Effects of Scale on Interpretation and Management of Sediment and Water Quality (Proceedings of a Boulder Symposium, July 1995). IAHS Publ. no. 226, 1995.

Variations in sediment transport at a variety of temporal scales in the Murrumbidgee River, New South Wales, Australia

L. J. OLIVE
Department of Geography and Oceanography, Australian Defence Force Academy, Canberra, ACT 2600, Australia

J. M. OLLEY, A. S. MURRAY & P. J. WALLBRINK
Division of Water Resources, CSIRO, PO Box 1666, Canberra, ACT 2601, Australia

Abstract Forty-three years of daily turbidity and discharge data from Wagga Wagga, New South Wales, Australia, were used to examine temporal variability in sediment transport in the Murrumbidgee River basin (area 82 000 km^2). Variation in discharge, sediment concentration, and sediment load are considered at a variety of time periods from inter-event to inter-annual. There was no simple relation between discharge and sediment concentration, and sediment concentration and load were highly variable over a range of time scales. This variability resulted mainly from the variable frequency and size of floods, and was more pronounced with load than with sediment concentration. Implications of the observed temporal variability for sampling regimes designed to characterize sediment concentration and load are discussed.

INTRODUCTION

Sediment flux and load have been used to characterize denudation and erosion and to determine movement of associated nutrients and pollutants (Walling, 1988; Symader *et al.*, 1994). Recently, however, the reliability of such examinations has been questioned because sediment load is often based on limited time-series data (Parker, 1988; Walling & Webb, 1988; Olive & Rieger, 1992; Walling *et al.*, 1992). Consideration of the nature and role of temporal variability has been hampered by a lack of long-term records. Here we examine variability of suspended sediment concentration and load at a range of temporal scales using 43 years of turbidity and discharge data from the Murrumbidgee River at Wagga Wagga, New South Wales (NSW).

THE MURRUMBIDGEE RIVER

The Murrumbidgee River forms part of the Murray-Darling Basin and drains an area of approximately 82 000 km^2 (Fig. 1). The river rises in the Snowy Mountains and flows through undulating terrain and a well defined valley to Wagga Wagga. Downstream of Wagga Wagga there is a considerable decrease in relief as the river enters the Riverine and

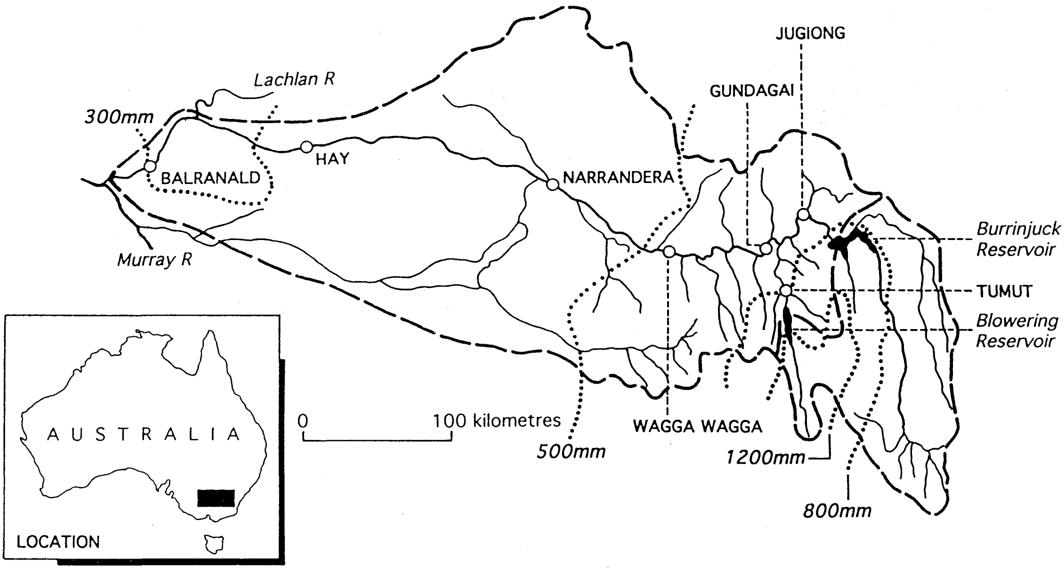

Fig. 1 Map of the Murrumbidgee River basin.

