SUSPENDED SEDIMENT CONCENTRATION AND TURBIDITY RELATIONSHIP IN TWO SMALL CATCHMENTS IN PERLIS, MALAYSIA

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Abstract: The estimation of suspended sediment transport in river is generally based on relationships between suspended sediment and discharge, but these correlations are often poor and are frequently difficult to measure especially during storm events. Extrapolation using discharge in regular sampling involved large errors. An alternative approach is event sampling using automatics sampler but it is expensive and large numbers of samples needed for analysis. In response to this problem, the relationship between suspended sediment and turbidity approach offers a relatively rapid and inexpensive method. A study were conducted from October 2001 to October 2002 involving a fortnightly water sampling and discharge measurement, and two intensive sampling programs (1-4 October 2001 and 11-12 October 2001) at two small catchments areas in northern Perlis. Results from this study show that strong relationships existed between suspended sediment concentrations and turbidity, and vise versa. A good positive relationship suggests that turbidity is possibly the best surrogate for suspended sediment concentrations in estimating the river suspended sediment transport.

***Keywords**: Turbidity; suspended sediment; storm events; Perlis*

Abstrak: Anggaran pengangkutan endapan terampai sungai lazimnya berdasarkan kepada pertalian antara beban ampaian dengan luahan, tetapi pertalian ini agak lemah dan selalunya sukar untuk diukur terutamanya semasa kejadian aliran ribut. Extrapolasi menggunakan luahan melalui persampelan regular melibatkan banyak ralat. Satu pendekatan alternatif ialah dengan melakukan persampelan semasa kejadian siri ribut menggunakan alat persampelan automatik. Namun ini memerlukan belanja yang besar dan melibatkan banyak sampel yang perlu dianalisis. Sebagai respons kepada masalah ini, pertalian antara kepekatan endapan terampai dengan kekeruhan memberikan satu kaedah yag cepat dan murah. Satu kajian bermula daripada Oktober 2001 hingga October 2002 yang melibatkan persampelan dan pengukuran luahan setiap dua minggu dan dua persampelan intensif (1-4 Oktober 2001 and 11-12 Oktober 2001) di jalankan di dua batang sungai kecil di Utara Perlis. Keputusan kajian ini mempamerkan pertalian yang kuat antara kepekatan endapan terampai dengan kekeruhan dan sebaliknya. Pertalian positif ini menjadikan parameter kekeruhan itu sebagai indikator yang terbaik bagi kepekatan endapan terampai dalam penganggaran pengangkutan endapan terampai sungai.

Kata kunci*: Kekeruhan; endapan terampai; kejadian ribut; Perlis*

1.0 Introduction

Suspended sediment is one of the major pollutants of streams (Wade and Heady, 1978). The suspended sediment transport is of considerable interest when studying catchments hydrology and the impacts of land management (Lewis, 1996). Information on the sediment yield of a river, especially the suspended sediment load, can provide a useful perspective on the rate of erosion and soil loss in the upstream catchments (Pavanelli and Pagliarani, 2002). Increasing awareness of the detrimental effects of increased suspended sediment inputs to river systems and the importance of suspended sediment as a vector for nutrient and contaminant transport and in diffuse source pollution, has in turn directed attention to the potential for implementing sediment control strategies in river basins (Russell et al., 2001). Suspended sediment transport monitoring is then designed to establish the stream water quality and basin morphology dynamic, but monitoring programmed are strongly dependent on sampling protocol and sample analysis techniques (Pavanelli and Bigi, 2005).

Many methods have been developed for the estimation of suspended sediment loads in rivers. The most common method is the relationship between suspended sediment concentrations with river discharge and are well documented (Thomas, 1985; Walling and Webb, 1996; Wood, 1977; Klein, 1984; Williams, 1989; Ismail and Rahaman, 1994; Asselman, 2000; Ismail, 2000; Jansson, 1996). However, the relationship between suspended sediment and discharge are often poor when sediment inputs to the channel are highly episodic (Grayson et al., 1996), and spatial variations in channel sediment supply and availability, inputs from tributaries and delivery unrelated to discharge (e.g. bank collapse) (Richards, 1984; Gippel, 1989; Walling et al., 1992). High suspended sediment concentrations are in most cases associated with periods of high discharge but closer inspection of this example indicates that suspended sediment concentration is not a simple function of discharge and that other factor such as the time elapsed since a previous storm event are also important (Walling and Webb, 1996).

Transport changes in suspended sediment concentrations due to natural or human-induced causes are difficult to characterise because suspended sediment concentrations varies rapidly and unpredictably during storm events. Capturing the extreme variation in suspended sediment during storms requires sampling at high temporal frequency, which is usually impractical and expensive (Hasholt, 1992). The underlying problems with these approaches are that discharge is not a good predictor of suspended sediment concentrations and the sampling strategies used provide a poor representation of high discharge events (Grayson et al., 1996). Regular sampling and extrapolation using discharge involved large errors. The other alternative, event sampling using automatic samplers, is expensive, due to the large number of samples which need to be analyzed, and can be unreliable (Grayson et al., 1996). Walling (1977a) suggested separate rising and falling stage curves in order to improve sediment yield estimation.

