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River sediment monitoring for baseline and change characterisation: a new management tool for the Ramu River Communities in Papua New Guinea

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Abstract The 18 719-km^2 Ramu drainage basin has a water quality regime largely unaffected by mining operations. The Ramu River Communities believe that this may change over the coming months and years, and have initiated their own state-of-the-art monitoring of the main river. These observations have centred on high-frequency (10-minute) observations of turbidity and flow giving possibly the first such annual data at this sampling frequency on New Guinea Island. The first year of monitoring has demonstrated a marked seasonality in the delivery of suspended sediment from the 5866 km^2 Upper Ramu basin, with considerably more natural variability in response within the 6-month wet season. Were new mining operations to release fine sediment (contaminated with heavy metals) into the watercourses of the Upper Ramu, then such shifts in the sediment signal may be more identifiable within the dry season. With evidence of an increase in fine sediment load, the Ramu Communities would have a more robust case to request increased monitoring of heavy metal levels within the Ramu, and if necessary to request improvements to the erosion and drainage management of mine areas.

Key words mining; Papua New Guinea; Ramu; suspended sediment; turbidity

INTRODUCTION

Over 250 000 Papua New Guineans are reliant on the maintenance of water quality along the 640 km River Ramu (Fig. 1). If upstream mining activities were to adversely affect the water quality of this river, then fish and/or crayfish stocks and riparian agriculture (sago, yams and sweet potatoes) may be threatened. The impact of opencast mining on the water quality of the 1050 km Fly River elsewhere in Papua New Guinea is well known locally and internationally (Markham & Repp, 1992; Boulton, 2009). If deterioration in water quality can be identified quickly by villagers reliant on the River Ramu, then they would have their own scientific evidence to help persuade or compel those contaminating the river to improve their operations. Thus monitoring water quality is an essential tool for those with a vested interest in managing a catchment to sustain water quality.

Opencast mining can lead to river contamination either by direct discharges of mine tailings into a watercourse or by inadequate control of on-site erosion and drainage. Where the fine sediment mobilised from the mine site is rich in heavy metals (e.g. cadmium, chromium, cobalt, copper, nickel), then these may reach the main river in suspension to contaminate the river bed sediment and water body. Further downstream, annual inundation of agricultural clearings with alluvium could see these elevated metal loads entering the food chain (Stauber *et al.*, 2009).

Storm events can produce marked temporal changes in the metal concentrations and loads within rivers. Ten-fold or even 100-fold changes in concentration or load can take place over a few hours within some large rivers (e.g. Lourino-Cabana *et al.*, 2010). These dynamics must be captured to allow accurate estimation of the natural load of particular metals (i.e. t year^{-1}) or allow changes arising from anthropogenic disturbances to be separated from the natural variability. Laboratory analyses of water samples for heavy metals, by e.g. Inductively-Coupled Plasma Mass Spectrometry (ICP-MS) or Inductively-Coupled Plasma Optical Emission Spectrometry

