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Sediment delivery from a landslide to a stream in a drainage basin in Hong Kong

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Abstract Landslides commonly occur on undeveloped hillslopes in Hong Kong, China. Heavy rainfall in June 2001 and May 2003 resulted in small landslides in a headwater drainage basin. Measurements of suspended sediment concentration made during the storm events, along with observations on sediment colour and C and N content, indicate that the suspended matter in streamflow was derived from the landslides, evidencing the connectivity of hillslope and channel systems. Estimates of the volume of failed material when compared to those of deposition revealed that much of the debris from the landslides remained on the slope in an ephemeral drainage line. At-a-point erosion from the landslides is much greater than that recorded by erosion pins in the same catchment.

Key words hysteresis; landslide; sediment colour; suspended sediment

INTRODUCTION

In Hong Kong, landslides commonly occur both within the developed urban area, often in association with cut and fill slopes (cf. Brand, 1985), and on undeveloped hillslopes, termed "natural terrain" (Ng *et al.*, 2002). The Natural Terrain Landslide Study identified some 8804 recent landslides for hillslopes in Hong Kong (Evans *et al.*, 1999) from approximately 50 years of aerial photographic records. Research on landslides in "natural terrain" has focused upon identifying controlling factors in their location and generation (e.g. Franks, 1999; Dai *et al.*, 2001; Ruse *et al.*, 2002) and assessing susceptibility and hazard (e.g. Franks, 1999; Dai & Lee, 2002; Parry *et al.*, 2002). However, comparatively little attention has been given in Hong Kong to other geomorphological aspects of landslides, and in particular the linkage, or coupling, between hillslope and channel systems. Harvey (2002) suggests that understanding coupling within the fluvial system is important because it is influential in determining the geomorphic response to environmental change. He also observes that within headwater fluvial systems the most significant aspect of the linkage is hillslope channel coupling. Knowledge of hillslope channel connectivity in headwater streams is also important because, as Haigh *et al.* (1998) and Gomi *et al.* (2002) indicate, headwater catchments exert a control upon downstream fluvial systems. This study documents the linkage between hillslope and channel systems consequent upon landslides in terms of sediment production for a small headwater drainage basin in Hong Kong.

STUDY AREA

Monitoring of suspended sediment concentration began in 1993 in a small (0.052 km^2) drainage basin located near Wong Chuk Hang in the New Territories of Hong Kong, China. The basin, termed RDH, is a headwater stream of the Kam Tin River. The average slope gradient is 30º, with some areas being over 50º and the highest point of the drainage basin being around 380 m. The upper parts of the basin consist of granodiorite and volcanic tuffs with siltstone and sandstone interbeds, all of which have been subjected to weathering. Colluvium deposits occur on the slopes whilst soils are shallow, moderately acid Acrorthoxes. The hillslopes are covered in a mix of *Dicranopteris* fern, grassland, shrubland and a small area of *Acacia* trees. Hill fires have occasionally affected the area.

Climatically the area is subtropical monsoonal with about 80% of the rain falling between May and September. The mean annual rainfall of 2214 mm for the period 1961–1990, measured at the Hong Kong Observatory, hides a considerable range. The extremes, since 1884, are 901.1 mm in 1963 and over 3330 mm in 1997. At the Kadoorie Agricultural Research Centre (KARC), located close to the study basin, the mean annual rainfall for the period 1991–2001 is 2747 mm, with an annual maximum of over 3600 mm in 2001. May to August are hot and humid, with a mean daily temperature of 28.8ºC in August (1961–1990), whilst the winters are more temperate with an average daily temperature of 15.8ºC in January over the same period.

METHODS

Sampling to monitor suspended sediment concentrations at the outlet of the small headwater catchment began in 1993. The samples (a water-sediment mixture) have been collected over a range of flow conditions and have been collected manually and by means of an ISCO 2700 automatic sampler. Typical sample volumes are around 400 to 500 ml for the automatic sampler with larger volumes sometimes being collected by manual sampling in order to ensure sufficient sediment for analysis of C and N. Upon return to the laboratory the suspended sediment was separated using pre-weighed GF/C filter papers. Total C and N was measured on a Perkin Elmer 2400 elemental analyser after the sediment was disaggregated and passed through a 250 micron mesh sieve. Sediment colour was determined using standard soil colour charts. Water level was manually recorded at the time of sampling by means of a stage board at a v-notch weir located at the catchment outlet.

