The Hydrology, Geomorphology
and Quaternary Palaeochannels
of the Lachlan Valley, New South Wales

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CHAPTER ONE
Introduction: Some Questions concerning Late Quaternary
Hydrology of Southeastern Australia

1.1 Introduction

The work in this thesis arose from a desire to extend the Quaternary history of vegetation and landscapes from the southeastern highlands, where it was well known for late-glacial and post-glacial times from peat bog and lake records above 800m altitude, into the drier parts of the central Lachlan basin from sediments infilling Lake Cowal. The broad aim was to improve the accuracy of reconstruction of Quaternary hydrological and climatic history in southeastern Australia, which in a global context is a key region, antipodeal to the well-studied North Atlantic region. Subsequent investigation showed this lake to be probably Tertiary in age and barren of micro-fossils, but my attention was drawn to the complex maze, apparent in large-scale photo mosaics, of well-preserved palaeochannels on the surrounding alluvial plains. Since the work of Hills (1939, 1940) on the longitudinal dunes and lunettes of northwest Victoria, studies of the palaeohydrology and geomorphology in inland southeastern Australia have concentrated on the distinctive landforms, lakes and river systems of the Riverina and the Riverine Plain (reviewed by Bowler 1986) (Fig. 1.1). Over the last twenty-five years, a chronology of the fluvial evolution has been developed for this area, based initially on radiocarbon dating (Bowler 1967, 1978) and later supported by thermoluminscence dating techniques (Page et al 1991, 1996). None of these studies extended into lakes or rivers of the Lachlan Valley, which was considered to possess notably fewer sandy dunes of any description and a lower diversity of palaeochannel types (Bowler 1978).

Some perplexing problems emerged from work on palaeochannels in the Riverina to the south, the Murray, Goulburn and Murrumbidgee and from the Darling River to the west. One of these concerned the nature and relative size of palaeochannels which developed before or during the period of the peak of the Last Glacial Maximum (LGM), c. 21,400 years and the late glacial from 17,500 – 11,500 years ago. Fried (1993) offered an explanation of high
Fig. 1.1 Map of the Murray-Darling basin, showing its location within Australia (inset), the principle rivers, and places mentioned in the text.
suspended loads to explain the sinuous form of LGM rivers in the Riverine Plain, which appeared to contrast with the braided channel pattern of rivers elsewhere in the world during this period. That mainland Australian glacial rivers at the LGM were sinuous and meandering rather than braided may not be too surprising given their unglaciated and relatively low elevation catchments, and the relative aridity suggested by other evidence that would have resulted in lower discharges. The exact nature of channels spanning the LGM remains to be resolved (Page et al. 1991), and Page et al. (1996) suggested that the large meandering palaeochannels of the Riverine Plain were active before and after the maximum, but that the LGM itself was characterised by low fluvial activity. It has been harder to explain the relatively large size (compared to modern channels) of meandering palaeochannels that were apparently active at the time thought to have been the windiest (Wasson 1983), driest (Bowler and Wasson 1983, Kershaw 1989) and most barren of vegetation (Bowler 1978) of any period in the c.100,000 years of the last glacial cycle.

The catchment of the Lachlan Valley differs from those further south in that it is lower (average 600-800 metres altitude) and does not contain sub-alpine zones. During the last glacial period, when the large meandering palaeochannels in the Murray basin were thought to have been active, most of its catchment would have escaped the effects of direct periglacial activity, although it may have suffered from higher erosion rates caused by low vegetation cover and high winds, and approximately 11% of the catchment was above the altitudinal treeline, estimated at 600 metres (Singh and Geissler 1985). Large meandering palaeochannels in areas without a snow-fed catchment are also known from the Darling River (Bowler et al. 1979). However, the regional position of the Lachlan, between the monsoon-influenced catchments to the north, and periglacially affected catchments to the south, places it in an important location for determining the palaeohydrology of this period in southeastern Australia.
The fluvial history of the Lachlan Valley is of particular importance to the history of the Riverine Plain, where it overlaps with the Lachlan basin downstream from Hillston and the area now known as the Benabee drainage basin located between the lower Lachlan and the lower Darling river catchments. This area now contains the archaeologically significant Willandra Lakes, including Lake Mungo, which has a well-dated record of environmental change and human occupation to before 60,000 yr ago (Bowler et al 1976, 1986, 1998). Now the lakes are dry and occupy a semi-arid landscape; their waters are supplied only by drainage along local creeks with some overflow from Willandra Creek, but in the late Pleistocene the lakes were connected to the Lachlan system via the palaeo-Willandra Creek, then the principal channel of the lower Lachlan River, remnants of which can clearly be identified from aerial photo surrounding the much smaller and less active present-day stream (Bowler et al 1976, Adamson et al 1987). The supply of water to the lakes is partly controlled by climate, but is also geomorphically controlled since the feeder stream was an active anabranch of the palaeo-Lachlan. Although Willandra Creek lies outside the study reach, it was hoped that description and dating of the palaeo-river system upstream of the Willandra Lakes would provide evidence that would support the lake level record.

Palaeohydrologic reconstructions in Australia have been bedevilled by the fact that Late Quaternary palaeochannels are very different from the modern rivers. For a long time, the suite of large palaeochannel features surrounding the rivers of the Murray Basin was considered to be geomorphically more interesting than their modern counterparts, which were described as “mud-lined gutters” by Gill (1973). In recent years this situation has partly been redressed by Rutherfurd (1991, 1994) for the Murray River and its anabranches, by Schumm et al (1996) for Murray River tributaries, and by Page (1988) for the Murrumbidgee River. More is known about the present-day inland rivers of the Darling basin, to the north of the Lachlan, from studies of the Namoi-Gwydir system (Riley 1973, 1977), the Castlereagh River (Alam 1983), and the Darling River (Taylor 1976, Riley and Taylor 1978, Woodyer et al 1979). However, the present narrow and discontinuous floodplains of these rivers and their large
channels that filled relatively rarely raised questions about their Holocene and post-European evolution. The possibility that channels were recently incised into the surrounding alluvial plains (Dury et al 1963) led Woodyer (1968) to base his estimates of the channel-forming discharge and its recurrence interval on stages below the natural banktop, a practice that continues to be recommended by Pilgrim and Doran (1987). Whether this inferred incision was a result of European land use practices or was related to Holocene climate change was not resolved (Dury et al 1963).

Investigations into the coastal rivers of New South Wales showed that their hydrologic and geomorphic characteristics differed in many ways from rivers described in North America and Europe, particularly with respect to their bankfull return periods, which were longer than average (Pickup and Warner 1976), and their floodplain geomorphology, which showed features that were routinely shaped by floods that would be considered catastrophic events elsewhere (Pickup and Warner 1976, Nanson 1986, Erskine 1986, 1999). The question of whether these features are natural or the result of post-European changes in vegetation and run-off characteristics was raised for coastal rivers by Brooks and Brierly (1997). On some alluvial reaches of the Lachlan downstream from Cowra, distinctive floodplain features had been observed that suggested that geomorphic evidence for high variability found in higher gradient streams east of the Great Divide may exist in the Lachlan, in this area. Thus, as a basis for comparing the present and Late Quaternary fluvial systems of the Lachlan, it is necessary first to identify the processes of the present floodplain and channels.

1.2 The study reach

The Lachlan Valley covers a broad swathe across some 400 km of central New South Wales (Fig. 2.1). A detailed geomorphological description of the entire valley was impractical, therefore the study reach was limited to the area between Cowra, at the start of the alluvial valley, and Kiacatoo, where the anabranching channels rejoin for a short distance before breaking out into anabranches and distributary channels further downstream. Thus the study
area covers the principal alluvial reaches of the Lachlan Valley, including the confined, single channel reach containing alluvial terraces from Cowra to Gooloogong, the unconfined, single channel reach from Gooloogong to Cadow, and the unconfined, anabranching reach from Cadow to Kiacatoo. Investigation of the Lachlan Valley palaeochannels was limited to surface or shallow buried palaeochannels that could be described in some detail from aerial photographs, and where segments of their upper and lower reaches could be recognised in the study reach.

1.3 Methods

Fieldwork in the Lachlan Valley was carried out over approximately four months in total, including time spent assembling streamflow records from the regional hydrology office of the Department of Land and Water Conservation (DLWC) at Forbes as well as from the central office at Parramatta. While some records had been entered into the DLWC database and were available on computer, many had to be photocopied and even handcopied from the original, daily cards sent by post to Sydney from remote locations along the Lachlan River from 1890 to around 1930.

Rates of recent channel activity were gauged from early maps, aerial photographs, and from estimates of the age of River Red Gums (*Eucalyptus camaldulensis*) growing on inner bank positions, normally the youngest fluvial sediment in laterally migrating rivers. Size-age relationships for this species have proved difficult to study owing to irregularities in their tree ring development (Dr. J. Banks, pers.comm.), but the oldest individuals may live more than 500 years (Jacobs 1955, Gill 1971).

Sediment analysis to $4\phi$ ($63\mu$m) was carried out using conventional sieves at half phi intervals, and the finer fraction ($<63\mu$m pan residue) was analysed using hydrometer techniques. The Quaternary Dating Research Centre at ANU gave access to radiocarbon dating, but the inorganic sediments filling and transported by the older palaeochannels defied the best attempts to find dateable
material. However, radiocarbon dating techniques were used to date sediments in younger palaeochannels and the modern channel.

Optically stimulated luminescence (OSL) dating offers the best opportunity to date fluvial sediments in the Australian context because of low organic contents of the coarse, fluvial sediments precluding radiocarbon dating, but also because of the “bright”, radiation-dose sensitive characteristics of Australian quartz grains (Dr. Nigel Spooner, pers. comm.). Luminescence ages are also more closely related to the depositional event, in contrast to preserved charcoal, which may have been derived from portions of trees that grew several hundred years before the depositional event. However, the backlog of samples in the one-man-run OSL lab at ANU meant that analysis of only two samples was possible.

Reconstructions of palaeochannel cross-sectional area were encouraged by the work of Erskine et al (1992) and Rotnicki (1983), which showed that infilled cut-offs in meandering rivers accurately preserve the original channel morphology. Rotnicki’s (1983) reconstructions of bankfull discharge based on cross-sectional area and velocities derived from a modified Chezy equation were tested on alluvial cut-offs on the Murrumbidgee River by Page (1994), who showed that they estimated bankfull discharges to within 20% of present flows. This approach appeared to have advantages over the more commonly used empirical relationships between width or meander wavelength and bankfull discharge (e.g. Dury 1976), which have been subject to uncertainties resulting from differences in measurement methods and erosional degradation of the channel.

Transects across palaeochannel sections were drilled from a truck mounted Edson 360 Versdrill top drive rotary rig with solid augers. The decision to use solid augers rather than extracting continuous cores was made because of the need for numerous drillholes from several transects in order to reconstruct a representative number of channel cross-sections in upstream and downstream locations. Evidence of sedimentary structures and
uncontaminated sediment samples was available, at least for bank and point bar sediments, from bank exposures in the present channel.

1.4 Measures

River discharges are given in m$^3$s$^{-1}$, converted from ft$^3$s$^{-1}$ where necessary, except where larger discharges or volumes made the use of megalitres (Ml) or gigalitres (Gl) more practicable. Channel morphology is expressed as bankfull width and depth based on the natural banktop, i.e. the intersection between the channel and the floodplain, although mean depth was used for hydraulic geometry relationships. Downstream channel and valley gradients are expressed as ratios (1 in 2000) in the text and as numbers (0.0005) in the tables. Ages refer to calendar years or thermoluminesce ages unless suffixed with years before present (BP) for radiocarbon years (uncalibrated). Calibration of radiocarbon years was performed using the OxCal calibration program, version 3.5 (Bronk Ramsey 2000), using an offset of 24±3 years, as recommended by Stuiver et al (1998) and are expressed as a range (95% probability) in years calBP.

