River regulation and sediment transport in a semiarid river: the Murrumbidgee River, New South Wales, Australia

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Abstract The Murrumbidgee River is a major supplier of irrigation water, and flow is heavily regulated. This paper examines sediment transport in the regulated reach of the river between the water storages and the irrigation abstraction points. While approximately one third of the annual flow is abstracted, the impact on sediment transport is less, with only 20% of the sediment load being removed. The regulated irrigation flows have low sediment loads because they are dominated by relatively clean water from reservoir releases. Sediment transport in the river is dominated by storm events with the larger floods generally occurring outside the irrigation season, or where they occur during the irrigation season, only a small proportion of the sediment associated with them is removed by abstraction. The majority of the sediment remains within the fluvial system. The river management system, which is based on flow control, has inadvertently resulted in a system that extracts a larger proportion of water than sediment.

INTRODUCTION

River regulation is achieved through the installation of flow control structures such as dams, weirs and canals. Controlling the flow inevitably also affects sediment transport. For example, dams and weirs often act as effective sediment traps, so that discharge waters are often cleaner than the inflows. As a result, discharge waters often have a renewed capacity to erode and transport sediment, causing channel erosion. Thoms & Walker (1992) in a study of the effects of regulation on the Murray river (an adjacent river to the one examined here) found that most of the sediment transport in the regulated reach occurred during the irrigation season, with most of the sediment (69%) being derived from channel erosion. In this paper we examine the effects of regulation on sediment transport in the middle reach of the Murrumbidgee River, New South Wales, Australia.

THE BASIN AND RIVER REGULATION

The Murrumbidgee River is one of Australia's largest rivers, draining approximately 84 000 km^2 of the Murray-Darling Basin (Fig. 1). The basin can be divided into three distinct geomorphic regions; the upper, mid, and lower Murrumbidgee (Page, 1994). The upper region is mountainous and hilly, and is separated from the mid region by two large storage reservoirs, Burrinjuck and Blowering (Fig. 1). These

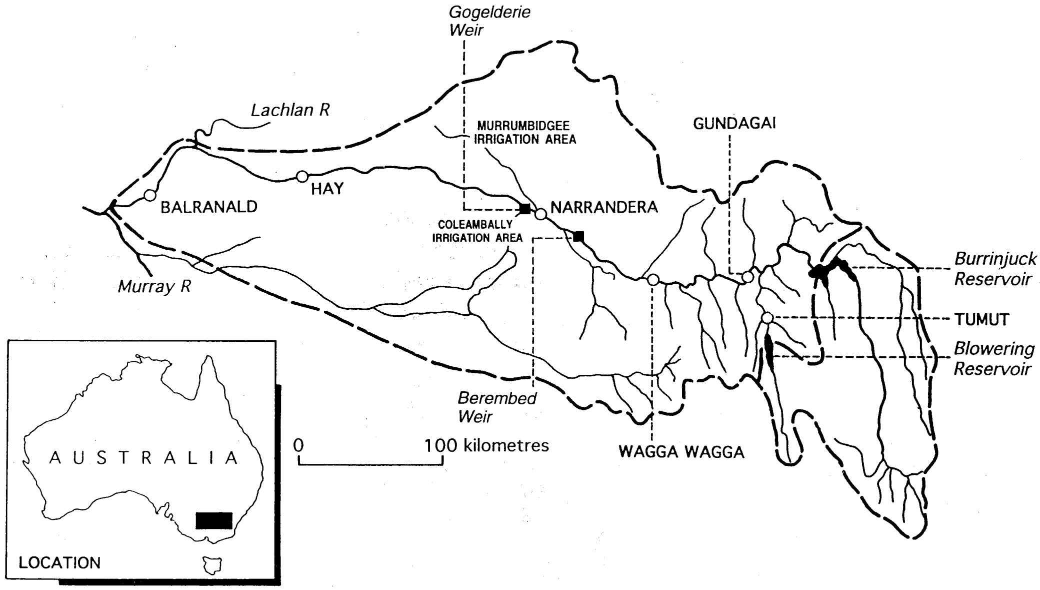

Fig. 1 The Murrumbidgee basin.