In response to the problem associated with relationship between suspended sediment concentrations and discharge, the relationship between suspended sediment concentrations and turbidity approach offers a relatively rapid and inexpensive method (Sun et al., 2001). This relationship has been widely used for suspended sediment monitoring and generally strong and well document (Asselman, 2000; Hasholt, 1992; Banasik and Walling, 1996; Hodson et al., 1998; Walling, 1977b; Gilvear and Petts, 1985; Krause and Ohm, 1984: Kunkle and Comer, 1971; Gippel, 1995; Finlayson, 1985). The relationship between suspended sediment concentrations and turbidity is quite good for most rivers, particularly when changes in particle size during storm events are minimal. It has been founds that turbidity is a much better predictor than discharge for estimating suspended sediment loads (Lewis, 1996). This study describes the relationship between suspended sediment concentrations and turbidity of fortnightly samples over a year (October 2001 to October 2002) and during two storm events (1-4 October 2001 and 11-12 October 2001) in two small catchments in Perlis, Malaysia.

2.0 Study Area

The study area is close to the Thailand border near Padang Besar Town (Figure 1). The studied catchments are the Upper Jarum river and its main tributary, and the Khlong Wang Rua (KWR); both were gauged at R1 and R2, respectively. The two catchments are close together and can be considered as a paired catchment having similar soil types, and rainfall are therefore could be considered spatially uniform in volume and intensity. The catchment area of Jarum measured from the gauging station R1 (06° 38' 71" N; 100° 17' 17" E), is 6.12 km^2 with a drainage density of 2.09 km km^{-2} and an elevation of 40 m a.s.l. Sugarcane plantation is the main land use accounted for 83.1% of total catchment, rubber plantation - 6.1% and shrubland - 10.8%. The catchment area of Khlong Wang Rua, measured from the gauging station R2 (06° 38' 22" N; 100° 17' 18" E) is 6.26 km^2 with a drainage density of 1.28 km km^{-2} and an average elevation of 40 m a.s.l. The catchment area consists of rubber plantation (53.2%), urban and associated areas (43.3%) and mixed crop (3.5%).

Perlis received the lowest rainfall compared to the other states in Malaysia. In north Perlis, the expected annual rainfall is as low as 1600 mm (Chan, 1982). The total annual rainfall recorded during this study period was 1719.5 mm. The total monthly rainfall pattern shows a double peaked distribution with two maxima occurring in October 2001 (265.5 mm) and September 2002 (386.0 mm) and two minima occurring in January (18.0 mm) and February (0.0 mm). Relative humidity is constantly high ranging between 82 and 86 % on the lowland (Siew, 1969).

The geology of the area is the Singha (Kubang Pasu) Formation from Carboniferous period, which is composed of mudstones, siltstones, shale and sandstones. A small pocket of sedimentary rock belonging to the tertiary (probably Miocene) period is located in the North-east near the Thai-Perlis border. This sedimentary rock is younger than granite and is thought to be a small basin deposit either lacustrine or estuarine whose successions include sandstones, shale, conglomerate and a thin coal seam (Siew, 1969).

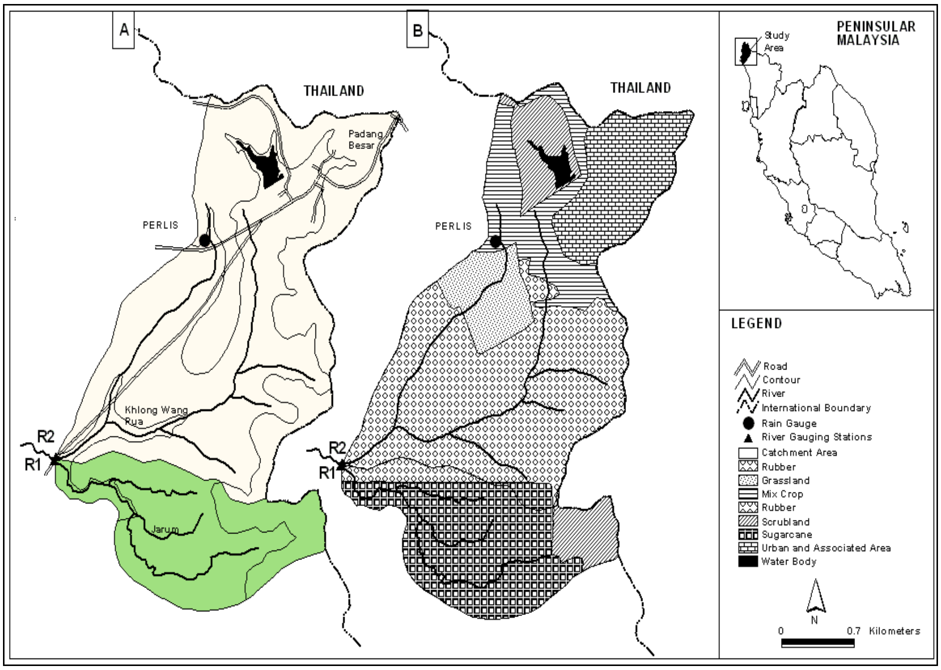

Figure 1 : Study area showing (A) locations of rainfall and gauging stations and (B) land use of the catchment area

3.0 Data

The data sets were collected as part of a wider study on the sources of sediment and nutrients in several river catchments surrounding the Timah Tasoh reservoir and its effect on the reservoir located some 13 km downstream (Rahaman, 2004; Ismail and Ku Hashim, 2002). The storm data presented here essentially resulted from two intensive studies during wet seasons and a fortnight sampling program from October 2001 to October 2002 (Bakar, 2004). The first intensive sampling was from 1-4 October 2001 and the second was from 11-12 October 2001. In the wider study, water quality parameters were analysed but in this paper only relevant information was used i.e discharge, suspended sediment concentration (SCC) and turbidity.

