} (see below). River discharge from the 74-km^2 catchment has exceeded 30 m^3 s^{-1} (observed in 2006).

4. Methods

4.1. Rainfall and discharge measurements

The study was conducted from 10 July to 3 September 2005, during the height of the monsoon rainy season. Rainfall was recorded at 1-min intervals with tipping-bucket rain gages (Onset; 15.4-cm receiving orifice) situated at 11 measurement locations in the basin (Fig. 1). 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 (Ziegler et al., 2009). Stream stage was measured automatically in an unmodified cross-section of the main channel with a Campbell Scientific CS425 pressure transducer and CR10X data logger (Station 434; Fig. 1b). A stage-discharge rating curve was determined from 56 stage–velocity–profile measurements made during flow volumes ranging from 0.3 to 30 m^{3}s^{-1} (Ziegler et al., 2011). A total of 29 measurements were made during 2005, the year of this study. The streambed profile was monitored continuously to correct for stage–discharge relationship variations related to changes in the stream bed.

4.2. Bedload measurements

Bedload was measured with a Helley–Smith sampler (Helley and Smith, 1971). Internal dimensions of the sampler intake were 7.62 cm × 7.62 cm. 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-bottom stream bed at 1-m intervals across the stream. Thus, each interval sample was the aggregate of 5–7 subsamples (more subsamples were taken as stream width increased during runoff events). The target sample collection interval was 60 s per channel location. For consistency, the same sampling locations were used for all measurements. Sampling was performed standing in the stream.

The study was designed to collect samples during baseflow, rising limb, peak, and falling limb conditions of individual events; however, some periods only contained a few base flow samples, taken on days when rainfall did not occur. Each sample was dried at 50°C in the laboratory to a constant mass. Bedload transport rate (BL$_t$; kg s^{-1}) was calculated as

$$\mathrm{BL_t} = \frac{\mathrm{W_{stream}}}{\mathrm{W_{HS}} * \mathrm{n}} * \sum_{i=1}^{n} \frac{\mathrm{M_i}}{\mathrm{t_i}}. \qquad (5)$$

where W$_{\text{stream}}$ is the width of the stream, and W$_{\text{HS}}$ is the width of the intake of the Helley–Smith collector (0.0762 m); n is the number of sample locations across the stream (n = 5–7); M$_i$ is the mass of bedload collected at each location; and t$_i$ is the collection time for each measurement.

To investigate the relationship between discharge and size of material transported, grain-size distributions were determined by sieving 45 bedload samples into the following fractions: >2.0 mm, 1.0–2.0 mm, 0.5–1.0 mm, 0.25–0.5 mm, 0.125–0.25 mm, 0.063–0.125 mm, and < 0.063 mm. From these data, the geometric mean particle diameter was determined by Yuen et al. (2012).

4.3. Total suspended solids and turbidity measurements

We used a self-cleaning, infrared, 90° optics, Analite (McVan 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. During deployment, the probe was housed inside a perforated PVC pipe (7.6 cm diameter), which was suspended from temporary bamboo bridge, approximately 2 m above the river bed (Ziegler et al., 2011). This cantilever system allowed the probe to remain immersed in the water column, approximately 10–20 cm below the water surface for all flow ranges (Ziegler et al., 2011). 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 (minutely during runoff events). Each recorded value was the median of several readings taken over a period of about 45 s.

We also collected 300-mL suspended sediment samples with a hand-held US-DH-48 depth-integrated sampler to quantify total suspended solids (TSS). Samples were paired with turbidity readings to provide a means of calibrating the probe to estimate TSS concentrations from the automated turbidity time series. Samples often 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. Continuous monitoring of stream turbidity was necessary because sediment in the Mae Sa River moves in asynchronous pulses; therefore, sediment rating curves based solely on discharge are inadequate (cf. Ziegler et al., 2011). Thus, the synoptic sampling employed in the study allowed for capturing changes in the turbidity–TSS (also Q–TSS) signal associated with the rising and falling limbs of the stream hydrograph.

5. Results

5.1. Runoff events

Either one or both of bedload and total suspended solids were sampled during 23 sampling occasions in 2005 (Table 2). Both bedload and TSS were collected during 17 events; however, only during 15 events were bedload, TSS, turbidity, and discharge sampled completely (Table 3). Stream discharge was characterized by base flows ranging from 0.4 m^3 s^{-1} to 1.3 m^3 s^{-1}, with the higher values occurring later during the field campaign in September (Table 2; Fig. 2). Storm response was flashy; with peak discharges (>10 m^3 s^{-1}) typically lasting only a few minutes (Fig. 2). Turbidity, which is a proxy for total suspended solids, also had a flashy signal (Fig. 2). However, flushes of turbid waters were at times asynchronous with runoff discharge peaks, and maximum turbidity values were recorded over a wide range of measured discharges (Fig. 2). Sediment peaks often arrived after discharge peaks; and high sediment concentrations were often seen on the falling limbs of storm hydrographs, creating an anticlockwise hysteresis effect.

5.2. Bedload transport

A total of 136 bedload samples was collected during 23 sampling events; and the number of samples per sampling occasion varied from 1 to 19 (Table 2). Stream cross-section width during the bedload measurements ranged from about 6–8 m during the measurements.

Table 2
Summary data for sampling occasions when bedload (BL) and total suspended solid (TSS) samples were taken in 2005.

Sampling Occasions	Q_{min} ($m^3\ s^{-1}$)	Q_{max} ($m^3\ s^{-1}$)	BL_{min} ($kg\ s^{-1}$)	BL_{max} ($kg\ s^{-1}$)	n_{BL}	TSS_{min} ($kg\ m^{-3}$)	TSS_{max} ($kg\ m^{-3}$)	n_{TSS}
10-Jul-05	0.4	0.5	0.001	0.002	3	0.03	0.05	3
12-Jul-05	0.4	0.5	0.001	0.002	3	0.02	0.02	2
13-Jul-05	0.4	2.2	0.008	0.038	9	1.33	5.35	37
14-Jul-05	0.4	2.4	0.002	0.096	7	0.13	3.74	15
15-Jul-05	0.4	8.6	nd	nd	nd	4.28	10.08	10
19-Jul-05	0.4	1.0	0.005	0.009	3	0.06	0.07	3
22-Jul-05	0.9	2.1	0.032	0.071	4	0.51	2.02	36
24-Jul-05	1.0	2.1	0.011	0.018	2	nd	nd	nd
26-Jul-05	1.2	2.1	0.030	0.036	2	0.16	0.47	8
27-Jul-05	1.2	1.9	0.020	0.042	3	0.17	3.36	27
13-Aug-05	1.3	1.7	0.089	0.379	9	nd	nd	nd
16-Aug-05	1.1	1.6	0.074	0.082	2	nd	nd	nd
17-Aug-05	1.1	2.1	0.079	0.338	9	0.10	0.78	8
18-Aug-05	0.6	2.5	0.119	0.187	9	0.10	1.42	14
22-Aug-05	0.6	1.2	0.067	0.127	3	0.16	0.16	1
24-Aug-05	0.6	0.9	0.036	0.106	7	0.04	0.05	2
25-Aug-05	0.7	4.4	0.030	1.137	19	0.07	9.10	29
26-Aug-05	0.8	27.5	0.054	0.185	2	1.54	14.05	20
27-Aug-05	0.9	2.6	0.053	0.130	4	nd	nd	nd
30-Aug-05	1.2	3.2	0.024	0.149	11	1.63	3.64	37
1-Sep-05	0.6	3.2	0.043	0.129	11	0.12	1.33	14
2-Sep-05	0.6	3.2	0.068	0.068	1	0.50	0.50	1
3-Sep-05	0.6	3.9	0.025	1.060	13	0.15	13.54	20

