Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation
(Proceedings of the Vienna Symposium, August 1991) IAHS Publ. no. 203, 1991.

ASSESSING THE IMPACT OF LAND USE CHANGE ON STREAM SEDIMENT TRANSPORT IN A VARIABLE ENVIRONMENT

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ABSTRACT Many studies have examined the influence of land use change on erosion and sediment transport, commonly using the paired or multiple basin approach. Most of these techniques were developed in North America and Europe, areas with relatively low hydrologic variability. This study examines the influence of logging and wildfire on sediment transport in six small forested basins in south eastern New South Wales using such an approach. Problems arose in quantifying and interpreting any changes where sediment transport associated with disturbance was frequently within the normal range experienced by the undisturbed streams. It is suggested that many of these problems are related to the high hydrologic variability which occurred during the study. Such high variability is a feature of Australian streams and the paper examines the implications of applying traditional techniques in an environment which has high natural variability.

INTRODUCTION

With increasing awareness and concern for the environment, considerable research interest has been generated in attempting to assess the impact of land use change, especially that associated with human activity, on stream hydrology and erosion. Commonly, this research has been based on the paired or multiple basin approach where a series of small basins are monitored and while retaining control basins in their undisturbed state, the remainder are subjected to the land use change. Comparisons are then made to attempt to quantify any changes which have occurred. A major underlying assumption of this experimental design is that the relationship between basins is spatially and temporally constant. This approach, which was developed in North America has been widely applied throughout the world.

In Australia, commonly recognized as the driest continent, considerable evidence now exists that stream hydrologic regimes differ considerably from those of North America and Europe where most of the techniques for examining the impact of environmental change on streams, including the paired basin approach, were developed (Finlayson & McMahon, 1988). The major difference is that Australian streams are characterized by highly variable flow regimes with variation occurring both temporally and spatially. This has important implications for the application of models commonly developed in the northern hemisphere where there is considerably less variability. This paper examines the application of traditional techniques in the Australian environment using results from a multiple basin experiment in the Eden area in south eastern New South Wales which was established to examine the impact of forest harvesting operations on erosion and sediment transport.

BACKGROUND

The study of basins to attempt to assess the impact of land use change has a long history and Walling (1979) has traced this back for at least one hundred years. A number of experimental designs have been used during this time. The classic experiment which established the paired basin approach was the Wagon Wheel Gap investigation in Colorado initiated in 1910 (Bates & Henry, 1928). This involved the comparison of two basins for an initial calibration period in an undisturbed state and then the subsequent clearance of one of them. The affects of clearance were assessed by comparison of the two basins and the pre- and post-treatment periods. The paired basin methodology is based on the establishment of two essentially similar basins which can be calibrated against each other with respect to their natural response patterns. Once this relationship is established one of the basins is subjected to disturbance while the other is retained in its natural state as a control. The effects of the basin modification are determined using the calibration to estimate the natural response of the modified basin from the records of the control and then comparing this to the actual response in the disturbed basin. The technique was originally developed to examine changes in water yield but has been subsequently extended to studies of water quality and erosion.

A large number of experiments have subsequently been undertaken using this basic paired basin approach, particularly with respect to changes in forested basins. Many of these studies involved an examination of changes in streamflow and hydrologic regime. One of the better known of these is the Coweeta experiment in North Carolina which examined the impact of clear-felling on water yields (Hibbert, 1967). Based on a three year calibration period changes in monthly water yields after clearing were determined. The experiment was repeated after 23 years producing almost identical results strengthening the validity of the technique. Following the successful application of the technique to stream flow studies it has been utilized to assess land use change on stream erosion and water quality, again especially with respect to forested basins (Davies & Pearce, 1981; Swanson *et al.*, 1987).

An extension of the paired basin approach has been utilized where a number of basins have been monitored in a small area. This multiple basin approach enables the examination of the impact of a range of different basin disturbances. Again this technique has been widely applied to the study of various treatment practices in forested basins. An example of such a study is the experiment at Moutere in New Zealand (New Zealand Ministry of Works, 1968).