dams trap most of the sediment delivered from the upper basin (Wasson *et al.*, 1987). The mid-basin area is characterized by undulating terrain dissected by numerous gully networks. Between Gundagai and Wagga Wagga the river has formed a well defined flood plain approximately 1 to 2 km wide (Page, 1994). Downstream of Wagga Wagga (the lower region) the gradient decreases and the flood plain width increases to between 5 and 20 km. At Narrandera the Murrumbidgee enters the Riverine Plain, and from there follows a highly sinuous course to its junction with the Murray River downstream of Balranald. A strong rainfall gradient exists across the basin; average annual totals vary from 1600 mm in the Snowy Mountains to 300 mm at Balranald.

Grazing is the main land use in the upper basin. The region around Wagga Wagga is a major grain producing area. There is extensive grazing on the Riverine and Hay plains, and intensive cropping and horticulture in the irrigation areas.

Prior to regulation the river experienced extreme annual flow variation, with most of the flow concentrated in winter and spring (Ebsary, 1994). The river is now a major source of irrigation water and flow is heavily regulated, both by the two major dams located in the upper catchment, and by a series of weirs below Wagga Wagga (Fig. 1). Major water abstractions occur at Berembed Weir to supply the Murrumbidgee Irrigation Area and Gogelderie Weir for the Coleambally Irrigation Area (Fig. 1). The combination of regulation and extraction for irrigation has resulted in flow now being spring and summer dominated when water demand by irrigators is highest. Regulation of the flow in the river involves daily assessment of the irrigation needs, tributary inflows, transmission losses, and travel times. The aim is to release sufficient water from the upper basin dams to satisfy all of the downstream requirements, and provide a flow of 125 Ml day^{-1} at Balranald (Ebsary, 1994).

The impact of regulation on flood events varies according to their magnitude; there has been a decrease in the occurrence of small and moderate flood events (Page, 1979, 1988) as flow from the upper catchment can often be controlled by the storage reservoirs. For larger events, the flow response of the river is similar to the pre-regulation regime, especially in the mid and lower reaches where the weir gates are raised during these events.

FLOW

As outlined above, the Murrumbidgee River system is heavily regulated and the flow regime has been significantly altered. The flows for Wagga Wagga and the irrigation abstraction for the period January 1991 to December 1992 are shown in Fig. 2. Summer flows in the mid and lower river have been greatly increased due to large releases from the storages to supply the irrigation areas, with flows being maintained at elevated levels for extended periods during the irrigation season. This is in contrast to the pre-regulation period when summer flows would commonly be low or non-existent, with only occasional increased flows occurring as a result of storm events. The winter flow regime has been less altered by regulation, although there is some reduction of flow as storages are replenished, and there is a decrease in the incidence of small to moderate floods (Page, 1988). The current flow pattern is one of elevated, generally less variable flows during the irrigation season, and lower more variable flows in the non-irrigation period (Table 1). The irrigation abstraction shows the least variation in flow as it is not significantly influenced by storm events.

SEDIMENT DATA

While a good discharge record is available from a network of continuous gauging stations located throughout the basin, the suspended sediment concentration record is far less detailed. The official suspended sediment monitoring program is based on sampling at 4-6 weekly intervals. As significant changes in suspended sediment concentration occur over intervals of several days, the official record does not adequately characterize the variations in suspended sediment concentration. Consequently, these data can only be used to determine sediment loads using the rating curve method that has previously been shown to result in major errors (Walling, 1977; Walling & Webb, 1988; Walling *et al.*, 1992; Olive & Rieger, 1992). In this current study we have used data based on daily turbidity observations made at water treatment plants at towns that take their water supply from the river (Fig. 1).