Hay plains where stream gradient is low. Annual precipitation in the basin declines from about 1600 mm in the Snowy Mountains in the east to 300 mm at Balranald. The river is highly regulated with flow diversion from the Snowy River and a series of storage reservoirs in the upper basin. In the study section two reservoirs, Burrinjuck and Blowering (Fig. 1), store water predominantly for the Murrumbidgee and Coleambally Irrigation Areas. Most of the extraction occurs around Narranderra. Regulation of the upper river alters flow regime to higher summer flow, whereas before regulation summer was dominated by low flow. The river has highly variable flow regime with floods common in winter/autumn but occurring throughout the year. The impact of regulation on floods varies with magnitude, with small to moderate floods now reduced (Page, 1988).

THE DATA

We examine data from Wagga Wagga, where turbidity has been measured daily at the water treatment plant since 1949. Observations were made using a visual comparator and a relation was established between turbidity and suspended sediment concentration ($r^2 = 0.88$) by sampling a range of turbidities and concentrations over a 3-year period. Although this technique was used for the entire period, the authors recognize that the relation may change through time. Analysis, however, indicates that the range of values remained constant with no apparent drift in trend.

The discharge record used in this study is from the NSW Department of Water Resources (DWR) continuous gauging station at Wagga Wagga. This station is in a network of gauging stations maintained by DWR throughout NSW. Rainfall data come from the Australian Bureau of Meteorology.

RESULTS

In following sections we examine variation in sediment concentration, discharge, and load at three temporal scales. We first compare four flow events of 1990-1991, then we examine the entire 1990-1991 record, and finally we consider the 43-year record.

Intra-event variation

Discharge, sediment concentration, and sediment load data for four flow events from the 1990-1991 period are presented in Fig. 2, and the full 2-year record is presented in

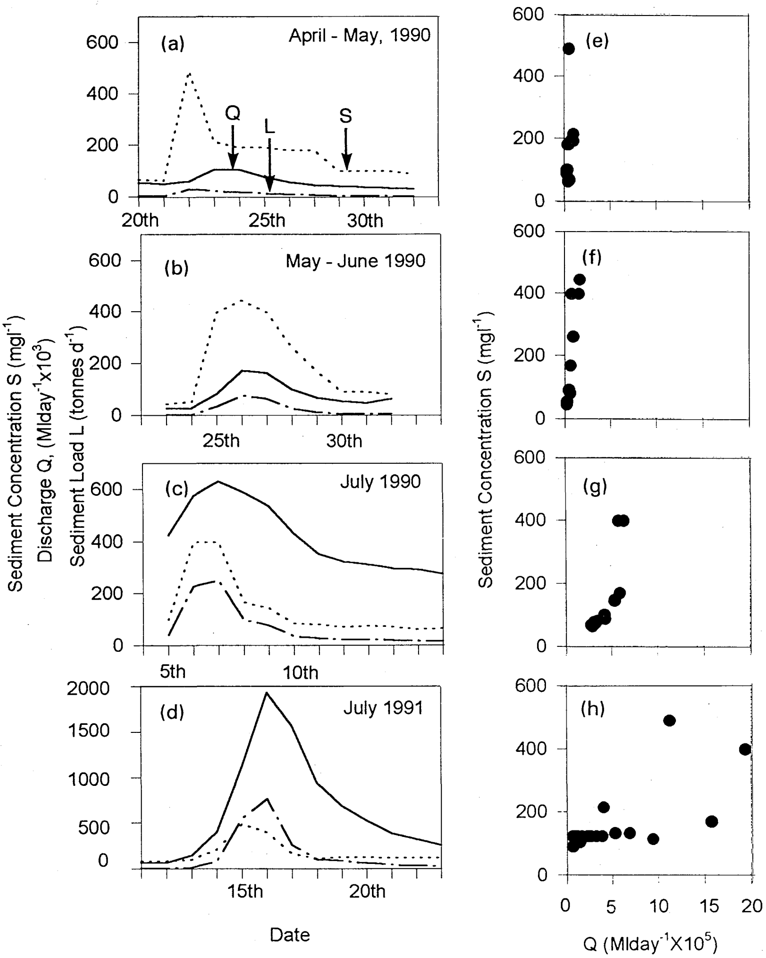

Fig. 2 Discharge and sediment concentration data for four flow events (events 1 to 4) on the Murrumbidgee River at Wagga Wagga, 1990-1991. The four events had similar peak sediment concentrations but the associated peak discharges ranged from 105 000 Ml in event 1 to 2 000 000 Ml in event 4 (Fig. 2(a)-(d); note the change in scale in (d)). The relation between sediment concentration and discharge for each of the four events (Fig. 2(e)-(h); note the figures all have the same scale).

