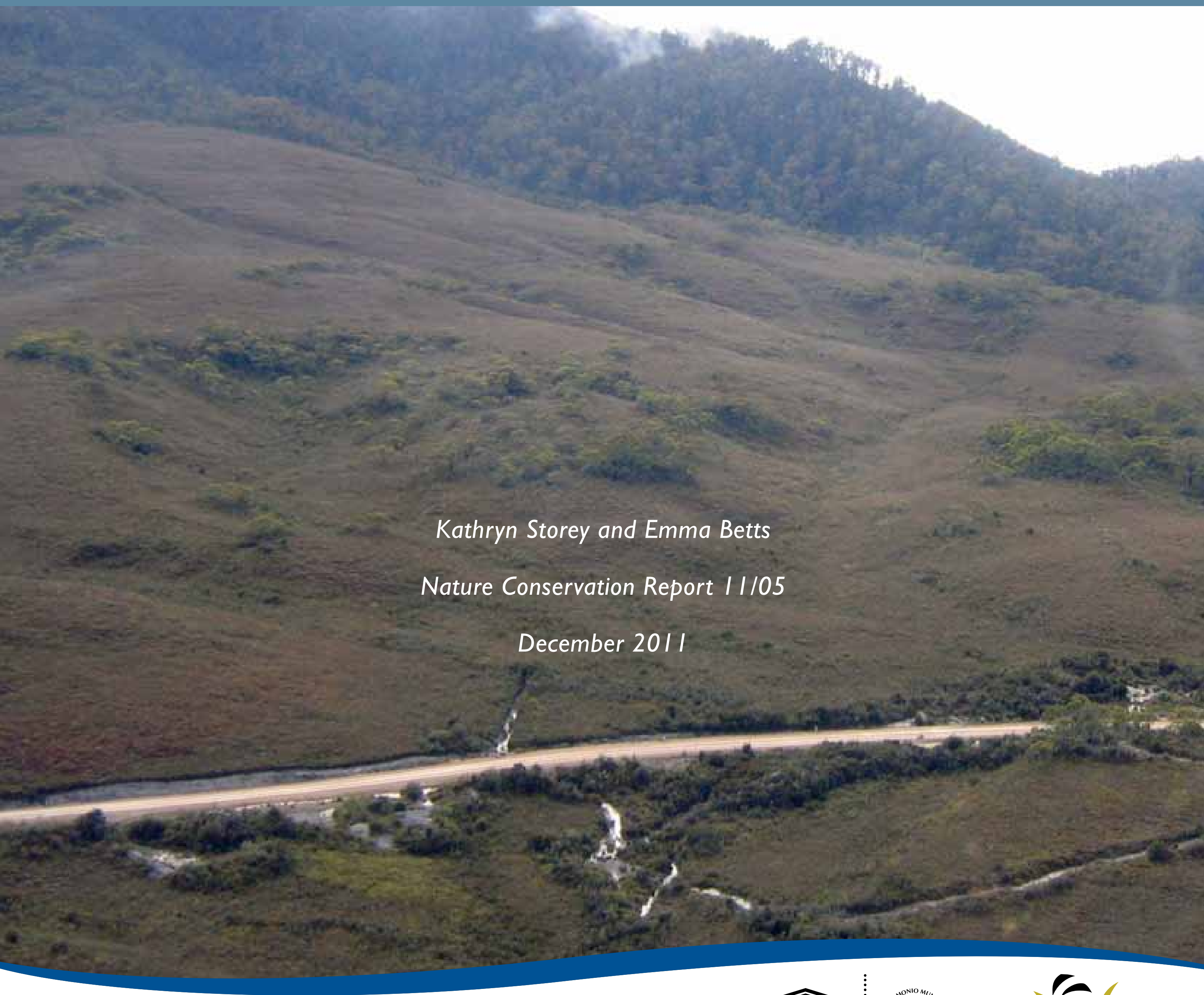
Fluvial ***geomorphology*** *and* ***hydrology*** *of*

small buttongrass moorland streams:

the ***Gelignite Creek*** *case study*



Kathryn Storey and Emma Betts

Nature Conservation Report 11/05

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Department of
Primary Industries, Parks, Water and Environment

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Geodiversity Conservation and Management Section

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Summary

This report presents the results of a long term study into the fluvial geomorphology and hydrology of small buttongrass moorland streams. The project has involved monitoring stream hydrology and geomorphology in two small catchments on Scotts Peak Road in south western Tasmania within the Tasmanian Wilderness World Heritage Area. The study sites are at Gelignite Creek (hydrological and geomorphological monitoring over four years) and Condominium Creek (hydrological monitoring over two years). The project has a second, experimental phase, presently underway, where the effects of fire on the Gelignite Creek catchment will be monitored.

The principle findings of this project are:

- The hydrology of Gelignite Creek differs from most catchment hydrology studies in the literature in that:
  - The sapric organic soil horizon (i.e. the muck peat) common in moorlands appears to be acting as an aquitard (i.e. a very low permeability layer that slows infiltration of water).
  - Base flow appears to be dominated by soil water drainage rather than ground water (unusual even in other blanket bog catchments).
  - Storm flow is dominated by overland flow (typical of blanket bog catchments but not on other soil types).
- The fluvial geomorphology of Gelignite Creek incorporates some unusual features. Some of these have not previously been described, while others have been noted elsewhere in earlier work but have not previously been quantified. These include:
  - Very low width to depth ratios dominate wherever continuous channels are present.
  - The trunk stream has unexpectedly high sinuosity for the landscape context.
  - There are frequent subsurface drainage lines (i.e. soil pipes and tunnels).
  - Large undercuts are frequent wherever banks are close to vertical.
  - Organic soil can act as a bed control where catchment areas are small.
  - Channel pinches, a composite feature part erosion headcut and part fine sand deposit, control the long profile of the stream where catchment areas are large.
  - The trunk stream carries a very small low calibre sediment load, despite initial impressions of sediment mobility on slopes and within the channel.
  - There are frequent multiple channel sections, particularly in smaller catchment areas.

The geomorphic character of Gelignite Creek fits within the context of other moorland streams described in the literature. It is probable that stream power plays an important role in determining the type of influence that moorland soils and vegetation have on stream form.

The implications of these findings for the fire sensitivity of moorland streams should be made clear in the second, experimental phase of the project. However, there is significant potential for geomorphic change following fire, with a variety of channel features being potentially sensitive to the flow on effects of fire. The hydrology findings suggest that fire in this environment may have less of an impact on

catchment hydrology than in other types of landscape, as storm flow is already dominated by overland flow.

The project has now entered the second phase, a study of the effects of a management burn on one of the study catchments. The Gelignite Creek catchment was burnt in mid 2009 and post fire analysis of data is planned for 2013.

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1 Introduction

Buttongrass moorland

Tasmania's buttongrass moorlands are a distinctive suite of vegetation types occurring mainly in high rainfall, low fertility sites in western Tasmania (Harris and Kitchener, 2005). Vegetation mapping shows that moorland extends over almost 600,000 ha of the state (Department of Primary Industries and Water, 2007). The vegetation type is strongly associated with organic soils (di Folco, 2007), and in western Tasmania is not confined to depressions, but covers extensive areas of the landscape including slopes. In this sense, buttongrass moorland and the associated organic soils are similar to the blanket bogs of Europe, although they differ in many characteristics such as soil structure, depth, and hydrology. Tasmania's buttongrass moorland blanket bogs have been recognised as having World Heritage value (Sharples, 2003), and are listed in the Tasmanian Geoconservation Database (http://www.dpiw.tas.gov.au/inter.nsf/WebPages/LBUN-6TY32G?open) as having global significance.

The combination of the distinctive vegetation and soil characteristics across large areas creates the potential for moorland areas to have unusual geomorphology and hydrology. Nationally and internationally, peatlands have been found to produce unusual features in rivers and streams, in terms of geomorphology, hydrology and water chemistry (e.g. Conway and Millar, 1960, Burt and Gardiner, 1984, Vogt and Muniz, 1997, Grover, 2001, Holden *et al.*, 2001, Burt *et al.*, 2002, Epstein, 2002, Holden, 2002, Holden and Burt, 2003a, Worrall *et al.*, 2003, Evans and Warburton, 2007, Watters and Stanley, 2007, Nanson, 2009, Nanson *et al.*, 2010). Previous work in Tasmania looking at moorland streams (Jerie *et al.*, 2003, Jerie, 2005), has found a range of distinctive features present in the geomorphology. Sharples (2003) suggests that the river systems of the Macquarie Graben (south of Macquarie Harbour) have World Heritage value, in part because of the influence of organic soils on the development of the landforms. However, existing publications present only the earliest stages of understanding moorland streams.

Buttongrass moorlands present a difficult management proposition. Although Aboriginal people used fire as a landscape management tool throughout the Holocene details of those practices have now been lost. The vegetation type is fire adapted and in many areas requires fire to prevent succession to other vegetation types (e.g. Jackson, 1968, Bowman and Jackson, 1981, di Folco, 2007, Balmer and Storey, 2010 amongst many others). It is highly flammable (Marsden-Smedley and Catchpole, 1995a, Marsden-Smedley and Catchpole, 1995b) and can carry intense wildfires. It occurs over very large areas. It is also closely associated with fire sensitive values, such as neighbouring fire sensitive vegetation types, and its own organic soil. Fire frequency in moorland has been shown to be correlated with vegetation type and decreases in soil carbon content, carbon density, nitrogen content and soil depth, particularly on low nutrient slopes (di Folco, 2007). Even cool fires have been shown to impact on moorland soils (di Folco and Kirkpatrick, 2011). Similarly, it is reasonable to expect that catchment scale fire will have an impact on the fluvial geomorphology and hydrology of moorland areas (Shakesby and Doerr, 2006, Storey, 2010), although these effects have not yet been demonstrated.

So, management of moorland areas must balance the need to burn to achieve ecological and hazard reduction goals against the need to protect fire sensitive values. Significant effort has gone into researching the effects of fire on moorland on vegetation and fauna (see reviews by Balmer and Storey, 2010, Driessen, 2010). Rather less work had occurred examining the effect of fire on the physical components of the ecosystem, and although this has increased in recent times the emphasis has been on the effects of fire on the organic soils (Bridle *et al.*, 2003, di Folco, 2007, di Folco and Kirkpatrick, 2011). This project is a first step to extending this focus to including the impacts of fire on fluvial geomorphology and hydrology.

An overview of the buttongrass moorland stream and fire project

This report is part of a long term effort which aims to identify the impacts of management burning on fluvial geomorphology and hydrology of buttongrass moorlands, in terms of immediate impacts and flow on effects, recovery pathways and relaxation times. With this knowledge one could identify the maximum frequency of control burn that would allow fluvial systems time to reflect the full range of conditions, from recently burnt to long unburnt. This information could then be fed into the already complex process of fire management planning, with the hope of avoiding unintended permanent drift in stream character. It could also be used to identify indicators for areas that have been too frequently burnt where such a drift is occurring.

This report presents the results of the first phase of this research effort – documentation of the form and behaviour of streams in long unburnt catchments. It is based on data collected between late 2004 and mid 2009, when the Gelignite Creek catchment was burnt. The second phase of the project involves monitoring and analysis of the effects of that fire.

This phase of the project aimed to measure and monitor hydrology and geomorphic form and process in a small, long unburnt buttongrass moorland catchment for long enough to capture the character and climate driven variability in behavior. The project focuses on a headwater catchment of Gelignite Creek, where both catchment hydrology and fluvial geomorphology have been investigated. This forms the treatment catchment for the second, experimental phase of the project. Hydrology has been monitored at a second catchment, a headwater of Condominium Creek, which will be the control site for the hydrological component of the project in the experimental phase. The criteria for study catchment selection were that they be dominated by moorland vegetation types that were long unburnt, with organic soils typical of moorland areas, and have readily identifiable surface and subsurface catchments. There were also the added pragmatic requirements that they be a reasonable travel time from Hobart, have a site suitable for construction of a small weir for monitoring hydrology, and in the case of the treatment catchment, be possible to burn safely. Site selection for this project is more difficult than for fire impact studies in other disciplines, because of the need to include an entire catchment, rather than a set of sample plots.

Both study sites are very small (less than 30 ha). In part, this was a result of the difficulty of identifying any catchments that met selection criteria. However, the intention of the project was to target small catchments. Smaller catchments are typically simpler than larger ones, reducing the 'black box' effect that always troubles a catchment scale study. Also, the influence of moorlands, and the effect of fire on moorland streams, is likely to be particularly strong on small streams, where the scale of fluvial processes means that the physical effects of vegetation and soil will have their greatest impact (Rutherfurd *et al.*, 1995). Finally, small streams also present the greatest length of waterway present in moorland areas. Of the almost 18,000 km of mapped waterways that occur in moorland vegetation, some 12,000 km are first order streams (those with no mapped tributaries). Also, a significant part of the effect of fire on larger waterways is likely to be from the cumulative effect on sediment and water delivery from the headwaters (Burt, 1996, Alexander *et al.*, 2007). This is particularly the case in moorlands, where larger streams tend to have less flammable forested riparian zones, typically left intact in control burns.

One obvious criticism of this project design is its lack of replication. In large part, this is a response to pragmatic constraints. Catchment scale experiments with continuous long term monitoring are labour intensive, and require duplicate sets of expensive equipment. Also, finding appropriate replicate sites can be difficult. It is not unusual in the geomorphic literature to find intensive studies such as this one based on a single catchment or pair of catchments (O'Loughlin *et al.*, 1982, Jones and Crane, 1984, McCaig, 1984, Scott and Van Wyk, 1990, Giusti and Neal, 1993, Holden and Burt, 2002, Worrall *et al.*, 2003, Liu *et al.*, 2004, Stephens *et al.*, 2004, Worrall *et al.*, 2007, Nanson, 2009, Eaton *et al.*, 2010, Nanson *et al.*, 2010, Smith *et al.*, 2010). Especially in the context of an almost complete lack of knowledge of the systems in question, a lot of valuable information can and in this case has been gleaned from a single catchment or pair of catchments.

A further criticism of the project has been the lack of a complete control site. There is some argument as to whether a control catchment is the only way to increase our confidence that an observed response is related to an experimental treatment. Downes *et al.* (2002) list a series of criteria that can increase the strength of the inference that observed changes were caused by the applied treatment. They include the strength and consistency of association, temporality, ecological gradient and plausibility, and analogy with similar sites. All of these tests can be applied to the experimental phase of this project. Also, in geomorphic studies where a control site is used, identifying appropriate sites can be very difficult, as sites must match over many criteria. This is typically much harder to achieve at a catchment scale than the plot scale frequently used in biological studies.

However, the Condominium Creek control catchment was added approximately two years after initial data collection at Gelignite Creek. Unfortunately, as predicted, finding a control site that matched the geomorphic conditions of Gelignite Creek (including catchment size and topography, geological setting, vegetation character and age, soil character, and stream forms present), as well as meeting the pragmatic requirements of travel time, a weir site and in this case the ability <u>not</u> to burn the site proved difficult. Condominium Creek is used as a control for the hydrological components of the project, but because of differences in vegetation patterns (the stream channel flows for the most part through forest) was not a suitable comparison for the geomorphology.

As with many long term data intensive projects, this study has had a range of issues to overcome. As well as the usual issues of faulty data loggers and staff changes, there was the problem of a leaky weir at Gelignite Creek. The first time this occurred, the leak was not detected for some time, fixing was delayed while attempts were made to measure the size of the leak, and then repairing the leak proved difficult. This resulted in a sizable gap in the reliable data, which then required that the pre-fire monitoring time be extended.

Project results so far

The results of this project show that the hydrology of both Gelignite and Condominium Creeks is characterised by a very flashy flow regime, rising rapidly to peak flows during rain events and then falling rapidly as rain intensity decreases. Also, both have a very high specific yield (the amount of runoff generated per unit area of catchment), with around two thirds of average monthly rainfall leaving the catchments as stream flow. There are differences in the degree to which these patterns occur, with Gelignite Creek having flashier flow, more frequent cease to flow events, and higher specific yield than Condominium Creek. These differences are probably a result of differences in vegetation and soil, and potentially the underlying geology.

Evidence from water chemistry and the hydrology suggests that the organic soils are a major cause of these patterns. It appears that the sapric organic soil horizon (i.e. the muck peat) common in moorlands is acting as an aquitard (i.e. a very low permeability layer that slows infiltration of water). As a result, rainfall rapidly saturates the shallow fibrous organic horizon, and stormflow in the stream is dominated by rapid overland flow. This is typical of blanket bog catchments but not on other soil types. Base flow appears to be dominated by slow drainage of the organic soil, rather than ground water. This is unusual even in other blanket bog catchments.

There appears to be potential for developing a good predictive model of both daily and peak stream flow based on rainfall variables. Preliminary analysis has explained over 80% of the variability in flow, and it is expected that this will be improved with the addition of further variables such as modeled evapotranspiration.

The fluvial geomorphology of Gelignite Creek incorporates some unusual features. Some of these have not previously been described, while others have been noted elsewhere in earlier work but have not previously been quantified. These include:

- The trunk stream carries a very small low calibre sediment load, despite initial impressions of sediment mobility on slopes and within the channel.
- Very low width to depth ratios dominate wherever continuous channels are present.
- Large undercuts are frequent wherever banks are close to vertical.
- The trunk stream has unexpectedly high sinuosity for the landscape context.
- Channel pinches, a composite feature part erosion headcut and part fine sand deposit, control the long profile of the stream where catchment areas are large.
- There are frequent subsurface drainage lines (i.e. soil pipes and tunnels).
- Organic soil can act as a bed control where catchment areas are small.
- There are frequent multiple channel sections, particularly in smaller catchment areas.

Again, it is likely that the organic soils, in combination with the moorland vegetation itself, play a significant role in driving many of these features. Low sediment loads are probably a result of a lack of availability of mineral sediment in a catchment where mineral sediments are protected by cohesive organic soils, and dense groundcover, particularly on floodplains, slows the overland transport of sediment from slopes. The small width to depth ratio and large undercuts probably reflect low sediment loads, as well the bank profile of cohesive, root bound organic soils over a shallow erodible sandy horizon. This profile also promotes tunnel development, and smaller soil pipes on slopes mostly appear to be the work of burrowing crayfish.

Moorland streams and fire

While it is unwise to pre-empt the results of the fire impact phase of this project, these findings do make predictions of potential fire impacts possible. Hydrologically, we might expect an increase in specific yield, increased base flow, a lowering of the runoff initiation threshold, and changes to storm flow patterns. Geomorphically, some form of in-channel erosion appears almost inevitable, as does increased sediment fluxes through the stream. There may also be increased erosion on the floodplain, potentially resulting in channel changes such as meander neck cutoffs.

The project has now entered its second phase. The catchment was burnt in mid 2009. Unfortunately, weather conditions on the day did not live up to expectations, and the fire was only partially successful with over half of the catchment either unburnt or only very lightly burnt. Initially, there was an intention to repeat the fire to bring the burn standard up to that expected of a control burn (70% of fuel combusted over 70% of the area). However, this has not occurred because of the extremely crowded Parks and Wildlife burning program. Data collection in the catchment is continuing. Post fire analysis of data is planned for 2013.

2 The study area

The research was conducted in two small catchments on the Scotts Peak Road in the Tasmanian Wilderness World Heritage Area (TWWHA). These catchments are shown in Figure 1.

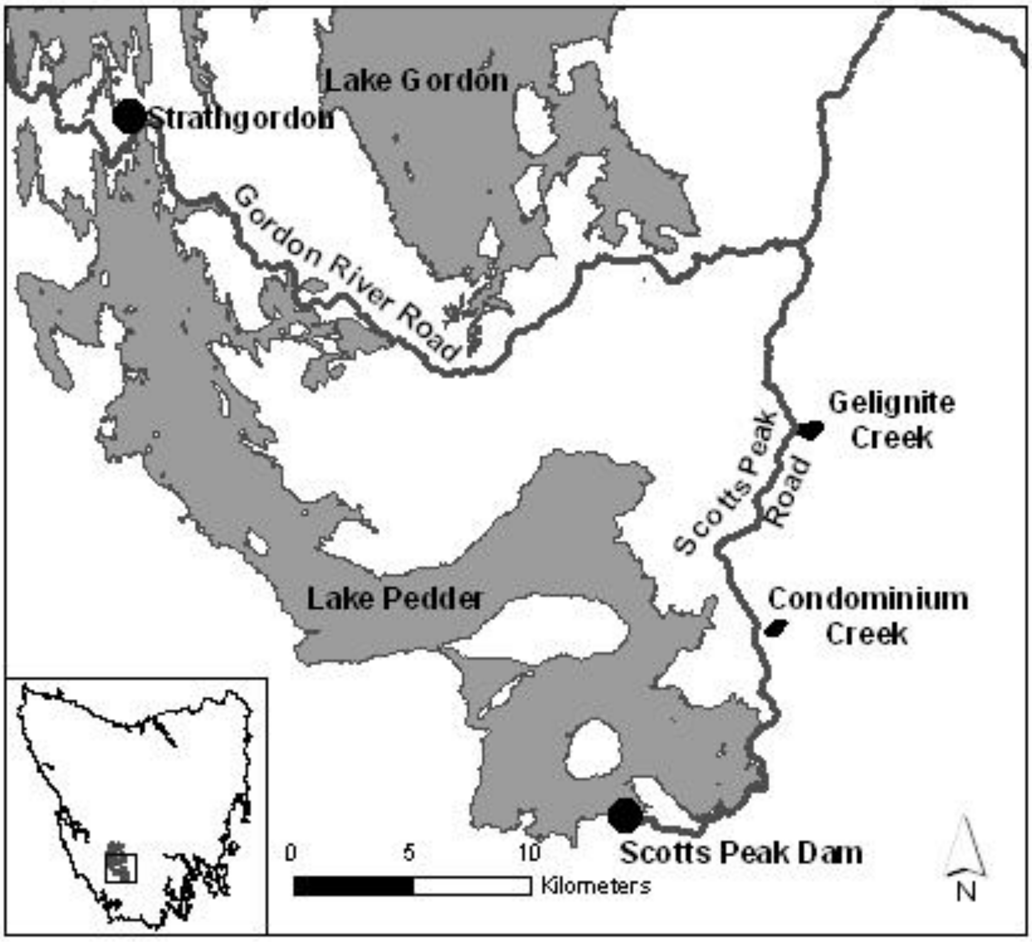


Figure 1. Map of western Tasmania, showing location of study catchments.

The northern catchment, in the headwaters of Gelignite Creek, includes both hydrological and geomorphological components of this study. In the second phase of the project which is presently underway, Gelignite Creek is the treatment catchment, and to this end was burnt in May 2009. The southern catchment, a headwater tributary of Condominium Creek, is included only in the hydrological component of the project. In the second phase, this will form the control. These sites were chosen because they were dominated by long unburnt buttongrass moorland vegetation and soils typical of slopes in western Tasmania, had definable surface and subsurface catchments, suitable sites to construct weirs, were easy to access, and could be burnt or not burnt as required. The basic characteristics of the catchments are outlined in Table 1.

Table 1. Characteristics of Gelignite and Condominium Creek study catchments.

	Gelignite Creek	Condominium Creek
Catchment area	28 ha	15 ha
Elevation	350 – 490 m asl	360 – 550 m asl
Catchment length	950 m	750 m
Geology*	Quartz sandstone derived colluvium flanking a ridge of Precambrian mudstone and quartz sandstone.	Precambrian orthoquartzite ridge in upper catchment, and quartz sandstone derived colluvium in lower catchment.
Vegetation [Ŧ]	Western buttongrass moorland (MBW).	Western buttongrass moorland (MBW), sparse buttongrass on slopes (MBR), *Banksia marginata* wet scrub (SBM), western wet scrub (SWW).
Soil [°]	Buttongrass moorland on slopes (B3)	Buttongrass moorland on exposed slopes (B2) Buttongrass moorland on slopes (B3) Character of soils under forest is unknown.
Aspect	West	South west
Average Discharge	4.1 L/s	2.4 L/s
Last Fire [+]	1971	1975

*(Turner *et al.*, 1985),
[Ŧ](Department of Primary Industries and Water, 2007),
[°](di Folco, 2007)
[+]Parks and Wildlife Tasmania fire history data 2010.

The study catchments are less that 10 km apart, so are subject to similar climate. Western Tasmania has a cool temperate maritime climate, with mild summers and cold winters. The Bureau of Meteorology has been recording climate data at the village of Strathgordon since 1968. Strathgordon is approximately 30 km to the north west of the study sites. Between 1968 and 2009 average annual precipitation at Strathgordon was in excess of 2500mm per year, with maximum rainfall in late winter and early spring and a marked reduction in rainfall typical over the summer months. Mean minimum and maximum temperatures are 2.9 and 9.9°C, and 8.3 and 19.6°C for winter and summer, respectively. In these cool, wet conditions humidity is typically very high and evapotranspiration quite low.

Gelignite Creek

The Gelignite Creek study catchment drains part of a moderately steep area of deep colluvium (slope deposits) on the western flank of a ridge to the south of Mt Bowes (see Figure 2). The catchment has moderate relief, with steep to moderate slopes common. Limited floodplain development means that slopes are highly connected to stream channels. Only one stream is marked on 1:25,000 maps of the area, however an on ground examination reveals a moderately high drainage density (6.6 km per square kilometre) of small channels that carry water for much of the year. Stream channels are steep and stepped, or on more moderate slopes highly sinuous. Short tunnels that take most of the base flow are common throughout the catchment. Hydrologically, the catchment is very flashy, with a low base flow punctuated by rapidly rising and falling floods.

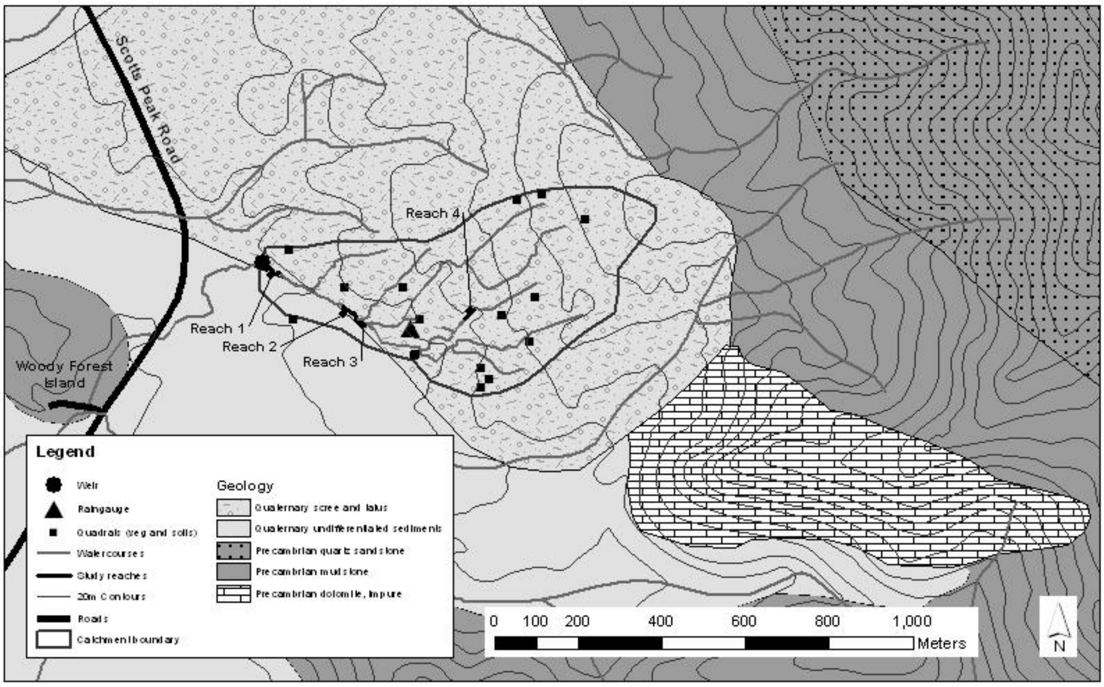


Figure 2. The Gelignite Creek catchment and surrounding area, showing significant features and locations of monitoring equipment. Geology data from Turner *et al*. (1985).

The catchment is formed entirely within thick colluvium (slope deposits) dominated by quartz sandstone clasts. The ridge above the catchment is mapped as Precambrian quartz sandstone flanked by Precambrian mudstone (Turner *et al.*, 1985), and is presumably the source of the material that forms the colluvial deposit that underlies the study catchment. Field observations have shown that quartzite gravel, cobbles and boulders dominate the colluvium, but these are set within a sandy clay matrix. No bedrock has been observed to crop out anywhere within the catchment. South of the study catchment and further to the west of Mt Bowes are areas of Precambrian dolomite, and it is possible that these rocks underlie the study catchment. However, there is no evidence from stream hydrology or water chemistry that karst processes influence the study catchment.

The catchment vegetation has been mapped by Tasveg as Western Buttongrass Moorland (Department of Primary Industries and Water, 2007). It is dominated by buttongrass moorland comprised primarily of *Gymnoschoenus sphaerocephalus*, *Baeckea leptocaulis*, *Bauera rubioides*, *Boronia pilosa* and *Leptospermum nitidum* with various sedge and moss species. There are several small areas of tall scrub, dominated by *Eucalyptus nitida*. Vegetation density varies across the moorland areas of the catchment. Tall heath is common around the boundaries of scrub. Vegetation density in the moorland areas is greatest along drainage lines and moderate slopes. On some steeper convex slopes there are areas of very sparse vegetation, where there are significant proportions of bare soil and rock. Aerial photograph analysis suggests that the catchment is 88% *Gymnoschoenus* dominated moorland, 7% sparse moorland and 5% scrub.

Soil in the study catchments is typical of the buttongrass moorlands of south-western Tasmania. Soils observed in the catchment generally fits within di Folco's classification of Tasmania's organic soils (di Folco, 2007) as type B3: Buttongrass moorland on slopes. Soil organic content is high, although soil depth and organic content varies considerably with topography and vegetation. Soils are generally deeper and higher in organic matter content in reliably wet areas along valley floors, on gentle to moderate slopes throughout the catchment, and on some steep slopes with a southern aspect. While slopes with a southerly aspect are expected to be less productive they are also less likely to burn. That is suggestive that fire has played a significant role in Holocene edaphogenesis. Steeper slopes, particularly those with a northern or western aspect, are more likely to have shallow stony soils with lower organic content. In moorland areas, soils tend to consist of shallow horizons of poorly humified fibric deposits that overlay deeper well humified sapric soils. In areas of mature scrub, fibric horizons tend to be deeper. In both vegetation types, these organic rich horizons are underlain by mineral horizons that are variable in nature, and may be dominated by sand and gravel or by clay. It is probable that this simply reflects the variability in the underlying slope deposits. The freshwater crayfish *Parastacoides tasmanicus tasmanicus* is present, with burrows evident along stream channels and on valley slopes.

Condominium Creek

The study catchment at Condominium Creek drains a steep asymmetrical catchment on the southern side of a steep ridge west of Mount Eliza (see Figure 3). The catchment is approximately half the size of the Gelignite Creek catchment and as such has lower annual average and maximum discharge. Similar to Gelignite Creek, Condominium Creek has a low baseflow condition but responds rapidly to rainfall with a flashy storm hydrograph.

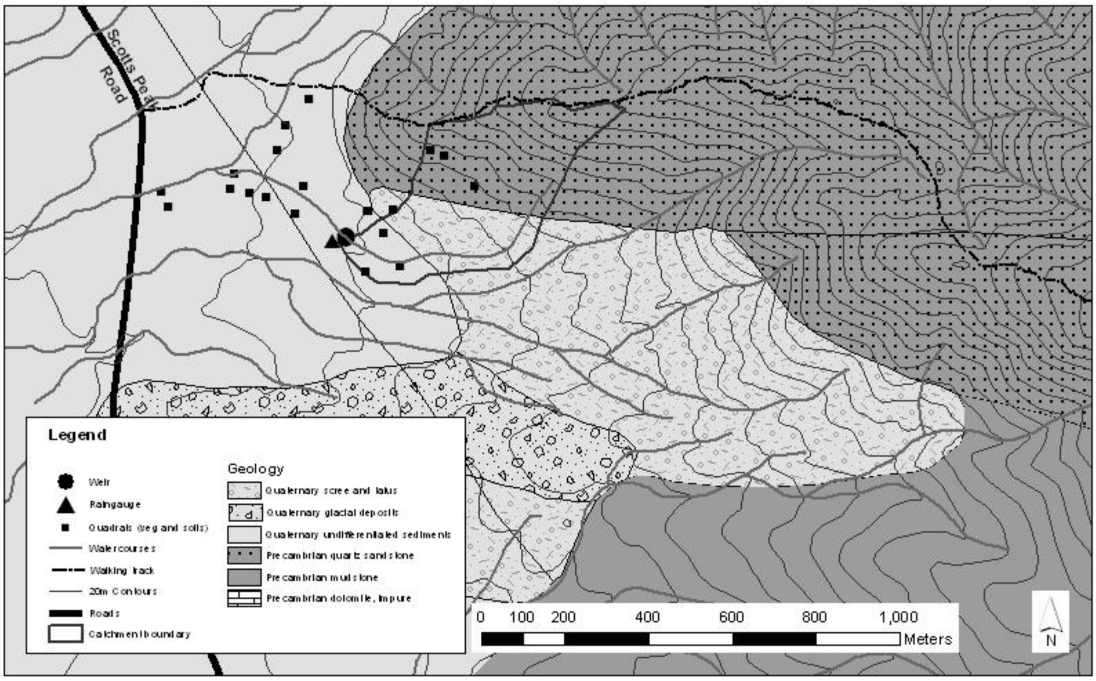


Figure 3. The Condominium Creek catchment and surrounding area, showing significant features and locations of monitoring equipment. Geology data from Turner et al. (1985).

The ridge forming the northern watershed of the catchment is mapped as predominantly Precambrian orthoquartzite with a small area of impure dolomite (Turner *et al.*, 1985). The lower slopes of the catchment and the southern watershed are formed on slope deposits derived from the quartzite ridge.

Vegetation in the catchment is far more variable than that found at Gelignite Creek. The Condominium catchment has been mapped by Tasveg as a mix of western buttongrass moorland, sparse buttongrass moorland on slopes, *Banksia marginata* wet scrub and western wet scrub (Department of Primary Industries and Water, 2007). Field observations suggest that there are also forest areas dominated by *Eucalyptus nitida*, some of which are likely to have a rainforest understorey.