River gauging was carried out using the velocity-area methods (Gordon et al., 1992) while SSC and turbidity were measured at the laboratory. Turbidity was measured using a laboratory turbidity meter model Hach DR/2000. The turbidity unit reported in

Formazin Turbidity Unit (FTU), which is a direct measure of the light attenuation caused by suspended particles in the water equivalent to Nephelometric Turbidity Unit (NTU) normally described in many other studies (Gippel, 1989). SSC was determined by filtering the samples through a 0.45 μm Whatman GF/C filter papers using a vacuum filter pump. After filtering, samples were oven-dried at 105 ^{o}C for 24 hous, and weighed until an equilibrium weights were achieved (APHA, 1989; Gordon et al., 1992).

The relationship between SSC and turbidity is often expresses in a linear regression equation (Sun et al., 2001). Rating curves for SSC as a function of turbidity were develop using linear regression methods. Higher correlation coefficients are indicative of lower variability and better prediction of SSC by turbidity. In addition, this curve described the rate of SSC changes with changes in turbidity through the slope of the regression in the equation:

$$Y = mX \tag{1}$$

where Y is SSC (mg l^{-1}), X is the turbidity (FTU), m being constant.

4.0 Results

4.1 Discharge

Discharge Q, of the study streams has two distinct seasonal periods. Discharge was low and constant during the early dry months. During this priming phase, precipitation infiltrated and recharged watershed soils and did not contribute to siginificant increases in stream flow. Q is responsive to rainfall and often elevated rapidly when the soils approach saturation. Discharge is affected by both the intensity and distribution of rainfall and these may be affected by interception and evapo-transpiration losses before the excess water reaches river channel (Bowen, 1982). In general, the discharge is highly seasonal and directly related to rainfall (Fig. 2). Most of the rainfall received during April to May 2002 and September to October 2002 inter-monsoon periods, The water discharge was highest in these periods compared to other months. Wet seasons have the highest discharge compared to dry season. The discharge during wet seasons is highly responsive and flashy and rises to a seasonal peak in September to October, lagging behind the annual rainfall distribution (Brasington et al., 1998).

4.2 Relationship between discharge and SSC

Accurate measurement and estimation of suspended sediment transport are dependent on the timing and frequency of data collection. The relationship between instantaneous measurements of SSC and discharge is generally too variable to detect any shift in the relationship over time (Lewis, 1996). In some cases, a rating curve relating these parameters were used to estimate the suspended sediment load. . In our study, the relationship between discharge and SSC at R1 and R2 was poor with R^2 of 0.205 and 0.470, respectively. This implied that only 20% of the variation of SSC at R1 is explained by the variation in discharge and only 47% for R2.

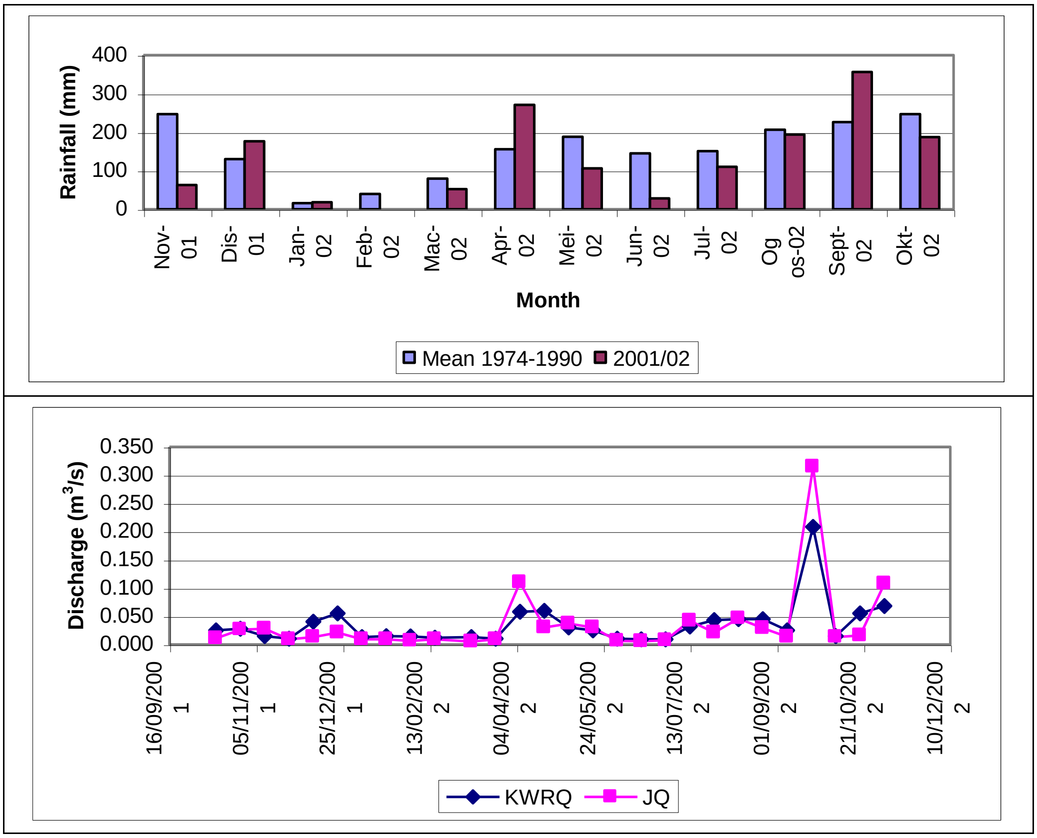

Figure 2 : Monthly rainfall distribution during the study period and the long term average (above) and river discharge of Jarum and KWR rivers during the study period (bottom)

The weak relationship between SSC and discharge in our study may be due to several factors. One of them is the proximity of the sediment sources from within the catchments that are locally influenced by subsoil sources (Grayson et al., 1996). Another reason could be due to "hyteresis phenomena" in recession flow owing to greater dilution by groundwater and a reduced transport capacity in the recession part of the flood (Wotling and Bouvier, 2002). A lag in the hydrologic response system could also influenced the correlation. Soil eroded in the early monsoon is not flushed from the hill slopes and through the channel network until the catchment has wetted up and sediment transport become more continuous and efficient (Wotling and Bouvier, 2002).