Fig. 3. The four events examined had similar peak sediment concentrations, but the associated peak discharges ranged from 105 000 Ml day^{-1} in event 1 (Fig. 2(a)) to 2 000 000 Ml day^{-1} in event 4 (Fig. 2(d)). Event 4 was a one-in-ten year flood (Murray *et al.*, 1993), and was the largest event of the 2-year period. Event 1 was a minor local storm at the end of the irrigation period. Discharge in events 2 and 3 (Figs 2(b) and (c)) were intermediate between these.

In each event, the sediment peak led the discharge peak, independently of event size. Sediment concentration is plotted against discharge for each of the events in Figs 2(g) and 2(h). In each case hysteresis occurs because the sediment and discharge peaks are out of phase. The relation between discharge and sediment concentration varies with event, having a high slope for the small local event (1) and a lower slope, with more pronounced hysteresis, for the large flood (4). These data show that the discharge to

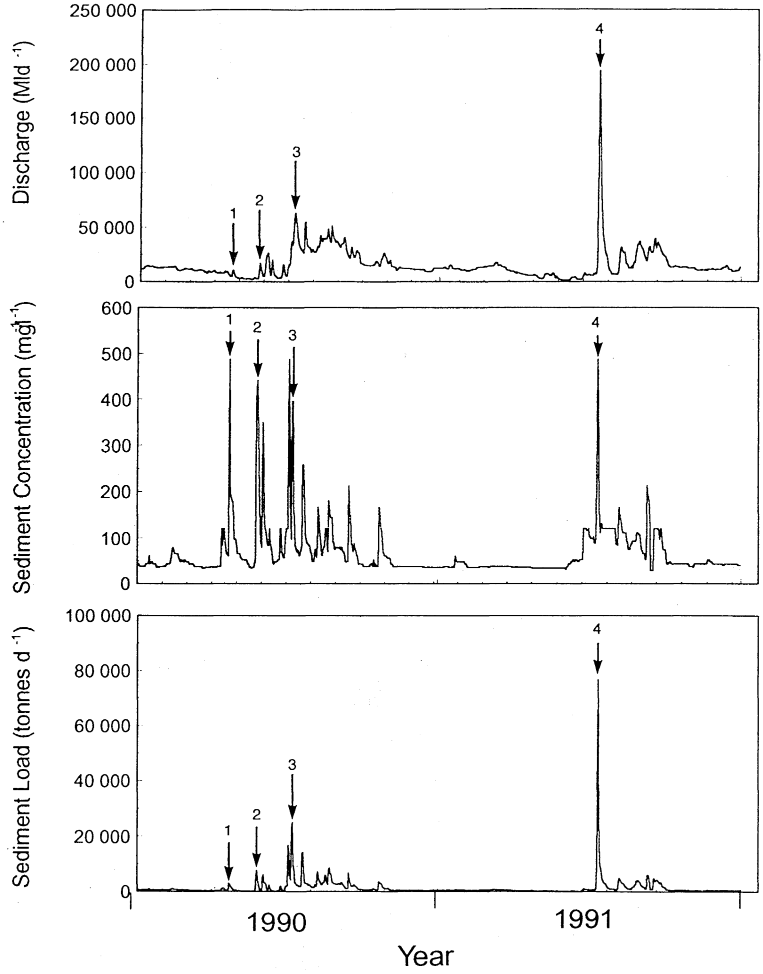

Fig. 3 Graphs showing discharge, sediment concentration, and sediment load changes, 1990-1991, Murrumbidgee River at Wagga Wagga.

sediment concentration relation is highly variable on an event-to-event scale. Peak sediment load for all four events was coincident with peak daily discharge (Figs 2(a)-(d)) and increased systematically with discharge.

