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Morphological and hydrological characteristics of a recovering river landscape: Wollombi Brook, New South Wales

Ngarla Tetley

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Morphological and hydrological characteristics of a recovering river landscape: Wollombi Brook, New South Wales

Abstract
This study investigates the nature of hydrological changes in Wollombi Brook which have been inferred to be associated with changes in channel morphology and vegetation extent. This work addresses channel dynamics and hydrological characteristics of a recovering river landscape, having importance for flood prediction. Flood frequency analyses have been undertaken on Wollombi Brook from 1914 to the present. The flood record displays distinct multi-decadal periods of above and below average flood activity. The analyses spanned at least one Drought Dominated Regime (DDR) and one Flood Dominated Regime (FDR) per gauge and therefore provides insight into hydrological conditions under both regimes.

The investigation revealed that over the past three decades channel morphologies on Wollombi Brook have remained relatively stable. Total annual flows have declined since 1991 along with a decline in the magnitude of infrequent of events. In addition to reductions in total annual flow, flood velocities have also reduced (for example Payne’s Crossing returned 0.5 m/s in the first DDR compared with 0.42 m/s in this DDR to date) over at least the period of the last DDR (1991 to present). There has been an increase in the number of 2-5 year ARI events and a decline in large scale events such as those of 1949 and 1955. The results of this study therefore support the theory that Wollombi Brook is in a period of recovery following widespread channel change brought about by the 1949 flood and subsequent flood of 1955.

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Morphological and hydrological characteristics of a recovering river landscape: Wollombi Brook, New South Wales

By

Ngarla Tetley

A thesis in part of the fulfillment of the requirements of the Honours degree of Bachelor of Science in the School of Earth and Environmental Sciences, University of Wollongong, 2012.
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The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Ngarla Tetley
3 December 2012
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So this journey is finally over, the goal is about to be achieved. I won’t deny that it has been a long and, at times, arduous journey balancing work and study but 9 years later I have finally reached my destination, a destination that decades earlier several careers tests told me I would never achieve! I am proud of my achievements whatever the final result, and I now look forward to the next stage of my journey, beginning a new career in an area that I know will never cease to fascinate me.
Abstract

This study investigates the nature of hydrological changes in Wollombi Brook which have been inferred to be associated with changes in channel morphology and vegetation extent. This work addresses channel dynamics and hydrological characteristics of a recovering river landscape, having importance for flood prediction. Flood frequency analyses have been undertaken on Wollombi Brook from 1914 to the present. The flood record displays distinct multi-decadal periods of above and below average flood activity. The analyses spanned at least one Drought Dominated Regime (DDR) and one Flood Dominated Regime (FDR) per gauge and therefore provides insight into hydrological conditions under both regimes.

The investigation revealed that over the past three decades channel morphologies on Wollombi Brook have remained relatively stable. Total annual flows have declined since 1991 along with a decline in the magnitude of infrequent events. In addition to reductions in total annual flow, flood velocities have also reduced (for example Payne’s Crossing returned 0.5 m/s in the first DDR compared with 0.42 m/s in this DDR to date) over at least the period of the last DDR (1991 to present). There has been an increase in the number of 2-5 year ARI events and a decline in large scale events such as those
of 1949 and 1955. The results of this study therefore support the theory that Wollombi Brook is in a period of recovery following widespread channel change brought about by the 1949 flood and subsequent flood of 1955.
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Chapter 1: Introduction

During the last 200 years of settlement south eastern Australian river systems have undergone a dramatic change in fluvial condition such as channel incision and widening, channel aggradation, loss of riparian habitat and therefore a loss of a potential source of woody debris which provides a source of channel roughness (Lord et al, 2009). River channels adjust naturally in response to varying conditions, such as a fluctuation in climate, but the widespread clearing of riparian vegetation and the removal of in-channel woody debris has resulted in noticeable changes in many of Australia’s fluvial systems (Web and Erskine, 2003; Anderson et al, 2006). One of the major hydrological effects of a change in riparian vegetation (including in-channel vegetation and debris) is the effect on its water velocity (also referred to as speed or celerity). This occurs because the velocity of a river is inherently linked to its channel morphology (as well as local hydrological conditions) by the width-to-depth ratio combined with a roughness coefficient (Huang and Nanson, 1997).

For instance, rivers that are narrow and deep are able to throughput volumes of water generally faster than channels that are wide and shallow primarily because of a reduced total roughness (Manning’s $n$) value. Manning’s $n$, is a
roughness coefficient (or estimate), where the higher value represents increased channel roughness and therefore the higher the drag effect on the flow of water (Huang and Nanson, 1997). Thus changes in channel morphology, particularly when combined with a change climate, could have a significant influence on the channel’s ability to convey discharge (Lord et al, 2009). The extent of these effects may vary from catchment to catchment depending on local climatic, hydrological, and biological conditions.

Research by Erskine and Warner (1998) and Kiem and Franks (2004) and others, has determined that the Australian climate operates on a multi-decadal cycle, meaning that for the majority of this time period a wet or dry phase prevails. These cycles, referred to as Flood Dominated Regimes (FRD) and Drought Dominated Regimes (DDR), are defined by multi-decadal periods of high or low flood activity of which there will be evidence for each in the hydrological and morphological record. The concept of a dominant multi-decadal hydrological regime provides an explanation for channel morphologies which are out of phase with land use change (Erskine and Warner, 1998). Recent work on Wollombi Brook by Cohen and Reinfelds (unpublished data) indicates that there has been a significant downward shift in its flood hydrology which appears to have coincided with a change in climatic condition. Whether this is
purely the result of a change in climate, or whether there are other factors at
play, is the subject of this thesis.

While there has been extensive work undertaken on east coast rivers, and
Wollombi Brook in particular Erskine (1994), Erskine and Peacock (2002),
Erskine and Melville (2008), the significance of this work is that it is addressing
channel dynamics and hydrology in an recovering landscape. Hydrological
data and previously published research will be used to examine changes in
hydrological regime, channel morphology, and the extent of in-channel and
riparian vegetation. Gauging practices will also be examined to see what effect,
if any, they have had on Wollombi Brook’s flood hydrology.

The aims of this project are to:

- Assess velocity distribution change for each gauge associated with
  changes in vegetation growth
- Assess changes in flood frequency relationships
- Examine morphological changes on Wollombi Brook using historical
  cross sections
Chapter 1: Introduction

- Examine, using remote sensing data and historical photographs, the extent of change in riparian and in-channel vegetation over the last three decades.

Therefore a decrease in total annual flows and a reduction in the frequency and magnitude of flood events will promote an increase in in-channel and riparian vegetation leading to stability in channel morphology and an increase in flood transmission times as a function of flood wave celerity.

Chapter 2 will outline the key literature and their findings, and begin building the base on which this thesis will attempt to resolve the cause of an apparent decline in flood hydrology over the last three decades.

Chapter 3 sets out the regional setting for Wollombi Brook, broken down into the geographical setting and geology, including giving a detailed description of the Brook’s morphology and climate, as well as a brief description of its discovery and settlement.
Chapter 4 outlines the methods used in achieving the aims of this project and covers such areas as river gauge analysis, cross sections, velocity profiles and rating tables, land and aerial imagery, and discharge data and flood analysis. It concludes with a brief summary of the limitations and problems encountered in methodological approaches.

Chapter 5 contains an analysis of all the evidence collected to date and sets out to answer the aims of this project: to examine historical cross sectional area changes for gauges on Wollombi Brook; to quantify, using remote sensing data and historical photographs, the extent of riparian and in-channel vegetation changes over the last 30 years; and to assess velocity distribution change for each gauge associated with changes in vegetation growth.

Chapter 6 contains an interpretation of the results, which will be linked back to relevant scientific literature and makes findings primarily based on the results from Chapter 5 and published works. It also makes recommendations for future research, and Chapter 7 concludes the findings and discusses the limitations.
Chapter 2: Literature Review

2.1 Introduction

Compared with the global average, Australia’s climate produces the highest variation in terms of total annual flows, causing its rivers to have a correspondingly high degree of variability in flow and character. The size, geographical position, climate, and relative flatness of the Australian continent mean its rivers operate in several quite different and distinct climate zones, which hydrological regimes that match local geography, geology, and climatic conditions (Finlayson and McMahon, 1988; Brierley and Fryirs, 2005; Ladson, 2011).

The south eastern Australian coastal are strongly influenced by two distinct hydrological regimes, known as a Flood Dominated Regime (FDR) and a Drought Dominated Regime (DDR). These two distinct cycles were identified by the analysing historical climate and hydrological records and it is now known that they have been influencing these rivers since at least the time of European (Erskine and Warner, 1988; Kiem and Franks, 2004).
Thus in attempting to understand the cause of changes to flood transmission times, as identified in preliminary work on Wollombi Brook (Cohen and Reinfelds, unpublished data), it is extremely important to understand the effects that variables of climate (particularly its influence on discharge), catchment morphology, and vegetation have on a river system. Research which focuses on each of these variables, and their respective influences on channel morphology, are reviewed below, and information about Wollombi Brook’s geographical setting, including geology, climate and hydrology, catchment morphology, and discovery and settlement are outlined in Chapter 3.

2.2 Climate and Channel Morphology

Climate plays an important role in the function and shape of our river systems. One of the ways it does this is to influence the volume and frequency of rainfall that a catchment will experience over time (Finlayson and McMahon, 1988; Ladson, 2011). An analysis of the climate records for south-eastern Australia by Erskine and Warner (1988) indicates that for at least the last 200 years the south east Australian coastal region has been under the influence of either a ‘Drought Dominated Regime’ or ‘Flood Dominated Regime’ (referred to as DDR and FDR respectively). It is thought that the onset of a regime is related to changes in
secular rainfall patterns and, once initiated, they tend to persist for several decades at a time (Erskine and Warner, 1988).

These effects of these two regimes are thought to be responsible for changes in channel morphology, with the changes being common to a particular regime. For instance a FDR is characterised by higher levels of precipitation, with more frequent and higher magnitude floods than in a DDR. The power provided by these higher magnitude floods tends to erode channel banks, increasing channel capacity. Whereas during a DDR channels tend to contract due to aggradation (Erskine and Warner, 1988; Erskine and Warner, 1999; Hubble and Rutherford, 2010). There should, therefore be evidence of these regimes in the morphological and hydrological records. The regimes that were identified by Warner (1988) are presented below in Table 1.

<table>
<thead>
<tr>
<th>Flood Dominated Regime</th>
<th>Drought Dominated Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>1799 to 1820</td>
<td>1821 to 1856</td>
</tr>
<tr>
<td>1857 to 1900</td>
<td>1901 to 1948</td>
</tr>
<tr>
<td>1949 to 1991*</td>
<td>1992*</td>
</tr>
</tbody>
</table>

Table 1 Flood and Drought Regimes as interpreted from climate and discharge records by Warner (1999). 1991 has been used as the commencement of the DDR for this study as it has been recognised as an official drought period (Bureau of Meteorology, no date)
2.3 Channel Morphology and Flow Characteristics

Alluvial rivers fall into four broad categories based on their dominant style which is a function of physical and hydrological conditions that they operate within (their catchment). These conditions include slope, sediment load, width-to-depth ratio, discharge, and valley characteristics (Nanson and Knighton, 1996; Riley, 1975; Latrubesse, 2008). They receive energy from the elevation of the land over which they flow and use this energy to transport volumes of water and sediment along their length (Brierley and Fryirs, 2005).

When a river’s transport and energy needs are in sync it is considered to be in equilibrium, however natural rivers due to their dynamic nature are often either in equilibrium or in transition (referred to as disequilibrium) towards equilibrium (Nanson and Huang, 2008). As channel form is ultimately responsible for the efficiency of a river in transporting both water (discharge) and sediment (Brierley and Fryirs, 2005), a change in regime, such as described in Section 2.2, may also affect the flow efficiency of a river either to the positive or negative (Nanson and Erskine, 1988; Huang and Nanson 1997 and 2007).
There are several factors that can force a river into a state of disequilibrium for example catchment disturbance, changes in rainfall patterns, and a change in the magnitude and/or frequency of flood events (Huang and Nanson 1997; Knighton 1998). Erskine (1994) conducted a study on flood driven channel changes on Wollombi Brook since European settlement, paying particular attention to the effects of the 1949 and 1955 flood events. He found that river response varied according to confinement and erodibility, with the middle reaches experiencing the most significant change. The flood effect was described as having destroyed a ‘stable, small capacity, sinuous, well vegetated channel and replaced it with an active sand-bed stream’ (Erskine, 1994, 41) while preserved sections of pre-flood channel still existed above incision and below the depositional reach. Since then the channel has partially recovered, with bench development constricting the channel and much of the sand base had been removed by degradation. The conclusion was that the 1949 event was ‘catastrophic in magnitude and it’s geomorphic effects and clearly exceeded the boundary resistance threshold of the channel’ (Erskine, 1994, 63) and that river recovery would likely take as long as the estimated return period (~ 100 years) and that frequent successive perturbations continued to have an effect (Erskine, 1994).
Rustomji (2007) compared Holocene and historical change along the MacDonald River, near Sydney, and noted a significant amount of channel narrowing since the 1950’s associated with a decline in rainfall and flood magnitude (which is consistent with the DDR/FDR theory). He found that morphological change on the MacDonald River is indicative of a state of ‘episodic disequilibrium’, which is a model proposed by Nanson and Erskine (1988 and cited in Rustomji, 2007), where a river system changes rapidly in response to floods but then is followed by a period in which the river returns to a pre-flood state (Rustomji, 2007).