Q_{min} and Q_{max} are the minimum and maximum discharges during bedload sampling; BL_{min} and BL_{max} are the minimum and maximum recorded bedload transport rates for the entire stream cross-section; n_{BL} is the number of bedload samples taken during the period; TSS_{min} and TSS_{max} are the minimum and maximum total suspended solid concentrations. And n_{TSS} is the number of TSS samples taken during the event. nd indicates that no data were collected.

Corresponding discharges ranged from 0.4 to 4.5 $m^3\ s^{-1}$ (not reported in the table)—although much higher flows occurred during two sample occasions, forcing an end to sampling. Sampling for extreme flows >4.5 $m^3\ s^{-1}$ was not possible because of safety issues. Thus, our analyses focus on "low-energy" stormflow conditions ($Q_i < 5\ m^3\ s^{-1}$). In the Discussion section we explore the significance of not measuring high-energy flows.

The highest measured bedload rate (>1.14 $kg\ s^{-1}$) was associated with a discharge of 3.9 ms^{-1} during the 25 August event (intermediate of the range reported in Table 2). Values as low as 0.001 $kg\ s^{-1}$ were observed during low-flow conditions (Table 2). A reasonable power function relationship based on discharge (Q_i), was derived from the 136 samples ($R^2 = 0.73$; Fig. 3):

$$BL_i = 0.02{Q_i}^{2.47}. \quad (6)$$

The high degree of observed intra- and inter-event variability indicates that bedload transport was probably affected by the availability of material or source of material, rather than the transport capacity of the flow during the measured low-energy runoff events. We observed that sand material built up in the largely flat study reach in between events. This material was flushed as bedload during subsequent runoff events. Although more bedload material was likely transported from upstream, we believe the primary source for most of the events was sand material stored immediately above the study reach. Although we have no means to directly quantify this statement, this appears reasonable based on other measurements of bedload particle transport (e.g., Gomi and Sidle, 2003; Hill et al., 2010).

There was a general consistency in the geometric mean particle diameter (GMPD) of the material transported by a range of flow discharges. All but two of the 51 samples had a GMPD corresponding to course sand (values ranged from 600 to 1200 μm). Eighty percent of all material measured was 250–1000 μm, of which half was courser than 500 μm (not shown). Grain size was not correlated with discharge (Cullen and Hoey, 2003). For the range of discharges measured, we

Table 3
Summary of discharge (Q), bedload (BL), total suspended solids (TSS) calculations for 15 low-energy events.

Date	Start	Stop	D (s)	Q (m^3s^{-1})	Q_T (m^3)	BL_T (Mg)	TSS_T (Mg)	BL_p –
10-Jul-05	15:37	16:08	1860	0.6	1070	0.01	0.04	14%
12-Jul-05	14:17	16:10	6780	0.4	2735	0.01	0.05	21%
13-Jul-05	13:30	16:58	12481	1.4	17454	0.64	32.99	2%
14-Jul-05	15:37	18:11	9241	1.1	10213	0.38	14.63	3%
19-Jul-05	16:02	17:45	6180	0.8	5177	0.07	0.25	21%
22-Jul-05	13:20	15:56	9361	1.3	11723	0.32	8.92	4%
26-Jul-05	14:18	17:40	12121	1.3	15891	0.47	3.12	13%
27-Jul-05	14:45	18:04	11941	1.4	16448	0.53	16.47	3%
17-Aug-05	13:09	19:33	23041	1.4	31179	1.00	7.27	12%
18-Aug-05	16:57	19:44	10021	1.7	17342	0.84	9.54	8%
24-Aug-05	15:09	15:43	2040	1.0	2011	0.04	0.06	38%
25-Aug-05	14:30	18:40	15001	3.2	47582	6.19	173.34	3%
26-Aug-05	15:38	18:50	11521	9.5	109370	2.71	83.10	3%
30-Aug-05	16:33	21:12	16741	1.7	29138	1.41	56.71	2%
03-Sep-05	11:22	16:45	19381	2.4	47135	4.00	126.05	3%

D is duration; Q is discharge (Q_T/D), Q_T is total discharge, BL_T is total bedload transport, TSS_r is total suspended solid transport; BL_p is the percentage of the total load that is bedload.