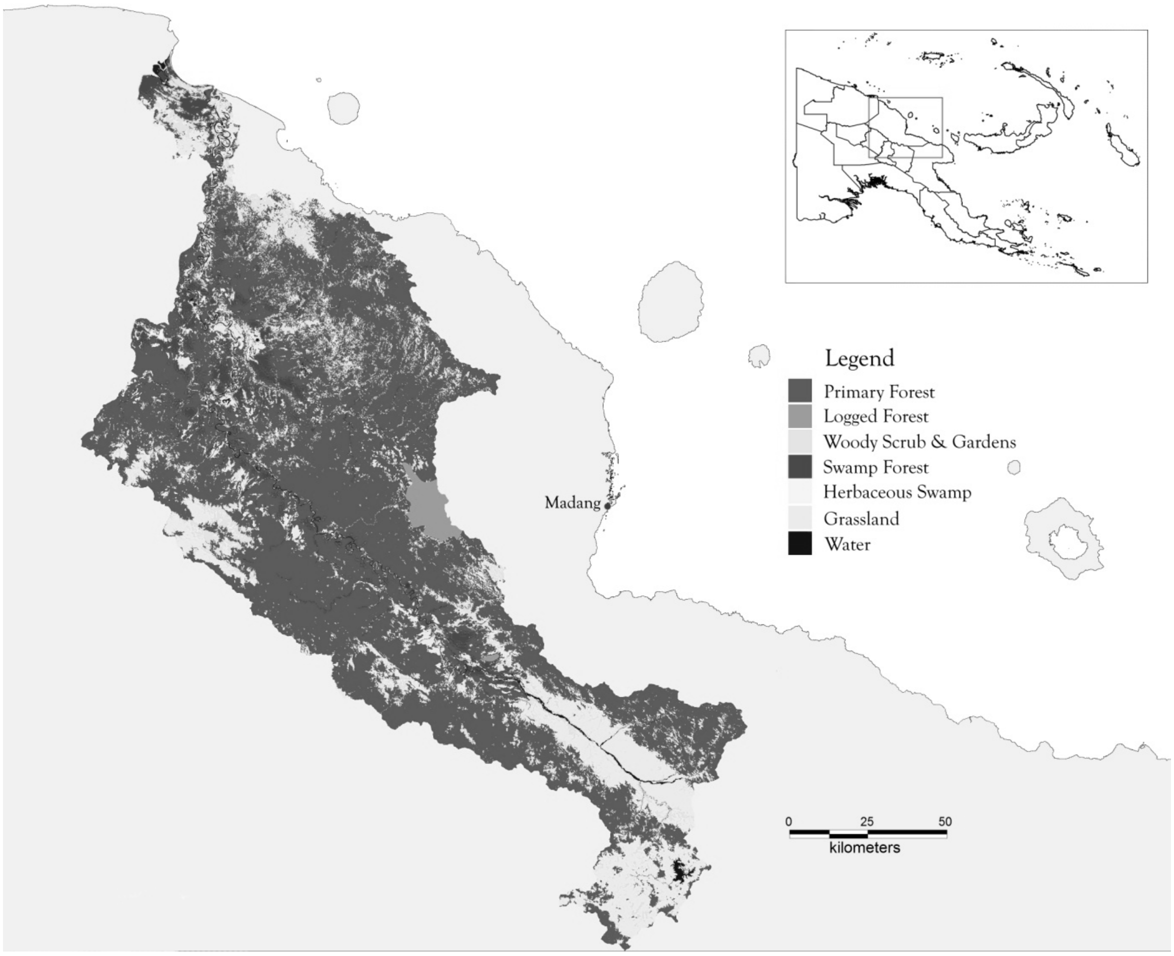

Fig. 1 The 18 719 km^2 Ramu drainage basin containing the 640 km long Ramu River. The principal vegetation cover is mostly primary lowland rainforest.

(ICP-OES), are individually expensive. Where sub-hourly sampling of highly dynamic, catchment systems is needed, laboratory costs may therefore become too restrictive, even for well resourced governments or multi-national companies.

The typical response has been to measure the dissolved chemical concentration only infrequently, and to correlate these data with sub-hourly data on river-level (or discharge), which requires comparatively few resources to obtain. Within highly dynamic systems this approach can be highly inaccurate (Walling & Webb, 1981; Sivakumar, 2006) as a result of differences in the timing of the dominant flows of water and chemical constituents during storms (i.e. “hysteresis”) and changes in the relationships through the year (i.e. “non-stationarity”).

An alternative approach is to measure another water quality parameter that is more likely to have temporal response characteristics similar to those of the chemical constituents of interest. Given that the source of heavy metals from an opencast mine is likely to be those bound onto fine sediment being eroded (or discharged) from the site (cf. Boulton *et al.*, 2009), the turbidity (or a derived suspended sediment concentration) is more likely to be a better measure of the dynamics of heavy metals than the discharge time-series (Truhlar, 1978; Christensen *et al.*, 2002). The discharge time-series is, however, needed in the calculation of the mass of a particular heavy metal (or mass of suspended sediment) exported from a headwater source to a downstream river reach.

Consequently, within this study we seek to define key baseline characteristics of the suspended sediment load of the Upper Ramu River within its current (largely) natural state. Critically, we seek to define those characteristics that can be observed to change if new mining operations intentionally or unintentionally add fine sediment (with elevated levels of heavy metals) to the tributaries draining to the main stem of the River Ramu. Consequently, the location for the proposed sediment monitoring was chosen at Sepu village on the main stem of the River Ramu, a few kilometres downstream of tributaries draining from an 18-km^2 site currently being developed for substantial opencast mining – the Kurumbukari mine near Usino village, Madang Province, Papua New Guinea (NSR Environmental Consultants, 1999).

THE UPPER RAMU BASIN

The River Ramu has an 18 719 km^2-drainage basin that discharges into the Bismarck Sea on the northern coast of New Guinea Island within Papua New Guinea (PNG). The Upper Ramu basin, which covers 5866 km^2 upstream of the Sepu gauging station (5°27.8′S, 145°12.6′E), has a wide valley floor flanked by steep mountain slopes. The northern divide transverses the Finisterre Range of mountains, and its southern divide is the Central Range of PNG. The highest point in the basin is Mount Wilhelm (4509 m), the highest summit in PNG.

