AUSTRALIA'S INNOVATIVE UNIVERSITY

EVALUATING THE EFFECTS OF FIRE AND OTHER CATASTROPHIC EVENTS ON SEDIMENT AND NUTRIENT TRANSFER WITHIN SCA SPECIAL AREAS

Technical Report 1: Review of the hazards, triggers, mechanisms and frequency-magnitude of extreme erosion-sedimentation events in southeastern Australia with emphasis on post-fire erosion

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EXECUTIVE SUMMARY

Event based movement of large volumes of sediment in the Sydney Catchment Authority (SCA) Special Areas can potentially pose a significant threat to water quality and quantity in the major water supply reservoirs. Examples include landslides, rockfall from cliffs, debris flows on slopes, and cut and fill events in upland swamps draining into the storages. To date, very little is known about the distribution, morphology, triggers and impacts of such extreme events. The SCA Business Plan 2002 – 2007 (2004) identifies the minimization of threats to water quality as a high priority, and hence has commissioned research into the effects of wildfire and other catastrophic events on sediment and nutrient transfer within the Special Areas (this project). This technical report is the first of a number of reports which will present the findings of the research.

This report provides an overview of the hazards, triggers, mechanisms and frequency–magnitude of catastrophic and extreme erosion–sedimentation events using literature from southeastern Australia and elsewhere combined with observations from preliminary investigations in the Special Areas. The aim is to gain a good understanding of event based movement of sediments and nutrients in the landscape, including the geological and meteorological hazards which facilitate them and the range of internal and external triggers which induce them. Those relevant to the SCA areas include:

- drought (meteorological hazard);
- wildfire (meteorological hazard and external trigger);
- extreme rainfall or severe storms (meteorological hazard and external trigger);
- floods (meteorological hazard);
- earthquakes (geological hazard and external trigger);
- mine subsidence (human induced hazard and external trigger);
- catchment clearing (human induced hazard); and,
- intrinsic thresholds (internal trigger).

External triggers, particularly wildfire, extreme rainfall and earthquakes are the most widely cited causes of catastrophic and extreme erosion–sedimentation events. However, many studies describe scenarios whereby one external trigger is followed by another trigger, for example, wildfire followed by severe storms or extreme rainfall followed by earthquakes. It is the coupling of triggers, rather than a single trigger which initiates extreme erosion–sedimentation events.

Coupling may explain the low frequency of extreme events compared with formative events which typically shape the landscape and appear to be driven by intrinsic thresholds. Previous work on the upland swamps on the Woronora Plateau suggests that they have eroded and refilled at intervals of thousands of years during the last 10,000 years (Holocene), whilst mass movement on slopes in the Nattai catchment, appears to be occurring at intervals of hundreds to thousands of years. Extreme events will continue to occur in the future under similar climatic conditions. Thus there is the real possibility that a catastrophic or extreme event(s) will occur within the Special Areas during the lifetime of the water supply reservoirs.

The findings of this report will enable the development of a research strategy that targets the most relevant aspects of erosion–sedimentation events in the Special Areas. For the SCA, knowledge and awareness of the triggers of these events, the mechanisms by which sediment is moved and the return periods of events will assist with determining the likely threat of a future event to water quality and quantity. Although little can be done to prevent or stop these events, awareness of the impacts will enable contingency arrangements to be developed.

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Cover: Blue Gum Creek hillslope, Nattai catchment, 18 months after the Christmas 2001 wildfires.

1. INTRODUCTION

1.1. Preamble

Catastrophic or extreme events are often regarded as a type of hazard with a rapid onset in which surprise is a major reason cited for the lack of preparedness. But this situation is only applicable if the hazard is not recognized. The recent Asian tsunami event provides a graphic example. The following account attempts to address this by identifying the main hazards of erosion–sedimentation and how these might manifest themselves as catastrophic events. An important element in this is the realization that a catastrophic erosion-sedimentation event is often just at the extreme of a continuum of events and one that might occur via the unusual coincidence of a sequence or chain of events. But, though the concept is simple enough, it is the recognition of past catastrophic events and an estimation of the likelihood of a future occurrence that presents the greatest challenge. In the case of the former it relies on seeking appropriate evidence and for the latter it is a prediction based on probability.

For the Sydney Catchment Authority (SCA), knowledge of the prior existence and future likelihood of catastrophic and extreme erosion-sedimentation events occurring in the Special Areas is critical for the management of risk to water quality and quantity. That is, relevant staff need to be aware of where and when these events occur and what the water supply related impacts are should such an event happen within the lifetime of the dams. In which case, contingency arrangements are required to mitigate those impacts. In using the term *erosion–sedimentation event*, we mean the short term or instantaneous movement of a large volume of material *en masse* from one place to another (mass movement). An example is a landslide of rock and other debris sourced from the failure of cliffs at the edge of a plateau which are deposited at the toe of the hillslope and in the valley floor below. The opposite involves the single grain movement of sediment from the surface usually by the processes of slope wash and sheet flow, and through rills and gullies where flow becomes concentrated. Whilst the sediment and nutrient supply made available through slope wash and gully erosion can be high and is often well studied (e.g. Melville and Erskine 1986; Prosser and Slade 1994; Shakesby *et al.* in press), the instantaneous input of sediment and nutrients from mass movement events is poorly understood. A large input of sediment into the storages could have severe implications for water quality and quantity, especially if the event is located in the areas surrounding a water supply reservoir.

1.2. Approach, aims and objectives

This report provides an overview of the likely natural hazards that can reasonably be expected to impact as catastrophic or extreme erosion–sedimentation events on SCA areas in general and SCA Special Areas in particular. An important part of our thinking at present is that if an extreme event occurred during the Holocene, i.e. in the last 10,000 years, then there is no reason why it could not happen again in the immediate future. The rationale behind this is that the present environment has been relatively similar over this time period (Bowler *et al.* 1976) and therefore similar geomorphic processes are continuing to form the landscape.

Whilst the concept of catastrophic and extreme events is straightforward, the unequivocal recognition of such events is not. Nor is there a good understanding of the role of these events in landscape development. Accordingly, our approach is a review of information available from southeastern Australia and elsewhere relating to erosion and sedimentation events, with particular emphasis on the triggers or conditions leading to those events, mechanisms and timing (frequency–magnitude). The aim is to gain insight into event based movement of sediments and nutrients in the landscape, the hazards which facilitate them and the triggers which induce them.

From this information, a theoretical framework can be used to assist in recognising past catastrophic and extreme erosion–sedimentation events in SCA areas and to assess the potential of future events. Finally, quantification of the volumes of sediment made available via extreme events through on-ground measurement will assist with determining the importance of event based sediment movement in the Special Areas and the likely threat of future catastrophic and extreme erosion-sedimentation events to water quality and quantity.

2. THE IMPORTANCE OF EXTREME EROSION–SEDIMENTATION EVENTS

The importance of large magnitude - low frequency events in the landscape remains an area of debate within the earth sciences. The potential impact of an extreme or catastrophic event in causing significant change in the environment is widely acknowledged, the difference being that the landscape can often recover with difficulty and very slowly after an extreme event, whereas for a catastrophic event the original landscape is obliterated such that it develops from a very different geometry (Brunsden 1996). In this review the term extreme is used and it includes catastrophic events.

Though the impacts of extreme events are large and obvious, there remain attempts to marginalise them in scientific reporting. This marginalisation takes several guises and is most common to those studies that rely on average rates to effect comparisons between different geomorphic regimes and to compare the relative importance of different mechanisms within a system. In this case the approach tends to down play the effect of extreme values. It is also seen in what may be described as the phantom acknowledgment, where the researcher acknowledges the potential role of extreme events but then marginalises them by suggesting that they are not of concern through downplaying the formative conditions: such as the extreme event happened a long time ago and is unlikely to occur again; or is unlikely to occur during the life of the structure; or suggesting that the boundary conditions are different. A less obvious example is the approach of Wolman and Miller (1960) who introduced the term “effective forces” in the landscape i.e. the ability of an event to overcome the prevailing stresses (geomorphic thresholds), which are not spatially or temporarily uniform across the landscape (Schumm 1979). They argued that a catastrophic event, such as a large flood, is not necessarily the critical factor responsible for landform development based on findings that the most effective flow in channels is of moderate magnitude and occurs more frequently than once in two years. This example, translated as low magnitude–high frequency events, has had a major impact on geomorphic thinking and lead to an undervaluing of extreme events.

A workable definition of an extreme event in terms of frequency and magnitude has yet to be fully resolved and this has hindered the development of large event analysis. Brunsden (1996) introduced a classification of events based on hierarchy, frequency, effectiveness, impact, life expectancy on the resulting landscape (Figure 1). Of particular importance is event effectiveness and the concept that an event can be effective, redundant, formative or extreme. It seems likely that over a given period, a landscape will experience numerous events which will fall into each of these categories, depending on catchment characteristics, antecedent conditions and intrinsic or “geomorphic” thresholds (Schumm 1979). Brunsden (1996) argues that the *formative event* is most relevant to landscape development and it occurs at a certain frequency and magnitude. This argument may be considered as similar to the effective channel flow argument put forward by Wolman and Miller (1960). However, it is possible that some landforms are created by extreme events, with very little landscape change in between events, which could span hundreds to thousands of years or more. In this case the extreme event and formative event are the same and are both high magnitude and low frequency.