The works presented above confirm that rivers are most efficient when in equilibrium and after disturbance will generally work towards an equilibrium if possible. They also highlight that river systems are highly susceptible to changes in flow regime such as those brought about by changes in rainfall, catchment disturbance, or a change in the magnitude and frequency of flood events. Therefore in order to understand why Wollombi Brook’s flood transmission times appear to have declined in this last DDR it is essential that historical cross-sectional changes are compared with discharge data to gain an understanding of the nature and frequency of flood events of the last few decades and the impact they have had on channel morphology, and therefore flow characteristics.
2.4 Vegetation and Channel Morphology

Vegetation is an important factor in river systems because it controls sediment supply, acts as a source of friction to impede flow, and it also contributes to bank strength which assists with the maintenance of channel form (Brooks and Brierley, 1997; Anderson et al, 2006). Bennett and Simon (2004) stated that vegetation plays an important role in the ‘physical, biological, and hydraulic function of rivers’ (Bennett and Simon, 2004, vii) and it ‘can modulate the pace and characteristics of river channel change…in some cases, vegetation can initiate fluvial adjustment’ (Bennett and Simon, 2004, vii).

Since European settlement many riparian communities have been highly disturbed or destroyed. One of the major contributors to vegetation disturbance or destruction along our east coast river systems was the practice of ringbarking, grazing, and clearing (Webb and Erskine, 2003b; Chalmers et al, 2012). Research by Webb and Erskine (2003b) suggests that for east coast rivers this was a regular practice between 1886 and 1995 and was supported by government legislation. The results of these practices included an increase in velocity, extensive bed degradation, massive channel enlargement and loss of
fish habitat (Mahony and Whitehead, 1994; Brooks and Brierley, 1997; Webb and Erskine, 2003b).

Several studies have been conducted on the importance of riparian vegetation on channel morphology and flow characteristics, including by Huang and Nanson (1997), Brooks and Brierley (1997), Erskine and Webb (2003b), and Anderson et al (2006). For instance Huang and Nanson (1997) conducted a study on vegetation and channel variance in several small south-eastern Australian streams and specifically looked at the impact of in-channel and riparian vegetation on the hydraulic geometry of each stream.

Their study compared the relationship between in-channel and bank vegetation with channel width and depth and demonstrated that streams with in-channel vegetation were more likely to increase their width with without a corresponding change in depth (the additional roughness, Manning’s $n$, deflects the onto the bank and causes a decrease in flow velocity) whereas streams without in-channel vegetation were more likely to be deeper under the same or similar flow regimes (Huang and Nanson, 1997). They cautioned on using models which only took into consideration discharge and vegetation because bank composition is also a significant factor in whether a channel will widen or
narrow under vegetated and non-vegetated conditions (Huang and Nanson, 1997).

Brooks and Brierley (1997) conducted a study of the geomorphic effects of catchment disturbance using the Bega River as their study site. They found that the river had undergone a ‘dramatic metamorphosis in the character and behaviour’ (Brooks and Brierley, 1997, 291) during the latter half of the 19th Century associated with human disturbance of both the catchment and channel margin. This resulted in changes to the sediment budget and hydrological regime, influencing flood effectiveness. They found that while human disturbance may not have been as influential on other eastern Australian catchments, the traits demonstrated on other river systems (bench development, channel widening, avulsion, and stripping) may be an indication of post-disturbance flood effectiveness (Brooks and Brierley, 1997).

In another study, Webb and Erskine (2003) examined the characteristics, distribution and significance of large woody debris (LWD) on channel and floodplain morphology. A relatively undisturbed reach of Tonghi Creek was selected to model real-world Australian river conditions that could give a glimpse into past, present, and future conditions under as natural
circumstances as possible (ie. before land clearing and after river rehabilitation programs have been established long enough for riparian conditions to return to a more or newly natural state). They found that ‘high loadings of large woody debris (LWD), including log steps, in combination with high densities of riparian vegetation, contribute to roughness and energy dissipation within the channel’ (Webb and Erskine, 2003, 123). This is because vegetation is a key element for reducing flow velocity (Manning’s $n$) and enhancing bank strength. Anderson et al (2006) also modelled the influence of changes in riparian habitat, specifically the increased presence of LWD, on the propagation of flood waves and concluded that ‘…channel roughness, and hence riparian condition, is a significant determinant of wave celerity, hydrograph dispersion, and skew’ (Anderson et al, 2006, 1295).

The works presented above demonstrate the influence of vegetation on channel morphology and flow characteristics. All of these studies are relevant to Wollombi Brook in that they we all conducted on south-eastern Australian river systems, operating under similar environmental and climatic conditions. Similarly, the work of Huang and Nanson (1997) and Anderson et al (2006) are equally relevant in that they model the effect of vegetation on channel stability, velocity characteristics, and flood wave propagation which recent work by Cohen and Reinfelds (unpublished data) indicates is an area for further research on Wollombi Brook.
Chapter 3: Regional Setting

3.1 Geographical Setting

Wollombi Brook is located on the New South Wales (NSW) central coast near Newcastle, and to the west of Cessnock. It is a major tributary of the Hunter River system, occupying the south central portion of the catchment (Figure 1, below).

Wollombi Brook has an overall catchment size of approximately 2000 kilometres square (km$^2$) and is bounded by several mountain ranges, the Watangan Range to the east, the Hunter Ranges to the west, and the Broken Back and Myall Ranges to the east (Pritchard, 2005).
Figure 1 Location and extent of the Wollombi Brook catchment. The study area covers the main trunk of Wollombi Brook which starts in the bottom centre and flows northward to Warkworth in the top left of the image.

3.2 Geology

The Wollombi catchment lies within the greater Sydney Basin, a geological basin composed of almost horizontal sandstones and shales, Permian to Triassic in age, which overlie basement rocks of the Lachlan Fold Belt. The sedimentary layers have been uplifted and minor folding and faulting occurred during the
formation of the Great Dividing Range (Department of Environment and Heritage, 2011). Figure 2 outlines the geology of the northern Sydney Basin within which the Wollombi Catchment lies to the west of Cessnock. Cessnock is located in the bottom left corner of this figure.

![Regional Geology Map of the Hunter Valley Region, northern Sydney Basin, showing the different age and types of geological units and the complex structures](image)

*Figure 2 Regional Geology Map of the Hunter Valley Region, northern Sydney Basin, showing the different age and types of geological units and the complex structures (Department of Trade and Investment, Resources and Infrastructure, 2012, 3)*
Chapter 3: Regional Setting

Triassic aged sandstones and shales make up most of the overall catchment geology although Permian aged shales, conglomerates, and sandstones interspersed with Quaternary aged alluvium, basalt, conglomerate, and coal are also found in the lower catchment (Erskine and Saynor, 1996; Lamontagne et al, 2005; Department of Environment and Heritage, 2011). Figure 3 below depicts the extent of the Sydney Basin (Wollombi Brook is located to the east of Newcastle) and the age of major geologic units in the region.

Figure 3 (a) Sydney Basin location which is between several ancient fold belts and (b) its geological age and divisions (Division of Resources and Energy, no date)
3.3 Climate and Hydrology

Wollombi Brook falls within the temperate climate zone, as defined by the Bureau of Meteorology and displayed in Figure 4 below. This means that the catchment experiences a generally mild climate with cold, dry winters and warm, humid summers (Commonwealth Bureau of Meteorology, no date). A review of daily maximum temperatures recorded at Broke, which is in the lower catchment, for the period 1957-2002 demonstrated a summer average temperature of 29°C compared with 18°C in winter (Pritchard, 2005).

![Climate zones based on temperature and humidity](image)

*Figure 4 Australian Climatic Zones based on temperature and humidity, Wollombi Brook resides in the warm summer-cool winter zone (Commonwealth Bureau of Meteorology, no date)*
Chapter 3: Regional Setting

Rainfall dominance trends towards the autumn-summer seasons and is variable across the catchment. The coastal area (near Broke) experienced a mean annual rainfall of 651 millimetres (mm) for the period 1889 to 2002, with the upland (the Watangan Range) experiencing nearly double that, a mean annual of 1122 mm for the same return period. The catchment can experience intense, infrequent storms and is considered to have a high flood variability compared to the global average as a consequence (Erskine and Saynor, 1996; Pritchard, 2005).

These climatic conditions result in correspondingly variable hydrological conditions, meaning that Wollombi Brook can experience prolonged periods of low flow as well as intense, infrequent flood (low frequency high magnitude) events that can result in ‘catastrophic’ changes in river morphology (Erskine and Bell, 1982; Erskine and Peacock, 2002). The flood history for Wollombi Brook will be examined in later chapters in an attempt to explain the cause of altered flood transmission times over the last three decades.
3.4 Catchment Morphology

The headwaters of Wollombi Brook rise in the Watangan Ranges above Will-O-Wyn (Figure 3) and from here travel in a northerly direction some 120 kilometres, initially through steeply incised valleys, before broadening and flattening out into alluvial floodplains where it joins with the Hunter River near Warkworth (Figure 1) (Bennett and Mooney, 2003; Pritchard, 2005). The 400 metre change in topographic relief over Wollombi Brook’s entire length, which is a rapid change in elevation over a relatively short period of time, means that Wollombi Brook is a ‘flashy catchment that converts rainfall rapidly into relatively large flow rates and elevated flood levels’ (Pritchard; 2005; Lyons, 2011).

Wollombi Brook is considered to have four distinctly different reaches owing to their different physiographic regions. The region upstream of Millfield on the eastern edge of the catchment; the area to the west of this through which Congewai Creek flows; from Millfield to Adam’s Peak, just below Payne’s Crossing; and the lower reach between Adam’s Peak and the Hunter River confluence (Erskine, 1994). Only the three main reaches will be discussed here, upstream of Millfield (purple), Millfield to Adam’s Peak (red), and Adam’s Peak to the Hunter River confluence (green) (Figure 5 below).
Figure 5 Approximate location and extent of the three reaches of Wollombi Brook. Each reach is represented by different colour (adapted from Pritchard, 2005, 17)

The upper catchment (upstream of Millfield) contains three distinct sub-reaches, an unincised small capacity channel within a vegetated reach; a more recently incised reach with a correspondingly large channel capacity; and a stable section in the lower section. Cutoffs, eroded and drained chains of ponds, and sand slugs are features of the upper two sub-reaches, whereas flood plain lakes, a vegetated bed, and a fine grained channel boundary are features of the
lower sub-reach (Erskine, 2008). This upper catchment is considered to be the most natural portion of the entire length of Wollombi Brook.

In contrast, the middle reach (Millfield to Adam’s Peak) of the catchment consists of a Triassic sandstone plateau through which both Wollombi Brook and Congewai Creek have incised ‘...to form a narrow sinuous valley’ (Erskine, 1994, 45). Vertical jointing in the sandstone unit controls their orientation and morphology and both experience bedload erosion in response to flood events (Erskine, 1994).

The lower reach (Adam’s Peak to the Hunter River) of the catchment is where Wollombi Brook leaves the plateau and begins flowing through lowlands, which are Permian in age. Like the middle reach this reach also is prone to bedload erosion and is only partially confined by bedrock and terraces (Erskine, 1994).

The combination of a dominant alluvial (sand bed) stream classification and a highly variable flow regime means that Wollombi Brook undergoes cycles of erosion (stripping), and recovery and channel in-filling over time (Erskine, 1996; Downs and Gregory, 2004). It is thought that Wollombi Brook may still be in a
recovery phase following a major flood event which occurred in the late 1940’s (Erskine, 1996) and therefore this thesis will focus data recorded by the river gauges located at Payne’s Crossing, Brickman’s Bridge (both in the upper reach), Bulga (middle reach), and Warkworth (lower reach) over the last few decades to ascertain whether Wollombi Brook is in a state of recovery, and whether this is the cause of a corresponding change (reduction) in flood hydrology (For a map of the location of the gauges refer to Figure 6 below).

The second reach (as defined by Erskine in the Way of the River) to the west of Congewai Creek is not considered here as it has no gauges to measure changes in hydrology or channel morphology. Therefore this research will primarily focus on the main channel of Wollombi Brook and the physical and hydrological changes it has undergone in the last few decades.

3.5 Discovery, Settlement and Land Use

Wollombi Brook was first occupied by local Aboriginal groups and was probably maintained in accordance with tradition until it was discovered and settled by Europeans in the 1820’s (Mahony and Whitehead, 1994). Since then several major towns have been established along the winding length of
Chapter 3: Regional Setting

Wollombi Brook, including Laguna, Wollombi, Broke, Bulga, and Warkworth, amongst others.