The Upper Ramu basin is underlain primarily by greywacke, conglomerate and limestone (Peart, 1991). The mountain slopes experience considerable tectonic activity (Sapiie & Cloos, 2005) that has triggered many large landslides (e.g. Drechsler *et al.*, 1989; Peart, 1991) and has periodically mobilised so much sediment that the main channel has been choked and diverted (e.g. Yu *et al.*, 1991; Lakamanga, 2005). The natural vegetation is predominantly lowland rainforest in the valley floor (< 1000 m) and montane forest on the mountain slopes (Robbins, 1976; Shearman *et al.*, 2008). Some of the slopes have been cleared by fire (Shearman & Bryan, 2010), while parts of the valley floor have been used for cattle ranching and sugar cane production (Hartemink, 2001), with oil palm estates being introduced recently. This contrasts with the Middle and Lower Ramu basin, which remain largely covered by undisturbed, lowland rainforest (Shearman *et al.*, 2008; Fig. 1), but with some recent commercial, selective felling. The soils close to the main stem of the Upper Ramu are predominantly Fluvisols (Hartemink, 2001) and Phaeozems, while Cambisols dominate elsewhere within this headwater basin (FAO, 2007).

Infrastructure for the Kurumbukari opencast mine is currently under construction at 5°33′S 145°12′E. These works are located within the centre of a 143.2 Mt nickeliferous laterite deposit. Small tributaries (i.e. Banap, Eastern, Ban and Aanagn Creeks) drain from this site for 4–10 km to the main stem of the Upper River Ramu (NSR Environmental Consultants, 1999).

MONITORING SYSTEMS

A monitoring station was newly established on the River Ramu at Sepu village (5°27.8′S, 145°12.6′E) in early June 2009. At this station an OBS-3+SB-2.5-T4 turbidity probe (D & Instruments / Campbell Scientific Inc., Logan, USA) mounted on a self-cleaning Hydro-Wiper device (Zebra-Tech Ltd, Nelson, New Zealand) was attached to a protective steel manifold (Fig. 2). A CR1000 data-logger (Campbell Scientific Inc., Logan, USA) was used to monitor turbidity every 30 seconds (on both 0–2000 and 0–4000 Nephelometric Turbidity Units or NTU ranges), with the average stored every 1 minute. Averaging and storage was changed to every 10 minutes after the first month of monitoring. A relationship between turbidity (NTU) and suspended sediment concentration (mg L^{-1}) was established using water samples collected from the Ramu River over the ranges of 37 to 810 NTU and 74 to 2676 mg L^{-1}. The values of suspended sediment concentration were determined by the gravimetric method (BS 3680: Part 10B, 1980).

The sediment load (mg s^{-1}) is the product of the suspended sediment concentration (mg L^{-1}) and river discharge at the gauging station (L s^{-1}). The discharge time-series was derived from measurements of river stage (m) at the turbidity monitoring station converted to discharge (m^3 s^{-1} and L s^{-1}) using the Mean-Section Method (Shaw *et al.*, 2010) and modelling with the Slope-Area Method (BS 3680-5, 1992). The river stage was monitored using a Druck PDCR1830 (700 mbar range: GE Measurement and Control Solutions, Pforzheim, Germany) pressure transmitter mounted alongside the turbidity probe (Fig. 2) and data stored at the same intensity on the CR1000. The rating of the channel cross-section at Sepu was undertaken using a Braystoke 001 current meter and 0001002 suspension set (Valeport Ltd, Totnes, UK) from a fibreglass boat tethered across the river. A river-level station has been maintained by Highlands Pacific Ltd and Ramu NiCo Management Ltd at Sepu, though this was not operational during the 2009–2010 period. Some years previously (1966–1994), a river-level monitoring station was in use further downstream at Aiome village (Jayawardena *et al.*, 1997), though this station is no longer maintained. Monitoring at most of the gauging stations in PNG was stopped in the early 1990s.

An automatic raingauge (SBS500: Environmental Measurements Ltd., Wearfield, UK) was installed at Sepu and the number of 0.2 mm rainfall tips per 10 minutes recorded on the single CR1000 data-logger. These data were complemented by new daily rainfall measurements at Bosmun village (4°10′60S, 144°40′0E) in the Lower Ramu, and by access to daily rainfall records from a raingauge in the centre of the Upper Ramu basin at 5°59′S, 145°52′E (c/o Ramu Agri Industries Ltd).

The Sepu monitoring station is powered by two 18W solar panels (BP Solar, Frederick, USA) and a 24 Ah battery reserve; with the people of Sepu village maintaining site security. All equipment was installed in a period expected to be the early part of the dry season (i.e. early June 2009: Short, 1976). Data retrieval was undertaken using a Toughnote DA-05 ruggedized PDA (Terralogic Ltd., Cardiff, UK).