1.5 Thesis layout

Chapter Two describes the physiography of the Lachlan basin including its geology and Tertiary evolution and includes a brief description of the geomorphology and hydrology of the present river system from the beginning of the alluvial plains near Cowra to the distributary channels on the plains west of Hillston. Alluvial terraces between Wyangala to Cowra are also described. The present climate and its influence on streamflow at Cowra are examined, with some consideration given to changes in streamflow and precipitation over approximately the last 100 years. The chapter concludes with a brief account of reported changes to the geomorphology and vegetation of the upper catchment and to the river downstream from Wyangala.

Chapter Three looks in more detail at the Cowra region, including the alluvial terraces between Cowra and Gooloogong, the streamflow records, which cover the periods prior to and following river regulation. The unusual floodplain
morphology and sediments are described in detail for separate reaches downstream from Cowra and their relationship to the flood history is examined. Changes to the floodplain are investigated over the historical period and late Holocene times.

In Chapter Four, the modern river geomorphology is described for single channel and anabranching reaches between Gooloogong and Kiacatoo, and downstream trends in flow and channel morphology are analysed from Wyangala to Booligal. Surveyed cross-sections in these two reaches, and gauging stations downstream provide the data for hydraulic geometry relationships for the Lachlan. An additional data set based on data from the Murray-Darling basin allowed regional hydraulic geometry relationships to be constructed and compared to similar relationships developed elsewhere around the world.

Chapter Five describes the palaeochannel systems of the Lachlan Valley, including sub-surface data obtained from drilling and establishes a skeleton chronology for the consecutive fluvial phases, and compares them to similar fluvial histories developed along the Murrumbidgee, Murray and Darling rivers. Some discussion and conclusions to the thesis are provided in Chapter Six.
### CHAPTER TWO
#### Background to the Study Area

#### 2.1 Introduction

The Lachlan River is a lengthy waterway within of the Murray-Darling basin, located between the Murrumbidgee and the Macquarie rivers. Its catchment of approximately 85,000 km$^2$ spans most of central New South Wales (Fig. 2.1). The river rises in swampy plains near the Great Divide and flows north through increasingly rugged gorges to meet its major tributary, the Abercrombie River. Here it turns west and flows another 370 km through the wide alluvial plains of the Lachlan Valley. At Willandra, the Lachlan enters the Riverine Plain and flows south to join the Murrumbidgee River. The river only reaches the Murrumbidgee during larger floods, approximately every 5-7 years (O'Brien and Burne 1994). In all other years the Lachlan is a terminal river, dissipating near Oxley in the Great Cumbung Swamp. European settlement in the basin began in the 1830s and the basin's population today is close to 100,000 (DLWC 1989). No major urban centres are located within the catchment although there are several small towns in the east of the basin and along the Lachlan River. The catchment has been extensively cleared for agriculture, especially in the valleys. The alluvial floodplains in particular are utilised for beef, lamb and wool production and for irrigated crops such as commercial vegetables, wine grapes and lucerne upstream from Condobolin.

#### 2.2 Geology

The rocks of the upper catchment form part of the south eastern Australian highlands west of the Great Divide. Here they are dominantly composed of Palaeozoic sequences of the Lachlan Fold Belt (Fig 2.2). Above Wyangala, Ordovician metasediments and Devonian granites underlie most of the gently undulating tableland country at 600-800 metres above sea level. The metasediments are extensively folded and faulted along a north-south axis. Smaller outcrops of Silurian and Devonian volcanics, mostly porphyry, andesite and rhyolite, make up some of the rugged, higher hills over 1000 metres along the Abercrombie River. Remnants of Tertiary basalt
Fig. 2.1 The Lachlan river catchment and its position within the Murray-Darling basin (inset) showing ephemeral wetlands (shaded) within area inundated by floods (dashed line). Modified from DLWC (1989).
Fig. 2.2 Geology of the Lachlan Valley upstream of Jemalong Weir. Modified from Williamson (1986).
flows have preserved the pre-Tertiary drainage pattern in many places throughout the upper catchment and are now hilltop residuals that sit 5-30 metres above the modern streams (Bishop et al 1985). A larger area of Tertiary volcanics associated with the Toogong basalt is found around Mt Canoblas on the basin's northern margin (Fig. 2.2). At 1396 metres, the remains of this mid-Miocene volcano, K/Ar dated at 12.5 Ma (Wellman and McDougall 1974), are now the highest peak in the catchment.

Westward from Cowra, north-south trending bedrock ridges are dominantly composed of Devonian siltstone, sandstone and shale. These gradually decrease in elevation westward and are separated by broad valleys filled with increasing depths of alluvium. Ridges run perpendicular to the present drainage system and sit 200-300 metres above the alluvial plains. The Lachlan runs westward through one of several gaps cut through the ridges, the westernmost of which crosses the plain at Willandra Weir.

The oldest unconsolidated alluvial deposits in the Lachlan Valley downstream from Wyangala have been provisionally named the Glen Logan Gravels (Williamson 1986) and are visible only in isolated remnants either capping or flanking bedrock hills in elevated positions. They have been mapped around Cowra where they conform closely to the 300 metre contour, 25 metres above the river bed, and extend as far west as Bogan Gate (Chan and Goldrick 1995). They consist of coarse, well-rounded quartz gravel, mostly 3 cm in diameter, in a reddish-brown silty matrix. A Miocene age has been assumed for the deposit (Williamson 1986). The eroded remnants of the Glen Logan Gravels are thought to be the remains of a more extensive formation that provided the source material for the younger alluvial fill of the valley below.

The alluvial deposits of the Lachlan Valley between Wyangala and Jemalong has been divided into the Lachlan and Cowra Formations (Williamson 1986). The Lachlan Formation occupies the base of the valley and consists of interbedded and inter-lensed grey to off-white sand and rounded, medium to coarse gravel with brown, yellow and grey clays. The sands and gravels are almost entirely comprised of quartz with very small quantities of chert and jasper. The clays are either variegated or
carbonaceous. The pollen assemblage preserved in the carbonaceous clay beds and occasional wood fragments of *Podocarpus* conifers encountered in the sands and gravels of the Lachlan Formation suggests that its base may be mid-Miocene in age (Martin 1987). Age relationships between sediments of the Glen Logan Gravels and Lachlan Formation are obscure.

The Lachlan Formation is unconformably overlain by the Cowra Formation, comprised of moderately well sorted lithic sand and gravel interbedded with clay. The clays are dominantly brown, and the sands and gravels include lithics of the more resistant rock types in the catchment. Pollen is not well preserved in this unit but points to a Pleistocene age (Martin 1987). Both the Lachlan and Cowra Formations are horizontally bedded and are marked by an erosional hiatus at their surface; both units are assumed to have been thicker in the past. The combined depth of the Lachlan and Cowra Formations 6 km upstream of Cowra is around 40 metres, increasing to 130 metres at Forbes. By Hillston, at the western end of the Lachlan Valley, the alluvium varies between 100 metres and 170 metres in thickness (Williamson, 1986).

To the west of Hillston, the alluvial sediments of the Lachlan Valley pass laterally into the extensive sedimentary sequences of the Riverine Plain, which are up to 400 metres thick in the lower Lachlan. The oldest sediments are the Renmark Group, up to 300m of fluvio-deltaic sediments which sit on a pre-Cainozoic basement. These sediments were marginal to the marine sequences of the southern Murray Basin, which was repeatedly inundated by shallow, epicontinental seas throughout the Tertiary (Brown and Stephenson 1986). The Renmark Group is overlain by up to 60 metres of fluvio-lacustrine deposits (Calivil Formation) laid down from the late Miocene. Another fluvio-lacustrine unit (Shepparton Formation) was deposited after the final marine transgression, which occurred around 4-2 Ma, and deposition continued throughout the Quaternary. Quaternary dunefields, last mobilised 12-20,000 years ago, provide a thin cover of sand over the extreme western edge of the basin although smaller, locally sourced, fluvial dunes and lunettes tend to be more common (Wasson 1983, Bowler and Wasson 1983). In the Holocene, fluvial activity became limited to the margins of the major rivers systems. The longevity of shallow wetland
depressions such as the Great Cumbung Swamp points to low sedimentation rates in the river's lower reaches (O'Brien and Burne 1994).

2.3 Topography and drainage

Basin topography

The basin has an elongated form with a total length of 550 km, giving an elongation ratio of 0.53, calculated as the $A^{10}/L$ (Fig. 2.1). The total basin relief from Mt Canoblas to the Murrumbidgee is 1318 metres; however, the river has a total fall of only 680 m.

The eastern catchment boundary forms part of the Great Divide, which extends along the entire eastern side of Australia. To the north-west, the Canobolas Divide separates the Murray from the Darling catchments, and a series of dry valleys and low gradient plains to the south divide the Lachlan and the Murrumbidgee River basins. Most of the runoff and sediment is derived from its small highland catchment, roughly one-fifth of its total area, approximately 18,700 km². Four major tributaries rise from this area, namely the Abercrombie, Belubula and Boorowa Rivers and Mandagery Creek. After leaving the highlands, the Lachlan has no permanent tributaries. The channel contracts with distance downstream of Forbes until, at Hillston, its capacity is only 16% that at Cowra.

Most of the higher country is located upstream of Cowra and in the Abercrombie catchment where the ranges are steep to rugged, the streams have incised deeply into gorges or deep valleys, some of which still possess areas of native forest. More mountainous areas are covered by tall open forest dominated by *Eucalyptus* species with an understorey of *Acacia* and other sclerophyllous shrubs. Poorer soils on the hill tops support open forests of red stringybark (*Eucalyptus macrorhyncha*) with white box (*E. albens*) at higher altitudes. The streams typically have sandy and pebbly beds and fine-medium sandy channel banks. Along the upper Lachlan and Boorowa catchments the country is gently undulating with scattered savannah woodland and areas of grassland, which some of the first explorers observed to have been recently fired by Aborigines (Craze and Marriot 1988). The streams flow in broad open valleys with gentle down-valley gradients. Most smaller streams were probably chains of ponds
before extensive clearing began, with incised channels found only in the deep valleys and more mountainous terrain (Eyles 1977).

The drainage pattern is essentially dendritic with a rectangular appearance in places where the modern westerly courses of the trunk streams, the Abercrombie, the Belubula and the Lachlan downstream of Wyangala, intersect with the north-south directions pursued by the smaller and headwater streams. The valleys of these streams are thought to represent the remains of northerly, Mesozoic drainage into the Surat Basin before being re-directed to the west soon after the development of the Murray Basin in the Palaeocene (Gibson and Chan 1988, Ollier and Pain 1994).

The western slopes below Cowra are characterised by low bedrock hills flanked by extensive low angle, colluvial-mantled pediments and alluvial fans adjacent to, and grading into the higher alluvial terraces of the Lachlan, Back Creek, Belubula and Mandagery Creek valleys (Chan 1999). Medium open forest of red ironbark (E. sideroxylon) and black cypress pine (Callitris endlicheri) appears on the ridges with grey box (E. wooliana) - yellow box (E. melliodora) open woodland on the higher terraces and pediments.