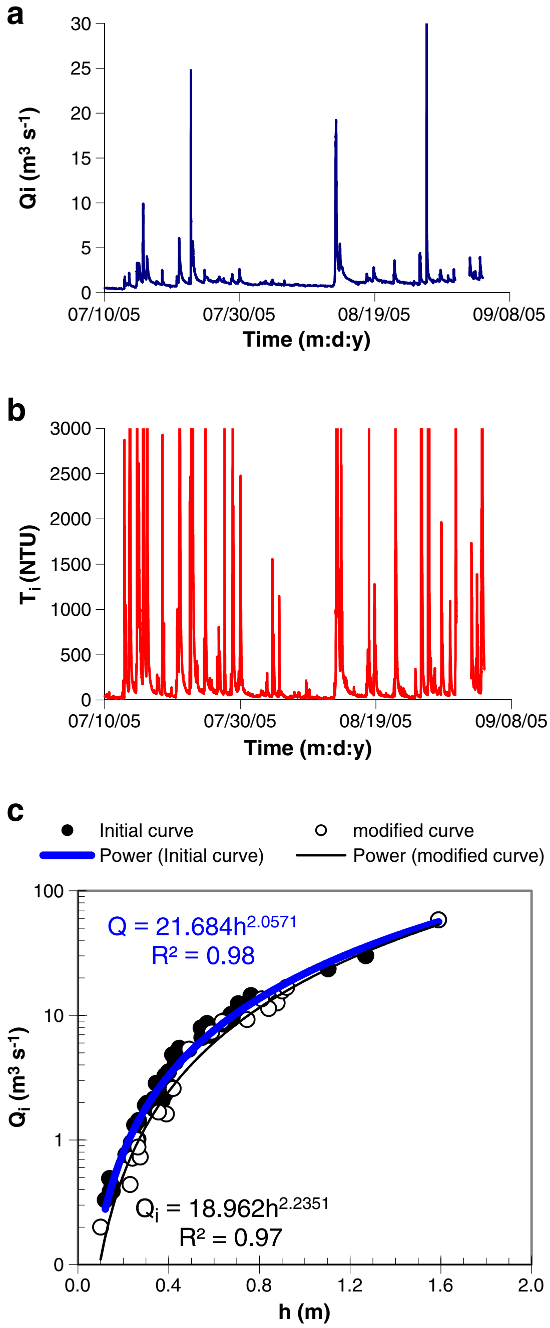

Fig. 2. Automatically recorded (a) discharge (Q_i) and (b) turbidity (T_i). Values are recorded every 1 to 20 min, depending on flow conditions, during the 10 July–3 September 2005 study period. A data gap occurs from 1 to 2 September. (c) The discharge (Q_i) rating curve for station 434 on the Mae Sa River (h is river stage). The modified equation was determined following a noticeable change in the stream channel bed on 27 July 2006.

did not see a noticeable change in the size of bedload, which is often associated with transitions in the movement of temporarily-stored sands that are entrained by increases in flow energy and the initiation of movement of coarser channel material (Church and Hassan, 2002; Ryan et al., 2002). We interpret this simply as the measured discharge that had not reached the threshold needed to mobilize larger material. Doing so would require energy greater than during the events we could measure, but less than bankfull discharge, as has been found elsewhere (cf. Lisle, 1995).

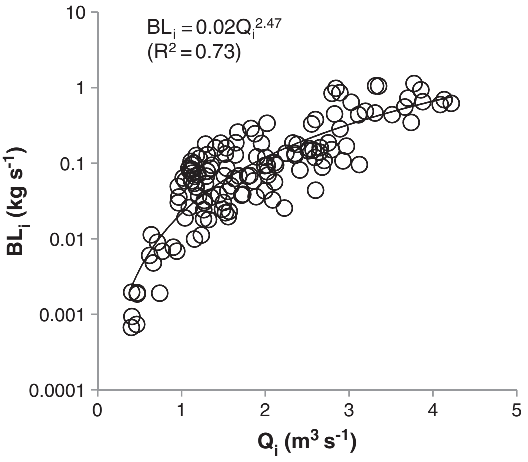

Fig. 3. Power relationship between measured bedload rate (BL_i) and discharge (Q_i). Eq. (6) is calculated from these 136 sample values (circles).

5.3. Total suspended solid concentrations

A total of 287 TSS samples were collected during 19 events (Table 2). Concentrations of total suspended solids (TSS) ranged from 20 to 14,000 mg l^{-1}. Peak concentration exceeded 10,000 mg l^{-1} during three separate events (Table 2). TSS concentrations are generally predicted poorly by discharge, as is demonstrated in the discharge–TSS relationship ($R^2 = 0.59$; Fig. 4a). In addition, a turbidity-based prediction of TSS is inaccurate at high concentrations that surpass the detection limit of the sensor (T = 3000 NTU), despite the fit being reasonable ($R^2 = 0.92$; Fig. 4b). To address this problem, we relied on results from prior work on the river. That study showed that TSS (mg l^{-1}) at high concentrations could be best estimated with a complex equation based on both Q and T (Ziegler et al., 2011):

$$TSS = \begin{cases} 1.10T^{0.99} & T \leq 200\ \text{NTU} \\ 146.35Q^{1.61} + 0.0019T^{1.82} & 200\ \text{NTU} < T \end{cases} \tag{7}$$

where all coefficients are determined from regression analysis on the 287 samples collected in this study; and TSS is restricted to ≤14,050 mg l^{-1}, the maximum observed value. The inclusion of discharge in the complex function overcomes the problem of turbidity–sensor readings maxing out at high TSS concentrations. Ongoing research shows that unique, year-specific variations of Eq. (7) provide the best annual load estimates. In the prior work we discuss the rationale for separating at a moderate turbidity threshold of 200 NTU. Importantly, the separation allows Eq. (7) to have a good fit ($R^2 = 0.73$) throughout the range of observed TSS values (Fig. 5b). The fit for predicted bedload is also reasonable ($R^2 = 0.81$), but has substantial scatter (Fig. 5a).

5.4. Bedload versus suspended load

We calculated bedload and total suspended solid loads for the low-energy (i.e., $Q < 5$ m^3 s^{-1}) portion of each of the 15 events for which Q, TSS, and bedload were all available (Table 3). To do so we use the automatically collected discharge and turbidity time series along with Eqs. (6) and (7). Exclusion of high-energy periods affected only 58 and 112 min periods during the 22 July and 26 August events, respectively. Suspended solids dominated the total transported loads during all events (Table 3). For all but one event (24 August), the bedload proportion (BL_p) was ≤21% of the total load. During the 24 August event, BL_p (38%) was characterized by low mean discharge (1.0 m^3 s^{-1}) and low turbidity (24 to 41 NTU; not shown). The event was therefore unusual compared with the others that mobilized much more TSS.