Soil in the moorland area of the catchment has not been systematically sampled, but generally fits within di Folco's classification of Tasmania's organic soils (di Folco, 2007) as types B2 Buttongrass moorland on exposed slopes, and B3: Buttongrass moorland on slopes.

Methods

3 Methods

This long term study aims to characterise a small buttongrass moorland catchment in terms of:

1. Catchment hydrology, based on monitoring rainfall, stream discharge, water chemistry, and catchment vegetation and soil surveys;
2. Geomorphic stream form, based on catchment characterisation and detailed surveys of stream long profile, planform and cross sections, and
3. Sediment transport, based on turbidity measurements, a stream bedload trap and some limited measurements of slope sediment transport.

Table 2 summarises the measurements that have been taken as part of this study.

Table 2: A summary of measurements and observations taken in the study catchments. Note that collection of most datasets has continued past 2009, but is not included in this report.

Variable type	Parameter	Gelignite Creek	Condominium Creek
Vegetation surveys	Species cover and height Vegetation and litter density	2004 and 2008	2010
Soil survey	Profile description Carbon content	2004 2008 - 2009	None
Rainfall		Sept 2004 – 2009	Feb 2007 - 2009
Stream Discharge		July 2004 – 2009	May 2006 - 2009
Water Chemistry (instream probe)	Temperature, pH, Conductivity, Dissolved oxygen.	July 2004 – 2009	None
Water Chemistry (grab samples)	Total suspended sediment, Volatile suspended sediment, Alkalinity, Cl, SO_4, $N0_x$, Ca, Mg, Na, K, Fe, DOC, Si.	Discontinuous 2007 – 2009	None
Channel surveys		2004 and 2008	None
Instream sediment transport	Turbidity, Bedload sediment trap	July 2004 – 2009 May 2005 – 2009	None
Slope sediment transport	Astro turf Gerlach troughs erosion pins	2009	None

3.1.1 Catchment description

Vegetation surveys

Vegetation surveys were conducted with the two goals of characterising the vegetation floristics, and characterising the physical structure that will influence the movement of water through the catchment. At Condominium Creek, floristic data have been collected, but time constraints prevented collection of structural data.

Aerial photograph interpretation was used to map three classes of vegetation density: Scrub, Buttongrass and Sparse buttongrass. Within each density class, five two by two metre quadrats were used to characterise vegetation in each class. Note that while the range of vegetation types present at Gelignite Creek have been sampled, the existing monitoring at Condominium Creek has not sampled the dense stands of forest and rainforest that occur in this catchment.

Botanical composition was characterised by estimating cover and height of vascular species present, and the cover or algae, lichens, mosses, litter and bare ground. Surveys were completed at Gelignite Creek in summer 2004 at the beginning of the project, and in summer 2009 prior to the burn. Condominium Creek was surveyed in early 2010.

Vegetation structure and biomass in each quadrat was characterised in order to track the impact of altering vegetation on catchment hydrology. The biomass was considered as three strata: groundcover, shrub and tree canopy. An index was developed to classify biomass density in the shrub and tree storeys into four categories (none, low, moderate and high), based on the density of material and the proportion of the quadrat covered. The groundcover index includes five categories (very low, low, moderate, high and very high), based mainly on depth and density of biomass close to the ground. Both indices are described in detail in Appendix 1.

Finally, environmental factors were described for each quadrat. These were soil depth (5 measurements per quadrat), aspect, slope, and soil drainage class. Soil drainage classes can be found in Appendix 2.

Vegetation data analysis.

Floristics

Multivariate analysis was used to investigate the floristic relationships between vegetation types identified from aerial photography. Analyses were conducted using PC-Ord (McCune and Mefford 1999). The data comprised cover values for each quadrat at each visit. The data were ordinated using the Non-metric Multidimensional Scaling module in PC-Ord (Bray-Cutis distance matrix, 250 random starts with real data and 250 random starts with randomised data). The lowest appropriate dimensionality for the final output was determined by comparing the final stress values among the best (lowest stress) solutions. Species cover estimates were correlated with the ordination axes using the joint plot function in PC-Ord. Vectors were obtained from Pearson and Kendall Correlation (PKC) in PC-Ord.

Vegetation volume and density

A vegetation volume index was used to indicate the quantity of vegetation available to intercept rainfall and transpire soil water. This was calculated by multiplying cover and height estimates for all species in the quadrat, giving a result in cubic metres. This was then extrapolated across the catchment according to the proportional cover of that vegetation type. This is not intended to be a precise measure of biomass, but rather a simple indication of the volume of space within which plants can be found, to allow comparison between catchments and time periods. It is acknowledged that this is a very approximate measure. It assumes that each species occupies all the space between the top of the canopy and the ground rather than taking into account plant density or habit (e.g. loose cone shaped *Sprengelia* compared to dense hemispherical *Gymnoschoenus*).

The vegetation density data was examined and the average (for ground strata) or median value (for shrub and tree strata) was calculated for each vegetation type.

Soil survey and analysis

Soil pits were dug adjacent to each vegetation quadrat at Gelignite Creek. The soil profile was described by horizon depth, soil colour, root frequency, degree of humification on the von Post humification scale, (Von post and Granlund 1926 in Egglesmann *et al.*, 1993), the field texture any mineral soil content and moisture status. Samples of all horizons were taken for soil carbon analysis. Samples had the main live biomass removed, and were oven dried at 35 °C. Samples were then posted to CSBP Soil and Plant Laboratory (Bibra Lake, Western Australia) for total organic carbon analysis using the Heanes wet oxidation method (Rayment and Higginson, 1992).

Soils were put into informal groups with similar horizon depth, character and carbon content.

3.1.2 Hydrology

Rainfall measurement

Rainfall was measured in each catchment using a tipping-bucket rain gauge. See Figures 2 and 3 for locations. Initially only the Gelignite Creek rain gauge was installed. However, a comparison of the stage records for the two catchments showed that the timing and relative size of response to rain events varied. This suggested there were sometimes important differences in timing and intensity of rainfall between the two catchments despite their proximity. As a result, the second gauge was installed at Condominium Creek.

Several gauges have been used in this study. Between 2004 and 2007 a gauge with a catchment diameter of 205mm was in use at Gelignite Creek. A Hydrological Services TB3 tipping-bucket rain gauge was installed at Condominium Creek in February 2007. In March 2007, Rimco 7499 tipping bucket rain gauges were installed in both catchments (Figure 4). Loggers recorded the number of bucket tips (0.2mm) per 15 minute period.

Figure 4. Tipping bucket rain gauge installed at Gelignite Creek.

Rainfall analysis

Rainfall data was aggregated to form annual and seasonal totals for each catchment across the study period. Cumulative rainfall for the 2008 calendar year was plotted for both catchments to identify the degree of similarity in rain patterns. Seasonal variations in rainfall patterns were examined by calculating the proportion of the average annual rain that falls within each season for both catchments.

Rainfall intensity patterns were investigated by calculating for each rainday the total daily rainfall, and the proportion of the total rainfall for the period of record contributed by that rainday. In this way, the frequency of rain days of different intensity could be calculated, as could the proportion of the total rainfall that falls in given rainday intensity classes.

Stream Flow measurement

Sharp-crested V-notch weirs with 90° angle and 25 cm maximum flow depth were installed in July 2004 at Gelignite Creek and May 2006 at Condominium Creek (Figure 5). Weir pond stage height was recorded every 15 minutes using a YSI 6600 Sonde with pressure transducer at Gelignite Creek and a Level Troll 500 (In-Situ Inc.) pressure transducer at Condominium Creek.

Rating curves for each weir were developed using Hydstra TSM, with the assistance of the DPIPWE Water Monitoring Section. The standard curve for a 90° V-notch weir was used for lower stages, and discharge was gauged at a range of stages close to the top or exceeding the capacity of the weir notch. Gauging was based on the velocity-area method. Velocity was measured with an OSS-PC1 Pygmy current meter.

Leaks developed around Gelignite Creek weir twice since the site was installed. Periods effected are from December 2004 to May 2006, and late October 2007 to late November 2007. Data from these periods can be considered to accurately represent the timing of changes in stage, but does not accurately represent flow volumes. Condominium Creek weir has never had a leak detected.

Figure 5. Sharp-crested 90° V-notch weir at Gelignite Creek (left) and Condominium Creek (right).

Stream Flow analysis

The following analyses have been completed on flow data. Unless otherwise stated, only 'good data' (unaffected by leaking weirs) has been used in analysis. Hydstra TSM was used for all basic data manipulation.

Basic description

Average monthly flows were calculated for both catchments across the period of record. Flow duration curves were developed for both catchments.

Seasonality

Seasonal variations in stream flow were examined by calculating the proportion of the average annual rain that falls within each season for both catchments. The distribution of high and low flow events was also examined, by looking at a flow duration analysis on a seasonal basis.

Antecedent conditions

The role of antecedent conditions in determining streamflow response to rainfall was examined by visual interpretation of the rainfall and stream flow records.

Base flow analysis

Base flow analysis was completed using the River Analysis Package (RAP) produced in 2005 by the CRC for Catchment Hydrology. This program requires daily flow data without gaps. For this reason, Gelignite Creek data used in the analysis dated from 25/5/2006 (when the first weir leak was fixed) to immediately pre fire (20/05/09). This includes a 35 day gap when the second weir leak occurred. This gap was filled using RAP's gap filling feature, using multiple linear regression with Condominium Creek as reference data. For Condominium Creek, the entire period of record up to the Gelignite Creek fire was used (1/06/06 to 20/05/09). As recommended by Nathan and McMahan (1990) an alpha value of 0.925 was used.

Specific Yield
Specific yield was calculated on a monthly basis. It is the volume of water discharged from the catchment divided by the catchment area. It is expressed in mm/month (or ML/month/km^2). Specific yield was plotted against monthly rainfall.

Flow Prediction
Simple and multiple regressions were used to investigate the relationship between rainfall and both daily flow and daily peak flow. Daily flow was calculated as the average flow over a 24 hour period. Peak flow was calculated as the maximum flow that occurred for at least 15 minutes (two data points). This was intended to reduce the noise caused by differences between the actual time of greatest water depth and the moment when data collection occurred, while maintaining as much as possible of the real short term variability in flow. Flow data for Gelignite Creek were used untransformed. However, flow data for Condominium Creek was more strongly skewed, and better results were obtained using the square root of flow.

Rainfall variables investigated were the total rainfall on the day, and the total for the previous 2, 3, 4, 5, 6, 7, 10, 14 and 21 days. Investigations of peak flow also included the maximum rainfall intensity over a 1, 3, 6 and 12 hour period each day.

Regression analysis was done using Statgraphics Plus 5.0. In multiple regressions, severely autocorrelated rainfall variables (correlation coefficients ≥7) were removed, as were those found to be not significant at the 95% confidence level. The simple regression that had the greatest ability to predict flow values is reported here.

Bankfull flow frequency estimates
Identifying a bankfull stage on a stream where channel capacity varies greatly over very short distances is somewhat arbitrary. A stage of 30 cm at the Gelignite Creek weir was selected as bankfull, as field observations suggest that at this stage overbank flow is occurring at most channel pinches (equivalent to riffles). For the 2008 calendar year Hydstra TSM was used to calculate the number and duration of events during which this flow level was exceeded for at least one hour, with individual events separated by at least 24 hours.. No bankfull flow frequency analysis was developed for Condominium Creek, as there were insufficient observations of what stage might constitute bankfull in this catchment.

Geomorphically dominant discharge
The amount of geomorphic work achieved during stream flows of any given size is a product of the ability of the flow to transport sediment, and the amount of time for which that flow occurs. The sediment trap provides a sample integrated over weeks or months with insufficient resolution to determine the most important flows for transporting medium and coarse sediment. For Gelignite Creek, calculations were made using turbidity as a surrogate measure of suspended sediment to identify the flow ranges that transport the bulk of fine sediments. Data used covered the period of record where both flow and turbidity data were considered reliable.

A multiple regression was used to relate suspended sediment transport to turbidity as measured by the YSI Sonde. Regression analysis was completed using Excel 2007. The constant was excluded from the model, as it was felt that zero turbidity would be indicative of zero suspended sediment loads.

The relationship between turbidity and suspended sediment was then used to calculate estimated total suspended sediment load in 5L/s flow classes. This data was then used to graph sediment load against discharge and so predict the dominant discharge for suspended sediment in Gelignite Creek.

Equivalent calculations for Condominium Creek were not completed as there is no sediment transport data available for that catchment.

Water chemistry

Continuous water chemistry observations were made at Gelignite Creek using a YSI 6600 multiparameter sonde with temperature, conductivity, dissolved oxygen, pH, turbidity (860nm 90° optical backscatter) and depth (pressure transducer) sensors. Sensors were calibrated every six to eight weeks at time of logger download. No water chemistry data is available for Condominium Creek.

Periodic grab samples were taken from Gelignite Creek under a range of flow conditions and analysed for physical and chemical parameters at the Analytical Services Tasmania laboratories (NATA accredited) in Hobart. Water samples were stored at 4°C and submitted for analysis within 48 hours of collection. Analytes tested were total suspended solids (TSS), volatile suspended solids (VSS), alkalinity, anions (SO_4^{2-}, Cl^-), cations (Ca^{2+}, Mg^{2+}, Na^+, K^+, Fe^{2+}), dissolved organic carbon (DOC) and dissolved silica (DSi).

3.1.3 Stream geomorphology

Stream character

All drainage lines in the Gelignite Creek catchment were divided into reaches with reasonably homogenous form and behaviour and classified using variables such as stream and valley slope, channel form, substrate, number and continuity of surface channels and vegetation. This loosely follows the River Styles approach to stream characterisation (Brierley *et al.*, 1996). Channels were mapped using a handheld GPS. Gelignite and Condominium Creek catchment boundaries were determined from field reconnaissance with handheld GPS.

Stream surveys

Reach scale morphology

In addition to the qualitative assessment of stream form at Gelignite Creek, a series of measurements were taken in four focus reaches of approximately 50 m. The location of these reaches is shown in Figure 2. Reaches were chosen to represent different channel environments where change may be expected to occur following fire. Three of the reaches measured were along the main trunk stream, two high sinuosity reaches (R1; 80 m and R3; 65 m), and one high energy reach (R2; 45 m). The fourth study reach was in the upper headwaters of the catchment, in a steep and densely vegetated gully (R4; 35 m). Measurements were initially made in 2004/05 and repeated over the 2008/09 summer.

Surveys were conducted to characterise the channel and valley in each study reach. Longitudinal profiles and channel planform surveys were completed with a Leica TPS700 theodolite, with a step length of approximately 30-50 cm. Valley cross-sections were surveyed at the upstream and downstream end of each study reach with an additional mid-reach cross-section completed for R1. All valley cross-sections were carried out using the Leica TPS700 except for the R1 sections surveyed in 2004 which were completed using a Leica NA720 Dumpy Level. Bed material in the thalweg was recorded in the categories boulder, cobble, gravel, sand, organics, moss, vegetation/roots, litter and peat. More than one category could be recorded at any one location.

Data analysis

Spatial data were analysed to produce a long profile and planform of the thalweg, as well as valley slope, channel slope and sinuosity (channel length divided by valley length). Channel width to depth ratios were calculated from groups of measurements (left bank top, thalweg, right bank top).

Bed material categories were grouped into categories of:

- Boulder (all boulder records) – a size class beyond the conceivable competence of the stream even in extreme events.
- Coarse (cobbles, with or without gravel, sand, or moss) – a size class that may move in extreme events, but most likely to be a lag deposit.
- Gravel (gravel with or without moss) – a size class with some sorting suggesting movement in large events.
- Fine (sand, with or without gravel or organics, but without moss) – a size class that can be regularly transported by the stream.
- Moss (moss vegetation or roots, with or without sand or organics present) – a deposit stabilised by vegetation.
- Peat (peat with or without litter) – present only in the smallest channel surveyed, indicative of the lack of dominance of fluvial processes.

Detailed cross sections

In addition, detailed channel cross section sites were established in each reach. Rolled aluminium tubing was hammered into the left and right stream bank until firmly stabilised in the underlying gravel. A cross-beam was placed across the reference pegs and levelled using a spirit level. The distance (height) was measured from the cross-beam down to the bank or stream substrate to the nearest millimetre. This equipment is shown in Figure 6. For narrow sections (≤140 cm), height and substrate type were measured every 5 cm. At wide sections (140-180 cm) height and substrate were measured every 10 cm. Height and depth of any left and/or right back undercuts were also measured to the nearest centimetre. A detailed description of the cross section measurement method to be followed for repeat measurements can be found in Appendix 3.

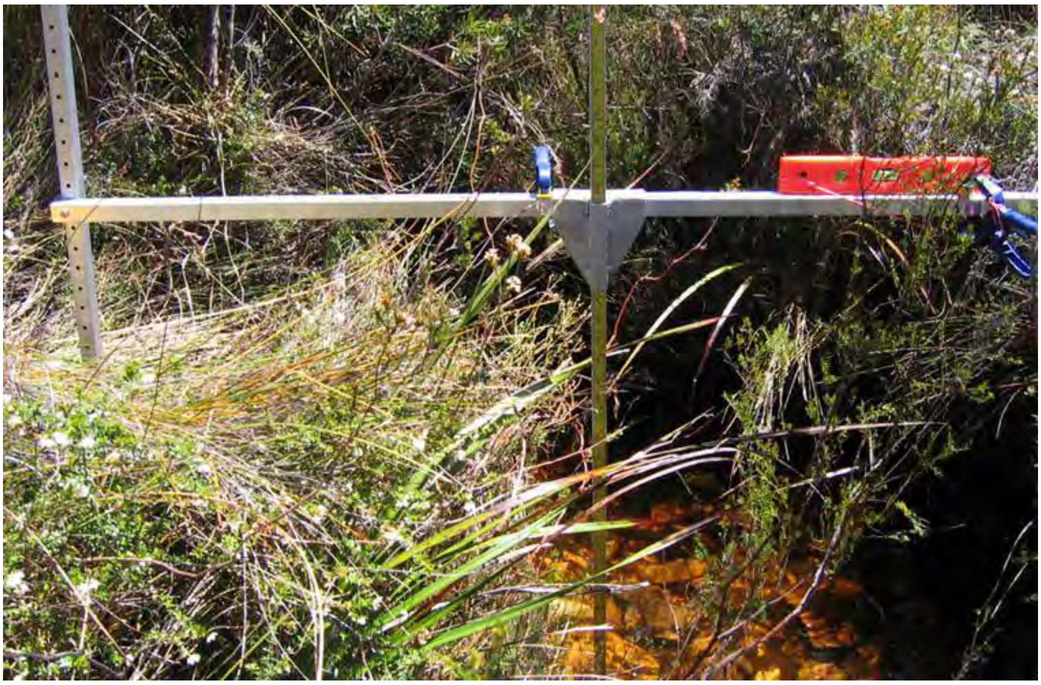


Figure 6. The measurement frame set up over a permanent cross section on Reach 1 of Gelignite Creek.

Data analysis

Results from detailed cross sections were used to calculate rates of channel change, and undercut cross sectional area. Several cross sections were excluded from calculations where the data was felt to be untrustworthy. In several cases this was because of a complete lack of resemblance between the 2004 and 2009 measurements, suggesting errors in cross section re-location. Another reason was significant channel contraction caused by apparent deposition on near vertical banks, as there is no obvious geomorphic process that could achieve this. It is more likely that on these upright banks, a small error in horizontal measurement occurred that caused a large error in vertical measurement.

Rates of channel change were calculated from the detailed cross sections. On each cross section, a bankfull level was identified from the break of slope on one or both banks. The cross sectional area was calculated from this level for both years of measurement. Any difference in cross sectional area was expressed in cm^2, and as a proportion of the 2004 cross section.

The undercut cross sectional area was calculated using the measurement of vertical height and depth into the stream bank, assuming the undercut narrowed towards the back in a triangle. This was not always the case, but detailed measurements of undercut form were not possible.

In-stream sediment transport measurement

A sediment trap was used to monitor stream bed-load and particle size distribution in Gelignite Creek. The trap has been in use since January 2005. The trap was installed approximately 15 m upstream of the weir. This is upstream of any backwater effects from the weir. The sediment trap (30 x 50 x 35 cm) spanned most of the width of the open stream channel, with less than 10 cm on either side to allow for a lip on the trap and room to lift the trap out of the channel for emptying. Undercuts are present at the site, and were not sampled by the sediment trap. The trap was positioned at the downstream end of a straight run with incised banks. The rate of sediment movement was found to be very small in the stream and so samples were collected only after some sediment had accumulated and when flow conditions allowed the trap to be returned to the stream without contamination.

Samples collected from the in-stream sediment trap were oven dried, at 105°C and then at 500°C to determine total dry weight and ash-free dry mass (loss on ignition). Material retained after muffling was sieved (64 µm and 2 mm mesh; Rowe Test Sieves) and weighed to determine the proportions of each particle size classes (<64 µm – fines, 64 µm to 2 mm – sand, 2 to 64 mm – gravel, >64 mm – cobble). Particles larger than 2 mm were hand measured.

Suspended sediment was monitored through a series of grab samples analysed for total and volatile suspended sediment. Base flow samples were collected opportunistically. High flow samples were collected with an ISCO 3700 Autosampler (Teledyne) during the rising and falling limbs of at least one summer and one winter high flow event. The autosampler was equipped with a stage water level trigger, and set to time-paced sampling. Samples were analysed by Analytical Services Tasmania.

Data storage

All rainfall, stream stage and water chemistry data is stored in the DPIPWE Hydrological Database.

Results

4 Catchment characterisation results

4.1 Vegetation

Interpretation of aerial photographs yielded three classes of vegetation: Buttongrass, Sparse buttongrass and Scrub/forest. This mapping and the locations of vegetation monitoring quadrats sampling each class are shown in Figures 7 and 8. From these maps, and from Table 3, it can be seen that the Gelignite Creek catchment is dominated by buttongrass with a small proportion of scrub and sparse vegetation. In contrast, Condominium Creek is almost 40% scrub and forest.

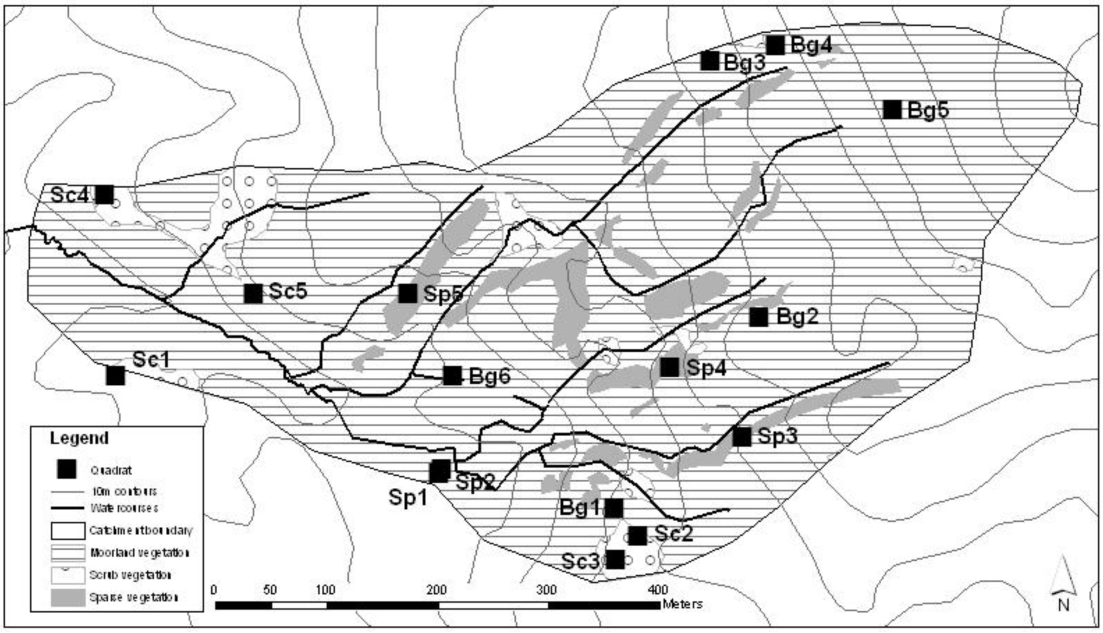


Figure 7. Vegetation classes from aerial photograph interpretation and the locations of monitoring quadrats at Gelignite Creek.

Table 3. Cover of the three identified vegetation classes in the Gelignite and Condominium Creek catchments.

	Buttongrass		Sparse buttongrass		Scrub/forest	
	Area (ha)	**Percent**	**Area (ha)**	**Percent**	**Area (ha)**	**Percent**
Gelignite	24.5	88	1.9	7	1.3	5
Condominium	9.1	59	0.3	2	6.0	39

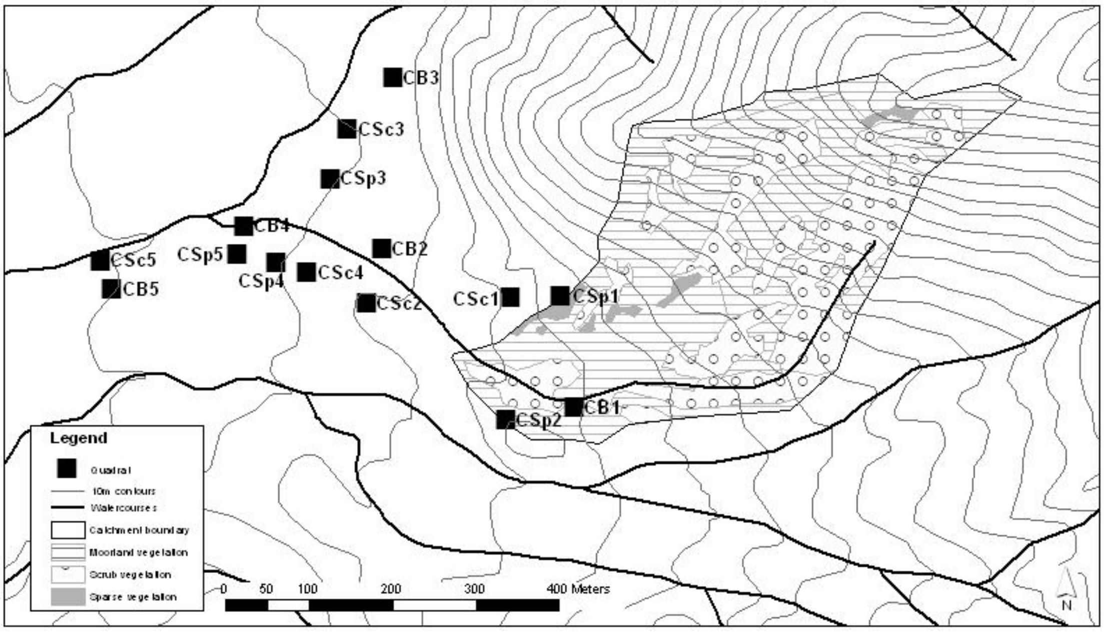


Figure 8. Vegetation classes from aerial photograph interpretation and the locations of monitoring quadrats at Condominium Creek.

4.1.1 Floristics

The multidimensional scaling of the floristic data for all quadrats delivered adequate stress levels (12.2) with two dimensions. The result is shown in Figure 9. The buttongrass quadrats and the sparse quadrats form two abutting but clear groups. Species correlations with the ordination axes showed that the differentiation between these two groups was caused by an increasing dominance of *Gymnoschoenus* in the buttongrass plots, and increasing cover of *Bauera rubioides* in the sparse plots. In contrast to these two groups, the scrub quadrats are highly variable. This matches with field observations that areas identified on the aerial photographs as scrub include forest copses with mature *Eucalyptus nitida*, and areas of tall heath where the shrub strata is high and dense. The former is floristically distinct. These quadrats fall at the bottom right of Figure 9. The tall heath sites have some similarities to buttongrass sites and on Figure 9 fall close to the buttongrass sites.

Note that the Condominium catchment includes substantial areas of wet forest and rainforest, which have not to date been surveyed and are at present lumped in the scrub category. If this survey was completed, it would be expected that those quadrats would form a further distinct cluster.

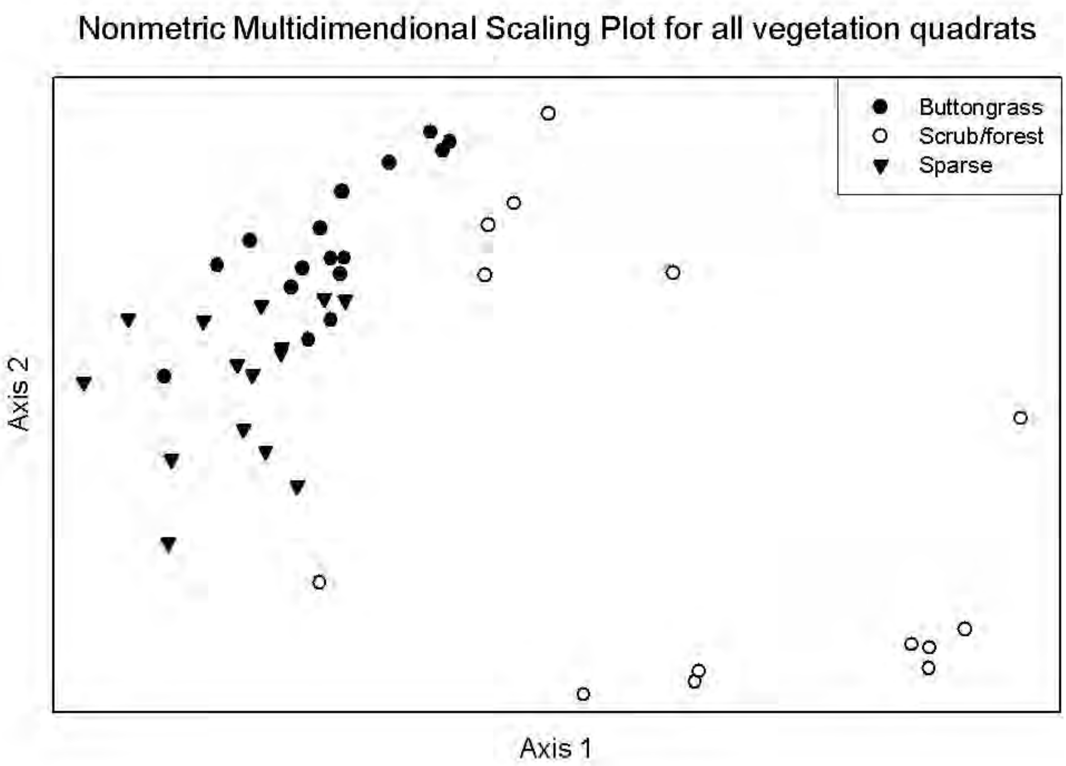


Figure 9. Plot of the first and second axis from the NMS of vegetation plots at Gelignite and Condominium Creeks.

4.1.2 Vegetation structure

Vegetation volume

The vegetation volume index calculated for both catchments is shown in Table 4. From this it can be seen that buttongrass vegetation has a moderate and fairly consistent vegetation volume, scrub vegetation has a much higher and more spatially variable vegetation volume. As might be expected, sparse vegetation has the lowest vegetation volume. A breakdown of results from 2004 and 2009 at Gelignite Creek revealed only small differences likely to be artefacts of different field staff. This data is not presented here.

Note that the vegetation volume index for Condominium Creek is likely to be a significant underestimate. This was caused by insufficient data for dense forest and rainforest areas, which have been included in the 'Scrub' class.

These results show that, as might be expected, scrub contributes a large proportion of vegetation volume across both catchments. Largely because of the greater cover of scrub and forest at Condominium Creek, this catchment has a vegetation volume index per unit area almost double that of Gelignite Creek. This difference would be greater if denser forest and rainforest patches at Condominium Creek had been surveyed.

Table 4. A comparison of the vegetation volume index for the study catchments. Results for Gelignite Creek are averaged across both sampling years. *This volume is underestimated due to a field sampling bias away from denser forest types.

Vegetation type	% of catchment area	Average volume(m^3) of vegetation per quadrat (range)	Total vegetation volume (m^3) per catchment	% of vegetation volume per catchment
Gelignite Creek				
Buttongrass	88.4	2.68 (2.12 – 3.15)	164,168	68.2
Scrub	4.8	20.98 (4.06 – 33.77)	69,660	28.9
Sparse	6.8	1.47 (0.81 – 2.13)	6,954	2.9
All types	**100.0**	**347.11**	**240,781**	**100.0**
Condominium Creek				
Buttongrass	58.9	2.09 (0.92 – 3.27)	47,496	18.8
Scrub	39.0	*13.54 (2.48 – 32.41)	203,663	80.8
Sparse	2.2	0.98 (0.32 – 1.65)	820	0.3
All types	**100.0**	***652.58**	**251,978**	**100.0**

Vegetation density

Vegetation density data is only available for Gelignite Creek. The results are shown in Table 5. From this it can be seen that the density of the ground strata is typically highly variable within a 2 m quadrat, including some areas of almost bare ground, and some thickly mulched by live and dead vegetation. However, there are some general trends. Buttongrass vegetation tends to be dominated by denser biomass categories. Sparse vegetation is reliably dominated by the lower density categories. Scrub vegetation is highly variable between quadrats, reflecting the variation in character of the vegetation included in this group.

Table 5. Density of vegetation strata at Gelignite Creek, 2009 data, generalised across each vegetation type. For ground strata, value is the average cover of specified litter density across all quadrats within the vegetation type, with the range in brackets. For shrub and tree strata, value is the median observation across all quadrats.

			Ground			**Shrub**	**Tree**
	very low	**low**	**moderate**	**high**	**very high**		
Buttongrass	0 (0-0)	7.5 (0-10)	28 (5-60)	37 (20-60)	27 (0-70)	medium	none
Scrub	12 (0-50)	48 (20-70)	16 (0-40)	18 (0-60)	6 (0-20)	high	medium
Sparse	30 (20-40)	26 (10-40)	25 (0-40)	12 (10-20)	5 (0-10)	low	none

4.2 Soils

Soil character varies across the Gelignite catchment, probably in response to a combination of topography, vegetation, underlying substrate and fire history. Soil sampling occurred at vegetation monitoring quadrats. Soil character was relatively uniform across the buttongrass quadrats, but both scrub and sparse vegetation were more variable. Scrub sites fell into two groups which matched the floristic division – sites dominated by *Eucalyptus nitida* scrub and those dominated by tall heath. The sparse sites show a dichotomy that is not obvious in the vegetation data, between sites with deeper soil and those with shallow soil. Table 6 summarises the characteristics of soils across all quadrats.