A number of erosion plots (6 × 20 m) with 30 erosion pins, regularly spaced in three rows of 10 (to aid relocation), have been maintained to measure the change in ground surface. The pins were inserted to a minimum depth of 40 cm in the soil to provide a stable datum. Pins were measured at least annually in January of each year since observations began on six plots in 1992. Average slope angles for plots 1 to 6 are 15°, 15°, 26°, 27°, 25° and 26°, respectively.

The landslides that activated during rainfall in June 2001 and May 2003 were accessible and field surveyed to gather data. The information recorded included data relating to both the landslide source (e.g. slope angle above the main scarp, rupture surface angle, main scarp depth, width) and the associated debris trail (e.g. depth, width, length). Volume calculations of both source and debris trail were obtained by multiplying measured area by their average measured depth. These were based upon a tape/chain field survey of the failure. These calculations permitted the determination of a mass balance for the landslide in terms of volume of material produced from the source and the volume of debris remaining in storage in the debris trail.

LANDSLIDES

Two rainfall events have generated landslides in the basin since observations began in 1992. The first occurred on 9 June 2001, in association with a low pressure trough near the South China coast. Nearly 100 mm of rainfall was recorded at KARC from 09:00 h on 8 June to 09:00 h on 9 June, with subsequent hourly rainfall totals of 68 and 52 mm. The monthly rainfall of 1083.6 mm at the Hong Kong Observatory was roughly three times the normal. In the second rainfall event, a trough of low pressure arising from an unstable maritime airstream produced rainfall sufficient for the issuance of a landslide warning on 5 May 2003. Around 190 mm of rainfall were recorded at KARC between 09:00 h on 4 May to 09:00 h on 5 May, with an hourly maximum of around 40 mm. Based upon the record of landslides in Hong Kong from the Natural Terrain Landslide Inventory for the period 1985 to 1994 inclusive, Evans *et al.* (1999) report the possible existence of rainfall thresholds. They suggest that for areas receiving an annual rainfall of between 2000 and 2400 mm landsliding will start with a 24-h rainfall total of 60–70 mm whilst in areas receiving an annual rainfall in excess of 2400 mm the threshold for landslide initiation is 70–110 mm. Both the landslide events observed in the study basin support these thresholds. Evans *et al.* (1999) state that their thresholds are average values and that site-specific rainfall thresholds will depend on a complex combination of factors and may vary widely.

Both landslides occurred at the head of an ephemeral drainage line between two minor spurs, at an altitude of around 336 m and in an area of low shrub and grass. The studies of Franks (1999), Dai & Lee (2002) and Ruse *et al.* (2002) in Hong Kong reveal that many landslides occur within or adjacent to significant drainage lines or hollows. Relict failures are evident on the western spur, with minor retrogression of the main scarp observed in 2000. The June 2001 failure occurred immediately upslope of the relict scarp and the landslide of May 2003 was a further scarp retrogression. Franks (1998) and Ruse *et al.* (2002) report that landslides in Hong Kong may be associated with areas of previous instability. The failures occurred in colluvium containing considerable amounts of sub-angular cobbles and some boulders. Both were relatively shallow; just over 1 m deep in 2001 and around 0.8 m deep in 2003. Pre-failure slope angles and rupture surface angles were around 44° and 46°, respectively, in 2001, 37° and 42° in 2003. The 2001 event was around 9 m wide, about 7 m long and had an estimated source area volume of around 50 m^3. The rather smaller 2003 mass movement had a maximum width and length of 4 and 2 m, respectively, and an estimated volume of 7 m^3.