The catchment underwent a dramatic change as land clearing for farming and settlement took hold, and these changes have been reflected in Wollombi Brook’s channel morphology, which is discussed in Section 2.4 above. Initially settlers were producing mixed crops for the colonial market but after that failed in the late 1850’s, dairy farming became a growing concern until it too reached its peak in the 1930’s. There was a shift in demand from large scale farming to small acreages which occurred in the 1960’s and 1970’s which is attributed to ‘urban drift’ (Mahony and Whitehead, 1994) and the onset of mining operations in the area in (1970’s). Mining is still a major economic concern in the region today but has also become a community concern as people have become more aware of the impacts of mining on river and other ecological systems (Mahony and Whitehead, 1994; Pritchard, 2005).
Chapter 4: Methodology

4.1 Introduction

A variety of techniques were employed to assess changes in the morphological and hydrological conditions for Wollombi Brook over the last few decades. These techniques included hydrological data analysis for the purpose of creating channel cross sections, velocity profiles, flood frequency curves, and the analysis of aerial and historical photography to examine changes in channel morphology and vegetation extent. This chapter discusses the methodology used in each type of analyses.

4.2 Flood Frequency Analysis

There are four gauges along the length of Wollombi Brook that have been used for the analysis of flood frequency, for the assessment of velocity characteristics of individual floods and for cross-sectional changes. Figure 6 below identifies the approximate location of each of the gauges.
This includes the uppermost gauge at Payne’s Crossing (1941 to 2000), Brickman’s Bridge (1996 to present), Bulga (1949 to present) and finally the most downstream, Warkworth (1908 to present). Table 2 below highlights the gauge number and record characteristics. All data was sourced from the Maitland or Wollongong branch of the Office of Water (OoW).
Table 2 A list of the four gauges along the length of Wollombi Brook, showing their catchment area and period of gauging, and the percentage of records missing for the period(s)

<table>
<thead>
<tr>
<th>Location</th>
<th>Station Number</th>
<th>Catchment Area (sq km)</th>
<th>Period of record</th>
<th>% Records Missing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payne’s Crossing</td>
<td>210048</td>
<td>1064</td>
<td>1941-2000</td>
<td>33%</td>
</tr>
<tr>
<td>Brickman’s Bridge</td>
<td>210135</td>
<td>1088</td>
<td>1996-2012</td>
<td>0%</td>
</tr>
<tr>
<td>Bulga</td>
<td>210028</td>
<td>1672</td>
<td>1949-2012</td>
<td>28%</td>
</tr>
<tr>
<td>Warkworth</td>
<td>210004</td>
<td>1848</td>
<td>1908-2012</td>
<td>0%</td>
</tr>
</tbody>
</table>

4.2.1 Data Gap Filling

The data was quality checked to ensure that the discharge record demonstrated a good representation of annual flow. Records with partial years, such as at the commencement or end of a gauge, were eliminated from the study. As an additional quality check individual gauge records were compared against one another to ensure that gaps in data were true gaps and not instances of extremely low or no flow.

In order to provide a more accurate Annual Recurrence Index (ARI) for Wollombi Brook, gauges with missing data were, where possible, compared with another gauge with a complete record for the same period using a process
called regression. Regression analysis is a process in which a gauge with the most complete record (Warkworth in this example) is used as a baseline (independent variable) for infilling gaps using in the discharge record for other gauges using a correlation coefficient \( y = mx + b \) as described in Gordon et al (2004). There are limitations with this using this method which Ladson (2011) addresses where the ‘add trendline’ function of Microsoft Excel ignores the results scattered around the regression line and downward biases the variance of the extended record. The regression line \( r^2 \) derived by Excel using this format was around 79% between the Warkworth and Bulga gaugings.

4.2.2 Annual Series

Once the records were checked (start and current year excluded) they were entered into FLIKE, a software program designed by the Department of Civil, Surveying, and Environmental Engineering, University of Newcastle, for the purpose of conducting flood frequency analyses. Table 3 below lists the data availability for each gauge and outlines the percentage of records used. Different outputs were produced, both on the full record for each gauge and also, where sufficient records existed, according to the different Flood and Drought Dominated Regime (FDR and DDR respectively) as described by Kiem and Franks (2004).
While the use of the Generalised Pareto method has been recommended for south eastern Australian rivers (Rustomji et al, 2009), there were computing the data on short records, such as Brickman’s Bridge and Payne’s Crossing. Instead the Log Pearson III method was used to derive flood frequencies for all ASA and PSA. The NSW Office of Water tested both methods on data from the Nymboida River and determined that the Log Pearson III method was in closer agreement to the data than the Generalised Pareto method between the 2 and 10 year ARIs, and that the Generalised Pareto method significantly underestimates flows for extreme events in short records (Reinfelds, unpublished data).

One limitation with FLIKE is that it requires a minimum of 10 records in order to perform the analysis, this was particularly problematic with the Payne’s Crossing and Bulga gauges which have poor records, and/or less than 10 consecutive records. Records with missing data must be able to be correlated to other gauges (that is the record with incomplete data must be excluded if the missing month is the same month as the biggest annual flood in a gauge with a complete annual record), and when constraining the data to known DDR and FDR periods for South Eastern Australia, this meant that significantly large periods of records were at times excluded. Regression analysis was undertaken using Warkworth as the baseline, this has been discussed in more detail above.
Chapter 4: Methodology

The newest gauge, Brickman’s Bridge, commenced in the most recent DDR and therefore was not able to be compared with earlier records.
### Annual Series Gauging Analysis

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Name</th>
<th># in Period</th>
<th># Used</th>
<th># Unsuitable</th>
<th>% Used</th>
<th>% Unused</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>210004</td>
<td>Warkworth A (1914 to 1947)</td>
<td>40</td>
<td>30</td>
<td>10</td>
<td>75.0</td>
<td>25.0</td>
<td>1908 to 1913, 1944 to 1947 excluded</td>
</tr>
<tr>
<td>210004</td>
<td>Warkworth B (1948 to 1990)</td>
<td>43</td>
<td>32</td>
<td>11</td>
<td>74.4</td>
<td>25.6</td>
<td>1948 to 1958 excluded</td>
</tr>
<tr>
<td>210004</td>
<td>Warkworth C (1991 to 2011)</td>
<td>22</td>
<td>21</td>
<td>1</td>
<td>95.5</td>
<td>4.5</td>
<td>2012 excluded</td>
</tr>
<tr>
<td>210028</td>
<td>Bulga A (1949 to 1990)</td>
<td>42</td>
<td>14</td>
<td>28</td>
<td>33.3</td>
<td>66.7</td>
<td>1949 to 1964, 1979 to 1990 excluded</td>
</tr>
<tr>
<td>210048</td>
<td>Payne’s Crossing A (1940 to 1947)</td>
<td>8</td>
<td>0</td>
<td>8</td>
<td>0.0</td>
<td>100.0</td>
<td>Less than 10 consecutive years</td>
</tr>
<tr>
<td>210048</td>
<td>Payne’s Crossing B (1940 to 1990)</td>
<td>43</td>
<td>0</td>
<td>43</td>
<td>0.0</td>
<td>100.0</td>
<td>Less than 10 consecutive years</td>
</tr>
<tr>
<td>210048</td>
<td>Payne’s Crossing C (1991 to 2012)</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>0.0</td>
<td>100.0</td>
<td>Less than 10 consecutive years</td>
</tr>
<tr>
<td>210135</td>
<td>Brickman’s Bridge</td>
<td>18</td>
<td>16</td>
<td>2</td>
<td>88.9</td>
<td>11.1</td>
<td>1995 and 2012 excluded</td>
</tr>
</tbody>
</table>

Table 3: A list of gaugings selected for analysis indicating the period of record by gauge and regime and details of number and percentage of records subsequently used in the analysis.
Flood frequency data obtained from FLIKE was then entered into Excel to create Annual Recurrence Index (ARI) and Partial Series Analysis (PSA) Graphs. These graphs represent the probability associated with the recurrence of a flood of a particular size, as well as their distribution throughout periods of time (their frequency). Floods are firstly ranked in order of size, from largest to smallest, and then a theoretical probability formula is applied. Each flood is assigned to a ‘recurrence’ category, ranging from 0.1 to 100, which represents the average length of time between floods of a given size. Thus a 1:100 year flood has a one percent (1%) chance of being equaled or exceeded in any given year (Gordon et al, 2004).

**4.2.3 Partial Series Analysis**

The PSA uses a particular flow threshold, for instance the 2 year ARI, to examine the frequency of particular sized flows throughout the year which may have otherwise been obscured by the ASA (Knighton, 1998; Pilgrim, 2001). All floods greater than the 2 year ARI, the ARI value derived from the Annual Series Analysis, for each gauge were re-entered into FLIKE to give a recurrence category, again based on a range from 0.1 to 100, which in this instance represents the frequency of events equal to or greater than the 2 year ARI.
As the hydrological records for Wollombi Brook only began in 1908 for Warkworth, and more recently for the other gauges, the recurrence categories were limited to 100 years. The results of these analyses including ARI and PSA results for full (all years) and partial years (only those eligible for FLIKE) are presented in Chapter 5.

4.3 Historical Gaugings Analysis

Historical gaugings were selected based on the dates contained in Table 4 below to create velocity profiles for comparison with the modern (Acoustic Doppler Profiler or M9) gaugings. Measurements were generally taken at set intervals across the width of the channel and then taken down profile at each of these locations based on a standard formula (percentage of depth) (e.g., 0.2, 0.4, 0.6, 0.8, 1.0, etc), which is relatively consistent with the way modern measurements are taken by the ADP. The ADP method is discussed in more detail below. In terms of the historical gaugings, there were occasional variances in the above measurement method, most of which were associated with areas of low flow or where channel narrowing had occurred, but overall most gaugings followed this method. Figure 7 below provides a visual representation of the method described above (Gordon et al, 2004).
Figure 7 Diagram of the method of measuring the velocity of a river using set horizontal distances and vertical depths (Gordon et al, 2004, 94)

Table 4 shows the individual gaugings used for the historical gauging analysis and their respective estimated discharge (Q), area of flow (Area), and mean velocity (Mean V). It also indicates the records required for this study and their subsequent availability and relevance.

As the older gaugings were recorded using the imperial system they were firstly converted to the metric system (in Excel) in line with the with the more modern gaugings, to enable comparisons to be made between gaugings from different time periods. Some gaugings were recorded from different sides of the river so for consistency they were converted to reflect cross-sections recorded from left to right, with the left representing the left bank when facing downstream.
Velocity profiles were then created in Excel using the information contained in individual gauging records, which included width, depth, depth of observation, and velocity at each observation. In most instances the data needed to be converted to the metric system to ensure consistency with the M9 gaugings. Both the historical and modern gaugings were checked to ensure that they
Chapter 4: Methodology

reflect the same direction as in the left side representing the left bank when facing downstream.

As Excel is limited to two dimensions and the velocity profiles are three dimensional, a work-around needed to be found in order to create profiles for comparison with the modern M9 gaugings. This involved manually loading the data (width, depth, multiple readings at each depth, and velocity) into Excel then creating a graph based on width and depth, where up to 5 depths were recorded for most distance markers on the x axis. This method only gave the location of the readings, not the velocities so the data labels form each individual point were changed to reflect the velocity at that particular point. However, while this provided a visual record of velocities according their relative width and depth it still didn’t allow for the creation of velocity zones as in the M9 gaugings. Therefore using the eye and hand method, velocity zones were created to adjoin areas of similar velocity. These zones were then refined using a drawing tool in a commercial software program.

4.3.1 Modern Gaugings Using an M9 Acoustic Doppler

The modern velocity profiles were created using the SonTek RiverSurveyor software. This software is designed for a mobile or stationary Acoustic Doppler
Chapter 4: Methodology

Profiler (ADP) which collects river data to produce a measure of discharge, creating 3-Dimensional profile of water currents, depths, and bathymetries. The NSW OoW uses an M9 ADP for hydrological analysis. Its microcontroller adjusts the cell size and allocates the acoustic beam as the ADP crosses the river so that changes in depth and velocity are automatically accommodated to ensure that the data collected is both continuous and accurate, therefore making M9 ideally suited to dynamic river systems (Sontek, 2011) such as Wollombi Brook.

While the ADP is able to provide more readings more consistently and accurately, there are several limitations in using an Acoustic Doppler to measure discharge. These limitations include a minimum operating depth below which the velocity and discharge must be estimated based on velocity and depth measurements on the edges, this method is used for the Start and End Edges; the area between the profiler to the point where velocity measurements first commence, known as the blanking distance, leaves a section of unmeasured water at the surface known as the Top Estimate; and the potential for data contamination from contact with the riverbed means that a section of the base of the river must be left unmeasured, this is known as the Bottom Estimate. Figure 8 below identifies all of these areas.
Total discharge is derived from a number of different calculations, including estimates for the Start Edge, Top Estimate, Bottom Estimate, and End Edge, which are derived using a standard calculation based on Velocity Profile Power Law (Figure 9) proposed by Simpson and Oltman (1990) and Chen (1991). The results of this Velocity Profile Extrapolation are then added to the M9 results for the Measured Area to provide total discharge (Sontek, 2011).

\[
\frac{U}{u_*} = 9.5 \left( \frac{z}{z_0} \right)^b
\]

Figure 9 The Velocity Profile Power Law which is used by the ADP to calculate discharge (Sontek, 2011, 37)

In this equation U represents the velocity at height z measured from the river base, \( u_\ast \) represents the bottom shear velocity, \( z_0 \) is the height of the bottom
roughness, and b is a constant representing 1/6. The use of this equation relies on currents in the profile travelling in virtually the same direction. In calculating the velocities in the upper and lower unmeasured areas, RiverSurveyor uses this Law on the entire measured profile to estimate velocities. Discharge can then be calculated using the velocity from each of the measured areas, depth, and transect areas. The Start and End Edge discharges are calculated based on a mean velocity profile, shape of bank (vertical or sloped), and mean depth whereas discharge in the Transect is derived from the depth, distance, and mean water velocity.