Identification of landforms created by a single or accumulation of extreme erosion-sedimentation events has yet to be undertaken. Earlier Brunsden and Thornes (1979) suggested the concept of *diagnostic landforms* which includes deposits as well as erosional features that depart from the average, i.e. they have the hallmarks of being unusual in the landscape. But how these unusual landforms are to be recognized has not been resolved. However, at the beginning of an investigation this is not the point. The real significance of the approach developed by Brunsden is that it provides a framework from which to evaluate what are / are not diagnostic landforms. Two examples, pertinent to the project, are used to illustrate this approach: upland swamps and colluvial hillslope mantles.

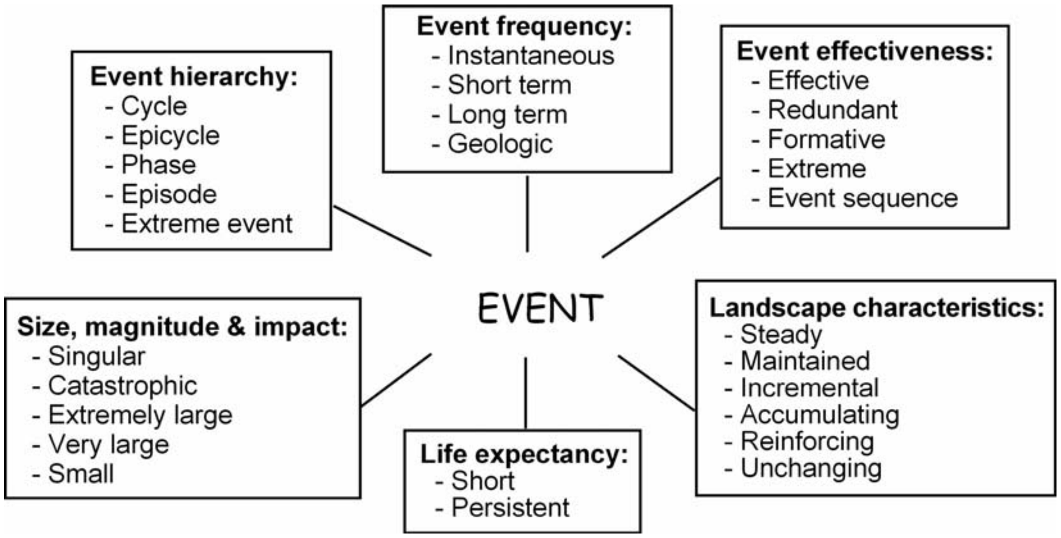

Figure 1. Classification of events according to Brunsden (1996).

3. EVIDENCE IN THE SCA SPECIAL AREAS FOR EXTREME EVENTS: TWO POSSIBLE DIAGNOSTIC LANDFORMS

Two landforms in the SCA Special Areas that are thought to have been formed by extreme erosion and / or sedimentation events are the colluvial hillslopes surrounding the plateau's in the Nattai catchment and the upland (headwater) swamps on the Woronora Plateau (see Figure. 2 for locations). Both sites show unexpected or unusual characteristics compared with observations and previous research on similar types of landforms in southeastern Australia. Hence it is hypothesized that these sites might represent *diagnostic landforms* as proposed by Brunsden and Thornes (1979) and investigations of their morphology could potentially reveal information on the triggers, mechanisms and frequency–magnitude of extreme events.

3.1. Colluvial hillslope mantles in the Nattai catchment

The geology of the Nattai catchment (Rose 1966; Ray 2003) is characterized by cross-bedded quartzose units of the Triassic Hawkesbury Sandstone forming the ridge tops, plateaus, cliffs and upper slopes with remnants of Wiannamatta Shale and Tertiary volcanics capping the higher ridge tops. Underlying the Hawkesbury units are interbedded sandstones and shales of the Triassic Narrabeen Group, which commonly form the mid – lower slopes, and the valley base in Blue Gum Creek, an upper tributary. Permian Illawarra Coal Measures and siltstones, shales and sandstones of the Shoalhaven Group form the lower slopes and valley base in the mid - lower portion of the Nattai River and the lower portion of Little River, a major tributary.

Hillslopes formed on Hawkesbury Sandstone and Narrabeen Group rocks in the Sydney Basin (e.g. Cattai and MacDonald River catchments in the north-west of the Basin) have been described in the literature as being dominated by texture contrast soils (e.g. Chapman and Murphy 1989; Humphreys 1994), which are characterized by a mobile sandy topsoil overlying a clay rich subsoil produced by *insitu* weathering of the bedrock and often a clear stone layer in between (Figure 3a). The dominant processes identified on these hillslopes include weathering, bioturbation and slope wash of finer material (Humphreys and Mitchell 1983; Paton *et al.* 1995).

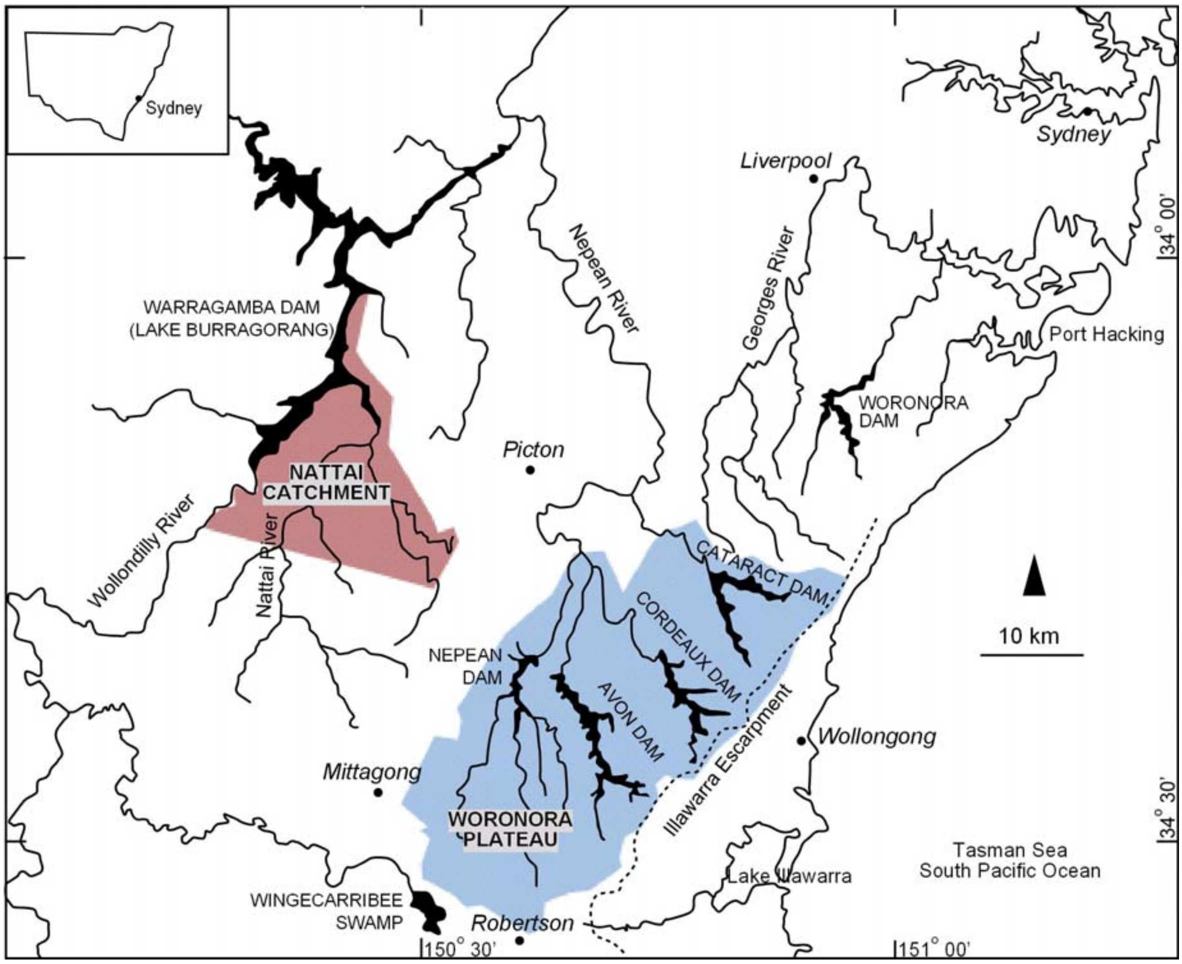

Figure 2. Location of areas to be investigated within the Special Areas in the Nattai catchment (including the foreshores of Lake Burragorang) and Woronora Plateau (shaded).