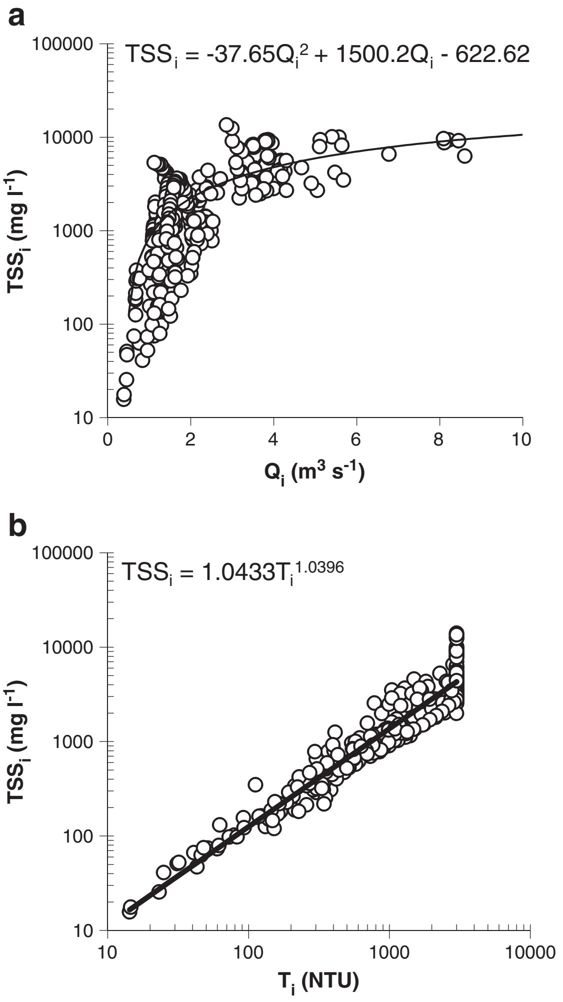

Fig. 4. (a) Relationship between discharge (Qi) and total suspended solids (TSS_i); $R^2 = 0.59$. (b) Relationship between turbidity (T_i) and TSS_i; $R^2 = 0.92$. Total suspended solid concentrations are poorly predicted by discharge for most of the range of values; and turbidity reaches a maximum at 3000 NTU, producing poor fit at the high end of the range, despite the good fit of the exponential regression.

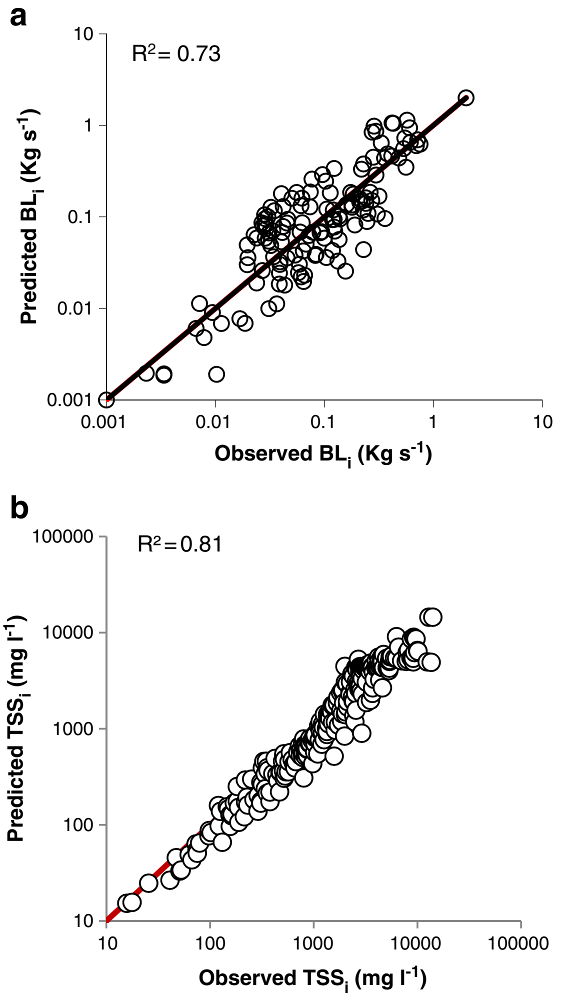

Fig. 5. (a) Observed BL versus that estimated from discharge using (Eq. (6)) for bedload transport rate (BL_i); (b) Observed TSS versus that estimated using a combination of turbidity and flow (Eq. (7)) for total suspended solid (TSS_i).

Similarly, the other two events when $BL_p = 21\%$ were both short (<2 hour long), had discharges ≤ 0.8 m^3 s^{-1}, and maximum turbidity values <80 NTU. In general, relatively high BL_p was found on the rising limbs of low-energy events, largely because discharge peaks arrived ahead of TSS peaks.

In contrast, BL_p was very low for periods with high turbidity—i.e., high TSS. While high turbidity was often associated with large runoff events with high discharge, this effect was amplified when TSS increases occurred without corresponding discharge increases (e.g., in the case of a bank failures upstream). A low BL_p was also generally associated with extended falling limbs with low discharge and relatively high turbidity, as can be seen for the event on 25 August (Fig. 6). The asynchronicity between discharge and turbidity creates an anti-clockwise hysteresis effect in the discharge–TSS relationship during many runoff events (not shown).

Events in which the entire hydrograph was sampled typically contained a sediment load of more than 95% suspended solids—e.g., the 25 August event (Table 3). The lack of a strong correlation between bedload and TSS transport is partly due to flushes of high TSS that are asynchronous with the discharge energy that drives bedload transport in the Mae Sa River (Figs. 6,7). While complicated hysteresis patterns occurred for the TSS–discharge relationship, we do not have sufficient data to determine if the hysteresis in the bedload transport is related to supply- or energy-limited conditions, and over which time scales (cf. Sidle, 1988; Moog and Whiting, 1998; Recking et al., 2012; Wilson et al., 2012). Observations suggest it is supply-limited: e.g., sand bed forms were often absent in the long flat channel where we made the measurements following high flows. During the inter-storm periods, sand bedforms would once again develop, forming the main source of bedload transported during low-energy events.

When Eqs. (6) and (7) are applied to all low-energy periods during the entire study period (10 July–3 September; Fig. 2), estimated bedload comprises <5% of the total load, which is substantially lower than the wide range of values reported elsewhere for various streams in tropical Asia (10–80%; Table 1). Again, we did not include periods when Q > 5 m^3 s^{-1} in this calculation. If we apply the equation to all time periods, the BL_p increases to 9%. These low values result, in part, by considering only a three-month period in the middle of the wet season when TSS are elevated by accelerated erosion on disturbed hillslopes and an extensive catchment-wide road network, which has been shown in many catchments in northern Thailand (Ziegler et al., 2004; Turkelboom et al., 2008).