Where there is difficulty in establishing twin basins a single basin has been used with a pre-treatment calibration period being compared with the disturbed period. Calibration is established in the natural state between the basin response and some hydrometeorological variable which is independent of modification. Walling & Gregory (1970) carried out such an experiment to examine the influence of urbanisation on a basin near Exeter.

In Australia the majority of the research examining the influence of land use change has concentrated on forested basins with an examination of the impact of various treatment practices and also wildfire, a common occurrence in many Australian forests. Both Olive & Rieger (1988) and Campbell & Doeg (1989) have reviewed the Australian forest research. Only limited research has been done on other impacts. Virtually all the studies have used one of the methodologies outlined above while in recent years there has been a trend towards larger multiple basin experiments.

All three experimental designs outlined above rely on some inferred assumptions. The major requirement is that there is consistency in the hydrologic response of a basin over time and between adjacent basins to allow the establishment of a reasonable calibration relationship. If the hydrologic response of a stream varies temporally then it becomes difficult to distinguish between natural variability and any change due to the disturbance. If this temporal variation also has a spatial expression and there is variation between basins over time, then calibration becomes increasingly difficult. Because of these factors it may be that the problems intensify with increasing variability in stream flow regimes.

On a continental basis Australia has highly variable flow regimes with Finlayson and McMahon (1988) showing coefficients of variation of annual flows for Australian basins ranging from 0.59-1.12 depending on basin size while those of Europe are 0.19-0.35 and North America 0.3-0.63. This could just be due to Australia's aridity but a comparison of streams in equivalent climatic regimes reveals that Australia's variability is commonly higher than those of the rest of the world with the exception of southern Africa where the results are similar. Australian flow regimes also appear to be far more dominated by storm or flood events with the mean annual flood and the ratio of the one-in-one hundred year to annual flood consistently higher than the rest of the world and especially the traditional areas of hydrologic model development, North America and Europe. This greater variability leads to questions about the validity of the assumptions underlying most comparative experiments.

THE STUDY

The Eden study is a multiple basin project, involving six basins, which was established to assess the impact of timber harvesting operations on native eucalypt forests. It is a large integrated project which involved a number of organizations considering the impacts on wildlife, vegetation, nutrient balance and various hydrologic characteristics including water balance, runoff dynamics, water quality and erosion and sediment transport. This paper examines only the sediment aspects which were researched by the authors. The project is located south of Eden in south eastern New South Wales (Fig. 1).

The area experiences a moderate temperate climate. Average annual rainfall is approximately 900 mm with no strong seasonal pattern. Much of the rain occurs in long duration storms associated with stationary depressions off the coast during winter while thunderstorms are common in summer. There is considerable inter-annual variation in precipitation with a co-efficient of variation of 0.96, although this is not high by Australian standards. Rainfall distribution within individual years is strongly non-uniform with no strong seasonal trend and it is common for over half the annual total to fall in 2 to 3 months (Mackay & Robinson 1987). In hydrologic terms, rainfall is commonly dominated by a small number of storms, the timing and magnitude of these events varies considerably from year to year.

The area is underlain by adamellite and soils are of variable depth and range from uniform coarsely textured yellow earths to podsolics. Vegetation of the area is dry sclerophyll forest with a eucalypt overstorey and a discontinuous understorey. The area experiences frequent wildfires during the summer season. The basins range from 75 to 225 ha and have an easterly aspect. Data collection was based on v-notch weirs with automatic water samplers providing a relatively detailed sampling pattern for storm events normally on an hourly basis. Monitoring commenced in April 1977 and Stringybark Creek was logged using the small alternate coupe method commencing in May 1978. The pre-disturbance calibration period was very short due to an urgent need to have some indication of the impact of logging. Logging of this basin was not completed when much of the research area was burnt by an uncontrolled wildfire in January 1979 (Fig. 1). Following this fire a special salvage logging operation was carried out in Germans Creek during 1979 where 85% of the basin area was felled. Further logging was carried out in Grevillea, Peppermint and Geebung Creeks during 1987 but results of this treatment are not yet available. More detailed descriptions of the study area and the treatments are provided in Mackay & Robinson (1987) and Olive & Rieger (1987).