4.3 Relationship between turbidity and suspended sediment concentration

In general, the SSC is strongly related to turbidity (Fig. 3) compared to river discharge. Therefore it's worthwhile to explore such relationships for estimating SSC. In this study, the relationships between SSC and turbidity at R1 and R2 show good correlation with R^2 of 0.781 and 0.792, respectively.

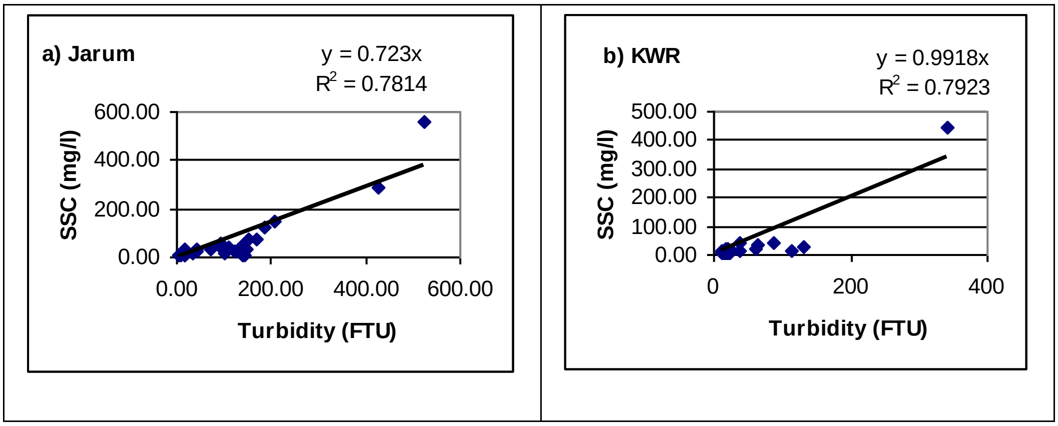

Figure 3 : The relationship between SSC and turbidity at (a) Jarum river (R1) and (b) KWR river (R2) based on fortnightly sampling data

During rainy period, river turbidity is higher than during periods a constantly changing phenomenon (Fig. 4 and Fig. 5). During dry period, turbidity levels usually drop to a somewhat stable value for the river. Rainfall in the catchments can then bring additional suspended sediment into the river and greatly increase the turbidity. The terminal velocity is much higher for larger particles, and as fluvial energy decreases during flood recession, coarse material is rapidly deposited while the finer material remains in suspension. This could explain the higher turbidity values in relation to suspended sediment concentration responsible for the hysteresis (Wass et al., 1997).
Generally, the more intense the rainfall results in higher turbidity values. However, the relation between stream discharge and turbidity can also be affected by conditions such as the differences in timing or hysteresis, between turbidity and peak discharge (Costa, 1977). Scatter in this rating relationship may be due to the exhaustion of available sediment during an interval of intense storm activity, resulting in a temporally variable pattern of sediment load for equal floods (Brasington and Richards, 2000). Possible explanations could include the presence of a significant sediment source distant from the zone of major runoff production, or a significant difference between flood wave celerity and the mean flow velocity that carries the bulk of the suspended sediment (Brasington and Richards, 2000).