Statistically significant relationships ($r^2 > 0.79$) between turbidity and suspended sediment concentration have been established at each location by sampling a wide range of turbidities and sediment concentrations over a 3-year period. The sediment loads have been calculated using the daily discharge and the suspended sediment concentration determined from the daily turbidity readings. Inevitably errors result from the use of single daily values, however, the magnitude of these errors was assessed during a flood in 1991 at Narrandera, and was found to be relatively small

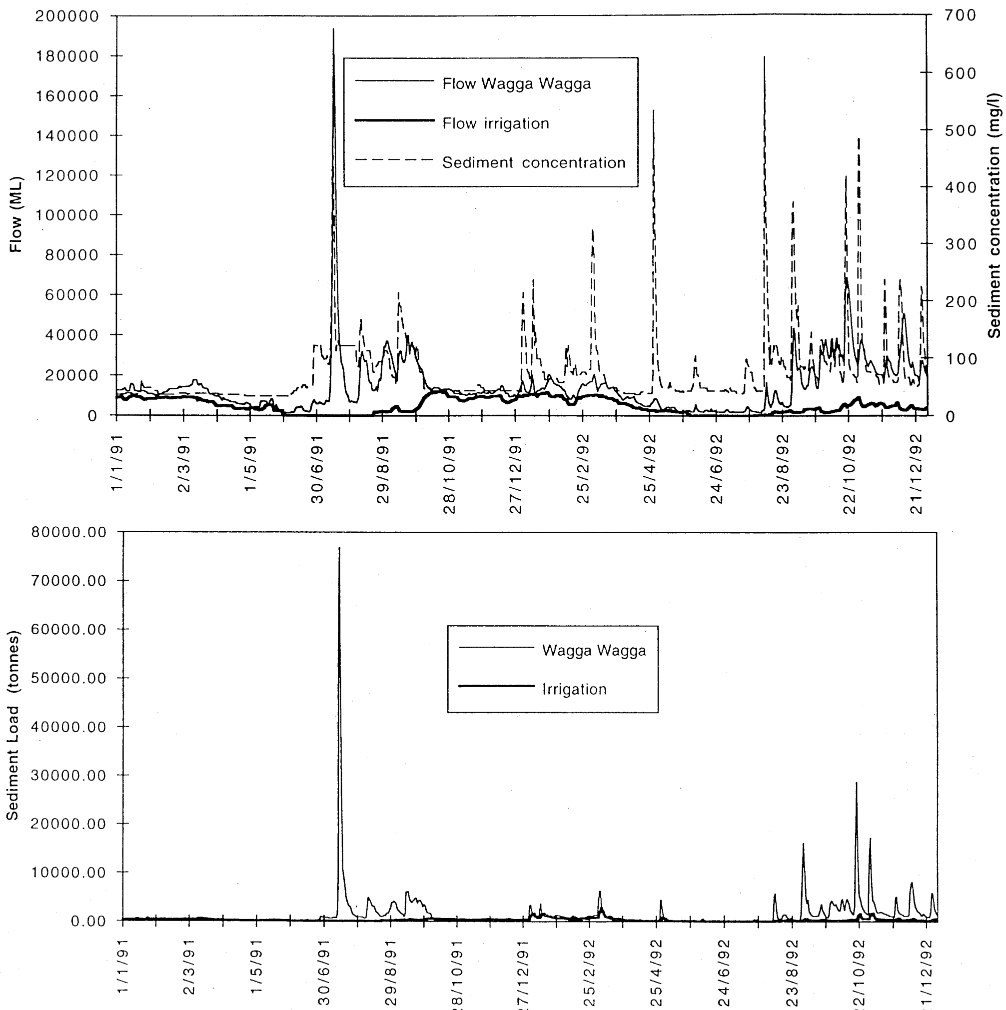

Fig. 2 Flow, sediment concentration and load in the Murrumbidgee River 1991-1992.

(Olive *et al.*, 1996). Sediment loads for irrigation extraction were calculated assuming that the sediment present at Wagga Wagga was delivered to the extraction point, and then removed with the irrigation water. The travel times used for the timing of extraction after Wagga Wagga are based on those determined by Ebsary (1994). The travel time from Wagga Wagga to Berembed Weir is 2 days, with an additional 2 days to Gogelderie Weir.

SEDIMENT CONCENTRATION

The overall pattern of sediment concentration in the regulated reach is one of extended periods of low concentrations with short periods of high concentrations

Table 1 Summary statistics for river flow (Ml day^{-1}) in the Murrumbidgee River at Wagga Wagga and irrigation abstraction 1991-1992.