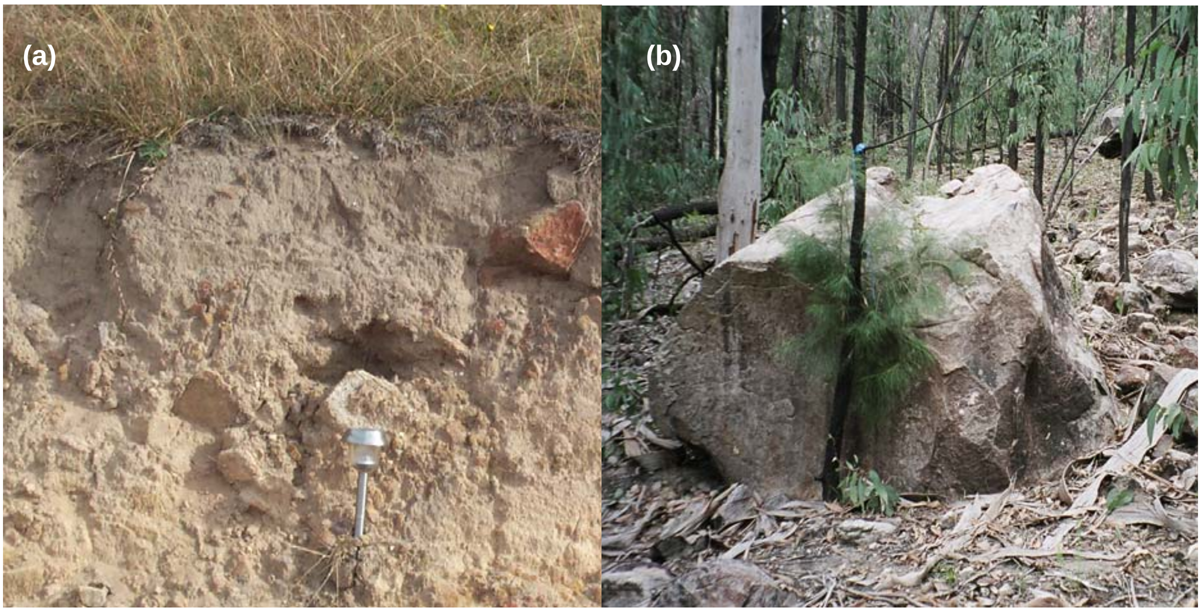

Figure 3a) Typical soil developed on Narrabeen Group rocks. b) Blue Gum Creek hillslope showing the chaotic arrangement of boulders on the surface typical of debris flows.

In contrast, the hillslopes in the Nattai catchment are characterized by coarse gravelly, colluvial mantles which thicken downslope (Tomkins *et al.* 2004b). On the ridge tops, cliffs and steep upper slopes, bedrock outcrops frequently (mostly Hawkesbury sandstone), generating rockfalls and debris flows into drainage lines leading off the plateau (Figure 3b). Occasionally large landslides are encountered (both pre-European and post-European associated with coal mining) whereas previously most landslides have been reported to occur in the Sydney Basin on the Illawarra Escarpment where rainfall exceeds 2000 mm a^{-1} (Walker 1963; Bowman 1974; Young 1977; Young 1978). Gravels armour the surface on the mid slopes but do not form a stone line within the profile and apart from where shale lens' are intersected there is very little evidence of weathering of bedrock. Overall the dominant processes operating on the hillslopes in the Nattai catchment seem to be erosion and mass movement (debris flows, landslides).

The hillslopes in the Nattai catchment clearly differ from the typical hillslopes formed on the same geology in the Sydney Basin, but why this is the case is unknown. The surface expression indicates that the Nattai colluvial mantles are forming through extreme erosion and sedimentation events, so study sites within the catchment such as at Blue Gum Creek have been chosen for detailed investigation to test the event hypothesis and identify the triggers, mechanisms and frequency-magnitude of these events. Research is also being conducted on the amount of bioturbation and slope wash following the 2001 wildfires to determine post-fire erosion rates (Shakesby *et al.* in press).

3.2. Upland swamps on the Woronora Plateau

The notion that upland swamps form by the gradual accumulation of sediments has formed the back-bone of many pollen based studies of swamps (e.g. Mooney *et al.* 1997; Sweller and Martin 2001). Hiatus' in sedimentation (mostly identified through disparities in radiocarbon ages) occasionally have been reported (e.g. Sweller and Martin 2001) but these are generally regarded as a problem in the record rather than as representing something significant in the evolution of the swamp under investigation.

A study by Young (1986a; 1986b) on the distribution and character of upland (or headwater) swamps on the Woronora Plateau provides radiocarbon dates and an example of the stratigraphy of one of the swamps, Drillhole Swamp in the Avon catchment (this swamp has a good exposure of sediments due to gully erosion that occurred in the late 1970's) (Figure 4). The record from Drillhole Swamp indicates disparities in the timing of sedimentation and 3 possible cut and fill events not including the most recent late 1970's event. Furthermore, Young (1986b) provides basal radiocarbon dates for several upland swamps on the Woronora Plateau with ages ranging from 8,470 ± 130 to 16,950 ± 140 years BP indicating a Late Pleistocene - Holocene existence and a possible earlier flushing event if the swamps had formed prior to the Last Glacial Maximum (LGM).

The problem to be addressed is whether these upland swamps develop by the gradual accumulation of sediments (as traditionally believed) or whether they form by episodic depositional and erosional events, as the evidence from Drillhole Swamp suggests. Drillhole Swamp and other eroding swamps on the Woronora Plateau are ideal locations to test the event hypothesis due to the good exposures of sediments and opportunities for detailed interpretation and dating of stratigraphy. From the results, the triggers, mechanisms and frequency-magnitude of events can be determined.

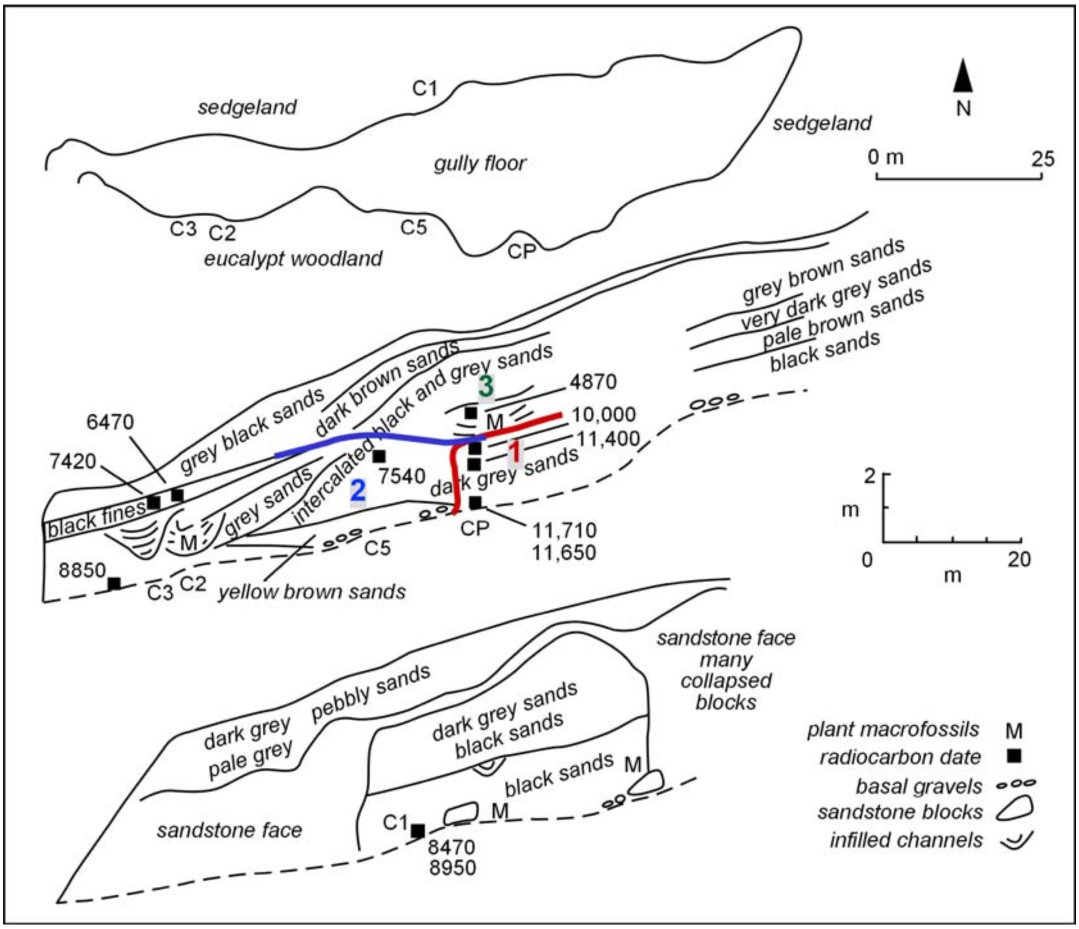

Figure 4. Stratigraphy of Drillhole Swamp (Young 1986a), showing an interpretation of 3 cut and fill events based on radiocarbon ages.