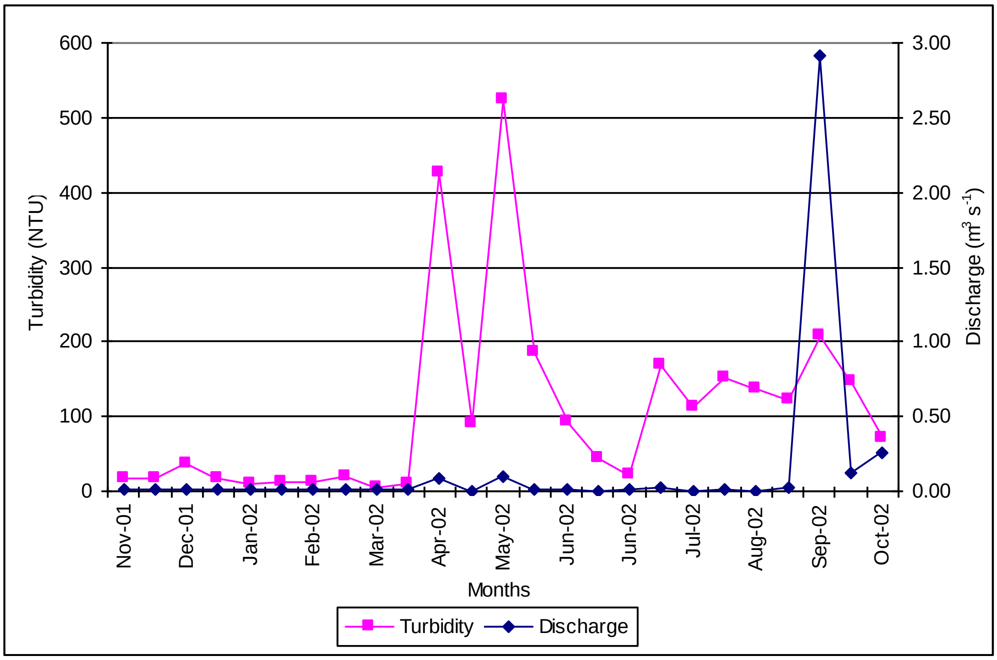

Figure 4 : Relationship between turbidity and discharge at R1

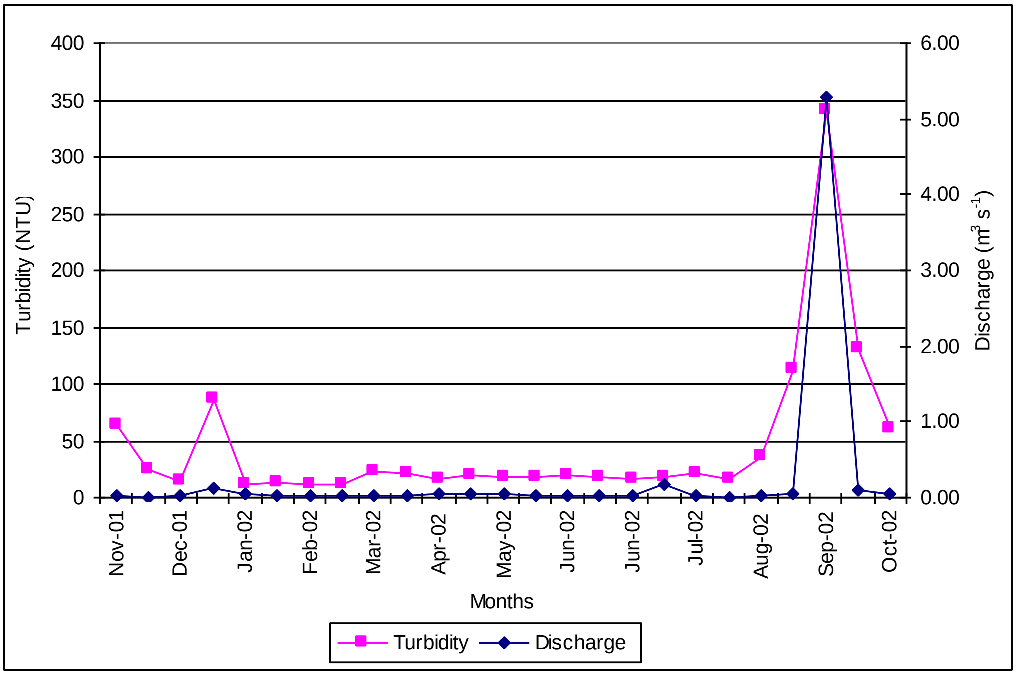

Figure 5 : Relationship between turbidity and discharge at R2

4.4 Turbidity and SSC during storm events

Most of sediment movements occurred during infrequent flood event (Jansson, 1988). As such non continuous sampling such as on a weekly or monthly basis may miss these storm or flood events, leading to an under-estimation of sediment loading (Gippel, 1995; Littlewood, 1992). The relationship demonstrates some degree of scattering.

Turbidity and SSC for storm samples show strong linear correlations. The relationships between SSC and turbidity, and discharge with SSC for two storm events are shown in Figures 6 to 9. There were good correlation between SSC and turbidity at both stations. At R1, the first storm event on 1/10/01 to 4/10/01 shows a good SSC-turbidity relationship (R^2 = 0.8336) (Fig. 6a) while the discharge-SSC relationship was quite weak (R^2 = 0.5415) (Fig.7b). The second storm on 11/10/01 to 12/10/01 also show strong turbidity-SSC relationship (R^2 = 0.8225) (Fig. 7a), and similar to R1, the discharge and SSC were weakly correlated (R^2 = 0.4563) (Fig. 7b).

Similarly, strong relationships between turbidity and SSC were obtained during the storm events at R2. The turbidity-SSC relationship was good (R^2 = 0.9552) for storm event on 1/10/01 to 4/10/01 (Fig.8a), and R^2 of 0.8161 for storm event on 11/10/01 to 12/10/01 (Fig. 9a). Weak discharge and SSC relationships (R^2 = 0.0415) were observed during storm on 1/10/01 to 4/10/01 (Fig.8b). However, the discharge and SSC for the second storm on 11/10/01 to 12/10/01 was moderately correlated (R^2 = 0.6331, Fig. 9b).

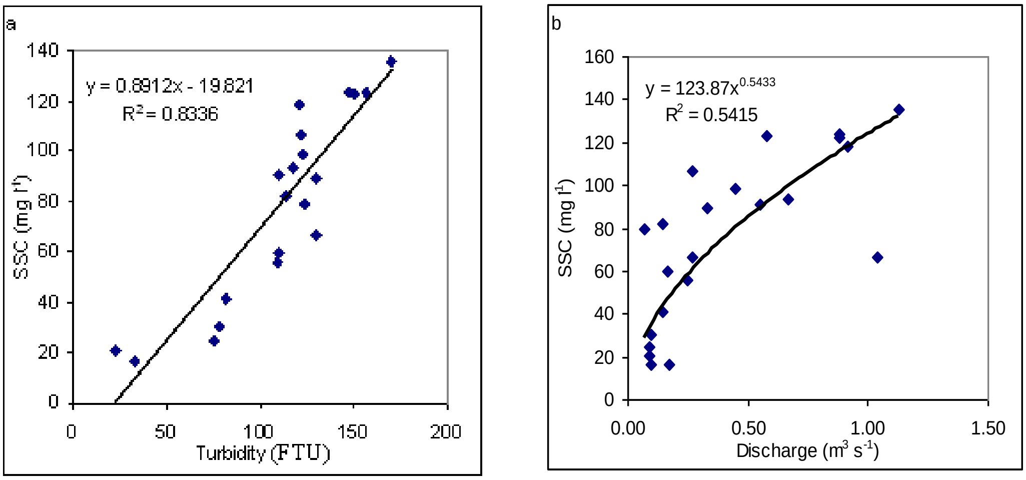

Figure 6 : Relationship between: (a) turbidity and SSC, and (b) discharge and SSC during storm event on 1/10/2001 to 4/10/2001 at R1