The main debris trails extended around 20 m on the 2001 failure and around 26 m for the 2003 event and are within the range of values reported by Franks (1999) for a study based on landslides that occurred on hillslopes in Lantau Island, Hong Kong. Based upon the area of failed material deposition and the depth of the materials, deposition in the two events was estimated at 52 and 14 m^3 for 2001 and 2003, respectively. These simplistic estimates of deposition illustrate that much of the failed material remained in storage on the slope and in the ephemeral drainage channel. No pronounced scouring of the channel downstream of the failure was observed, suggesting that for these two events additional erosion caused by the landslide itself scouring the hillslope and channel was not important. This may reflect the fact the two failures did not develop into debris flows, in which scouring can lead to the incorporation of material into the landslide, a process referred to as bulking by Scott *et al*. (2001). They provide a number of examples of bulking whilst the work of Franks (1999), Ruse *et al*. (2002) and King & Williamson (2002) show that the process can occur in association with landslides in Hong Kong. Evidence that some of the failed material left the slope is provided by observations of suspended sediment transport made in a small stream downstream of the failures.

SUPSPENDED SEDIMENT TRANSPORT

For both the landslide affected storm events of June 2001 and May 2003 pre-storm values of suspended sediment were low, around 10 mg l^{-1}, levels to which suspended sediment concentrations returned at the end of the two events. However, exceptionally high suspended sediment concentrations were recorded during the June 2001 failure, with four samples exceeding 2600 mg l^{-1}. The much smaller landslide event of May 2003 produced, in comparison to the June 2001 storm, rather lower levels of suspended sediment, with a maximum of 227 mg l^{-1}. This may reflect the considerably smaller size of the 2003 failure. During 1993–2000, only 10% of all storm period samples (n = 566) exceeded 200 mg l^{-1}. This indicates that even the lower May 2003 suspended sediment maximum value of 227 mg l^{-1} is unusually high for the basin, while the concentrations recorded in June 2001 are exceptional. Prior to this event, the recorded maximum for this stream was 1419 mg l^{-1}, and only two samples had sediment concentrations in excess of 1000 mg l^{-1}.

The time series plots in Fig. 1(a) reveal that peak suspended sediment concentrations for both events lag behind the maximum water level, although this trend is less clearly developed for the June 2001 event with its two maxima of suspended sediment. Figure 1(b) reveals the hysteresis, a feature of storm period response reported by a number of studies (e.g. Wood, 1977; Williams, 1989), is present for the two events. Figure 1(b) reveals that for both landslide events an anti-clockwise loop is present, which results when sediment concentration peaks on the recession limb of the hydrograph. As Williams (1989) observes, one possible cause of such a feature is the relative travel time of the flood wave and the sediment flux with the former travelling faster than the latter and the lag time between the two increasing with distance downstream. He reports a second cause of anti-clockwise loops as being the combination of highly erodible soil and prolonged erosion during the flood, whilst a third cause relates to annual hydrographs on large rivers and is not applicable to this small basin. In this well-vegetated basin highly erodible conditions do not exist and this is supported by the generally low concentrations of suspended sediment that have been observed in the basin with, as noted previously, only 10% of all storm period samples exceeding 200 mg l^{-1}. Given the small size of the basin, differences in travel time between sediment and water peaks may be discounted as causing anti-clockwise hysteresis. For these particular storms anti-clockwise hysteresis is likely to reflect sediment release/production consequent upon the mass movement event and the fact that the failures occurred in the upper reaches of the basin, thereby maximizing travel distance. It is also noteworthy, given the small size of the study basin, that Williams (1989) indicates that in small streams the maximum sediment concentration usually occurs prior to the peak water discharge.

SEDIMENT PROPERTIES

Evidence for the contribution from the landslides to the sediment being transported in the stream is provided by sediment colour. Dry soil colour of bulk samples in the soil horizons is dull yellowish brown or yellowish brown for the organic topsoil horizon and dull yellow/yellowish and light yellow orange for the underlying colluvial substrate. In the storms preceding both landslides, sediment colour is associated with