4. METEOROLOGICAL AND GEOLOGICAL HAZARDS IN THE SCA SPECIAL AREAS

The main meteorological and geological hazards identified in the SCA Special Areas are:

- drought
- wildfire
- extreme rainfall
- catastrophic floods
- earthquakes
- subsidence
- land use change (not normally considered a hazard but relevant in this project)

The first four hazards occur frequently in temperate, sandstone environments (Table 1). Prolonged drought is expected to provide a major constraint on water yield and requires evaluation. Other research projects (funded by SCA) are exploring climate variability and likely impacts on yield should be considered by those projects. In particular, the consequence on water yield if there was a return to dry conditions as experienced throughout eastern Australia between the 1920's and late 1940's where precipitation was <75 % of the long term average needs to be investigated. It is known from experience within SCA and other recent research that even modest fires impact on water quality. The question remains as to what might happen in a widespread and intense wild fire. The last to approximate this was the 1968 fire of which there is limited information (see Sydney Catchment Authority 2003) and the existing data have probably not been fully evaluated. Subsequent widespread fires occurred in November 1997 and over the Christmas period in 2001 (Sydney Catchment Authority 2003). Investigations of the 2001 fires by Chafer *et* *al.* (2004) found an inverse relationship between slope and fire severity indicating that the low relief plateau's and valley floors were the most severely burnt. This has implications for post-fire sediment and nutrient generation (Blake *et al.* 2004).

Table 1. Geological and Meteorological Hazards impacting on SCA Special Areas.

Hazard	***Frequency over last 50 years****	***Effect***	***Consequence***
Drought *(slow onset)*	Several, largely ENSO connected	– reduced water yield	– inadequate supply
Fire *(rapid onset)*	Several; usually during dry periods	– widespread post-fire erosion	– decline in water quality
Extreme rainfall *(rapid onset)*	Several, largely ENSO connected	– increased water yield	– very localized to widespread flooding – decline in water quality
Floods *(rapid onset)*	Several with largest event in 1978	– increased water yield	– decline in water quality – possible overtopping of dam wall
Earthquake *(extremely rapid onset)*	534 events recorded but none that triggered failure	– trigger landslides – destabilize structures	– decline in water quality – block channels/rivers – impact on dam wall
Subsidence *(moderately rapid onset)*	Widespread due to mining, but develops over time	– local ground lowering – fracturing of ground & rock	– divert drainage – drain swamps – reduce short term yield
Catchment clearing (deforestation, urbanization) *(slow onset)*	Varies from very little to considerable	– increased runoff during storm events – increased erosion – increase in pollutants	– increase variability in supply – decline in water quality

*Events are those that have not occurred during since the construction and commissioning of Warragamba Dam *c.* 1960 and for convenience is regarded as approximately the last 50 years. Frequency does not apply to the last two since they tend to be one off at a location but their effects may intensify over time.

A similar situation occurs with extreme rainfall events which are known to impact on water quality. What happens after extreme runoff events? Is the impact on water quality vastly greater than numerous small runoff events? Large magnitude rainfall events have been recorded around the catchment within the last 50 years e.g. 189 mm at the Nattai causeway on 22 March 1983, yet there does not appear to have been any quantification of the input of sediment compared with storm intensity and magnitude. Catastrophic floods are another hazard in the catchment and the discovery of high level slack-water deposits in the Fairlight Gorge, downstream of Warragamba Dam provides evidence of a palaeoflood occurring at around 4 ka years BP which peaked at least 8 m higher than the largest flood on record (1867) (Saynor and Erskine 1993). Erskine and Saynor (1996) found that catastrophic floods occurring on rivers with high flood variability in southeastern Australia generated between 11 - 283 times the mean annual sediment yield, through erosion of sediment stored in the channel bed and floodplains.

The next hazard earthquakes, are less recognized although data from the Geoscience Australia earthquake database shows that a total of 541 earth movements of between 0 – 9.99 magnitude have been recorded in the Warragamba area (-33.5° to -35° S; 150° to 151° E) since 1872 (Figure 5). Earth movements may trigger slope failures where sediments are close to the threshold angle of stability (Summerfield 1991) or where structural characteristics of the lithology such as vertical joints promote dislodgement of blocks and rockfall. Subsidence, which is demonstrably associated with underground coal mining, is widespread (Cunningham 1988) but the full impact has yet to be assessed.

The last hazard, catchment clearing involves the replacement of woodland and forest with a range of land uses including pasture, cultivation, urban settlement and tree plantations. Like drought this type of hazard is normally described as slow to take effect (slow onset) but it differs dramatically in its effect. Within southeastern Australia clearance has sometimes led to a recognizable effect within a few decades but in other catchments there is a delayed response that may exceed a century.

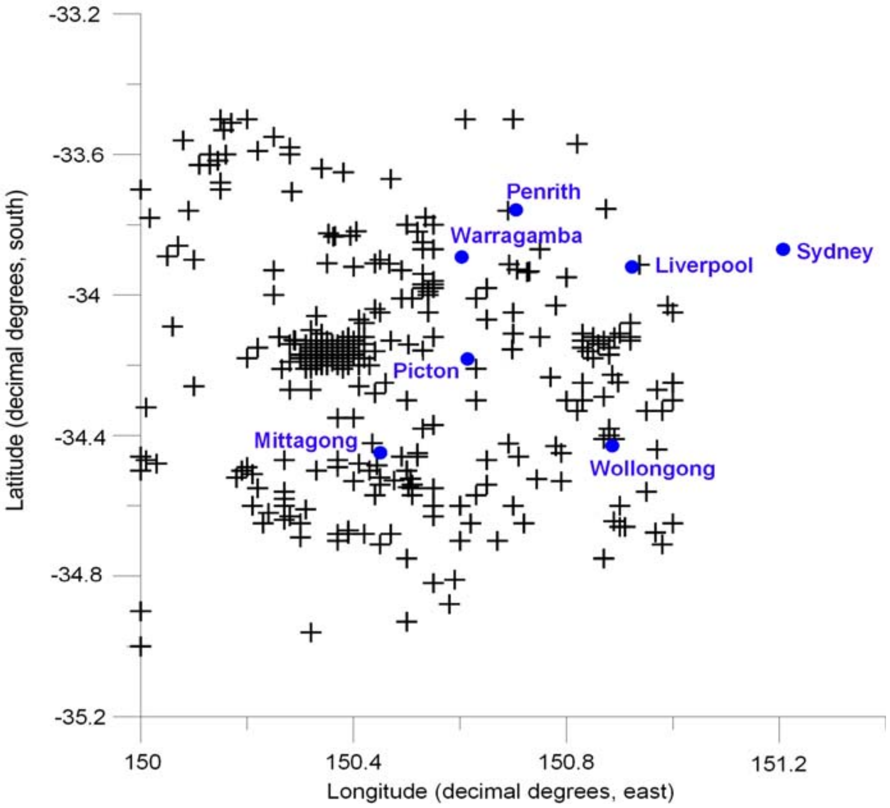

Figure 5. Distribution of earthquakes recorded between 33.5° to 35° S and 150° to 151° E. (Source: Geoscience Australia earthquake database)

5. TRIGGERS OF EXTEME EROSION AND SEDIMENTATION EVENTS

Previous research on extreme erosion and sedimentation events in southeastern Australia and elsewhere has identified fire, severe storms, intrinsic thresholds and earthquakes as central triggers. All of these hazards exist in the SCA Special Areas so a review of each is relevant to the project. In many cases, a combination of triggers has been reported such as fire followed by severe storms, which indicates that the relationship between events and response might be complex and not easy to predict. Each trigger is discussed below in this context with an emphasis on the main issues arising from the literature.

5.1. Erosion following wildfire

Increased erosion

The impacts of wildfire on vegetation, soils and catchment hydrology has been widely reported in Australian and overseas (e.g. Brown 1972; Vertessy 1984; Prosser and Williams 1998; Legleiter *et al.* 2003; Shakesby *et al.* 2003). In particular, many studies have focused on post-fire runoff and erosion via overland flow. For example, Atkinson (1984) found soil losses of 0.17-1.4 t ha^{-1} in response to individual storm events following the 1983 fires in the Royal National Park, Sydney, whilst Blong *et al.* (1982) found post-fire sediment yields of 2.5 – 8 t ha^{-1} y^{-1} following fires at Narrabeen, Sydney, in 1979. Prosser and Williams (1998) proposed a model of post-fire runoff and erosion (Figure 6) which describes an increase in susceptibility to erosion immediately following fire depending on fire intensity and the magnitude of runoff events, with the exponential return to pre fire conditions with time. This model, produced for fire prone bushland near Sydney, is supported by results of several studies (Figure 6) as compiled by Humphreys (1985, in Paton *et* *al.* 1995). Both Brown (1972) and Benavides-Solorio and MacDonald (2001) report the return to pre-fire conditions within 6 years of fire and this is consistent with the trend in Figure 6. Though Scott (1993) and Prosser (1990) have recognized that fire intensity plays a key role in determining erosion potential there is insufficient data to explore this effect in terms of erosion.