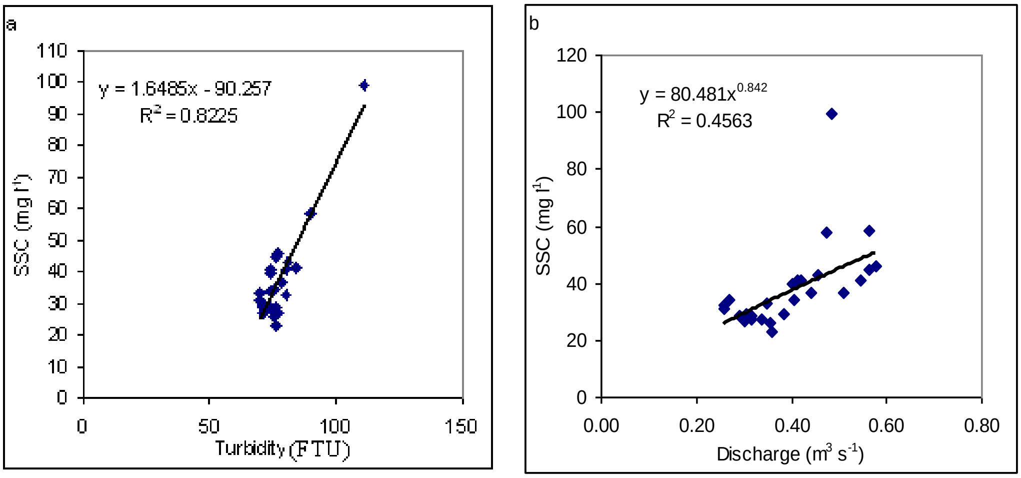

Figure 7 : Relationship between: (a) turbidity and SSC, and (b) discharge and SSC during storm event on 11/10/2001 to 12/10/2001 at R1

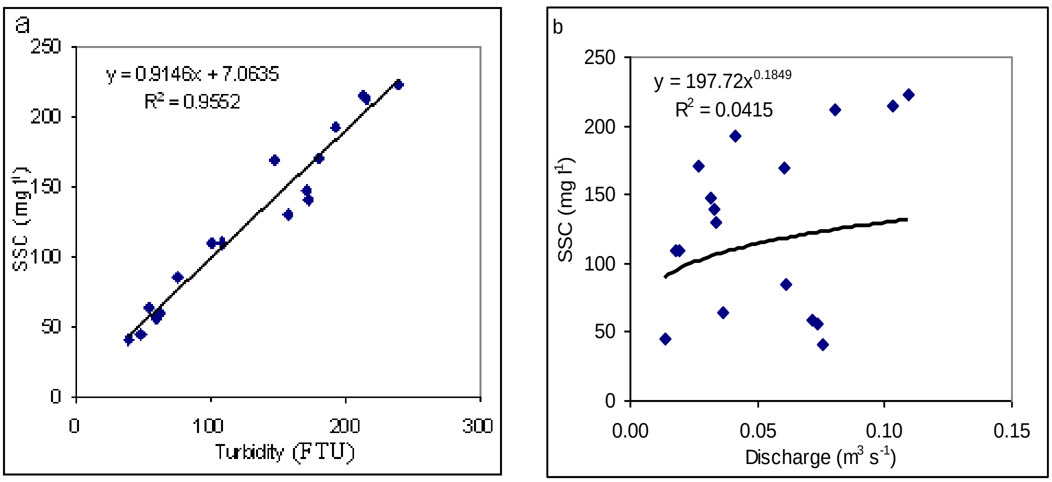

Figure 8 : Relationship between: (a) turbidity and SSC, and (b) discharge and SSC during storm event on 1/10/2001 to 4/10/2001 at R2.

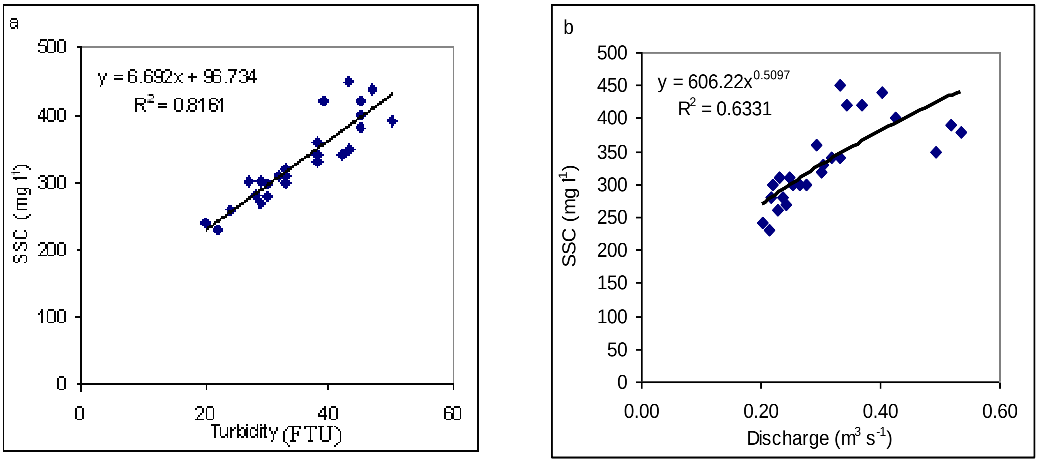

Figure 9 : Relationship between: (a) turbidity and SSC, and (b) discharge and SSC during storm event on 11/10/2001 to 12/10/2001 at R2