In a prior work, we estimated the total catchment suspended solid sediment yield to be 1076 Mg km^{-2} y^{-1} for the year 2006 (Ziegler et al., 2011). This estimate was computed for hourly discharge values ranging from 0.27 m^3 s^{-1} (baseflow) to 63 m^3 s^{-1}. We have recently modified this initial estimate to 839 Mg km^{-2} y^{-1}(Ziegler et al., submitted for publication). Taking uncertainty into consideration, the plausible TSS range for 2006 is 649–1037 Mg km^{-2} y^{-1}. Applying our bedload transport equation to the low-energy periods of the annual

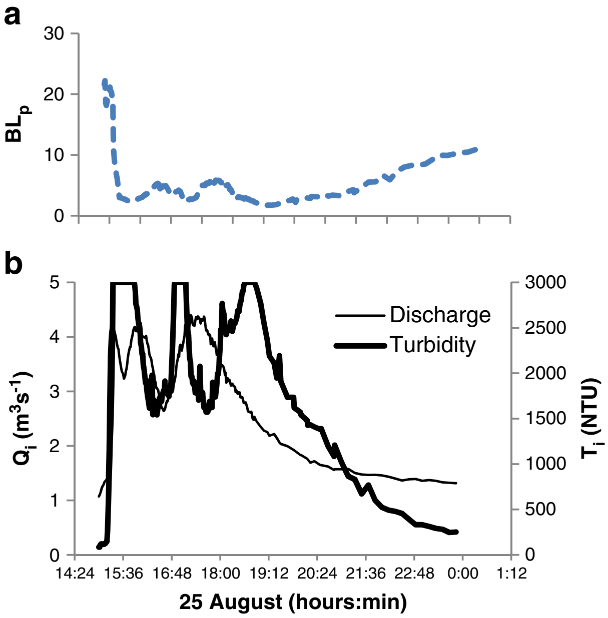

Fig. 6. For the 25 August 2005 event, the following (Tables 2 and 3): (a) proportion of total sediment load that is bedload (BL_p); and (b) corresponding discharge (Q_i) and Turbidity (T_i). Note: BL_p is low when turbidity is high. Asynchronous flushes of high turbidity water and discharge peaks produce an anti-clockwise hysteresis effect in the TSS-signal (not shown).

time series produces an estimated BL_p of 18%. Predicted values in this range hold for calculations using flows up to 20 m^3 s^{-1}. Applying the equation to the entire discharge time series yields a BL_p value of 25%, but this estimate has no physical meaning because the equation is not valid for high flow periods.

Again, we believe bedload in Mae Sa is supply limited—and this has important implications for estimating the bedload transport at high flow conditions. Specifically, under supply-limited conditions, bedload transport relative to TSS transport would not be expected to increase greatly (assuming the channel is not incised). Therefore, BL_p is probably not higher than our high-end estimate of 25%, which is in-line with that of many rivers worldwide (Turowski et al., 2010).

From the annual calculations of TSS and bedload in the Mae Sa river, we conclude that the latter likely comprises 9–25% of total sediment yield, with 18% representing our best estimate. This percentage equates to a catchment bedload yield of 189 Mg km^{-2} y^{-1} (the plausible range is 81–279 Mg km^{-2} y^{-1}) versus the TSS estimate of 839 Mg km^{-2} y^{-1} (range = 649–1037 Mg km^{-2} y^{-1}). Total annual sediment yield for year 2006 is therefore an estimated 730 to 1313 Mg km^{-2} y^{-1}, with the best estimate being 1028 Mg km^{-2} y^{-1}.

6. Discussion

6.1. Uncertainties

Foremost, our bedload yields are based on only a few hundred samples collected during a 3-month period, and only for low-energy flows. The maximum discharge for which we could sample was 4.5 m^3 s^{-1}, which is about 13% of the largest value recorded during the study period (40 m^3 s^{-1}). In the annual yield prediction, there were 231 hourly periods where hourly discharge was higher than 4.5 m^3 s^{-1}. These periods represent only about 16% of the total annual flow. A drastic change in bedload transport during very high discharges could produce yields higher than our estimates, particularly if the river channel was incised. In such cases, it is plausible that the bedload percentage to the total load could exceed the upper bound of 25% we predicted for all flows, but this is largely speculation. In all likelihood, few of the prior bedload studies in SE Asia could make such a calculation, with a possible exception being those studies using trap methods (Table 1).

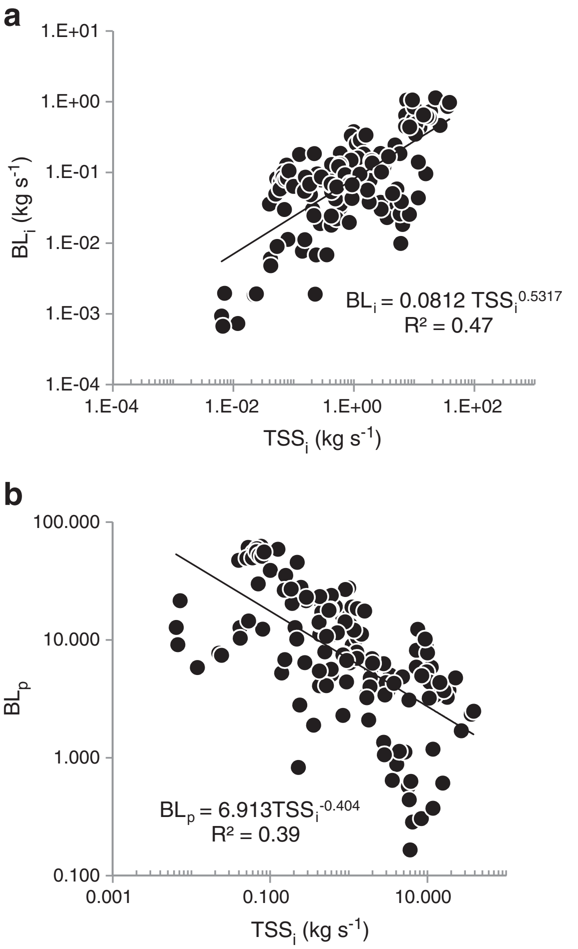

Fig. 7. (a) Relationship between measured total suspended solids (TSS_i) and bedload transport (BL_i) during the field study. (b) Relationship between measured total suspended solids (TSS_i) and the proportion of the total sediment load that is bedload (BL_p).

The Helley–Smith sampler was initially chosen because of our assumption that sand would dominate the measured bedload fraction in the river. We encountered two major problems with the sampler. First, we could only deploy it for low-energy events for safety reasons. Second, the collection bag became choked with suspended sediment and organic material when TSS concentrations exceeded values of 2000–3000 mg l^{-1}, forcing us to discard these measurements. Even the use of a larger collection bag did not alleviate the problem entirely (cf. Vericat et al., 2006). Use of other collection methods (e.g., traps), or a combination of methods, may have produced a better overall result (Sterling and Church, 2002; Bunte et al., 2008; Schindler et al., 2012). However, given the size of the stream and budget restrictions we were not able to incorporate other methods. Further, the flow restriction in the collection bag draws attention to interchangeability of TSS and bedload material, as well as our inability to partition the material collected in the Helley–Smith sampler. Operationally, all material collected in the sampler is assumed to be bedload.