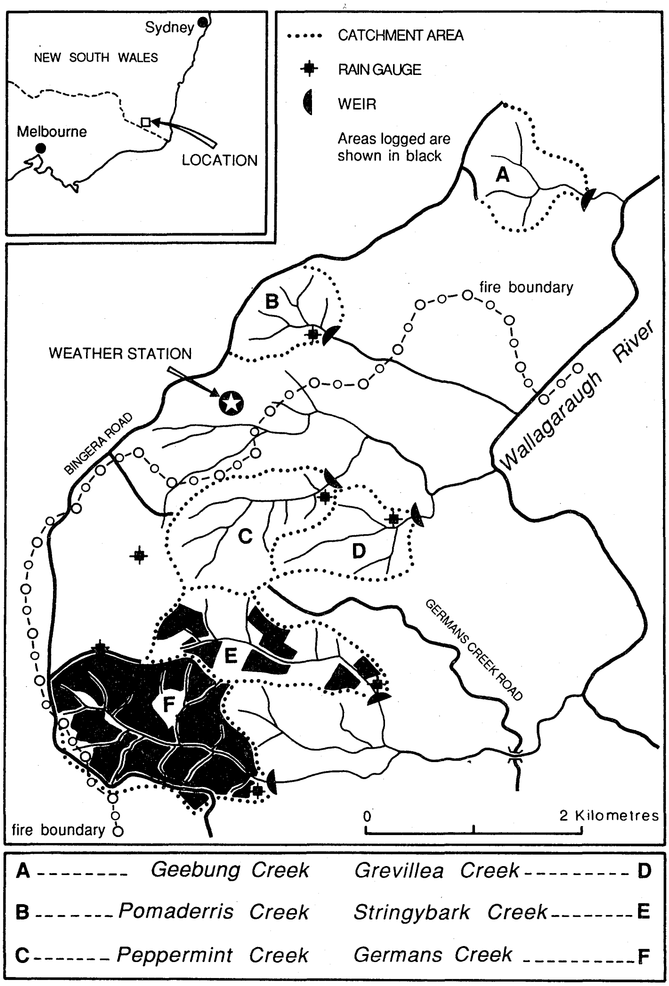

FIG.1 The study area.

STUDY RESULTS

Rainfall during the study period was highly variable with annual totals varying from 478 to 1616 mm. The magnitude of this variability can be seen from the data from Eden, the nearest station with longer term records, which has a mean annual rainfall of 888 mm and a co-efficient of variation of 0.96. The distribution pattern of Eden's annual rainfall record is shown in Fig. 2 and the annual totals for the critical disturbance years are also indicated.