Three basic groups of soils have been described – those under *E. nitida* (Sc1, Sc3 and Sc4), those under moorland, including tall heath and some sparse vegetation (Sc2, Sc5, Bg1 Bg2, Bg3, Bg4, Bg5, Sp1, Sp2 and Sp5), and shallow soil under sparse vegetation (Sp3 and Sp4). Photographs of examples of scrub, buttongrass and sparse soils appear in Figure 10.

Soils under *E. nitida* scrub, described from two pits, have a surface horizon of fibric organic deposits that are the least humified of any in the catchment (H2 on von Post humification scale). The depth of this fibric horizon is highly variable, from a few centimetres to tens of centimetres. Where it is deep, there is typically some increase in humification and decrease in organic content with depth. Mineral horizons are variable in depth and texture and probably mainly reflect the underlying substrate. Live root density is high in organic horizons. These soils are generally much drier than those of surrounding areas.

Soils under moorland are described from 10 soil pits. They have a characteristic pattern of an upper horizon of reddish brown fibric organic deposits above a second organic horizon of well decomposed sapric material that is generally dark brown or black. This is typically underlain by a sandy mineral horizon with variable content of gravel, clay and organic material. Root density is very high in the organic horizons, and medium to low in the mineral horizons. These soils are typically wetter than those under forest, and it is notable that the organic horizons are often much wetter than the underlying sandy layers.

Shallow soils under sparse vegetation are described from only two pits. However, they are distinctive in that they have a single organic horizon of hemic deposits, intermediate between the undecomposed fibric and well decomposed sapric horizons found on standard moorland soils. Underlying mineral horizons are similar to those of deeper moorland soils. Root density is high to very high in the organic horizons, and medium to low in mineral horizons.

A

B

C

Figure 10. Examples of (A) a scrub soil (site Scrub 4), (B) a buttongrass soil (site Buttongrass 3) and (C) a sparse soil (site Sparse 4).

Table 6. A comparison of basic soil characteristics across Gelignite Creek catchment. Sites are grouped according to vegetation class, but the Scrub class has been further split into *E. nitida* and tall heath, and the Sparse class into shallow and deep soil. Almost all soil pits reached angular quartzite gravel in a sandy matrix at the base. *Note results from Buttongrass 6 have been excluded due to possible errors in the data.

Horizon	Depth (cm) to base average (range)	Character	% carbon average (range)	pH average (range)	Conductivity (dS/cm) average (range)
***Eucalyptus nitida* scrub (Sc1, Sc3 and Sc4)**					
Organic horizon	13 (4-25)	Red brown fibric organic deposit	40 (32 – 47)	3.6 (3.3 – 3.8)	0.265 (0.148 – 0.363)
Mineral horizons	29 (14 – 37)	Grey, grey brown or mottled clay or loamy sand.	8 (6-10)	3.9 (3.8 – 4.1)	0.132 (0.152 – 0.110)
Tall Heath (Sc2 and Sc5)					
Organic horizon 1	13 (12-14)	Reddish brown fibric organic deposit	39 (38 – 40)	3.9 (3.7 – 4.2)	0.371 (0.317 – 0.426)
Organic horizon 2	31 (27 – 35)	Dark brown to black sapric organic deposit	29 (16 – 42)	4.0 (3.9 – 4.0)	0.118 (0.100 – 0.136)
Mineral horizons	34 (33 – 35)	Grey brown clay loam, variably sandy	NA	NA	NA
Buttongrass (Bg1 Bg2 Bg3 Bg4 and Bg5)*					
Organic horizon 1	8.5 (7 – 11)	Reddish brown fibric organic deposit	40 (36 – 49)	3.7 (3.6 – 3.8)	0.297 (0.201 – 0.528)
Organic horizon 2	27 (15 – 35)	Brown to dark brown sapric organic deposit	30 (24 – 43)	3.8 (3.6 – 4.0)	0.180 (0.154 – 0.234)
Mineral horizons	40 (36 – 45)	Grey to dark grey sandy clay/sandy clay loam or loamy sand	11 (7 – 16; n=2)	3.9 (3.9 – 3.9)	0.074 (0.056 – 0.091)
Sparse buttongrass on deep soil (Sp1 Sp2 and Sp5)					
Organic horizon 1	15 (12 – 24)	Reddish brown fibric organic deposit	45 (37 – 51)	3.8 (3.7 – 4.0)	0.222 (0.202 – 0.237)
Organic horizon 2	27 (22 – 33)	Brown sapric organic deposit	28 (24 – 36)	4.0 (3.8 – 4.6)	0.109 (0.065 – 0.188)
Mineral horizons	37 (32 – 41)	Grey clayey sand or loamy sand, gravel at base	NA	NA	NA
Sparse buttongrass on shallow soil (Sp3 and Sp4)					
Organic horizon 1	10 (7 – 14)	Reddish brown hemic organic deposit	19 (12-26)	3.9 (3.7 – 4.3)	0.106 (0.072 – 0.141)
Mineral horizons	26 (17 – 26)	Grey clayey sand or loamy sand	3 (1 – 5)	4.2 (4.0 – 4.3)	0.046 (0.042 – 0.050)

5 Catchment hydrology results

5.1 Catchment rainfall

Across the four year study period total annual rainfall at Gelignite Creek ranged between 1348 and 1700 mm, with a slight trend towards increased rainfall during the winter and spring seasons compared with summer and autumn (Table 7). The record at Condominium Creek is much shorter, with annual rainfall for the only complete year (pre fire) at 1462 mm.

Table 7. Rainfall (mm) in Gelignite Creek and Condominium Creek catchments. Total annual rainfall calculated January – December, and seasonal totals; summer (December – February), autumn (March – May), winter (June – August) and spring (September – November). *A data gap of several days exists in these seasons.

	Annual	Summer	Autumn	Winter	Spring
Gelignite Creek					
2005	1529	242	296	444	376
2006	1348	412	386	364	383
2007	1700	238	*436	489	471
2008	1554	282	269	459	532
2009		337	*480		
Condominium Creek					
2007			395	463	420
2008	1462	314	264	420	454
2009		340	428		

A full year of rainfall data was collected at both Gelignite and Condominium Creeks in 2008. These data show the study catchments received similar precipitation during that time, with 1462 and 1554 mm at Condominium and Gelignite Creek, respectively. Moreover, the magnitude and timing of rainfall at the two study sites was very similar as evidenced by their cumulative rainfall during 2008 (Figure 11).

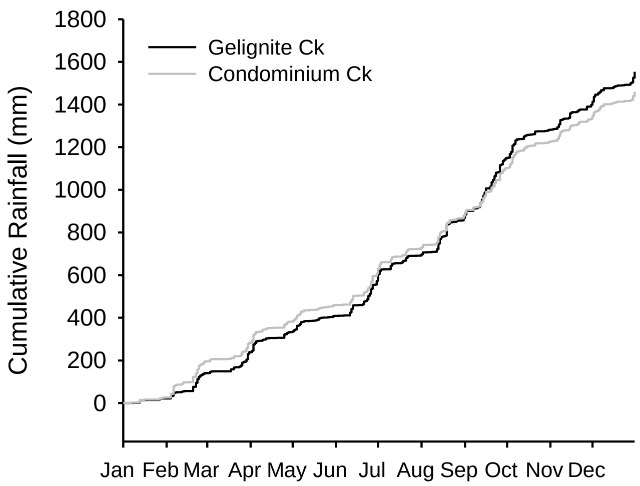


Figure 11. **Cumulative rainfall (mm) collected at the Gelignite and Condominium Creek study catchments in 2008.**

An analysis of the distribution of rainfall through the year shows that each catchment is weakly seasonal, with less rain falling in summer and more in autumn, winter and spring (Table 8). Note that particularly for Condominium Creek, this analysis is based on a very short data set and should be viewed as indicative only.

Table 8. Average seasonal rainfall as a percentage of average annual rainfall in both study catchments. Note that this data is based on a short period of record, and should be regarded as indicative only.

Percent of average annual rainfall	Summer	Autumn	Winter	Spring
Gelignite Creek	19	24	28	28
Condominium Creek	16	28	28	28

An analysis of daily rainfall intensity over the period of record to 2009 for both catchments shows a remarkably similar pattern (Figure 12). The majority of rain days have very little rainfall - around 45% of rain days total 2 mm or less, and yield less than 6% of the rain. The majority of rainfall occurs across a smaller number of medium intensity rain days - around a third of rain days total between 5 and 25 mm and yield 65% of rainfall.

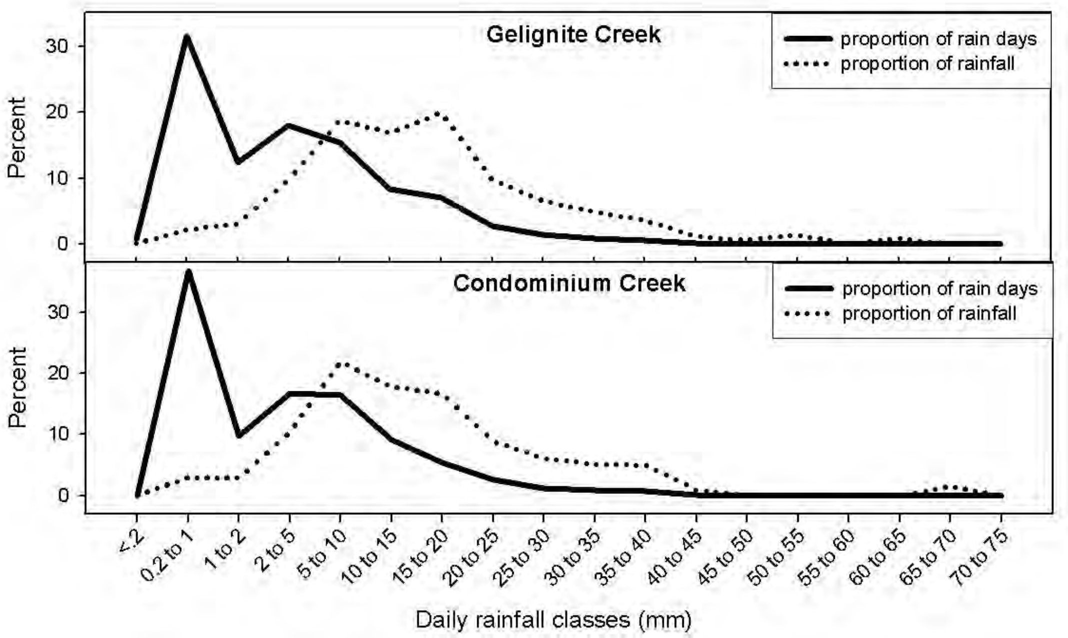


Figure 12. The relationship between frequency of daily rainfall and proportion of total rainfall in Gelignite Creek and Condominium Creek catchments.

5.2 Stream discharge

5.2.1 Overview

At Gelignite Creek, stream level was measured from the end of August 2004 (Table 9). However, this four and a half year period of record was interrupted by two significant periods where a leak around the weir reduced the accuracy of flow measures. Good quality data is available for roughly three years. Only this good quality data was used to generate the flow statistics discussed below. At Condominium Creek, stream level was measured continuously from July 2006 (Table 10).

Ratings have been developed to convert stream level to flow at both Gelignite and Condominium Creeks. However, a shortage of data points at high flow means that these ratings are classed as poor. Ratings may be refined in the future as more data becomes available.

Table 9. Average stream flow (L/s) by month at Gelignite Creek for the period of record. *Months that include poor quality data.

Gelignite Ck	2004	2005	2006	2007	2008	2009
January		*6.0	*4.0	11.0	0.0	6.3
February		*1.8	*2.4	0.1	1.7	2.6
March		*0.7	*1.9	1.9	3.9	8.7
April		*6.1	*22.7	1.1	6.3	11.1
May		*13.7	*13.0	23.0	4.7	16.1
June		*1.4	8.3	4.7	13.5	
July		*15.5	16.9	11.8	11.3	
August	19.6	*25.8	13.2	26.1	12.8	
September	11.5	*7.2	17.6	15.7	23.7	
October	8.7	*16.7	11.6	*21.6	9.5	
November	9.3	*8.9	4.4	*0.1	5.1	
December	*6.3	*24.3	3.7	*5.9	8.4	
Annual		**10.7**	**10.0**	**10.2**	**8.4**	

Table 10. Average stream flow (L/s) by month at Condominium Creek for the period of record.

Condominium Ck.	2006	2007	2008	2009
January		4.8	0.0	3.6
February		0.2	2.8	2.0
March		1.3	1.5	4.0
April		0.8	3.3	5.0
May		8.4	2.5	7.7
June	5.2	3.6	6.2	
July	9.7	5.2	5.8	
August	5.7	13.5	5.9	
September	7.9	7.8	9.1	
October	4.7	9.2	4.8	
November	1.6	0.2	2.6	
December	1.2	1.5	2.6	
Annual	**5.1**	**5.9**	**5.3**	

Average flow at the Gelignite Creek across the whole record (good data only) is 10.12 L/s with a standard deviation of 1.5 L/s. Stream discharge duration analysis indicates the stream has effectively zero flow for 4% of the time, less than 1.2 L/s discharge for around 50% of the time, and exceeds 24.5 L/s less than 10% of the time (Figure 13 Left).

Average flow at the Condominium Creek weir across all years (2006-2009) was only 4.9 L/s, with a standard deviation of only 0.3 L/s. Stream discharge duration analysis shows Condominium Creek has a discharge less than 1 L/s for around 50% of the time (Figure 13 Right). No periods of zero flow have been recorded, and flows over 10 L/s were observed only 10% of the time.

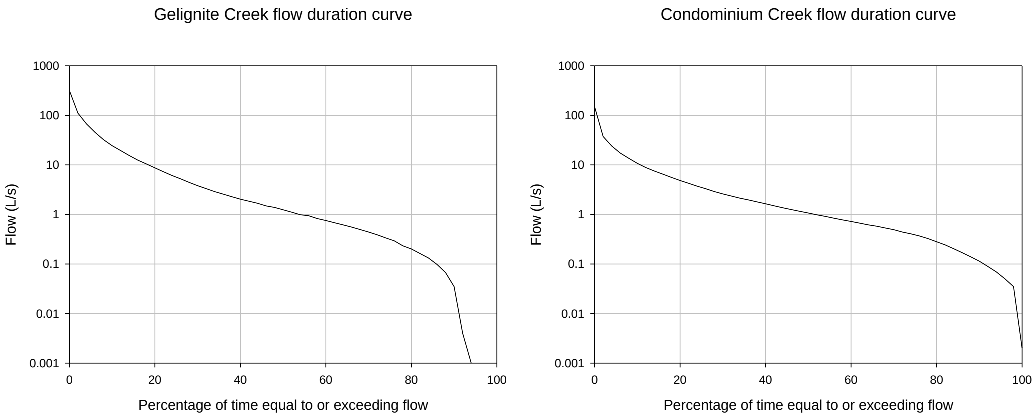


Figure 13. Flow duration curve for Gelignite Creek (left), based on data from August 2004 to May 2009 and Condominium Creek (right) based on data from June 2006 to May 2009.

5.2.2 Diurnal fluctuations

During periods of very low base flow, both Gelignite and Condominium Creeks show a distinct diurnal variation in flow (Figure 14).

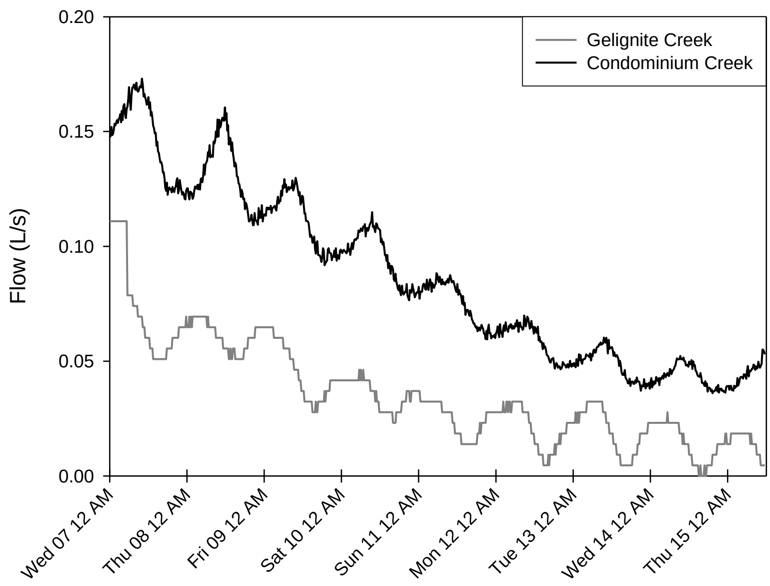


Figure 14. Diurnal flow fluctuations at very low discharge in February 2007. Variability in flow over 24 hrs is approximately equal to 5 or 6 mm in stream level at Gelignite Creek, and up to 3 mm at Condominium Creek.

Although small, if these fluctuations are real, they could constitute a significant proportion of the daily flow rate. In Gelignite Creek, this can be as much as 6 mm in stream depth, which is beyond the reported ±2 mm sensitivity of the depth sensor. However, similar diurnal variations are present in the depth record from the summer of 2006, when the leaky weir meant that the water level had dropped below the water level sensor. For this reason, it is felt that it is not possible to differentiate between a real phenomenon (like that found by (O'Loughlin *et al.*, 1982) and an artifact of the data collection.

5.2.3 Flow seasonality

Both Gelignite and Condominium Creeks show a seasonal flow pattern (Table 11) with summer accounting for a much smaller proportion of the annual flow than winter. This pattern is stronger in Condominium Creek than Gelignite Creek. The seasonal signal in streamflow is stronger than that in rainfall (Table 8).

Table 11. Average seasonal flow as a percentage of average annual flow in Gelignite and Condominium Creeks. Note that the short period of record means that data should be viewed as indicative only. *Calculations for Gelignite Creek include data affected by leaks around the weir in order to create sufficient years for analysis. Given that weir leaks extended across all seasons, it is hoped this will not alter results.

Percent of average annual flow	Summer	Autumn	Winter	Spring
Gelignite Creek*	**14**	**23**	**34**	**30**
Condominium Creek	**12**	**21**	**38**	**29**

Both high and low flow events occur throughout the year at Gelignite Creek. However, there is a distinct seasonal signal, with winter and spring being the most reliably wet seasons, summer the driest, and autumn in between (Table 12). This is particularly evident in the distribution of low flows, with zero flow occurring on average for 17% of summer, and not at all in winter and spring. The seasonal signal is less evident in high flows. However, summer has a smaller proportion of the highest flows, and the largest floods have occurred in winter and spring.

Flow in Condominium Creek is much more strongly seasonal (Table 13). Summer is dominated by flows of less than one liter per second, and has only a small proportion of the larger flows. Winter is by far the wettest season, with none of the low flows (<0.25 L/s) and little of the medium flows (<1 L/s) that occur for almost half the time in summer. Instead, winter is dominated by medium to high flows. The highest flows have occurred in winter. It is notable that unlike Gelignite Creek, Condominium Creek has not had periods of zero flow during the period of record.

Table 12. Flow seasonality in Gelignite Creek, as shown by the proportion of time that flow is less than or equal to the specified volumes.

Flow less than or equal to:	Annual	Summer	Autumn	Winter	Spring
0 L/s	4.5	17.1	2.6	0.0	0.0
0.25 L/s	16.5	46.3	20.4	0.2	4.4
1 L/s	38.9	66.6	44.2	20.8	39.1
10 L/s	80.3	89.6	83.8	75.0	74.9
140 L/s	98.7	99.6	98.8	98.1	98.4

Table 13. Flow seasonality in Condominium Creek, as shown by the proportion of time that flow is less than or equal to the specified volumes.

Flow less than or equal to:	Annual	Summer	Autumn	Winter	Spring
0 L/s	0.0	0.0	0.0	0.0	0.0
0.25 L/s	18.3	45.7	19.5	0.0	8.3
1 L/s	48.2	71.7	51.6	26.9	43.2
5 L/s	80.5	90.0	83.8	72.7	75.7
50 L/s	98.8	99.6	98.9	97.9	98.7

5.2.4 Antecedent conditions

Catchment moisture levels prior to a rain event affect both the total size of the flow response, and the lag between rainfall and stream level rises. Neither of these effects has been quantified. However, they can be easily observed in the relationship between rainfall and runoff (see Figures 15 and 16). Small isolated rain events (for example early and mid March 2008) yield little or no increase in flow. Significant rain events after an extended dry period (for example, late March 2008) yield a small and delayed flow increase. Successive rainfall pulses in prolonged events lead to rapid and complex changes in flow, where stage rises and falls are almost simultaneous with variations in rainfall intensity (for example late March and early May 2008).

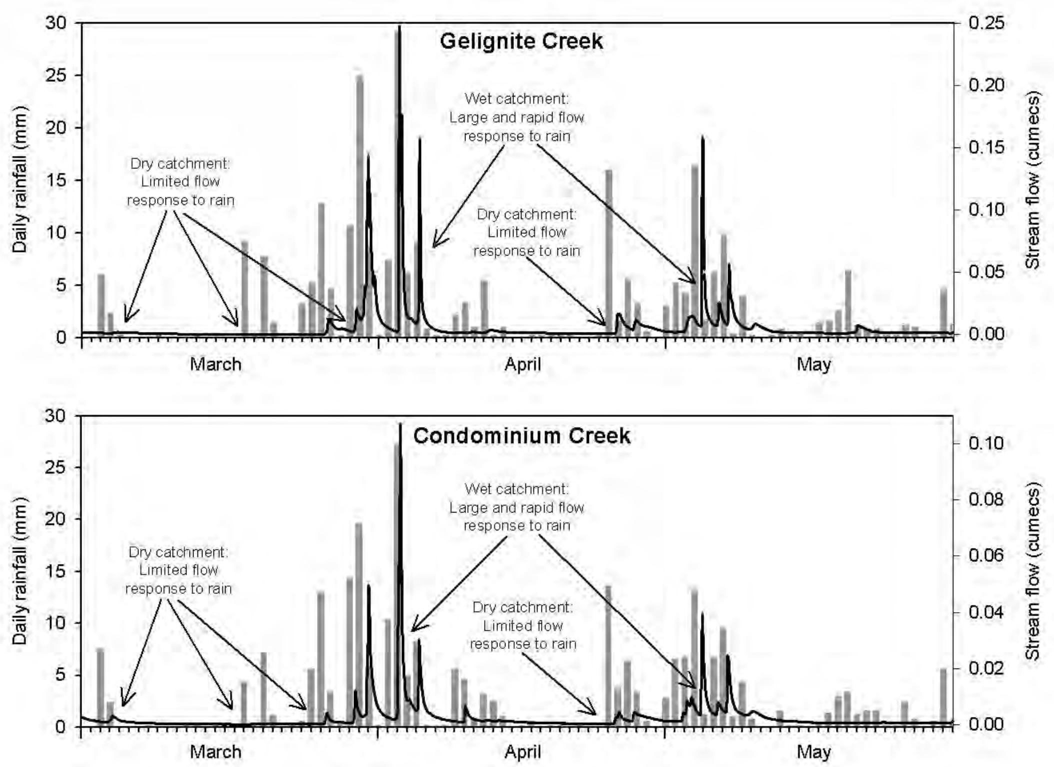


Figure 15. The relationship between antecedent rainfall and flood size at Gelignite Creek (above) and Condominium Creek (below) through autumn 2008. The magnitude of the increase in stream flow depends on rainfall over the preceding days, as well as the individual rain event. Note different scales on stream flow axes.

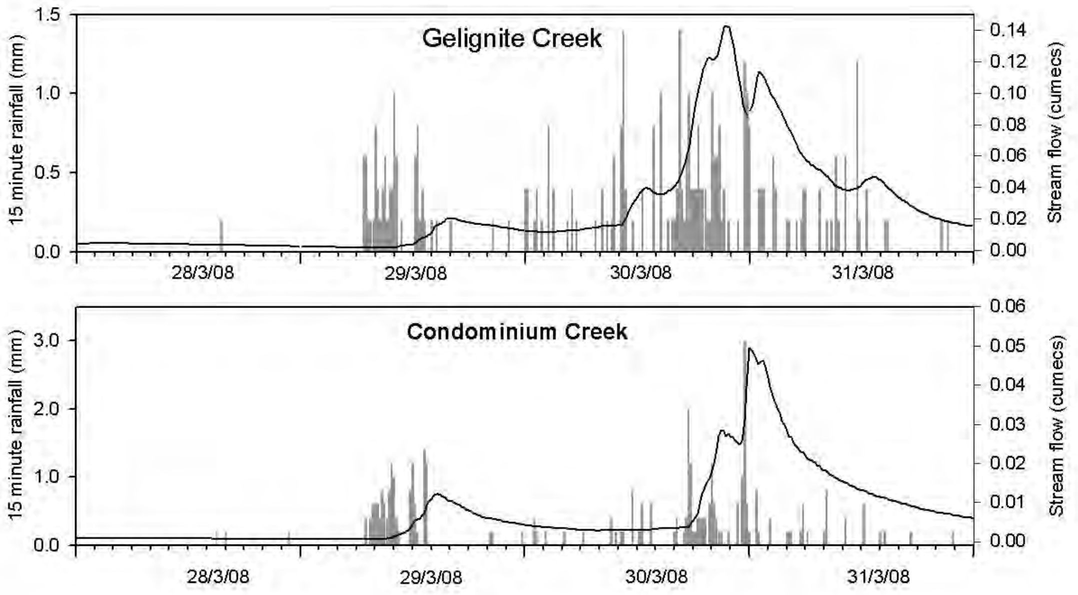


Figure 16. The relationship between antecedent rainfall and flood lag time at Gelignite Creek (above) and Condominium Creek (below) in late March 2008. The time between initial and peak rainfall, and the initial and peak increase in flow depends in part on rainfall over the preceding period. Note different scales on stream flow axes.

5.2.5 Base flow and flashiness

Both catchments have a very flashy hydrology, with extended periods of base flow punctuated by rapidly rising and falling stage in response to rainfall (Figure 15). To some extent, this flow pattern can be characterised using the base flow index. The base flow index indicates the proportion of total stream flow that is delivered as base flow between rain events, as opposed to direct runoff during events. Values range from 0 to 1. Smaller values are indicative of catchments where most discharge occurs as floods during rainfall, with very low flows between events.

Results of the base flow analysis for both catchments are shown in Table 14.

Table 14 Results of base flow index analyses for Gelignite and Condominium Creek catchments. Index calculated using the River Analysis Package, alpha = 0.925. Comparisons should only be made with similarly derived data. To allow comparison with other Tasmanian rivers, BFI results are included from the Huon River at Judbury the Meredith River at Swansea, the Brid River upstream of the tidal limit, and the Duck River upstream of Scotchtown Road. These results reproduced from Water Assessment Branch (2010).

	Base flow index
Gelignite Creek	0.123
Condominium Creek	0.161
Huon River at Judbury	0.281
Meredith River at Swansea	0.112
Brid River upstream of the tidal limit	0.401
Duck River upstream of Scotchtown Road	0.368

From Table 14 it can be seen that base flow represents a relatively small proportion of stream flow in both catchments. This is comparable to dry east coast catchments such as the Meredith River, and a significantly lower proportion than occurs in catchments in climatically similar areas such as the Huon River, which has a much larger proportion of discharge as baseflow. This may in part be an effect of catchment size, as smaller catchments tend to have much flashier hydrology than large ones, but is also likely to reflect the nature of the drainage system.

5.2.6 Specific yield

Specific yield calculations show that Gelignite and Condominium Creek catchments have a similar range of yield relative to rainfall (Figure 17). Gelignite Creek has an average monthly specific yield of 92 mm (or 92 megalitres per km^2). Condominium Creek has a lower average yield of 77 mm (or 77 megalitres per km^2).

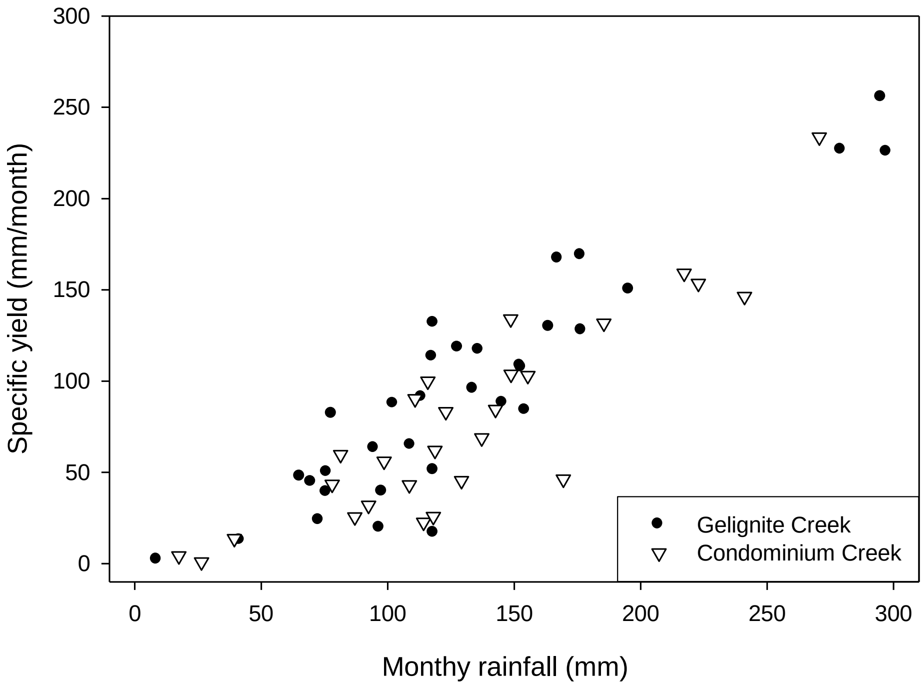


Figure 17. The relationship between monthly specific yield and monthly rainfall at Condominium and Gelignite Creeks.

5.2.7 Flow prediction

Gelignite Creek daily flow predictions

The simple regression that best predicted the variability in Gelignite Creek daily stream flow was between daily flow and rain over a two day period. This relationship explains over 78% of the variability in stream flow (see Table 15 and Figure 18). Almost 82% of the variability in flow could be predicted in a multiple regression using daily rainfall and rain over a three and seven day period (see Table 16 and Figure 19).

Table 15. Results of the simple linear regression between Gelignite Creek daily stream flow and rain over the preceding two days.

Simple regression: daily flow and two day rain					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
Intercept	-2.01293	0.344854	-5.83706	0.0000	
Slope	1.40703	0.022174	63.4547	0.0000	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	357052	1	357052	4026.5	0.0000
Residual	97011.1	1094	88.6756		
Total (Corr.)	454063	1095			
Correlation Coefficient			0.886763		
R-squared =			78.6 percent		
R-squared (adjusted for d.f.) =			78.6 percent		
Standard Error of Est. =			9.41677		
Mean absolute error =			5.73329		
Durbin-Watson statistic =			2.21559 (P=0.0002)		
Lag 1 residual autocorrelation =			-0.10785		
Equation			Flow (L/s) =-2.01293 + 1.40703*two day rain		

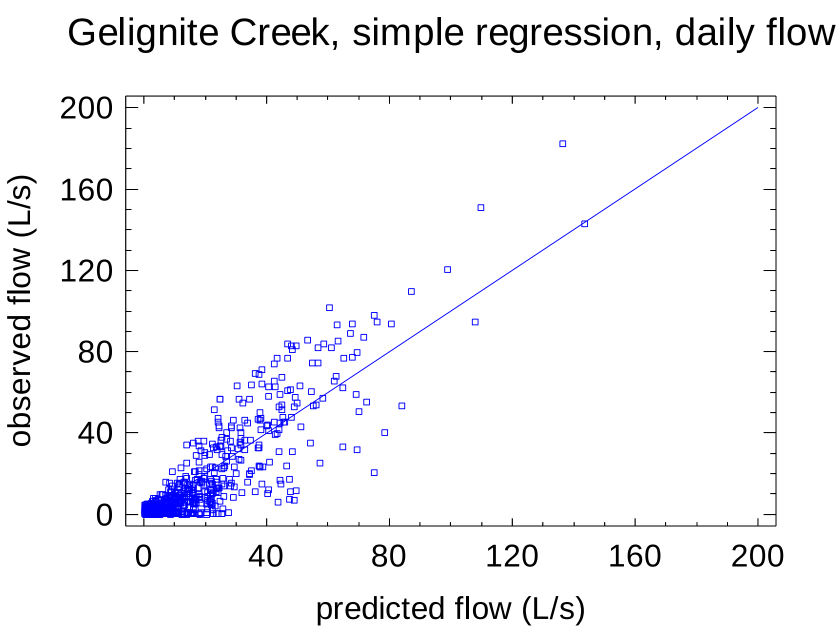


Figure 18. Plot of the observed versus predicted flow for the simple regression between Gelignite Creek daily flow and rainfall over the preceding two days.

Table 16. Results of the multiple regression between daily stream flow at Gelignite Creek and selected rainfall variables.