We observed following one very high flow event, with Q reaching 30 m^3 s^{-1}, movement of stones with diameters exceeding 20–30 cm. Some bed scour downstream from our sampling site was also apparent. Rock movement of this size is impossible to measure with a Helley–Smith because of the narrow opening. Again, large channel traps, and in some cases radio transmitters and magnetic tracers, may have been useful in estimating the movement of this type of material (Ergenzinger and Custer, 1983; Church and Hassan, 2002; McNamara and Borden, 2004; Habersack et al., 2012). As we only observed evidence of very coarse material once during the study period, we feel that our assumption of a dominance of sand-transported material is still valid for the range of flow measured.

Another error that may have caused an over-estimation of bedload transport is related to situations where one large storm removed the relatively easily transportable bedload stored in the channel near the gauging site, thereby creating a supply-limited condition (e.g., Sidle, 1988). Use of our discharge-based estimate would therefore over-predict bedload during such conditions. However, this over-estimation may balance with the limitations outlined previously that lead to under-estimation. We therefore believe our estimate of an 18% bedload proportion to the total load is realistic.

We recognize the possibility of great annual and seasonal variability in both TSS and bedload, originating from changes in hillslope erosion, river channel and bank erosion, and mass wasting rates. These processes are affected by both annual rainfall variability, and anthropogenic activities. For example, we witnessed the occurrence of several road-related landslides in the year prior to the study. The prior year was also hallmarked by a noticeable increase of tourist activities that contribute to accelerated erosion—chiefly elephant trekking (Sidle and Ziegler, 2010), but also off-road biking and 4-wheeling. The commencement of the construction of several resorts, homes, and other structures in flood plains and other areas directly connected with the stream system also increased greatly during this time. Furthermore, agriculture in the catchment has been transitioning from smallholder systems to larger commercial endeavors, including greenhouse agriculture systems that require substantial landscape modification. Many of the high sediment concentrations we observed during the study occurred during large rainstorms situated in areas where construction or hillslope disturbance had occurred.

Finally we recognize that there is an unknown lag-time between sediment production in the catchment versus when it is transported in the stream as TSS or bedload. This time could be immediate, in the case of landslides occurring on slopes above the stream system. In contrast, it may be decades or longer for material eroded on hillslopes that are not well-connected with the stream system (Sidle and Ochiai, 2006). Our measurement program did not allow us to determine such rates.

6.2. Comparison with other SE Asia catchments

A wide range of bedload yields has been reported for catchments across SE Asia (Table 1):<1 to >3000 Mg km^{-2} y^{-1}. Again, our range was much narrower, 81–279 Mg km^{-2} y^{-1}. Arguably, the sites most similar to Mae Sa were the small (1–2-km^2) agricultural catchments at Huay Pano (Lao PDR) and Babon (Indonesia), as well as the sub-catchments at Huai Ma Nai (Thailand), where bedload yields were 69–117, 158–174, and 32–129 Mg km^{-2} y^{-1}, respectively. Yields for the main catchment at Huai Ma Nai were much higher: 95–869 Mg km^{-2} y^{-1}. Our upper bedload yield estimate of 279 Mg km^{-2} y^{-1} also corresponds with yields from highly disturbed catchments in Malaysia (Table 1). While there are distinct source areas of erosion in Mae Sa, catchment-wide disturbance is much less and more sparse than in logged catchments, for example in Bukit Tarek, where the bedload yield was ironically much lower (6–28 Mg km^{-2}). Nevertheless, various activities within the riparian zone and on the flood plains adjacent to the river contribute sand material to the stream system throughout the rainy period (May–November). Shallow, landslides related to the road network, which frequently parallels the stream system, is an important example, as is construction/excavation on the flood plain. In addition, the complex network of roads and trails in Mae Sa facilitates the transport of road-related sediment to the river (Sidle and Ziegler, 2012). In comparison, bedload yield was only 28 Mg km^{-2} y^{-1} at our other Thailand site, Pang Khum, which also contains substantial steep slope hillside agriculture, but has a much smaller stream with little stored material that can be mobilized as bedload (Ziegler et al., 2000). It also has a smaller road network on which Hortonian overland flow causes substantial erosion, but mass wasting is limited (Ziegler et al., 2001a,b, 2004).

In general, the proportion of the total sediment load that was bedload in most catchments across the region was general higher than ours for Mae Sa—some extending to 50–70% (Table 1). Most of these values are for small catchments (Fig. 8). We believe BL$_p$ in Mae Sa is

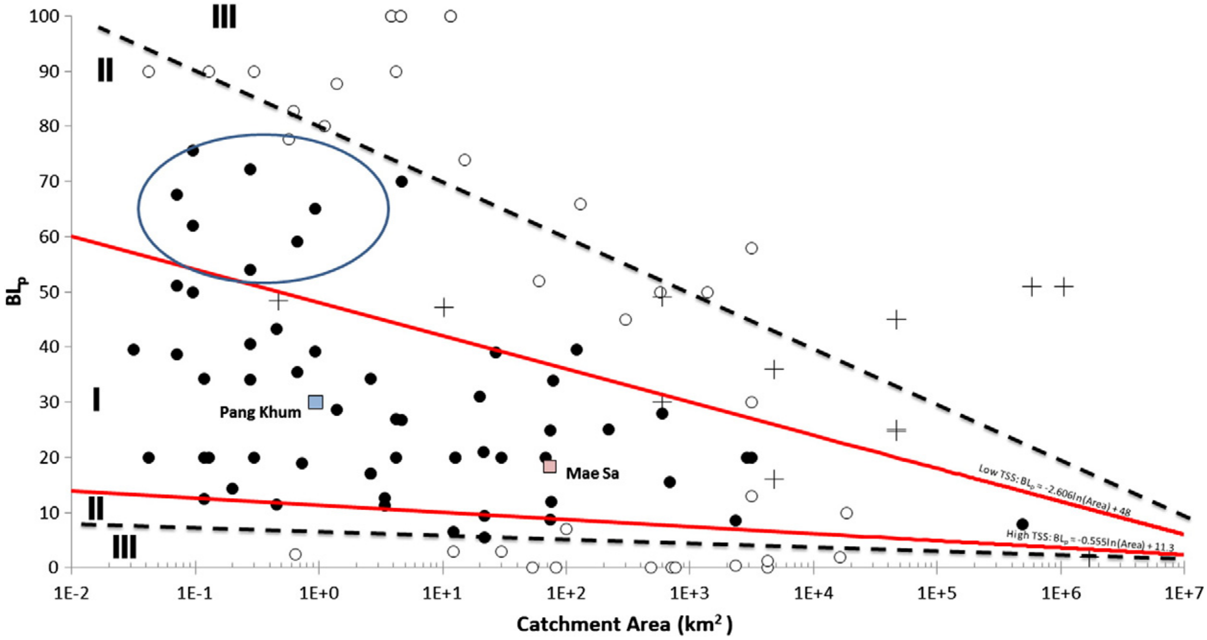

Fig. 8. Relationship between the proportion of the total sediment yield that is bedload (BL$_p$) for the stream catchments listed in Table 1 (includes all available data). Field I represents the most plausible BL$_p$ values for SE Asian rivers. Field II represents values that are possible, but less likely. The large circle in this regions demarcates a possible threshold at about 1 km^2 where BL$_p$ in some instances is in excess of 50%. Field III values are highly unlikely. The data are partitioned into three sets: those for which we have confidence (closed circles); those for which we have reservations about the data quality or representativeness for the region (open circles); and those from the greater region (crosses; Table 1). Mae Sa (this study) and Pang Khum (another Thailand site) are shown with a square.