Intra-annual variation

Daily discharge, sediment concentration, and sediment load data for the period 1990-1991 are plotted in Fig. 3. Annual flow and sediment load are similar to the annual means, but there was a significant flood (4) in July 1991. The reversal of the river's natural summer flow regime is evident (Fig. 3). Prior to regulation the river had baseflow during summer, but summer flow is now consistently high to satisfy irrigation demand. Superimposed on the seasonal flow trend is high variability associated with storm or flood events.

At this temporal scale, sediment concentration was characterized by long periods with low concentrations and short periods of high variability. Generally, sediment concentration was low during periods of either baseflow or regulated flow. Virtually all high concentrations were associated with storms generated in tributaries below the storages (Olive *et al.*, 1994). High sediment concentrations can be associated with relatively small, short-lived events and were not just associated with large events (e.g. event 1). As would be expected from the previous discussion of variability from event to event, the relation between discharge and sediment concentration over the 2-year period is complicated and highly variable (Fig. 4). Development of a realistic sediment rating curve from these data may be difficult, if not impossible.

Annual sediment load was dominated by a restricted number of floods and showed fewer significant increases than did sediment concentration (Fig. 3). Significant load occurred only when there was a coincidence of high discharge and sediment concentration. In some instances of increased flow, sediment concentration increases were short-lived, whereas in others high sediment concentration was associated with small flow increase. In each case there was little load.

For 1990 and 1991, 50% of the sediment load occurred during 23% of the total flow in 8% of the time. For the years when there was high sediment load, this concentration in flood events was even more marked. In 1974, when load was high (Fig. 5), sediment transport was concentrated in a few large events in which 50% of the load was transported by 15% of the flow in 3% of the time. The large flood in August/September, 1974, transported approximately 800 000 t in 10 days. This load exceeds the annual load for 35 of the 42 years for which load has been determined (see next section). In drought years, storm events are much less important; this is shown for 1980 (Fig. 5) when 50% of the load was transported in 24% of the time. The mass of sediment transported, however, was low.

Inter-annual variation

Analysis of longer-term variation was based on the total record for the period 1949-1991. Missing record of 1965 results in data for 42 years. This period (1949-1991) was relatively wet with mean annual rainfall of 591 mm compared to the long-term mean of

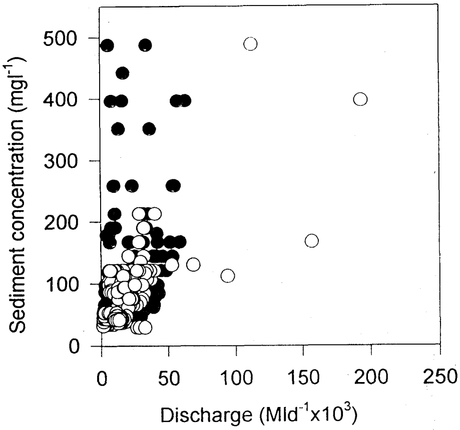

Fig. 4 Plot of sediment concentration against daily discharge for 1990 (closed circles) and 1991 (open circles), Murrumbidgee River at Wagga Wagga.

558 mm. Mean annual flow for the period was 4 900 960 Ml; this compares to a mean for the period 1901-1986 of 3 671 000 Ml, which is consistent with the results of Riley (1988). During the period 1949-1991, flow in the study section was regulated to supply irrigation water to areas downstream of Wagga Wagga.

Annual discharge and sediment load were determined for the period 1949-1991 and are presented in Fig. 6. Summary statistics for discharge, sediment load, and rainfall (Table 1) indicate considerable variation in annual flow and load, with sediment load varying more than discharge, which in turn varies more than rainfall. These variations are consistent with findings of Olive & Rieger (1992). The dominance of high-discharge years is clearly shown in Fig. 6, with 1950, 1952, 1956, and 1974 contributing approximately 35% of the sediment load for the period in less than 10% of the time. In drought years, sediment contribution was small, with the lowest year contributing 0.3% of the load in 2.3% of the time. Sediment load was proportionately small during low-flow years, showed equivalence during moderate-flow years, and was disproportionately large during high-flow years. Approximately 50% of the sediment was transported in 20% of the years when flow represented 35% of the discharge.