Multiple regression					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
CONSTANT	-2.83739	0.372521	-7.61672	0.0000	
Daily rain	1.63041	0.047116	34.6044	0.0000	
Three day rain	0.405423	0.027306	14.8473	0.0000	
Seven day rain	0.021785	0.012806	1.70122	0.0889	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	376062	3	125354	1754.92	0
Residual	78001.4	1092	71.4299		
Total (Corr.)	454063	1095			
R-squared =		82.8 percent			
R-squared (adjusted for d.f.) =		82.8 percent			
Standard Error of Est. =		8.45162			
Mean absolute error =		5.4911			
Durbin-Watson statistic =		1.9881 (P=0.4219)			
Lag 1 residual autocorrelation =		0.005926			

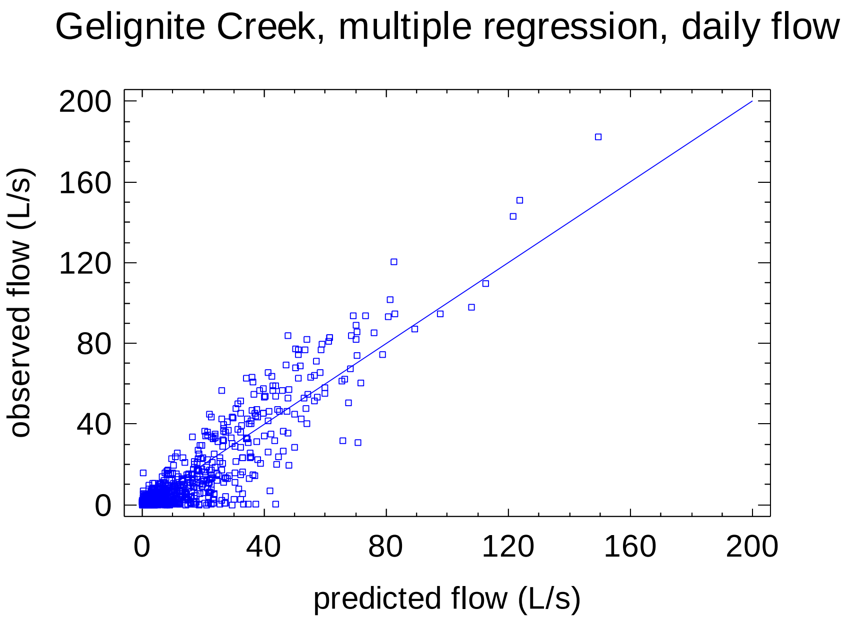


Figure 19. Plot of the observed versus predicted flow for the multiple regression between Gelignite Creek daily flow and selected rainfall variables.

Condominium Creek daily flow predictions

The simple regression that described the greatest proportion of variability in Condominium Creek daily flow was between the square root of daily flow and rainfall over a four day period (see Table 17 and Figure 20). This relationship explains over 67% of the variability in the data. In multiple regression, the best relationship, predicting almost 84% of variability, was between the square root of daily flow and rain over a one, three and seven day period (see Table 18 and Figure 21).

Table 17. Results of the simple regression between the square root of daily stream flow at Condominium Creek and rain over the preceding four days.

Simple regression: square root of daily flow and four day rain					
Parameter	**Estimate**		**Standard Error**	**T Statistic**	**P-Value**
Intercept	0.016833		0.001244	13.5322	0.0000
Slope	0.001935		0.000479	40.3728	0.0000
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	1.11639	1	1.11639	1629.96	0.000
Residual	0.545192	796	0.000685		
Total (Corr.)	1.66158	797			
Correlation Coefficient			0.819685		
R-squared =			67.1883 percent		
R-squared (adjusted for d.f.) =			67.1471 percent		
Standard Error of Est. =			0.026171		
Mean absolute error =			0.018224		
Durbin-Watson statistic =			1.74119 (P=0.0001)		
Lag 1 residual autocorrelation =			0.129061		
Equation			Flow (L/s) =(0.016833 + 0.001935*four day rain)^2		

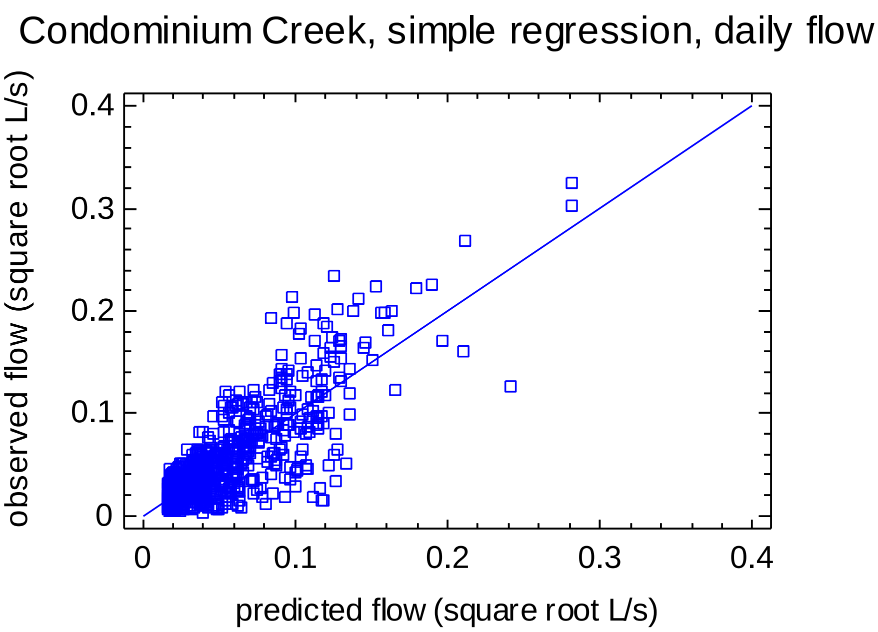


Figure 20. Plot of the observed versus predicted flow for the simple regression between Condominium Creek the square root of daily flow and rainfall over four days.

Table 18. Results of multiple regression between the square root of daily stream flow and selected rainfall variables for Condominium Creek.

Multiple regression					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
CONSTANT	0.007369	0.001334	5.52228	0	
Daily rain	-0.00327	0.000125	-26.1388	0	
Three day rain	0.002707	7.28E-05	37.1932	0	
Seven day rain	0.000348	3.96E-05	8.78766	0	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	1.39362	4	0.348405	1031.08	0
Residual	0.267958	793	0.000338		
Total (Corr.)	1.66158	797			
R-squared =		83.8733 percent			
R-squared (adjusted for d.f.) =		83.7919 percent			
Standard Error of Est. =		0.018382			
Mean absolute error =		0.01274			
Durbin-Watson statistic =		1.36535 (P=0.0000)			
Lag 1 residual autocorrelation =		0.31702			

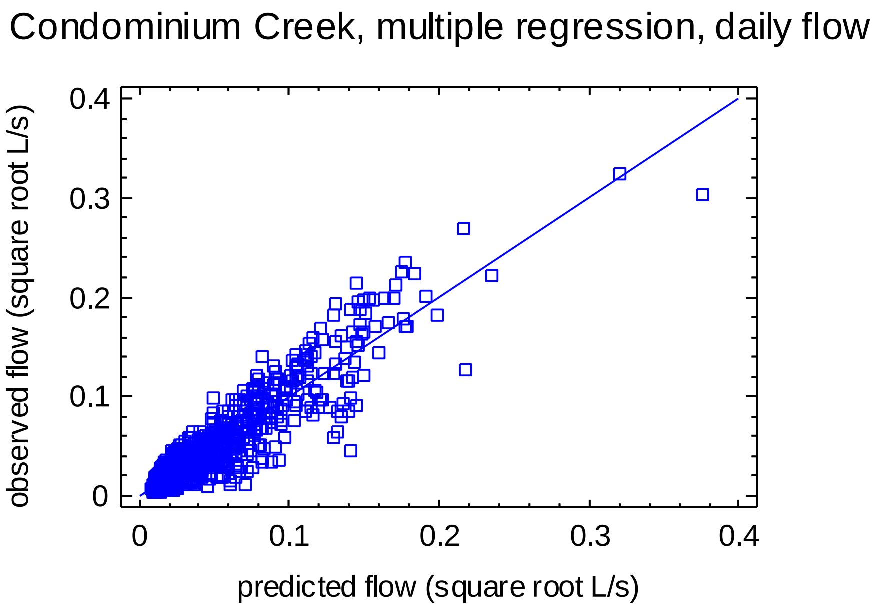


Figure 21. Plot of the observed versus predicted flow for the multiple regression between Condominium Creek the square root of daily flow and selected rainfall variables.

Gelignite Creek peak flow predictions

The best basic prediction of maximum daily stream flow in Gelignite Creek comes from a simple regression of maximum flow per day against total daily rain. This regression explains 73% of the variability in maximum flow (see Table 19 and Figure 22).

Table 19. Results of a simple regression between maximum daily flow and total daily rainfall for Gelignite Creek.

Simple regression, Max daily flow against Rain 1 day total.					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
Intercept	-0.177056	1.12508	-0.157372	0.87490	
Slope	6.88184	0.126237	54.5151	0.0000	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	3116610	1	3116610	2971.9	0.000
Residual	1150420	1097	1048.69		
Total (Corr.)	4267020	1098			
Correlation Coefficient =			0.854631		
R-squared =			73.0394 percent		
R-squared (adjusted for d.f.) =			73.0148 percent		
Standard Error of Est. =			32.3835		
Mean absolute error =			17.2602		
Durbin-Watson statistic =			1.81828 (P=0.0013)		
Lag 1 residual autocorrelation =			0.0907629		
Equation			Max flow (L/s) =-0.177056 + 6.88184*one day rain		

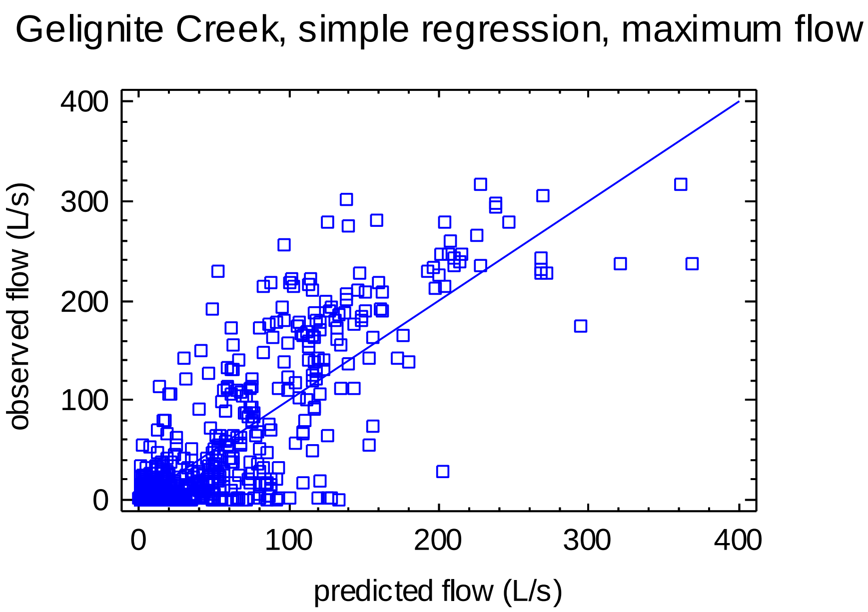


Figure 22. The plot of observed versus predicted data for the Gelignite Creek maximum flow simple regression

The result of the multiple regression that best explained the variability in maximum daily stream flow in Gelignite Creek was with daily, five day, ten day and three week rain. This can be seen below in Table 20 and Figure 23. This regression explained over 75% of the variability in stream flow, and was highly significant.

Table 20. Results of multiple regression between maximum daily flow and selected rainfall variables for Gelignite Creek.

Multiple regression					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
CONSTANT	-8.61051	1.84341	-4.67096	0	
Daily rain	6.15825	0.143115	43.0301	0	
Five day rain	0.513963	0.069116	7.43624	0	
Ten day rain	-0.12395	0.052234	-2.37299	0.0176	
Three weeks rain	0.063144	0.025463	2.47979	0.0131	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	3209510	4	802376	830.06	0
Residual	1057520	1094	966.652		
Total (Corr.)					
R-squared =	75.2165 percent				
R-squared (adjusted for d.f.) =	75.1259 percent				
Standard Error of Est. =	31.091				
Mean absolute error =	18.3128				
Durbin-Watson statistic =	1.88022 (P=0.0235)				
Lag 1 residual autocorrelation =	0.0597115				

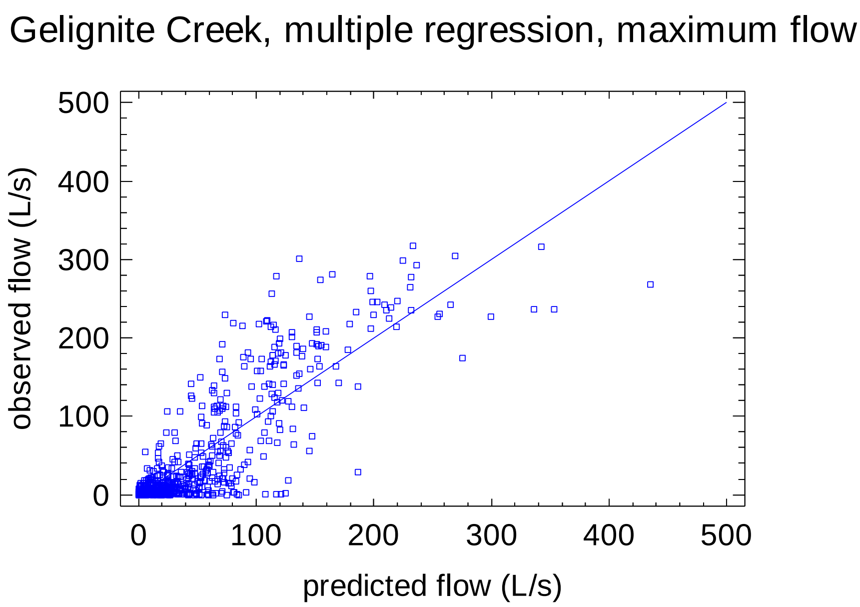


Figure 23. The plot of observed versus predicted data for the Gelignite Creek maximum flow multiple regression

Condominium Creek peak flow predictions

The best basic prediction of maximum daily stream flow in Condominium Creek comes from a simple regression of maximum flow per day against total rain over two days. This regression explains 78% of the variability in maximum flow (see Table 21 and Figure 24).

Table 21. Results of a simple regression between maximum daily flow and two day rainfall for Condominium Creek.

Simple regression, Square root of Max daily flow against two day rain					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
Intercept	0.710427	0.048849	14.5433	0.000	
Slope	0.172637	0.003275	52.7156	0.000	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	3429.32	1	3429.32	2778.94	0
Residual	958.85	777	1.23404		
Total (Corr.)	4388.17	778			
Correlation Coefficient =			0.884021		
R-squared =			78.1492percent		
R-squared (adjusted for d.f.) =			78.1211percent		
Standard Error of Est. =			1.11087		
Mean absolute error =			0.715011		
Durbin-Watson statistic =			1.63368 (P=0.0000)		
Lag 1 residual autocorrelation =			0.181555		
Equation			Flow (L/s) =(0.710427+ 0.172637*two day rain)^2		

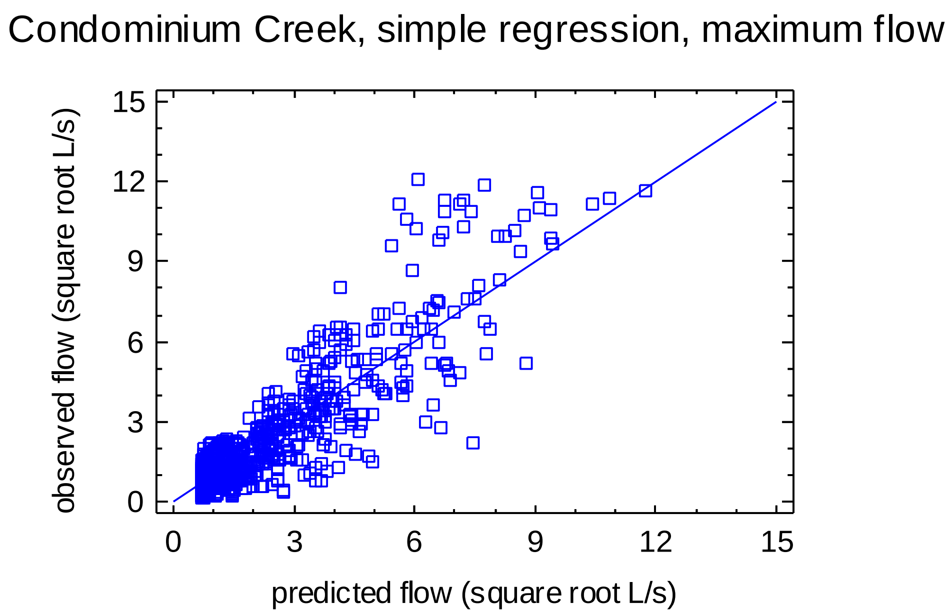


Figure 24. The plot of observed versus predicted data for the Condominium Creek maximum flow simple regression

The result of the multiple regression that best explained the variability in maximum daily stream flow in Condominium Creek was between the square root of maximum daily flow and two day, five day and three week rain. This can be seen below in Table 22 and Figure 25. This regression explained over 80% of the variability in stream flow, and was highly significant.

Table 22. Results of a multiple regression between Condominium Creek maximum daily flow and various rainfall parameters.

Multiple regression					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
CONSTANT	0.158055	0.077146	2.04878	0.0405	
Two day rain	0.150016	0.004353	34.4623	0.0000	
Five day rain	0.011643	0.002601	4.4765	0.0000	
Three weeks rain	0.005501	0.000869	6.33072	0.0000	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	3539.14	3	1179.71	1076.85	0.0000
Residual	849.033	775	1.09553		
Total (Corr.)	4388.18	778			

R-squared =	80.6518 percent
R-squared (adjusted for d.f.) =	80.5769 percent
Standard Error of Est. =	1.04667
Mean absolute error =	0.616215
Durbin-Watson statistic =	1.7721 (P=0.0007)
Lag 1 residual autocorrelation =	0.11316

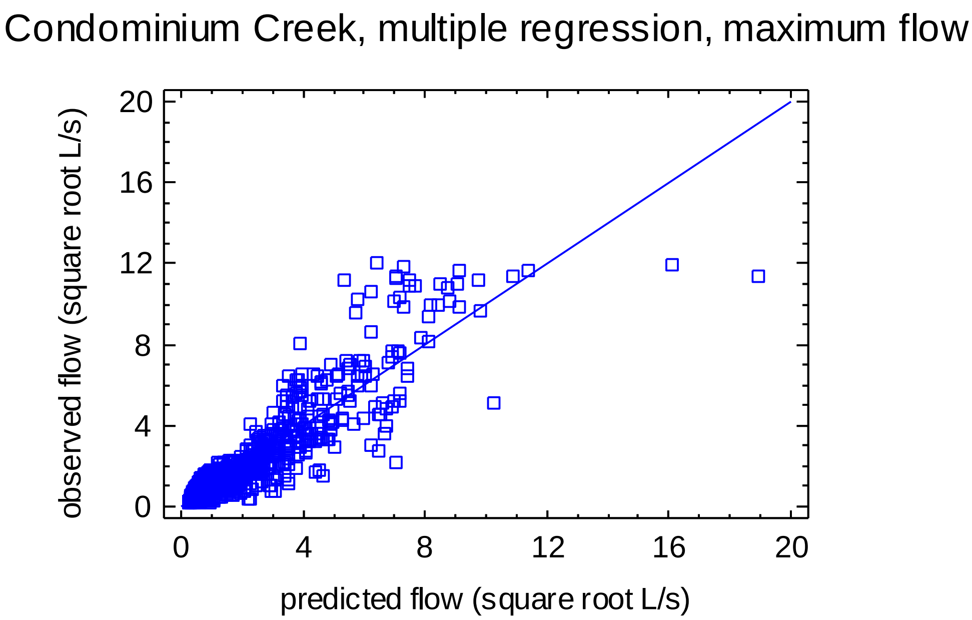


Figure 25. The plot of observed versus predicted data for the Condominium Creek maximum flow multiple regression

5.2.8 Bankfull flow

In the 2008 calendar year, Gelignite Creek reached bankfull flow stage (arbitrarily set at 30 cm) in 27 events separated by at least 24 hours. This flow level was exceeded for 2.6% of the year.

5.2.9 Dominant discharge

The results of the regression analysis between measured suspended sediment and turbidity at Gelignite Creek can be found below in Table 23, and viewed in Figure 26. This relationship between suspended sediment and turbidity should be viewed as tentative, as it explained only 63% of the variability in suspended sediment data and is based on a limited data set. This relationship was used as a basis for calculating the relationship between suspended sediment load and flow (Figure 27). This relationship shows that no single flow range dominates the transport of fine sediment. Rather, a wide range of lower flows are responsible for the bulk of fine sediment movement.

Table 23. Results of the regression between suspended sediment and turbidity in Gelignite Creek.

Multiple regression					
Parameter	**Estimate**	**Standard Error**	**T Statistic**	**P-Value**	
Turbidity (NTU)	3.7890	0.5004	7.5725	0.0000	
Analysis of Variance					
Source	**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-Ratio**	**P-Value**
Model	4883.463	1	4883.463	57.34319	0.0000
Residual	2384.537	28	85.16204		
Total (Corr.)	7268	29			
R-squared =			67.1912 percent		
R-squared (adjusted for d.f.) =			63.6198 percent		
Standard Error of Est. =			9.22832		
Equation		TSS(mg/L) = 3.78900*Turbidity(NTU)			

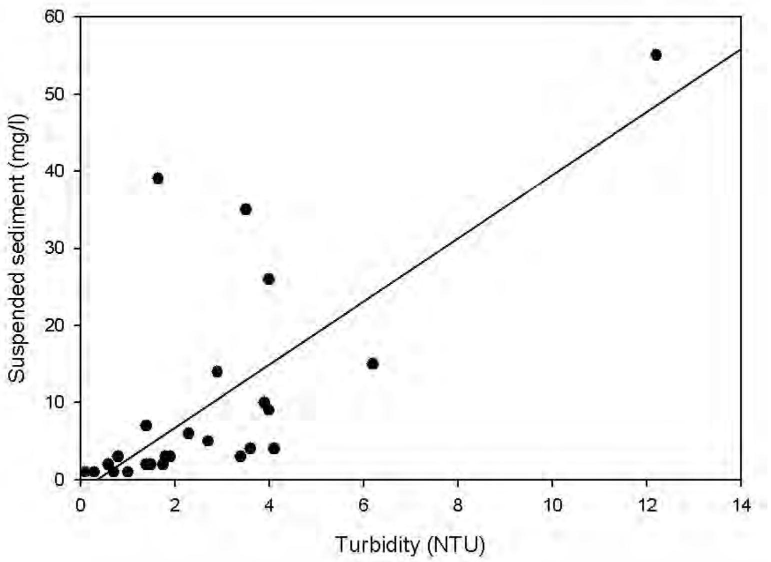


Figure 26. The turbidity and suspended sediment dataset with the regression line.

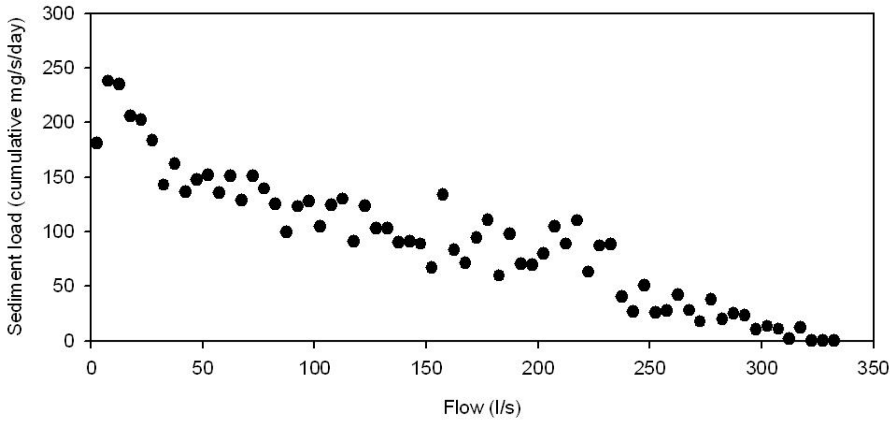


Figure 27. The relationship between estimated average suspended sediment load and flow at the Gelignite Creek weir site.

5.2.10 Observations of hillslope hydrology

No quantitative measurements of soil or slope hydrology have been made. However, the following observations do provide some indications of processes.

During extended rain events overland flow is very widespread under buttongrass and sparse vegetation. Typically, all surface depressions are full, and water can be observed flowing between them. This is the case on upper and convex slopes, as well as lower or concave slopes.

Crayfish burrows sometimes act as conduits for water and sediment. During rain events, it is not unusual to see water and sediment 'fountaining' out of burrows on slopes. Burrows can also transport sediment, with deposits of sand or fine organic material evident around some entrances. This implies water flowing rapidly through passages from the base of the organic soil to the surface. The source of water has not been investigated, but might be overland flow captured by upslope burrow entrances, throughflow from the organic soil horizons, or from the underlying mineral soil horizons.

Soil pits have been dug across the catchment at several times, allowing the following observation of soil moisture patterns. In moorland areas organic horizons may be wet or saturated when the underlying sandy soil is almost dry. On some occasions, water has been observed ponding on the soil surface when the deeper soil profile is almost dry.

There is also a contrast between the soils of moorland areas and those of scrub and forest. The fibrous organic horizons of forested areas have been observed to be dry or only very slightly damp when the organic horizons of moorland areas are still very wet.

5.3 Stream chemistry

Temperature

Stream temperature at Gelignite Creek fluctuates throughout the year with highest temperatures in summer and lowest in winter. Mean monthly temperature ranges between

5.7 and 11.8°C with an overall mean of 8.6°C (Figure 28). Although average temperature is very consistent, daily in-stream conditions vary considerably depending on flow regime. Stream temperature is well moderated when the stream is flowing but during periods of zero flow, typically during summer, temperature can vary as much as 20°C a day.

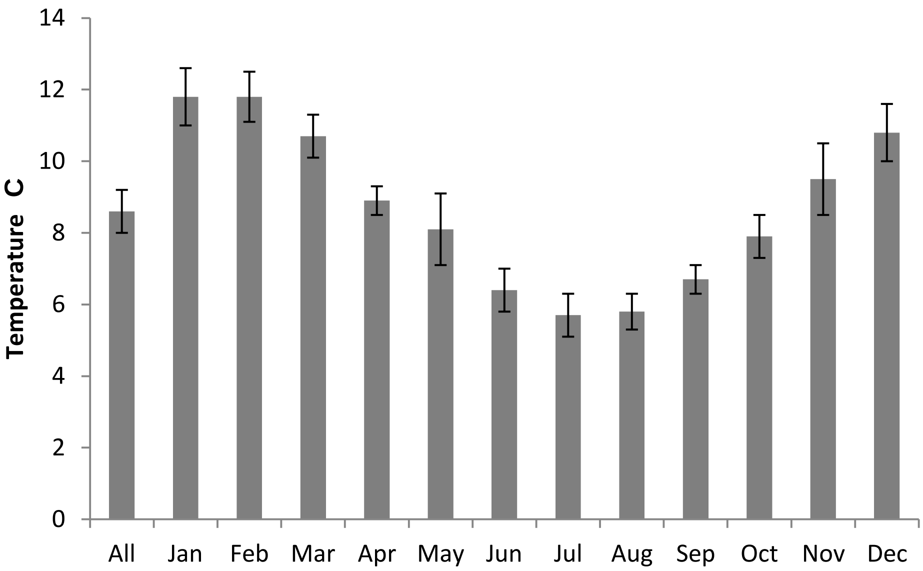


Figure 28. Monthly mean (±SD) stream temperature (°C) at Gelignite Creek averaged across years 2004-2009 and total mean temperature from 2004 - 2009.

pH

The Gelignite Creek study stream is very acidic, with annual average pH ranging between 3.52 and 4.03 (Table 24). Indeed, a pH of 2.3 was recorded in March 2008, and did not exceed 5.9 during the study period. This is very low by national standards (ANZECC and ARMCANZ, 2000), but at the lowest end of typical for humic rich streams in western Tasmania. Waterman and Waterman (1980?) report several water monitoring stations with similar pH ranges in south west Tasmania.

Stream pH appears fairly stable during both baseflow and stormflow conditions but fluctuates widely during periods of stream ponding (Figure 29). Fluctuations are diurnal with lowest pH recorded in the early afternoon and highest pH in the early morning.

Table 24. Annual mean (±SD) specific conductivity, pH, turbidity, dissolved oxygen and temperature for the Gelignite Creek study stream.

	Conductivity (µS/cm)	pH	Turbidity (NTU)	DO (mg/L)	Temperature (°C)
2005	41.38 (12.25)	4.03 (0.16)	1.28 (1.41)	9.99 (1.63)	9.60 (3.02)
2006	44.81 (18.79)	3.87 (0.41)	0.69 (3.77)	10.40 (1.64)	8.03 (2.17)
2007	47.45 (10.62)	3.79 (0.19)	0.99 (1.18)	8.35 (2.97)	8.85 (2.72)
2008	56.33 (8.05)	3.52 (0.17)	0.67 (0.67)	9.09 (2.79)	8.48 (2.36)

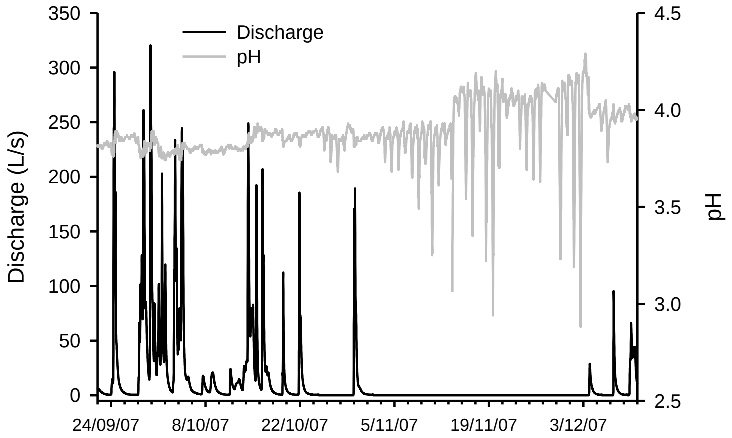


Figure 29. Gelignite Creek discharge and pH between 22/9/2007 and 10/12/2007. Note that pH is generally stable while the stream is flowing, but fluctuates wildly once flow ceases.

Conductivity

Total ions in solution, as measured by specific conductivity, were low in the Gelignite Creek study stream. A minimum and maximum of 7 and 86 µS/cm were measured during the study period. Annual mean conductivity was between 41.38 and 56.33 µS/cm from 2004 to 2008 (Table 24). Mean values are at the lower end of typical of upland rivers in southeastern Australia (ANZECC and ARMCANZ, 2000),and are similar to other data reported in the region (Waterman and Waterman, 1980?). However, the minimum value is well below those reported for other streams in south west Tasmania (Waterman and Waterman, 1980?, Fuller and Katona, 1993).

Conductivity responded strongly to changes in stream discharge, with the nature of the relationship taking one of three forms (Figure 30).

- A rapid reduction in conductivity on the rising limb of storm flow followed by a gradual increase as discharge returned to baseflow conditions was the predominant pattern.
- An increase in conductivity with rising discharge, which then declined as the stream level dropped.
- A complex response where an initial increase or decrease in conductivity with rising discharge was rapidly followed by the opposite response during a successive pulse in stream flow.

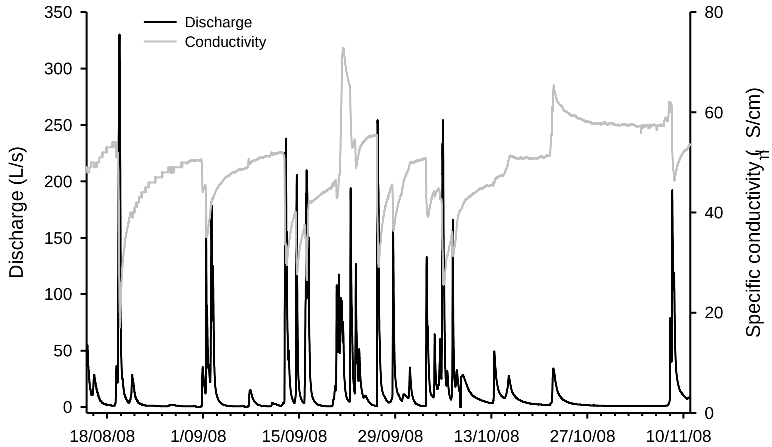


Figure 30. Gelignite Creek stream discharge and specific conductivity between 16/8/2008 and 10/11/2008.

Dissolved oxygen

The annual mean dissolved oxygen (DO) concentration in the Gelignite Creek study site ranged between 8.35 and 10.40 mg/L (Table 24), however, DO varied substantially depending on season and stream discharge. Across the study period, the lowest monthly mean DO occurred in February (6.45 ± 2.2 mg/L) and highest in August (11.7 ± 0.52 mg/L). Given the negative relationship between stream temperature and DO concentration it is expected that highest oxygen concentrations would occur over the winter months while the stream is coolest. In addition to seasonal patterns, DO concentration varied according to stream flow, with very low or zero flow conditions accompanied by decline in percent DO saturation (Figure 31). Increased stream flow usually resulted in a substantial increase in DO percent saturation.

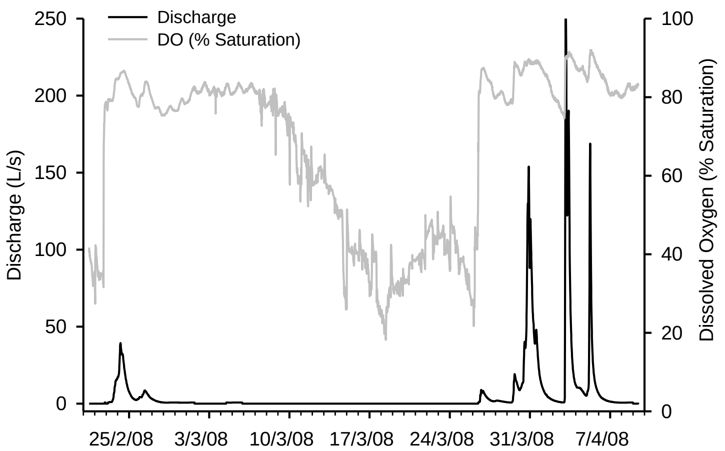


Figure 31. Gelignite Creek stream discharge (L/s) and percent dissolved oxygen saturation during late summer and early autumn 2008.

Turbidity

Gelignite Creek exhibited low turbidity with an overall mean of 0.9 NTU, and annual means ranging from 0.67 to 1.28 NTU (Table 24). Turbidity was often zero and reached a maximum of 75 NTU during the study. Turbidity increased substantially on the rising limb of flood events with maximums of 5 to 15 NTU typical (Figure 32). This is at the lower end of the typical range for south eastern Australia.