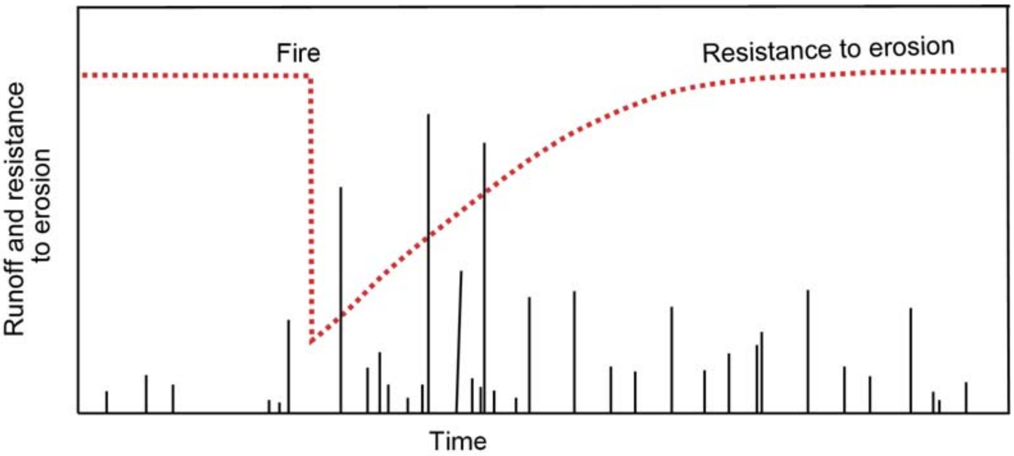

Figure 6. Model of the impact of fire on runoff and resistance to erosion (Prosser and Williams 1998).

Shortcomings with most of the studies investigating erosion following wildfire, however, is the short time frame over which observations are made (mostly less than 12 months), the lack of replication of the study (no investigation of successive fires), the failure to place the individual fire event in context with the prevailing conditions, and finally, the failure to measure rates of erosion between fire events i.e. does fire truly trigger extreme erosion or are other triggers more important. Several studies (e.g. Good 1973; Blong *et al.* 1982; Prosser and Williams 1998) have commented on dry or drought conditions in the year(s) following wildfires and used this as an explanation for lower than expected runoff and erosion. However, no study appears to have analysed fire events in terms of antecedent conditions and past events (i.e fire history). The reality is that erosion levels in the post-fire period are higher and reduce as recovery takes place. The perception is that erosion levels would be much greater if wetter conditions prevailed (e.g. Zierholz *et al.* 1995; Prosser and Williams 1998; Shakesby *et al.* 2003). It is recognition of this problem that led to the model representation of Prosser and Williams (1998) where they highlight the potential for erosion through decreased resistance (Figure 6) rather than actual erosion (Figure 7).

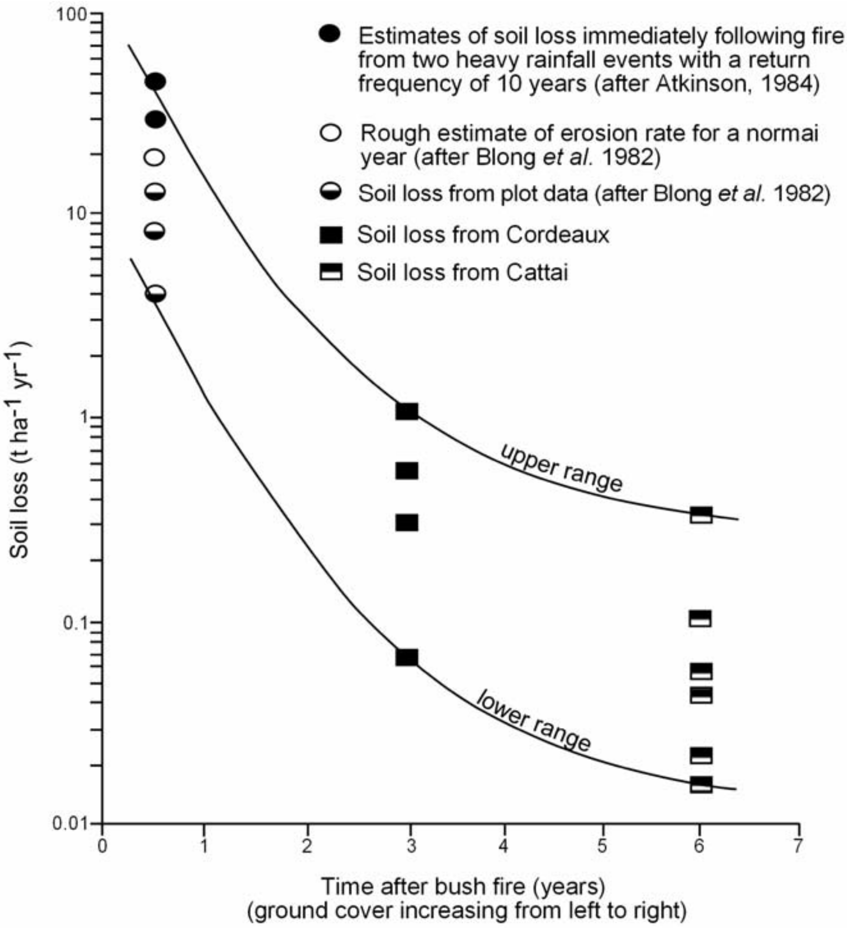

Figure 7. Post-fire erosion on modest slopes on sandstone (Paton *et al.* 1995) showing that erosion levels in the year following fire are two to three fold greater than erosion 3 - 6 years after fire. Various corrections were required to standardize data obtained from different studies.

Runoff following wildfire

Another issue identified in the literature is post-fire hydrology and the impact of fire on runoff velocities and stream discharge. An increased peak discharge from burnt areas in the immediate post-fire period has been widely reported (e.g. Brown 1972; Mackay and Cornish 1982; Scott 1993; Pierson *et al.* 2001) and is generally accepted. This peak discharge occurs despite the drier conditions that often occurs in the post-fire period. However, other effects have been noted too. One of the most intriguing is the observation of Brown (1972) who recorded a sharp secondary peak in discharge preceding a return to a more normal rounded peak following the 1965 fires in the Snowy Mountains NSW (Figure 8). He attributed the secondary peak to the direct effect of increased runoff from severely burnt areas, with the normal rounded peak representing runoff from unburnt areas. There has been no other observation of this effect in the more recent studies (e.g. Prosser and Williams 1998) but this may be due to the lack of continuous data recording (as against recording discharge at time intervals). More recently, Moody and Martin (2001) have suggested that a sensitive hydrological indicator of the post-fire rainfall-runoff response is unit-area peak discharge (Q_u) (expressed as peak discharge divided by area burnt), relative to maximum 30 minute rainfall intensity (I_{30}). They found a change in slope in the rainfall-runoff relationship in burnt catchments suggesting a threshold of rainfall intensity, above which the magnitude of flood peaks increased. It seems likely that increasing rainfall intensity will have a corresponding impact on runoff velocities and sediment entrainment (erosion). Indeed Blong *et al*. (1982) found that at low rainfall intensities following fire the organic matter (leaves and charcoal) were flushed first leaving quartz sand behind, but at high intensities (e.g. I_{30} of 41 mm hr^{-1}) a high proportion of quartz sand to 0.4 mm mode was mobilised. This raises the issue of a rainfall-runoff-erosion relationship, which has not been specifically addressed in the post-fire literature. However, it was observed by Wasson (1994), who found that unchannellised hillslopes have the highest spatial variance of sediment yield due to correlations between rainfall, erosion and runoff rate.

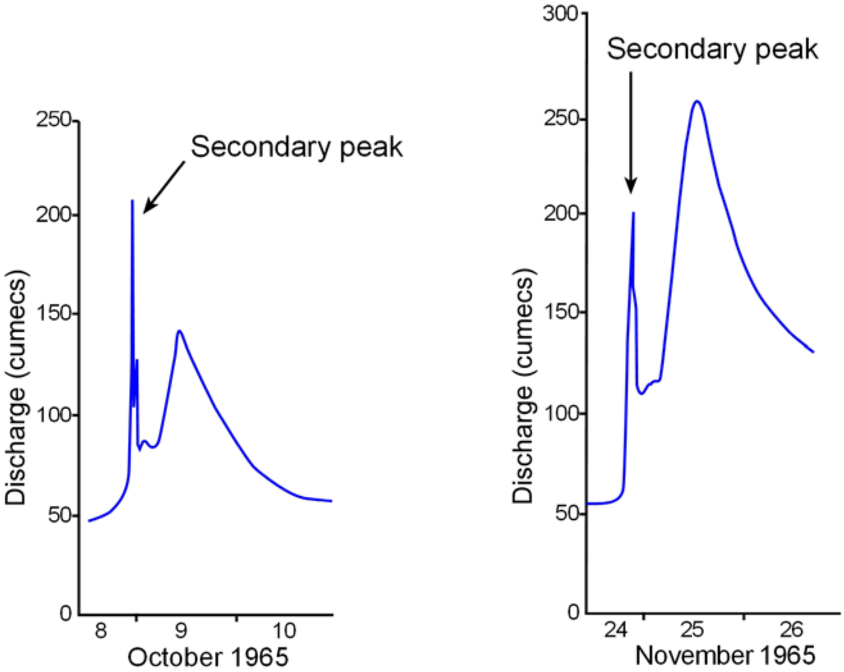

Figure 8. Hydrographs of the Yarrangobilly River at Hospital Flat following wildfire in March 1965, showing a sharp secondary peak in discharge caused by runoff from burnt areas preceding a more normal rounded peak representing runoff from unburnt areas (Brown 1972).