**Floodplain and terraces above Cowra**

A significant alluvial floodplain has developed on the Lachlan River beginning about 13 kilometres upstream from Cowra. From here to Wyangala, some 17 kilometres further upstream, the bed of the river is incised into granitic bedrock. Terraces have formed within large, entrenched valley meanders with a wavelength around 4000 metres and a sinuosity (measured as the ratio of channel length to valley length) of 1.5 (Fig. 2.3). Williamson (1986) surveyed and described several "erosion terraces" about 5 kilometres upstream from Cowra (Fig. 2.3, section 1) and up to five terraces have been traced between Cowra and Wyangala at the junction of the Lachlan and Abercrombie Rivers (Bishop and Brown 1992).
The highest two terraces are alluvial terraces formed in sediments of the Cowra Formation at 60 metres and 53 metres above the river bed (Fig. 2.4). Some of their surfaces possess scattered pebbles and cobbles although they are chiefly recognisable by their stepped morphology. The next terrace, roughly 47 metres above the river bed, is underlain by up to one metre of quartz pebbles and cobbles and occasionally basalt in a finer matrix (Bishop and Brown 1992). The lowest two terraces are alluvial surfaces at 29 and 17 metres above the river and have been described by Rutherfurd et al (1995). The higher of these, the "Red terrace", is underlain by 20 metres of gravel, sand and clays of the Cowra Formation. The lower "Brown terrace" is clearly inset into the sediments of the Cowra Formation and is underlain by 15 metres of very fine to fine sand, deposited in fining-upwards, 1-2 metre thick beds in convex-up drapes (Fig. 2.5). The lowest two terraces are paired across the valley and converge together downstream. Throughout this thesis, the terraces that can be traced above Cowra to the dam wall at
Fig. 2.4 Schematic section of the terrace sequence above Cowra. A typical vertical scale is shown on the left. $^{14}$C and TL-dated sequence through the Brown terrace is shown in Fig. 2.5. Modified from Williamson (1986).

Fig. 2.5 Eroded section of Brown terrace 1 km downstream from Wyangala dam, from Rutherford et al. (1995).
Wyangala are named in descending order the Newham, Cudgelo, Kember, Red and Brown terraces.

The terraces between Wyangala and Cowra have not been extensively mapped or correlated along the valley. The ages on the upper three terraces are unknown but clearly post-date the mid-Miocene basalt caps (Bishop and Brown 1992). A sample collected by Dr. Goldrick from the Red terrace near Wyangala and analysed using thermoluminescence techniques returned a saturated (minimum) age of 42,000 years (Goldrick, pers.comm. 1997). Rutherfurd et al (1995) reported five TL and ¹⁴C samples analysed from fine sand beds on the Brown terrace, which yielded ages ranging from 21,000 (TL) to 2,600 years BP, in correct stratigraphic order (Fig. 2.5).

**Lachlan channels below Cowra**

At Cowra, the Lachlan emerges from its gorge into a wide alluviated valley where it intersects with the Back Creek valley, also deeply alluviated. Downstream to Gooloogong, the valley is constrained by bedrock ridges of Devonian metasediment and has an average width of five kilometres. At this point the river maintains a single channel thread of low sinuosity except where it is ingrown within larger, palaeo-meanders. In cross-section, the channel is box-shaped with a width-depth ratio of 13, decreasing to 7 at Gooloogong. The channel bed is composed of medium to coarse sand and fine pebbles within steep banks of fine sand and silt. The floodplain is an irregular surface with deep scours, chutes, potholes roughly two metres below the lowest terrace. River red gum (*E. camaldulensis*) and river she-oak (*Casuarina cunninghamiana*) dominate the river bank and uncleared parts of the floodplain. The average gradient from Cowra to Gooloogong measured from topographic maps and surveyed channel sections is 1 in 2000.

A few kilometres upstream of the junction with its last substantial tributary, Mandagery Creek, near Eugowra, the river enters the extensive alluvial plains of the Lachlan Valley (Fig 2.1). Downstream of this point the terraces grade gradually toward the floodplain and the channel gradient decreases to 1 in 5000. Downstream of Mandagery Creek, all tributaries are ephemeral and enter the river via anabranches connected to the modern
channel network during medium to high flows. South of the river on the western side of broad valleys, tributaries terminate in expansive, shallow semi-permanent lakes or wetlands, typically surrounded by reed beds (*Phragmites australis*) with small areas of cumbungi (*Typha* sp.), *Azolla* and spikerush. Wetland margins support river red gum forest intermingled with black box (*Eucalyptus largiflorens*) and lignum (*Muehlenbeckia cunninghamii*) swamp. Fluvial lakes in the Lachlan Valley lack the distinctive sandy lunettes of the Murrumbidgee and Murray but clay lunettes up to 0.5 metres in height accentuate their eastern shorelines. Several of these lakes have been regulated and hold a constant water supply, but most are dry at least 50% of the time.

Low rates of lateral migration and low sediment loads have resulted in the preservation of several generations of palaeochannels after repeated anabranching and avulsion, or as meander cutoffs. Most of these are clearly visible as surface palaeochannels on aerial photographs and as swampy depressions on the ground. Downstream of Gooloogong the main channel is narrow and deep with a width-depth ratio between 5.0 and 6.0. The calibre and quantity of coarse bedload in the channel bed decreases downstream although erosion into older palaeochannel sediments provides local sources of sand and some gravel. The banks are composed almost entirely of silt and clay and may be partially cemented. During low flow the river maintains a single thread but is highly sinuous and pursues an often tortuous course around inherited meander forms where sinuosity can be as high as 3.5. Meander cutoffs are rare but several over-embellished bends have recently been abandoned through avulsion of the main channel. Rates of lateral migration are extremely slow, perhaps 3% of channel width per century, and the river is regarded as essentially stable (Kelly 1971). During higher flows, palaeochannels of various morphologies and ages function as distributaries or flood channels. Kelly (1971) also identified a system of "floodways" not associated with the palaeochannel networks. These floodways are one of the unusual features of the plain and were attributed by Kelly (1971) to the variable frequency and duration of high level flooding compared to the regularly snow-fed rivers of the Riverine Plain. The regular occurrence of large floods, which even today can exceed the capacity of Wyangala dam, has resulted in localised depositional activity along the
major floodways as well as within the main channel (Kelly 1971). A significant proportion of high level floodwaters is directed into large areas of internal drainage such as Lakes Cowal and Nerang Cowal and the Bland Plain (Fig. 2.1). Smaller areas of internal drainage also occur between elevated, bifurcating palaeochannels. After a flood, water may remain standing in depressions and lake systems for several months or years.

At Condobolin and Euabalong, the river changes into a wide and complex anabranching network on plains that have the lowest gradients in the basin (Fig. 2.1). Downstream declivity is as little as 1 in 30,000 (0.000033) and channel gradients decline to 1 in 66,000 (0.000015). Areas of convexity on the Condobolin and Euabalong Plains are apparent on the longitudinal river profile, as measured from the 1:100,000 topographic map series (Fig. 2.6). Like the upstream flood channels, the anabranches are modified palaeochannels morphologically different to the Lachlan and to one another. There is evidence, described in Chapter Five, that palaeochannel systems may have maintained more than one active channel over this reach in the past.

Below Willandra Weir, the Lachlan dissipates its remaining water in distributaries which do not return to the channel, the main stream terminating below Oxley in the Great Cumbung Swamp. A series of distributaries branch out westward toward the Willandra Lakes system (Fig. 2.1). Flow from the Lachlan does not reach the end of these today and the area is mapped as the 'Benabee' drainage basin, unconnected to any major river system. Channel flow does occur but is entirely locally generated (M.A.J. Williams pers. comm. 1998). The distributaries are thought to represent a series of palaeochannels of the Lachlan, which progressively avulsed to its present position to the south of the plain. The oldest west-heading palaeochannel, now Willandra Creek, was thought to have been abandoned in late glacial times (Bowler 1986, Williams et al 1986, Adamson et al 1987).
Fig. 2.6 Longitudinal profile of the Lachlan River above Booligal.
2.4 Palaeogeography

Uplift of the southeast Australian highlands probably commenced in the late Palaeozoic, and was enhanced with further uplift in the late Cretaceous, following rifting along the eastern continental margin (Bishop and Goldrick 2000). Since then, the highlands have been tectonically stable, although isostatic uplift has continued, compensating for mass eroded (Lambeck and Stephenson 1986). Drainage reorganisation has been minimal with low rates of stream incision and denudation (Young 1983, Taylor et al 1985, Young and McDougall 1985). Locally, basalt-dammed streams created large lakes in several areas. On the Lachlan, a Miocene lava drowned the palaeo-Jerawa Creek and Lachlan River valleys near Dalton and is thought to have altered the course of the Lachlan to its present position west of Narawa mountain when it was drained (Bishop 1985). Relief has increased through time as a result of gorge retreat at the highland margins and low rates of downwearing near the Divide (Bishop and Brown 1992).

The upper Lachlan catchment has provided much field evidence that has been used to support models of the Tertiary evolution of the southeast highlands (Bishop 1985, Bishop et al 1985, Lambeck and Stephenson 1986, Bishop and Brown, 1992, Bishop and Goldrick 1992, Goldrick and Bishop 1995). Denudational unloading has apparently caused isostatic uplift in the order of 100 metres since mid-Miocene times, probably at rates of around 5-10 m/Ma, roughly equal to the mean long term denudation rate (Lambeck and Stephenson 1986). The transitional zone in the upper Lachlan Valley between the rising highlands and the subsiding sedimentary basin to the west exhibits a number of features diagnostic of flexure or faulting associated with these movements (Bishop and Brown 1992). These include a prominent 'mountain front' at the tablelands' western boundary flanked with well-developed alluvial fans on west-facing ranges and retreating knickpoints on smaller bedrock streams (Bishop and Goldrick 1992).

Oversteepened palaeo-reaches on the Lachlan River have been recognised from offset Tertiary bedrock valley profiles below the alluvium (Williamson 1986). Offsets of up to 20 metres near Cowra have been
reconstructed from down-valley profiles of the Red and Brown terraces between Wyangala and Gooloogong (Fig. 2.7) (Bishop and Goldrick 2000).

Fig. 2.7 Surveyed heights of terraces above Cowra between Wyangala Dam and the Belubula River, from Bishop and Goldrick (2000).

The Lachlan catchment is believed to have been under dense rainforest vegetation throughout the lower to middle Tertiary (Martin 1987, 1991) with abundant *Nothofagus* ('brassii' group) and gymnosperms indicating a relatively high annual rainfall. In the late Oligocene and mid-Miocene, the character of the vegetation changed to one dominated by Myrtaceae species with *Acacia* and *Nothofagus* in a mosaic of rainforest, wet sclerophyll and dry sclerophyll forest, reflecting more seasonal rainfall and a higher frequency of bushfires. A brief return to closed forest in the Pliocene was followed by a transition to drier, sclerophyll communities while rainforest elements dwindled and become restricted to moist gullies. The transition to the Pleistocene is marked by the spread of Myrtaceae and Casuarinaceae woodland and increasing areas of grassland (Martin 1987, 1991).

Although most of the upper Lachlan Valley was too remote from the coast for changing sea levels to have induced any significant vegetation change related to local climate, its lower reaches would have been susceptible to increasingly continental climates during the low sea level
stands in the Oligocene and late Miocene. In the upper Lachlan, lower sea levels and higher temperatures during the late Miocene are thought to have induced widespread erosion with subsequent fill of the valley with younger sediments (Martin 1987).

2.5 Climate and streamflow

At 34°S, the Lachlan basin experiences a temperate climate. A Koppen classification of Cfb (marine) and Cfa (humid subtropical) applies to the highlands and western plains respectively, both describing moist, mid-latitude climates with mild winters. Meteorological data used in this and later chapters were supplied by Bureau of Meteorology (BM) (1998) from archived records in Canberra. Average daily maximum and minimum temperatures at Boorowa in the tablelands range from 28.6°C to 12.2°C in summer and 12.6°C to 0.9°C in winter. Further west at Hillston, temperatures increase to 32.3°C to 12.1°C in summer and 15.7°C to 4.7°C in winter. Frosts are common on the tablelands in winter and occur occasionally on the western plains although frequencies decline westward from an average of 80 each year in the highlands to 10 in the west of the basin (DLWC 1989).

The catchment is overwhelmingly rainfed; however, light snowfalls are common above 900 metres in winter. These rarely exceed a few millimetres although more than 300mm has fallen in a 24 hour period at higher altitudes (DLWC 1989). In the tablelands and slopes above 250 metres elevation, annual rainfall averages 650 mm, almost evenly distributed throughout the year. At higher elevations, rainfall increases with altitude. The upper Abercrombie receives the highest average annual precipitation, over 900 mm (Fig. 2.8). On the plains, average annual rainfall decreases rapidly with distance inland, from a mean of 520 mm at Forbes to 300 mm at Oxley.

