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Magnitude–frequency analysis of suspended sediment loads in the subtropical Richmond River basin, northern New South Wales, Australia

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Abstract Data from coastal northern New South Wales, Australia, are used to provide an analysis of magnitude and frequency characteristics in a subtropical river. Over a 14-year period, annual discharge varied by 26 times, suspended sediment (SS) load varied 910 times from 668 t to 607 671 t (mean = 105 620 t year^{-1}) and 90% of the SS load was transported in only 2.3% of the time. The 4000–4999 Ml day^{-1} discharge class appears to be most effective for SS transport. The centroid of the annual series (4500 Ml day^{-1} or 52 m^3 s^{-1}) has a return interval of 1.01 years. Discharges in this class occurred for 68 days (an average of five days per year) and carried 50 857 t SS (3.4% of the total). There may be multiple effective discharges that may be verified by channel features. Future field studies are planned to test this hypothesis.

Key words magnitude; frequency; effective discharge; suspended sediment; subtropical; Richmond River; Australia

INTRODUCTION

An understanding of the timing and magnitude of fluvial fine sediment transport is essential, given the ever-increasing need to reduce the environmental impacts of drainage basin development through proactive management, yet so often there are a lack of data for determining typical suspended sediment (SS) loads and variability. The concept of magnitude and frequency as forces shaping the morphometry of fluvial channels has long been proposed (Wolman & Miller, 1960). Wolman & Miller (1960) asserted that the discharge that shapes fluvial systems occurs relatively frequently (around once every year), and that an analysis of sediment loads in a river can be used to test this premise. The most effective discharge is that which over the long term, transports the greatest mass of sediment and approximately equates to bankfull. Since 1960, it has been demonstrated that the recurrence interval of effective discharge can range from several weeks to 11 years (Nash, 1994). Studies in Queensland and New South Wales (NSW), Australia have suggested a recurrence interval for effective discharge between 1.1 and 1.85 years (Dury *et al.*, 1963; Dury, 1967; Pickup, 1976; Pickup & Warner, 1976). The recurrence interval of effective discharge did not equate to the determined recurrence intervals (4–10 years on the annual series) for bankfull discharge in the same streams (Pickup, 1976; Pickup & Warner, 1976), a conclusion later reached in studies in other parts of the world (e.g. Ashmore & Day, 1988). Despite complexities not initially recognized by Wolman & Miller (1960), the concepts of magnitude and frequency still provide a valuable framework for understanding fluvial fine sediment transport and the impacts of humans on the form and function of river systems. In this paper we will present an analysis of sediment loads in the subtropical Richmond River drainage basin and discuss implications for the determination of morphometric and channel forming processes and sediment delivery to, or through subtropical estuaries.

STUDY AREA AND METHODS

The Richmond River basin, with an area of 6860 km^2, is on the northern coast of NSW, Australia. The data presented were collected in Casino, a town on the Richmond River, and represent an area of 1790 km^2 in the northwestern corner of the greater Richmond River basin (Fig. 1). Annual rainfall for the Richmond River sub-basin averages 1222 mm and runoff averages 380 mm (31%) (Hossain, 1998).

The NSW Department of Land and Water Conservation provided discharge data on a daily basis for the period from 1 September 1985 to 31 August 1999 (14 years) (Fig. 2). The average annual runoff for this period was 269 mm compared to 380 mm calculated for the available records (51 years). The region suffered a 5-year drought between 1990 and 1995 typical of the high variability in climatic patterns in Australia.

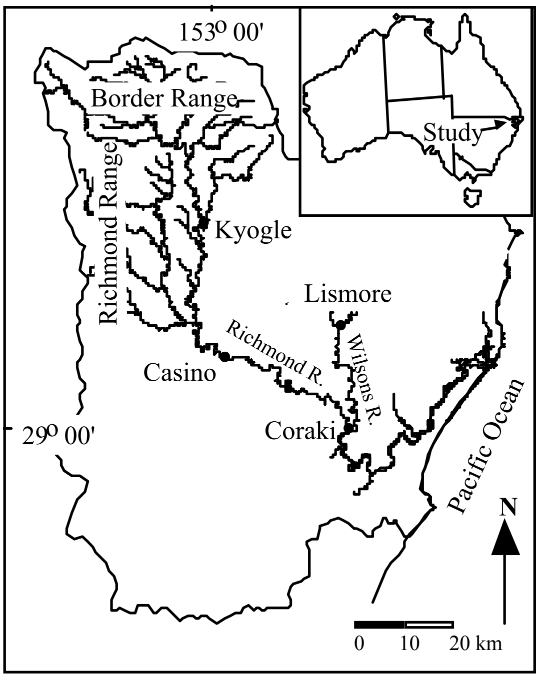

Fig. 1 Location of the Richmond River basin, northern NSW, Australia.