METHODS OF DATA PROCESSING

The datafiles recorded by the CR1000 data-logger were loaded into MATLAB (Mathworks, Natick, USA) and saved as compressed MAT files. All quality assurance, calibrations and subsequent analyses were then applied to the raw data within the same programme file (M-file). The analysis of the variance in the discharge and suspended sediment load (SSL) was undertaken

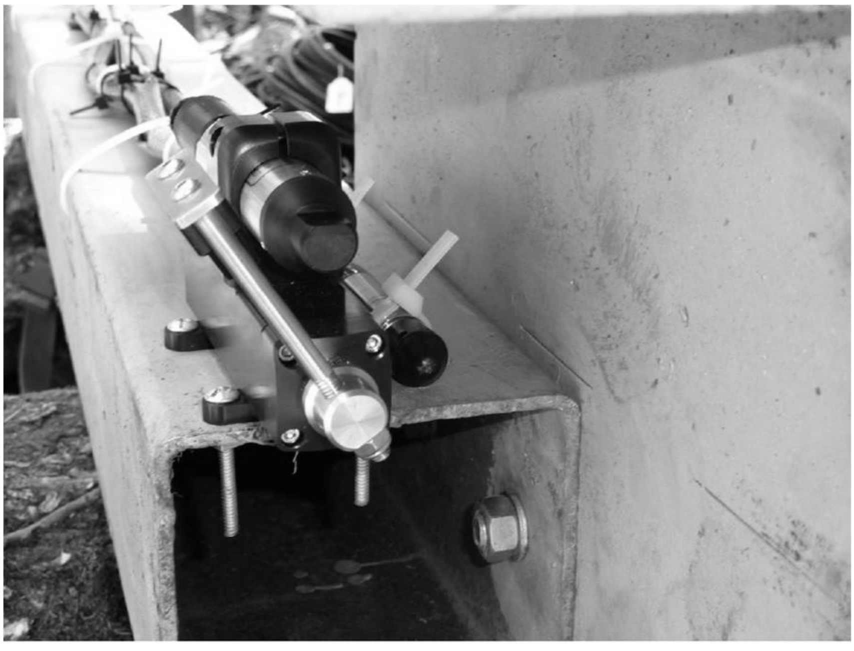

Fig. 2 The steel manifold at the Sepu monitoring station (5°27.8′S, 145°12.6′E) supporting and protecting an OBS-3+SB-2.5-T4 turbidity probe and self-cleaning Hydro-Wiper device (centre left) plus a Druck PDCR1830 pressure transmitter (centre) for monitoring river stage. The unit is shown prior to its insertion into the river.

after first smoothing the 10-minute data using the IRWSM (Integrated Random Walk SMoothing and decimation) method within the CAPTAIN toolbox (Taylor *et al.*, 2007). An NVR (Noise-Variance-Ratio) of 1×10^{-4} was used within this method for both time-series.

SEASONALLY-INTEGRATED SUSPENDED SEDIMENT CHARACTERISTICS

The 12-months time series of river discharge, turbidity, suspended sediment concentration and load for the Sepu monitoring station are presented in Fig. 3. Strictly, 98% of a year's data (i.e.