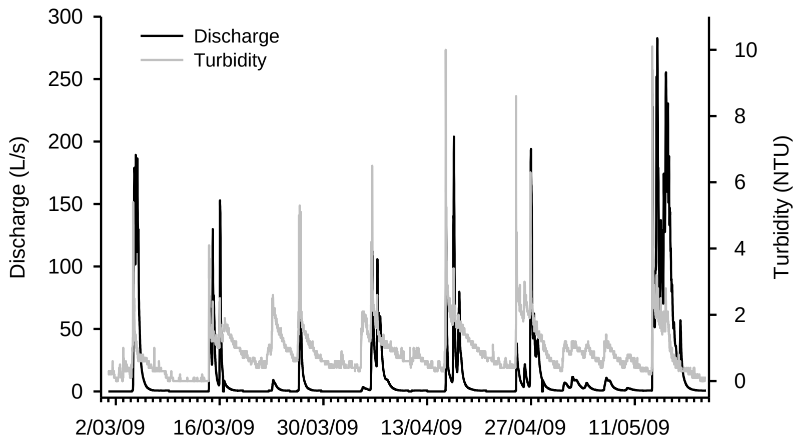


Figure 32. Gelignite Creek stream discharge (L/s) and turbidity (NTU) over autumn 2009. The relationship between discharge and turbidity of the 26 – 29 March flood is graphed in Figure 33.

During the four and a half year study period turbidity exceeded 20 NTU on only four occasions. Highest readings were usually during high stream flow after a sustained period with minimal rainfall. Successive floods typically resulted in only small pulses of turbidity with each increase in flow.

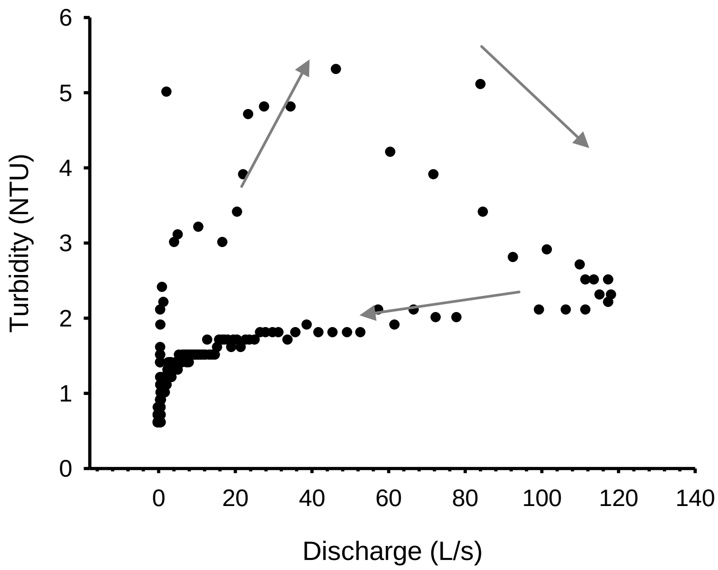


Figure 33. Turbidity/discharge hysteresis during a storm at Gelignite Creek (26-29/3/2009). Arrows indicate direction of the turbidity/discharge relationship.

It was noted that throughout the study period turbidity peaked well before maximum stream flow during discharge events. Figure 33 shows the relationship between stream discharge and turbidity during a single storm in March 2009. In this representative example, maximum turbidity was reached when discharge was 50 L/s then began to decline throughout the rest of the storm despite discharge reaching up to 120 L/s. This observed peak in turbidity preceding peak discharge is universal across the four year study period.

Laboratory analysis

Laboratory analysis indicates the Gelignite Creek study stream is low in both nutrient and ion concentrations but high in dissolved organic matter (Table 25). Total suspended sediments were low with a mean of 1.67 mg/L. Volatile suspended sediment concentrations were too low to be determined from the available samples. Alkalinity, as measured by the concentration of calcium carbonate in solution, was very low with all samples returning less than 2 mg/L. Oxidised nitrogen (nitrate + nitrite) was also low, ranging from less than 0.002 to 0.046 mg/L while sulphate varied between 0.3 and 3.6 mg/L. Chloride was the dominant ion in solution with a mean of 5.60 mg/L whereas with 0.12 mg/L calcium and magnesium had the lowest concentration.

Ionic dominance took the order Na > Mg > Ca and K for cations. Although samples were not tested for bicarbonate concentration, it does not exist in solution below a pH of approximately 4.5. Given the pH of Gelignite Creek rarely exceeded 4.5 we can assume anionic dominance in the order Cl > SO_4 > HCO_3. Since the same proportions of ions were found in all samples these cation and anion orders of dominance were uninfluenced by discharge

Table 25. Mean (±SD) solute concentrations in Gelignite Creek grab samples, taken over a range of stream flow conditions (0.6 – 154 L/s).

	Number of Samples	Mean concent-ration	Minimum concent-ration	Maximum concent-ration
Total Suspended Solids (mg/L)		1.67 (0.75)		
Alkalinity (mg $CaCO_3$/L)	8	< 2.0 (0)	n/a	n/a
Chloride (mg/L)	9	5.60 (2.57)	1.58	9.04
Sulphate (mg/L)	9	1.00 (0.92)	0.3	3.6
Nitrate + Nitrite (mg-N/L)	7	0.010 (0.014)	0.002	0.046
Calcium (mg/L)	9	0.12 (0.05)	<0.05	0.17
Magnesium (mg/L)	9	0.36 (0.18)	0.05	0.59
Sodium (mg/L)	9	3.21 (1.17)	1.29	4.60
Potassium (mg/L)	9	0.12 (0.06)	0.03	0.24
Iron (µg/L)	9	37.8 (19.9)	<20	70
Dissolved Silica (µg/L)	6	131 (69)	36	224
Dissolved organic carbon (mg/L)	9	13.69 (5.09)	7.1	20.0

Stream dissolved organic carbon (DOC) was quite high, with a mean concentration of 13.69 mg/L and range of 7 to 20 mg/L. There was a negative linear correlation between DOC and discharge, with DOC concentration declining substantially with increasing discharge. Similarly, iron, magnesium, sodium, chloride and dissolved silica also had a negative linear correlation with stream discharge (Figure 34). There was no correlation between discharge and potassium, calcium, sulphate and oxidized nitrogen.

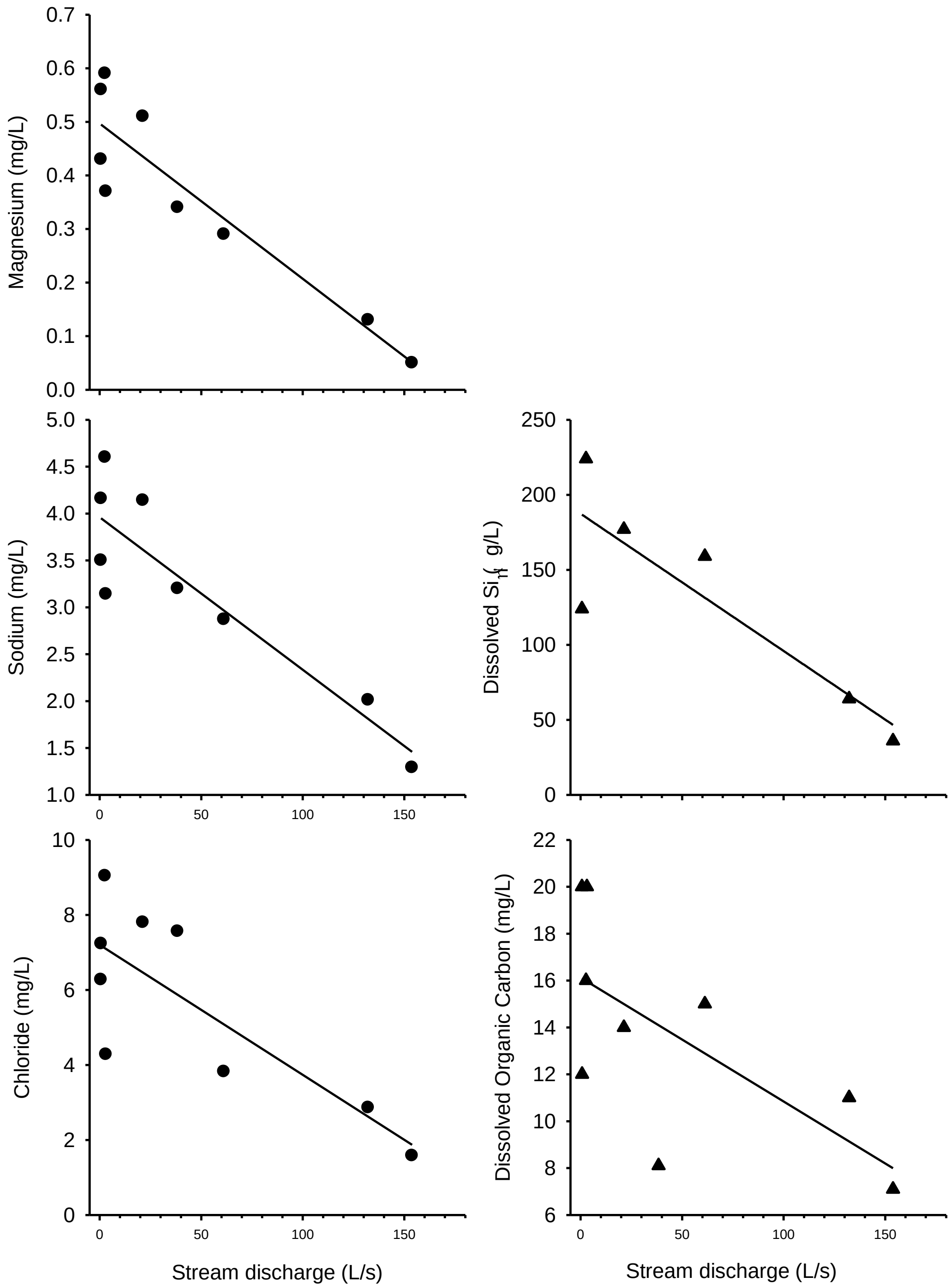


Figure 34. Relationship between stream discharge and concentrations of dissolved silica (µg/L), magnesium (mg/L), and dissolved organic carbon (mg/L). Results from linear regression are shown on the graphs. Analysis of silica, Chloride, sodium and DOC completed using untransformed data, magnesium was log transformed to fulfill assumption of constant variance.

6 Geomorphology results

Assessments of stream geomorphology have focussed on Gelignite Creek. The assessments fall into two parts, a qualitative description of stream character in the catchment, and quantitative measures of stream form in cross section, planform and long profile.

6.1 Stream characters observed at Gelignite Creek

Five different types of stream channel were observed within the Gelignite Creek catchment (Figures 35 and 36). They vary in terms of typical channel slope and form, bed and bank material, the number and continuity of surface channels and riparian and in-channel vegetation, but share common features of variable channel size, frequent steps in the long profile, a complex relationship with subsurface flow, and a dominance of sand sized transport. All are small channels where, even on the steeper slopes, fluvial processes struggle against the influence of dense riparian vegetation and the erosion resistant bed and banks. If these streams were viewed in the context of a large catchment it is likely that they would be lumped into a single category with a name such as 'headwater peatland streams'. However, there is significant variety between different sections of channel, and therefore potential differences in the stream response to catchment scale fire. The focus on the small study catchment allows this variability to be explored.

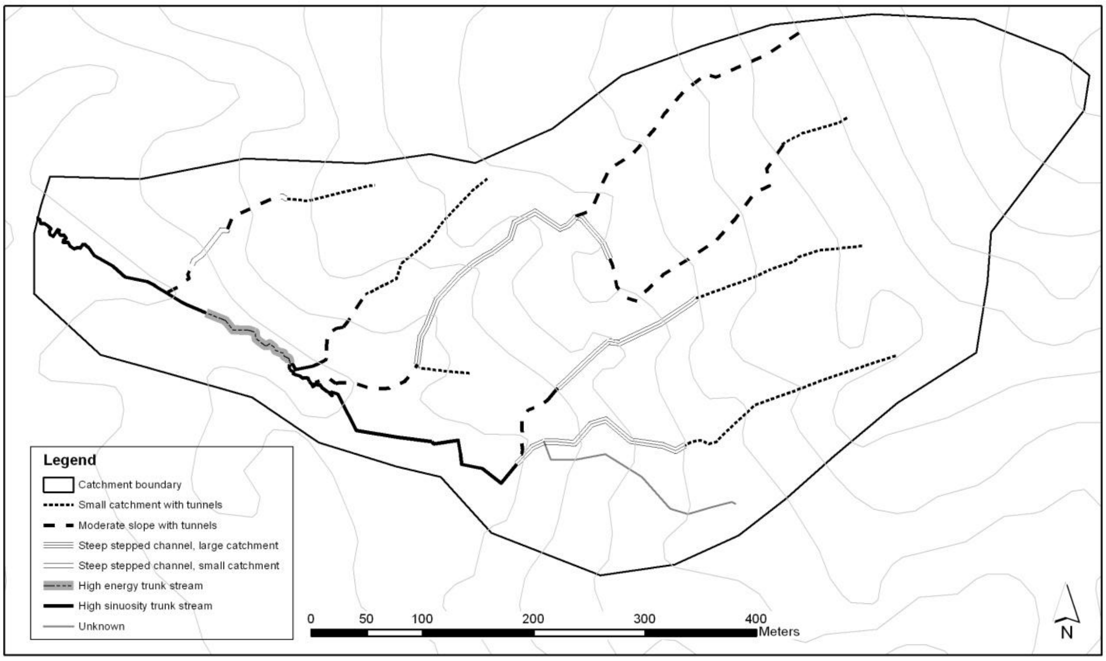


Figure 35. The distribution of different stream characters in the Gelignite Creek catchment.

The landscape context for the streams of the study catchment is of a valley system developed entirely in a thick deposit of colluvium. The underlying bedrock has not been observed anywhere in the catchment. The slope deposits are dominated by sub rounded quartzite gravel and cobbles, with a variably sandy and clayey matrix. This can make it difficult to differentiate between modern stream deposits and the underlying substrate.

Because of the small size of the stream, and the almost universally dense riparian vegetation, it is all but impossible to take photographs to illustrate the variations in stream character described below.

6.1.1 Small catchment with tunnels

This stream type represents the upstream limit of fluvial processes. It occurs where there is a distinct but shallow valley with a floor one to five metres across, slope between 4 and 8°, typically vegetated with a mix of buttongrass tussocks and woody shrubs, with a ground cover of dense moss.

Distinctive features:

- Planform:
  - braided network of multiple small discontinuous channels
  - strongly influenced by vegetation
- Tunnels:
  - many small diameter tunnels frequently visible discharging water and sand on valley floor
  - occasional larger tunnels
- Long profile:
  - difficult to describe given lack of main channel
  - determined by valley long profile with occasional steps
  - vegetation is a secondary control on long profile
- Channel:
  - small shallow channels generally wider than deep
  - transports sand and fine organic material
- Base flow:
  - through tunnels and valley fill
  - surface flow ceases between rain events

Multiple small and discontinuous surface channels (typical width 10 to 20 cm, depth 5 to 10 cm) are scattered across the valley floor. They only flow during and immediately after rain events. Channel bed and banks are typically composed of fine, soft organic rich sediments with some fine to medium sand. In steeper sections, there may be small deposits of coarse sand or fine gravels. Channel segments appear to be connected by a system of small (< 4 cm diameter) tunnels, but diffuse flow through the valley floor and vegetation is probably also important. Base flow, when it occurs, is likely to be largely through the tunnels, and even during rain events surface flow may be absent for multiple metres. In other areas, the inefficient surface channels quickly become full during rain events and shallow overbank flow covers the valley floor. At steep sections in the valley long profile, surface and sub surface flow paths may coalesce to form a pool with a distinct headwall. The overall impression has some similarity to a chain of ponds, with distinct pools separated by a confusing, three dimensional network of flow paths each of which takes only a small portion of flood flows.

This stream type appears to exist around the point where stream power (influenced by catchment size and valley slope) hovers around the threshold for overcoming the resistance to erosion on the valley floor. Given the dominance of highly erodible fine sands and fine particulate organic material, the resistance to erosion comes mainly from vegetation. A buttongrass tussock forms a major obstacle, and even the mossy valley floor is sufficient to prevent erosion. It is only where a step in the valley long profile leads to greater stream power that a distinct channel can form. It is possible that under well vegetated conditions, these sections of valley are depositional, trapping sand washed from surrounding slopes. If there is disturbance to the vegetation, stream power may be sufficient to erode that sediment.

6.1.2 Moderate slope with tunnels

This stream type probably represents a higher stream power version of the small catchment with tunnels type described above, occurring where stream powers are higher because of steeper valley slopes and larger catchments. It can occur with quite large catchment areas, but only on gentle slopes. The character of the vegetation is variable, and may be dominated by buttongrass or riparian scrub.

Distinctive features:

- Planform:
  - wandering channel
  - distinct primary channel with smaller secondary channels
  - strong vegetation influence
- Tunnels:
  - small tunnels
  - larger tunnels may be associated with control points
- Channel long profile:
  - occasional steps associated with pools
  - no obvious control on step location (i.e. step in soft sediment)
- Channel:
  - surface flow volumes highly variable over short distances
  - channel often thatched by buttongrass leaf litter
  - surface channel cross section highly variable, may be deeper than wide in pools
  - transports some fine gravel, sands, fine organic material and leaf litter
- Base flow:
  - through main channel or tunnels
  - surface cease to flow common in dry periods

This stream character is notable for losses and gains of surface flow and the variable nature of surface channels. Surface channels tend to have a wandering planform, and are larger, more distinct and continuous than the small catchment with tunnels character described above. Multiple channels may be present though they are less common and there is often a clearly dominant channel. Channels may be hidden by buttongrass leaf thatch, but are often genuinely discontinuous, with small or large tunnels taking much of the base flow. Even in reasonably large catchments, all signs of a surface channel can be lost for multiple metres. Where stream power is locally high pools have formed. Channel cross sectional area is highly variable with smaller sections as small as 20 cm wide and deep, and pools often surprisingly deep (e.g. width 40 cm, depth 50 cm).

Channel banks are typically organic rich fine sediments, and the bed typically is sand or fine gravel. Gravel or even cobbles may be exposed in pools below a step in the stream profile.

It is probable that cobbles represent a lag from the underlying colluvium rather than having been transported by the present stream.

Vegetation and valley slope still play important roles in controlling stream form, and appear responsible for much of the variability in channel size. A buttongrass tussock, shrub or tree can obstruct flow and cause local deposition of sand and litter, blocking the channel and encouraging overland flow. Pools are often associated with a step in the stream long profile. However, even given these influences, this stream type is clearly dominated by fluvial processes, in contrast to the small catchment form where fluvial processes are almost swamped by vegetation and slope processes.

6.1.3 Steep stepped channel

This stream type occurs in narrow valleys where the overall slope is moderate to steep (up to 20°), and there are distinct steps in the valley profile. In the steepest sections, the stream appears powerful enough to mobilise the cobbles of the underlying colluvium. Vegetation varies between scrub and buttongrass dominated heath.

Distinctive features:

- Planform:
  - o multiple channels and tunnels on flatter areas, single channel on steps in long profile
  - o some influence of vegetation on flatter areas
- Tunnels:
  - o many small diameter tunnels can be seen discharging on headwall of steps
  - o large diameter tunnels evident where they are briefly open to the surface on flatter areas
  - o tunnels can take all flow in some areas
- Long profile:
  - o distinctly stepped long profile
  - o often no obvious control on position of steps
  - o steps either entirely in soft sediments (small catchments) or combination soft sediment and colluvium (larger catchments)
- Channel:
  - o channels can be deep and narrow but may also be small and inconspicuous
  - o may alternate with tunnel sections
  - o pools downstream of step headwall
  - o transports sand and fine particulate organic material in flatter areas, gravel downstream of steps
- Base flow:
  - o through tunnels on flatter areas, in channel on steps.
  - o cease to flow common in dry periods

This stream type usually has distinct and continuous channels which vary in number and dimension according to where they occur in the long profile. The distinctive feature of this stream type is the stepped long profile of alternating gently sloping zones and steep steps, which play a major role in determining channel form.

Where the valley slope is gentle, the stream may have multiple channels and tunnel sections. Channels dimensions are variable but typically small (e.g. 30 cm wide, 10 cm deep) and wander across the valley floor. Small tunnels are relatively common, but there are also larger passages well over 10 cm diameter. Tunnels are visible where they discharge into a surface channel (particularly in steep zones), or at 'windows' where for the tunnel roof is missing and flow can be observed. These larger tunnels have a bed of mobile sand and gravel. Tunnels can also be inferred where all surface flow disappears.

Step sections of channel take the form of a distinct knickpoint in the stream long profile, with headwalls steep or close to vertical and up to 1 m high. Immediately below these steps may be pools up to 150 cm wide and 40 cm deep. Tunnels are frequently evident emerging from these walls, and are the source of much of the baseflow. There is no evidence that knickpoints are presently retreating, such as undermined vegetation or slump blocks in the channel.

The material exposed in headwalls varies with catchment size. In smaller catchments, the step is cut into fine, organic rich material similar in appearance and texture to the organic soils of the surrounding slopes. The scour pool at the base of the step exposes gravel and sometimes cobbles that may be the underlying colluvium. In these cases, it is not clear whether the steps are formed purely by erosion, or whether in part they are constructed by the deposition of fine sediments and organic material in the flat areas immediately upstream of the knickpoint. However, it seems that any upstream progression of these knickpoints is unlikely to cause lowering of the valley floor cut into the pre-existing gravels.

In larger catchments, steps are typically a combination of fine organic rich sediments draped over gravels. In these cases, it is difficult to differentiate between gravels that may have been transported by the modern stream, and those of the underlying colluvial material. It is possible that these cases, any upstream movement of knickpoints would cause a lowering of the valley cut into the colluvium.

6.1.4 High energy trunk stream

This stream type is found in a single, narrow, section of valley just downstream of the confluence of the two main tributaries. Valley slope is just over 3°. The high stream power is a result of catchment size and valley slope, and is sufficient to transport the modern sediment load, and the finer portions of the underlying colluvium. Vegetation is a narrow band of riparian scrub in moorland

This section is the most 'conventional' in the catchment, and is similar to partly confined small streams in many environments. There is a continuous single thread channel that for the most part is in contact with a distinct valley wall in the colluvium. Tunnels may occur, but are not obvious and are unlikely to take a significant portion of the flow. Channel form is variable, but is generally between 60 and 120 cm wide and 40 to 70 cm deep. Undercut banks are common. There are frequent small steps in the long profile which appear to expose underlying colluvium, which sometimes includes boulder size clasts. Otherwise the stream has a cobble and gravel bed. The near vertical banks are organic rich sands. A small floodplain is consistently identifiable on the south side of the channel, and discontinuous benches occur on the north side.

Distinctive features:

- Planform:
  - single low sinuosity main channel
  - controlled by form of valley wall
- Tunnels:
  - no obvious evidence of tunnels in stream zone or floodplain
- Long profile:
  - steep with many small steps
  - steps controlled by larger clasts in underlying colluvium
- Channel:
  - channel generally wider than deep
  - some pools but mainly riffles and run sequence
  - transports sand and gravel
- Base flow:
  - in channel
  - ceases to flow only in prolonged dry periods

6.1.5 High sinuosity trunk stream

This stream type is found where catchment areas are relatively large, but the valley wide and gently sloping (< 3°) compared to elsewhere in the catchment. This causes a drop in stream power and has lead to the development of a relatively wide floodplain, allowing the stream to meander uninfluenced by the valley walls. Vegetation is typically buttongrass moorland on the floodplain, with a thin belt of shrubs in the riparian zone.

Distinctive features:

- Planform:
  - high sinuosity main channel
  - dominated by single main channel
- Tunnels:
  - a few small diameter tunnels
  - short large diameter tunnels vertically bypass steps
  - possible large diameter tunnels under floodplain
- Long profile:
  - distinct series of pools, runs and small steps
  - high points formed by fine sediments stabilised by vegetation
- Channel:
  - cross section highly variable over short distances
  - frequent large undercuts
  - transports mainly sand
- Base flow:
  - through tunnels under riffles, in channel in pools and runs
  - ceases to flow only in prolonged dry periods

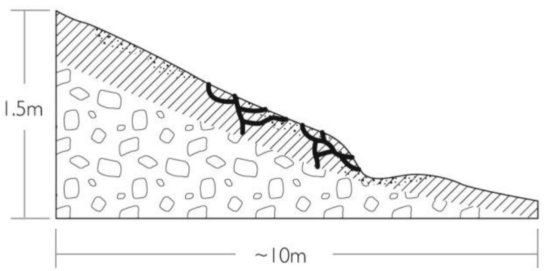
This stream type is dominated by a single sinuous channel, although short multiple channel sections are not uncommon. Channel dimensions in this stream type vary widely between narrow run sections which can be almost as deep as they are wide (e.g. 90 cm wide by 80 deep), pools where the channel is substantially wider than deep (e.g. 150 cm wide by 80 deep) and channel pinches where the capacity of the surface channel is much smaller (e.g. 70 cm wide by 30 deep). The variability in channel capacity is obvious during flood events, when banks are overtopped first at pinches, then in the runs, and seldom reach the top of the channel in pools. Pool location appears to be related to high turbulence zones downstream of pinches, rather than planform. Runs and pools typically have near vertical banks with dense moss cover, and a gravel and cobble bed. Pinches generally have sloping banks with a mossy sand bed.

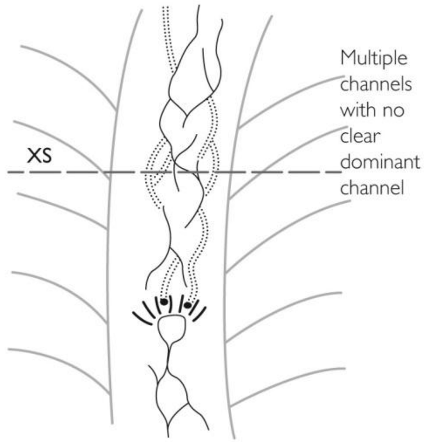
Pinches are very small sections of channel. Like riffles in a conventional gravel bed stream, they act as hydrological controls, determining the level of the pool immediately upstream, and they form steep sections in the long profile. However, unlike standard riffles, they tend to have very steep downstream faces, so they resemble small headcuts in the long profile. Also, they are typically narrower than pools or runs. They appear to be partly eroded into the underlying colluvium, and partly constructed by deposits of sand that have been stabilised by a combination of roots from riparian vegetation and a dense mat of moss and liverwort. This fine sediment layer can be up to 30 cm deep. Another common feature of pinches are tunnels that flow under or beside this vegetated deposit, transmitting most lower flows.

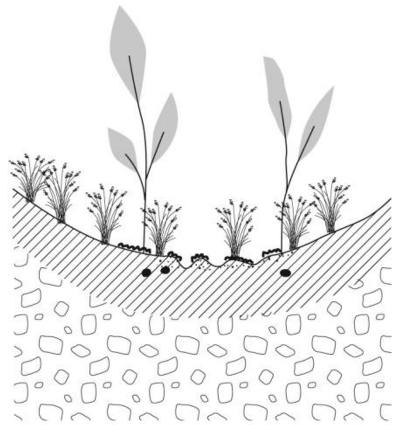
The sinuosity of the channel means that meander neck cutoffs at high flows are relatively common. There is however no sign of active scour in these areas. However, there are lengths of channel that take flood flows but not significant base flow, indicating that longer cutoffs may have occurred.

Runs and pools typically have a gravel and cobbles bed. Clasts sit loosely, giving the impression of mobility, but there is no sign of imbrication and little sorting. The banks are organic rich sand, grading to brown sand near the bank toe. The channel often has large undercuts in this sandy layer in one or both banks. A slight levee is sometimes present, perhaps most evident where tributaries are deflected downstream.

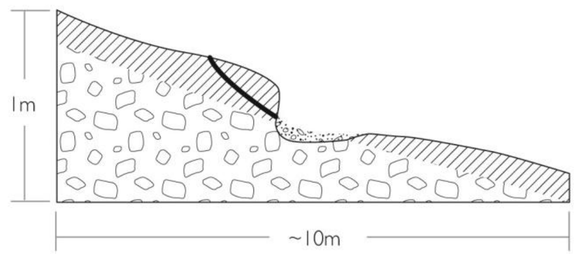
Small catchment with tunnels

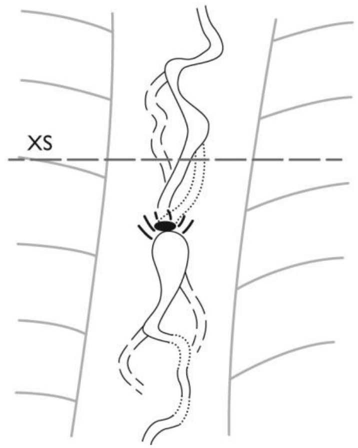


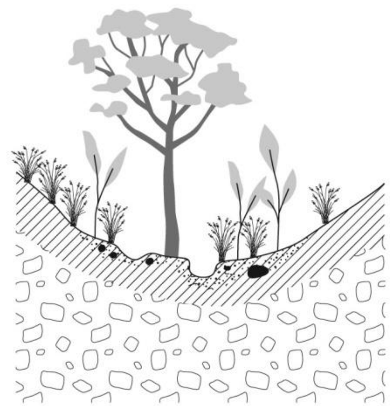




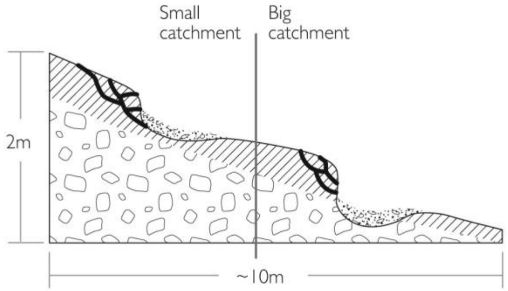
Moderate slope with tunnels

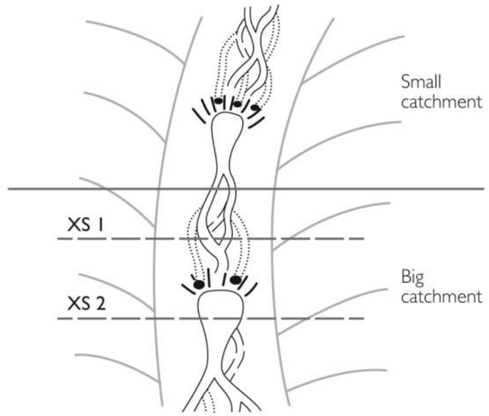


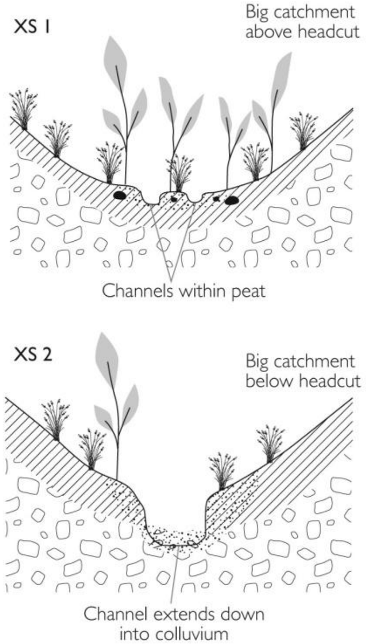




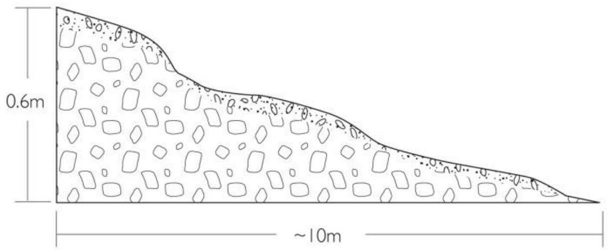
Steep stepped channel

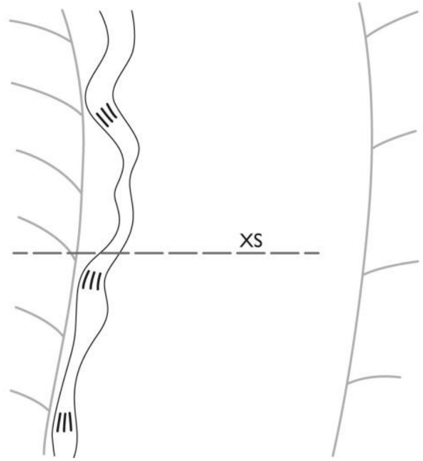


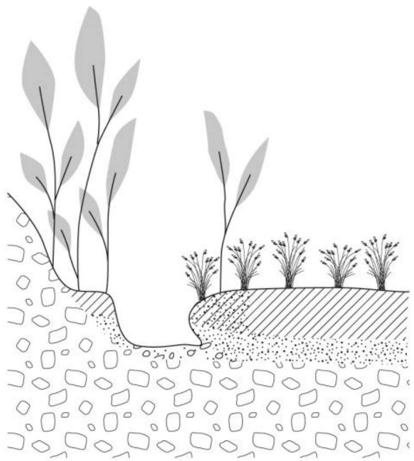




High energy trunk stream







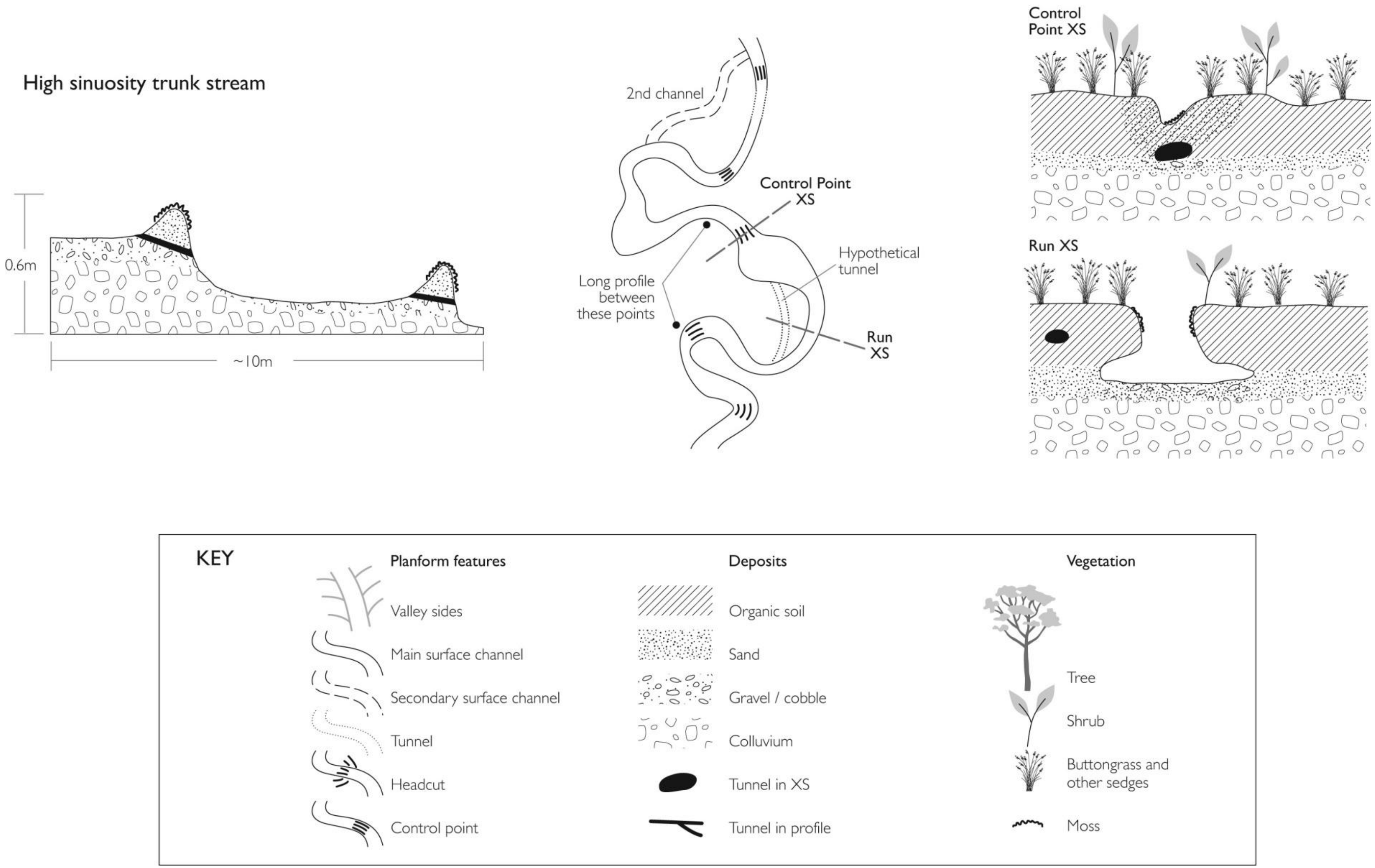


Figure 36. Diagram showing the typical long profile, planform and cross section characteristics of each stream character.