	Total river flow	River flow irrigation period	River flow non-irrigation period	Irrigation abstraction
Mean	14 476	15 526	10 666	5 875
Standard deviation	14 390	10 123	23 891	3 158
Coefficient of variation	0.99	0.65	2.24	0.54
Median	11 736	12 780	2 672	5 225
Maximum	112 539	68 484	193 574	11 882
Minimum	1 391	1 918	1 391	200

marked by sharp peaks associated with storm events (Fig. 2). A significant proportion of the flow associated with these peaks is derived from the tributaries between the storage dams and the extraction weirs (Olive *et al.*, 1995). While storms occur throughout the year, they are more common in winter and spring, and the larger flood events occur almost exclusively during this period. The summary statistics of sediment concentration for the total data set, and the irrigation and non-irrigation periods, are presented in Table 2.

During the irrigation season, sediment concentrations are generally lower and less variable than those in the non-irrigation period (Fig. 2, Table 2). There are two reasons for this pattern. First, flow during the irrigation period tends to be dominated by releases from Burrinjuck and Blowering reservoirs that are efficient sediment traps (Srikanthan & Wasson, 1993), and their releases are characterized by low sediment concentrations. Second, while there are concentration peaks resulting from storm events in the tributaries during the irrigation season, these tend to be smaller and more short lived than those that occur during the non-irrigation period. An exception to this is evident in the 1992-1993 irrigation season where there are a large number of sediment producing storm events (Fig. 2). In the non-irrigation season, storm events tend to be larger and of much longer duration, resulting in extended periods when sediment concentration is elevated. This is indicated in the flood event in July 1991, where concentrations are high and remain elevated through to October 1991 (Fig. 2).

Table 2 Summary statistics for sediment concentration (mg l^{-1}) in the Murrumbidgee River at Wagga Wagga 1991-1992.

	Total study period	Irrigation period	Non-irrigation period
Mean	74	70	90
Standard deviation	63	52	92
Coefficient of variation	0.85	0.74	1.02
Median	48	48	52
Maximum	626	534	627
Minimum	32	32	32

SEDIMENT LOAD

Sediment transport within the Murrumbidgee system is dominated by storm events that can occur throughout the year, but the larger events tend to be concentrated in winter and spring (Olive *et al.*, 1995). This is illustrated in the sediment loads for 1991-1992 (Fig. 2) where loads are dominated by the large flood event in July 1991. Significant sediment transport also occurs during other storm events, especially in the latter part of 1992. The major source of this sediment is the tributaries below the two main storage reservoirs (Olive *et al.*, 1994).

Sediment loads during the irrigation season tend to be low as flows are dominated by the relatively clean water released from the main storage reservoirs. However, there are storm events in which significant sediment transport occurs as in the latter part of 1992 (Fig. 2). During these storm events, when sediment concentrations and loads are high, the total flow in the river increases but the total volume abstracted remains unchanged, so the proportion of sediment removed is much less than under low flow conditions. In some cases the volume abstracted is reduced as local rainfall associated with the event decreases demand for irrigation water.

The larger flood events with their high sediment loads primarily occur during winter and spring when there is minimal irrigation abstraction, so the sediment remains within the river system (Fig. 2). The influence of irrigation abstraction on cumulative sediment load is illustrated in Fig. 3. In the irrigation season in early 1991 there were few storm events, and while most of the sediment load was removed