relatively low for two reasons. Firstly, the total suspended solid load in the Mae Sa river is high throughout much of the rainy season. Sediment concentrations exceeding 2000–3000 mg l^{-1} were common for moderate to large storms; and concentrations ranging from 10,000–14,000 mg l^{-1} were observed during brief spikes during large storms. Secondly, the accuracy of TSS measurements in many of the other studies reporting both suspended and bedload yields is not known.

Very few studies were conducted for more than one year, and therefore, fail to capture the temporal variability of bedload transport. Variability is high because of differing degrees of anthropogenic activity and unpredictable storm activity. Great variability in bedload transport in the Jengka catchment in Malaysia was related to logging disturbances (Kasran, 1996). Anthropogenic disturbances that accelerated hillslope erosion may increase total suspended loads, thereby reducing the contribution of bedload to total sediment loads (cf. Kasran, 1996). This was demonstrated in the Bukit Tarek experimental catchments, where BL_p decreased from a value of 60% before logging, to 40% after logging (Yusop et al., 2006). If however mass wasting occurs, the bedload proportion may become a larger component of the total load, especially if landslides and debris flows are directly linked to streams (Imaizumi and Sidle, 2012). Importantly, large rainfall events often associated with tropical storms late in the monsoon season (Wood et al., 2008; Lim et al., 2012) can mobilize the bulk of the annual load in some systems (e.g., Shallow, 1956; Peart and Jayawardena, 1994). The presence/absence of large storms was largely responsible for periods of high and low bedload transport during the 15-year study in the small catchment in Hong Kong (Peart and Fok, 2006).

Although our estimates had errors related to sampling with the Helley–Smith sampler, they are useful from a management perspective. We now believe our total sediment yield estimate is higher than what has generally been reported/assumed for rivers and streams in Thailand. The scant literature on sediment transport in Thailand shows the annual TSS yield in the Mae Sa River (679–1037 Mg km^{-2}) is several times higher than those reported for other rivers draining catchments <100 km^{-2} (Meybeck et al., 2003; Hartcher and Post, 2008): Mae Suk (100–154 Mg km^{-2}), Mae Kong Kha (46–69 Mg km^{-2}); and Huai Mae Ya (100 Mg km^{-2}). Furthermore, the values are an order or two higher than the mean 14-y (1993–2006) annual sediment yield (53 Mg km^{-2} y^{-1}) of the Ping River, to which Mae Sa drains (Wood and Ziegler, 2008; also see Alford (1992)). Thus, Mae Sa may be a hotspot for sediment entering the Ping river—at least for the year of our study—and this has implications for reservoir management.

7. Part III: implications for reservoir management

The objective of combining a summary of prior studies in SE Asia along with our case study in Mae Sa was to explore trends in bedload transport variables for various-sized catchments in the region. Such comparisons have direct application for river management, including improving estimates of reservoir filling times. In Fig. 8, we partition the BL_p data (including long-term means as well as annual values if available) into data we think are reliable (solid circles) or potentially problematic (open circles). Examples of the latter include estimates and back-calculations from limited data, as well as data originating from studies with considerable experimental error, or those representing unusual circumstances. In fairness, many of the data that we identify as reliable also have errors and associated uncertainty. Also shown are values from neighboring regions (crosses; Table 1).

With these uncertainties in mind, we identified fields corresponding to plausibility (Fig. 8). Field I delineates the BL_p values that are most representative for the range of identified catchment areas. The Field II values are possible, but they tend to be associated with situations that are unusual. Examples include severe catchment disturbances on the high end (e.g. landslides), or diminished/disrupted stream on the low end flow (for example obstructed by upstream dams). One of the high values was determined for an undisturbed forest stream with minimal suspended sediment. Field III values are improbable or unrealistic.

For Field I, values of 20–50% are possible for small catchments (<1 km^2). Catchments on the order of 1000 km^2 may have values ranging from 10 to 30%. Even for very large catchments BL_p ranges from 5 to 25%, but data are very limited. These data demonstrate that bedload in tropical rivers and streams can be a substantial proportion of the total load, as indicated in Section 2 (e.g., Roberts, 1991; Lai, 1993; Nagle et al., 1999; Saynor et al., 2006; Erskine et al., 2011). Also shown in Fig. 8 is a threshold at about 1 km^2 where BL_p in some instances is in excess of 50% (demarcated with the large circle in Field II). In several of the reviewed studies, researchers remarked upon the episodic nature high bedload volumes with respect to the occurrence of large storms and/or disturbance. These phenomena have a significant effect on both the availability of bedload material and its transport, particularly for short time scales. Again, most of the data shown in Fig. 8 are from very short campaigns. The high values may in some cases correspond to extreme years within a long time series for which the mean would be lower. At larger catchment sizes, the effects of these short-term extremes are not noticeable because the time scale of bedload movement is much slower. Similarly, some of the low values may also be related to extreme situations.

These identified fields do not specifically account for differences that may be related to suspended sediment concentrations, bed material, or channel type (Maddock and Borland, 1950; Lane and Borland, 1951; Turowski et al., 2010). While such differences would ultimately affect the bedload partitioning, there simply are not sufficient data in the region to make these distinctions with confidence. However, values in the lower portion of Field I appear to be representative of BL_p for streams with high suspended sediment concentrations. This boundary line fits slightly below the BL_p values for our Mae Sa catchment (TSS yield = 839 Mg km^{-2} y^{-1}), but is well below that of Pang Khum (TSS = 61 Mg km^{-2} y^{-1}). It is also just below that of the large Fly River drainage, which as a very high TSS yield (TSS yield = 1006 Mg km^{-2} y^{-1}). Similarly, the upper line may be representative of situations where TSS is low. Owing to uncertainties with most of the bedload data, we urge judicious use of the fields shown in Fig. 8. They are rough guides for estimating a range of possible bed load fractions from accurate TSS yields. In Fig. 9, the bedload and TSS yield data from the regional studies are plotted together for comparison with Fig. 8.