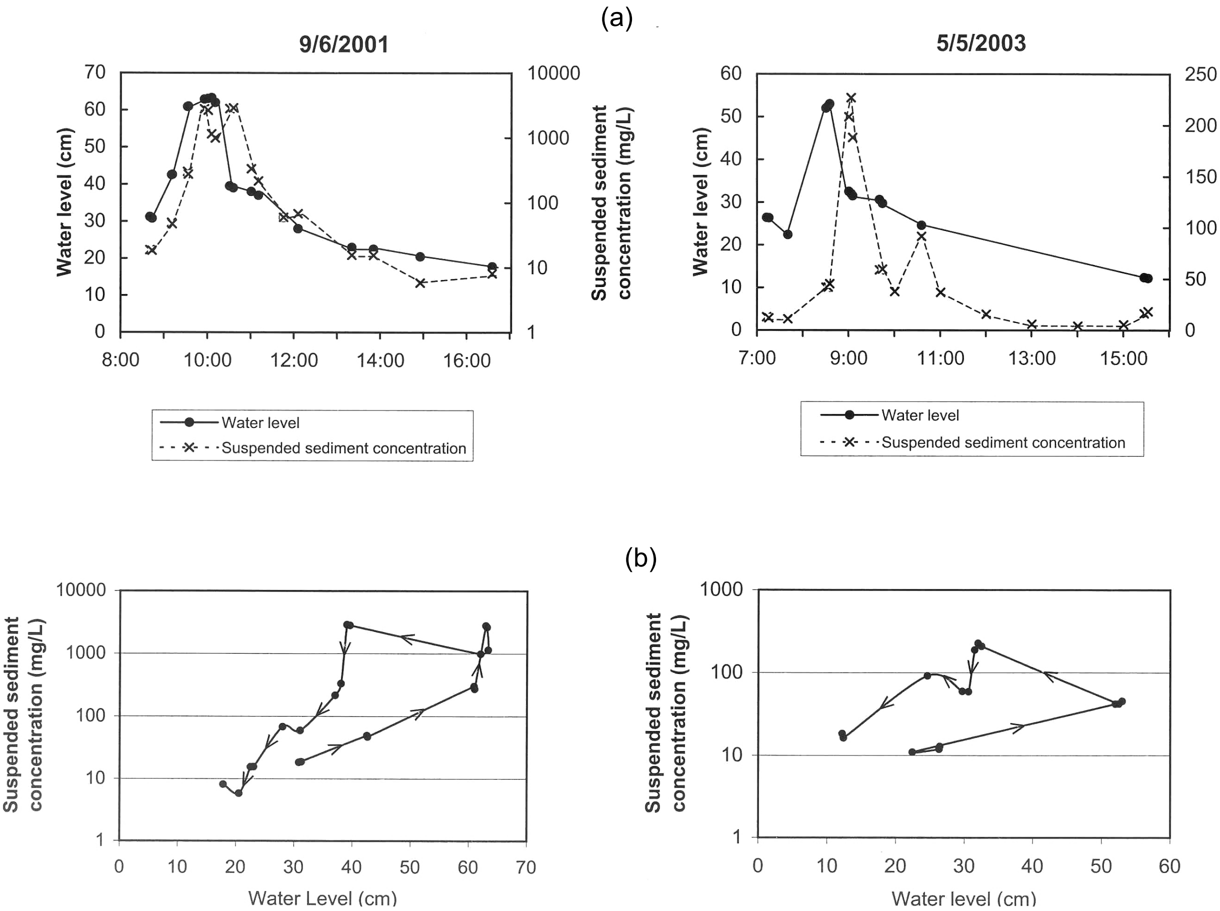

Fig. 1 Temporal variation of water level and suspended sediment for the two events (a), and hysteresis plots (b).