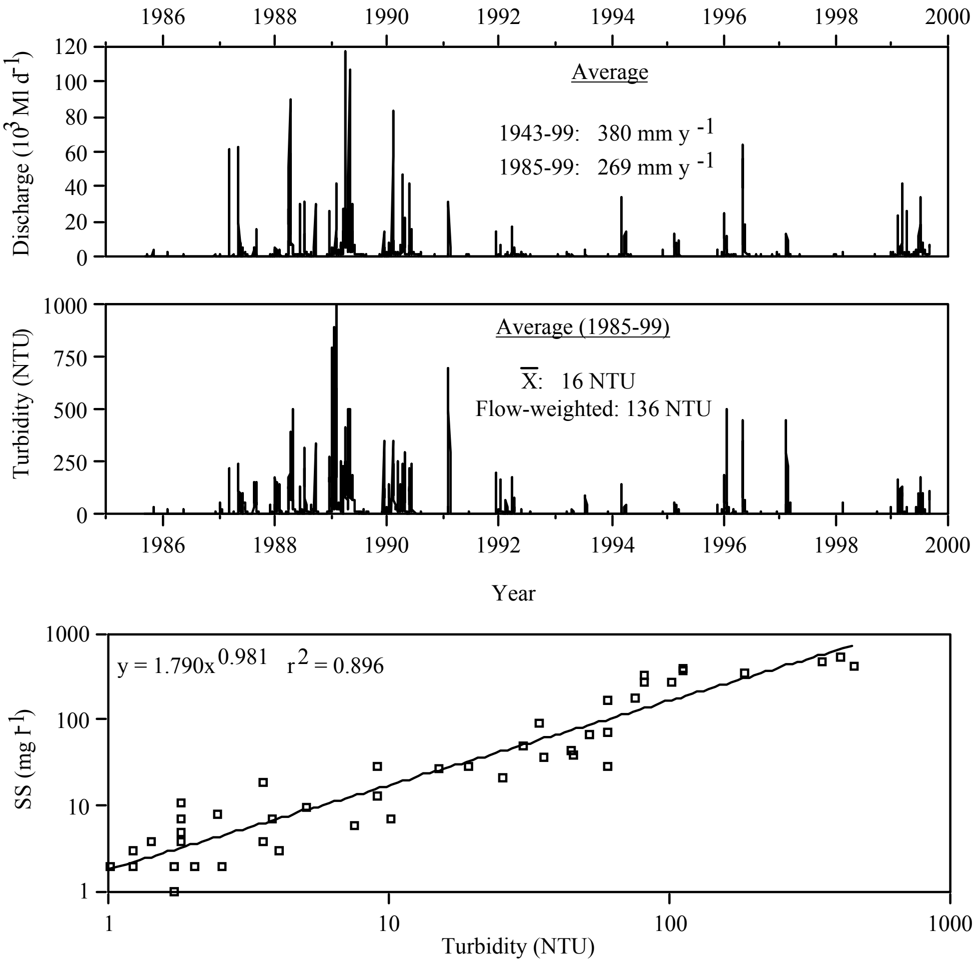

Fig. 2 Runoff, turbidity, and the relationship between turbidity and SSC.

Daily turbidity recorded by the Casino Shire Council provided a unique opportunity to analyse SS loads from 1985 to 1999. Turbidity data (Fig. 2) are collected routinely 365 days a year for the purposes of assessing treatment requirements for the Casino town water supply. Water is drawn from the Richmond River 3 km upstream from Casino above a 3-m weir, 1 m from the bottom, and 8 m from the river bank (river width at this point is approximately 30 m). Turbidity is measured at source at about 12:00 p.m. daily using a Great Lakes Instruments Inc. turbidity meter, Model 8202. Comparisons are made at regular intervals by the treatment technician using a Hach Model 2100A. Data were near continuous with infrequent failures of only 1–2 days. Data gaps were filled using interpolation.

During July 1994–June 1996, water samples for the analysis of suspended sediment concentration (SSC) were collected from a road bridge in Casino 3 km downstream from the turbidity collection point. Details of sampling methods and analysis have been described previously (Hossain, 1998; Hossain *et al.*, 2002). On days when more than one sample was collected an arithmetic average was calculated. In total, there were 45 days of sediment data and approximately 66% of the data were collected during floods.