6.2 Surveys

6.2.1 Reach scale morphology

The morphology of four reaches was characterised by a detailed survey of the planform and long profile, and a series of detailed cross sections. Results of the surveying are shown in Table 26 and Figures 37, 38, 39 and 40.

Table 26. Channel characteristics across the four study reaches. Sinuosity is the ratio of channel length to valley length. *Excludes outlier of 152 where channel was very shallow due to bypass tunnel. **Sampled only where there was a clear channel, therefore data does not represent typical situation of small, multiple channels or absent surface channel.

	Sinuosity	Valley slope (%)	Channel slope ° (%)	Channel width (m) average (range)	Channel depth (m) average (range)	Width to depth ratio
Reach 1 (high sinuosity trunk)	1.61	3.0 (5.2)	1.8 (3.2)	0.74 (0.28-2.02)	0.36 (0.01-0.66)	2.38 (0.71-9.66)*
Reach 2 (high energy trunk)	1.24	3.2 (5.6)	2.6 (4.6)	0.85 (0.45-1.54)	0.43 (0.12-0.69)	2.39 (0.94-6.08)
Reach 3 (high sinuosity trunk)	1.37	2.7 (4.7)	1.9 (3.4)	0.81 (0.51-1.39)	0.46 (0.21-0.59)	1.94 (1.07-3.07)
Reach 4 (steep stepped channel)	1.20	9.7 (17.1)	8.1 (14.3)	**No data	**No data	**No data

From Table 26 and Figures 37 and 39, it can be seen that the two examples of high sinuosity trunk stream, Reaches 1 and 3, are characterised by an irregularly sinuous channel (shown by the high channel to valley length ratio) with highly variable width and depth, with frequent short tunnel sections. Reach 2 (Figure 38) is an example of the high energy trunk stream, and has a channel that is steeper, straighter and on average larger than the sinuous reaches. In contrast, Reach 4 (Figure 40) is an example of a small catchment stream where, despite the steep valley, stream power is too low to form a consistent channel. Here the discontinuous surface channel is evident, as are the steps in stream profile.

In all reaches there is an association between bed material and channel form (see Figures 37, 38, 39 and 40). In Reaches 1, 2 and 3, at channel pinches it is typical to find the bed dominated by sand and moss, and in runs and pools the bed is dominated by gravel and cobbles. This confirms patterns observed in the stream characterisation. In Reach 4, where the far smaller stream is dominated by litter, moss and fine sediments, the only place coarse sediments are found are pools immediately below steps in the long profile.

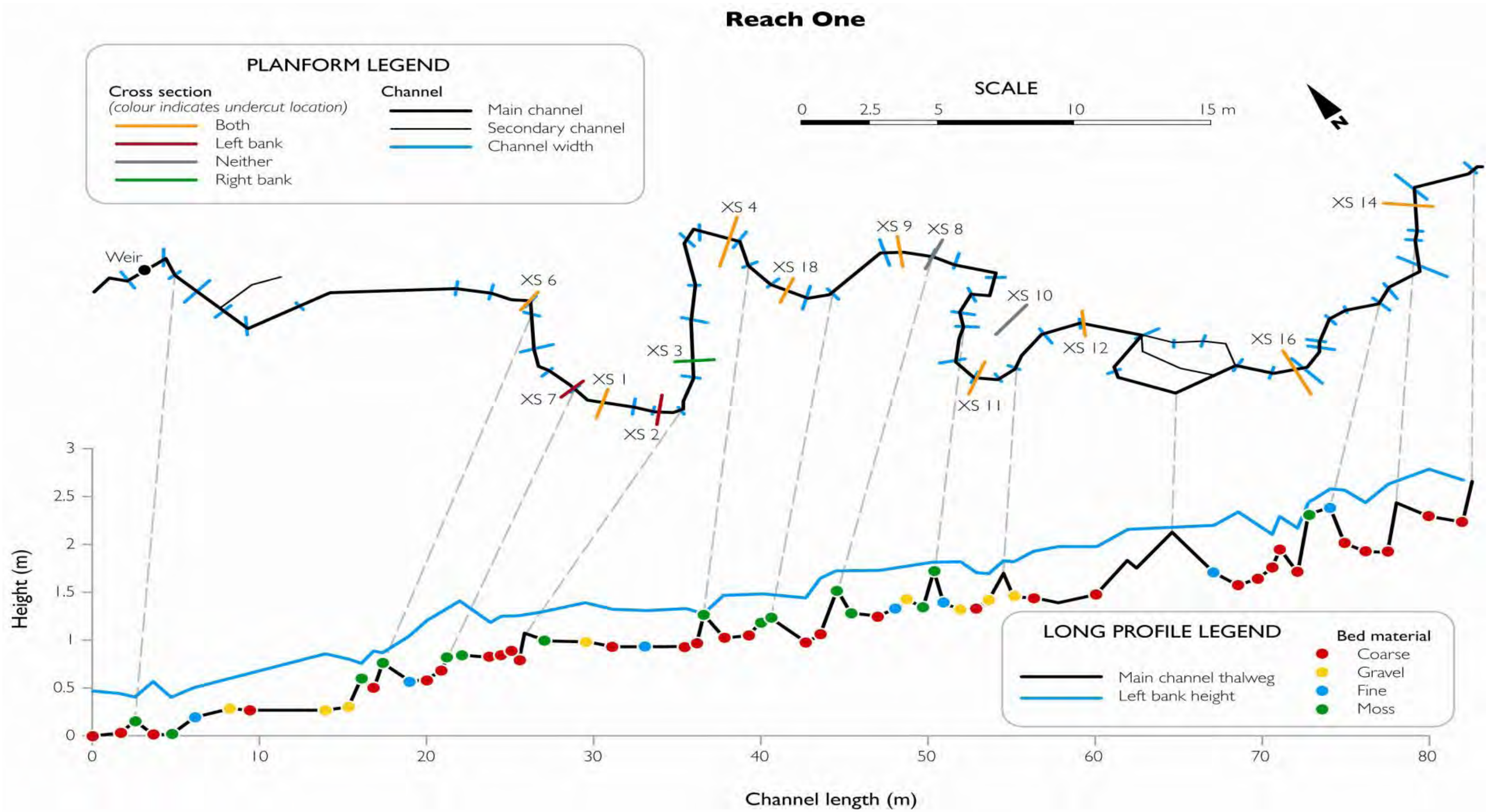


Figure 37. Reach one planform (top) and long profile (in metres from end of reach). Also shown on the planform are channel width at various points, locations of detailed cross sections, and distribution of undercuts. Also shown on the long profile is the height of the left bank and the bed material on the thalweg. Lines between the diagrams indicate where the control points occur on the planform. Note that scales differ between Figures 37, 38, 39 and 40.

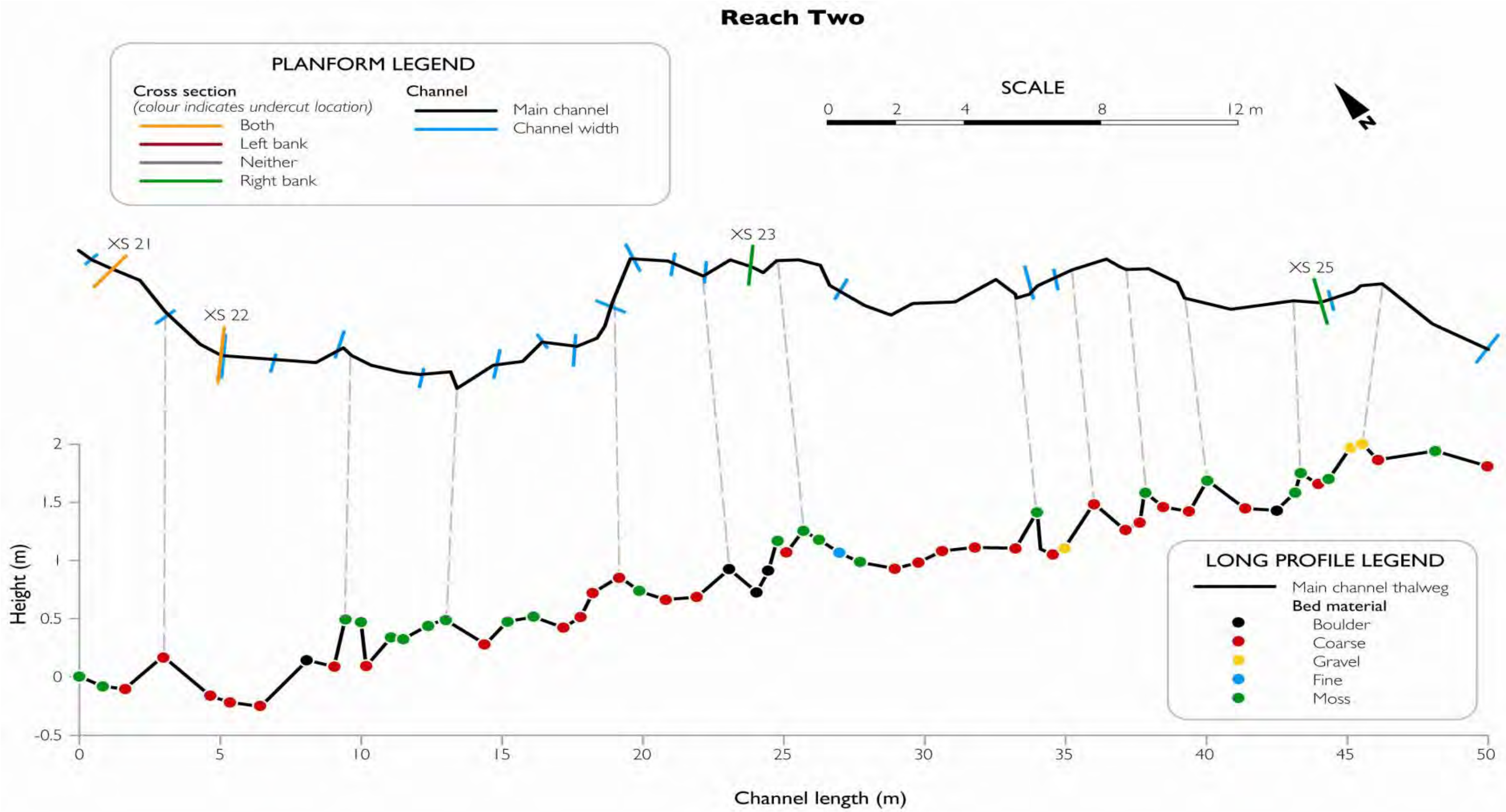


Figure 38. Reach two planform (top) and long profile (in metres from end of reach). Also shown on the planform are channel width at various points, locations of detailed cross sections, and distribution of undercuts. Also shown on the long profile is the bed material on the thalweg. Lines between the diagrams indicate where the control points occur on the planform. Note that scales differ between Figures 37, 38, 39 and 40.

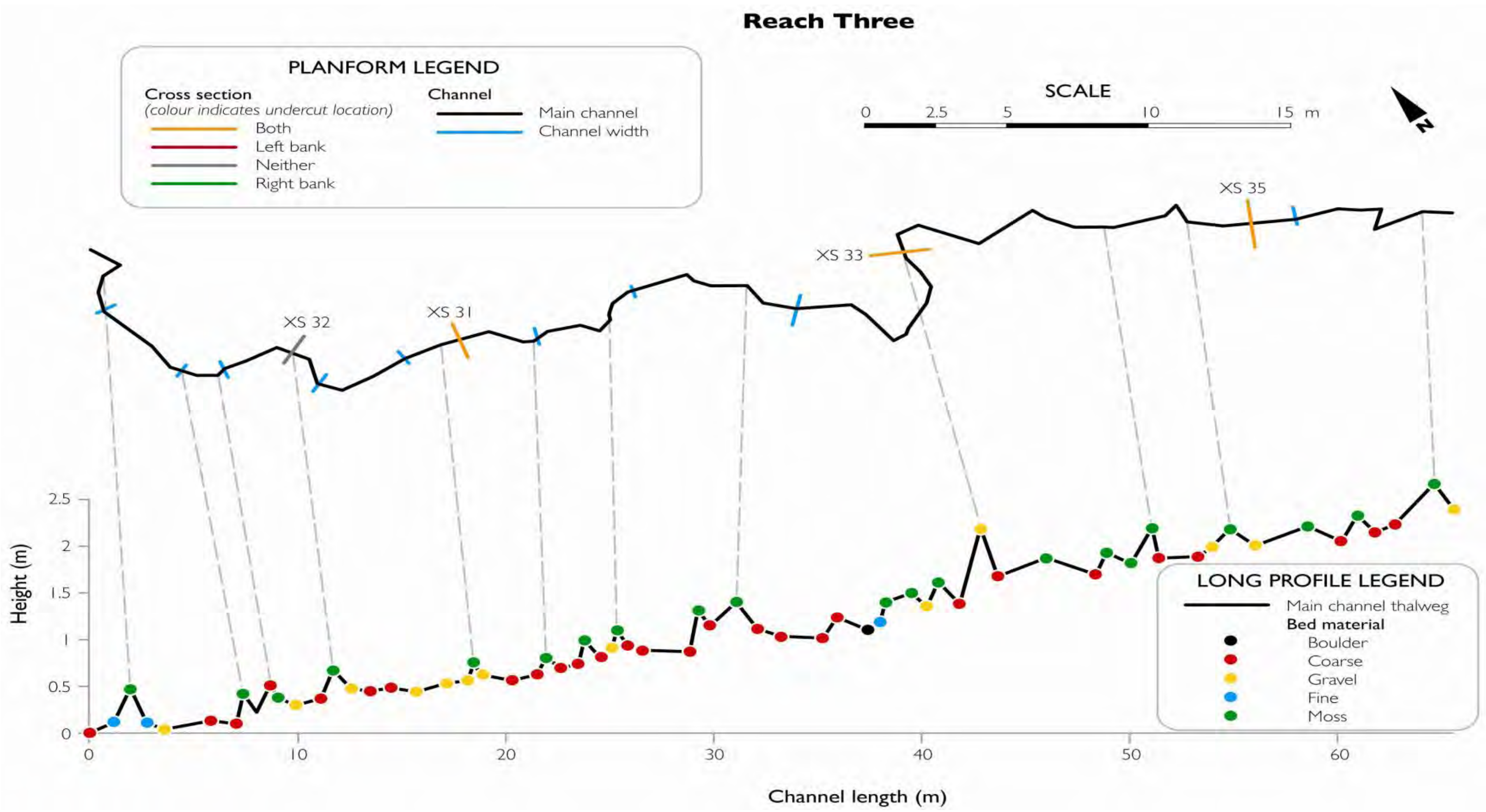


Figure 39. Reach three planform (top) and long profile (in metres from end of reach). Also shown on the planform are channel width at various points, locations of detailed cross sections, and distribution of undercuts. Also shown on the long profile is the bed material on the thalweg. Lines between the diagrams indicate where the control points occur on the planform. Note that scales differ between Figures 37, 38, 39 and 40.

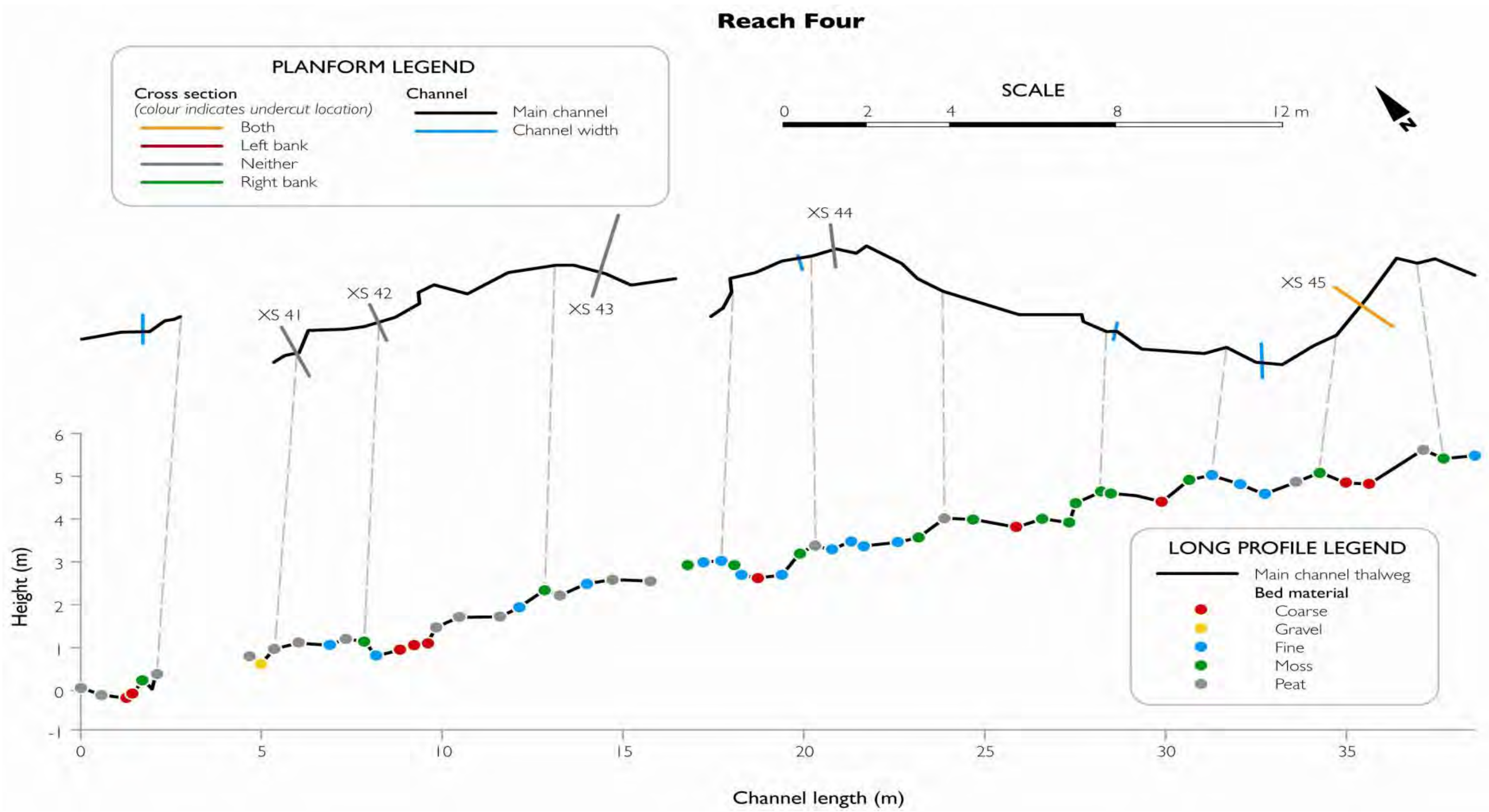


Figure 40 planform (top) and long profile (in metres from end of reach). Gaps in lines reflect the discontinuous nature of the surface channel. Also shown on the planform are channel width at various points, locations of detailed cross sections, and distribution of undercuts. Also shown on the long profile is the bed material on the thalweg. Lines between the diagrams indicate equivalent locations. Note that scales differ between Figures37, 38, 39 and 40.

Undercuts are common on all larger sections of channel (Table 27). Measuring undercuts accurately is extremely difficult, given that they must be identified and measured by touch rather than sight at the bottom of a narrow channel, are crowded with roots, irregularly shaped, and highly variable along a length of channel. As such, the results presented are indicative of order of magnitude, rather than precise measurements. It is notable that where present, undercuts can be large, contributing on average an extra 10% of the cross sectional area of the open channel, and in extreme cases can increase cross section area by over 30%.

There is no obvious connection between the presence of undercuts and channel planform (Figure 37). However, there is a greater tendency for undercuts to occur on steep banks, particularly where the channel has a rectangular cross section. Undercuts are least likely to occur in channel pinches. As may be expected from this pattern, undercuts are frequent on Reaches 1, 2 and 3, but only occur in Reach 4 where large pools have developed downstream of steps in the long profile.

Table 27. Undercut frequency and average size as proportion of the cross sectional area of open channel

	% no u/cuts	% one bank u/cut	% two banks u/cut	U/cut height (cm) average (range)	U/cut depth (cm) average (range)	U/cut area (cm^2) average (range)	% of open channel volume average (range)
Reach 1	21	14	64	14 (2 – 30)	23 (5 – 50)	227 (10 – 774)	11 (1 – 36)
Reach 2	0	40	60	16 (5 – 30)	20 (5 – 48)	240 (6 – 1023)	10 (1 – 23)
Reach 3	40	20	40	16 (3 – 25)	24 (2 – 40)	294 (3 – 860)	11 (2 – 24)
Reach 4	80	0	20	16 (9 – 25)	10 (5 – 15)	120 (9 – 25)	5 (4 – 6)

6.2.2 Rates of channel change

Rates of channel change were estimated from repeated measurement of detailed cross sections. Cross sections 4 and 18 were excluded from the analysis because it was felt that the indicated channel contraction on a vertical bank was geomorphically unlikely. It appears more likely that on the upright banks, a small error in horizontal measurement has caused the large difference in vertical measurement. A similar error could explain the changes to Cross sections 32 and 35, which show significant bank erosion that is not consistent with casual field observations. However, this bank erosion is geomorphically feasible, so these cross sections were included in the analysis. Cross section 10 was excluded from analysis because it is a chute on the floodplain, rather than a genuine channel. The results show that on average only small changes in channel form occurred (Table 28, Figure 42). It is felt that in many cross sections, this small change is probably within the noise level of the repeated measurements. However, change did occur on some cross sections (e.g. Reach 1 XS's 2, 8 and 12).

In Reaches 1, 2 and 3, cross section changes mainly take the form of small scale reshaping of the banks, and reorganisation of the stream bed. Reach 4 behaved in a slightly different manner. In this reach channels are inconsistent but generally small, and the channel boundary is often covered by loose moss or litter and can be very difficult to identify. In this reach, both erosion (e.g. Reach 4 XS 42) and deposition (e.g. Reach 4 XS 41) were detected. In these channels with bed and banks formed in moss or soft sediments, precise relocation of the channel boundary is difficult. Because the channel is small, even small errors in re-measurement will appear as a significant proportion of the channel area. So, the degree to which such changes are real or an artefact of measurement is not known, and where changes are real it is unknown if they indicate changes in vegetation or in the mineral sediments.

Table 28. Changes observed in detailed cross sections between 2004 and 2009, expressed as change in cross sectional area, and as percentage of 2004 cross section area. Negative numbers indicate channel contraction, positive numbers indicate channel expansion.

	No. of cross sections	Average XS area change (cm^2) (range)	Average % channel change (range)
Reach 1	11	-35 (-136 – 131)	-3 (-14 – 2)
Reach 2	4	-4 (-201 – 112)	4 (-2 – 13)
Reach 3	4	176 (-59 – 512.5)	9 (-2 – 30)
Reach 4	5	-21.4 (-154 – 130)	-3 (-28 – 16)

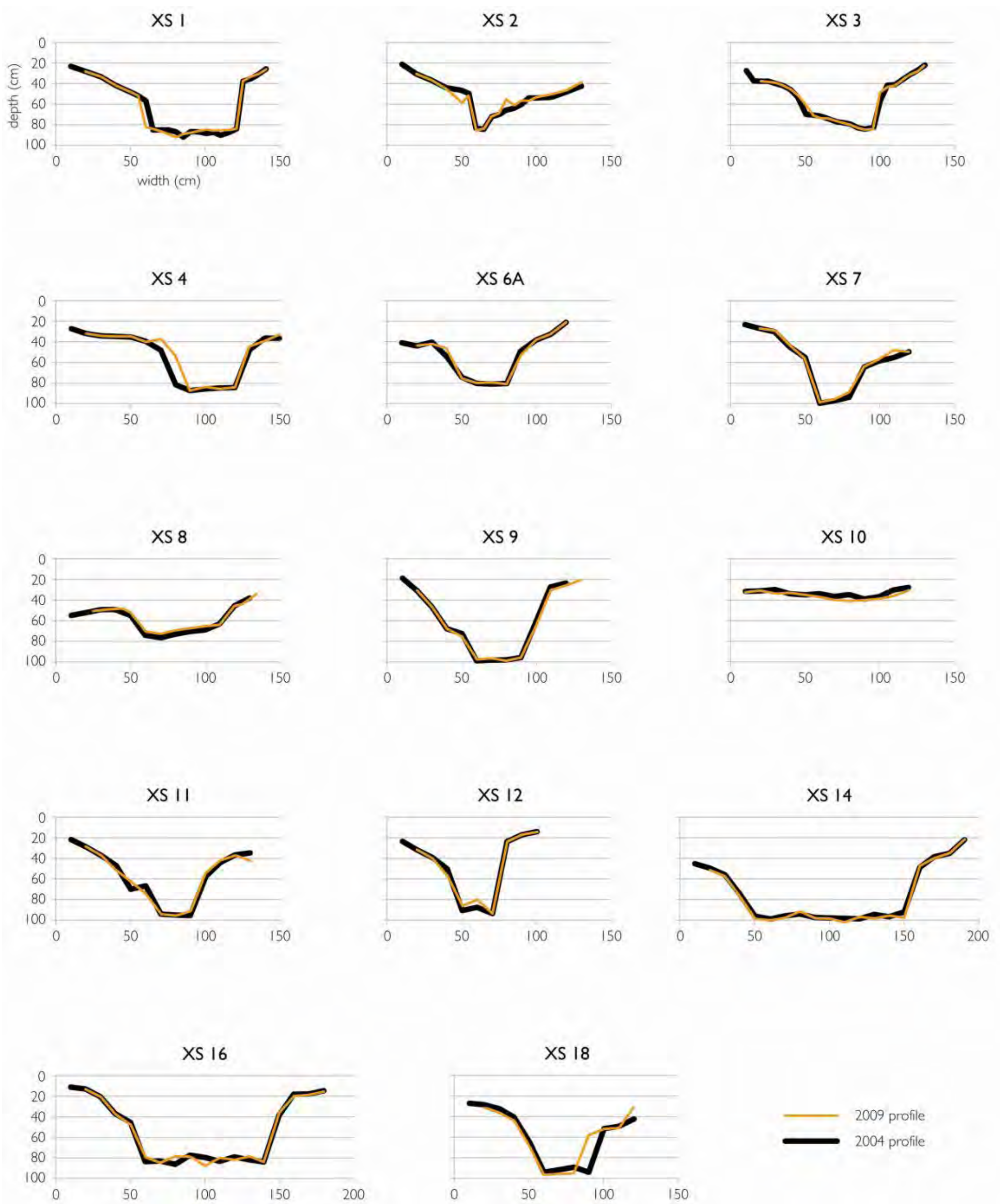


Figure 41. Gelignite Creek detailed cross sections from all sites where two measurements are available. Scales are comparable throughout. Undercuts are not depicted. Note that Cross section 43 is of a section where three channels zones were present, but the left most channel was hidden by buttongrass thatch when the cross section was established, and is not completely captured in this data. (figure continues next page)

Figure 42 (continued). Gelignite Creek detailed cross sections from all sites where two measurements are available. Scales are comparable throughout. Undercuts are not depicted. Note that Cross section 43 is of a section where three channels zones were present, but the left most channel was hidden by buttongrass thatch when the cross section was established, and is not completely captured in this data.

6.2.3 Sediment transport

Information on sediment transport within the Gelignite Creek catchment come from turbidity and suspended sediment measurements, from a sediment trap positioned just above the weir pool at the bottom of study catchment, and from general observations. Opportunities to empty the sediment trap were limited, as during low flow repositioning the trap results in displacement of turbid water which contaminates the next measurement, and at high flow the channel is too full to allow manipulation of trap and sediment.

Turbidity and suspended sediments are discussed in detail in 5.3 Stream chemistry, Turbidity and Laboratory analysis sections. Both lines of evidence suggest that suspended sediment transport in the study catchment is small.

Sediment trap results show that bedload sediment output from the catchment is also very small. Trapped sediment is dominated by sand and fine organic flock. On four occasions, a single gravel clast was found in the trap, and on one occasion a cobble. There is no obvious relationship between bedload sediment collected and either total or maximum daily rainfall during the collection period, possibly because the length of the collection period (averaging 5 months) masks the signal of any individual event.

Table 29. Results of bedload trap analysis. *Excludes a cobble weighing 277g found in the trap in April 2008.

	Sediment (g/day) *	Sediment (g/ha/year)	% organic *	% mineral *	% sand	%gravel	%cobble
Average	0.029	0.493	25	75	60	26	14
Minimum	0.000	0.075	41	99.8	2	0	98
Maximum	0.188	1.152	0.2	59	100	89	0

Observations of the stream during and following flood events suggest that sand is transported by the stream. Fresh sand drapes are frequently seen on bank tops and faces after high flows. It is possible that this particle size has been inadequately sampled as during high flow events it possibly moves as suspended load, rather than true bedload or saltating load to be captured in the sediment trap.

Initial impressions of cobbles on the stream bed suggest mobility, as they are generally clean of fine sediment and algae and lie loose on the surface. However, the lack of structures such as imbrication or sorting across the channel bed suggest that cobbles are more likely to be a lag left behind by the winnowing of finer particles than a product of modern sediment transport.

Discussion

7 Catchment hydrology discussion

7.1.1 Characteristics of moorland stream hydrology

Patterns common to both catchments

The hydrology of both Gelignite and Condominium Creeks share the characteristics of seasonality, flashiness and high catchment yield.

Both catchments show a mild seasonal variation in rainfall (see Table 7 and Table 8). Summer rainfall is slightly lower than the remainder of the year. This translates to a stronger seasonal pattern in stream flow, presumably caused by high rates of evapotranspiration in summer taking a larger proportion of rainfall than in the cooler seasons.

Both catchments are flashy with a very low base flow index, indicating that most rain water reaches the channel rapidly after a rain event, and between events stream flow is very low. A further manifestation of this pattern is the rapid rates of stream level rise and fall. These features are common to blanket peat catchments internationally (Burt *et al.*, 1990, Burt, 1996, Evans *et al.*, 1999, Holden and Burt, 2003b, Holden and Burt, 2003c, Evans and Warburton, 2007).

Both catchments have quite a high specific yield. Specific yield refers to the amount of runoff generated per unit area of catchment over a specified time. Obviously, yield over a given period depends on rainfall over that period. However, it also reflects the characteristics of the catchment that influence the proportion of rainfall that exits the catchment as stream flow such as the nature of soils and vegetation. Both Gelignite and Condominium Creeks have a relatively high monthly specific yield compared to average monthly rainfall of 69% and 57%. It should be acknowledged that these numbers are very sensitive to errors in calculation of stream flow, and so may change if the weir rating is changed in the future. These numbers are very high compared with forested or agricultural catchments (Zhang *et al.*, 1999), however they are in line with runoff ratios found in other peat catchments. For example, Labadz 1988 (in Burt *et al.*, 1990) found specific yield values between 50 and 62% for a blanket peat catchment in the UK, and Holden and Burt (2003c) found values between 72 and 82% in a similar area.

Contrasts between catchments

Beyond these basic similarities, the study catchments differ in several interesting ways. Gelignite Creek has a smaller seasonal flow variation (14% of annual flow in summer, 34% in winter) than Condominium Creek (12% and 38% summer and winter flows). Gelignite Creek has zero flow on average for 4.5% of the year, where Condominium has not ceased to flow in the period of record. Gelignite Creek is slightly flashier than Condominium Creek (base flow index 0.123 and 0.161 respectively). Also, Gelignite Creek has a higher monthly specific yield than Condominium Creek (average of 92 mm compared to 77 mm), despite the two catchments having a similar average monthly rainfall (133mm compared to 136mm). In other words, a greater proportion of rain leaves the catchment as stream flow at Gelignite Creek than it does at Condominium Creek, and that flow is more likely to occur during or soon after rain events.