The climate of the catchment in winter is dominated by the cool southern maritime air mass and sub-polar belt of low pressure centred to south of the basin (Linacre and Hobbs 1977). The prevailing winds are from
Fig. 2.8 Climate of the Lachlan basin showing isoheyts and evaporation, modified from DLWC (1989).
the west and frontal systems embedded in low pressure troughs sweep through the basin regularly from west to east, perhaps once a week, providing most of the winter rainfall. Rainfall intensity during individual events has not been well documented but up to 100 mm has fallen in a 24 hour period (Bureau of Meteorology 1998). In summer, the rain-bearing westerlies are located to the south of the continent and the region is dominated by the mid-latitude anti-cyclone and the tropical continental air mass. The winds swing around to the east and south-east as the Trades bring moist maritime air in from the coast. Precipitation derived from this source declines rapidly west of the Dividing Range. Local convective activity in summer following intense heating of the land surface produces little significant rainfall even in the highlands and often only "dry" thunderstorms further west (Linacre and Hobbs 1977).

Rainfall in the eastern parts of the basin is distributed almost evenly throughout the year although there is a slight rainfall peak in winter. At Cowra the number of rain days each month increases from an average of 6 in summer to 10 in winter. The coefficient of variation of total annual precipitation (Cv, measured as the standard deviation of annual rainfall divided by the mean) is only 0.31 at Cowra, but variability increases further west (DLWC 1989). Annual precipitation totals can vary substantially; at Cowra, the lowest annual rainfall was measured as 189 mm in 1919 and the highest at 1098 mm in 1950. On a monthly basis, precipitation is significantly more variable during summer, with Cv peaking in February at Cowra, at 1.04 and falling to 0.52 in August.

The following summary is based on data reported by Bureau of Meteorology (1998) and fully described in Chapter Three. Annually, potential evaporation exceeds precipitation throughout the catchment. At Cowra, 380 metres above sea level, mean annual evaporation averaged 1360 mm from 1965-1998, more than twice the annual rainfall for the same period. At Hillston, this ratio increases to 5.0 (mean annual evaporation 1825 mm, precipitation 35 mm). At Cowra, the mean monthly P-E index remains negative for eight months of the year, from September to April (Fig. 2.9). During these months, the runoff generated (measured here as the
Fig. 2.9 (a) mean monthly precipitation (dark hatched) and evaporation (light hatched) at Cowra and (b) monthly runoff coefficient calculated from gauging at Cowra and rainfall stations at Gunning, Boorowa and Cowra.
proportion of average rainfall in the upper catchment which ends up as streamflow at Cowra) is extremely low and averages only 3% during the summer months. During winter, Figure 2.9 shows that runoff represents up to 23% of precipitation and for the months of July and August the Lachlan upstream of Cowra becomes quite an efficient catchment (sensu Bowler 1978). From May to August, higher effective precipitation results in a strongly seasonal streamflow throughout the tablelands and higher uplands. 1st and 2nd order streams may dry out in summer although the larger streams only cease to flow during major droughts. The proportion of no-flow from 1893-1934 at Cowra before river regulation in 1935 was 6% and increases to 25% further downstream at Booheroi Weir.

The large range in annual precipitation as well as high runoff variability has regularly produced both floods and droughts. Periods of prolonged and heavy rainfall can occur at any time of year but are more likely to produce major floods in late winter and early spring when evaporation levels are lower and repeated rainfalls arising from the passage of several fronts will saturate the catchment. Most large floods at Cowra have occurred between June and October when the average monthly water yields are also greatest (Fig. 2.10). There has never been a major flood recorded in the upper Lachlan Valley in the months from December to March.

Floods on the upper and middle Lachlan Valley are usually most severe when the catchments of all four major tributaries receive heavy downpours. However, a significant storm on any one tributary can cause a major flood downstream. The 1990 flood at Forbes, which was the largest in that town's history, was produced by significant rainfall only in the Belubula catchment. Further upstream at Cowra, the 1990 flood was a modest event with a return period of only four years on the annual series.

The 1974 flood, which peaked at almost 3000 m³s⁻¹ at Cowra, with a return period of 25 years, provides a good example of the passage of a major flood from the hills to the lower plains (Fig. 2.11). A significant downpour overnight on 4 September was not followed by any subsequent heavy falls of
Fig. 2.10 (a) mean monthly water yield at Cowra and precipitation in the upper Lachlan prior to river regulation, 1893-1934, and (b) mean monthly water yield and precipitation following river regulation, 1935-1995. Numbers in (a) show the number of large floods in each month since 1844 (listed in Tab. 3.1 excluding 1885 for which the month is unknown).
rain until several weeks later. 49 mm rainfall fell both at Boorowa and Cowra although the extent of the rainfall over the upper catchment is not known. The Lachlan peaked at Cowra at 13.8 m on the gauge roughly 36 hours later and after 2-3 days the peak had reached Forbes. By the time it had reached Willandra, the flood peak had attenuated significantly, reaching only 3 metres on the gauge and was barely registered further downstream at Hillston and Booligal. The floodwaters took approximately 25 days to pass between Nanami and Willandra, indicating that the flood peak travelled at velocities of roughly $0.12 \text{ m/s}^1$ (0.46 km/hour) through the plains.

The attenuation of floodwaters is due to a number of factors, including evaporation of shallow and long-standing floodwaters on the extensive low-gradient plains and distribution into multiple channels. The width of the floodplain at Forbes is 3-4 kilometres, with several additional flood channels north and south of the town. Downstream from Willandra, a large flood may spread out to inundate the entire lower catchment, an area exceeding $10,000 \text{ km}^2$ (Fig. 2.1). Water also dissipates into numerous lagoons, anabranches, wetlands and lakes. Significant losses to the deep coarse-grained alluvium are also expected and have been noticed on the lower Lachlan, where the water has "lower than expected salinity levels", according to O'Brien and Burne (1994).

The amount of floodwater passing through Cowra from 6-21 September approximated 610,000 Ml, or roughly 20% of the annual water yield. Taken together with the other two floods that year, in July and August, overbank flows accounted for over 40% of the annual water yield for 1974.

Secular changes in precipitation

Changes in the rainfall regime this century have been noticed in several areas of Australia (Pittock 1975) and are reflected in the flood frequency and stage heights in NSW coastal rivers (Bell and Erskine 1981) producing both "drought- and flood-dominated regimes" (Warner 1987). Drought-dominated conditions prevailed during the early part of the century from 1900-1945, followed by a period of increased annual rainfall of 10-30% from 1941 to 1974 in central and eastern New South Wales (Pittock 1975,
Fig. 2.11 Hydrographs of 4 September, 1974 at major Lachlan gauging stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>1894-1934</th>
<th>1945-1994</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cowra</td>
<td>1.02</td>
<td>0.94</td>
</tr>
<tr>
<td>Forbes</td>
<td>1.04</td>
<td>1.02</td>
</tr>
<tr>
<td>Booheroi</td>
<td>-</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Tab. 2.1 Coefficient of variability of annual daily flows before and following river regulation.
Cornish 1977). During a similar period (1947-1985) substantial increases in annual streamflow of around 200% compared to the period 1901-1946 have been demonstrated for middle reaches of the Macquarie, Murrumbidgee and Lachlan Rivers (Riley 1988).

Rainfall data for the years 1886-1998 are available from Boorowa and Gunning near the headwaters of the upper Lachlan. These were combined to give an average upper catchment precipitation, and were then combined with data from two stations at Cowra. (There is no comparable record from the Abercrombie catchment.) The records from Cowra PO (1896-1905) and Cowra AGRS (1906-1998) were combined as the stations are only two kilometres apart. Changes in the average annual precipitation were plotted as cumulative deviations from the mean, calculated as the annual precipitation minus average precipitation divided by the average. The cumulative totals were then plotted against each year, subtracting 1.0 at each step (Fig. 2.12A). The record of lake level fluctuations at Lake George also provides an indication of average rainfall conditions for the period between 1886 and 1998 (Fig. 2.12C). Lake George is a closed lake basin of some 795 km² that straddles the Great Divide near the southeastern head of the Lachlan catchment. A close correspondence between lake level fluctuations and rainfall gauges located at Bungendore and Canberra has been demonstrated (Singh and Jennings 1984). The record has been extended by Russell (1886) back to 1820 from historical accounts. Both records can be compared to the annual water yield of the Lachlan River at Cowra (Fig. 2.12B).

Changes in rainfall over the past century in the upper Lachlan accord with general trends elsewhere around New South Wales, discussed by Cornish (1977). The end of last century, from 1886 to 1894, was characterised by higher than average annual rainfall but rainfall started to decline from 1895, earlier than elsewhere in NSW. Water levels in Lake George reached 4.5 metres in 1894 and declined thereafter. There was only one significant flood on the Lachlan, in 1891 and the Centenary Drought in 1887-88 also occurred during this interval. Streamflow for the years
Fig. 2.12 Comparison of various climate records in the upper Lachlan basin for the period 1886-1998. (A) cumulative deviation from mean annual precipitation from Cowra, Boorowa and Gunning stations, (B) annual water yield passing through the Lachlan at Cowra, (C) water levels at Lake George, provided by Australian Geological Survey Organisation (2000) and Russell (1886) in Singh and Jennings (1984).
1893-94 was high. This period was followed by several drier than normal years from 1895-1914, with significant droughts on the Lachlan in 1902 and 1908 and lower than normal streamflow. Lake George remained low or dry during this interval. The total annual rainfall was fairly stable for the years 1915-1937 but declined again during the 1940's. The period 1950-1978 was extremely wet, particularly during the 1950's and 60's. By 1958, Lake George had again risen to 4.5 metres and major floods occurred at Cowra in 1950, 1952, 1960, 1961, 1963 and 1974. From 1978-1998, annual rainfall was nearly stable. There is an apparent increase in the number of large floods in the years of higher than average rainfall, but major flood events have also punctuated the drier periods. It is also interesting that part of the change in annual precipitation between the early and latter part of the century is due to increases in summer rainfall (Cornish 1977).

Australian rivers are noted for their highly variable streamflow, which is significant even after the effect of latitude and greater aridity is taken into account: Australian annual flood series are, on average, about twice as variable as comparable climatic zones on all other continents except South Africa (Finlayson and McMahon 1988). Streamflow variability in the upper Lachlan valley reaches values rarely recorded in sub-humid areas elsewhere around the world (Finlayson and McMahon 1988). McMahon (1978) has noted that the coefficients of variation of annual flows for the central western slopes are extremely high (>1.5), even for Australia. The only other rivers with comparable values occur in the central highlands of southeast Queensland. Average Cv's for Australian rivers with catchments 1,000-10,000 km² in climate zones Cfb and Cfa are 0.87 and 0.92 respectively. Cv's greater than 1.0 are normally only found for rivers in the semi-arid and arid interior (Finlayson and McMahon 1988) and McMahon (1978) suggested that such extreme variability may caused by regional orographic effects such as multiple rainshadow barriers, which are occasionally penetrated by severe storms. The Cv of daily flows on the Lachlan at Cowra, calculated here for the period 1894-1934 is 1.02, and decreases slightly to 0.94 after river regulation (1945-1994) (Tab. 2.1). On the plains, Cv of streamflow at Forbes is close to 1.0 prior to regulation (1.04), and after regulation (1.02). Further downstream at Booberoi, the Cv is higher, and averages 1.07 for the period following regulation (1945-1989). Unusually, the Lachlan does not
exhibit one of the common responses to river regulation, namely a decline in
the variation in annual flows (Petts and Lewin 1979), nor has it reflected the
higher variability seen in other inland NSW rivers after 1945 that has been
attributed to secular changes in rainfall regime (Riley 1988). The dominant
effects of river regulation appear to be a noticeable reduction in the seasonal
variation of streamflow and a shift in the peak monthly water yield from July
to September (Figs 2.9 and 2.10).