4.4 Cross Sections

The cross-sections used in this thesis are a derived from both historical and modern records, including additional cross sections sourced from previous work by Erskine (1994). The data provided was used to create simple width-depth cross-sections in Excel. Where there were multiple cross-sections from the same location a single graph was created so the cross-sections could be superimposed on one another to better demonstrate the changes in channel morphology over time. Table 5 below shows the records used for this analysis including their date, location.
Table 5 - List of cross-sections used in the analysis of morphological changes, identifying their date, location, and source

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Date</th>
<th>Location</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payne’s Crossing</td>
<td>1980</td>
<td>At Gauge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Payne’s Crossing</td>
<td>1985</td>
<td>At Gauge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Brickman’s Bridge</td>
<td>1995</td>
<td>At Gauge</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>Brickman’s Bridge</td>
<td>2004</td>
<td>At Gauge</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>Bulga</td>
<td>1949</td>
<td>At Bridge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Bulga</td>
<td>1955</td>
<td>At Bridge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Bulga</td>
<td>1981</td>
<td>At Bridge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Bulga</td>
<td>2004</td>
<td>At Bridge</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>Bulga</td>
<td>2007</td>
<td>At Bridge</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>Bulga</td>
<td>1955</td>
<td>Downstream</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Warkworth</td>
<td>1980</td>
<td>At Gauge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Warkworth</td>
<td>1983</td>
<td>At Gauge</td>
<td>Erskine (1994)</td>
</tr>
<tr>
<td>Warkworth</td>
<td>2004</td>
<td>At Gauge</td>
<td>NSW Office of Water</td>
</tr>
<tr>
<td>Warkworth</td>
<td>1934</td>
<td>At Bridge</td>
<td>Erskine (1994)</td>
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<tr>
<td>Warkworth</td>
<td>1990</td>
<td>At Bridge</td>
<td>Erskine (1994)</td>
</tr>
</tbody>
</table>

4.5 Land and Aerial Imagery

Historical land and air photographs can be used to demonstrate changes in channel morphology (mainly width and position) and changes in vegetation cover. For authenticity and accuracy the location and date should be recorded on each photo so that they can be referenced back to the same location on the modern river. There are two different methods that were used this thesis to correlate historical data with modern locations on the river or on a GIS layer of the river, comparing historical photos from known locations with the same location on the modern river, and geo-referencing photos to locations on the river using coordinates of latitude and longitude.
A number of historical photos were obtained from both OoW archives and previous studies of Wollombi Brook, with the purpose of comparing them with more recent images of the same location. A field trip with an OoW staff member was undertaken in November 2011, copies of photos from the OoW archives were taken on this trip so that photos of the same location could be reproduced. For the most part this process was as simple as taking photographs of from the same location using the same landmarks (eg. trees, tree lines, bridges, etc) and then visually comparing them with historical photos. For other locations, such as in the upper catchment several photos were taken in a panorama-like manner which were later ‘mosaiced’ in Microsoft Powerpoint, ensuring that there was a good correlation between features while maintaining the same scale.

The second method is to geo-reference photos to locations on the river using coordinates of latitude and longitude. Using this process corrects the photo to the same scale as distances on the earth’s surface, as set within the GIS system itself, and produces a digital image which has been corrected for scale, topographic relief, lens distortion, and tilt (Hughes et al, 2006).

Landsat imagery is available through the US Geological Service (USGS) and its various satellites have been continually streaming remotely sensed images of
the Earth’s surface since 1972, completing an orbit every 16 days. Images are displayed as composite bands of red, green, and blue (or RGB), and are resampled to a pixel size of 240 metres from the original 28.5 metres. Each image covers an approximate area of 183 x 170 km and a 2% linear stretch is applied. The technology behind Landsat imagery is that it detects and collects bands of reflected energy (also known as radiance), the information is then used to differentiate between the levels of radiation (or signature) given off different surfaces such as plants and water as indicated in the Figure 10 below (National Aeronautics and Space Administration, no date).

![Figure 10 Diagram depicting how Landsat identifies ground features by their different spectral reflectance curves (National Aeronautics and Space Administration, no date, 47)](image)

Landsat imagery of Wollombi Brook only exists as far back as 1984 so it had limited application for this study however, several images from a range of dates
were selected and converted into a geo-rectified map using ArcGIS. Only Landsat imagery of Wollombi Brook with no cloud (0%) cover was selected for comparison. Upon further analysis the poor quality of the Landsat imagery meant that shapefiles of vegetation extent were not able to be created due to extensive pixelation. Instead, the images were orthorectified to Wollombi Brook coordinates and then added to the Appendix.

Images from previous scientific studies, historical collections, and modern photos were used in this thesis to examine changes in channel morphology and vegetative extent over the last few decades. Where possible these photos were geo-referenced using a Geographical Information System (GIS), in all other circumstances photos were selected on the basis of being able to accurately identify the locality either by identification of physical features such as landmarks, or through the historical accounts which record location and era.
Chapter 5: Results

5.1 Introduction

This chapter details the hydrological and morphological analyses conducted on Wollombi Brook using a variety of techniques as described in Chapter 4. Recent channel conditions are compared with past conditions by analysing changes in channel capacity, hydrological analysis including flood frequency analysis and velocity changes, and changes in the extent of riparian and in-channel vegetation.

5.2 Total Annual Flow

The total annual flow for three of the gauges on Wollombi Brook are presented separately below. Brickman’s Bridge was excluded from this analysis as it only commenced in 1996 and therefore is unable to be compared with any previous hydrological regimes.
Figure 11 Chart of total flows received per year for Payne’s Crossing. No flows were recorded for the period 1950-1957 and the gauge was decommissioned in 2000.

Figure 11 represents the total annual flow for Payne’s Crossing between 1940 and 2000 when the gauge was decommissioned. The data for this gauge was often poor in quality and, as is demonstrated above, there are several periods where no data is recorded at all. This figure shows that the latter part of the first DDR (1940-1948) contained some wet years including the largest on record, 1946. Flows in this gauge are relatively small compared with Warkworth which could be an indicator of both poor data quality and possibly rainfall events which occurred downstream of the gauge. The values in the two DDRs (1901-1948 and 1991-present) are consistently small compared with that of the FDR but since this gauge has now been decommissioned it is no longer able to be used to detect any consistent pattern of low flow events.
Chapter 5: Results

Figure 12 Diagram showing total flows per year for Bulga, no flows were recorded for the periods 1960-1962 and 1988-1999. Data is colour coded by hydrological regime.

Figure 12 above for Bulga contains flow data from just after the commencement of the FDR (1949-1990) and, as for the Payne’s Crossing gauge, it also contains periods of poor quality data in which little or no flow was returned. A review of the records indicate that some of these periods such as 1960-1962 and 1988-1999 had either zero or no flow recorded however when these time periods were compared with the other gauges it was apparent that these gaps are due to non-gauging for these periods as there are flows recorded both above and below this gauge at Payne’s Crossing and Warkworth respectively. Maximum
Chapter 5: Results

flows in the FDR are in the order of 62000 megalitres (ML) compared with 19,000 megalitres (ML) in the second (only DDR for this gauge).

![210004 Total Total Flow By Year](image)

Figure 13 Diagram of the total flows for Warkworth, regimes are identified by using different colours. Data labels show the highest annual flow in each of the three regimes.

Figure 13 represents the total annual flow for Warkworth starting in 1908 at continuing through to 2011. This gauge contains the most continuous and complete record of all four gauges and the results demonstrate the highly variable nature of rainfall within the catchment. The outlier is from 1951, within the early stages of the FDR (1949-1990). Flows in the DDRs (1901-1948 and 1991-present) are consistently small compared with that of the FDR.
Though early into the current DDR, the results suggest that this present hydrological period may result in flows even lower than in the previous DDR.

5.3 Flood Velocity Analysis

An annual and partial series analysis (ASA and PSA respectively) were conducted for each gauge on Wollombi Brook. Table 6 lists the records used and results of the ASA, and Table 7 lists the records used and the results of the PSA. A discussion of the results is provided below.

The results of the ASA are presented in Table 6 below and shows that predicted discharge for events less than the 5 year ARI were all larger in the FDR (1949-1991) than in either of the DDRs (1901-1948 and 1991-present). In terms of the predicted discharge between the two DDRs, the records for Bulga and Payne’s Crossing had to undergo regression using Warkworth as the baseline.
## Chapter 5: Results

### Recurrence Interval and Discharge Estimates in Different Hydrological Periods

<table>
<thead>
<tr>
<th>Gauge #</th>
<th>Location</th>
<th>Period</th>
<th>1.01</th>
<th>1.25</th>
<th>1.5</th>
<th>2.0</th>
<th>5.0</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>210004</td>
<td>Warkworth</td>
<td>1900 to 1948</td>
<td>0.46</td>
<td>15.96</td>
<td>38.65</td>
<td>93.72</td>
<td>469.42</td>
<td>1024.87</td>
<td>1893.52</td>
<td>3656.69</td>
<td>5564.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1949 to 1990</td>
<td>0.88</td>
<td>31.33</td>
<td>70.25</td>
<td>151.51</td>
<td>546.68</td>
<td>959.27</td>
<td>1448.18</td>
<td>2182.07</td>
<td>2783.6</td>
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<tr>
<td></td>
<td></td>
<td>1991 to 2012</td>
<td>0.55</td>
<td>7.65</td>
<td>15.96</td>
<td>34.66</td>
<td>159.96</td>
<td>357.33</td>
<td>697.4</td>
<td>1486</td>
<td>2466.24</td>
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<tr>
<td>210028</td>
<td>Bulga</td>
<td>1900 to 1948</td>
<td>0.26</td>
<td>26.39</td>
<td>68.32</td>
<td>161.25</td>
<td>592.05</td>
<td>978.88</td>
<td>1366.44</td>
<td>1840.34</td>
<td>2155.62</td>
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<td></td>
<td></td>
<td>1949 to 1990 *</td>
<td>0.67</td>
<td>61.45</td>
<td>150.75</td>
<td>332.69</td>
<td>1047.3</td>
<td>1585.25</td>
<td>2058.77</td>
<td>2564.27</td>
<td>2860.4</td>
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<td></td>
<td></td>
<td>1991 to 2012 *</td>
<td>0.06</td>
<td>3.97</td>
<td>11.41</td>
<td>33.09</td>
<td>234.55</td>
<td>613.18</td>
<td>1313.57</td>
<td>2993.43</td>
<td>5083.27</td>
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<tr>
<td></td>
<td></td>
<td>1991 to 2012 *</td>
<td>0.85</td>
<td>22.34</td>
<td>47.37</td>
<td>97.44</td>
<td>330.53</td>
<td>569.93</td>
<td>853.84</td>
<td>1283.96</td>
<td>1641.4</td>
</tr>
<tr>
<td>210048</td>
<td>Payne's Crossing</td>
<td>1900 to 1948</td>
<td>0.92</td>
<td>61.74</td>
<td>139.54</td>
<td>283.43</td>
<td>767.57</td>
<td>1083.11</td>
<td>1335.17</td>
<td>1579.82</td>
<td>1711.19</td>
</tr>
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<td></td>
<td></td>
<td>1991 to 2012</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>210135</td>
<td>Brickman's Bridge</td>
<td>1900 to 1948</td>
<td>0.31</td>
<td>4.77</td>
<td>10.55</td>
<td>24.75</td>
<td>138.8</td>
<td>352.85</td>
<td>775.26</td>
<td>1914.77</td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>

* = regressed data

Table 6 Results of the Annual Series Analysis for all gauges by hydrological regimes. Records marked with an * represent regressed data, and blank cells indicate that there were no records analysed for that period, generally this was because of poor records or in the case of Payne’s Crossing decommissioning in 2000, and Brickman’s Bridge commenced in 1996.
As the data quality in the Payne’s Crossing and Bulga gauges was poor, a regression analysis was also performed on some of the data for these two gauges (1959-2011) using Warkworth as the baseline because as it had the most complete and continuous data for the periods concerned (refer to Chapter 4 for methods). Regression prior to this was not possible due to equally low quality records in the Warkworth gauge for the same period. The program used to conduct these analyses, FLIKE, requires a minimum of 10 records per analysis and as the Payne’s Crossing was decommissioned in 2000 it was not possible to perform an ASA on this gauge for the most recent DDR (1991-present). Regressed records are represented as FDR_EDITED and DDR_EDITED in the graphs below.
Chapter 5: Results

Frequency of Floods Greater than 2 Year ARI by Gauge (in Cumecs)

<table>
<thead>
<tr>
<th>Gauge No.</th>
<th>Location</th>
<th>Data Used</th>
<th>1.01</th>
<th>1.1</th>
<th>1.25</th>
<th>1.5</th>
<th>1.75</th>
<th>2.0</th>
<th>3.0</th>
<th>5.0</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>210004</td>
<td>Warkworth</td>
<td>1908 to 2011</td>
<td>81.13</td>
<td>93.39</td>
<td>107.88</td>
<td>128.21</td>
<td>146.36</td>
<td>163.19</td>
<td>222.63</td>
<td>321.32</td>
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<td>817.09</td>
<td>1476.36</td>
<td>2291.96</td>
</tr>
<tr>
<td>210028</td>
<td>Bulga</td>
<td>1949 to 2011</td>
<td>103.18</td>
<td>119.53</td>
<td>136.73</td>
<td>159.25</td>
<td>178.38</td>
<td>195.52</td>
<td>252.68</td>
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<td>Payne's Crossing</td>
<td>1941 to 2000</td>
<td>43.76</td>
<td>51.48</td>
<td>60.01</td>
<td>71.61</td>
<td>81.77</td>
<td>91.07</td>
<td>123.32</td>
<td>175.45</td>
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<td>423.92</td>
<td>736.89</td>
<td>1109.31</td>
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<tr>
<td>210035</td>
<td>Brickman's Bridge</td>
<td>1996 to 2011</td>
<td>22.38</td>
<td>27.04</td>
<td>32.13</td>
<td>39.08</td>
<td>45.21</td>
<td>50.86</td>
<td>70.70</td>
<td>103.43</td>
<td>167.76</td>
<td>266.19</td>
<td>497.94</td>
<td>741.61</td>
</tr>
</tbody>
</table>

Table 7 Results of the second series analysis showing the recurrence interval for all floods greater than the 2 year ARI taken from the annual series. Results appear to be relevant to catchment size owing to the size of the events generally becoming larger downstream. These gauges are in reverse order, from bottom to top of catchment.
5.3.1 Annual Series Analysis: Payne’s Crossing

The Payne’s Crossing gauge commenced in 1948 at the beginning of the FDR and was decommissioned in 2000 in the ‘middle’ of the current DDR, which at present is only 20 years long. The records for this gauge are poor and therefore it was not possible to complete an ASA without performing a regression analysis using Warkworth as a baseline. Although the regression was performed for the period (1959-2000) the end result was that only one analysis able to be performed, from the FDR (1949-1990), because there were less than 10 consecutive years of data in the current DDR for FLIKE. The results are presented in Figure 14 below.