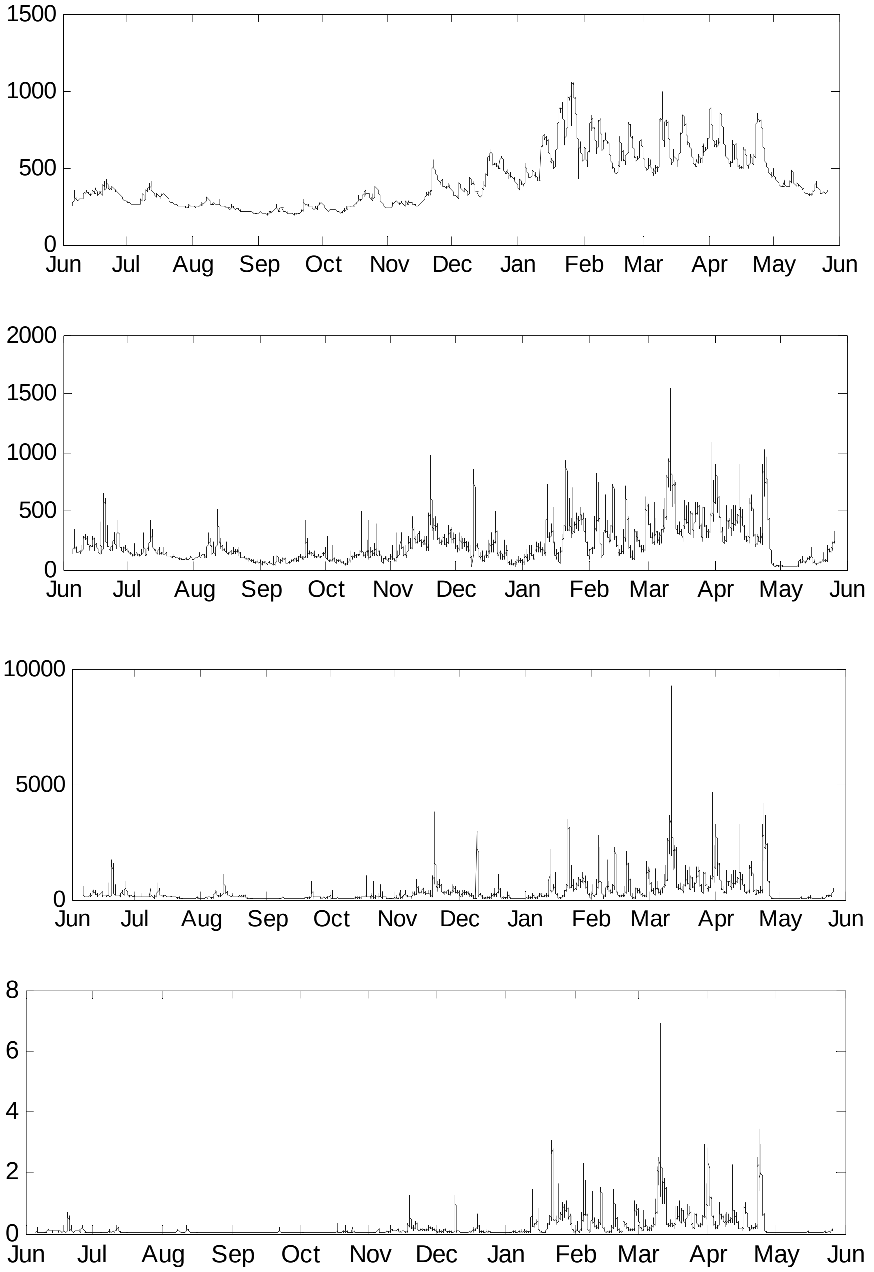

Fig. 3 The 12-months time series of river discharge (m^3 s^{-1}; top), turbidity (NTU; upper middle), suspended sediment concentration (mg L^{-1}; lower middle) and load (t s^{-1}; bottom) recorded every 10 minutes at the Sepu monitoring station (5°27.8′S, 145°12.6′E), Upper Ramu drainage basin, Papua New Guinea.

51 166 values) averaged at 10-minute intervals were available for the analyses presented here. The turbidity observations may be the first such annual data collected at such a high frequency anywhere on the geomorphologically important New Guinea Island. Table 1 gives the annual and 6-month totals or averages for the discharge, turbidity, suspended sediment concentration and load for this station from June 2009 to May 2010. Figure 3 confirms that the monitoring station was installed in the second month of the expected dry season.

It is equally clear from Fig. 3 and reinforced by summary characteristics within Table 1 that there is a pronounced seasonality in the discharge and suspended sediment load. Two thirds of the discharge and 86% of the suspended sediment load were delivered in the 6 months of the November–April wet season. The observation that two thirds of the discharge occurs in the 6-month wet season is expected given that the 30 year rainfall record (1980–1999) for the raingauge at the centre of the Upper Ramu basin shows that 70% of the annual average rainfall (1987 mm) is received in the November–April wet season. This raingauge is, however, expected to have a lower annual rainfall total in comparison to the catchment average rainfall, given that it is located on the valley floor (at 390 m) of the basin that rises to 4509 m. The Bosmun raingauge captured a rainfall total of 2202 mm for the June 2009–May 2010 period that was similarly lower than the discharge per unit area of the Upper Ramu basin (i.e. a runoff of 2161 mm year^{-1}: Table 1). This raingauge is, however, similarly located in the valley floor (less than 30 km upstream from where the Ramu discharges into the Bismarck Sea), and expected to receive less rainfall than the high mountains comprising the northern and southern divides of the Upper Ramu basin (Stewart, 1993; Jayawardena *et al.*, 1997). For reference, Hall (1984) estimated the mean annual runoff for the whole of Papua New Guinea to be 2100 mm.

The annual suspended sediment load, delivered mostly in the wet season (Table 1), is relatively high, but within the range of those observed for other catchments within Papua New Guinea and elsewhere in the tropics (e.g. Milliman & Meade, 1983; Walling & Webb, 1983; Milliman & Syvitski, 1992; Kao & Milliman, 2008; Table 2).