In terms of characterizing long-term transport, these data yield a mean annual rate with an uncertainty of 15% (standard deviation). In studies of Australian rivers, however, longer-term temporal variation in flow regime has been recognized. Warner (1987) outlined a series of flood- and drought-dominated regimes in NSW coastal rivers, where over decadal periods there was a marked shift in flood frequency curves. During flood-dominated periods, a succession of large floods had major geomorphic impact (Erskine & Warner, 1988). Riley (1988) recognized similar patterns in the Murray-Darling Basin, including that of the Murrumbidgee River, and he suggests that the Murrumbidgee River experienced a flood-dominated regime from 1947 through at least 1985, a period similar to that covered in this study. Although the data of this study represent sufficient time to produce a reliable long-term mean annual load, they apply to a period when there was frequent flooding and almost certainly high rates of sediment transport.

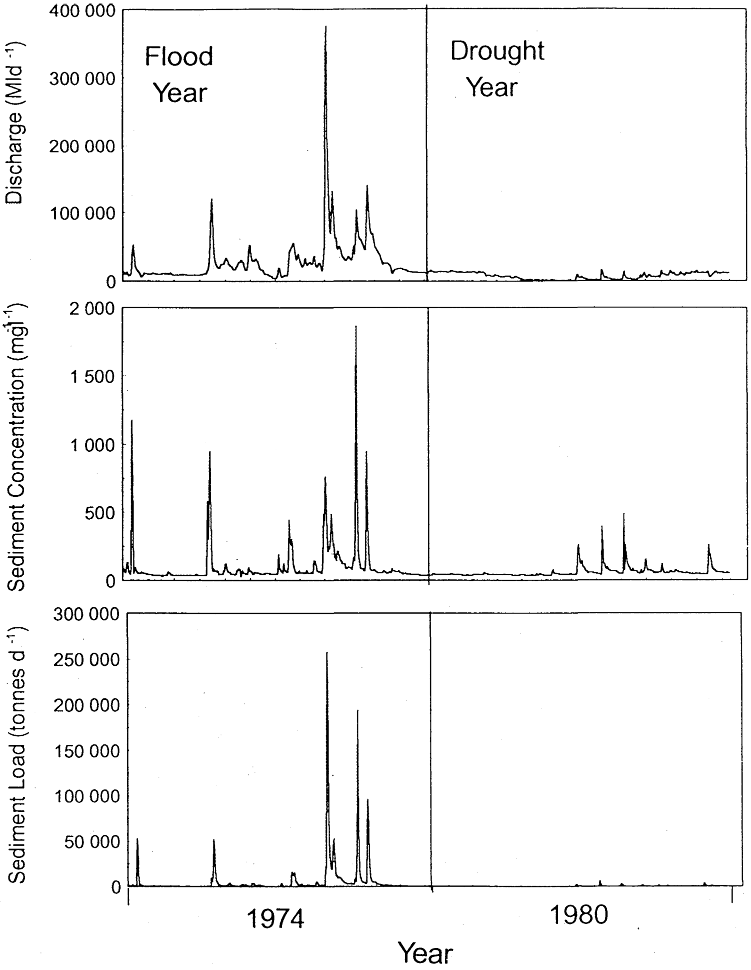

Fig. 5 Graphs showing discharge, sediment concentration, and sediment load for the flood year 1974 (left side) and the drought year 1980 (right side), Murrumbidgee River at Wagga Wagga.

DISCUSSION

The results described above outline the considerable temporal variation in suspended sediment concentration and sediment load that is recognized at a range of temporal scale. There is no simple relation between discharge and sediment concentration. Very high sediment concentration is not only associated with the largest precipitation events, but can also occur with relatively small storms. Large loads, however, are restricted to large floods that are highly variable in occurrence.