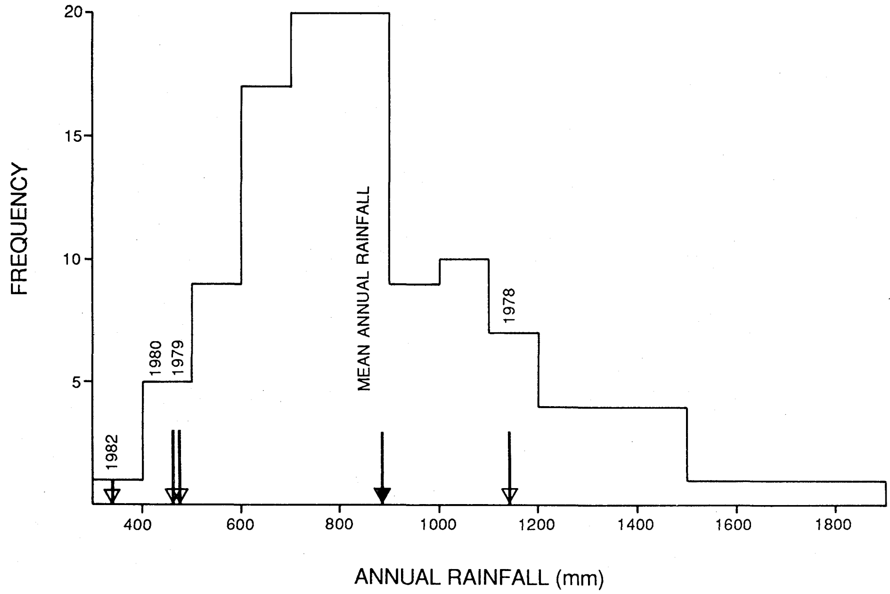

FIG. 2 Frequency distribution of Eden's annual rainfall for the period 1869-89 with the rainfall for critical distubance years indicated.

1978 was a wet year where rainfall was approximately one standard deviation above the mean while the area experienced a severe drought during the period January 1979 to mid 1983 with three of these years having rainfall greater than 1.5 standard deviations below the mean and in 1982 the rainfall total of 339 mm was the lowest in 114 years of record. Within these years individual storms dominated the record, for example the large storm in June 1978 of 339 mm at the basins represented 21% of the annual total while in the drought year 1979 one storm of 140 mm in March made up 28% of the annual total. Runoff during the period showed similar variability as shown in the hydrograph for Pomaderris Creek (Fig. 3). This hydrograph shows the importance of storm events in the discharge regime while the dominance of the storms in 1978 and the reduced runoff during the drought are clearly evident. Mackay & Cornish (1982) examined the hydrologic impact of logging and fire on these basins. They reported marked increases in the relative magnitude of peak flows during storm events with increases of up to ten times where basins had suffered the dual impact of both logging and wildfire.

Suspended sediment concentrations in these basins before disturbance were relatively low and rarely exceeded 100 mg l^{-1} with sediment transport being entirely storm dominated. During storms, sediment responses were of short duration and there was considerable variation in the response patterns found (Olive & Rieger, 1985). It was difficult to establish any constant response pattern either within a basin over time or between different basins. One consistent feature occurred in longer duration events where multiple stream rises were common and these showed clear sediment depletion with peak sediment concentration decreasing with each successive stream rise. This pattern continued in the disturbed basins where following both logging and wildfire the supply of sediment would be expected to be optimized but there was well defined depletion (Fig. 4).

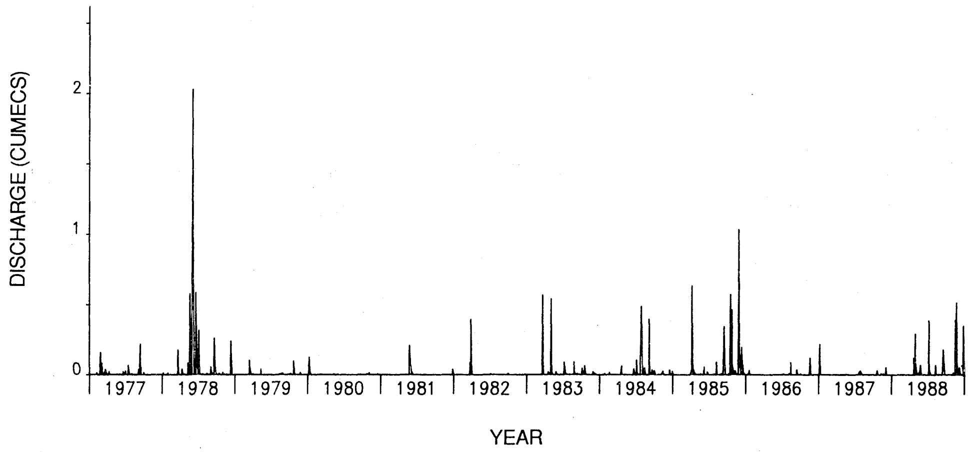

FIG. 3 Hydrograph for Pomaderris Creek for the study period.