For this gauge the 1 year annual recurrence interval (ARI) is an event in the order of 0.92 cumecs (79.48 ML) and the 1:100 year flood would be in the order of 1711 cumecs (147830 ML) indicating the highly variable nature of flow. The values for the 1:100 event are approximately half the value for the same criteria in the Bulga and Warkworth gauges.
Figure 14 Annual recurrence index (extended) based on data from Warkworth as a baseline. The results may be overestimated given that Warkworth is downstream and has a bigger catchment area.

5.3.2 Annual Series Analysis: Brickman’s Bridge

The annual series analysis for Brickman’s Bridge contained the records from 1996 to 2011, as this gauge is relatively new it had no other periods for it to be compared with. For this gauge (Figure 15) a 1 year annual recurrence interval (ARI) would be 0.31 cumecs or higher and the 1:100 year flood would be in the order of 3500 cumecs, Bulga returned 0.06 (0.85 regressed) and 5083 and Warkworth 0.55 cumecs and 2466 cumecs for the same return period. The values for this gauge are particularly low compared with Warkworth for the same period.
Figure 15 Annual recurrence intervals for Brickman’s Bridge, the inverse curve is possibly due to the short period of records and that it commenced operation during the latest DDR in which total annual flows have been particularly low interspersed with several flood events in 2007 and 2011.

5.3.3 Annual Series Analysis: Bulga

The annual series analysis for Bulga (Figure 16) contained the records from two different hydrological regimes, a Flood Dominated Regime (FDR) and a Drought Dominated Regime (DDR) spanning 1949 to 1990 and 1991 to 2011 respectively. The results indicate that a 1 year flood would be in the order of 0.06 cumecs in a DDR and 0.36 cumecs in a FDR, and the 1:100 year flood would be in the order of 2156 cumecs in a FDR and 5083 cumecs in a DDR. The results from this analysis suggest that after the 1:20 year ARI there is a downward shift in hydrological condition in the FDR meaning that 1:50 and 1:100 year floods are significantly smaller in a FDR than in a DDR. This result was not replicated.
Chapter 5: Results

in the Warkworth gauge which suggests that it may be related to the quality of records in the period concerned.

As indicated in Section 5.2 above there was poor quality data for two particular periods for both the Payne’s Crossing and Bulga gauges and therefore the following table displays both the original and the regressed data.

![Bulga: Recurrence Interval & Discharge Estimate in Different Hydrological Periods](image)

Figure 16 Annual recurrence intervals (annual series) for Bulga showing both the original and regressed (extended) data. The DDR (1991-2011) curve may be a reflection of the low annual flows in this period whereas the DDR_EXTENDED may have been influenced by its source data, Warkworth which is downstream and has a bigger catchment area.

While the regressed data plotted higher than that of the non-regressed data, the 20 year ARI seems to represent a turning point in the results as they both start tracking towards the values for the FDR beyond this point. This may be a function of the length of records.
5.3.4 Annual Series Analysis: Warkworth

The records for Warkworth (Figure 17) spanned three different regimes which is useful because it allows for comparison of hydrological events in the past two DDRs. The results below indicate that in the last DDR there has been a downward shift in predicted magnitude beyond the 2 year ARI. The 1:100 year event in the most recent DDR is closer in size to the same event in the FDR than the previous DDR, suggesting a significant shift in flood frequencies.

Figure 17 Annual recurrence intervals based on annual series, showing there has been a downward shift in the size and frequency of large events
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5.3.5 Flood Frequency - Warkworth

Figure 18 below presents the results of an analysis of events greater than the 2 year ARI by gauge.

![Warkworth: Frequency of ARI Events by Size (Normalised)](image)

Figure 18 Results of the Partial Series Analysis showing the relative frequency of events greater than the 2 year ARI (annual series by gauge). Showing there has been an increase in the number of events between 2-5 year ARI whereas all other relationships remain unchanged.

As the regime lengths and the records able to be used were of different durations the records were normalised in order to enable comparison. The results show that the frequency of events in the 2-5 year ARI is higher for the most recent DDR than in either of the earlier regimes. At the 5-10 and 10-20 mark the relationship between DDRs remains the same.
5.3.6 Flood Frequency - Bulga

In Figure 19 below the results show that the frequency of events in the 2-5 year ARI is higher for the most recent FDR than in the current DDR, and the relationship is continued across the 5-10 and 10-20 ARIs.

![Figure 19: Bulga: Frequency of ARI Events by Size (Normalised)](image)

**Figure 19** Results of the Partial Series Analysis showing the relative frequency of events greater than the 2 year ARI (annual series by gauge). The results presented here were expected given it is comparing an FDR and DDR, the latest DDR returning low annual flows compared to previous (to date)

5.3.7 Partial Series Analysis

A partial series analysis (PSA) was performed on all flows for all gauges. The 2 year Annual Recurrence Index (ARI) was selected for analysis as it was a common ARI beyond that of normal annual flows and could therefore be used to demonstrate the frequency of events in this range across the gauges. Figure
Chapter 5: Results

20 below shows the results of all four gauges (combined) which demonstrates that the true variance between gauges for the 2 year ARI becomes apparent at the 10 year ARI when there is a shift of frequency between Warkworth and Bulga, for instance at the 10 year the variance was relatively small (516 cumecs compared with 495 cumecs) but by the 1:100 year ARI the variance was much larger (2292 cumecs versus 1576 cumecs). The relationship between Payne’s Crossing and Brickman’s Bridge remain relatively the same throughout the entire period.

![Predicted Discharge Greater than the Partial Series 2 Year ARI](chart.png)

Figure 20 Chart showing the predicted discharge greater than the 2 year ARI by gauge. The relationship between gauges remained the same until the 10 year ARI when there was a reversal in values between Warkworth and Bulga, possibly reflecting their location, the Warkworth gauge is near the Hunter River confluence.
5.4 Channel Morphology

A review of channel morphology for each gauge was conducted where there was more than one cross-section taken from the same location. Additional cross-sections were sourced from work conducted by Erskine (1994) for comparison. The results for each gauge are discussed below.

5.4.1 Payne’s Crossing

The Payne’s Crossing gauge was situated in the upper catchment (refer to Figure 6) and was operational between 1940 and 2000. Figure 21 below demonstrates that there has been very little change of channel width and depth over the 5 year period. There is evidence of only very minor aggradation across almost the entire channel, with only a fraction more stripping of the right bank.
Chapter 5: Results

Figure 21 Comparison of cross-sectional change between 1980-1985, the short duration between surveys probably explains the only minor variation in channel morphology

5.4.2 Brickman’s Bridge

Brickman’s Bridge is now the uppermost gauge on Wollombi Brook, which is considered to be the most natural, undisturbed extent of the catchment (Erskine, 1994).

In 1995 (Figure 22) the floor of the channel in the Brickman’s Bridge cross section was at the same level as the next survey period (2004). Between this period the four benches on the left bank had been extensively stripped, losing up to 2.5 metres of sediment in some areas. This may have occurred during the 1998 flood event. In summary, the channel cross section shows minor scouring.
of the channel base and right bank, and excessive stripping of the benches on the left bank between 1995 and 2004.

![Brickman's Bridge: Cross Sectional Changes](image)

**Figure 22** Cross-sectional analysis of Brickman’s Bridge between 1995-2004 showing minor channel base incision and extensive stripping of the left bank. This was probably a consequence of a low frequency, high magnitude event during the latest DDR

### 5.4.3 Bulga

The bed level for 1949 was extrapolated based on Figure 5 in Erskine (1994). By the next survey period (1955) there had been up to one metre of scouring and lowering of the channel base. Between 1955 and 1981 there has been significant aggradation of the between 1-3 metres at the channel base and between 0.5 metres and 2 metres of bank development on the left and right bank respectively, leading to significant narrowing of the channel. By 2004 extensive
scouring had returned the deepest part of the channel base to 1955 levels while the rest of the channel base only experienced minor scouring. Bench development on the right bank continued during this period. In the last three years of the survey period (to 2007) there was very minor bed variability and the right bank had been dissected. In summary this channel cross section (Figure 23) showed that channel bed aggradation and bench development were both initiated post 1955 and continued until at least 2007.

Figure 23 Cross-sectional changes on Bulga, the 1949 bed estimate was based on Erskine (1994). The major implication here is that the channel base has returned to 1995 levels due to aggradation
5.4.4 Bulga Downstream

In 1955 the floor of the channel at the Bulga cross section (Figure 24) was one metre lower than present with little to no bar development. Between 1955 and the next survey period (1981) the channel had aggraded by two metres. This was followed by bench development on the right bank between 1981 and 2004 and in the last 7 years of the survey period there has been increased bed level variability and dissection of the right bank bench. In summary, the channel cross section at Bulga has aggraded with bench construction along with more recent scour on the channel margin and base.

![Figure 24 Changes in cross-sectional area downstream of Bulga gauge, showing extensive aggradation in the channel base and margin post 1955, some stripping of the right bank is also apparent](image-url)
5.4.5 Warkworth

Figure 25 below demonstrates that there has been very little change of channel width and depth over the 21 year period that the cross-sectional analysis covers at the Warkworth gauge. There was minor scouring of the right bank between the surveys of 1980 and 1983 and more significant scouring of the channel base. Between 1983 and 2004 the thalweg had deepened by up to two metres and a bench is developing on the right side of the channel. In summary these cross sections show a general persistence in the banks but with a deepening of the thalweg on the left side of the channel and bench development commencing on the right in between the most recent survey periods.
Figure 25 Cross-sectional analysis of Warkworth (at gauge) between 1980-2004 showing minor variation in channel width and scouring of the channel base and deepening of the thalweg.

5.4.6 Warkworth At Bridge

These changes in cross-sectional area in Figure 26 are based on Erskine (1994), and demonstrates that between the first survey period of 1934 and the latest from 1990 the channel base has aggraded by up to 2 metres, the left bank has been incised and the right bank has aggraded. The deepest part of the channel (the thalweg) has shifted from its former position on the left side of the channel to the right side of the channel. In summary these cross sections show a channel of essentially the same width that has undergone bed aggradation and
a switch in the thalweg which is associated with scouring of the left bank and building of the right.

In summary, of the six cross sections examined, the Bulga (at gauge) cross sections show the greatest change while the Warkworth (at gauge) cross section shows little evidence of morphological change through time. Payne’s Crossing was excluded from this analysis due to the short duration between events.
5.5 Flow Velocity Analysis

A range of records from each gauge were selected for further analysis. Table 8 below provides a list of the gaugings and their respective discharge, area of flow and mean velocity.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Date of Gauging</th>
<th>Discharge (ML/d)</th>
<th>Area of Flow (sq m)</th>
<th>Mean Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>18/10/1942</td>
<td>3,073</td>
<td>71.16</td>
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<td>0.97</td>
</tr>
</tbody>
</table>

Table 8 List of records selected for analysis changes in mean velocity over time, records have been shaded to identify the different regimes.
5.5.1 Payne’s Crossing

There were six records selected for analysis spanning from 1942 to 1976, covering one FDR and one DDR. An analysis of one of the earlier gaugings indicates that mean velocity (Mean V) was 0.50 metres per second (m/s) or 43.2 kilometres per day (km/d) for a flow depth of 3.5 metres. There were three distinct velocity zones (Figure 27, B) with the centre zone having the highest velocity at >0.7 m/s, it was surrounded by a zone of velocity ranging from 0.5-0.7 m/s.