Based on the above analysis, it is found that SSC fluctuates considerably, following the rise and fall of turbidity. The relationship does show scatter, probably due to natural variability in suspended sediment size, shape and composition. Normally, the first storm event after a dry period, has a larger initial flush of suspended sediment concentration which results in higher turbidity than the subsequent storm, even with a larger size (Paustian and Beschta, 1979). The weak discharge- SSC correlation at R2 during the 1/10/2001 to 4/10/2001 storm was probably due to limited quantity of sediment, and the likelihood that the main sources of sediment are due to the exhaustion of available sediment during an interval of intense storm activity (Brasington and Richards, 2000). The flushing of accumulated materials near the channel by surface runoff and the subsequently exhaustion of these sediment sources also could be the causes of this weak correlation (Klein, 1980).

5.0 Conclusions

The variability of turbidity and SSC values observed in the study catchments is the reflection of the hydrology and land use characteristics of these catchments. About 70% of the SSC variation could be explained by turbidity when both forthrightly and storm samples are considered, and more than 80% during storm events only. Results indicated that turbidity which is influnced by suspended and dissolved particles, is a more reliable surrogate for determining suspended sediment loads. The discharge-SSC relationship is rather weak because of the spatial variations in channel sediment supply and availability, inputs from tributaries and delivery unrelated to discharge.

The regression analysis should be carried out with caution because turbidity is very sensitive to variations in the size distribution and composition of suspended sediment. In order to minimize errors related to the use of different monitoring instrumentation and any spatial variations, sensor and site specific relationships should be established between SSC and turbidity. The relation between turbidity and SSC is good, particularly when changes in particle size during storm events are minimal as shown in our study because relatively good estimation results are generally associated with small storm events, low concentration and large time intervals. This study shows that turbidity is a good indicator of suspended sediment concentrations and may be used as a surrogate to estimate suspended sediment transport.

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References

APHA (1989) Standard Methods for Examination of Water and Wastewater. 17th Edition. Washington D. C.: *American Public Health Association*.

Asselman, N. E. M. (2000) Fitting and interpretation of sediment rating curves. *Journal of Hydrology*, 234: 228 – 248.

Bakar, S. 2004, Soil erosion and nutrient losses from agricultural and urban land uses: Case study of Relau River, Penang and Jarum river , Perlis. Unpublished MA thesis, Geography Department, Universiti Sains Malaysia (in Malay).

Banasik, K. and Walling, D.E. (1996) Predicting sedimentgraphs for a small agriculture catchment. *Nordic Hydrology* 27(4): 275 – 294.

Bowen, R. (1982) Surface Water. London: Applied Science Publishers.

Brasington, J., El-Hames, A. and Richards, K. S. (1998) Hydrological modelling in humid tropical catchments. In: Harper, D. M. & Brown, T. (Eds.). Sustainable Management of Humid Tropical Catchments. Chichester: John Wiley & Sons, pp. 314 – 334.

Brasington, J. and Richards, K. (2000) Turbidity and suspended sediment dynamics in small catchments in the Nepal Middle Hills. *Hydrological Processes*, 14: 2559–2574.

Chan, N. W. (1982) The reliability of rainfall in relation to wet rice cultivation in northwest Peninsular Malaysia. Journal of Tropical Geography, 6: 14 – 23.

Costa, J. E. (1977) Sediment concentration and duration in stream channels. *Journal of Soil and Water Conservation*, 32: 168 – 170.

Finlayson, B. L. (1985) Field calibration of a recording turbidity meter. Catena, 12: 141 – 147.

Gilvear, D.J. and Petts, G.E. (1985) Turbidity and suspended solids variations downstream of a regulating reservoir. *Earth Surface Processes and Landforms*, 10: 363 – 337.

Gippel, C. J. (1989) Use of turbidimeters in suspended sediment research. *Hydrobiologia* 176(17): 465 – 480.

Gippel, C. J. (1995) Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes*, 9: 83 – 97.

Gordon, N. D., McMahon, T. A. and Finlayson, B. L. (1992) *Stream Hydrology: An Introduction for Ecologists*. Chichester: John Wiley & Son Ltd.

Grayson, R. B., Finlayson, B. L., Gippel, C. J. and Hart, B. T. 1996, The Potential of Field Turbidity Measurements for the Computation of Total Phosphorus and Suspended Solids Loads. *Journal of Environmental Management*, 47: 257–267.

Hasholt, B. (1992) Monitoring sediment load from erosion events. In: Bogen, J., Walling D. E. and Day, T. J. (Eds.). Erosion and Sediment Transport Monitoring Programmes in River Basins. Proceedings of the Oslo Symposium, August 1992. IAHS Publication No. 210, pp. 201 – 208.

Hodson, A., Grurnell, A., Tranter, M., Bogen, J., Hagan, J. O. and Clark, M. (1998) Suspended sediment yield and transfer processes in a small high arctic glacier basin, Svalbard. *Hydrological Processes* 12(1): 73 – 86.