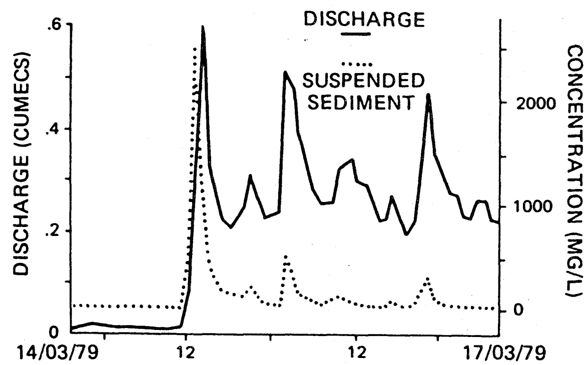

FIG. 4 Storm hydrograph and sedigraph for Stringybark Creek March 1979.

Because of the high variability of both rainfall and sediment response it was difficult to quantify the impact of logging and wildfire on sediment transport. In the pre-disturbance calibration period, rainfall patterns were similar to the long term average while those associated with the disturbances were more extreme. Logging and its associated roadway development in Stringybark Creek during 1978 were associated with a very wet period with several large storms, the largest having a return period on the order of one in twenty years. In the undisturbed control basins this one storm accounted for 70-80% of the measured suspended sediment load during the study period. It was estimated that in the logged basin sediment concentrations increased but it was difficult to quantify the magnitude of the increase as the storms were larger than those experienced in the basin before disturbance. While there was an apparent increase, peak concentrations were higher in some of the control basins than they were in Stringybark Creek. At least this situation did give some indication of the maximum likely increase where disturbance was associated with a large event.

The wildfire was followed by a severe drought with only a few storm events. While similar difficulties arose in quantification it did appear that the wildfire resulted in increases in suspended sediment concentration greater than those associated with logging. As wildfire is a natural and common occurrence in this area it does suggest that the influence of logging is within the normal range of sediment concentrations for these streams as it is less than that associated with fire. There is a possibility however that the recurrence interval of fire also has changed in response to human activity in the area. Where basins experienced the dual disturbance of logging and wildfire (Stringybark and Germans Creeks) concentrations showed a much greater increase and there appeared to be on the order of a ten fold increase.

In the case of suspended sediment loads, increases associated with both disturbances were generally less than expected given the magnitude of the increases in both storm discharge and suspended sediment concentration. While load is a function of both discharge and concentration the expected multiplier effect did not occur due to the nature of the storm response patterns. There were extremely rapid response patterns where both peak discharge and sediment concentration were short lived and frequently the peaks were out of phase resulting in a lower total sediment load. Again, the greatest increases occurred where there was the double impact of both fire and logging while logging produced the smallest increase.

DISCUSSION

This study was designed to utilize the paired or multiple basin approach, a widely accepted technique for the examination of the impact of basin disturbance. While the technique has produced satisfactory results elsewhere, serious problems arose in its application in this study. Many of these problems appear to be related to the high variability of the hydrologic environment. The technique is based on the establishment of a constant relationship between the control and disturbed basins and also the assumption that there is consistency in the system through time especially with respect to the pre-treatment calibration and the disturbance periods. In a variable environment it is difficult to establish such a calibration. The streamflow regimes are characterized by long periods of low flow interspersed with storm events of varying magnitudes and intensities which can occur throughout the year as there is no strong seasonal pattern. Suspended sediment transport is completely dominated by these storm events. In the undisturbed basins sediment concentrations and response patterns are highly variable and it was not possible to establish any real calibration relationship either over time or between the control and disturbed basins. In addition, peak concentrations associated with disturbance were frequently within the natural range of the basins prior to disturbance so that the natural variability in the system was often greater than the magnitude of any increase associated with basin disturbance. These problems may be overcome by extending the calibration period to achieve a wider range of storm events and thus a more representative sample, but in a highly variable environment the required length of such an extension would probably prove to be uneconomic.