The 1976 (Figure 27, C) gauging taken at Payne’s Crossing during the FDR (1949-1990), exhibits a Mean V was 1.01 m/s but a central filament of >1.4m/s. This event had a gauged discharge of 11,055 ML/d with an overall depth of almost 4 metres.
Chapter 5: Results

Figure 27 – Velocity profiles for a) Warkworth during the FDR b) Payne’s Crossing during the first DDR, and c) Payne’s Crossing during the FDR. The isovels demonstrate that velocity increases with distance from the channel margins and base, and from obstructions such as piers.

5.5.2 Brickman’s Bridge

The only usable gauging (Figure 28) was taken using modern acoustic Doppler (ADP) in 2011, it shows a discharge of 63.68 m³/s or 5501 ML/d, and velocity of 0.54 m/s. As indicated in the diagram there is a central area of velocities in the
0.8-1.0 m/s with an equally large part of the water column containing velocities between 0.2-0.6 m/s.

Figure 28 – ADP profile of Brickman’s Bridge from 2011 showing a central filament of velocity in the 0.8-1.0 m/s zone. Mean velocity was 0.54 m/s for this gauging.

5.5.3 Bulga

Seven records for this gauge were selected for sampling. Excluded from this analysis were records not taken from approximately the same location, they have been added to the Appendix.
Figure 29 Velocity profiles for Bulga from 1950 labelled A and B, and 1972 labelled C. As per the previous graph these demonstrate increasing flow velocities away from channel margins.
Chapter 5: Results

The first record was from 1950 (Figure 29, B) during the FDR (1949-1990) and was taken from the upstream side of the bridge. The discharge for this event was 52,430 ML/d, the area was 306 sq m and mean velocity was 1.98 m/s. A second gauging was taken (Figure 29, C) presumably, from the same location the following day. It returned a significantly lower discharge of 15,413 ML/d, the area was nearly halved at 150 sq m and the mean velocity had also reduced to 1.19 m/s. In assessing the velocity profile for the first event, there were three distinct velocity 'plumes' due to the presence of piers. The left plume (looking downstream) was approximately 10 metres wide and varied between 2-5 metres in depth. Velocities in this plume ranged from <1 m/s and >1 m/s. The middle plume was located between the piers and was approximately 30 metres wide and 5 metres deep, it contained two velocity zones <2 m/s and between 2-3 m/s. The third plume on the right bank was also around 5 metres deep, with shallowing on the bank edges, and contained three plumes ranging from <1 m/s around the edges, between 1-2 m/s rising up to the surface and containing a centre plume of between 2-3 m/s.

The modern gauging from 2011 (Figure 30) was taken from 10 metres upstream of the bridge and had a discharge of 21,889 ML/d and a mean velocity 0.97 m/s or 84 km/d. Like earlier gaugings it also contained several velocity plumes ranging from 0-1 m/s near the banks, between 1-2 m/s in the large plume in the
centre of the channel which contained two areas of about 3-5 metres wide with velocities in the range of 0.5-1 m/s.

Figure 30 – ADP velocity profile for Bulga, dated 2011. Showing a very broad zone of velocities in the range of 1-2 m/s. Mean velocity for this reading was 0.97 m/s

5.5.4 Warkworth

Seven gauging records were selected as potentially relevant for this study. As the modern gauging was taken ‘at site’, historical gaugings from ‘at bridge’ or downstream side of bridge only were used. All other gaugings were added to the Appendix.

The first historical gaugings were from a flood event in 1949 (Figure 27), five gaugings in total were taken over the period 20 June 1949 to 24 June 1949. Four of these gaugings were ‘at bridge’ and one was taken from upstream (21 June 1949). Discharge ranged from 14,295 ML/d on 20 June 1949 to 3,117 ML/d at the end of the event; similarly area (of flow) ranged from 186 sq m to 48 sq m; and the mean velocity ranged from 0.84 m/s on the first day, rose to 1.49 on day
two and then ranged between 0.74 and 0.76 m/s for the remaining three days.

One gauging (Figure 27), taken from the middle of this event was selected for further analysis. The cross-section was in three zones, two piers were noted in the record but the velocity profiles either side of each pier remained broadly consistent. At the bottom and sides of the channel there was a velocity zone of <0.9 m/s, above that were two zones (either side of the pier) of 0.8-1.3 m/s and 0.9-1.2 m/s, within those zones near the surface there were two zones, again either side of the pier of >1.2 m/s and >1.3 m/s respectively.

Of the two modern gaugings (14 June 2011 and 17 June 2011) the second gauging was selected for analysis as it was the only gauging where the location was identified (at site). There were 7 separate gaugings recorded for that day, after reviewing the data the record for 1138 hours was selected as a sample as it was about mid range of the mean velocities for all 7 records (ranging from 0.069 m/s to 0.257 m/s) and gave a clearer representation of the zones of velocity. As indicated in Figure 31 below, velocities at the sides and shallow sections of the channel ranged in the 0-0.5 m/s range, between these was a large plume of velocity which although interspersed with smaller velocities, was predominantly within the 1-1.25 m/s range. There were occasional hot spots of high velocity (for this reading) in the centre of the channel where the water is
deepest. Total discharge for this gauging was 21178 ML/d and the mean velocity was 0.68 m/s or 59 km/d.

Figure 31 – ADP velocity profile for Warkworth taken in 2011 showing a large plume of velocities in the low range 0-0.5 m/s and a mean of 0.68 m/s

5.6 Vegetation Changes

Changes in vegetation extent were analysed using historical and modern photography plus aerial imagery from Google Earth. The results are presented below.

5.6.1 Payne’s Crossing

The earliest ground image available for Payne’s Crossing was from 1988 (Figure 32). This image was taken during the FDR (1949-1990) and shows a stretch of river within a steep sided valley with a high bench on the right-hand side. The channel had an unvegetated bar in comparison to the 2011 image (Figure 32) which is in a DDR (1991 to present) where the bar is heavily vegetated.
Chapter 5: Results

Figure 32 Two images of Payne’s Crossing taken two decades apart and showing that the sand banks on the left of the image have become been colonised by vegetation. There is also increased vegetation on the right bank.

The two images below show a section of Wollombi Brook, the Main Arm Terrace, between the township of Wollombi and the Payne’s Crossing gauge. The first image (Figure 33, A) was taken circa 1974 during the FDR showing a single channel within a wider channel margin, a large semi-vegetated island (former chute) at the top of the image, and barely any riparian vegetation particularly on the inner image, which appears to be farmland. The second image (Figure 33, B) is from 2007, during the DDR, and shows a smaller, well vegetated channel most of which appears to be on the banks although the channel has contracted compared with the earlier image.
Figure 33 A comparison of an aerial image from Page (1974) compared with a Google Earth image from 2007 showing a narrower channel, a substantial increase in riparian vegetation including of the chute from the earlier image.

5.6.2 Brickman’s Bridge

Modern images of Wollombi Brook at Brickman’s Bridge were not to be obtained due to extensive vegetation regrowth. As this gauge only commenced in 1996 there is also no historical images. Instead aerial imagery, taken from Google Earth, was used to show how this stretch of river has changed over recent times. Two images from 2007 and 2012 were sourced and are presented in Figure 34 below. Image A shows an aerial image of the river several months before a large flood event, the channel is small occupying only a portion of the entire width of the channel and is probably quite shallow. The are some mature trees occupying the channel and there is an extensive sand base. The greenish area around the flow area indicates the presence of vegetation within the channel. Image B, from 2012, shows a slightly larger channel than in the earlier
image, there is more in-channel vegetation and the riparian vegetation appears to be slightly more extensive. The images are taken either side of the 2007 and 2011 floods.

Figure 34 Two Google Earth views of Brickman’s Bridge which was virtually inaccessible on the ground in 2011. These images were taken either side of the 2007 and 2011 flood events and show that the vegetation either persisted through or recolonised after the floods

5.6.3 Bulga

The earliest image available of Bulga was from circa 1967 (Figure 35) and shows a sparsely vegetated wide channel with an extensive sand bed. The main flow appears to be on the left but is very narrow and shallow considering the overall width and depth of the channel. There appears to be a small pool in the upper right of the image, it is difficult to tell whether this is attached to a flow or not. This image of Wollombi Brook more resembles a beach than a river. In contrast, the modern photo, taken in August 2012, shows extensive revegetation of the banks and sand bars, compared with the photo from September 1967. Vegetation lining the banks and in-channel is a mixture of grasses, reeds, small
shrubs and maturing trees. The channel flows around a small vegetated island just downstream of the bridge.

Figure 35 Wollombi Brook at Bulga, looking downstream from right side of bridge, approximately September 1967 and August 2012, photos courtesy of NSW Office of Water

Aerial imagery of this same location ranges from 2002 until 2009, an image from 30 October 2002 and 13 January 2009 were selected for analysis and are labelled A and B in Figure 36 below. Pools are no longer present in the 2009 image, and the channel and channel margin are well vegetated. These images were taken either side of the 2007 flood event, with figure B being taken approximately 18
months after. In this later image the channel (flow) has moved and appears to have deepened.

The marker used in these images is only indicative and does not represent the actual gauge location which is across the road and on the opposite side of the river.

![Google Earth images of Bulga (at gauge) from 2002 and 2009](image)

**Figure 36** Two Google Earth images of Bulga (at gauge) from 2002 and 2009, the latter image showing an increase in in-channel and riparian vegetation and perhaps widening of the channel in the upper portion

### 5.6.4 Warkworth

The earliest image of Warkworth, presumably taken near the bridge from the right bank and looking downstream from downstream show a river with barely any vegetation on the banks, and a wide channel containing an extensive sand bed. Both this image and the one for Bulga were taken during the last FDR (1949-1990). The main flow is on the right hand side of the channel and there is
a large inner bank attached sandbar. The shadowing in the water near the bottom right of the image appears to indicate submerged sand banks though it is difficult to tell with any degree of accuracy without having other images to conform this. Figure 37 from 2007 (Cohen and Reinfelds, unpublished data) shows extensive riparian and in-channel vegetation growth, a single channel or pool is observed in the bottom left corner of the image. Similar to in nature to the Figure 38 from 2007, the more recent images in Figure 39 from 2011 show the left bank of the river at Warkworth, the left image was taken from the bridge looking downstream and the right image is looking upstream towards the bridge from the left bank. Note the intrusion of riparian vegetation growing to the edge of the channel and the presence of extensive reed beds. There are also vegetated sand islands within the channel itself.

Figure 37 A scene of Warkworth 1967 showing a wide channel with an extensive sand base, little to no vegetation, and the bank appears to be have collapsed in the top centre of photo (photo courtesy of NSW Office of Water)
Chapter 5: Results

Figure 38 The same location as in Figure 37, 4 decades later, showing a vastly different river, riparian vegetation appears mature and in-channel vegetation has colonised the former ‘sandy beach’ that was Warkworth in 1967.

Figure 39 Images of Warkworth from 2011 a) at bridge looking downstream and b) downstream looking back towards the bridge. Both show maturing riparian vegetation and the channel is thick with reeds.

Figure 40 below shows two aerial images of Warkworth from 2002 to 2009. Image A shows a long, continuous channel within an extensive sand bed base. There appears to be some vegetation within the channel but the colouring
suggests grasses or reeds with an occasional shrub or tree. Discolouration of
the water is indicative of shallowing in several areas. Image B is from 2009,
approximately 18 months after the floods of 2007 and shows slightly wider area
of flow, which may be deeper than the previous image. Pools are present in the
upper top of the image, and the in-channel vegetation seems to consist of
shrubs or immature trees rather than the grasses or reeds.

Figure 40 Two Google Earth images of Warkworth (at bridge) from a) 2002 and b) 2009 the
latter image shows an increase in riparian vegetation and the channel appears deeper
particularly on the downside of the bridge

5.7 Summary of Findings

There are several main findings of this study, firstly that there is evidence of a
stabilisation of channel morphology following the catastrophic floods of 1949
and subsequent floods of 1955. There is also evidence of a decline total annual
flows and velocity characteristics in this latest DDR compared with both the
previous DDR and the FDR, and riparian and in-channel vegetation has vastly improved compared with earlier conditions for Wollombi Brook.
Chapter 6: Discussion

6.1 Introduction

The aim of this project was to examine the cause of changes to flood transmission times for Wollombi Brook as identified in recent work by Cohen and Reinfelds (unpublished data). A decrease in total annual flows and a reduction in the magnitude and frequency of flood events will promote and increase in riparian and in-channel vegetation which lead to channel stability and an increase in flood transmission times a function of flood wave celerity (Huang and Nanson, 1997; Anderson, 2006; Rustomji, 2007).

While this apparent change in flood hydrology coincides with a change in climatic condition, the current Drought Dominated which began in 1991, it appears that total annual flows for this DDR may be significantly lower than that of the previous DDR (1901-1948). However, a reduction in total annual flows is just one factor which may have an effect on flow velocities. The data presented in Chapter 5 also shows that there is evidence channel stabilisation following the catastrophic floods of 1949 and 1955, as well as a decline in flood velocities and in the magnitude of infrequent events in this latest DDR compared with both the previous DDR and the FDR. In addition riparian and
in-channel vegetation has vastly improved compared with earlier conditions for Wollombi Brook.