These contrasts suggest that the two catchments have important differences in flow routing. It is interesting to speculate on the causes of such differences. In comparison to Condominium Creek, the Gelignite Creek catchment is larger, flatter, has a greater dominance of moorland vegetation and associated soils, and is underlain by quartzite slope deposits rather than quartzite bedrock. As the smaller steeper catchment, Condominium might be expected to have flashier flow, and be more prone to zero flow. As this is not the case, it is likely that differences in vegetation and soils are playing an important role in influencing hydrology. The effect of the underlying geology is not known.

Vegetation differences

Only 5% of Gelignite Creek catchment is mapped as scrub vegetation. In contrast 39% of Condominium Creek is mapped as scrub and forest. This means that Condominium Creek has on average almost double the volume of vegetation per square metre present at Gelignite (see Table 4). This has two direct impacts on the hydrology of the catchment, through interception of rain and through evapotranspiration.

Rainfall in a vegetated area is intercepted by the canopy, and a fraction of that water is stored on the leaves and stems from where it will evaporate without ever having reached the soil. Interception losses depend on the characteristics of the vegetation and of the rain event, but can be very significant. For example, Williams *et al.* (1987) (in Ruprecht and Schofield, 1989) found that an open Eucalyptus forest in Western Australia caused an interception loss of around 13% of rainfall. Under similar rainfall conditions, interception in a forest would be expected to be higher than in moorland because of the greater total leaf area and number of layers in the canopy (Brooks *et al.*, 1997). For this reason, it seems likely that the vegetation at Condominium Creek will be trapping a larger proportion of rainfall than the vegetation at Gelignite Creek. This effect will be largest in small rain events.

Vegetation uses water through evapotranspiration. Transpiration rates vary with species and conditions, but generally transpiration rates are likely to increase with increasing leaf area and increasing exposure to wind (Brooks *et al.*, 1997). Although no attempts at measurements have been made, it is highly likely that evapotranspiration rates from the extensive scrub, forest and rainforest at Condominium Creek will be higher than those of the moorland vegetation that dominates at Gelignite Creek.

The net effect of the forest at Condominium Creek is likely to be a smaller proportion of rain that initially reaches the soil, and a smaller proportion of water reaching the soil that is available to form stream flow. This could explain the lower specific yield at Condominium Creek. The lower summer flows at Condominium may be caused by high evapotranspiration rates in the forest. However, this does not explain the lack of zero flow events at Condominium Creek.

Soil differences
Soils character in southwest Tasmania is strongly associated with vegetation (di Folco, 2007). While Condominium Creek soils have not been systematically surveyed, it is reasonable to expect that soils under the forest in this catchment will follow patterns found elsewhere, and lack the dense sapric peat horizon that is characteristic of many moorland soils. Forest soils are therefore more likely to allow rain to infiltrate the soil, from where water may be lost to evapotranspiration or to groundwater, or be slowly released to the stream as baseflow. Moorland soils, as discussed below, are more likely to generate overland flow and contribute directly to stream flow.

Soil differences between the two catchments could explain the greater flashiness at Gelignite Creek (greater dominance of overland flow). Greater infiltration into soil and groundwater, from where water can drain slowly to the stream, would also explain the more consistent base flow at Condominium Creek.

7.1.2 Stream flow prediction
This project included an initial investigation of the ability to predict stream flow from rainfall. Similar analyses will be completed in more detail when a significant period of post fire data is available for comparison.

This initial analysis suggests that a large proportion of the variability in flow could be predicted from rainfall over the preceding period. Including evaporation data, and further investigation of thresholds such as the minimum size rain event needed to initiate a change in stage, should allow further improvement in predictive capacity.

It is worth noting that some caution should be used in interpreting and using the relationships reported here. The strongly skewed data made meeting the assumption of normal distribution difficult. Also, the assumption of equal variance in flow for different values of rainfall was difficult to meet. As such, these results should be viewed as identifying patterns and generating hypotheses for further investigation.

The rainfall variables used in the regression analysis (see Table 30) were selected to maximise the flow variability explained by the model, rather than being chosen on a theoretical basis. Often, advantages offered by one variable over another were small, as may be expected given a degree of autocorrelation between variables. However, the following interesting points are raised by the selection of variables:

- Peak flow simple regressions are best predicted by shorter rain periods than the daily flow regressions. This may be explained as the response of flood peaks to short term increases in rainfall intensity, while overall runoff responds to the larger rainfall event.
- In contrast, peak flow multiple regressions include the very long three week rain period, while daily flow refers only to one week rainfall. This suggests that after the effects of short term rainfall intensity are accounted for, the antecedent conditions become important in determining size of peak flows.
- Gelignite Creek is more responsive to short term variation in rain than Condominium Creek, both in terms of daily total flow and daily peak flow. The more buffered flow

in Condominium Creek may be caused by the much larger proportion of the catchment covered by scrub, forest and rainforest, with the associated deeper soils with higher infiltration capacity than moorland soils.

Table 30. A summary of the flow modeling completed for both catchments. Note that all models for Condominium Creek used the square root of flow data.

	Simple regression variable	% variation explained	Multiple regression variable	% variation explained
Gelignite Daily flow	2 day rain	78%	3 day and 7 day rain	82%
Condominium Daily flow	4 day rain	67%	1 day, 3 day and 7 day rain	84%
Gelignite Peak flow	1 day rain	73%	1 day, 5 day, 10 day, and 3 week rain	84%
Condominium Peak flow	2 day rain	78%	2 day, 5 day and 3 week rain	81%

Several further points of interest were raised by the regression analyses:

- Relationships are generally quite clear at lower flows, but include much more variation at higher flows.
- Extreme events are more difficult to predict. These include both long dry periods when small rain events create little stream flow response, and very wet periods when small rain events generate a big response. Further work may allow thresholds between these responses to be identified and therefore better prediction of extreme events.
- Condominium Creek is best fitted by a curvilinear relationship, while Gelignite Creek is best fitted by a linear relationship. Causes of this difference are worthy of further investigation.

This preliminary work on the relationship between rainfall and flow suggests that a useful predictive model could be developed and used to investigate changes in flow yields following catchment scale fire.

7.1.3 Flow routing at Gelignite Creek

Having a conceptual model of water movement through the Gelignite Creek catchment (and by extension, to other similar catchments) would improve our ability to understand and predict how fire influences stream flow. However, development of a robust model able to make accurate predictions requires a large range of data and extensive study of many different components of hydrology over many years (Croke and Jakeman, 2001, McGlynn *et al.*, 2002). Some important datasets and their availability in the Gelignite Creek catchment are listed in Table 31.

Table 31. Some of the data required to develop a detailed model of catchment hydrology, and the extent to which that information is available at Gelignite Creek.

Dataset	Availability
Rainfall and discharge	Available
Measurements of all storm flow generation processes in a range of event sizes	Casual observations only
Water chemistry under a range of flow conditions	Limited data available
Rain, soil water and groundwater chemistry	Not available
Spatially distributed evapotranspiration, infiltration and recharge rates	Not available
Plant water use	Not available
Soil pipe and macropore density and connectivity	Casual observations only
Soil moisture dynamics	Casual observations only
Susceptibility of soils to hydrophobia following fire	Casual observations only

Obviously, a model produced from the limited data available at Gelignite Creek will include many uncertainties. However, it will still be useful for generating hypotheses to be tested by further data collection, and serve to focus future efforts to understand the fluvial geomorphology and hydrology of buttongrass moorlands.

Baseflow

It is generally assumed that the bulk of stream baseflow comes from groundwater (Burt, 1996, Davie, 2003). Many studies of peat catchments are consistent with this. For example, Vogt and Muniz (1997) working in a blanket bog catchment in Norway found that baseflow water chemistry reflected the chemistry of the mineral soil beneath the peat, while stormflow reflected the chemistry of organic horizons. Similarly, Worrall *et al*. (2003) examining water chemistry in an upland peat catchment in the UK found that baseflow was characterised by groundwater inputs, and that higher concentrations of colour, iron and aluminum at higher flows were associated with flow through the upper organic horizons. Ringrose *et al*. (2001), working in forested headwater streams at Warra in southern Tasmania, found that colour (indicative of dissolved organic carbon concentration), nitrogen and iron were lower at base flow than during flood flow.

In contrast, water chemistry at Gelignite Creek does not appear to follow this pattern. Here, baseflow has the highest concentrations of dissolved organic carbon and iron, which are associated with organic soil horizons. This suggests that slow drainage of the soil profile plays an important role in maintaining baseflow. This has been shown to be feasible (Burt, 1996). Levels of dissolved silica at baseflow suggest that there is also a component of groundwater present, but this may be small. The dominance of base flow by soil water explains the relatively frequent zero or close to zero flow events at Gelignite Creek, as this would occur whenever the soil dries out. This may also explain why base flow represents a relatively small proportion of total stream flow at Gelignite Creek (base flow index only 0.123), as base flow volume would be limited to the water holding capacity of the soil profile, and would have to compete with evapotranspiration for a share of that water.

Stormflow

During a storm, water is transmitted to the channel through a range of processes. Water can flow over the surface, through the soil matrix, through preferential paths such as macropores or soil pipes, or from ground water. The water reaching the stream can be 'new' (i.e. rain water) or 'old' (i.e. water that was already present in the soil or watertable prior to the rain event). Old water can contribute significantly to a flood, either because of straightforward mixing in the soil profile, or because of translatory flow through this soil. Translatory flow is where rain impacting and infiltrating on the slopes pushes out existing old water further down the slope by processes such as piston flow (Hewlett and Hibbert, 1967) transmissivity feedback (Bishop *et al.*, 2004) or a kinematic wave (Williams *et al.*, 2002).

Gelignite Creek would be expected to have a flashy hydrology because it is a small, relatively steep catchment with high drainage density (Gordon *et al.*, 2004). However, the extremely rapid response to rainfall and the low base flow index suggest that a substantial proportion of rainfall is reaching the stream channel via rapid flow pathways such as overland flow, macropores and pipes, with limited water storage capacity in catchment soils (Burt, 1996). Observations made during moderate to large rain events of extensive areas of sheetflow across the catchment, and water 'fountaining' out of crayfish burrows (Figure) support this theory.

Figure 42. Water 'fountaining' out of a crayfish burrow (note pencil for scale)

The character of the dominant soils in the catchment has a big influence on stormflow generation processes. The soil surface is most commonly a fibric organic horizon likely to have high infiltration rates. This horizon is relatively shallow and is underlain by a much denser sapric organic horizon, which would act as an aquitard and quickly allow the surface soil to saturate, creating conditions for throughflow in the upper horizon, and also overland flow once surface irregularities have filled with water. Similar patterns have been found in hydrological studies of other peat landscapes (Grover, 2001, Holden *et al.*, 2001, Holden, 2002, Holden and Burt, 2003b). It is possible that infiltration excess overland flow occurs at Gelignite Creek, but it is likely to be restricted to small areas, and short periods of time when rainfall is at maximum intensity.

Macropores and soil pipes have the potential to transport a significant volume of water down and through the soil profile (Burt *et al.*, 1990). For example, Holden and Burt (2002) found that pipeflow contributed over 10% of stream flow in an upland catchment with deep blanket peats in Northern England. However, the pipes in Holden's study were up to one metre in diameter, were several hundred metres long and were obvious where they joined the stream channel. The density and connectivity of macropores or soil pipes at Gelignite Creek is unknown, but there is no evidence of features on such a scale. Observations from soil pits suggest that in the sapric organic horizon, macropores are uncommon, and while soil pipes up to several centimetres in diameter have been observed, they are relatively uncommon. Observed pipes have been identified as burrows of freshwater crayfish. These typically extend from multiple entrances at the soil surfaces, often emerging in small pools. Burrows can extend down to the mineral soil underlying the organic horizons (Horwitz and Richardson, 1986, Growns and Richardson, 1988). Burrows are not likely to be interconnected. As such, they would form an effective route for water to penetrate the organic soil to the underlying sands and gravels, but are unlikely to transmit water laterally for significant distances.

Available information on water chemistry during flood flows does not present a clear picture. On the one hand, the limited data available shows dissolved organic carbon and iron concentrations typically decrease with increasing flow. This is an unusual response, and suggests limited inputs of soil water to higher stream flows. Other monitored parameters have not proved useful in investigating water sources. For example, dissolved oxygen concentration mainly reflects flow level, presumably because it responds rapidly to flow turbulence, and so any signal from source waters is rapidly lost. Stream pH is generally stable through rain events, probably because the water is well buffered, although it may indicate that organic acids are mobilised enroute to the channel, and that throughflow in the organic soil horizons is important.

Finally, the conductivity record shows that the overall dissolved load has three different responses to rain events:

1. rapid decrease in conductivity followed by gradual increase to pre flood levels (most common);
2. rapid increase followed by gradual decrease to pre-flood levels, or
3. a composite of the two responses during successive pulses in stream flow.

This suggests that different flow processes can dominate in the catchment, one which allows low conductivity water (presumably rain water) rapid access to the channel, and one that flushes a reservoir of high conductivity water to the channel. It is striking that the high conductivity water appears to enter the stream as a pulse during the flood event. Once the stream returns to base flow, conductivity typically returns to background levels. At this stage, we have no hypothesis as to where in the catchment the high conductivity water may be stored and flushed only in selected events. Also, we have no hypothesis as to what the trigger for this flushing may be, as examination of rainfall, stage, pH and conductivity records shows that there is no obvious correlation of the different conductivity responses with intensity, length or overall magnitude of rain event, antecedent conditions, water level or change in pH. By chance, no detailed water chemistry analysis is available for events when conductivity increases.

At this stage, the implications of the different conductivity responses are unknown. The pattern does not fit that expected if initial rainfall flushed high conductivity water from the catchment which is then diluted by further rainfall, as the response to a single rain event is a single and immediate rise or fall in conductivity. There are situations described in the literature where a threshold controls the dominance of different runoff processes. For example, large rainfall events may create vertical bypass flow, where macropores carry water rapidly to depth, while smaller events wet the profile gradually from the surface (McGlynn *et al.*, 2002). Also, Williams *et al*. (2002) found that for a kinematic wave to transmit down a slope and so cause the release of soil water requires a threshold catchment wetness. However, while these would result in different flow paths dominating, it seems unlikely that either of these processes would result in such fundamentally different conductivity responses in the stream water.

Vegetation effects and influences

Vegetation can influence flow routing through canopy interception and through evapotranspiration. Evapotranspiration influences flow routing by affecting levels of soil moisture within the root zone. No measurements of evapotranspiration rates are available for the vegetation types at Gelignite Creek.

Canopy interception can also be important. The proportion of a rain event that is lost to interception depends on how much water the canopy can hold, the total rainfall and meteorological conditions such as windiness and the rainfall intensity (Zhang *et al.*, 1999, Dunkerley, 2000). Burt *et al*. (1990) state that dense ground vegetation such as heather may have storage capacities of 2mm, grasses are around 1mm. No measurements of moorland storage capacity have been made, but it is likely to be of this order of magnitude. Even though the total storage is likely to be small, this can still have a significant impact on catchment hydrology - Dunkerley and Booth (1999) estimated that canopy interception losses of 30% can occur in semi arid grassland if rainfall occurs spread over many small rain days. However, this is unlikely to be the case at Gelignite Creek. Figure 12 shows that although 44% of rain days total less than 2 mm of rain (likely to be largely lost to canopy interception), this represents only 5% of total rainfall. Most rain falls in rain days between 5 and 25 mm, where evaporation from the canopy is likely to form a smaller proportion of total rain.

A conceptual model of flow generation at Gelignite Creek

The following conceptual model of flow generation at Gelignite Creek is proposed as a hypothesis, based on the data discussed above.

Between rain events, water drains very slowly through the sapric organic soil horizons, and then more rapidly through underlying sands to the stream. Deep organic soils in headwater drainage lines take longest to drain, providing DOC rich water to the stream. Some groundwater inputs to the channel also occur, but the relative contribution is unknown and may be small. Very low or zero flow events occur relatively frequently, once soils have completely drained.

In the smaller rain events, particularly after a dry period, there is little stream flow response. In this situation, rainfall would be partitioned largely between canopy interception and soil storage. The threshold conditions below which there is no flow response to rain have not been quantified by this project.

In larger rain events, water rapidly infiltrates the upper horizon of fibric organic soil. The lower sapric horizon acts as an aquitard, causing the upper horizon to become saturated. At this point, throughflow in the upper horizon becomes important. Once surface depressions are filled with water overland flow is also important. This mix of overland and shallow throughflow rapidly delivers mainly ‘new’ water to the channel. Where they occur, macropores (mainly crayfish burrows) move significant volumes of water a short distance downslope. Their overall contribution is not known but outside of drainage lines is likely to be small as there is no evidence for significant interconnectivity. Translatory flow pushes water out of both organic horizons, introducing to the channel a proportion of chemically ‘old’ water from the sapric organic horizon, but the balance of evidence suggests that this component is relatively small.

Streamflow in a rain event can be dominated by low or high conductivity water. As yet we have not identified either the source of high conductivity water, or the mechanism which causes its release in some events but not others.

Groundwater recharge would occur from water that seeps through the organic soil, and also through crayfish burrows. The latter is likely to be an important route, given the low hydraulic conductivity of sapric organic soils. The high specific yield for the catchment suggests that losses to groundwater are relatively small.

This system is unusual in that base flow appears to be dominated by drainage of soil water. It is also striking that the dominance of rapid flow paths and high proportion of ‘new’ water contributing to flood flow are a contrast to catchments in other types of landscape (e.g. forested study sites in the Warra LTRS (Ringrose *et al.*, 2001). It seems highly probable that the moorland vegetation and associated soil is a major control on this hydrology.

8 Fluvial geomorphology discussion

8.1 Distinctive geomorphic features of buttongrass moorland streams

Previous work on the fluvial geomorphology of Tasmania's buttongrass moorlands is limited to the descriptive studies Jerie *et al.* (e.g. Jerie *et al.*, 2003) and Jerie (2005). That work described qualitatively a set of features distinctive to moorland streams, some of which have now been described quantitatively at Gelignite Creek. These are:

- Small streams have low width to depth ratios.
- Channels in moderate gradient valleys are more sinuous than would be expected for that valley slope.
- Anabranching channels are common in low gradient areas (not relevant to this study as valley slopes are too great).
- Channels have very low capacity, so that bankfull flow occurs many times each year.
- Subsurface drainage networks that on small streams accept part or all of base flow.

This study has identified further distinctive features at Gelignite Creek, namely:

- Frequent large undercuts.
- Channel pinches stabilised by vegetation, controlling pool level and long profile instead of conventional riffles.
- Organic soils as a bed control.
- Stable channels in a stable landscape.
- Small sediment loads.
- Multiple channels in small catchments.

Nationally and internationally, there is a relatively small body of research looking at the geomorphology of peatland streams (Watters and Stanley, 2007). Further, the context of these studies varies widely in topography and peat depth and character, including: the relatively well studied deep blanket moorlands of the UK (e.g. Gilman and Newson, 1980, Jones and Crane, 1984, Lindsay *et al.*, 1988, Labadz *et al.*, 1991, Evans and Warburton, 2001, Burt *et al.*, 2002, Holden and Burt, 2002, Warburton, 2003, Evans and Warburton, 2005, Yeloff *et al.*, 2005, Holden, 2006, Worrall *et al.*, 2006); shallow tussock and grass peatlands in the Barrington Tops in New South Wales (Nanson, 2009, Nanson *et al.*, 2010); fibrous forest peats in North America (e.g. Epstein, 2002, Smith and Pérez-Arlucea, 2004); and terrestrialised lakes filled with sphagnum peat (e.g. Watters and Stanley, 2007). Much of the international literature involves streams draining wetlands confined to depressions rather than blanket bogs, so channel slopes tend to be very low, and peat is often deep enough that it forms the channel bed as well as banks. However, while the nature of the effects vary between streams, a common conclusion is that where it occurs, peat exerts a strong influence on stream processes and morphology, so that a channel through peat has a different form than one through mineral substrates (e.g. Epstein, 2002, Smith and Pérez-Arlucea, 2004, Watters and Stanley, 2007, Nanson, 2009, Nanson *et al.*, 2010).

Width to depth ratios

Width to depth ratios found in this study varied between 0.7 and 9.6 with an overall average around 2. An examination of the data shows that the higher values of the ratio (where the channel is much wider than it is deep) come from cross sections located at channel pinches, where the channel may be narrower than typical, but is also far shallower than typical. For the most part, the ratio is between 1 and 3. Low width to depth ratios are typical of small catchments, where sediment transport is dominated by suspended load rather than bedload, and of channels with cohesive banks (Church, 1996, Rosgen, 1996).

Relatively small width to depth ratios are a common, though not universal finding amongst peatland streams (e.g. Epstein, 2002, Jurmu, 2002, Smith and Pérez-Arlucea, 2004, Nanson *et al.*, 2010). The ratio is often not as small as those found at Gelignite Creek, although this may in part be an effect of the much larger catchment areas of many studies. For example, Epstein (2002) (working in a low relief catchment the eastern USA) found that peaty reaches formed an exception to the general pattern of gradually increasing width to depth ratios with increasing catchment size, and had ratios well under 10. The most similar findings come from the work of Nanson and others (Nanson, 2009, Nanson *et al.*, 2010) working in grass and tussock peatlands in NSW. They found very similar small streams with vertical banks and width to depth ratios around 2.

In contrast, Smith and Pérez-Arlucea (2004) found that peat was associated with very high width to depth ratios, but this was where it formed the stream bed, encouraging erosion of much less cohesive bank sediments. It appears that the effect of peat depends on where in the channel it occurs.

Channel sinuosity

or 5% (Schumm, 1985), and in a channel that is so narrow and deep (Parker 1976 in Jurmu, 2002).

Bankfull flow frequency

The capacity of channels throughout the Gelignite Creek catchment tends to vary markedly over very short distances. This makes defining a bankfull flow difficult, as overbank flow may be observed at channel pinches while in the rest of the channel the flow is only half way to the bank top. However, when stage at the weir reaches 30 cm, field observations suggest that banks are overtopped at most pinches. If this somewhat arbitrary level is taken to be bankfull, then in the 2008 calendar year, bankfull flow was exceeded for 2.6% of the year, spread across 27 events separated by at least 24 hours. While work on alluvial channels in Australia and internationally includes considerable variation in the expected frequency of bankfull flows, it is generally accepted that bankfull flows occur roughly every one or two years (Gordon *et al.*, 2004), and variations to this average tend to be towards longer rather than shorter recurrence intervals. Nanson *et al.* (2010) working in low gradient peaty swamps in the Barrington Tops in New South Wales also found that bankfull flow occurred multiple times each year, although not with the frequency observed at Gelignite Creek. They attribute this to a close relationship between hydrological control of swamp water tables and therefore peat development on the swampy floodplain, the erosion resistant stream banks, the absence of sediment and the hydraulic drivers of channel geometry. It is not clear whether similar hydraulic controls are operating at Gelignite Creek, given differences in topography, sediment load, and vegetation character.

Subsurface drainage

Jerie (2005) described frequent tunnels on moorland streams, falling into three forms: small pipes formed by crayfish burrows (<5 cm), medium sized tunnels at the interface of organic soil and underlying mineral horizons, and larger diameter tunnels similar to a channel with a roof. This pattern was also found at Gelignite Creek. It is somewhat similar to the two classes of pipe found by Gilman and Newson (1980), working in shallow peats of the Wye catchment in Wales – small diameter ephemeral pipes found close to the surface on slopes, and larger seasonal or perennial pipes found deeper in the soil profile. In deeper peats elsewhere in the UK, pipes are more variable in nature and this distinction is not applicable (Holden and Burt 2002).

At Gelignite Creek, pipes occur on the slopes and in the channel zone. On slopes, the only pipes identified are thought to be crayfish burrows. Whilst not uncommon, they are not present in huge numbers, and were seldom intersected in soil pits. They can be observed during and after rain events discharging water, sand and fine organic material, showing that they can result in rapid transfer of water through the soil profile, and in delivering sediment from below the erosion resistant organic horizons to the soil surface. However, these pipes are relatively uncommon in the catchment. Furthermore, they are unlikely to form interconnected networks over significant distances (Horwitz and Richardson, 1986), which limits their potential to be a major influence on fluvial geomorphology.

Small pipes are found in much greater densities along waterlogged drainage lines where catchment areas are small enough that a continuous channel has not formed. In these areas it is possible that pipes interconnect and transmit significant quantities of water and sediment, and this could mean that a larger catchment is needed to maintain a continuous identifiable surface channel.

Medium sized pipes occur in the channel zone at the interface of the organic horizons and the underlying sand and gravel. They were observed at the downstream face of channel pinches and steps, and occasionally encountered during installation of monitoring equipment in the stream zone, but never on the slopes. It seems likely that these tunnels augment the surface channel and do not extend far beyond the channel zone. These tunnels can be an important path for base flow around obstacles in the channel (such as weir plates). They could be a locally important source of coarse sediment to the stream, as they can contact the underlying colluvium below the surface channel. They are almost universally observed providing a vertical bypass for water and coarse sediment around channel pinches. We speculate that this is an important factor in the formation of pinches (see discussion below).

Finally, the largest class of pipe observed are the 'channels with a roof' found at moderate catchment sizes either replacing or in combination with a surface channel. They occur higher in the profile than the medium sized pipes described above, and can at times be tracked by a series of 'windows' where they are briefly open to the surface. Their length is difficult to determine, but observations of increases and decreases in flow suggest that they do not usually extend for tens of meters. These tunnels possibly have an influence on the stream hydrology, as they would contribute greater form roughness to the stream than an open channel. They may also increase the sensitivity of system to vegetation disturbance.

Subsurface drainage has the potential to play a significant role in terms of catchment hydrology and sediment transport (e.g. Gilman and Newson, 1980, Jones, 1997, Holden and Burt, 2002, Jones, 2004, Holden, 2006). Massive proportions of storm flow have been shown to be generated by pipes – up to 46% in a Welsh experimental catchment (Jones and Crane, 1984), and between 10 and 30% in a catchment in Northern England (Holden and Burt, 2002). Unfortunately it is not possible to calculate the flow or sediment output of pipes at Gelignite Creek. Pipe outlets could not be easily identified in stream banks, and sufficient time was not available for the labour intensive and potentially destructive process of tracing pipe networks.

Mechanisms of pipe formation are interesting to speculate on. Small pipes in Tasmania can usually be attributed to burrowing crayfish, while in the moorlands of the UK, animal burrows are not considered important because of the acid soil water(Holden, 2006). Rather, in these environments, desiccation cracking is thought to be the initial stage of pipe formation, followed by fluvial erosion enlarging the cracks (Jones, 2004, Holden, 2006).

Undercuts

Wherever channel banks of Gelignite Creek are steep, it is likely that banks have significant undercuts. These can be big enough to form a significant fraction of the channel cross section, although it is not known what proportion of water or sediment flow occurs in these zones. Flow measurement in undercuts would be difficult, but flow rates may not be very high. Undercuts are usually hydraulically very rough, as although they may extend a long way into the bank, they are often not very high, have a rough bed with exposed cobbles, may be partly choked by roots, and have dimensions that vary greatly down channel. It is not known if the undercuts are formed by fluvial scour which would require significant flows in these zones, or by sapping from lateral groundwater movement at the base of the peat which would require only sufficient flow to entrain already detached sand grains.

Bank profiles at Gelignite Creek are conducive to undercut formation, as the most erodible sediments are found at the base of the bank. The upper bank is typically cohesive sandy peat or organic rich sand, further reinforced by dense root networks of the moorland vegetation. Between this and the erosion resistant gravel and cobbles of the underlying colluvium lies a relatively thin layer of far more erodible sand within which the larger undercuts have formed.

Undercuts in peat streams are mentioned by several authors across a variety of peat environments where the peat is underlain by less cohesive material (e.g. Evans and Warburton, 2001, Watters and Stanley, 2007). Where undercuts reach sufficient size, the overhanging block of cohesive bank will fail and fall into the stream. In the rivers of the blanket peats of the UK, this process delivers large peat blocks to the channel, where they behave as bedload (Evans and Warburton, 2001).

The undercuts at Gelignite Creek are of interest because they appear to be very stable, with no evidence of failure blocks at the bank toe. This suggests that possibly because of the small size of the channel, undercuts do not reach the threshold size to cause bank failure.

Channel pinches

In the high sinuosity trunk stream reaches at the bottom of the study catchment, the long profile of the channel appears to be controlled by a series of channel pinches. Conventional riffles are formed from coarse bed material deposited in the bed, gently rising then falling into the next pool, with greater channel width and bankfull height than pools, occurring at relatively regular intervals downstream and showing some relationship to planform (Jurmu, 2002). Channel pinches at Gelignite Creek do not fit this pattern. They are formed like small headcuts with very steep downstream faces, and typically have very low bank heights and small channel widths. They occur at irregular intervals along the channel, and are not clearly related to planform (see Figures 37 and 41).

The steps in the long profile at channel pinches are in part eroded into the underlying colluvium and partly constructed by fine sediment deposits stabilised by mosses, liverworts and roots of surrounding riparian vegetation. This fine sediment can form around half of the height of the control point above the stream bed. This creates a strange situation in which the long profile of the stream, which influences the hydrology and habitat structure, is controlled by deposits of highly erodible sediment at the highest energy locations in the channel.

How these strange features form is unknown, but we hypothesize the following steps:

1. At small headcuts, the stream bed is colonised by mosses and other species, possibly because at low flow these are the first points that are exposed to the air. Because of the small size of the channel, shear strength during floods is not sufficient to scour mosses from the gravel.
2. Once mosses and other species have established, they trap a portion of the fine sand that is transported in the channel at high flows. This further improves the habitat, allowing continued growth of moss and continued trapping of sand.
3. As the deposit develops, base flow seeps through the gravels underneath the moss and sand bed, eventually eroding a tunnel at the contact between gravels and sands. Again, this improves the habitat available to the mosses, by increasing the proportion of the year that the area is not submerged. The cycle of plant growth and sediment trapping continues.
4. Eventually, the feature builds up in to the characteristic narrow and shallow channel pinch identified in this study.

Whether and how these features fail is also unknown. It may be that the smaller the channel becomes, the more flood flows are forced overbank into the dense riparian vegetation, encouraging the stream to form a new channel and abandon the old choked channel. Alternatively, as the depth of fine sediment increases, the size of the tunnel below may become sufficient to cause the collapse and erosion of the moss covered roof, so enlarging the channel and allowing the pinch construction process to start again. Possibly, during this process the location of the channel pinch may migrate upstream. Finally, it is possible that without some disturbance to the vegetation these features may reach a stable size where flow is sufficiently constricted that no more sediment is deposited and trapped.

A very similar feature to the channel pinches of Gelignite Creek is reported by Evans and Warburton (2007) from the blanket moorlands of the UK. In gravel bed streams with peaty banks, peat bocks eroded from the banks can partially block the channel, creating a stepped long profile and having a major control on bedload transport. Peat blocks can fail in very large floods, resulting in major changes to channel form. The long profile of these streams is remarkably similar to that of Gelignite Creek, with abrupt constrictions of the channel rather than a classic pool and riffle profile. However, it seems likely that the process by which the pinches form at Gelignite Creek is different, as peat blocks have never been observed, and pinches appear to be sand rather than peat deposits.

Jurmu (2002) found that in some very low slope wetland streams, channel width and bankfull height were greater in pools than riffles. Unfortunately, Jurmu does not comment on the long profile or the materials that form the riffles, so more detailed comparison is difficult.

Channel and landscape stability

Informal observations of Gelignite Creek suggest a very stable system. However, the monitoring cross sections show a variety of behaviours, from channel contraction, through no change, to channel expansion. The average rate of channel change across all monitoring cross sections is close to 0, although a handful of locations do show significant change. However, there are many sources of noise in this dataset. On soft surfaces, or surfaces obscured by litter or vegetation, it is easy to have repeated measurements vary in the order of 1 cm. On banks close to vertical, a very small horizontal error can give rise to a massive vertical difference. On cobble stream beds, a change in location of a single cobble can change a vertical measurement by 10 cm without truly indicating a change in height of the stream bed. Finally, the two sets of measurements were taken by different staff, further increasing the potential for differences in interpretation. This means that results at this stage must be interpreted with caution.

Evidence from the planform and long profile of Gelignite Creek does suggest that channel change can occur. Within Reach 1 there are several sections where multiple channels are present (see Figure 37), suggesting that channel change through avulsion can occur. In some cases, the capture of the new channel is incomplete. For example, around 60 m from the weir, three channels are present, which share flows. The southern channel takes all of the base flow through a tunnel below a channel pinch. The northern channel receives most of the flood flows. This situation has not changed during the project to date, suggesting that the rates of change may be slow. It is also possible that erosion of the channel bed may occur, particularly at the channel pinches described above.

Internationally, some authors have found that peatland streams are typically very stable (Watters and Stanley, 2007). This has been attributed to the cohesive stream banks caused by the physical properties of peat and the associated dense root mat. For example, Micheli and Kirchner (2002b, 2002a) have shown that the dense root systems associated with wet meadow vegetation is sufficient to increase bank strength and the size of the undercut required to cause bank failure, and that this will increases the amount of time required to bring a block to failure point, which will slow bank erosion. However, these are typically in very low energy environments. In the deep blanket peats of the UK, sheet erosion of hillsides, rapid soil pipe development, gully erosion and stream erosion are common responses to disturbances such as pollution, artificial drainage, grazing, and climate change amongst other causes (Burt and Gardiner, 1984, Holden, 2006, Evans and Warburton, 2007). Expansion of the channel network through gully erosion creates very high drainage densities or up to 11.15 km km^{-1} (Burt and Gardiner, 1984). Certainly there is no sign of such forms or rates of erosion in the Gelignite Creek catchment either on slopes or within the channel system. Drainage density at Gelignite Creek is only 6.6 km km^{-1}.