High sediment loads for New Guinea Island are reported by others (e.g. Pickup *et al.*, 1981); indeed Douglas & Guyot (2004) demonstrate that the island generates 1.5 times the sediment load of the Amazon basin, despite comprising only one eighth of the area. The island's regular tectonic activity and steep mountain slopes are the primary cause of the high sediment delivery (Milliman & Syvitski, 1992; Milliman, 1995; Douglas & Guyot, 2004; Sapiie & Cloos, 2005).

THE VALUE OF HIGH-FREQUENCY SUSPENDED SEDIMENT MONITORING

The sub-daily sampling allows the short-term characteristics of sediment delivery from the Upper Ramu to be examined. Figure 4 shows the 10-minute sampled load and discharge data over the first two months of the wet season (i.e. November–December 2009). Even though the suspended

Table 1 Annual and 6-month averages or totals for the discharge (Q), turbidity, suspended sediment concentration (SSC) and load (SSL) for the Sepu monitoring station in Papua New Guinea (5°27.8′S, 145°12.6′E) for the June 2009 to May 2010 monitoring period. The Upper Ramu drainage basin covers 5866 km^2 upstream of Sepu.

Parameter	June–Oct. 2009 + May 2010 (6 months)	Nov. 2009 – Apr. 2010 (6 months)	Annual (12 months)
Q	284 m^3 s^{-1} 730 mm 6-month^{-1}	537 m^3 s^{-1} 1431 mm 6-month^{-1} 66% annual runoff	413 m^3 s^{-1} 2161 mm year^{-1}
Turbidity	125 NTU	291 NTU	209 NTU
SSC	113 mg L^{-1}	512 mg L^{-1}	316 mg L^{-1}
SSL	87 t km^{-2} 6-month^{-1}	868 t km^{-2} 6-month^{-1} 91% annual load	955 t km^{-2} year^{-1}

Table 2 Example annual suspended sediment loads for selected catchments in Papua New Guinea (PNG) and elsewhere in the tropics, sorted by specific sediment yield, plus the global average estimated by Milliman & Syvitski (1992).

Load ($t\ km^{-2}\ year^{-1}$)	Catchment (Region/Country)	Reference
150	Global average	Milliman & Syvitski (1992)
156	Kaihunga (Kenya)	Brown *et al.* (1996)
306	Ulu Segama (East Malaysia)	Chappell *et al.* (2004)
312	W8S5 (East Malaysia)	Douglas *et al.* (1992)
448	Segama (East Malaysia)	Murtedza (1992)
690	Magdalena (Columbia)	Restrepo *et al.* (2006)
955	Upper Ramu (PNG)	Chappell *et al.* (2011) (this study)
1053	Fly[a] (PNG)	Milliman (1995)
1161	Sepik & Ramu (PNG)[c]	Milliman (1995)
1389	Lawing (West Malaysia)	Lai *et al.* (1999)
1513	Fly[b] (PNG)	Milliman (1995)
2124	All basins, New Guinea Island[d]	Milliman (1995)
2167	Purari (PNG)	Pickup *et al.* (1981)
3200	Beni Tiver (Brazil)	Douglas & Guyot (2005)
9500	16 basins (Taiwan)	Kao & Milliman (2008)
11126	Aure (PNG)	Pickup *et al.* (1981)
13000	Jhuoshuei (Taiwan)	Kao & Milliman (2008)

[a] prior to mining at Ok Tedi; [b] post start of mining at Ok Tedi; [c] modelled 115 Mt $year^{-1}$ (Milliman, 1995) from the 99 040 km^2 of the Sepik and Ramu basins combined; [d] modelled 1670 Mt $year^{-1}$ (Milliman, 1995) from the 786 000 km^2 area of New Guinea Island.