6.2 Annual Flow Analysis

It has been well established that the south eastern Australian rivers exist within a highly variable climate, strongly influenced by a cycle of flood and drought dominated regimes (FDR and DDR) that tend to persist for periods of up to fifty years, both of which have a significant effect on a river’s hydrology and morphology (Knighton, 1998; Warner, 1999). DDR’s are typified by periods of extremely low flows interspersed with intermittent ‘runs’ of the opposite characteristic. The reverse is true for FDRs (Erskine and Warner, 1998).

The total annual flows were examined by regime and are presented in Chapter 5, Figure 11, Figure 12, Figure 13. The analysis showed that there has been a consistent decline in the mean total annual flows for this current DDR (to date) than the previous DDR and FDR. For example total mean annual flows (normalised) for Warkworth were 3,444 ML, 5,829 ML and 2,399 ML for the three regimes in chronological order. Poor quality data produced by the Bulga and Payne’s Crossing gauges and a larger catchment area may explain the variation between these three gauges for the FDR which produced mean annual
flow (normalised) returns of 3,333 ML and 1,612 ML compared with Warkworth’s high of 5,829 ML for the same period. Warkworth’s mean annual flow is nearly twice the return of the Bulga and Payne’s Crossing gauges respectively (Figure 41). Records for the current DDR were much more consistent apart from Payne’s Crossing which was decommissioned in 2000 and was not able to be used to detect any consistent pattern of low flow events.

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Figure 41 - Low, High and Mean Annual flows by gauge and regime

Four particularly significant high flow events, each causing widespread flooding and associated damages, occurred for Wollombi Brook in 1949, 1955, 2007 and 2011 (Cessnock Council Report, 2011). Figure 13, Chapter 5 from Warkworth presents the total annual flows, with the significant flood years identified. This gauge was used as an example as it has the longest span of records for demonstrating where these events fit in the broader scheme of total
annual flows. The first two of these events occurred in an FDR and the latter in the most recent DDR. These last two events are interesting in that they both occurred during a period where there has been a significant downward trend in annual flows, highlighting not only the variable nature of flows during a DDR as pointed out by Erskine and Warner (1998), but also that floods of significance can still occur during what is essentially a dry period.

Overall the results show that flows across regimes and gauges were consistent apart from those anomalies mentioned above which may be a reflection of catchment size, location of the storm cells, and also data quality. The DDR regimes produced consistently low flows compared with that of the FDR, as expected, and the decline in annual flows in the most recent DDR correlates with the findings of a study on the MacDonald River, in the Hawkesbury, where there has been a decline in rainfall and in the magnitude of floods since the 1980’s (Rustomji, 2007).

6.3 Annual and Partial Series Analysis

Annual and Partial Series analyses were conducted for Wollombi Brook using the software program FLIKE developed by the Department of Civil, Surveying, and Environmental Engineering, University of Newcastle. This software
implements the principles outlined in Micevski et al (2005) for modelling flood frequency intervals. A recently published paper by Rustomji et al (2009) recommends the use of the Generalised Pareto method for modelling flood frequency curves for south east Australian rivers as it better represents recurrence intervals for rivers with high flood variability. In conducting these analyses there were issues with using this method for some of the gaugings for Wollombi Brook and therefore for consistency the Log Pearson III method was used instead.

The NSW Office of Water recently tested both methods on data from the Nymboida River, under the influence of the same hydrological regime, and noted that while the two methods model distributions differently, the Log Pearson III method was in closer agreement to the data than the Generalised Pareto method between the 2 and 10 year ARIs, and that the Generalised Pareto method significantly underestimates flows for extreme events in short records, several of which were produced for Wollombi Brook (Reinfelds, unpublished data).

One of the better examples was from the Warkworth gauge which provided coverage of all regimes, refer to Table 6, Chapter 5. The results show that there has been a decline in all recurrence intervals between first DDR and the current DDR apart from the 1.01 ARI (0.46 cumecs compared with 0.55 cumecs).
most significant change for this gauge occurred beyond the 2.0 interval, where the values (cumecs) are between 2-3 times higher in the first DDR (1901-1948) compared with the current DDR (1991-present). This means that, for instance, the 1:10 event was nearly three times higher in the first DDR (1024.9 versus 357.3 cumecs) than it is today. These variances are associated with the significantly lower total annual flows for this DDR to date. The results of this analysis are presented in Chapter 5, Figure 17. Page (1974) also noted a sharp upward turn in the area of the 2 year ARI and an increase in flood frequency downstream.

The data produced by the ASA again highlights the significance of the downward shift in total annual flows and frequencies associated with the influence of the most recent DDR. These findings are consistent with the work of Rustomji (2007) who also noted that the last three decades have produced both lower rainfall and lower magnitude floods for the MacDonald River, which is in the Hawkesbury region.

A Partial Series Analysis (PSA) was also conducted on flow data for Wollombi Brook, the results for Warkworth are presented in Chapter 5, Figure 18. The PSA uses a particular flow threshold, for instance the 2 year ARI, to examine the frequency of a particular flow throughout the year which may otherwise be obscured by the ASA. The 2 year ASA has been used previously to relate
changes in channel form to a particular discharge event (Knighton, 1998; Pilgrim, 2001).

These records were normalised to give a more accurate distribution of events, the results show that the frequency of events in the 2-5 year ARI is higher for the most recent DDR than in either of the earlier regimes. At the 5-10 and 10-20 mark the relationship between DDRs remains the same. The results produced for Bulga were slightly different in they demonstrated a stronger relationship for the FDR in the 2-5 year ARI but this was likely due to the length and quality of the records able to be used.

The high frequencies returned for the 2-5 ARI are significant in that floods which cause changes in channel morphology beyond base channel changes or bench development tend to occur beyond the 1.01 ARI (Page, 1974; Pickup and Warner, 1976; Thomas and Goudie, 2009).

6.4 Velocity Profile Analysis

The measurement of flow can provide an estimate of the volume and power of the water in the river at any given time, this is particularly important for understanding the amount of water available and the likely effect of the
available power in the channel to perform work, it is also an important tool in assessing flood risk and potential for flood damage (Huang and Nanson, 1997; Ladson, 2011).

The speed or velocity of a river is determined by the gradient, the volume of water, the width-depth ratio of the channel, and friction imposed upon it by the banks, bed, and other forces such as rocks, plants, and debris (known as channel roughness or Manning’s $n$) (Huang and Nanson, 1997; Huang and Nanson, 2007). In natural rivers, open channel flow is highly dynamic and is strongly influenced by the forces of gravity and friction which will vary along the length of the channel and within the column of water itself (Knighton, 1988; Ladson, 2011).

Because of the effects of time, both manual and automatic measurements were used to create gaugings for Wollombi Brook. A review of the methodology used by the Acoustic Doppler Profiler (ADP) indicates that it uses essentially the same principles as for historical gaugings whereby measurements are taken at set intervals across the width of the channel and then down profile measurements are taken at these intervals. This is known as the ‘percentage of depth’ method of estimating flow which has been described in Gordon et al (2004) and Sontek (2011).
Chapter 6 – Discussion

Twenty velocity profiles were used in this study, the events were selected on the basis of being similar in stage and discharge, spanning the FDR and one or both of the DDRs. The results of the analysis are presented in Table 8, Chapter 5 which shows that modern velocities have declined in comparison with both the FDR and the previous DDR and that the values returned correspond with an similarly low return for annual flows in the latest DDR (as discussed above).

Brickman’s Bridge returned flood velocities of 0.42 (1998) and 0.57 for (2001) and 0.54 (2011) m/s in the latest DDR, the result for 2011 is significant in that it correlated with a major flood event for the region and this velocity occurred during a flood between 3 to 3.6 times the volume of the earlier events. Two similar sized events from Warkworth, one each from the FDR and latest DDR, repeated the trend of lowered velocities, returning 1.38 m/s for a flow of 25,200 ML/d and 0.68 m/s for a flow of 21,178 ML/d. Bulga also demonstrated the same decline in velocity across regimes, returning 1.47 m/s for a flow of 20,062 ML/d and 0.97 m/s for 21,889 ML/d for the FDR and DDR respectively. Some differences in area of flow were noted.

Everard (no date) compared the results of 21 gauged flows using an ADP (or ADCP) and a current metre (used for the historical gaugings on Wollombi
Brook) and determined that the ADP performed the same as the current metre in 7 out of 13 high flows; 12 out of 19 medium flows; and 7 out of 21 low flow sites. He concluded that there are differences in estimations of velocity between the two methodologies, particularly at low flows and the main differences were between the vertical velocity profiles (Everard, no date).

This is an area that has been identified as requiring more study as it has significant implications for determining the accuracy of flows (and therefore available water and potential risk) and also to assist in truly clarifying how much velocity has truly changed particularly in low flow scenarios.

There have been no changes in rating tables which needed to be considered in this study.

6.5 Channel Morphology

The channel form of a river is defined by a three dimensional relationship between its width, depth, and slope. This relationship is, at its simplest level, controlled by geology and discharge, but is also influenced by a number of external variables including climate, vegetation, basin characteristics and, at times, anthropogenic influences (Knighton, 1988; Erskine and Warner, 1998).
Wollombi Brook’s variable climate and hydrological characteristics means that it has a high flood variability compared to the global average (Erskine and Saynor, 1996; Pritchard, 2005). It typically experiences periods of both little to no flow as well as intense, infrequent floods also known as low frequency high magnitude events. Both of these extremes can have a profound influence on channel morphology and both usually involve changes in vegetation which will also influence bank stability and flow velocities, and therefore either enhance or suppress changes in channel morphology (Warner, 1987; Huang and Nanson, 2007; Rustomji, 2007).

While the annual flow records presented in this thesis indicate that Wollombi Brook’s hydrology has been highly variable throughout gauging history, one of the most significant periods of channel change occurred in 1949 following a flood with a peak discharge of nearly 27 times the mean annual flood and a return period of 87 years (Nanson and Erskine, 1998). Page (1974) conducted a study on the bankfull discharge concept using Wollombi Brook as his test site and reported that the pre-flood morphology of the main trunk of Wollombi Brook consisted of a channel with a broad sand bed that was deeply incised into its own alluvium; and channel width varied with drainage area (Page, 1974). He found that the flood caused widespread channel incision, channel widening and terrace destruction particularly downstream of Payne’s Crossing, the
creation or aggradation of levee surfaces, which was followed by an ongoing period of erosion and redistribution of sediments, reinforced by subsequent large scale floods in the 1950’s (Page, 1974). Erskine and Warner (1998) also found evidence of an increase in cross-sectional area, width, and width-depth relationships.

In the years following the floods, erosion and channel instability continued due to successive flooding associated with the FDR. Mitigation works were necessary in the upper reaches to stabilise the channel and reduce excessive sedimentation in the lower reaches. The formation of benches led to channel constriction, which was assisted by the return of riparian vegetation, resulting in improved channel capacity and an increase in flow velocities (Erskine and Bell, 1982; Webb and Erskine, 2003b; Chalmers et al, 2012). Continued riparian colonisation into the new DDR led to a stabilisation of the in-channel sand beds and a decline in the amount of sediment being contributed to the Hunter River (Erskine, 1998). Page (1974) concluded that Wollombi Brook demonstrated evidence of channel equilibrium following a period of flows that exceeded a resistance threshold but the most significant factor in this stage of Wollombi Brook’s (gradual) recovery has been the lack of floods of high magnitude, low frequency such as those experienced in the 1940’s and 1950’s (Page, 1974; Erskine, 1994).
This research assessed changes in channel morphology over a range of years. The most significant and useful evidence was from Bulga (Figure 23, Chapter 5) where the morphological history spans 1941 to 2007, with the earliest being only an estimate of the base of the channel from Erskine (1994). Between 1955 and 1981 the channel base had aggraded by 1-3 metres at the channel base and between 0.5-2 metres channel margin aggradation had occurred, leading to significant narrowing of the channel. Subsequent and extensive scouring had returned the deepest part of the 2004 channel base to 1955 levels while the rest of the channel base only experienced minor scouring. Bench development on the right bank continued during this period. The last three years of the survey period (to 2007) demonstrated only minimal bed variability and the right bank had been dissected. In summary this channel cross section showed that channel bed aggradation and bench development were both initiated post 1955 and continued until at least 2007.

The cross section from Warkworth indicated that it had experienced very little change in channel width over the survey period (1980-2004) with only minor scouring of the base, deepening of the thalweg, and the development of a bench all occurring the middle and later stages of the survey period.

These results demonstrate that the period of stability reported by Page (1974) and Erskine and Warner (1998) continues through to present times. The
findings are consistent with the later work of Erskine (1998) and are supported by the work of Rustomji (2007) on the MacDonald River, part of the Hawkesbury River system which also suffered catastrophic channel change associated with the 1949 and 1955 floods. As in the case of Bulga, Rustomji (2007) also found that the MacDonald river bed was close to pre-flood dimensions. He concluded that the reversion to pre-flood morphology over time supported the theory of cyclical (episodic) disequilibrium (with some limitations) whereby a channel varies rapidly in response to the breaching of a threshold and then readjusts during drier periods (Rustomji, 2007).

Erskine and Warner (1998) and Rustomji (2007) both concluded that the changes experienced during 1949 and 1955 were due to variations in rainfall rather than catchment disturbance, and that morphological changes are more a consequence of floods than annual flows or the effect of rainfall intensity (Erskine and Warner, 1998; Rustomji; 2007).