Streamflow and ENSO

Secondary effects on the climate of southeastern Australia
significantly include the Southern Oscillation or ENSO (El Nino/Southern
Oscillation), a large-scale pattern of climate fluctuations centred on the
equatorial Pacific, with a cyclicity of between 2-10 years (Allan 1988). The
Southern Oscillation specifically refers to a pressure fluctuation between the
tropical eastern and western Pacific although the term ENSO is now widely
used to describe both atmospheric and oceanic changes associated with the
phenomenon. ENSO enhances the inter-annual climate variability in
Indonesia, northern Australia and South America although correlations
have been made with climatic events around the world (Diaz and Kiladis
1992). Historical accounts of floods and droughts suggest ENSO has
influenced climate in Australia over at least the last 200 years (Nicholls
1988) and has probably been a feature of the environment for a much longer
period (Nicholls 1992). Extreme phases of the Oscillation, termed El Nino
and La Nina, have been linked to major droughts and floods, respectively, in
southeastern Australia, including the Lachlan on the basis of historical
accounts (Williams et al 1986, Adamson et al 1987, Whetton and Baxter
1987).

The influences of ENSO on rainfall in the Australian region have been
winds and decrease in sea surface temperatures north of the continent
during the El Nino phase of the Oscillation reduces the ingress of tropical
moisture into southeast Australia and cuts off a major source of
precipitation in summer. Lower rainfall is accompanied by a higher
incidence of cloudlessness and frosts. A swing to the opposite, La Nina
phase, tends to intensify the ‘normal’ summer pattern. A deep trough of low
pressure dominates northern Australia, intensifying the trade winds and causing more moisture to penetrate further into the continent. Summer rainfall is particularly enhanced over the north east of the continent.

The influence of *La Nina* events on southern winter rainfall is more complex. The high pressure system which normally dominates the continent is weaker and further north and the low pressure systems associated with the westerlies are stronger and extend further north than in normal years. Higher rainfall in the south is a consequence of extensive tropical to midlatitude cloud bands, resulting from convective activity generated by anomalously warm SSTs in the Timor Sea and North West shelf regions and linked to mid-latitude frontal systems which traverse southern Australia at this time (Allan 1991). The existence of complex and lagged relationships between ENSO and winter rainfall in southern Australia have been investigated but are not fully understood (McBride and Nicholls 1983). Nicholls (1984) demonstrated the existence of a negative correlation between northern Australian sea surface temperatures in summer-autumn and the following winter rainfall in eastern Australia. Winter rainfall variability has also been attributed to variations in SST in the western Indian Ocean, which may have little or no relationship to large-scale ENSO patterns (Nicholls 1989).

Both *El Nino* and *La Nina* events typically begin in May and break in April the following year. The most significant correlation patterns over eastern Australia occur in winter-spring and least significant in summer-autumn (McBride and Nicholls 1983). The position of the Lachlan River well south of the zone of dominantly summer rainfall and its normal low summer streamflow means that *La Nina* events may result in greater rainfall over the catchment but will rarely produce large discharges in summer. *La Nina* related floods are most likely to occur in late winter and early spring when the river is already high. Drier, *El Nino* years may further reduce summer river levels but are likely to be less influential during the winter months with the major source of precipitation coming in from the west. Pittock (1975) found a correlation coefficient of 0.35 between mean annual rainfall and the SOI for the years 1941-1970 applied to the Lachlan district. The southern inland rivers including the Lachlan, the Murray and Murrumbidgee Rivers,
therefore, should be less susceptible to ENSO than rivers like the Darling which have their headwaters in areas sensitive to summer rainfall changes.

The gauged streamflow record at Cowra (1893-1995) has been extended by historical records back to 1839 and compared with more extreme phases of the Southern Oscillation (Fig. 2.13). Lachlan flows are derived from streamflow records beginning in 1893 with an interval of missing years from 1906-1910. Streamflow records have been supplemented with historical records that extend back to 1839 from early published accounts, farmers reports, newspapers and water marks on buildings. Flood stage has been converted to peak discharge on the basis of ratings between 1893-1918. Since all historical floods prior to 1893 appear to have exceeded those during the ratings period, the rating curve had to be extrapolated to cover the higher flows, providing only a rough estimate of discharge for these events. The plot of floods during this interval represents the peak discharge of the annual flood. The Southern Oscillation Index (SOI) is the most common measure of the intensity of ENSO, calculated as the pressure difference at mean sea level between Darwin and Papeete, normalised for each calendar month. The SOI covers the period from 1870 to the present (Bureau of Meteorology, 1998). Estimates of the state of the Oscillation in the period 1844-1869 were made on the basis of data from fragmentary records of SST, pressure and the number of rain days at Jakarta (Konnen et al 1998).

Roughly 50% of the significant droughts from 1839-1994 occurred during strong or moderate El Nino events. La Nina conditions prevailed during 6 out of the 19 years of higher water yield, over 1500 gigalitres, accounting for only 32% of flood years. However successive La Nina years during 1920-22 produced no large or even moderately high flows at Cowra. Of the larger flood events (over the 'critical height' of 12.2 at Cowra, after which town flooding commences), 31% occur in strong or moderate La Nina years, 39% when the SOI was normal and 23% of floods occurred during
Fig. 2.13 Peak discharge of annual floods at Cowra, 1893-1994 with major historical floods shown from 1840-1892. The general status of the Southern Oscillation is shown for floods over the critical height at Cowra, at which town flooding commences. SO index from Bureau of Meteorology (1999) and Konnen et al (1998).
El Niño years. Furthermore, inspection of the SOI record and Fig. 2.13 shows La Niña years not distinguished by floods (not shown in Fig. 2.13). Thus, overall, ENSO evidently has little to do with flood variability in the Lachlan.

2.6 Land use

The Lachlan region near Cowra was explored by Evans in 1815 but he, and subsequent explorers, did not think much of the poor grass and boggy ground, and the country remained almost uninhabited by Europeans until 1827. After this time, squatters, the "disciples of self-help", moved west of the Blue Mountains in search of new grazing country and by the end of the 1830's all the land in the Lachlan Valley had been occupied (Craze 1988, Fittler 1988). By the 1860's several small weirs had been constructed along the river by the local landowners and by the 1920's, six major weirs had been established in the larger towns. A major water storage, Wyangala Dam, 30km upstream of Cowra, was completed in 1935 "to augment and assure stock and domestic supplies and to promote the development of closer settlement of the Western and Central Divisions of the State, and only in a secondary capacity to provide for irrigation - in a 'drought-proofing' role" (Bayley 1965). After droughts in the 1940's and 50's, Wyangala Dam was enlarged to a capacity of 1,217,000 ML and work began on Carcoar Dam with a smaller capacity of 36,000 ML. Both storages were completed in 1971. Extensive irrigation in the plains downstream of Forbes was developed after World War II. The alluvial flats are used for sown crops, mainly wheat and lucerne, and to a lesser extent, corn, soybean and wine grapes. The hills and slopes are used only for grazing and some of the more rugged country has been left uncleared. The upper Lachlan Valley is now considered by local farmers to contain some of the most fertile land in New South Wales.

Since the turn of the century, rabbits have become firmly entrenched in the hills along with fox and wild boar. Introduced weeds include golden dodder in the ephemeral floodplain lakes, with St John's Wort, serrated tussock and blackberries in the highlands. The proliferation of introduced European carp and redfin has caused a decline in native fish species (Roberts and Sainty 1996). The widespread clearing of native vegetation has
had a number of effects. Native forest are known to be far more efficient at intercepting and utilising rainfall than introduced crops and pastures; therefore, their replacement increases surface runoff and produces a greater proportion of streamflow (Close 1990). Eyles (1977) documented evidence of increased runoff in the NSW Southern Tablelands, where the natural chain-of-ponds drainage has been almost totally disturbed and replaced with incised channel systems. The replacement of native woodland with shallow rooted pasture and crops has also resulted in rising ground water tables, leading to the salinisation of irrigated and dryland farming land in both the highlands and the western plains. Rises in the water table of tens of metres have been recorded in some areas relatively far from the river, such as near Lake Cowal (DLWC 1989), but this has little effect on flood generation. Salt-affected sites discharge water into the creeks during winter and salty groundwater makes up the base flow during periods of lower streamflow. Today, salinisation is the largest perceived problem affecting the catchment (DLWC 1989).

Downstream from Cowra, most reported changes attributed to European land-use practices are bank steepening and increases in channel width, a decrease in channel depth caused by siltation of the bed, and increasing muddiness of sand banks and loss of bank and aquatic vegetation (Roberts and Sainty 1996). Such changes are attributed by local landowners to the introduction of carp, trampling of banks at stock watering points, widespread tree removal and the continually fluctuating moderate to high water levels of the regulated flow regime. In 1948, the main channel downstream from Wyangala was noted to have suffered soil erosion caused by overstocking and overclearing (Bayley 1965). Minor bank erosion between Cowra and Forbes has also been attributed to water releases from Wyangala causing sudden rises and falls in river levels (DLWC 1997).

Some of the first detailed maps, dating from the 1880's, show minimal or no change in the position of the river. However, Martin (1922) comments on major differences in the channel near Cowra that occurred after 1844. "It is interesting to note that the Lachlan at that time had its bed some ten feet deeper than it now is. There were none of the sandbars that we now view. The bed and its banks were muddy and lined with reeds". Early
photographs of the river at the turn of the century also show a marked absence of riverbank vegetation, especially trees, presumably following their removal to allow easier access for stock. Erosion scours and considerable bank steepening were the obvious result although some reaches still feature the gentler banks characterised in artists' impressions and older photographs of the early Cowra landscape.

Near the major towns, large sand banks in the channel were extensively mined for building materials (Roberts and Sainty 1996) and the remaining sand bars are almost permanently inundated by the higher mean water levels, giving the river a muddier appearance. De-snagging programs involving the removal of fallen trees from the river bed began in 1858. The numerous fallen trees and snags gave the river an eerie and treacherous appearance to the early Europeans and caused drownings during floods as well as preventing river transport during all but the highest flows. The practice has since been discontinued due to adverse impacts on native wildlife and snags have accumulated again in the channel bed. Mining of alluvial sediments is now banned from within the channel banks and the river bank has been almost completely re-vegetated with trees and scrub that is at least fifty years old.
CHAPTER THREE
The Hydrology and Floodplain Deposits of the Lachlan Valley
from Cowra to Gooloogong

3.1 Introduction

The lateral stability of suspended load river systems in the western Murray-Darling basin has long been recognised (Bowler 1978, Taylor and Woodyer 1978, Adamson et al 1987). Nanson and Croke's (1991) classification based on stream power defines these floodplains as CI: laterally stable or slowly laterally migrating, low-energy cohesive floodplains with unit stream power $10^{-60}$ W m$^{-2}$. Their channels contain accreting in-channel benches while their distal floodplains are dominated by overbank sedimentation in the form of low levees and backswamps with a central zone of lateral accretion deposits. In the southern Murray-Darling basin, any geomorphic description of these rivers must also take into account the controlling influence on present-day meander wavelength, slope and sinuosity, and indirectly, on channel capacity, exerted by ancient, much larger meandering channels, which are well-preserved as meander cut-offs and lagoons behind the main river front. Indeed, Gill (1973) regarded the inland-flowing rivers of the Murray basin as geomorphically more interesting for their recent history than for their present manifestation as "mud-lined gutters". Recently, however, studies on modern rivers in the Murray-Darling have been undertaken by Rutherfurd (1991,1994) on the Murray River and by Page (1988) on the Murrumbidgee River.