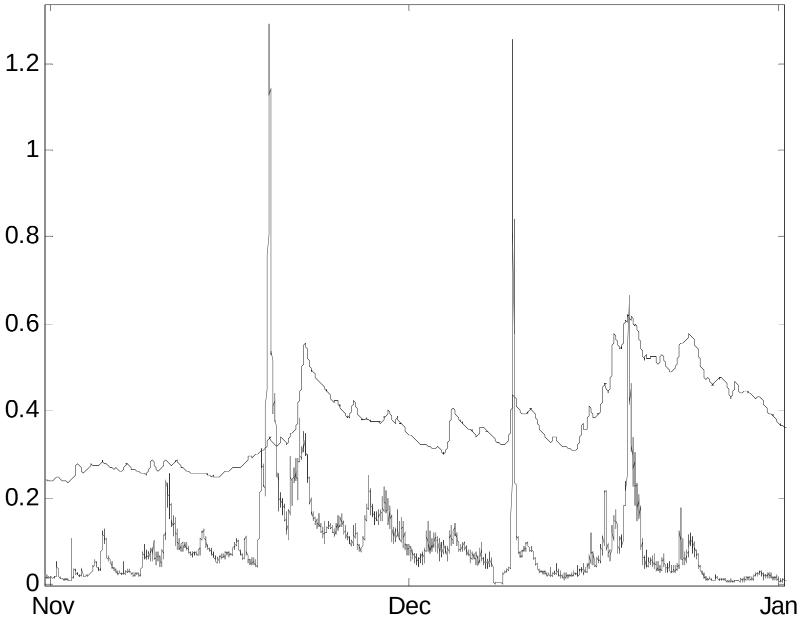

Fig. 4 The 10-minute sampled load (the time-series with faster dynamics: t s^{-1}) and discharge (the time-series with more damped dynamics: L s^{-1} / 10^6) data over the first two months of the wet season (i.e. November–December 2009) for the Sepu monitoring station, Upper Ramu drainage basin, Papua New Guinea.

sediment load is the product of the discharge and suspended sediment concentration, it is clear that the load sedigraphs have very different shapes (i.e., more flashy) than the discharge hydrographs. Furthermore, some of the larger sedigraphs are not associated with larger hydrographs. This variability in the discharge–load relationship is also seen in the variability about the power relationship between discharge and suspended sediment load sub-sampled at noon each day for the one year of Upper Ramu data (Fig. 5). The dynamics illustrated in Figs 4 and 5, therefore, reinforce the need for observing at least hourly suspended sediment concentration (or turbidity) data rather than deriving sub-daily estimates from a relationship with discharge.

As a further illustration of the need to avoid under-sampling of the sediment dynamics we calculate the load derived from a combination of 10-minute discharge and a discharge–SSC relationship based on a single suspended sediment value taken at the same time once per day over one year. The resultant estimates of the annual load vary between 619 and 784 t km^{-2} year^{-1} depending on the sampling hour chosen, and thus only 65–82% of the load estimated from the use of all 10-minute sediment data (i.e. 955 t km^{-2} year^{-1}). Given that infrequent sampling particularly under-represents more turbid periods, as a result of their short duration (see e.g. Fig. 4), sediment sampling only once per week would further bias the load estimates downwards. Indeed the four largest events in the data set of 51 166 values of SSC (Fig. 3) were larger than the 1–3744 mg L^{-1} range of the 591 samples collected over a five-year period (1972–1974 and 1980–1984) in the Upper Ramu by ELCOM (1985; Markham & Repp, 1992).

Observation of the hydrographs and sedigraphs over the year (Fig. 3) shows qualitatively that they have greater amplitude in the wet season in comparison to the dry season. This is shown more clearly within the time-series of smoothed variances (Fig. 6). The variance in the suspended sediment load increases dramatically between the dry and wet seasons. Discharge variance similarly increases between the two seasons and its increase is closely associated with the increase in mean discharge (Fig. 6). The IRWSM-smoothed data within Fig. 6 also shows that discharge and its variability increases faster than that of the suspended sediment load at the start of the wet season. Thus, there appears to be a delay in the mobilisation (or transport) of sediment of over one month with the onset of the wet season.

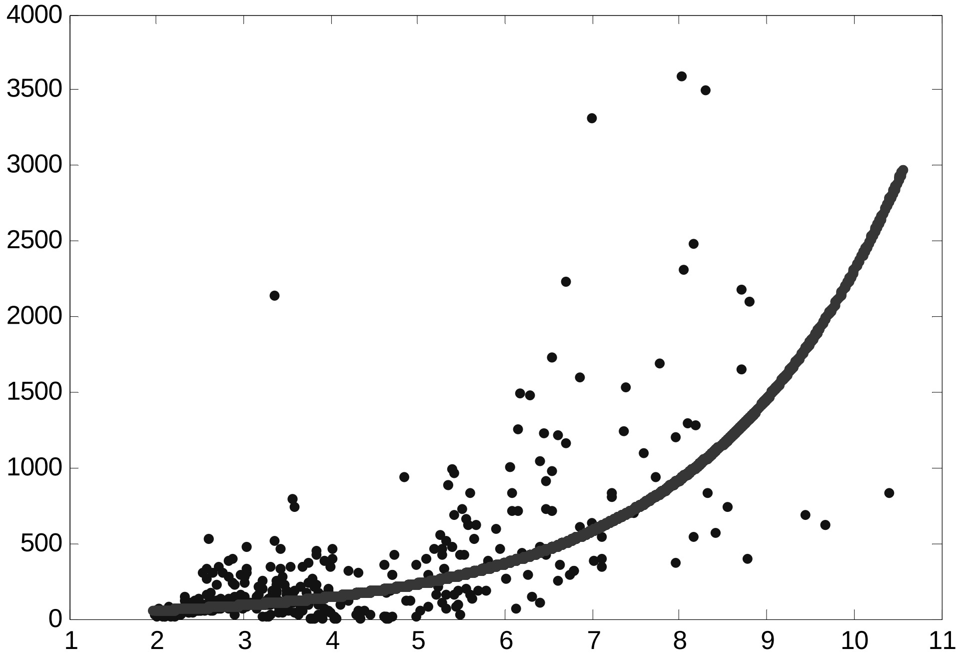

Fig. 5 The relationship between discharge (x-axis: L s^{-1}) and suspended sediment concentration (y-axis: mg L^{-1}) for the Sepu gauging station from June 2009 to May 2010 using only a single daily suspended sediment value sampled at noon each day. These data are abstracted from the full 10-minute dataset (Fig. 3).