Ismail, W.R. and Rahaman, Z.A. (1994) The impact of quarrying activity on suspended sediment concentration and sediment load of Sungai Relau, Pulau Pinang, Malaysia. *Malaysian Journal of Tropical Geography* 25(1): 45 – 57.

Ismail, W.R. (2000) The hydrology and sediment yield of the Sungai Air Terjun catchment, Penang Hill, Malaysia. *Hydrological Sciences* 45(6): 897 – 910.

Ismail, W.R. and Ku Hashim, K.A. (2002) Longitudinal Variation of Water Quality of Sungai Jarum catchment-Linking Ecology with Hydrology for Reservoir Management. Proc. International Conference Environmental Management: Ten Year after Rio, Bangi, Selangor, 22-23 October 2002, pp. 402-410.

Jansson, M. B. (1988) A global survey of sediment yield. *Geografiska Annaler*. Series A 70: 81 – 98.

Jansson, M. B. (1996) Estimating a sediment rating curve of the Reventazon River at Palomo using logged mean loads with discharge classes. *Journal of Hydrology* 183: 227 – 241.

Klein, M. (1984) Anti clockwise hyteresis in suspended sediment concentration during individual storm: Holbeck catchment, Yorkshire, England. *Catena* 11: 251 – 257.

Klein, M. (1980) Dissolved material transport-the flushing effect in surface and subsurface runoff flow. *Earth Surface Processes and Landforms* 11: 251 – 257.

Krause, G. and Ohm, K. (1984) A method to measure suspended load transports in estuaries. Estuarine Coastal Shelf Science 19: 611 – 618.

Kunkle, S. H. and Comer, G. H. (1971) Estimating suspended sediment concentrations in streams by turbidity measurements. *Journal of Soil and Water Conservation*, 36: 18 – 20.

Lewis, J. (1996) Turbidity-controlled suspended sediment sampling for runoff- event load estimation. *Water Resources Research*, 32: 2299 – 2310.

Littlewood, I. G. (1992) Estimating Contaminant Loads in Rivers: A Review. Report No. 117. Oxfordshire: Institute of Hydrology.

Paustian, S. J. and Beschta, R. L. (1979) The suspended sediment regime of an Oregon Coast Range stream. *Water Resources Bulletin*, 15: 144 – 154.

Pavanelli D. and Bigi, A. (2005) Indirect methods to estimate suspended sediment concentration: reliability and relationship of turbidity and settleable solids. *Biosystems Engineering*, 90 (1): 75 – 83.

Pavanelli, D. and Pagliarani, A. (2002) Monitoring water flow, turbidity and suspended sediment load, from an Apennine catchment basin, Italy. *Biosystems Engineering*, 83 (4): 463 – 468.

Rahaman, Z.A. (2004) The Sediment Balance and Sedimentation of the Timah Tasoh Lake, Perlis, Malaysia. Unpublished PhD Thesis, Department of Geography, Universiti Sains Malaysia (in Malay)

Richards, K. (1984) Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. *Earth Surface Processes and Landform* 9: 101–112.

Russell, M. A., Walling, D. E. and Hodgkinson, R. A. (2001) Suspended sediment sources in two small lowland agricultural catchments in the UK. *Journal of Hydrology*, 252: 1 – 24.

Siew, K. Y. (1969) Present Land Use Survey of Malaysia: Land Use Report of Perlis. Report No. 6. Kuala Lumpur: Ministry of Agriculture and Co-operatives.

Sun, H. Cornish, P.S. and Daniell, T.M. (2001) Turbidity-based erosion estimation in a catchment in South Australia. *Journal of Hydrology*, 253: 227 – 238.

Thomas, R. B. (1985) Estimating total suspended sediment yield with probably sampling. *Water Resources Research*, 21(9): 1381 – 1388.

Wade, J. C. and Heady, E.O. (1978) Measurement of sediment control impacts on agriculture. Water Resource Research, 14(1): 1 – 8.

Walling, D. E., Webb, B. W. and Woodward, J. C. (1992) Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport. *IAHS Publication* No. 210: 279 – 288.

Walling, D. E. (1977a) Limitations on the rating curve technique for estimating suspended sediment loads, with particular reference to British rivers. *IAHS Publication* No. 122: 34 – 48.

Walling, D. E. (1977b) Assessing the accuracy of suspended sediment rating curves for a small basin. *Water Resources Research*, 13: 531 – 538.

Walling, D. E. and Webb, B. W. (1996) Water quality: physical characteristics. In: Calow, P. and Petts, G. E. (Eds.). The River Handbook: Hydrological and Principles. Vol. 1. London: Blackwell Scientific Publications, pp. 48 – 72.

Wass, P. D., Marks, S.D., Finch, J.W., Leeks, G. J. L. and Ingram, J.K. (1997) Monitoring and preliminary interpretation of in-river turbidity and remote sensed imagery for suspended sediment transport studies in the Humber catchment. *The Science of the Total Environment*, 194/195: 263 – 283.

Williams, G. P. (1989) Sediment concentration versus water discharge during single hydrologic events in rivers. *Journal of Hydrology*, 111: 89 – 106.

Wood, P. A. (1977) Controls of variation in suspended sediment concentration in the River Rother, West Sussex, England. *Sedimentology*, 24: 437 – 445.

Wotling, G. and Bouvier, C. (2002) Impact of urbanization on suspended sediment and organic matter fluxes from small catchments in Tahiti. *Hydrological Processes*, 16: 1745 – 1756.