The coefficient of variability of flows in the Lachlan and similar western NSW rivers is high, as noted in Chapter Two, which raises the question of the role of larger floods in floodplain formation. The importance of large floods to floodplain morphology in high-energy coastal streams in NSW has been recognised by Pickup and Warner (1976) and Nanson (1986), which typically show evidence of localised floodplain stripping and channel avulsion. The geomorphic expression of catastrophic floods on temperate rivers in North America (occurring at intervals $>50$ years) is known from detailed descriptions shortly after the passage of single events (McKee et al 1967, Gupta and Fox 1974, Kesel et al 1974, Gardner 1977). Such
occurrences are considered to be spectacular though geomorphically less effective than more moderate and frequently occurring flows (Wolman and Miller 1960, Wolman and Gerson 1978), and may have little impact on the regional floodplain morphology (Gardner 1977). Exceptions have been found in tropical areas that are subject to frequent, intense monsoonal downpours on a regular basis (Kale et al 1994, Gupta 1995, Rajaguru et al 1995). Occasional large floods significantly modify floodplains in arid and semi-arid areas, where the absence of a low flow regime necessarily produces a floodplain dominated by larger events (Pickup 1991, Bourke 1995). Alluvial, low-gradient, meandering rivers in humid, temperate climates are believed to be unlikely to generate sufficient stream power during large floods to substantially modify their floodplains (Magilligan 1992). However, Baker (1977) points out that climate only provides the potential for catastrophic response; its occurrence is determined by catchment regolith and bedrock properties, resistance of floodplain material, vegetation, and the position of streams in the drainage hierarchy, as well as the flood magnitude and frequency characteristics. These factors are considered in this chapter with respect to the Lachlan River below Cowra, which aims to extend the geomorphologic understanding of Australian suspended-load rivers.

3.2 Flood history

The ferocity and magnitude of Australian floods surprised the early settlers to the Cowra region. Their first taste of the kind of transformation of which the Lachlan River was capable was reported by some of the first farmers in the district in 1844. The river at North Logan, 19 kilometres downstream from Cowra, rose to an estimated stage of 13.7 metres and drowned thousands of livestock. Pastoralists were reassured by the return of more 'normal' conditions for the next 25 years. The years 1839-1869 were, in fact, characterised by a greater than normal frequency of droughts. From 1839-1841, the drought was so complete that there were reported to be only two waterholes along the Lachlan between Cowra and Nanami (Martin 1922). Conditions improved after the 1844 flood but drought broke out again in 1850 when one-third of cattle in the district perished and small crops of wheat failed so that many pastoralists were forced to desert their homes and those who remained grew accustomed to severe droughts every
eight to ten years (Croft 1988). In April 1870, a flood reaching 15.9 metres all but wiped out the infant settlement of Cowra and destroyed the first road bridge across the river, opened earlier that year. This was followed in June of the same year by a flood of nearly the same magnitude. The *Australian Town and Country Journal* of 10 September 1870 reported "alluvial deposits that alike obliterate the ancient and the modern landmarks".

From the Burrowa township down to the junction of that river to the Lachlan, some ten miles above Cowra, not one settlers place has been left...The other branch of the river is in the same state; thirty miles above Cowra and from that down, with one or two exceptions, everything has been carried away, huts, buildings, fences, the country lying altogether ... unenclosed, and in its old natural state, and the inhabitants camped out in the hills.

*Australian Town and County Journal*, 7 May 1870

The town was moved to a higher location and major floods recurred in 1885, 1891, 1900, 1916, and 1925 (Tab. 3.1). The completion of Wyangala Dam in 1935 assured a constant water supply but offered little protection against the larger floods of the 1950's and 60's, particularly since several tributaries above Cowra, including the Boorowa River, remained unregulated. The effects of the 1952 flood on the town and surrounding country were reported by the press in some detail (Fig. 3.1). Graders and heavy rescue equipment were "lifted into the torrent and tossed about like toys" (Cowra Guardian, 20 June). When the waters subsided, main roads remained obstructed by landslips and by scours several feet deep. Several inches of sand had been deposited on the golf course and tennis courts, both located on the lowest terrace, 13 metres above the river's bed. Fig. 3.2 shows the hydrograph for the 1952 flood reconstructed from streamflow records and observations of peak flood stage. Flow peaked at 15.2 metres on the gauge on 18 June and peak flow conditions continued for 11 hours, inundating the lowest terrace to an average depth of 6 metres. Flow remained overbank for 5 days.

### 3.3 Flood frequency and duration

Daily streamflow observations exist for the Lachlan at Cowra for the period from 1893 to the present (with a small break from 1906-1912) with continuous records available after 1970. The record of daily observations on
<table>
<thead>
<tr>
<th>year</th>
<th>month</th>
<th>peak stage (metres)</th>
<th>peak discharge (m³/s)</th>
<th>ARI annual series (years)</th>
<th>ARI partial series (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1870</td>
<td>April</td>
<td>15.9</td>
<td>6720</td>
<td>172</td>
<td>112</td>
</tr>
<tr>
<td>1952</td>
<td>June</td>
<td>15.2</td>
<td>5380</td>
<td>101</td>
<td>103</td>
</tr>
<tr>
<td>1916</td>
<td>October</td>
<td>15.4</td>
<td>4690</td>
<td>63</td>
<td>87</td>
</tr>
<tr>
<td>1900</td>
<td>July</td>
<td>14.2</td>
<td>4160</td>
<td>49</td>
<td>61</td>
</tr>
<tr>
<td>1925</td>
<td>June</td>
<td>14.2</td>
<td>4160</td>
<td>49</td>
<td>61</td>
</tr>
<tr>
<td>1844</td>
<td>October</td>
<td>13.8</td>
<td>3990</td>
<td>43</td>
<td>58</td>
</tr>
<tr>
<td>1974</td>
<td>September</td>
<td>13.8</td>
<td>2950</td>
<td>26</td>
<td>29</td>
</tr>
<tr>
<td>1950</td>
<td>October</td>
<td>13.5</td>
<td>2850</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>1960</td>
<td>August</td>
<td>13.2</td>
<td>2640</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>1891</td>
<td>July</td>
<td>12.8</td>
<td>2240</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>1885</td>
<td>?</td>
<td>12.7</td>
<td>2280</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>1961</td>
<td>November</td>
<td>12.7</td>
<td>1920</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>1963</td>
<td>August</td>
<td>12.7</td>
<td>1920</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

Tab. 3.1 Major floods in the Lachlan Valley at Cowra since settlement above 'critical height' of 12.2 metres (at which town flooding commences). Average recurrence intervals (ARI) from the annual and partial flood series are also given.

Fig. 3.1 Photo of the Lachlan River in flood from Bellvue Hill lookout, June 1952.
flow stage were often supplemented with information on peak flood stage for larger flood events. Flood stage was converted into discharge using ratings curves developed by NSW Department of Land and Water Conservation (DLWC). There is a greater degree of uncertainty associated with the early flood estimates before seasonal ratings curves were developed; a single rating curve was used for the years 1893-1918 with historical records extending the flood record back to 1839 (outlined in Chapter Two).
Flood frequencies were calculated for the period covered by streamflow records from both annual and partial series data. The annual flood series is the highest instantaneous discharge of each year of record although by itself it is considered inadequate for the Australian environment where several flood events may occur in a single year (Pilgrim and Doran 1987). The annual series selects only the largest flood each year and can unduly skew the probability distribution since it can include peak flows in dry years which are not really floods. However, it is easily constructed, gives more accurate estimates of return periods for lower frequency events and provides a basis for comparison with the partial series. A water year beginning in May was chosen, given the seasonal nature of the streamflow, to assure the independence of individual flood events. The annual series of floods was plotted using a Log Pearson III (LPIII) distribution, which has an upper asymptotic limit for negatively skewed data but which has been shown to be the only suitable general distribution for many Australian streams (McMahon and Srikanthan 1981). Ideally, the peak annual discharge is log normally distributed; i.e. such data plot as a straight line on LPIII graphs. Skewed data plot as gentle curves; negative skew as convex-up curves tending to an asymptote. The procedure used for deriving the LPIII curve was that outlined in Pilgrim and Doran (1987) from rank order series of peak annual discharges. LPIII curves were derived separately for the entire period of record (1892-1995) (Fig. 3.3), and for the periods before and following streamflow regulation (1892-1934, 1945-1995) (Fig. 3.4) to assess the effects of regulation on flood flows. For the latter, ten years of record from 1935-1944 while the dam filled, were excluded.

The Cowra station skew value of -0.24 is moderately negative but less than the regional skew of -0.54 calculated for the Murray system (McMahon and Srikanthan 1981)°. The LPIII model with skew of -0.24 gave a very good fit to the annual series although discharges at both low and very high recurrence intervals were over-estimated (Fig. 3.3) When applied to the pre- and post-regulated periods separately, the LPIII curve estimatedlarger floods

°the skew value, \( g \) is calculated as \( g = \frac{N^2 \sum x^3 - 3N \sum x \sum x^2 + 2(\sum x)^3}{N(N-1)(N-2)S^2} \)

where \( N \) is the number of years, \( \sum x, \sum x^2 \) and \( \sum x^3 \) are the sums, squares and cubes of the logs of the discharges, and \( S \) is the standard deviation.
Fig. 3.3 Log Pearson III (LPIII) plot of annual flood series for the Lachlan at Cowra, 1893-1994 (n=115 years) (small solid points) including one historical flood in 1870 (H). Crosses are LPIII model points calculated with skewness coefficient of 0.24, following methods given by Pilgrim and Doran (1987).
Fig. 3.4 LPIII plot of annual flood series for the Lachlan at Cowra, 1893-1934 (solid points) and 1945-1995 (triangles). Crosses are fitted LPIII models points, calculated with skewness coefficients of -0.31 and -0.29 respectively.
adequately but tended to overpredict the magnitude of the smaller floods with an average recurrence interval less than 2 years (Fig. 3.4).

A partial flood series was constructed which covered the entire streamflow record following methods given by Pilgrim and Doran (1987). This precedent is based on the occurrence of every flood above an arbitrary base flow regardless of which year it occurred. The number of floods was chosen to equal the number of years of record in order to exclude low flows from the analysis, which gave 102 floods with a base flow (or minimum flood) of 400 m$^3$s$^{-1}$, approximately two-thirds of bankfull stage. Missing years were excluded except for 1908 where the general drought made a high flow unlikely. Peak monthly flows were used and care was taken that floods in sequential months were independent of one another as far as possible. Normally this requires flood separations of at least ten days on a catchment the size of the Lachlan, as well as an intervening fall to below 25% of the preceding flood peak (Beard 1974). A number of years held four or more floods, namely 1916-17, 1925, 1950, 1952, 1956, 1974. It is interesting to note that most of these years also held a flood which exceeded the critical height at Cowra of 12.1 metres (Tab. 3.1), suggesting that total independence of flood events during the winter months is unlikely. As all significant flows are included and drought years where the largest flows <400 m$^3$s$^{-1}$ are excluded, the partial series produces a better representation of flood distribution for this station. Consideration of the partial series may be essential in an environment in which four significant floods may occur in a single year, especially when consecutive floods may have a greater geomorphic effectiveness on the floodplain than isolated floods with a higher peak discharge, as suggested by Costa and O'Connor (1995) and demonstrated on Australian coastal streams by Nanson (1986).

Although LPIII distributions have been successfully fitted to the partial series in Australian streams, a simple log-linear plot was used here and a smooth curve drawn by eye as recommended by Pilgrim and Doran (1987) (Fig. 3.5). The data do not assume the usual exponential distribution of most partial series flood data; however, the fit of this distribution has not been extensively tested for Australian rivers (Pilgrim and Doran 1987). Recurrence intervals for low and high frequency events derived from both
**Fig. 3.5** Plot of the partial flood series for the Lachlan at Cowra, 1893-1994 (with number of floods chosen to equal the number of years of record). Smooth curve has been fitted by eye following recommendations of Pilgrim and Doran (1987).