Least squares regression was used to define a relationship between turbidity and SSC for the July 1994–June 1996 period (Fig. 2). Daily SSC for the 14-year period was estimated using the regression equation, and these estimates were combined with daily discharge to give the daily loads.

RESULTS

When the 14 water years (WYs) are viewed together, the highest turbidity occurred during floods (Fig. 2). However, during a single year (for example 1988/89), complex hysteresis patterns were observed between discharge and turbidity. Highest turbidity occurred during the first discharges of the wet season (December, January, and February) and lower turbidity occurred during subsequent larger discharges in April. During individual events, turbidity displayed hysteresis that varied between events.

When annual flow-weighted mean concentration (FWMC) was plotted as a function of annual discharge (Fig. 3), the 1991 WY and 1997 WY showed much higher than expected FWMC and therefore loads of sediment. During these two years, there was one flood event and low dry season discharges. During the 1986 WY and 1998 WY there were lower than expected FWMC and sediment loads in relation to the annual discharge as a result of no flood events during these years. This demonstrates that, over the discharge range encountered, supply is not exceeded by discharge. Daily discharge varied by >5 orders of magnitude and daily sediment loads varied by >8 orders of magnitude. The fact that variation is greater for sediment loads than for discharge further suggests that supply is not exceeded during large floods.

Sediment transport is highly episodic in the Richmond River basin. During the 14-year period, 50% of the SS load was transported in 0.47% of the time and 90% of the SS load was transported in 2.3% of the time. The average annual suspended load

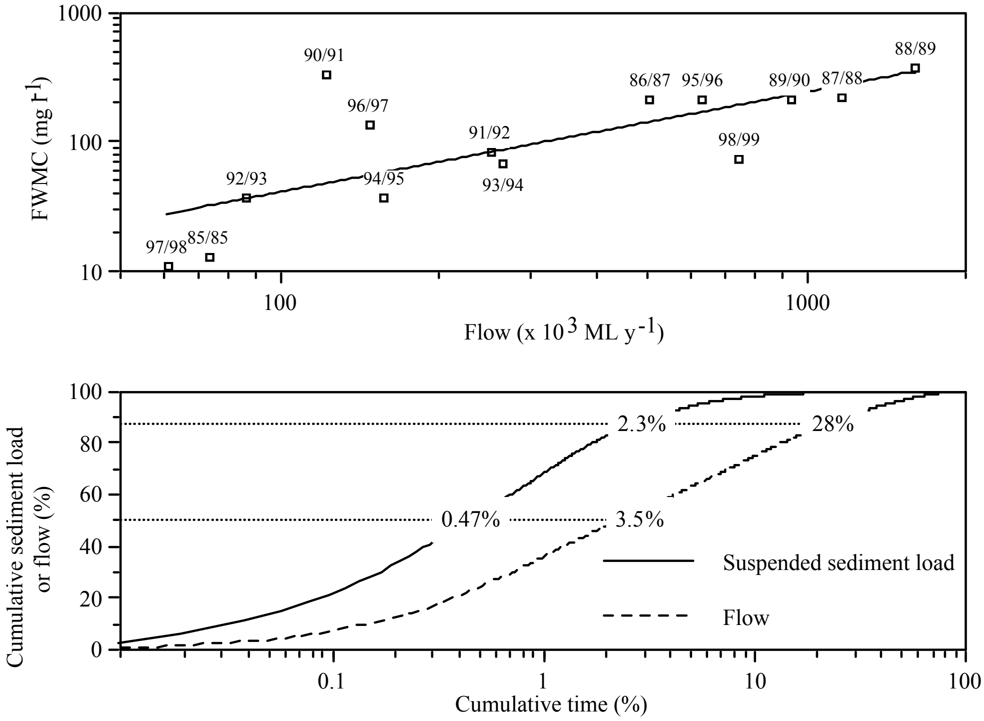

Fig. 3 Timing of SS loads and the inter-annual variability of FWMC.

Table 1 Annual SS loads from 1985 to 1999 calculated for water years (1 September to 31 August) and the percentage of the annual loads carried during flood.