Mass movement following fire

Extreme erosion events, even localized ones following wildfire such as landslides and debris flows, do not appear to have been reported in the literature. Shakesby *et al*. (2003) point out that no mass movement events occurred following the 2001 fires in the Nattai catchment, near Sydney, even though their study sites displayed evidence of mass movement in the recent past (Tomkins *et al.* 2004a). More specifically, the dating of debris flows and landslides in Chapparal terrain (western USA) found that the recurrence interval of fire was an order of magnitude less than the recurrence interval of large debris flows (Keller *et al.* 1988; Florshiem *et al.* 1991). This finding was interpreted as discounting fire as a prime trigger for these mass movement events. However, it could also be interpreted as fire being just one of several possible mechanisms.

Synthesis of fire effects on erosion

In general it seems that erosion following fire coupled with moderate to high intensity storm events is confined to local redistribution of coarse sediment downslope (Prosser and Williams 1998), with finer material and organics flushed further into and along drainage lines (Blong *et al.* 1982; Atkinson 1984; Zierholz *et al.* 1995; Shakesby *et al.* 2003). This raises the issue of the role of fire intensity in erosion events: Does fire enhance erosion or is it a trigger of erosion and how does rainfall intensity interact with burn intensity to generate runoff and erosion? Figure 9 expresses the latter part of this question on a threshold basis and provides a framework for future research.

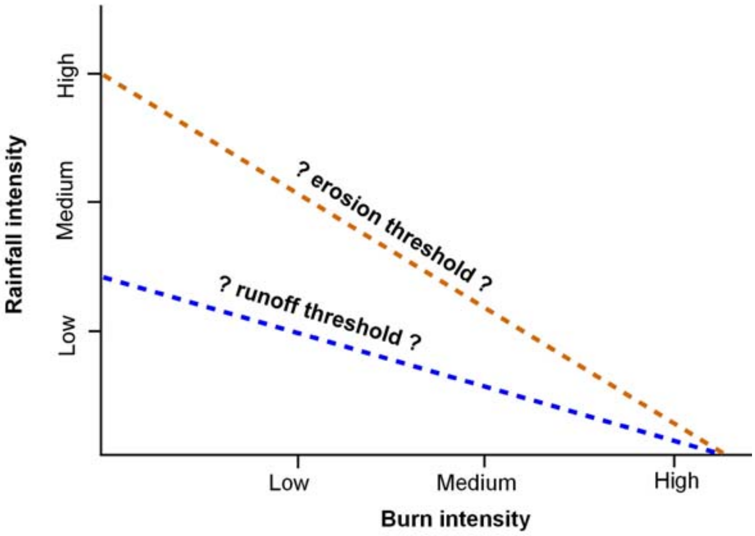

Figure 9. Hypothesised relationship between rainfall intensity and burn intensity, and triggers for runoff and erosion.

5.2. Erosion following severe storms

Mass movement events following severe storms has been widely reported overseas such as in New Zealand (e.g. O'Loughlin *et al.* 1982), and the USA (e.g. Swanson and Dyrness 1975; Renwick 1977) but rarely in Australia. Reinfelds and Nanson (2001) provide an analysis of a storm event in August 1998 which struck the Wollongong area following 400 mm of rainfall in 47 hours. The storm resulted in debris flows and hyperconcentrated flows that entrapped material mostly scoured from stream beds and to a lesser degree from colluvial slope failures. During the storm, 60 minute rainfall intensities exceeded 120 mm h^{-1} on the Illawarra escarpment, with a total rainfall of 249 mm over 3.5 hours (i.e. 71 mm h^{-1}). Debris flows were also recorded in northeast of Victoria following a storm event in 1993 (Rutherford *et al.* 1994). These debris flows were most common on the steeper (> 25°), more resistant rocks (mainly acid volcanics) where rainfall intensity reached approximately 50 mm hr^{-1} (recurrence interval exceeded 50 years). The debris flows removed soil and weathered rock from slopes depositing the debris as alluvial fans in creeks and across the floodplain.

A recurring theme in many reports is to relate the amount of erosion to wetness parameters such as total rainfall of the event and/or rainfall intensity, which attempt to capture the antecedent conditions at the time of the event and also serve as a proxy for soil saturation and increased pore water pressure and thus reduced soil strength to below shear stresses. Event analysis of this type lends itself to determining the recurrence interval of erosion generating events. Not surprisingly, however, a wide range of combinations is reported. Thus, Swanson and Dyrness (1975) found that landslides were triggered in Oregon, USA, by severe storms with a low recurrence interval down to 4 - 5 years in which the storms produced more than 300 mm of rainfall over 4 days. In contrast, Renwick (1977) found that a storm of intensity of 95 mm h^{-1} with a recurrence interval of 10 - 70 years was required to triggered landslides in New York State, USA. Many other examples are provided in texts such as Selby (1993) and collectively this serves to show that the few Australian examples fit this global pattern. In brief, threshold conditions appear to vary in terms of catchment topography (relief, steepness and curvature), lithology (the generation of erodible material, and the potential for failure plane development), and rainfall conditions leading up to the point of failure as well as transport efficiency post-failure. To date, however, these factor-based parameters have yet to be combined into a predictive model outside of the terrain the data was obtained from.

5.3. Erosion following earthquakes

Severe erosion following earthquakes is widespread in plate margin terrain such as Japan and New Zealand (e.g. Selby 1993). Not surprisingly the effect is much greater when coupled with heavy rain. In Taiwan, for example, landslides and debris flows are prominent in areas of weak lithology following an earthquake and a cyclone (typhoon) whereas the response to smaller yet localized rainfall and runoff was minimal (Dadson *et al.* 2003). In this setting high erosion rates depend on this coupling, which occurs decadally.

It may be possible that movement along the Lapstone Structural Complex (LSC) which includes the Lapstone Monocline and a series of faults to the west of Sydney (Branagan and Pedram 1990) could also trigger a similar erosion-sedimentation response particularly where the zone of movement coincides with steep upper and middle valley sidewalls formed of more weathered Triassic and Permian rocks (Bryan 1966; Rose 1966). Such movement has also been proposed to account for the formation of Thirlmere Lakes, an unusual landform located in the Nattai catchment. Fanning (1982) suggested that upwarping along an axis to the south of the LSC truncated the headwaters of the lakes and triggered infilling and therefore linked this event to the Lapstone Monocline. Bishop *et al*. (1982) place an age on the monocline as 15 ± 7 Ma, but more recent work indicates that faulting may have extended into the Quaternary (Pickett and Bishop 1992). Certainly, seismic movement has been measured in the area since European settlement (Figure 5), the most recent of which was a mild earthquake measuring 4.2 on the Richter scale that occurred in the Southern Highlands on 11 December 2003 and a smaller movement measuring 2.5 on the Richter scale that occurred at Narellen in the south-west of Sydney on 29 December 2004 (Geoscience Australia earthquake database). It is likely that more severe earthquakes associated with deep seated basement adjustments (Branagan and Pedram 1990) could trigger mass movement events in this region.

5.4. The role of intrinsic thresholds in triggering erosion and sedimentation

Erosion and sedimentation events occur when an intrinsic (geomorphic) threshold is exceeded even without the influence of an external event such as fire, storms or earthquakes. Schumm (1979) argues that these thresholds are developed within geomorphic systems by changes in the morphology of landforms with time. For example, an increase in valley floor slope may be sufficient to initiate a phase of incision (i.e. the flow velocity stresses exceed the threshold angle of stability of the material (e.g. Leopold *et al.* 1964; Summerfield 1991)). A common example is where flow velocity exceeds a critical threshold and erosion occurs rather than deposition. For example, Young (1986b) argues that erosion of upland swamps on the Woronora Plateau is governed by intrinsic thresholds. She prefers a scenario whereby vegetation removal by fire combined with declining water tables (e.g. during drought) leads to episodic flushing of sediment to bedrock. Sediments then gradually re-accumulate. Another example of this form of explanation is applied to the landslide activity on the Illawarra escarpment. Young (1978) suggests that the average excess of rainfall over evaporation is conducive to the gradual build-up to high pore water pressures in the weathered mantle especially at the boundary with solid bedrock. This explanation was offered as a counter to the storms event approach noted in a preceding section. However, it is more likely that a continuum exists such that the different views represent different end points and that it is the timing of the response (erosion event) in relation to the speed of change in the build-up of water that provides a clearer understanding.