Climatic variability can also lead to problems during the disturbance phase. The influence of disturbance can be relatively short lived and so its impact is as much dependent on the immediate post disturbance climate as the disturbance itself. This was certainly the case in the Eden study where the logging of Stringybark Creek was associated with a wet period with large storm events while the wildfire was followed by the drought. In the basins only affected by the wildfire, sediment transport during the study period is dominated by the storms in 1978 when the basins were undisturbed while following the fire, when drought conditions occurred, there was very little sediment transported despite the major disturbance to the basins. The Eden results probably represent an extreme case but they do illustrate the complications associated with any attempt to quantify changes due to disturbance particularly where there is variability in response patterns. These problems may be overcome by comparing relative values rather than the absolute sediment loads but again variability in any calibration relationship makes this more difficult. When considering the absolute influence of disturbance it would be useful to express such changes in terms of their probability of occurrence with respect to the duration of the impact and the likelihood of significant storm events occurring in that period

In many disturbance studies changes are determined using relatively simple statistical analyses, for example Langford *et al.* (1982) compared mean sediment concentration before and after disturbance. Where climatic variability has a strong influence on sediment transport such comparisons can be dubious. In the Eden study mean sediment concentrations associated with the wildfire were less than those preceding it. Sediment concentrations had increased significantly in relative terms but because of the different flow conditions the absolute values were reduced. These problems can be partially overcome by using relative rather than absolute values. Any use of measures of central tendency, such as means, is effectively applying a filter to the data reducing the importance of extreme values (Burt, 1986) whereas in disturbance studies it is the extreme values which are of most importance.

From the Eden study, problems have emerged in the application of the paired or multiple basin approach which appear to be related to the highly variable flow and sediment transport regimes experienced. It may also be possible that some of the problems arise due to the extension of the methodology from the analysis of water yield to sediment transport which is inherently more complex with a wider range of controls. Some of these problems could probably be reduced by extending the calibration period to ensure a wider range of storms sampled producing a more representative data set and by using relative rather than absolute values. Due to the importance of individual storms, the sampling program needs to be sufficiently detailed to ensure that storm response patterns can be adequately characterized and there is not a need to use bulk data. It still may not be possible however to establish any meaningful calibration where there is such a wide range of natural variability. None of these suggestions overcome the problems of the nature of the post disturbance storm events. Once the disturbance is initiated there is no turning back and the project is at the mercy of the weather. In a variable environment, where the impact of disturbance is relatively short lived, this can seriously compromise the integrity of the project. As variability increases these problems are likely to be increased. However, in more variable environments the influence of basin disturbance may be more significant as increasing variability commonly results in more marginal and fragile environments. It may be more useful to focus research on more fundamental studies of the processes which operate in the system in an attempt to more clearly identify changes due to disturbance. This type of analysis may appear less quantitative but could provide a more accurate characterization of the impact of basin disturbance.

CONCLUSIONS

A number of problems have emerged from the attempted utilization of the paired or multiple basin approach to examine the impact of basin disturbance through logging and wildfire on suspended sediment transport in small basins in south eastern New South Wales. Many of these problems appear to have resulted from the highly variable hydrologic environment which occurs. During the study period a wide range of flow conditions prevailed which tended to highlight the problems of characterizing change where it is superimposed on a variable system and the magnitude of the change is within the range of normal variability in the system. While some of the problems can be overcome, serious doubts remain over the viability of the methodology in this situation. It may be more rewarding to carry out more fundamental research which attempts to outline the processes operating in the system and any resulting change in it rather than attempt a simple quantification of change.

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