Nagle et al. (1999) warned that sedimentation of reservoirs could be one of the most crippling water-related problems in tropical areas in the future. They called attention to the fact that reservoir filling rates were often estimated based upon incomplete information and/or baseless assumptions, such as a fixed and often low bedload proportion (~10%). Bedload yields needed for engineering works may also be underestimated if one fails to consider large storms can transport disproportional loads of sediment (e.g., Peart and Jayawardena, 1994; Douglas et al., 1999; Thothong et al., 2011). Extreme events of uncertain return periods should be incorporated in to long-term estimates. Based on Fig. 8, a conservative BL_p estimate for rivers with drainages of 1000–10,000 km^2 is 20–30%—this corresponds to the upper half of Field I. This proportion would be higher for smaller rivers. Importantly, these estimates are all much greater than 10%.

In one recent example, Lorsirirat (2007) used an estimated BL_p value of 30% in his calculation of annual sediment filling rate in the 820-km^2 Lam Phra Phloeng reservoir in northeastern Thailand. This value falls within the upper boundary of the Field I in Fig. 8 and thus, arguably represents a sound estimate. Unfortunately, sound estimates are often not the case. For example, sediment accumulation rates in the Mae Taeng Reservoir in northern Thailand indicated that the reservoir lifetime had been over-estimated by 30 years because of an initial underestimation of the catchment sediment delivery ratio (cf. Janeau et al., 2003). Measurements of suspended sediment and bedload rates in upper catchment study areas also indicated an initial underestimation. However, the sediment delivery ratios determined in these

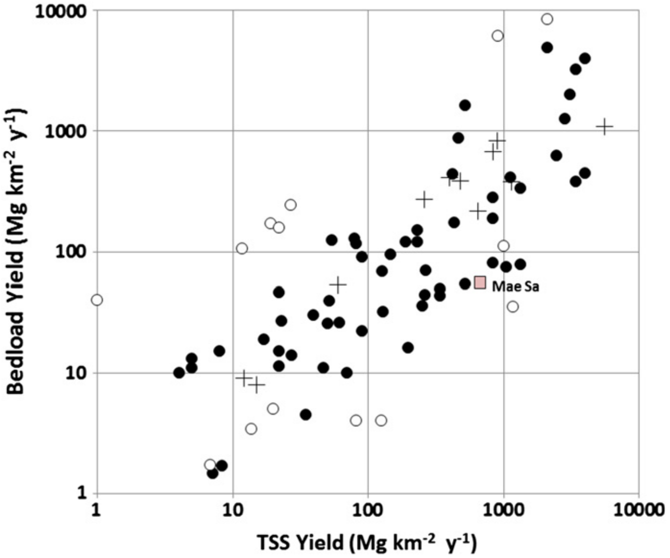

Fig. 9. The relationship between bedload and total suspended solid yields for the SE Asian streams. These data correspond with those shown in Fig. 8. The data are partitioned into three sets: those for which we have confidence (closed circles); those for which we have reservations about the data quality or representativeness for the region (open circles); and those from the greater region (crosses; Table 1). Mae Sa (this study) is shown with a square.

small-catchment studies were half what was needed to account for the reservoir sedimentation. This example demonstrates the need for complete sediment budgets and accurate determinations of sediment delivery for reservoir filling calculations.

Rarely have accurate sediment budgets been determined for catchments draining reservoirs worldwide prior to their building (Nagle et al., 1999). Yang et al. (2011) write that only after the construction of 50,000 dams along the Yangtze River, with changes in sediment load negatively affecting streams and deltaic regions, did research begin to focus on sediment loads. Rarely are sedimentation issues addressed prior to dam building (Nagle et al., 1999). There are many examples in the South and SE Asia region of unpredicted rapid declines in reservoir storage capacity and lifetimes (Kothyari, 1996; Janeau et al., 2003; Wang et al., 2007; Fu et al., 2008; Thothong et al., 2011; Siti et al., 2012). Of concern now in SE Asia is the aggressive building of dams on many tributary and main stems of rivers such as the Mekong and Salween without reliable sediment load data needed to estimate potential impacts. Some believe the impacts could be far-reaching and catastrophic (Ziv et al., 2012; Ziegler et al., 2013).

8. Conclusion

Despite uncertainties, our bedload estimates for the Mae Sa river are in line with what others have found for SE Asian streams. The bedload yield estimates were on the high end of what has been reported. In contrast, the proportion of bedload comprising the total sediment load was relatively low, probably because of the high suspended solid load in the stream. Bedload transport during the study may have been elevated by coarse material that entered the stream from landslide affected areas during the prior rainy season. High total suspended solid loads result from erosion on steep-slope and intensive agricultural areas, roads, and other surfaces impacted by anthropogenic activities (e.g., elephant trails, urbanized areas).

Collectively, our new measurements and the data from prior studies suggest the bedload contribution to total sediment loads is not insignificant, as has been often assumed in the past. The limited data suggest that bedload proportion could exceed 20–40% for streams larger than 10 km^2; higher for smaller streams. This finding reinforces the need for accurate estimates of river suspended and bedload sediment loads prior to building dams in the region. Past examples of rapid infilling of reservoirs and premature closure likely result, in part, from underestimating sediments loads, particularly the bedload component, as well as failing to factor in very high sediment loads associated with large storm events.

The 2011 Chao Phraya River flood in Thailand demonstrated the importance of understanding phenomena affecting river flow routing and reservoir storage management, including sediment loads that could potentially reduce reservoir storage volumes (Komori et al., 2012; Ziegler et al., 2012). The evolution of road systems, expansion and intensification of agriculture, development on wetlands and river flood plains, and increasing population density in many headwater catchments in SE Asia are undoubtedly altering the input of bedload material to streams, and should continue to do so in the future as land cover continues to change (Nagle et al., 1999; Sidle et al., 2006; Sidle and Ziegler, 2010, 2012; Fox et al., 2012; Sidle et al., 2013). From a larger perspective, the uncertain effects of climate change and its effect on the global hydrological cycle and storm activity create additional challenges for those tasked with managing water resources and mitigating hazards associated with river systems.

Our measurements and review demonstrate that some streams in SE Asia may be hotspots for sediment entering larger rivers above reservoirs (cf. Milliman and Syvitski, 1992). Throughout the region, dams are being built on the main branches and tributary streams of many important river systems without sufficient information for estimating reservoir filling times. Greater attention should be given to estimating all phases of sediment and elemental fluxes from more river systems in the region. Advances are also needed to reduce the uncertainty in the estimates. Little progress has been made in these areas in the last half century.

Acknowledgments

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