As noted elsewhere, it is inevitable that geomorphic thresholds will play a key role in landform change and that the breaching of thresholds by stresses will create positive and negative feedbacks in the landscape (Summerfield 1991). Thus the issue is whether intrinsic thresholds are sufficient enough to trigger the shift from the stable to unstable state. Schumm (1979) comments that some landforms are inherently unstable and require no external triggers for landform change e.g. alluvial fans, whereas other landforms, such as bedrock plateaus persist in the landscape and are likely to be unaffected even by large events. Consideration of thresholds as triggers for erosion and sedimentation events should be foremost. Returning to the rationalization offered in Figure 1 the formative events may be regarded as those that are controlled by intrinsic thresholds whereas the extreme events are triggered by high magnitude but rare sequences of external events.

6. THRESHOLDS AND MECHANISMS FOR MASS MOVEMENT OF MATERIALS

Mass movement of materials occurs when the frictional resistance or shear strength (dn cm^{-2}) of unconsolidated material (including weathered bedrock) is exceeded by gravity induced forces (Selby 1993). The type of mass movement event is determined by the failure mechanism, moisture content (and hence density), the type of material involved and the scale of the event. With increasing water content, and hence a reduction in sediment load and bulk density, debris flows (and mud or earth flows) may change to be hyperconcentrated flows before eventually becoming water floods (Costa 1984, Figure 10). Large rock falls may become rock avalanches if the event takes on the flow/slide mechanics of a snow avalanche. Translational slides tend to occur where the underlying rock is not deeply weathered and the lower boundary is a tilted bedding plane, whereas rotational slides extend into deeply weathered rock and hence tend to be deeply seated and larger. Ultimately the potential size of a mass movement event and the distance debris is transported down slope is governed by slope height and slope angle at both the point of failure and along the downslope pathway (Brunsden and Thornes 1979, Figure 11). Failure of materials occurs when the threshold angle of stability is exceeded (Summerfield 1991) which, as noted in previous sections, may be due to intrinsic geomorphic instability or the impact of an external event such as a severe storm (Schumm 1979). The former is normally manifested by a gradual increase in load via the accumulation of material including the biomass as occurs when vegetation recovers from an earlier disturbance event. The later is the more commonly cited explanation and the resulting increases in pore water pressure effectively leads to a lifting of the soil and biomass away from the basement.

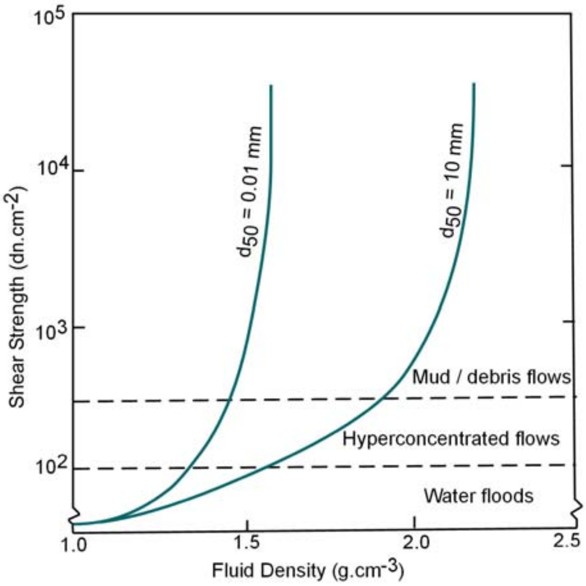

Figure 10. Thresholds which determine fluidized mass movement processes (after Costa 1984).

Debris flows on hillslopes commonly originate when intense rainfall follows antecedent rainfall resulting in increased pore water pressure and a corresponding decrease in shear strength (as soil particles loose coherency and change from a solid mass to a viscous fluid), leading to a slide or slump failure (O'Loughlin *et al.* 1982; Costa 1984). Hence the frequency of flows is determined by rainfall and sediment availability (i.e weathering) which can vary from years to hundreds or thousands of years recurrence interval (Costa 1984). Shallow debris flows, avalanches and slumps have been reported in the North Wollongong area at the face of the Illawarra escarpment where slopes exceed 30° (Young 1977) and rainfall intensity has been reported as high as 158 mm hr^{-1} (Reinfelds and Nanson 2001). Rock fall is common from the uppermost Hawkesbury Sandstone unit, whilst mass movement on the upper, mid and lower slopes often occurs at the boundary of weathered claystone members in the Narrabeen and Permian rocks (Young 1977).

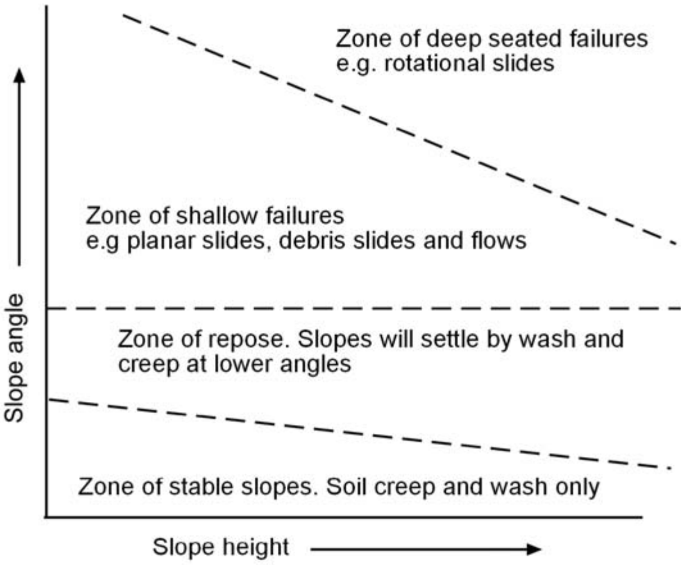

Figure 11 Impact of slope on mass movement processes (Brunsden and Thornes 1979).

Most studies on upland swamps provide only a cursory examination of the mineral sediment and its mode of emplacement, instead concentrating on the pollen record (e.g. Lloyd and Kershaw 1997; Harle *et al.* 1999). However, in many cases the sedimentary record in upland swamps shows a change from sands (or sandy clays) in the base to overlying peat (Young 1986a; Kodela and Dodson 1989; McKenzie and Kershaw 1997) yet the origin of this sandy basal unit is rarely commented upon. It may be likely that the deposition of the sands (and sandy clays) is by mass movement events or at least as distinct erosion–sedimentation events (cut and fill). Evidence of cut and fill is shown in the stratigraphy and age of sediments at Drillhole Swamp on the Woronora Plateau (Young 1986a) (Figure 4). Alternatively, deposition of the coarser material may be related to the formation of the swamp itself. For example, Vorst (1974) accounts for alternating sand and clay layers in Thirlmere Lakes as alluvial fan deposits from hillslopes and lake deposits respectively, deposited under fluctuating lake levels. A detailed analysis of the stratigraphy of upland swamp deposits is warranted to shed light on the processes and rate of movement of materials into and out of them. Upland swamps in particular have the advantage of being close to sediment source (bedrock outcrop and weathered material) meaning that movement of material from the adjacent slopes should reflect catchment conditions at that time.

7. FREQUENCY–MAGNITUDE OF EXTREME EVENTS

The frequency–magnitude relationship of erosion–sedimentation events is important as it can be used to predict the likelihood of those same events re-occurring in the future, assuming climatic conditions remain the same. As alluded to in the previous sections of this review, the frequency–magnitude relationship of an erosion–sedimentation event appears to be linked to the frequency–magnitude of the external trigger(s) i.e. frequency and severity of wildfires or rainfall events. Under much wetter climates, high rainfall events may occur more frequently than during drier climates, and visa versa for wildfires. The frequency–magnitude approach, however, implies a somewhat cyclical or repeated pattern of events, which may or may not be appropriate given the importance of the coupling of triggers as a likely control on event based movement. Presumably an increase in the frequency of an event trigger also increases the chances of coupling with another event trigger and this will enhance the probability of an erosion–sedimentation event occurring if they reinforce one another. Nevertheless, the relative frequency of high magnitude events can be put into the context of prevailing long term climates (Pleistocene and Holocene timeframes) and whether they are likely to occur or not under those same conditions, with estimations of recurrence intervals based on the ages of past events.

7.1. Climates in southeastern Australia during the Late Pleistocene and Holocene

During the Late Pleistocene at around 21 ± 3 ka years BP (LGM) much of the higher country in Tasmania and in the Snowy Mountains, NSW was glaciated indicating regional surface cooling (Barrows *et al.* 2002) of around 9° C below the average Holocene temperature (Jouzel *et al.* 1987). Periglacial activity extended down to 1100 m elevation in the Snowy Mountains (Barrows *et al.* 2001). The drier, cooler conditions combined with lower atmospheric carbon dioxide (Barnola *et al.* 1987; Cowling and Sykes 1999) influenced vegetation patterns and during the LGM much of the highland areas in southeastern Australia were characterized by a treeless alpine grassland (Sweller and Martin 2001). Cooler conditions probably extended over much of the Australian continent and certainly to the north of the Snowy Mountains into the Southern Tablelands and beyond. For example, sand dunes on the Newnes Plateau, Blue Mountains and in the mid-upper region of the Shoalhaven catchment, NSW were active during the LGM due to sparse vegetation cover and removal of forests (Nott and Price 1991; Hesse *et al.* 2003).