Water year	Discharge (Mm^3)	SS (t)	Percentage of annual load transported for each time period: 1-day maximum	7-day maximum	All floods
1986	73	969	23	40	76
1987	501	105 638	23	42	90
1988	1164	261 386	20	51	94
1989	1599	607 671	14	34	97
1990	929	203 323	16	37	91
1991	120	40 560	61	99	98
1992	250	20 851	23	34	61
1993	86	3 184	18	78	81
1994	265	17 965	25	62	96
1995	157	5 969	23	69	92
1996	631	134 119	27	78	96
1997	147	19 884	32	93	91
1998	61	668	43	68	66
1999	742	56 495	17	36	90
Average	480	105 620	26	59	87
Maximum/minimum	26	910			
Average 1986–1990	853	235 798	19	41	90
Average 1991–1999	273	33 299	30	68	86

was 105 629 t year^{-1} (Table 1). In response to a 26 times variation in annual discharge, sediment load varied 910 times from 668 t to 607 671 t. During the period 1991–1999, annual average sediment loads were about 7 times less than during the 1986–1990 period demonstrating substantial impact of drought. Floods in the basin lasted from a few days to greater than 20 days if there were several peaks. On average, the maximum daily SS load accounted for 26% of the annual load. The seven-day maximum load for the largest flood of each year accounted for an average of 59% of the annual SS load. When all flood loads for a given water year are added together, 61–98% of the load was transported during floods depending on the year.

The discharge conditions most effective for transport of SS load were estimated by summing the daily load for 14 years in each of 120 discharge classes each representing

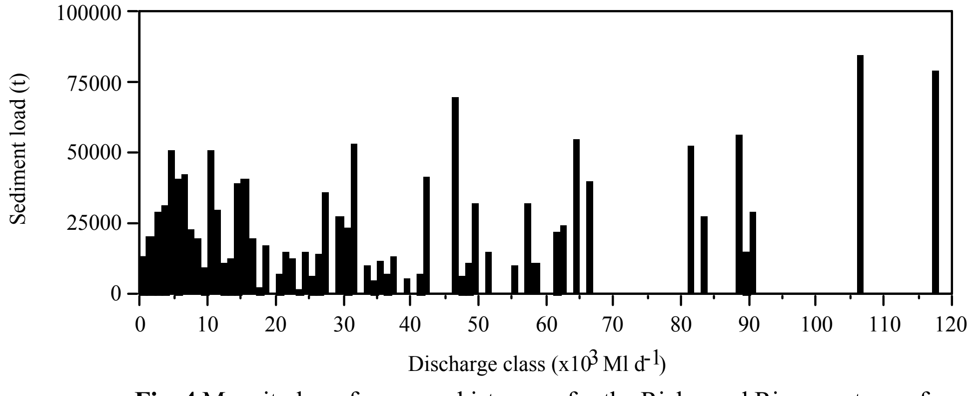

Fig. 4 Magnitude *vs* frequency histogram for the Richmond River upstream from Casino.

an increment of 1000 Ml day^{-1} (Fig. 4). A maximum load is associated with the discharge class of 4000–4999 Ml day^{-1} and this appears to be an effective discharge. Discharges in this class occurred for 68 days (an average of five days per year) and carried 50 857 t SS (3.4% of the total). The midpoint of this discharge class is 4500 Ml day^{-1} (52 m^3 s^{-1}) and has a return interval of 1.01 years on the annual series.

DISCUSSION

Over the 14-year period it took only 0.47% of the accumulative time to transport 50% of the accumulative load in the Richmond. This is less time than observed in Devon in southwest England (0.8% of the time) (Webb & Walling, 1982) or the Fraser River, British Columbia, Canada (3–22% of the time; average 14%) (Sichingabula, 1999). In addition, the inter-annual load variation is greater than in most temperate systems that might only vary one order of magnitude over a decade (e.g. Walling & Webb, 1988). These observations are in agreement with previous estimates in sub-basins of the Richmond for SS loads using only two years of data (Hossain, 1998). It follows that sediment loads are delivered in a more highly episodic nature to east Australian subtropical estuaries, resulting in much of the SS load being transported through the estuaries and deposited directly off shore (Hossain *et al.*, 2001). This temporal process provides a mechanism for maintaining long-term estuarine sediment and water quality.

In this study, effective discharge was calculated using a SSC record similar to previous workers (e.g. Webb & Walling, 1982; Ashmore & Day, 1988; Nash, 1994; Sichingabula, 1999). Pickup & Warner (1976) used bed load equations and Andrews (1980) used SSC records and combined these with computed bed loads. Bed load was ignored in the Richmond analysis because of the inherently unstable nature of bed load equations in basins of NSW, Australia, that might have confounded the analysis (Hean & Nanson, 1987).