<table>
<thead>
<tr>
<th>ARI (years)</th>
<th>AEP (%)</th>
<th>annual series (m³/sec)</th>
<th>partial series (m³/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.053</td>
<td>95</td>
<td>36</td>
<td>436</td>
</tr>
<tr>
<td>1.111</td>
<td>90</td>
<td>62</td>
<td>456</td>
</tr>
<tr>
<td>1.250</td>
<td>80</td>
<td>115</td>
<td>486</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>357</td>
<td>694</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>1026</td>
<td>1171</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
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<td>20</td>
<td>5</td>
<td>2628</td>
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<td>4137</td>
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<td>100</td>
<td>1</td>
<td>5549</td>
<td>4920</td>
</tr>
<tr>
<td>200</td>
<td>0.5</td>
<td>7212</td>
<td>6592</td>
</tr>
</tbody>
</table>

**Tab. 3.2** Comparison of flood discharges on the Lachlan at Cowra from the annual and partial duration series, 1893-1994.
the annual and the partial series are compared in Table 3.2. The recurrence interval of floods on the annual series specifically refers to the average number of years between years in which that flood is exceeded, though it may be exceeded more than once during a given year. On the partial series, the recurrence interval represents the average length of time before a flood of a given magnitude will occur (Laurenson 1987). Table 3.2 shows that according to the partial series, flood discharges with recurrence intervals below five year intervals are substantially larger than estimated by the annual series. This reflects the exclusion of drought years and inclusion of multiple floods within any year in the partial series. The differences between partial series and annual series estimates are not "inconsequential" for events with longer return periods (Langbein 1949), large floods tending to have longer recurrence intervals on the partial series. This is also apparent in relation to larger floods on the Lachlan at Cowra on Tab. 3.1. However, annual series estimates are usually preferred for lower frequency events (Pilgrim and Doran 1987).

3.4 Pre- and post-regulation changes in streamflow

Changes in the flood frequency distribution between the natural and regulated state of the river are small and primarily reflect the differences in rainfall regime discussed earlier (Chapter Two). The flood frequency curve for the regulated period is steeper than for the pre-regulated series (Fig 3.4), and floods with recurrence intervals less than 5 years tend to be larger since regulation. This reflects the greater number of floods in the 1950's and 60's, which is attributable, in turn, to the higher incidence of wet years in this period. Lower magnitude floods had slightly lower annual exceedence probabilities after 1945, and the mean annual flow increased slightly from 28 m$^3$s$^{-1}$ to 36 m$^3$s$^{-1}$. The frequency of the conventionally adopted mean annual flood, $Q_{2.33}$ (700 m$^3$s$^{-1}$) remained almost unchanged between the two periods.

Table 3.1 shows the flood frequencies estimated from both the partial and annual series for floods exceeding the critical height at Cowra. Since 1839, the river has experienced eight floods that have exceeded the mean annual flow of 28 m$^3$s$^{-1}$ by a factor of at least 100. The variability of high flows is reflected in the steep relationship between return period and
Fig. 3.6 Relationship between discharge (ratio of flood discharge to the conventionally defined mean annual flood with a return period of 2.33 years) and return period in years. Curve for the Lachlan at Cowra (1945-1994) has been fitted with a LPIII distribution with skewness -0.29. Crosses are floods with return periods >2.33 years. Other curves are regional averages for various areas around the world from Lewin (1989).
discharge. Figure 3.6 shows that the 50 year event on the Lachlan is 8.3 times the statistical mean annual flood \(Q_{2.33}\) compared to an average of 2-4 times for most other rivers around the world (Lewin 1989). As Pickup and Warner (1976) commented for streams east of the Great Divide, a normal flood in this environment would be considered a catastrophic event almost anywhere else in the world. This is more surprising given that the catchment size is far larger and better vegetated than that normally associated with severe flash flood country. Catchments of 10-50 km\(^2\) are thought to optimise flood depth and energy slope and flow velocities (Baker and Costa 1987), especially in short, steep and rugged and semi-arid catchments with thin soils and large areas of exposed bedrock (Costa 1987). Significant floods in larger catchments (over 1000km\(^2\)) are thought to be dependent on extreme tropical cyclones or snowmelt, or the extreme constriction of flow produced in bedrock gorges (Costa 1987). In south eastern Australia, rainfall is highly variable in intensity as well as amount, and variability of shallow groundwater storage is enhanced by high evapotranspiration, all of which contribute to flood variability.

3.5 Lachlan floodplain and terraces near Cowra: overview

Figure 3.7 shows the main geomorphic features of the valley within 15 kilometres downstream from Cowra. Terraces in the bedrock valley upstream from Cowra first described by Williamson (1986) and mapped by Bishop and Brown (1992) were reviewed in the previous chapter. In the present study aerial photos and floodplain surveys were used to map alluvial terraces downstream from Cowra; their sediments were described from limited exposures and power-auger holes ranging to 16 m, as well as borehole logs provided by DLWC. Three alluvial terraces were recognised between Cowra and Gooloogong, together with remnants of higher terraces that are considered to be equivalent to the Cudgelo and Kember terraces upstream of Cowra although they are not named separately here. Remnants the Glen Logan Gravel Formation crop out on some of the bedrock hills around Cowra at 31.2 and 33.7 metres above the river (Chan and Goldrick 1995) (shown on Fig 3.7) although they are difficult to distinguish from sediments composing the higher alluvial terraces above Cowra. The lowest three alluvial terraces at Cowra are named here in descending order the Crowther, Mulyan and Erambie terraces.
FIG. 3.7 Geomorphic map of the Lachlan Valley between Cowra and Meg's Wood showing bedrock (shaded), alluvial terraces and larger geomorphic features. Average alluvial valley width is 5 kilometres. Detailed maps for four parts of the valley are given in Figs 3.8, 3.10, 3.11 and 3.15. DL is a drilling transect referred to in Chapter Five. Flow is from right to left.
The Crowther terrace

The Crowther terrace is named after Crowther Creek, also known as Back Creek and Koorawatha Creek, that occupies the wide valley west of Cowra where this surface is most extensive (Fig. 3.7). Near the junction of Crowther Creek with the Lachlan, 12 kilometres north-west of Cowra, incision of the creek into the terrace surface reveals yellowish red (5YR5/8) to dark red (2.5 YR 2/6) silty clay/clayey silt, displaying a well-developed soil, usually with a lighter red 'A' horizon that may include fine aeolian silt (GR 463634). Rhizomorphs and incipient mottling and iron concretions typically occur at 1-2 metres depth. The sediments typically grade into hard yellowish brown clayey or silt/clayey sand below 2 metres and reach thicknesses of at least 3-4 metres. Crowther sediments pass into deposits previously assigned by Williamson (1986) to the Cowra Formation although whether the relationship is discontinuous could not be established. Sands and gravels of the Lachlan and Cowra Formation reach depths of 50 metres at the Cowra Airport and are underlain by weathered sandstone (Williamson 1986).

The Crowther terrace clearly corresponds to the Red terrace of Rutherfurd et al (1995), which can be traced continuously downstream from Wyangala to Cowra. At Cowra, it is an extensive surface, paired across the Lachlan River, which has not been reached by floods during the period of European settlement. Its height above the river bed declines from 23-25 m at Cowra to around 15 m at Gooloogong. From Cowra to Gooloogong, on the south side of the valley, its surface is almost flat except where crossed by meandering palaeochannels, largely infilled, near tributary streams. To the north of the valley, the terrace grades gradually upwards into low-angle alluvial pediments and is more irregular. The terrace tread is assumed to be the eroded surface of a formerly thicker Cowra Formation (Williamson 1986) although numerous surface palaeochannels in the vicinity of Cowra township suggest that the southern side has been recently reworked, as described later (section 3.6). The Crowther terrace below Gooloogong comprises most of the alluvial plain of the Lachlan Valley and numerous palaeochannels can be traced across its surface.
**The Mulyan terrace**

The Mulyan terrace is named after the property where remnants of the surface are preserved on both sides of the valley, 2 km north west of Cowra (GR 537557). The terrace is unpaired across the valley and limited outcrops are confined to the Cowra township (Figs. 3.8, 3.9). South of the river, the Mulyan terrace sits 16.0 metres above the river bed while its counterpart on the northern side of the valley is somewhat higher at 18.5 metres. The terrace surface slopes gently away from the river. No palaeochannels are visible on its surface near Cowra. Near Mulyan, it is composed of strong brown [7.5 YR 5/8] or dark yellowish brown [10YR4/4] silt or fine silty sand at the surface, grading down to red [2.5YR4/6] or yellowish red [5YR5/6] silt or yellowish brown [10YR5/6] or yellowish brown [10YR5/4] medium sand, mottled and containing carbonate nodules. The surface is inundated by the highest floods on both sides of the river and is capped by a thin deposit of overbank silt. The depth of alluvium is unknown but was found to exceed 12 metres north of the river. No corresponding alluvial terrace can be found between the Red and Brown terraces upstream of Cowra and no certain correlations have been made with the terrace sequence at Gooloogong. This terrace appears to be restricted to the vicinity of Cowra.

**The Erambie terrace**

The Erambie terrace is a well-defined surface at Cowra where it reaches widths of two kilometres (Figs. 3.8, 3.9). It is named from the early Aboriginal settlement (meaning "waterhole") located 1 km west of the present township. Surface sediments are yellowish brown [10YR5/4] to dark brown [10YR3/3] fine sand to clayey silt characteristic of suspended sediment during overbank flooding. This unit overlies strong brown [7.5YR4/6], occasionally mottled, fine silty sand and clayey silt. Stiff mottled grey clays are found in the abandoned channel fill. Sub-rounded gravels consisting of poorly sorted lithic small cobbles and coarse sand similar to the bedload of the present river occur in drillholes at 12-15 metres depth below the terrace surface. The thickness of the basal gravels is typically 2-5 metres and they disconformably overlie older clays, sands and gravels of the Cowra Formation.
Fig. 3.8 Geomorphic map of the Lachlan River and terraces at Cowra, showing rail and road bridges and the location of the streamflow gauge. A detail of the floodplain is shown in Fig. 3.11. Recognisable terraces between bedrock hills (shaded) in ascending order are the Erambie (E), Mulyan (M) and Crowther (C) terraces. Possible higher terraces are shown as dotted lines. Outcrops of Glen Logan Gravels are hatched. F = floodplain. Terrace topography and sediments are shown for section 1 in Fig. 3.9.
Fig. 3.9 Section 1 across alluvial terraces at River Park based on drillholes (power auger and hand auger) near section 1 (Fig. 3.8) (30 drillholes, including 12 drilled for this study, and 8 shallow hand augered holes).
At Cowra, the Erambie terrace is known locally as the valley flats and is inundated by floods with a return period exceeding 18 years on the annual series. In some places the surface morphology is highly undulating with ridges and swales related to two discrete phases of meandering palaeochannels that are visible on aerial photographs. In places where the sculptured floodplain morphology has been infilled the tread is flatter and slopes gently away from the river. The scarp above the younger floodplain deposits is not well defined and in places underlies broad natural levees associated with the present river. Average heights above the river bed around Cowra are 12-13 metres. The Erambie terrace can be traced upstream to the narrow Brown terrace identified by Bishop and Brown (1992) at Wyangala, and is almost continuous downstream to Payten's Bridge (location shown on Fig. 4.19) with occasional interruptions where bedrock ridges cross the valley.

3.6 The present floodplain and channel

The active floodplain varies in width and form but is generally narrow and inset within sediments of the Erambie terrace where it has a bench-like appearance, 8-10 metres above the river bed and 2 metres below the adjacent terrace. However, in places of active levee and chute bar development the top of the floodplain is level with the Erambie terrace or even overlaps it. Floodplain sediments are variable but bank exposures reveal horizontal or near horizontally bedded dark yellowish brown silt/fine sand often containing scattered pebbles and lenses of coarse sand. Hereafter, these sediments are referred to as the Cumberoona Floodplain Formation, the name derived from the property 8 km north west of Cowra that features a significant area of recently reworked floodplain. Higher levee banks are composed of pale yellowish brown, loose sand. Floodplain surface features, which include chute channels, chute bars, elliptical scour scars and flood channels, are described in detail for particular reaches, below. In summary, the occurrence of large scour features, stripped sections and coarse deposits on the floodplain surface, indicates episodic, intense flood action.