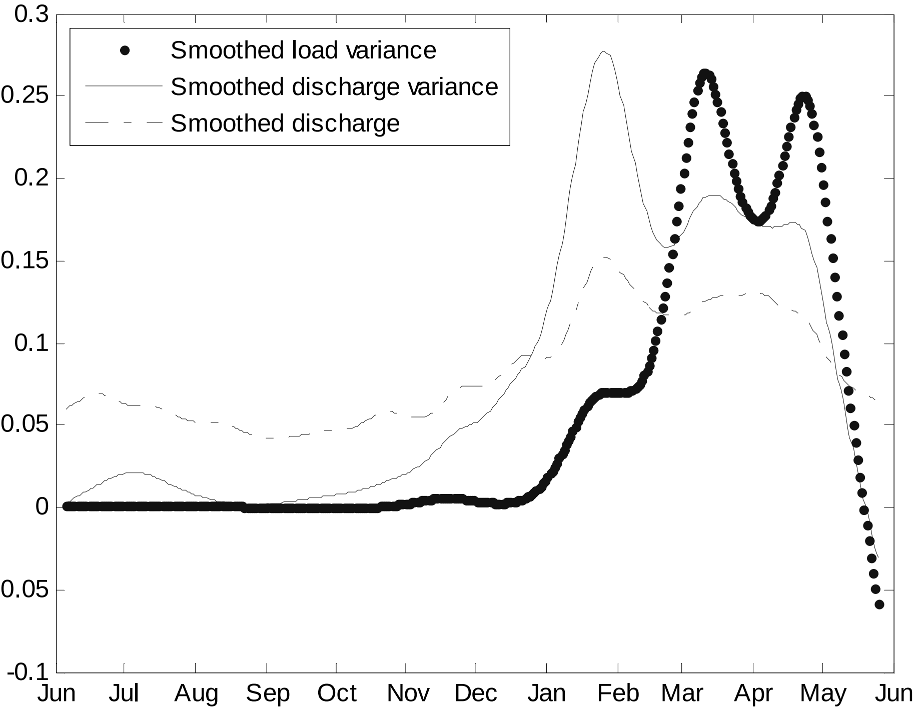

Fig. 6 Time-series of smoothed variances of suspended sediment load and discharge, plus the smoothed discharge for the Sepu gauging station from June 2009 to May 2010. The discharge variance and mean discharge are scaled by factors of 2E-11 and 2E-7, respectively, so that they can be plotted at the same y-axis location as the load variances.

MANAGEMENT IMPLICATIONS AND CONCLUSIONS

Given that the natural variability in the suspended sediment load is much larger within the sedigraphs of the wet season, small changes resulting from anthropogenic disturbances would be more difficult to identify within this wet season. Thus the Ramu River Communities are more likely to observe shifts from the baseline sediment behaviour in the dry season. While the suspended sediment loads within the Upper Ramu are naturally high, mining-related fine sediments may contain much higher heavy metal concentrations in comparison to fine sediment mobilised from natural slopes (Bolton *et al.*, 2009). Thus small changes in SSL within the dry season may indicate an anthropogenic shift in the heavy metal load. If sediment monitoring indicates the possibility of enhanced inputs of heavy metals bound to elevated fine sediment inputs, this would provide the impetus for the Ramu River Communities to seek help to initiate the more costly intensive chemical sampling of the Ramu main stem.

Given the different shapes of the sedigraphs and hydrographs and their flashy nature over sub-daily timescales (i.e. rapid rise and fall), it is important that sub-daily monitoring of turbidity (and stage) is maintained to not only help identify behavioural shifts in SSL within the dry season, but also to allow the calculation of reliable values of seasonal and annual sediment load. The increased reliability and reducing costs of current turbidity and stage monitoring systems means that such systems ought to be deployed more widely in the humid tropics, particularly in environments with high sediment loads, such as New Guinea Island.

Further time-series analysis of the dynamic relationships between the suspended sediment load and the natural or reference behaviour of rainfall and discharge are needed to help identify shifts in the behaviour of the sediment system during the dry season.

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