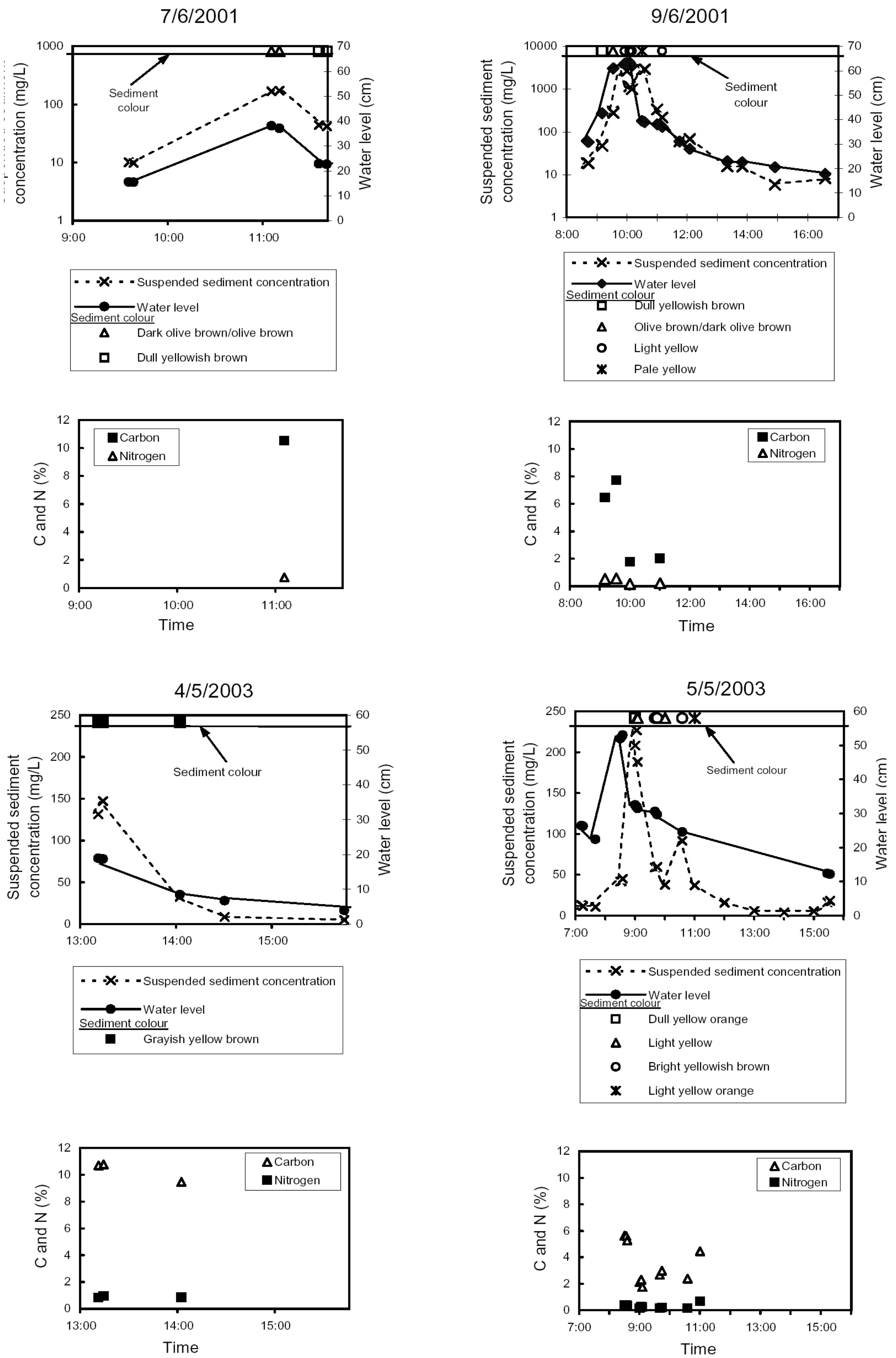

Fig. 2 Sediment property variation.

the organic topsoil colour descriptions, with, for example, dark olive brown or dull yellowish brown recorded in the 7 June 2001 storm preceding the first landslide event (Fig. 2). During the landslide event of 9 June 2001, sediment colour changes, with yellow colours predominating from 09:55 h, coinciding with the marked increase in suspended sediment concentration. The event of May 2003 also exhibits the bright yellow/brown and orange sediment colours that are associated with the description of soil colour for the deeper layers of the landslide scar.

The C and N content of the suspended matter provide further support for a change in source materials. Figure 2 reveals that the storm of 7 June 2001 and the early part of the 9 June 2001 landslide generating event are characterized by C and N contents that are considerably higher than those observed later in the 9 June event from around 1000 h, with, for example, C declining from 6–8% to 2% or less. A similar trend can be observed in May 2003, with the preceding storm event having suspended matter C and N contents that are considerably higher than those in the 5 May landslide event. This decline in C and N content is coincident with the large increase in suspended sediment concentration.