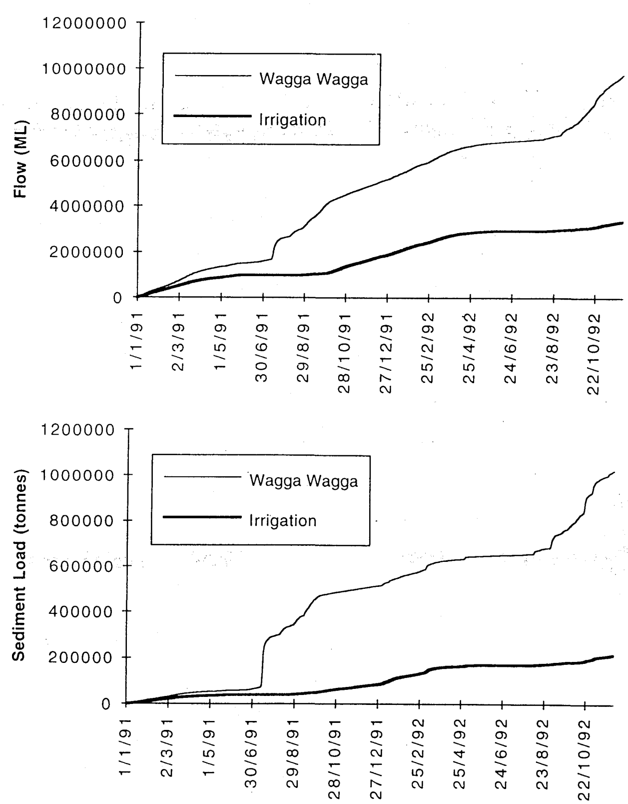

Fig. 3 Cumulative flow and sediment load of the Murrumbidgee River at Wagga Wagga and for irrigation abstraction 1991-1992.

by abstraction the total amount of sediment was small. A similar pattern occurs in the 1991-1992 irrigation season. The importance of the July 1991 flood, when no sediment was removed, is clearly evident. In the irrigation period in the latter part of 1992 there was significant sediment transport associated with several storm events, but much of this remained in the river system. The result of this is that, during this two year period, 33% of the total flow was abstracted for irrigation use, but only 20% of the sediment load was removed.

DISCUSSION

The flow in the Murrumbidgee River is heavily influenced by river regulation to provide water for irrigation. Approximately one third of the total flow is abstracted from early spring to autumn. The two major storage reservoirs have had a major impact on the transport of sediment through the basin with most of the sediment from the upland area being trapped in the reservoirs (Wasson *et al.*, 1987). The impact of regulation and abstraction on sediment transport below the reservoirs tends to be less pronounced. Channel erosion in the reaches below the dams does not appear to be a significant source of sediment (Murray *et al.*, 1993). The majority of the current sediment load below the reservoirs originates in the tributaries that enter the river downstream of the dams, and upstream of Wagga Wagga, with most of the sediment being transported during storm periods (Olive *et al.*, 1994; Wallbrink *et al.*, 1996).

Much of the abstracted water is derived from dam releases that have low sediment concentrations, and consequently low sediment loads. During storm events in the irrigation season, when discharge and sediment loads are higher, the abstracted volume either remains unchanged or is reduced. So while more sediment is removed with the irrigation water it is a smaller proportion of the flux of sediment being transported in the river. The largest flood events, when the majority of sediment is transported, are concentrated in winter and early spring when there is little or no irrigation abstraction. Consequently, much of the storm sediment transport remains in the river system. The net result of these processes is that while a third of the total flow in the regulated section of the river is abstracted, only about 20% of the sediment load is removed. The river regulation system is designed solely to control flows to optimize water availability for irrigation. As a consequence this results in a smaller proportion of sediment being removed than water.

The results presented here differ from those reported by Thoms & Walker (1992) for the neighbouring Murray River; which is also heavily regulated. They found that most of the sediment transport in the regulated reach occurred during the irrigation season, although they did not determine the abstracted load. This was attributed to the main river channel being the dominant source of the suspended sediment. There is evidence in their paper, however, that the major tributaries such as the Kiewa and Ovens Rivers provide significant sediment to the Murray River during non-irrigation periods, presumably associated with flood events (Thoms & Walker, 1992, p. 243). Thoms & Walker used the rating curve method to determine sediment loads. Consequently, care must be taken when comparing the results of our study with their's; the different approaches used could account for some of the differences. It may well be that river regulation effects these two adjacent river systems differently. Additional work is required to clarify the situation.

CONCLUSIONS

While approximately one third of the annual flow in the Murrumbidgee River is abstracted, only 20% of the sediment load is being removed. This is because, (a) the regulated irrigation flows are dominated by relatively clean water from reservoir releases, (b) sediment transport in the river is dominated by storm events with the larger floods generally occurring outside the irrigation season, and (c) where floods do occur during the irrigation season only a small proportion of the sediment associated with them is removed by abstraction. Consequently, the river management system, which is based on flow control, has resulted in a system that extracts a larger proportion of water than sediment.

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