At the inter-annual scale, there is high annual variability in load. There are few long-term records available from around the world for comparison, but the results of this study appear to show much more variability than do results from North America and Britain (Olive & Rieger, 1992). Care must be taken with this comparison, however, as

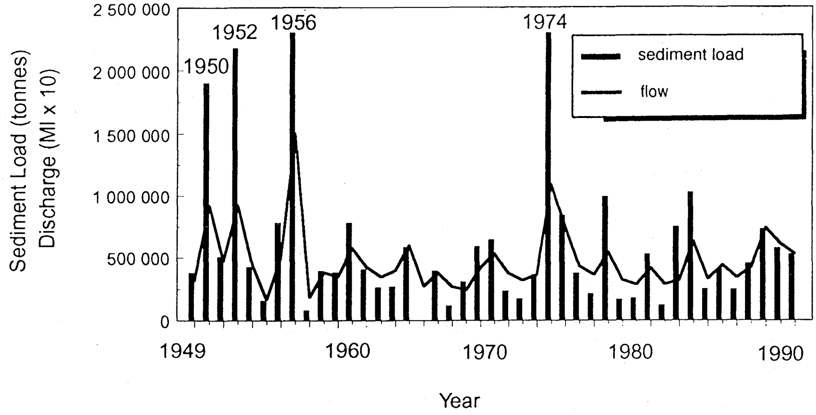

Fig. 6 Graph showing annual flow and sediment load for the Murrumbidgee River at Wagga Wagga, 1949-1991.

the basins cover a wide range of scales and there is doubt concerning the relation between variability and basin size (Parker, 1988). Nevertheless, at this longer timescale, the Australian inland basins appear to be more variable than do most in other parts of the world. It is also likely that there are variations at longer time scales due to alternating flood- and drought-dominated regimes (Warner, 1987).

At the intra-annual scale, which allows examination of variability on an event basis, load is concentrated in storm events with as much as 50% of the load being transported in 3% of the time. Interestingly, this is less concentrated than are the results of Walling *et al.* (1992) for the Exe basin which suggest that 50% of the load was transported in 1% of the time. However, the inter-annual variability in the Exe basin is far less than that of the Murrumbidgee. The importance of individual storm events is more important in the much smaller Exe basin, whereas the variation in the magnitude of events is greater in the Murrumbidgee basin.

These temporal variations are clearly important in designing adequate sampling strategies or determining the reliability of data. Where water quality is important, sediment concentration or turbidity are the most important variables. High concentrations are usually short-lived, and to characterize sediment concentrations adequately, a

Table 1 Summary statistics for annual rainfall, flow, and sediment load for Murrumbidgee River at Wagga Wagga, 1949-1991.

	Rainfall (mm)	Flow (Ml)	Sediment load (t)
Average	591	4 901 000	599 000
Maximum	927	15 010 000	2 295 000
Minimum	247	1 728 000	81 000
Standard deviation	155	2 525 000	566 300
Coefficient of variation	0.26	0.52	0.95

sampling program needs a sampling frequency that enables it to sample these short-lived concentrations. A routine sampling program with infrequent sampling, monthly for example, is unlikely to sample short periods of high concentration (Walling *et al.*, 1992). The whole range of concentration, however, occurs relatively frequently and there is less long-term variation in concentration, so the period of record required to characterize sediment concentration patterns and distributions may be relatively short.

If the interest is in sediment load, the situation is different. Load is dominated by large floods when there is a coincidence of high discharge and sediment concentration. There is considerable temporal and spatial variability (Olive *et al.*, in press) in the response of flow and sediment concentration. During storms, response patterns are frequently out of phase so flux or load can be determined only by direct measurement (Walling *et al.*, 1992). Sampling regime needs to be sufficiently frequent to characterize the variation of discharge and sediment concentration adequately. The resulting sediment load shows wide variation between floods, and the load is dominated by a few large floods. To determine load, and especially to estimate longer-term transport rates, the record needs to be sufficiently long to cover the range of floods. Hence, given the coefficient of variability of the annual loads, approximately 14 years of daily data are required to produce a mean annual load for Wagga Wagga with an uncertainty of ±25%.

CONCLUSIONS

The 43-year data set for the Murrumbidgee River at Wagga Wagga enables analysis of temporal variation in sediment response. There is considerable variability in sediment concentration and load at a range of time-scales. The variability, which is mainly a result of the variable occurrence of floods, is more marked with load than with concentration. This has important implications for sampling design and validity of results. To characterize patterns of sediment concentration adequately, sampling needs to be conducted at intervals shorter than the response time of concentration. In the Murrumbidgee River, daily is the longest sampling interval that provides adequate coverage. Systematic sampling at infrequent intervals, for example monthly, is unlikely to produce representative data. The range of sediment concentration occurs relatively frequently, however, and so the period of record required to produce a representative pattern is relatively short, probably in the order of a few years.