Sediment colour changes have been reported by Grimshaw & Lewin (1980) during individual storm events on the River Ystwyth in Wales. The colour change was interpreted by Grimshaw & Lewin (1980) as reflecting a change from "channel" sources to "non-channel" hillside erosion sites. A change in sediment colour in association with the spatial change of sediment source has been reported by Weaver (1967) and Schreier *et al.* (1998). Moreover, the changes observed in the small headwater basin of this study of sediment colour, in addition to C and N content, indicate that the occurrence of a landslide can influence the physical and chemical properties of the material being transported from the basin. The work of Schreier *et al.* (1998) on P further supports the influence of headwater areas upon nutrient content in sediment of downstream areas.

SEDIMENT DELIVERY FROM HILLSLOPE TO CHANNEL SYSTEMS

Data presented above indicates that the two landslide events delivered sediment to the drainage system of a small headwater catchment which was reflected in the suspended sediment transport. With the notable exception of the study by Butler & Malanson (1996) on the Flathead River in Montana, few direct observations have been made reporting changes in suspended sediment concentration consequent upon landslides. This study illustrates the linkage between hillslope and channel systems in the headwater basin, a point recognized as being important by Harvey (2002). It also indicates that in Hong Kong, as elsewhere, an understanding of sediment transport and production will need to consider processes in headwater catchments (cf. Haigh *et al.*, 1998; Gomi *et al.*, 2002).

The studies of Franks (1999) and Ruse *et al.* (2002) in Hong Kong permit this study to be placed in perspective. Ruse *et al.* (2002) investigated 121 landslides developed on the Tsing Shan Range. They classified 70 of the landslides as being open hillside failures and imply that failed debris remained on the hillslope. In contrast 51 landslides were classified as channelized debris flows suggesting that the debris reached drainage channels on the hillslope. The estimated total source volume of the

121 landslides according to Ruse *et al.* (2002) was 8600 m^3, with an additional 3100 m^3 being entrained by the landslide. Deposition within the landslide scars was estimated at 9700 m^3 or 83% of the sediment produced by mass movement. As for the two landslides in this study, much of the landslide debris remained in storage. Franks (1999) also reports examples of sediment delivery to drainage systems from landslides in Hong Kong. He notes that for a small source volume of less than 400 m^3 deposition predominated along the landslide debris trail: an observation supported by the two small landslides of this study.

Investigations outside of Hong Kong have also documented the role of mass movement and sediment production to the fluvial system. Researchers such as Becht (1995) and Cannon *et al.* (2001) have reported only small amounts of sediment reaching streams from mass movement, and are similar to the observations of this study. In contrast the work of Temple & Rapp (1972), Dietrich & Dunne (1978), Newson (1980), Page *et al.* (1994) and Harden *et al.* (1995) report an important contribution from mass movement to the fluvial system which affords a contrast to the sediment budgets for the landslides of this study.

EROSION

The existence of erosion pin data for the catchment permits some comparison to be made of at-a-point erosion. Surface change for the six erosion plots in 2001 ranged from a small gain of material (2.3 mm) on plot 4 to a loss of 3.2 mm on plot 6. In 2003 the values ranged from a small gain of 0.3 mm (plot 5) to a loss of 2.9 mm (plot 2). The two landslide events reveal far greater at-a-point changes than the erosion pin data, with an average scar depth of a little over 1.1 m in 2001 and that of the 2003 landslide being 0.8 m. Relatively shallow failures of this kind are considered common for Hong Kong in the general literature (c.f. Franks, 1999; Pinches *et al.*, 2002). The study of Lam (1977) also suggests that erosion by flowing water may produce much smaller rates of surface change, with an average surface lowering of 2.13 cm over a 15 month observation period on “badland” slopes, that is to say slopes with no protective cover of vegetation. Whilst the surface change is far greater than recorded by the erosion pins in the present study area, it is far below the at-a-point changes consequent upon a landslide.