Our analysis in the Richmond River suggests that the discharge that transports the majority of the SS load over the longer term has a recurrence interval of about one year. This discharge is about 12 times greater than average September discharges (driest month) and is associated with floods of varying magnitude (i.e. either with small floods or on the rising and falling stages of larger floods). There were 14 floods during the study period where the peak magnitude was between 4000 and 4999 Ml day^{-1}. This corresponds to an average recurrence of one flood per year. The rest of the days with a discharge between 4000 and 4999 Ml day^{-1} were associated with larger floods.

The analysis of most effective discharge for the Richmond, although suggesting an effective discharge of between 4000 and 4999 Ml day^{-1}, also showed many peaks associated with extreme flood discharges between 20 000 and 120 000 Ml day^{-1}. This phenomenon has been noted by other workers (e.g. Ashmore & Day, 1988; Nash, 1994; Sichingabula, 1999) and appears to be counter to the original hypothesis set out by Wolman & Miller (1960) who suggested there should be a uni-model histogram whose peak will represent effective discharge. In the Richmond, a daily time interval was used because turbidity data has been collected with a daily interval.

There are three possibilities for the cause of multiple peaks for most effective discharge: (a) there are multiple effective discharges, (b) the data set used here is not long enough to cover all the variability of the system, (c) the daily time interval used in the analysis causes a statistical bias. We cannot rule out the possibility that there are multiple effective discharges perhaps associated with alternating climatic regimes such as prolonged drought or flood. The main trunk of the Richmond River is highly incised and it is possible that smaller discharges mainly erode the channel bed whereas larger discharges may erode a low in-channel flood plain. This mechanism was previously suggested for the Cumberland basin, NSW (Pickup & Warner, 1976). The peaks at 11 000 Ml day^{-1} (comprising 22 data points) and at 15 000 Ml day^{-1} (comprising 16 data points) (Fig. 4) may be significant and associated with physical channel features. The return frequencies for these discharges are 1.05 years and 1.08 years. At this time we do not have field observations to verify this hypothesis.

The observed multi-peak for effective discharge associated with extreme events is partly caused by the length of the data set (14 years). Most of the peaks are associated with just a single day of discharge whereas the three broad peaks at <20 000 Ml day^{-1} are associated with a sum of many days of discharge and the peak at 4500 Ml day^{-1} is the sum of 68 data points. Another cause of the peaks associated with extreme discharge is the daily time interval for this analysis. If an hourly time interval were used, there would be little effect on the magnitude of the peaks associated with moderate and low discharges if the same 120 discharge classes were used. However, the peaks associated with the extreme events would be spread out over a range of discharge classes. This may have been the cause of the peaks associated with extreme events, and the interpretation of these peaks as effective, in previous studies in other parts of the world (e.g. Ashmore & Day, 1988; Nash, 1994; Sichingabula, 1999). These authors also used data sets that had been collected for other purposes and that had daily time intervals that probably did not define the true temporal flood variability associated with the river systems they studied.

Sichingabula (1999) discussed the problems associated with the methods for determination of effective discharge using arbitrarily selected discharge classes. In particular, Sichingabula (1999; p. 1365) quotes text for the selection of discharge classes from a number of other authors "equal intervals of stream discharge"; "small classes"; "increments of discharge range"; "20 equal increments"; and "23 equal increments of discharge". Sichingabula (1999) postulated that the inconsistent selection of discharge classes for the analysis of effective discharge may, in part, explain the wide range of reported frequencies of effective discharge in the literature. In our analysis, we selected 120 discharge classes (a large number compared to other workers) primarily because of the wide range of discharge in the subtropical Richmond River, and secondly because it reduces the chance of bias associated with the selection of a wide interval. In the case of the Richmond, the return interval of class-based analysis corresponds perfectly to an analysis of the return interval of floods for that class.

The highly episodic nature of water and sediment delivery to east Australian subtropical estuaries causes most of the sediment to be flushed directly to the Pacific Ocean with little retention over the longer term in the estuaries that experience zero salinity at their mouths during floods. The most effective discharge in the Richmond occurs at a discharge of 4500 Ml day^{-1} and is associated with small floods that have a return frequency of about 1 year. There may be multiple effective discharges associated with prolonged periods of drought and flood and field work can be used to verify this hypothesis. The combined effects of the data set being too short to capture all the variability and the effects of a daily time step biasing the apparent effectiveness of extreme floods cause the apparent effectiveness of extreme events.

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