Small sediment load

Results from the sediment trap analysis, the turbidity record and the dissolved and suspended sediment sampling all suggest that rates of material leaving the catchment are very low, and can be measured in tens of grams per hectare per year. In agricultural areas, soil loss is typically measured in tons per hectare per year. While this may be a slight underestimate, due to low trap efficiency of sand sized particles, and a small sample size for suspended and dissolved loads, this suggests that Gelignite Creek is part of a very stable landscape.

Sources of sand within the channel are limited to erosion from undercuts, stores in the stream bed or sand sourced from slopes. Given the roughness elements present in undercuts, and the overall stability of the channel, volumes of sand sourced from undercuts are likely to be small. Most sand within the channel is either protected by the cobble lag or stored in channel pinches stabilised by vegetation. Fresh sand deposits are frequently observed on slopes, particularly downslope of sparsely vegetated areas or crayfish burrows with large stormflow discharges. However, as slopes are for the most part separated from the channel by small but densely vegetated flood plains, much of the sand generated in these areas may never reach the channel. While some sand can be seen as drapes on upper banks following flood events, the lack of temporary storages of sand within the channel such as point bars suggests that the stream is effectively sediment supply limited.

Organic soil as a bed control on very small streams

Where catchment areas are small, the organic soil of the valley floor has sufficient cohesive strength to hold an almost vertical headcut of up to one metre, creating a distinctive stepped long profile (the Steep stepped channels of Figure 35). These are striking and unusual features. Peat has been found to act as a very effective bed control in a much larger and lower gradient system in Canada (Smith and Pérez-Arlucea, 2004). However, it is not clear to the authors why so much of the slope in these reaches of Gelignite Creek should be concentrated into these discrete steps, rather than distributed along the length of the channel. Possibly some variation in peat depth or character, or in the associated vegetation plays some role in creating the steps. How vulnerable these features may be to erosion should damage occur to vegetation is unknown.

Multiple channels

In this study, reaches with multiple channels are found in very small catchment areas with relatively steep valley slopes and are probably an effect of the scale of vegetation (e.g.

individual buttongrass tussocks) compared to the very small channels. Epstein (2002) found that peaty streams in the Oswego River catchment in the eastern USA often had multiple channels where catchments were relatively small and channel slopes low. However, these anastomosing reaches are probably more similar to those noted in Jerie 2005 than those found at Gelignite Creek.

8.1.1 Dominant discharge - an interaction of geomorphology and hydrology

Hydrology is a major control over the geomorphology of the stream channel. In alluvial waterways, many aspects of the flow regime influence sediment transport patterns, channel form, and rates of channel change. Identifying which flows are most important in a stream is notoriously difficult (Gippel, 2001) and depends in part upon which aspect of the channel is in question (such as channel depth, width, capacity, bedforms, bed material). Different features of the channel may be maintained by different flows (Charlton, 2008). However, as burning the catchment is expected to change the hydrology, this can then in turn change the geomorphology of the channel.

The dominant discharge concept is used here to identify the potential for changes in hydrology at Gelignite Creek to cause changes in stream flow. Flood flows transport large quantities of sediment, but occur relatively infrequently. Low level flows occur frequently, but move only a small quantity of sediment. The dominant discharge is the flow level that transports the most sediment over a long period of time, taking into account both the quantity of sediment moved and the frequency at which the flow occurs (Charlton, 2008). By looking at changes in the dominant discharge, changes in channel form can be predicted or explained (Tilleard, 1999, Gipple *et al.*, 2000 in, Gippel, 2001).

The dominant discharge for Gelignite Creek has been approximated using the turbidity record to estimate suspended load throughout the period of record. This represents the discharge of sand, finer mineral sediments and fine particulate organic material, which move as saltating and suspended load past the turbidity probe. The gravel and cobble components of the sediment require much higher stream energy to be transported. This material would move as bed load, and is detected in the sediment trap just upstream of the weir. Leaving this coarse sediment out of the discharge calculations means that the dominant discharge calculations presented here give an incomplete picture of channel maintenance. However, it is justified on the pragmatic grounds that no significant movement of coarse sediments have been observed in the period of record, meaning that we lack the data to calculate discharge of coarse material, or to relate sediment discharge to flow. In other words, the cobble bed will be altered by flows outside the range of those experienced in this study. In contrast, the channel banks and instream features such as undercuts, sand 'beaches' in pools, and constructed tunnels consist largely of sand and organic material. If the post fire analysis of hydrology detects a change in the dominant discharge of suspended sediments, it is these features that may be affected.

There are several sources of error in the dominant discharge results presented here. For this reason they should be viewed as tentative results only. The analysis is based on establishing the relationship between turbidity, flow and laboratory measured total suspended solids, and there are not enough points available to determine this with any certainty. This is reflected in the low R^2 value for the regression analysis. The available points do not cover the range of turbidity values that occur in the dataset. Turbidity peaks are very short and difficult to sample. However, this does mean that the relationship between turbidity and suspended sediment has been extrapolated beyond the known data points in order to cover the whole record. Finally, dominant discharge analysis should be based on long periods of record, as it in part relies on an accurate description of flow frequencies, and at this site there is an incomplete record across only four years.

The dominant discharge calculations for Gelignite Creek showed a very flat curve without a clear peak, suggesting that a wide range of flows influence channel form (Figure 27). This shape of curve is not unusual in Australian waterways (Gippel, 2001), although comparisons should be made with caution as most studies have been of substantially larger systems than Gelignite Creek. Very low flows are the most dominant transporters of sediment, because, despite the small quantity of sediment transported at any moment, of the large proportion of time over which they occur. This is to some extent surprising, as field observations suggest that no sand is transported at lower flows. It is likely that this part of the sediment discharge curve is dominated by transport of fine particulate organic material. Further water sampling at a range of flows, allowing analysis of both total and volatile suspended sediments will allow the transport of organic and mineral sediment to be considered separately. This would allow the thresholds in the transport of different materials to be identified.

8.2 Stream character

The survey of stream characters through the Gelignite Creek catchment found a repeating pattern of stream types, each defined by a characteristic pattern of channel and valley features (Figure 35), many of which reflect the influence of moorland soils or vegetation as discussed above. Thresholds between characters are probably strongly influenced by the influence of flow volumes (i.e. catchment size) and valley slope on stream power.

These stream characters fit broadly within the pattern of peatland stream characters described previously, namely the Spero River south of Macquarie Harbour (Jerie *et al.*, 2003), two small tributaries of the Gordon River above Lake Gordon referred to as Camp Creek and Surprise Creek, and the Crossing River near the Western Arthurs (Jerie, 2005). There are differences in both stream character and the style of classification, due to the different landscape context of the waterways, and also the scale of the catchment under consideration. However, the similarities are striking.

The only stream description at the smallest catchment size comes from the upper Spero River, with a catchment area of up to 0.6 km^2. Although both catchments drain unconsolidated gravels, the Spero differs from Gelignite Creek in that it rises on a plateau, so its uppermost reaches have extremely low slopes and therefore low stream power for the catchment area. However, it shares with Gelignite's small catchment with tunnels stream character a valley floor where vegetation and organic soils are the main controls on ill defined channels that occasionally manage to transport some sand.

A stream character broadly similar to the steep stepped channel of Gelignite Creek was described at Camp Creek, a small tributary of the Gordon River. Zone two of this stream has an irregular planform influenced by vegetation and boulders in underlying sediments, knickpoints in the long profile, variable channel size associated with knickpoints with gentle gradient sections with multiple channels and tunnels and steep sections being narrow and trench like, and relatively small width to depth ratio (varies between 4 and 1).

Channels with a medium catchment area and moderate slope have been described from the Spero River (segment two – low energy headwater, catchment area between 0.6 and 4.3 km^2). This segment of the Spero is described as moderately steep interspersed with gently sloping sections. In steeper zones, boulders or large cobbles form bed controls. Lower slope zones have moderate sinuosity, width to depth ratios that can be less than one, and a stable cobble bed with no signs of cobble transport. This appears to be a correlate of Gelignite Creek's high energy and high sinuosity trunk stream characters.

Several descriptions of stream character come from significantly larger catchments than Gelignite Creek, but are of interest because of what they say about the conditions where organic soils do or do not have a strong influence on stream character.

Surprise Creek is tributary of the Gordon River. It drains around 6 km^2 of the Dennison Range, and then flows across the floor of the Vale of Rasselass. This compares to the Gelignite Creek catchment area of 0.3 km^2. Where Surprise Creek first reaches the valley floor, it is a high energy system transporting cobbles and boulders and shows little influence of the moorland landscape it has entered. However, by the time it comes to its lowest flattest reach the influence of moorland vegetation and soil is strong. Here, the flow is dispersed by an anabranching channel network so any individual channel may have similar stream power to Gelignite Creek. Channel features still include some in common with Gelignite's trunk stream characters – a width to depth ratio that is frequently less than one, undercut banks, a stable cobble lag on the bed and sand drapes indicating at least some sediment transport on some banks.

In contrast, the Crossing River has a larger catchment area again (16km^2), draining the southern slopes of the Western Arthurs. This channel is well over the threshold for organic soils to have a strong direct influence. It is an active cobble bed river, with width to depth ratios typical of literature (13 to 15). The lowest floodplain units are forested, and composed mainly of sand and gravel alluvial sediments. The channel only comes into contact with organic soils where a meander bend contacts a terrace, and as the organic soil is only in the top 10% of bank and the channel has the competence to erode terrace gravels, the moorland soil and vegetation has little influence on bank stability. Similarly, the third segment of the Spero River has a catchment area greater than 4.3 km^2. This reach has sufficient stream power to erode the underlying sediments, and rapidly changes from the moorland controlled stream described above to a laterally active cobble bed stream with a width to depth ratio of around four.

8.3 Concluding comments on fluvial geomorphology

The downstream development of different stream characters in the Gelignite Creek catchment primarily reflects increasing stream power with increasing catchment size, overcoming the resistance of the peat and associated vegetation to fluvial erosion. The stream types that occur between the unchannelled drainage lines at the top of the catchment and the continuous channel of the trunk stream types (small catchment with tunnels, moderate slope with tunnels, and steep stepped channel) include a range of unusual features such as multiple discontinuous channels, tunnels and peat steps that probably reflect the gradual breaching of the peat erosion threshold. Crayfish tunnels in saturated headwaters could potentially carry enough water and sediment to delay surface channel development.

In lower study reaches, the catchment is big enough to have a far more conventional surface channel develop. Here there are a number of distinctive features present that have been discussed in the section above. There are several characteristics of the system that between them could cause these features. These are the nature of bed and bank materials, the low sediment load, and the small catchment size.

One potential cause of the distinctive features of Gelignite Creek is the nature of the channel boundary material. In the lower reaches, much of the bank height is very cohesive organic rich material further reinforced by dense roots from moorland vegetation. At the bank toe, there is typically a shallow layer of sand that is relatively erodible, but this is underlain by either a cobble lag or the underlying colluvium, both of which appear relatively immobile under the present flow regime. This situation could at least partially explain the small width to depth ratios (erosion resistant mid and upper banks), the common presence of undercuts (erodible sand outcropping at bank toe), at least some forms of tunnels (developed in the same erodible sand as the undercuts), and the probable slow rates of channel change (erosion resistant bed and banks).

A further distinctive feature of Gelignite Creek is the small sediment load. This is a point of similarity between the swamp streams of the Barrington Tops in New South Wales that have similar near vertical banks, small width depth ratios and frequent overbank flow patterns to those found at Gelignite Creek. Nanson and others (Nanson, 2009, Nanson *et al.*, 2010) attribute this stream form to the optimum channel dimensions for sediment free flow. While Gelignite Creek is not sediment free to the same extent as the Barrington Tops systems, it is potentially reflecting similar drivers of stream form.

The distinctive features of Gelignite Creek are in part a function of catchment size and stream power. As stream power increases with catchment size the control of the organic soils is gradually breached, first allowing the development of a continuous channel (between small catchment with tunnels and moderate slope with tunnels stream character), then with the bed eroding down to underlying sediments (in the steep stepped channel character). If the study catchment was larger, stream power may rise sufficiently to erode the mineral sediments underlying organic soils, allowing bank failure to occur. This would obviously result in increased rates of channel change, increased sediment load (including peat blocks) which would further impact on channel form, and probably also an increase in the width to depth ratios. This is a pattern that has been seen on other moorland streams (e.g. the Spero River (Jerie *et al.*, 2003), the Crossing River, and the middle reaches of Surprise Creek (Jerie, 2005).

This research suggests that the geomorphology of Gelignite Creek fits within the context of other buttongrass moorland streams described in the literature, but forms a significant variation on standard fluvial geomorphology of alluvial streams. Moorland streams are more similar to peatland streams researched elsewhere nationally and internationally, but they still present a distinctive set of features not found elsewhere.

9 Potential impacts of fires

The increased understanding of the controls on the hydrology and geomorphology of Gelignite Creek created by this project give us an opportunity to speculate on the ways in which catchment scale fire may change the system. On lowland slopes similar to the study catchments, both an individual fire and higher long term fire frequency have been shown to be correlated with soil characteristics such as lower carbon contents and carbon density in upper and lower horizons, and shallower soil depths (di Folco, 2007, di Folco and Kirkpatrick, 2011). It is not yet clear from this work how these trends might impact on those aspects of organic soils that influence stream hydrology and geomorphology. However, this, as well as fire effects common to many environments (Shakesby and Doerr, 2006) might be expected to result in changes to the stream system.

Hydrological responses to fire

A range of hydrological responses to catchment scale fire may occur. They include:

1. **An increase in specific yield**
   This is a measure of the total amount of water that leaves the catchment as stream flow. It can be used to compare catchments of different sizes, and the same catchment in different conditions (e.g. before and after fire). A change in the relationship between rainfall and yield can been used to track the hydrological effects of catchment scale fire (White *et al.*, no date). The size of this effect may depend on the response of the vegetation to fire – where plants are killed and must regenerate from seed the response may be large (Kuczera, 1987), but White *et al*. (2006) showed there was little impact of fire on long term catchment yield where the vegetation recovered by re-sprouting.
2. **Increased base flow**
   A lack of vegetation to transpire soil water can make a big difference to the rate at which soils dry out. If our conceptual model of flow generation is correct, soil water forms the bulk of base flow in the stream. Therefore, an increase in base flow volumes could be expected following fire. For example, O'Loughlin *et al.* (1982) found post fire baseflow was 3.5 times mean pre-fire.
3. **A lowering of the threshold rain event needed to initiate runoff**
   Destruction of vegetation means that a smaller proportion of rainfall is intercepted by the canopy, there is less leaf litter to form a physical barrier to overland flow, and reduced transpiration rates means that soils remain wet for longer. Also, fire can induce soil hydrophobia which reduces infiltration and increases overland flow (Scott and Van Wyk, 1990, Shakesby and Doerr, 2006). Together, these effects mean that smaller rain events would cause a rise in stream level.
4. **Changes to storm flow**
   In most environments, catchment scale fire results in flood events rising faster, being deeper, and transporting more water than in an unburnt catchment (Shakesby and Doerr, 2006). However, according to the model of flow generation proposed here, the soils of moorland will normally generate large quantities of overland flow because of low infiltration rates in the sapric organic horizon of the soil. Under these circumstances, it may be that fire has less effect on catchment hydrology in this environment than in the

forested catchments where most research has previously occurred. An effect may be found in small rain events, where the threshold to initiate overland flow may be passed sooner due to the lack of canopy interception but in larger events there may be little difference.

Geomorphic response

A series of interrelated geomorphic responses may also occur following fire.

1. **In channel erosion**

   A combination of post fire effects simultaneously increases erosion pressure on the channel boundary, while decreasing the resistance of boundary sediments to erosion. Flow velocity near the bed and banks are likely to increase as increased levels of storm flow from the burnt catchment flow faster down a channel that has lost some or all of the vegetation component of channel roughness. At the same time, roots of vegetation killed or even severely pruned by fire will gradually die and decompose, reducing bed and bank strength. These effects have been shown to lead to significant channel change in other systems (e.g. Eaton *et al.*, 2010).

   A big potential impact is on the channel pinches that control the long profile of the stream. These features are in part constructed from highly erodible sand stabilised by mosses, liverworts and roots of riparian vegetation. The loss of similar features has been observed by one of the authors following the wildfire at Twelvetrees Range, and a similar loss is expected at Gelignite Creek. The result is a loss of instream diversity (pools and riffles are converted to runs), and a further increase in stream power due to reduced channel roughness. This effect may be temporary, as pinches may be rebuilt in similar locations as the catchment recovers following the fire.

   Channel pinches also coincide with cobble controlled steps in the long profile, which have the form of small headcuts. With stream power increased and the protective moss and sand removed, it is possible that these headcuts will erode and move upstream, permanently lowering the stream bed.

   Bank erosion is also possible, either through direct scouring of the now bare banks, or through enlargement of undercuts to the point where mass failure occurs.

2. **Increased sediment budget in stream**

   In the unburnt state, Gelignite Creek appears to be almost starved of sediment. This situation may change following fire. In part, soil stability on slopes is due to the binding effect of the root mat. This will decrease as dead plants decay. Simultaneously, there may be an increase in overland flow. These effects could combine to increase sediment flux from slopes. Those sediments may be delivered to stream channels more effectively once the filtering effect of the riparian cover is reduced. Also, in-channel erosion provides a new sediment source. In combination, these processes could dramatically increase the sediment budget of the stream. Increased rates of sediment supply are a common finding of post fire studies (e.g. Benda *et al.*, 2003, White *et al.*, 2006, Woods and Balfour, 2008, Smith *et al.*, 2010).

With an unburnt catchment, Gelignite Creek is not competent to transport the cobble lag that forms the stream bed. However, changes to the hydrology and to channel roughness may increase stream power to a point where this material becomes mobile. This could cause significant changes to the stream.

3. **Flow on effects of increased sediment load?**
   Nanson *et al.* (2010) proposed that low sediment loads were a cause of the distinctive low width to depth ratio of peatland streams of the Barrington Tops in NSW. If similar processes are responsible for the form of Gelignite Creek, then any increased sediment load would put further pressure on channel form.

4. **Increased erosion caused by overbank flow**
   Gelignite Creek spends an unusually large proportion of the year in overbank flow, at least in areas of channel constriction. The sinuous planform and relatively steep valley slope mean that there is potential for meander neck cutoffs to occur. In the unburnt condition, dense riparian vegetation appears sufficient to keep these areas stable, but it is possible that following fire erosion will occur at these pressure points.

10 Conclusions

This report builds on earlier work that suggested stream systems in buttongrass moorland have unusual characteristics (Jerie *et al.*, 2003, Jerie, 2005). Many of the characteristics noted in that earlier work have now been quantified in the study catchment on Scotts Peak Road, and new features have been described.

Hydrologically, the moorland streams studied here have been shown to be extremely flashy (fast to rise and fall in rain events) with high specific yields (proportion of rainfall leaving the catchment as streamflow). Gelignite Creek has also been shown to have an extremely high frequency of bankfull flow.

These characteristics, in combination with data on water chemistry, have lead to the proposal of a conceptual flow generation model for the Gelignite Creek catchment. This model suggests that the distinctive features of the hydrology are largely a result of the organic soils in the catchment. Put simply, the typical profile of moorland organic soils is a shallow fibrous organic horizon with relatively high hydraulic conductivity overlying a thicker sapric horizon (the muck peat) which has a very low hydraulic conductivity. In rain events large enough to trigger a response in stream flow, the sapric horizon acts as an aquitard, causing the rapid saturation of the overlying fibric horizon and the generation of shallow throughflow and widespread overland flow. This results in the very flashy hydrology observed in the catchment. Between rain events, it is the gradual drainage of water from the soil including the sapric horizon that generates base flow. While a flashy hydrology is common in blanket bog catchments internationally, this is usually because of high watertables rather than an aquitard horizon in the soil. Base flow that is generated from soil water is uncommon even in other blanket bog catchments.

This flow generation model is in a very early phase of development, and would require further investigation and testing before it could be assumed correct. There remain some fundamental questions, such as why the response of conductivity to rainfall varies dramatically from an increase followed by a gradual dilution, to dramatic dilution followed by gradual return to the original concentration. This suggests two very different routes that water can travel through the catchment, which may have implications for land management.

Geomorphically, Gelignite Creek also presents some interesting features, including small sediment loads, low width to depth ratios, undercut banks, high sinuosity channels in moderately sloping valleys, constructed channel pinches instead of riffles, frequent subsurface drainage lines and multiple channel sections. These features form stream characters consistent with those found in similar contexts in other studies (Jerie *et al.*, 2003, Jerie, 2005). Again, it is thought that these features largely reflect the influence of the organic soils and moorland vegetation in the catchment and stream zone.

If the models of hydrology and geomorphology presented here are correct, they have implications for land management, including fire management, in moorland areas. There is increasing evidence that fire regimes impact on carbon content of moorland soils, even if a fire does not cause dramatic soil loss. It is less clear what impact fire regimes may have on the soil properties that influence hydrology and fluvial geomorphology, but there is clearly potential for impacts following an individual fire, and for a drift in catchment characteristics following a change in fire regime.

Where to from here? The next phase of this project involves burning the Gelignite Creek catchment, and attempting to measure the impacts that might theoretically be expected. The catchment was burnt in 2009. Data collection is continuing, and analysis of post fire data is expected to begin in 2013.

Other useful work would be to extend the spatial coverage of the project. One approach might be to develop a 'rapid assessment' style list of channel characteristics to see if moorland streams in general follow the pattern identified at Gelignite Creek and streams examined in previous work. For example, streams could be rapidly characterised in terms of width to depth ratios, the presence or absence of features suggesting of sediment transport such as sand deposits or flow structures such as imbrications of larger clasts. There would then be potential to extend this assessment to make judgements about stream condition.

Given the nature of buttongrass moorlands it is clear that they will burn, whether in wildfires, management burns, or both. This research is an important step on the path to understanding what impact our imposed fire regimes might have on the landscape, so that the implications of our management decisions might be better understood. It is also an important part of documenting the features and processes that make the TWWHA distinctive and special, and understanding where our landscape fits in a global context.

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Appendices

Appendix 1 Litter index

Living and dead vegetation influences catchment hydrology in three ways:

- Evapotranspiration – varies directly with live biomass – can estimate from cover and height measurements in vegetation data
- Precipitation interception – varies directly with cover and quantity of living and dead biomass
- Mulching - varies directly with biomass in contact with ground.

Consider the biomass in three parts: the sedge and ground; shrub; and tree stories.

Ground cover
Includes living and dead plant material that is in the sedge storey. Height of storey varies between sites, and is determined by the height of the dominant sedge species.

Estimate the cover of each class of biomass index (over page) for entire quadrat.

The index refers to four criteria:

1. the character of horizontal material (typically dead, but may still be attached to living plant)
2. the structure of all biomass, e.g. packing density and arrangement (horizontal or vertical)
3. the appearance of a hand at arms length pushed vertically down to soil surface. Is the biomass dense enough to obscure view of hand or fingers?
4. how visible is soil surface?

Shrub layer and tree storeys (use same rating table but do both separately)
Cover includes dead material, and species not classified as shrubs but present in the shrub layer e.g. bauera. Where there is a tree canopy, shrub storey is considered to go from top of ground/sedge layer to 2 m high.

Consider percentage cover of the quadrat that fits into each of the density categories. Use rating table below to derive a single number canopy biomass rating.

Canopy density categories

Low	Can easily see through, canopy depth less than 1.5 m
Medium	Can see through but view is obscured, canopy depth greater than 1 m
High	Cannot see through the bulk of the canopy, canopy depth greater than 1.5 m

Canopy biomass index

density/cover	< 3%	3 – 10%	10 – 20%	20 – 40%	40 - 75	75 - 100
Low	**none**	**none**	**low**	**low**	**med**	**med**
Medium	**none**	**low**	**low**	**med**	**med**	**high**
High	**none**	**low**	**med**	**med**	**high**	**high**

Ground cover and sedge biomass index – to estimate effect of vegetation on interception.

category	description	typical depth (cm)	density
very low	Litter very shallow, often only 1 or 2 leaves thick. Litter tends to sit flat on the soil surface and creating a surface area not hugely greater than a bare soil surface. Living vegetation sparse. On vertical hand, hand clearly visible and fingers easily differentiated. From above, soil surface (incl. algae) is easily and frequently visible between individual particles of litter or plant, or only covered by a thickness of one leaf or occasional thin and sparse moss and lichen.	< 0.5	very low
low	Horizontal layer generally shallow, up to a maximum of 2 cm deep but typically much less, and where deep loosely packed. Much biomass formed by upright supported rather than horizontal material. Fingers obvious on vertical hand. Ground is clearly visible from above, but is often covered by moss or lichen which may be shallow or sparse.	0.5 – 2	low
moderate	Horizontal layer typically several centimetres deep. Vertical and horizontal packing is loose and variable. Upright material fairly dense, but gaps between stems are larger than stems. Fingers on vertical hand can just be differentiated. Ground is visible from above through litter and plant, but is typically covered by moss or lichen which can form a solid mat centimetres deep. Soil surface is seldom visible.	2 -5	low to moderate
high	Horizontal layer typically 5 – 7.5 cm deep. Material is loosely packed and often supported by vertical plants. Gaps between particles are frequent and often larger than the particles. Upright biomass is fairly dense. Vertical hand just visible, but fingers difficult or impossible to differentiate. Ground is seldom visible from above, and is covered by moss or lichen. Soil surface is very seldom visible.	5 – 7.5	moderate to high
very high	Vertical and horizontal layers too dense and intermingled to differentiate. Leaves and litter particles are frequently in contact with their neighbours, gaps when present typically have similar dimensions to the leaves. The bulk of the biomass is horizontal and supported from below rather than supported by parent plant. Fingers invisible on vertical hand. No soil surface can be seen through the vegetation/litter.	over 7.5	high

Appendix 2 Soil drainage classes

These classes are based partly on McDonald *et al.* 1990 pg. 151-152.

Very poorly drained. Persistent pools. The water table is at or near the surface for most of the year. The soil is waterlogged. The main source of water (to the plot soil) is through surface or subsurface flow, although precipitation may still be important. These sites are often in a depression. The soils are usually high in organic matter. Mineral soils are often grey-greenish-bluish due to strong reducing conditions. Peats tend to be "muck peats". The vegetation is likely to consist of sedges, herbs and ferns with possibly some aquatic species. There will tend to be fewer woody plants (those that are present are likely to be known wet area species). Bryophytes and soft-leaved plants are usually quite abundant.

Poorly drained. Water is removed very slowly. Seasonal ponding. Mineral soils often grey-greenish-bluish due to reducing conditions. There is often a reddish-orange lining to root channels. Peats tend to be "muck peats". The main sources of water (to the plot soil) are sub-surface or groundwater flow, in combination with precipitation. All horizons remain wet for several months. Surface soil is often waterlogged, and would (probably) only become dry at the driest time of year. Vegetation is likely to consist of sedges, herbs and ferns with fewer woody species being present (most of those that are present are likely to be typical wet area species). Bryophytes and soft-leaved plants are often quite abundant.

Imperfectly drained. Water is removed slowly in relation to supply. Precipitation is more important as the water source although subsurface and/or groundwater flow can be significant if soil capacity is low. The surface soil is usually not waterlogged, and would (probably) dry out in the dryer seasons. Water pools for short periods after rain. At the wettest part of the year all horizons are wet for periods of several weeks. There may be a reddish-orange lining to root channels. Peats tend to be more fibrous. The vegetation may contain some sedges and ferns but will support a variety of woody species. Wet area woody species will be less prevalent than at poorly or very poorly drained sites. Bryophytes and soft-leaved plants may be quite abundant but perhaps to a lesser extent than for poorly and imperfectly drained soil classes.

Moderately well drained. Water is removed from the soil somewhat slowly in relation to supply, due to low soil permeability, a shallow water table, a lack of slope, or some combination of these. Some horizons may remain wet for up to a week after rain. Surface soil is wet in the wetter seasons (but is generally not waterlogged) and would dry out at dryer times of year. Soils are usually medium to fine in texture. These sites do not support peat build-up. This type of site often supports a higher biomass and greater diversity of woody plants, with fewer soft-leaved plants and bryophytes than above.

Well drained. Water is removed from the soil readily but not rapidly. Soil is (probably) quite damp in the wetter seasons but not exactly "wet" and becomes dry in the dryer seasons. Some soil horizons may remain wet for several days after rain. Soils are often medium in texture. This type of site often supports a higher woody plant biomass, and fewer bryophytes. There is likely to be a greater number of sclerophyllous woody plants and few or no soft-leaved plants.

Rapidly drained. Water is removed from the soil rapidly. Soils are usually coarse-textured, or shallow or both. No horizon is normally wet for more than several hours after rain. Soil is usually damp only after rain, becoming very dry in the dryer seasons. Vegetation is likely to consist of drought resistant herbs and grasses, sclerophyllous species, and succulents. There are likely to be few or no bryophytes.

Definitions

1. **Waterlogged:** Water comes out of the soil if you put pressure on it (i.e. moderate amount of pressure with your foot/hand)
2. **Very wet / Wet:** The soil feels wet to the touch but it is not “waterlogged”. Your fingers feel wet after handling the soil
3. **Damp:** The soil particles tend to cling together and the soil feels “damp” to the touch but the amount of water in the soil is low. Your fingers don’t feel particularly wet after handling the soil.
4. **Dry/Very Dry:** Soil particles generally don’t cling together when compressed into a ped. Soil doesn’t feel damp or wet to the touch.

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Appendix 3 Detailed cross section measurement method

To set up cross section frame:

- Locate permanent pegs on both banks.
- Face downstream to identify right and left banks. If necessary, stand in bed of stream upstream of frame, being very careful not to tread on cross section and attempting to minimise disturbance to bed and banks.
- Place vertical poles over pegs. Poles will slip down till they are either supported by the bolt that holds the cross beam, or a pin specifically inserted for the purpose of allowing cross beam to be higher than the peg top. Vertical poles should not rest on the ground, as this will not give a secure and consistent vertical control.
- Always measure from the upstream side of the frame. The uprights go over the pegs, the cross bar goes on the upstream side of the uprights, and the vertical goes on the upstream side of the cross bar.
- Left peg provides the vertical benchmark. If the cross beam is above the top of the left peg, note the number of holes so that vertical height can be replicated in future.
- Clamp level to cross beam, and adjust height on pegs till level, using pins through vertical poles if necessary. Rotate the bracket on the right bank upright to make fine adjustments.

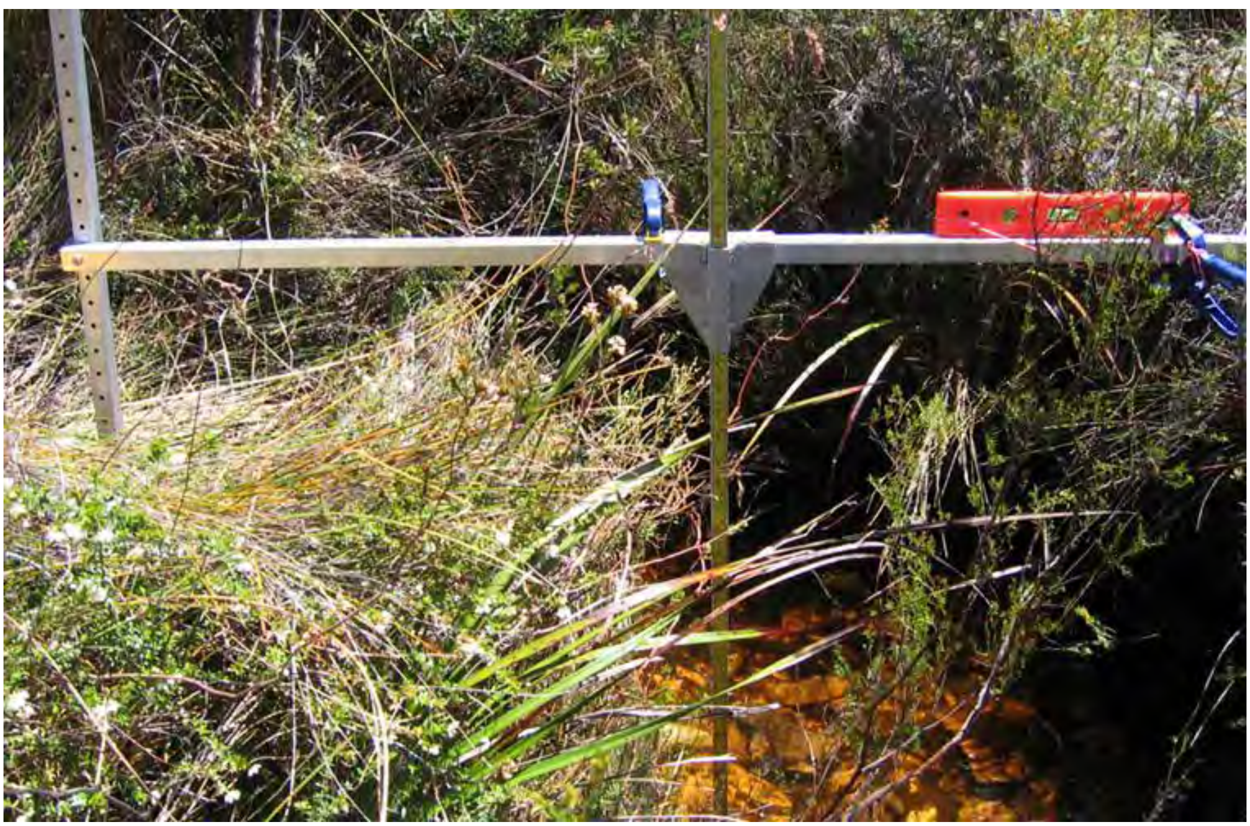

Figure A3-1. Cross section frame set up on Gelignite Creek. Flow is away from camera.

To make measurements:

- Always measure from left bank to right bank.
- Read horizontal measurements on the cross bar from the right hand side of the sleeve holding the pin. So, when taking the measurement at 10 cm, the right hand edge of the sleeve is at the line marked 1, and the measurement pin itself is 5 cm to the right of that mark, and 10 cm from the vertical pole.
- Measure heights to nearest millimetre on measurement pin to the top of the sleeve.
- Take care with soft peat or sand, pin must be lowered with care in order to prevent it hammering itself into the sediment.
- Attempt to find the contact between litter and soil, in some cases this is a continuum as litter becomes increasingly fine and has anincreasing sediment content with depth.

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