Where erosion pins recorded a surface lowering in 2001, the estimated total volumes range from 41.6 to 166.4 m^3 if the rates are extrapolated over the whole catchment area. For 2003, the estimated volumes associated with surface decline range from 10.4 to 150.8 m^3 of material. In both years, the lower range is approximately equivalent to the volume of debris produced by the mass movement. The higher rates of surface decline recorded by the erosion pins produce volumes of debris that are around 3.3 and 21.5 times those produced by mass movement for 2001 and 2003, respectively.

CONCLUSIONS

Heavy rainfall resulted in two small landslides in a headwater drainage basin. Observations made during the storm events of June 2001 and May 2003 of suspended sediment concentrations and timing, along with changes in sediment properties that included colour in addition to C and N, indicate that the suspended matter in streamflow was derived from the landslides. Few direct observations of this linkage between hillslope and channel exist in the literature. Given the prevalence of landsliding in Hong Kong this connectivity has important implications for the management of the sedimentation problem in downstream areas. Further investigation needs to be made of the frequency of this connectivity and the factors influencing the linkage. Moreover, the data on N content of suspended sediment indicate that consideration should be given not only to the volume of sediment delivered but also to the nature and type of materials. The nature of the materials provided from upstream sources has implications in terms of downstream ecosystems. However, the study also reveals that much of the debris from the landslides remained on the slope in an ephemeral drainage line. Further work on the factors controlling the amount of material that remains in storage is important as this also controls the amount of sediment delivered downstream. This study has revealed that simple observations of sediment colour can provide useful information concerning erosion processes and sediment sources.

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REFERENCES

Becht, M. (1995) Slope erosion processes in the Alps. In: *Steepland Geomorphology* (ed. by O. Slaymaker), 207–222. John Wiley, Chichester, UK.

Brand, E. W. (1985) Landslides in Hong Kong. In: *Proceedings of 8th Southeast Asian Geotechnical Conference*, Kuala Lumpur, Malaysia. V2., pp. 1–15.

Butler, D. R. & Malanson, G. P. (1996) A major sediment pulse in a Subalpine River caused by debris flows in Montana, USA. *Z. Geomorphol.* **40**(4), 525–535.

Cannon, S. H., Kirkham, R. M. & Parise, M. (2001) Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology* **39**, 171–181.

Dai, F. C. & Lee, C. F. (2002) Landslide characteristics and slope instability modelling using GIS, Lantau Island, Hong Kong. *Geomorphology* **42**, 213–228.

Dai, F. C., Lee, C. F., Li, J. & Xu, Z. W. (2001) Assessment of landslide susceptibility on the natural terrain of Lantau Island, Hong Kong. *Environ. Geol.* **40**(3), 381–391.

Dietrich, W. E. & Dunne, T. (1978) Sediment Budget for a Small Catchment in Mountainous Terrain. *Z. Geomorphol. Supplementband* **29**, 191–206.

Evans, N. C., Huang, S. W. & King, J. P. (1999) *The Natural Terrain Landslide Study: Phases I and II*. GEO Report No. 73. Geotechnical Engineering Office, Civil Engineering Department, The Government of the Hong Kong SAR, Hong Kong.

Franks, C. A. M. (1998) Study of rainfall induced landslides on natural slopes in the vicinity of Tung Chung New Town, Lantau Island. *GEO Report no. 57. Geotechnical Engineering Office, Civil Engineering Department, the Government of the Hong Kong SAR, Hong Kong, China.*

Franks, C. A. M. (1999) Characteristics of Some Rainfall-induced Landslides on Natural Slopes, Lantau Island, Hong Kong. *Quart. J. Engng. Geol*. **32**, 247–259.

Gomi, T., Sidle, R. C. & Richardson, J. S. (2002) Understanding processes and downstream linkages of headwater systems. *Bio Science* **52**(10), 905–916.

Grimshaw, D. L. & Lewin, J. (1980) Source Identification for Suspend Sediment. *J. Hydrol.* **47**, 151–162.

Haigh, M. J., Singh, R. B. & Krecek, J. (1998) Headwater Control: Matters Arising. In: *Headwaters: Water Resources and Soil Conservation* (ed. by M. J. Haigh, J. Krecek; G. S. Rajwar & M. P. Kilmartin), 3–24. Balkema, Rotterdam, The Netherlands.