Characterization of the more highly temporally variable sediment load has different sampling requirements. The relation between discharge and sediment concentration is highly variable and so load can only be determined using direct methods. This requires a short sampling interval, similar to that outlined above for concentration. High variability at longer time scales requires that the length of record be much longer, probably decades, to result in acceptable uncertainties. Even then, it will not cover longer-term variations such as phases of flood- and drought-dominated regimes.

Acknowledgements The authors would like to thank Daphne Mahon, who typed in the 43 years of daily turbidity records, the staff of the Wagga Wagga water treatment plant, who collected water samples which enabled us to convert this record to sediment concentrations, and Catriona Turley, Christine Clarke, and Craig Smith, who did most of the suspended sediment analyses.

REFERENCES

Erskine, W. D. & Warner, R. F. (1988) Geomorphic effects of alternating flood and drought dominated regimes on NSW coastal rivers. In: *Fluvial Geomorphology of Australia* (ed. by R. F. Warner), 223-244. Academic Press, Sydney.

Murray, A. S., Olive, L. J., Olley, J. M., Caitcheon, G. G., Wasson, R. J. & Wallbrink, P. J. (1993) Tracing the source of suspended sediment in the Murrumbidgee River, Australia. In: *Tracers in Hydrology* (ed. by N. E. Peters, E. Hoehn, Ch. Leibundgut, N. Tase & D. E. Walling) (Proc. Yokohama Symp., July 1993), 293-302. IAHS Publ. no. 215.

Olive, L. J. & Rieger, W. A. (1992) Stream suspended sediment transport monitoring – why, how and what is being monitored? In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symp., August 1992), 245-254. IAHS Publ. no. 210.

Olive, L. J., Olley, J. M., Murray, A. S. & Wallbrink, P. J. (1994) Spatial variation in suspended sediment transport in the Murrumbidgee River, NSW Australia. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 241-249. IAHS Publ. no. 224.

Olive, L. J., Murray, A. S., Olley, J. M. & Wallbrink, P. J. (in press) Patterns of sediment transport during floods in the Murrumbidgee River system, NSW. *Z. Geomorphol.*

Page, K. J. (1988) Bankfull discharge frequency for the Murrumbidgee River, New South Wales. In: *Fluvial Geomorphology of Australia* (ed. by R. F. Warner), 267-282. Academic Press, Sydney.

Parker, R. S. (1988) Uncertainties in defining the suspended sediment budget for large drainage basins. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 523-532. IAHS Publ. no. 174.

Riley, S. J. (1988) Secular change in the annual flows of streams in the NSW section of the Murray-Darling Basin. In: *Fluvial Geomorphology of Australia* (ed. by R. F. Warner), 245-266. Academic Press, Sydney.

Symader, W., Schorer, M. & Bierl, R. (1994) Temporal variation of environmental pollutants in stream channel sediments. In: *Variability in Stream Erosion and Sediment Transport* (ed. by L. J. Olive, R. J. Loughran & J. A. Kesby) (Proc. Canberra Symp., December 1994), 491-498. IAHS Publ. no. 224.

Walling, D. E. (1988) Erosion and sediment yield research – some research perspectives. *J. Hydrol.* **100**, 113-141.

Walling, D. E. & Webb, B. W. (1988) The reliability of rating curve estimates of suspended sediment yield: some further observation. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling) (Proc. Porto Alegre Symp., December 1988), 337-352. IAHS Publ. no. 174.

Walling, D. E., Webb, B. W. & Woodward, J. C. (1992) Some sampling considerations in the design of effective strategies for monitoring sediment-associated transport. In: *Erosion and Sediment Transport Monitoring Programmes in River Basins* (ed. by J. Bogen, D. E. Walling & T. Day) (Proc. Oslo Symp., August 1992), 279-288. IAHS Publ. no. 210.

Warner, R. F. (1987) Spatial adjustments to temporal variations in flood regime in some Australian rivers. In: *River Channels: Environment and Process* (ed. by K. S. Richards), 14-40. Blackwells, Oxford, UK.