An assessment of the evidence presented in this thesis confirms that Wollombi Brook is undergoing a process of channel stabilisation following a high magnitude infrequent flood event in 1949 and the successive flood of 1955, reinforcing the effects of the earlier flood. During the last three decades channel morphologies have been relatively stable, assisted by a decline in total annual flows and in the frequency interval of large magnitude events. Riparian
vegetation has substantially increased and this has contributed bank stability and also to a decline in flood velocities.

6.6 Vegetation Changes

Riparian vegetation communities play an important role in river systems, specifically in relation to channel morphology and hydrological characteristics. They can act as a source of friction to impede flow and thus influence flow velocities and flow direction, they also contribute to bank strength which assists with the maintenance of channel size and form (Huang and Nanson, 1997; Anderson et al, 2006). Bennett and Simon (2004) also stated that vegetation ‘can modulate the pace and characteristics of river channel change...in some cases, vegetation can initiate fluvial adjustment’ (Bennett and Simon, 2004, vii).

Vegetation communities will fluctuate due to natural conditions such a change in rainfall, or floods, or fires for example. The loss of vegetation along river bank can promote destabilisation of channel banks, increase velocity, and add to the sediment load, potentially causing an imbalance in the work-power relationship. Conversely, an increase in vegetation could have the opposite effect, depending on the type and volume of vegetation present and the local geology (Huang and Nanson, 1997; Jang et al, 2007).
Shortly after European settlement, around 1820 for Wollombi Brook, the banks of many rivers began to change due to the practices of ringbarking, grazing, and clearing (Chalmers et al, 2012). Research by Webb and Erskine (2003b) suggests that for east coast rivers this was a regular practice between 1886 and 1995, supported by government legislation. The results of these practices included an increase in velocity, extensive bed degradation, massive channel enlargement and loss of fish habitat. These effects can be further enhanced by flood activity such as the floods of 1949 and 1955 which occurred on Wollombi Brook. A discussion of the effects of these floods and the early stages of recovery has already occurred in Section 6.2 above so won’t be repeated here however, Page (1974) concluded in relation to these events that Wollombi Brook’s inability to resist erosion was probably enhanced by the loss of riparian vegetation and that it’s return is assisting in terrace stability (Page, 1974).

This research set out to find out the extent of change in-channel and riparian vegetation for Wollombi Brook using modern and historical photography of the river channel and edges. The results from the photographs are abundantly clear, that there has been a considerable change in riparian and in-channel vegetation across all the sites at least since the late 1960’s when Figure 37 of Wollombi Brook at Bulga was taken. This increase in riparian vegetation has assisted by the cessation of land clearing and grazing, which took place from
about 1886 until about 1995 and a decline in both annual rainfall and the frequency of flood events which can destroy the riparian habitat (Webb et al, 1999; Webb and Erskine, 2003b; Chalmers et al, 2012).

In the upper reaches, at Payne’s Crossing and Brickman’s Bridge, it was difficult to observe the channel due to the amount of vegetation now present within the channel and on the banks however field observation indicates that all sections of the river demonstrate a system thriving with in-channel and riparian vegetation.

The aerial images used in this analysis were not as conclusive as the land-based photos however for the most part they demonstrated a change in riparian and in-channel vegetation over time, particularly after the 2007 floods. Images of Brickman’s Bridge (2007 and 2012) showed a slightly larger channel of flow with an increase in both in-channel and riparian vegetation; and images from Bulga and Warkworth both showed a channel similar in form for both dates and locations, and their channel and channel margins are now well vegetated.

An image from Ken Page’s thesis (1974) taken in 1970 upstream of the Payne’s Crossing gauge, was compared with a Google Earth image from 2009 from the same location but in different hydrological regimes. The first image shows a single channel within a wide channel margin, a large semi-vegetated island
which was a former splay, and very minimal riparian and in-channel vegetation. In contrast, the modern image shows a smaller, perhaps deeper channel, a substantial increase in riparian vegetation and the sand splay has been reclaimed for farming or other activities, supporting the theory that the river is in a rehabilitation phase most likely associated with a decline in flood size and frequency.

While it wasn’t possible to examine the spatial distribution of vegetative changes for Wollombi Brook over time to determine the timeframe of recovery, it has been previously suggested that the response of vegetation to a decline in rainfall is rapid (Erskine and Bell, 1982; Tabacchi et al, 1998). Although the results between the on-ground photographs and aerial imagery didn’t always give the same result, the on-ground evidence provides more realistic view of current riparian conditions and the contrast between the stark image of Bulga from the 1960’s to the riparian habitat of 2012, there has clearly been a dramatic increase in both riparian and in-channel vegetation. These results are consistent with the work of Bennett and Simon (2004) and Capon and Dowe (2006) who found that while local climate and hydrological conditions ultimately determine the type and quantity of vegetation present in the riparian zone, riparian habitats are highly dynamic and changes in habitat can either be a gradual, such as in response to an equally gradual change in climate, or rapid
Chapter 6 – Discussion

change such as in response to a flooding or land clearing event (Bennett and Simon, 2004; Capon and Dowe, 2006).

Chalmers et al (2012) stated that the contraction of a river following a catastrophic flood will commence when the supply of sediment declines and recolonisation of riparian vegetation occurs. They further commented that localised incision will replace bed aggradation in response to smaller flows. Erskine (1996) and Erskine and Saynor (1996) confirmed that this had occurred on Wollombi Brook after 1949.
Chapter 7: Conclusions & Recommendations

South eastern Australian river systems have undergone a dramatic change since settlement in the early 1800’s. These changes include, for example, channel incision and widening, channel aggradation, loss of riparian habitat, and changes in flow regimes which are strongly influenced by the drought and flood dominated cycles that can dominate for decades. Where able to, rivers will adjust naturally to minor changes in condition but occasionally events of great magnitude and/or frequency, such as the Wollombi Brook floods of 1949 and 1955, bring about such substantial change that the river system has to adopt a new state of condition in an attempt to achieve equilibrium between the available power and the work to be performed.

This thesis demonstrated that Wollombi Brook has substantially changed both in response to these floods and in the period to date afterwards. The 1949 floods caused widespread channel incision and widening, changes to levee and terrace structures, and widespread erosion. The effects of this were reinforced by the 1955 flood.
Since 1991 the results indicate that there has been a decline in total annual flows compared with the previous DDR and FDR. At present the last 20 years of record exhibits fewer large magnitude events but an increase in the frequency of smaller events (2-5 year ARI). There has been an overall stabilisation of channel morphology that, while spatially variable, demonstrated little evidence of change in the upper two gauges (Payne’s Crossing and Brickman’s Bridge), whereas Bulga and Warkworth showed minor aggradation of the channel base compared with earlier surveys. There has also been a decline in flow velocities compared with similar events in the previous DDR (0.5 m/s and 3073 ML/d in the first DDR compared with 0.42 m/s and 1507 ML/d at Payne’s Crossing).

These changes have been assisted by a dramatic increase in riparian vegetation following the cessation of government sanctioned land clearing between 1886 and 1995. This in addition to the decline in total annual flows has allowed the establishment of riparian vegetation leading to enhanced channel stability and an increase in the Manning’s $n$ value, affecting flow velocities. Coupled with a decrease in high magnitude, low frequency events has effectively restabilised Wollombi Brook.
Therefore the results of this study suggest that changes in flood transmission times, as identified by Cohen and Reinfelds (unpublished data), are driven by changes in vegetation. These findings are consistent with work on the MacDonald River in the Hawkesbury.

7.1 Recommendations

As time progresses the quality and quantity of data collected on river systems will continue to improve, making comparisons over time easier and more accurate. In this study only the Warkworth gauge contained reliable long term data and consequently the interpretation of the results has drawn heavily from this data. It would be useful to conduct a similar study on another south eastern Australian river that has more complete historical gauging data to ensure that a better representation of flows during a FDR and DDR is obtained. An assessment of changes to inflows (runoff) may have enhanced the results presented here, and could be another area for future research.

Access to better GIS data would have benefitted this study as it could have provided a more thorough assessment of the entire length or selected reaches of the river over time. Further work on a comparison of current metres and ADPs for measuring velocity profiles would benefit the industry.
References


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Appendices

Hydrological Analysis:

Flood frequency analysis for Brickman’s Bridge, not used as it has no other regimes for comparison

Unused ARI for Brickman’s Bridge, excluded as it had no other regimes for comparison and is missing part of recent DDR

Brickman's Bridge: Frequency of ARI Events by Size

Brickman's Bridge: Recurrence Interval & Discharge Estimate in Different Hydrological Periods

133
Total annual flows for Brickman’s Bridge. This graph was not used as it had no other periods for comparison.

Landsat images of Wollombi Brook not used due to extensive pixilation when georeferenced in ArcGIS.
Landsat images showing the location of Wollombi Brook and extent of vegetation. Image A is from 1999, B is 2001, C is 2006, D is 2011

Table of Landsat images used showing the year, month, and season

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## Location and Date of Gauge Recordings

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**Legend:** AB - At Bridge; AC - At Control; AG - At Gauge; DS - Downstream of Gauge; DSSB - Downstream Side of Bridge; LNR - Location Not Recorded; US - Upstream of Gauge; USSB - Upstream Side of Bridge

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**Unused Velocity Profiles By Gauge**

![Graph: Brickman's Bridge: 12 August 1998](image)

This graph was excluded because there were no depths to create velocity profiles from, this one was created using 0.6 x depth
Brickman's Bridge: 14 March 2001

Payne's Crossing - 27 March 1976

As per the above gauging, velocity profile created using 0.6 x depth
Bulga: 17 June 1950

Date: 17 June 1950
Location: U/S Bridge
Mean V m/s: 1.98 m³/sec
Mean V km/d: 171.072
Q m³/sec: 606.829
Bulga: 18 June 1950

Date: 18 June 1950
Location: U/S Bridge
Mean V m/s: 1.19 m³/sec
Mean V km/d: 102.816
Q m³/sec: 178.391

Distance (m)
Maximum Water Depth (m)
Warkworth: 22 June 1949

Date: 22 June 1949
Location: Bulga Bridge
Mean V m/s: 0.74 m$^3$/sec
Mean V km/d: 63.936

Warkworth: 24 June 1949

Date: 24 June 1949
Location: Bulga Bridge
Mean V m/s: 0.76 m$^3$/sec
Mean V km/d: 65.664
Q m$^3$/sec: 36.0764
Annual Recurrence Intervals: Partial Series Analysis
Regression Analysis using Warkworth as the baseline

**All Floods Equal to or Greater Than 2 Year ARI (24.89 Cumecs) (1996-2011)**

Regression equation: 
\[ y = 0.9367x + 348.16 \]

Coefficient of determination: 
\[ R^2 = 0.7907 \]

**210004 v 210028 (1959-2011)**

Regression equation: 
\[ y = 0.9367x + 348.16 \]

Coefficient of determination: 
\[ R^2 = 0.7907 \]
Records used for hydrological analysis

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Unused Land and Aerial Imagery

Unused (compressed) Google Earth images of Bulga

30 October 2002

30 January 2003
Unused (compressed) Google Earth images of Payne’s Crossing

31 October 2009

15 February 2010

2 April 2007

28 September 2009

2 October 2009

20 October 2009
14 April 2012

Unused image of Payne’s Crossing from Page (1974)
Unused photos showing the modern river

Warkworth:

Looking downstream from the bridge, gauge beyond the edge of this photo (photos courtesy of Anthony Belcher, NSW Office of Water)

Looking upstream from bridge (photos courtesy of Anthony Belcher, NSW Office of Water)
At bridge, showing trees in the channel (photo courtesy of Anthony Belcher, NSW Office of Water)

Another image looking upstream demonstrating the thickness and maturity of riparian vegetation
Bulga:

Looking downstream from the bridge. Showing a large vegetated sand bank and a pool in on
the left (photo courtesy of Anthony Belcher, NSW Office of Water)

Looking upstream at Bulga, showing a well vegetated channel and at least two different flow
paths (photo courtesy of Anthony Belcher, NSW Office of Water)
Payne’s Crossing:

Image of Payne’s Crossing ? site of former gauge (photo courtesy of Anthony Belcher, NSW Office of Water)

1988 image of Payne’s Crossing at the gauge, possibly the same location as image above (photo courtesy of NSW Office of Water)
1988 image of Payne’s Crossing (photo courtesy of NSW Office of Water)

1984 image of Payne’s Crossing control and gauge (photo courtesy of NSW Office of Water)

Payne’s Crossing in December 1984 (photo courtesy of NSW Office of Water)
Image of control at Payne’s Crossing (photo courtesy of NSW Office of Water)

Image of Payne’s Crossing control (photo courtesy of NSW Office of Water)
Image of Payne’s Crossing, at control (photo courtesy of NSW Office of Water)

Image of Payne’s Crossing, exact location unknown (photo courtesy of Anthony Belcher, NSW Office of Water)
Warkworth:

At gauge, reeds extensive and mature trees in channel (photo by author)

Gauge in foreground, reed extensive and small trees in channel (photo by author)
Warkworth gauge, looking across stream (photo by author)

Another image of the gauge and surrounding vegetation, centre of screen (photo by author)
Upstream side of bridge, Warkworth gauge is downstream (photo by author)