Harden, D., Colman, S. M. & Nolan, K. M. (1995) *Mass Movement in Redwood Creek Basin*, *Northwestern California*. US Geol. Survey Prof. Paper 1454-G, G1–G11.

Harvey, A. M. (2002) Effective Timescales of Coupling within Fluvial Systems. *Geomorphology* **44**(3–4), 175–201.

King, J. P. & Williamson, S. J. (2002) Erosion along debris avalanche trails. In:, *Natural Terrain—A Constraint to Development* (ed. by C. A. M. Franks, J. Hall, D. Martin, S. Ng, S. Parry, G. Pinches, & M. Thorn), 197–205. Institute of Mining and Metallurgy, Hong Kong Branch, Hong Kong, China.

Lam, K. C. (1977) Patterns and Rates of Slopewash on the Badlands of Hong Kong. *Earth Surf. Processes* **2**, 319–332.

Newson, M. (1980).The geomorphological effectiveness of floods – a contribution stimulated by two recent events in mid-Wales. *Earth Surf. Processes* **5**, 1–16.

Ng, K. C., Parry, S., King, J. P. Franks, C. A. M., & Shaw, R. (2002) Guidelines for Natural Terrain Hazard Studies. *Special Project Report SPR 1/2002. Geotechnical Engineering Office, The Government of the Hong Kong SAR, Hong Kong, China.*

Page, M. J., Trustrum, N. A. & Dymond, J. R. (1994) Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology* **9**, 169–188.

Parry, S., Massey, C. I. & Williamson, S. J. (2002) Landslide susceptibility analysis for natural terrain hazard studies—Tsing Shan foothills area. In: *Natural Terrain—a Constraint to Development?* (ed. by C. A. M. Franks, J. Hall, D. Martin, S. Ng, S. Parry, G. Pinches, & M. Thorn), 113–123. Institute of Mining and Metallurgy, Hong Kong Branch, Hong Kong, China.

Pinches, G. M., Smallwood, A. R. H. & Hardingham, A. D. (2002) The study of the natural terrain hazard of Yam O Lantau. In: *Natural Terrain—a Constraint to Development?* (ed. by C. A. M. Franks, J. Hall, D. Martin, S. Ng, S. Parry, G. Pinches, & M. Thorn), 207–221. Institute of Mining and Metallurgy, Hong Kong Branch, Hong Kong, China.

Ruse, M. E., Waring, D. P., Kaldy, A., Chan, K. S. & Ng, K. C. (2002) Initiation and runout characteristics of a swarm of 121 landslides in the Tsing Shan Foothills, Hong Kong. In: *Natural Terrain—A Constraint to Development?* (ed. by C. A. M. Franks, J. Hall, D. Martin, S. Ng, S. Parry, G. Pinches, & M. Thorn), 77–87. Institute of Mining and Metallurgy, Hong Kong Branch, Hong Kong, China.

Schreier, H., Brown, S., Carver, M. & Shah, P. B. (1998) Linking land degradation to nutrient and sediment transport in a middle mountain watershed in Nepal. In: *Headwaters: Water Resources and Soil Conservation* (ed. by M. J. Haigh, J. Krecek, G. S. Rajwar & M. P. Kilmartin), 315–328. Balkema, Rotterdam, The Netherlands.

Scott, K. M., Macias, J. L., Naranjo, J. A., Rodriguez, S., McGeehin, J. P. (2001) catastrophic debris flows transformed from landslides in volcanic terrains: mobility, hazard assessment and mitigation strategies. *US Geol. Survey Prof. Paper 1630*.

Temple, P. H. & Rapp, A. (1972) Landslides in the Mgeta Area, Western Uluguru Mountains, Tanzania. *Geogr. Ann. A* **54**(3–4), 157–193.

Weaver, C. E. (1967) Variability of a river clay suite. *J. Sed. Petrol.* **37**, 971–974.

Williams, G. P. (1989) Sediment concentration versus water discharge during single hydrologic events in rivers. *J. Hydrol.* **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.