The deglacial period that followed the LGM from about 15 ka years BP to around 11 ka years BP was characterized by a period of warming (Jouzel *et al.* 1987). The dunes on the Newnes Plateau and in the Shoalhaven catchment stabilized (Nott and Price 1991; Hesse *et al.* 2003) and canopy species returned to the former treeless upland areas (Sweller and Martin 2001). From radiocarbon dates it appears that this was the time of major swamp development across southeastern Australia (e.g. Dury and Langford-Smith 1968; Stockton and Holland 1974; Young 1986a; Young 1986b; Kodela and Dodson 1989) although a few swamps were in existence during the LGM or earlier (e.g. Sweller and Martin 2001). A final period of rapid warming and an increase in precipitation marked the end of the Pleistocene deglacial and beginning of the Holocene (Rognon and Williams 1977).

The Holocene period which extends from 10 ka years BP to the present has been generally thought of as being climatically stable (Bowler *et al.* 1976), with maximum warming at 9 ka years (Jouzel *et al.* 1987). The evidence from the vegetation suggests warmer, wetter conditions with the expansion of cool temperate rainforest across southeastern Australia during the Early Holocene (Singh and Luly 1991; Dodson and Thom 1992; Dodson and Ono 1997). Deposition of peats in swamps during the Mid Holocene provides more support for wet conditions (Rognon and Williams 1977; Sweller and Martin 2001) however, in the Late Holocene, sclerophyll dominated forest expanded in the Sydney Region and elsewhere indicating drier conditions (Rognon and Williams 1977; Singh and Luly 1991; McKenzie and Kershaw 1997) and/or an increase in fire in the landscape (Dodson and Thom 1992).

7.2. Evidence for extreme erosion–sedimentation events during the Holocene in SCA Special Areas and indicative frequency of these events

The absolute age of a landform such as a swamp or hillslope is difficult to determine with certainty, primarily because of gaps in the preserved record. The upland swamps on the Woronora Plateau are a good example of this since the basal dates of the swamps indicate the timing of infilling with those sediments and not necessarily the timing of swamp initiation. Older sediments may exist but have not been dated, or older sediments may have been removed by prior erosion events, or there may have been a lag in sediment accumulation of hundreds to thousands of years. The best way around this is to employ multiple dating of several sections at one swamp. The only local example that satisfies this requirement is Drillhole Swamp on the Woronora Plateau (Young 1986a) which suggests 3 cut and fill events during the Late Pleistocene – Holocene (Figure 4). The first, a cutting event to bedrock pre – 12 ka years BP followed by rapid infilling with sands and clayey sands. The second, a cutting event to bedrock at around 9 – 10 ka years BP followed by infilling with sands, clays and organics, then development of peats at around 7.5 – 6.5 ka years BP. A third cutting event, but not to bedrock, appears to have occurred between 6.5 – 4.5 ka years BP interrupting the peat development through lowering of the water table (peat development continues in the adjacent swamps at the present suggesting that these swamps were not eroded by the same event). Post 4.5 ka years BP, sands, clays and organics were deposited within the erosion channels and over the peat to form a hummocky surface with sands infilling the depressions.

The indicative frequency of events at Drillhole Swamp is in the order of magnitude of thousands of years under present climatic conditions (Holocene). This means that future events are likely to happen and indeed, SCA catchment staff report that some of the other swamps on the Woronora Plateau have started eroding within the last few years with no obvious human disturbance. The triggers of these erosion–sedimentation events are unknown, but will be investigated as part of the project. Fire has been put forward as a likely trigger but this review, supported by recent results from a study of the post-2001 fire sediment and nutrient movement by slope wash and bioturbation at Blue Gum Creek (Shakesby *et al.* in press) along with work at the site using mineral magnetics (Blake *et al.* 2004) has shown that fire (followed by reasonable rainfall events) results in only localized sand-sized sediment redistribution slopes. Additionally, the return period of fire is in the order of years to tens of years whereas the swamp record shows accumulation of sediments over thousands of years. Other triggers need to be investigated to explain the cut and fill events in Drillhole Swamp along with an assessment of the likelihood of erosion triggered by exceeding intrinsic thresholds, which is argued by Young (1986a; 1986b).

Evidence for extreme erosion–sedimentation events at the Blue Gum Creek site has come through a preliminary investigation of the stratigraphy of the hillslope from the upper slopes to the valley floor (see Tomkins *et al.* 2004b). The site shows a gravelly colluvial mantle on the upper, mid and lower slopes, fluvial sediments in the valley floor and intermixed deposits on the foot slopes. Four radiocarbon dates were obtained from specific locations on the hillslope to indicate the timing of movement of sediments down the slope and deposition in the valley floor. The results indicate that sedimentation on the hillslope and in the valley floor (to bedrock) occurred during the Mid - Late Holocene (< 6 ka radiocarbon years BP) (Tomkins *et al.* 2004a). One of the radiocarbon dates was taken from below a large sandstone boulder perched within a gully on the hillslope to indicate the timing of a possible rockfall event, c. 1.4 ka years BP. A further two radiocarbon dates indicated older Late Pleistocene and Early Holocene deposits (14 – 10 ka years BP) preserved at the left valley margin. Combined, the dates provide evidence for a cutting event in the valley between the Early – Mid Holocene (c. 10 ka – 6 ka years BP), followed by at least 3.5 m of infilling with fluvial and intermixed sediments, along with movement of sediment down the slopes sourced from the cliffs and plateau above.

The indicative frequency of cutting events at the Blue Gum Creek site appears to be in the order of tens of thousands of years, whereas movement of sediment down the hillslope by rockfall and debris flows seems to be much more frequent, occurring at intervals of hundreds to thousands of years. The implications of frequent mass movement on the slopes, is the rate of sediment supply from cliff retreat and plateau denudation, and the realisation that this sediment must be flushed from the valleys (i.e. towards the reservoirs) at rates similar to movement on the slopes in order to prevent the valleys becoming chocked with sediment. Additionally, the same processes would be occurring on the slopes adjacent to the water supply reservoirs however, the potential for sediment storage on these slopes is minimal as the lower slopes and valley floor are under water. This situation was observed between the 1960's – 1980's when a series of mining induced landslides occurred at the North Nattai coal mine adjacent to Lake Burragorang, one of which reached the reservoir waters (Cunningham 1988). Such events have occurred prior to construction of the dam. For example, an older landslide (pre- European) which crossed the Nattai River, was discovered during recent reconnaissance investigations of the area. Under normal storage levels this landslide would be covered by water. A similar event occurring today into an > 80 % capacity storage would result in major impacts to water quality and perhaps threaten the structural integrity of the dam wall should a surge wave result.

8. CONCLUSIONS AND PROJECT IMPLICATIONS

Many landforms are formed by event based erosion and sedimentation processes, yet very little is known about the characteristics, triggers, mechanisms and frequency-magnitude of these events. Diagnostic landforms such as hillslopes and upland swamps can be used to analyse mass movement of materials such as landslides and debris flows, along with episodes of cut and fill. Study sites have been chosen within the Nattai catchment at Blue Gum Creek (hillslope) and on the Woronora Plateau (upland swamps) to investigate extreme erosion and sedimentation events and build on previous work in these areas (Young 1986a; Young 1986b; Shakesby *et al.* 2003; e.g. Blake *et al.* 2004).

A variety of triggers for extreme erosion and sedimentation events has been reported in the literature including wildfire, storms, intrinsic thresholds and earthquakes. Whilst is it clear that they are all potential triggers, the conditions (or coupling of triggers) which lead to extreme erosion and sedimentation events have not been specifically identified, for example, the rainfall–runoff-erosion relationship. There is a need to analyse wildfires in terms of prevailing conditions, fire history and fire intensity in order to gain a good understand of the role of fire and to determine if fire has a triggering or enhancing effect on erosion. Similarly, the hydrological response to storms needs to be analysed to determine runoff and erosion thresholds velocities for different rainfall intensities and if high intensity storms are sufficient to saturate soils and trigger debris flows. Additionally, intrinsic thresholds need to be considered before invoking external triggers.

The implications of the project for management of the Special Areas are many. Previous work at Drillhole Swamp and Blue Gum Creek has provided evidence for event based movement of sediments during the Holocene. These extreme erosion–sedimentation events are likely to continue under the present climatic conditions, however, when and where they will happen in the future cannot be determined with absolute certainty, and even so little can be done to prevent or stop them. Instead awareness of the triggers of extreme events, the mechanisms by which sediment is moved and the likely return periods of events will assist with determining the potential threat of an extreme erosion–sedimentation event to water quality and quantity. This knowledge can then be translated by SCA staff into contingency arrangements to ensure a clean and adequate water supply for Sydney residents.

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