The main channel is primarily a sand bed stream, with sections of poorly sorted pebbles and coarse sand separated by deeper waterholes
floored by fine and medium sand. Banks are steep and densely wooded. The presence of old trees near the river edge on the inner (convex) bank suggests that meander migration is very slow under present day conditions. However, evidence of greater lateral activity in the recent past exists in the form of highly sinuous cut-off reaches and infilled meanders with dimensions similar to the modern river. Nowadays the river is in a phase of channel straightening and chute development although some reaches are manifestly underfit within inherited meander troughs. Width-depth ratio decreases downstream from 12.9 at Cowra to 6.9 at Gooloogong. Channel gradient downstream from Cowra is 1 in 1700 (0.0006) decreasing to 1 in 3200 (0.0003) at Gooloogong.

Hydrologically, the active floodplain is defined by bankfull exceedence level although bankfull frequency varies downriver, as shown in Chapter Four. Bankfull stage at Cowra is approximately 10.0 metres above the river bed (9.0 metres on the gauge), corresponding to a discharge of approximately 830 m$^3$s$^{-1}$. The geomorphic definitions of bankfull stage, which separates channel flow from overbank flow across the active floodplain, are variously defined and is often complicated in Australia by extensive in-channel bench formations, the occurrence of levees, and the growth of woody vegetation at various heights above the river bed (Riley 1972). The irregular floodplain surface at Cowra, which varies from 8 to 14 metres above the channel bed, precluded the choice of mean floodplain elevation used by Wolman and Leopold (1957). In-channel benches have been chosen to represent "bankfull stage" on some inland flowing rivers in the Murray-Darling basin (e.g. Woodyer 1968); however, they are not an appropriate marker of the extent of channel activity on this floodplain and natural banktop was preferred.

The frequency of bankfull exceedence at Cowra is 4.2 years on the annual series or 2.5 years on the partial series. The mean annual flood discharge, calculated as the arithmetic mean of the peak annual flows, is 700 m$^3$s$^{-1}$ and has a return period of 3.4 years on the annual series (2.1 years on the partial series). Unusually, the mean annual flood of the Lachlan at Cowra is smaller and has a shorter return period than bankfull flows. Statistical world average return periods for bankfull and mean
annual floods are normally given as 1.58 years and 2.33 years respectively (Leopold et al 1964).

The alluvial valley between Cowra and Meg's Wood has an average width of 5 kilometres except where it intersects the alluviated Crowther Creek valley (Fig. 3.7). The floodplain, Erambie and Mulyan terraces are confined by the Crowther terrace to widths of 2-3 kilometres and all historical floods are similarly confined. Figures 3.10, 3.11 and 3.15 are geomorphic maps of selected floodplains that are described in greater detail below.

Recent changes to the channel and floodplain downstream from Cowra have been identified from sequential aerial photos taken in 1954, 1964 and 1974. The 1954 run took place two years after the largest gauged flood in 1952, which reached a stage of 15.2 metres on the gauge and has a return period of 85 years on the annual series (127 years on the partial series). The event occurred in June after two months of higher than average streamflow, which had produced minor overbank flows in April and May. The previous two years had also been extremely wet and the river broke its banks six times during 1950-1951. No significant flow occurred again before the 1954 aerial photos were taken. Photographs in 1964 and 1974 follow major floods in 1960, 1961 1963 and 1974.

The floodplain at River Park and Farleigh

Figures 3.8, 3.10 and 3.11 show reaches of the river 7 km and 3 km downstream from the gauge at Cowra. Below the Cowra road bridge, the river pursues an irregular course but is generally fairly straight, where it is unconfined by terraces. Where it is confined by terraces or by meander bends of much larger palaeochannels the channel pattern is more sinuous. This can be seen at Farleigh, where the channel is ingrown into a large palaeomeander and is underfit within it with respect to meander wavelength, 700 metres upstream of A to B (Fig. 3.10). The floodplain and Erambie terrace are disrupted by flood chutes and scour scars, with local relief of 2-6 metres (as shown on Figures 3.10 and 3.11). The relict scroll plain on the Erambie terrace is deeply entrenched by flood chutes up to 6 metres deep and from tens of metres to several kilometres in length. Similar features
Fig. 3.10 Geomorphic map of the floodplain and terraces at Farleigh near centre of Fig. 3.7. Lachlan River is ingrown into a large palaeomeander from 1 kilometre upstream of A to B. Width of the Erambie terrace (E) and floodplain (F) between bedrock ridges (shaded) and escarpment of the Crowther terrace (C) is 2.7 kilometres. The floodplain and Erambie terrace feature chutes, chute bars and other large flood effects. Arrow marks the direction of flow. FA refers to a dated bank exposure given in Fig. 3.26 and FB is a bench deposit shown in Fig. 3.18. The position of scour scar shown in Fig. 3.14 is marked with symbol \.
occur upstream of the Cowra rail bridge (Fig. 3.8). At their upstream ends, chutes are partially infilled with poorly sorted coarse sand and large pebbles and are armoured in places with a layer of surface cobbles. Chutes decrease in depth downstream and are blocked by large chute bars which rise slowly downstream and terminate in a steep slipface. Where a chute bar reaches the channel, the bank often makes a promontory which may later be modified by erosion from the stream (e.g. Fig. 3.10). Similar features have been described on the sand bed streams of the Colorado River and tributaries, which are undergoing a reduction in sinuosity (Baker and Penteado-Orellana 1977, Blum et al 1994). Flood prone, small bedrock valleys in Texas are also dominated by chute formation leading to the construction of large flood-flow channels on the inner margins of bends (Baker 1977). On the Amite River, the formation of chute channels is attributed to erosion during rapid-flow conditions of extreme flood while chute bars form during the sudden transition of high velocity floodwaters from confined to unconfined flow (McGowan and Garner 1970).

Recently active chute bars and point deposits can be seen in the 1954 aerial photos as unvegetated, fresh deposits of sand. By 1964, the chute bars appear stable and have a good grass cover despite the passage of large floods in 1960, 1961 and 1963 that would have inundated the bars by several metres. The downstream end of a major chute bar at River Park has been quarried for sand (Fig. 3.11). Infilled chutes visible on aerial photos which today have no topographic expression suggest that chute activity has been ongoing for a considerable period. The infilling rate can be gauged from a chute at Farleigh that contains a complete line of old fencing, probably erected in the late C19th and now buried by over a metre of medium sand (Fig.3.10).

Sandy benches, in-channel bars and point deposits occur downstream of chute exits, although they are a rare feature elsewhere along this reach. In-channel bars appear to be stable during mean flow conditions and are commonly vegetated with willow. Sand bars on convex bends downstream of chute bars exhibit typical point bar morphology but reach their maximum development on the upstream side of the bend facing chute exits (e.g. point bar opposite sand quarry, Fig 3.11). A number of sandy
channel bed deposits that appear in the 1954 aerial photos downstream chute bars appear to have been reworked by 1964 but others appear to be semi-permanent features. The predominance of sandy bars and point deposits immediately downstream of the active flood chutes suggests that a significant portion of the total bedload travels via chute channels.

Fig. 3.11 Detailed geomorphic map of the floodplain at River Park showing active geomorphic features of the floodplain, channel and Erambie terrace (E), including elliptical scour scars, flood chutes, chute bars, mid-channel bars and areas of floodplain stripping. Location of scour scar shown in Fig. 3.13 is given by symbol \( \Delta \).

Widespread channel erosion was not reported after the 1952 flood and cannot be seen on the 1954 aerial photos; bank erosion appears to have been limited to those areas facing active chute bars. Such places are also the only recognisable areas of recent channel migration. Ten years later these banks became reforested with dense stands of young trees. Bank
erosion also occurs on upstream facing bends and, in places, scouring has lowered parts of the floodplain by an average of 2 metres. Areas up to 100 metres wide and up to 200 metres downstream are affected, sometimes on the inside of a meander bend (Fig. 3.10) but also on both sides of the river (Fig. 3.11). Scoured surfaces are mantled by a veneer up to 50cm thick of fresh, coarse sand and pebbles. The date of the stripping episode(s) cannot be determined from aerial photographs. Fig. 3.12 shows an area of stripped floodplain on an upstream facing bend at "Anabranch", 32 kilometres downstream from Cowra. Similar floodplain stripping has been described by Nanson (1986) on steep gradient coastal rivers in New South Wales in response to several large floods in close succession.

Large elliptical scour pits, or "swirl pits", similar to features attributed to localised erosion by strong vortices and eddies in floodwater (Gupta and Fox 1974, Gardner 1977) occur on the floodplain in the Cowra area. Such features are concentrated on levees and in flood chutes cut into the floodplain and Erambie terrace. They are up to 40 metres long and over 2 metres deep, and are partly filled with coarse sand and pebbles. Most have formed around older river red gums although some scours have no apparent focus (Figs. 3.13, 3.14)

Discontinuous levees can be found on both sides of the channel and at various heights above the stream bed. Levees are typically 0.5-2.5 m high and 60-250 metres wide and may be longitudinally dissected by flood chutes. Chute levees have developed on the highest chutes, one kilometre below Cowra, similar to those described on the Clarence River (Huq 1995). The highest levee crests occur 1.2 kilometres downstream from the streamflow gauge at Cowra. These are 14 metres above the river bed, 5 metres higher than the floodplain and are inundated by floods with a return period greater than 40 years on the annual series. Nanson (1986) also describes very high levees and variable surface relief on much steeper coastal streams in situations where the floodplain is partly confined.

At Farleigh, pebbles occur scattered in a crevasse splay at the upstream end of a major flood chute (Fig. 3.10). Small deposits of pebbles and coarse sand have also been noted in the trunks of fallen trees,
Fig. 3.12 Area of stripped floodplain on upstream facing bank at "Anabranche", 30 km downstream from Cowra. Stripped area in shadow in foreground below sunlit bank in centre of photo measures approximately 80 metres wide, 100 metres long and over 3 metres deep.

Fig. 3.13 One of several large elliptical scour scars on the floodplain at River Park mapped in Fig. 3.11. This scour measures approximately 40 metres in length and is being used to contain tree cuttings. Its base is partly infilled with coarse sand and cobbles.
suggesting recent deposition. On the River Park floodplain, gravels occur as surface veneers in flood chutes and at the base of larger elliptical scour scars. The largest cobbles have an intermediate diameter of 115 mm and similar lithologies to gravels in the channel bed. The presence of gravels at levels above the channel bed is normally taken as evidence of transport.
during large floods, either as bedload or suspended load sediments (Ritter 1975). Gravel particles are capable of being deposited by saltation or even temporary suspension at quite high elevations with the aid of a ramp or other access to the floodplain (Knox 1987). Stripped areas of floodplain immediately upstream of the cobble deposits at River Park may well have provided such a ramp for the transport of large cobbles out of the main channel. Rounded pebbles and cobbles are also present in chute fill deposits at this location.

The floodplain at Meg's Wood

At Meg's Wood, ten kilometres downstream of Cowra the valley narrows to 700 metres between bedrock constrictions and the river is straighter with a sinuosity of 1.2 (Fig. 3.15). Generally, except for a 1 km meander near the southern end of this reach, the channel is not guided by inherited meanders. Active levee accretion is more prominent than further upstream, as shown by the burial of quite young trees on both sides of the channel. Elliptical scour scars are common around older trees along the channel banks and levees although these have smaller dimensions than in inherited reaches. Some bank retreat is occurring on outside bends and recent bank slumps (within the last ten years) have been restabilised by riparian forest. At lower levels on the banks, the exposed roots of young casuarinas indicate that bank retreat of around 1-2 metres has occurred in the last thirty years. Much older trees, perhaps as much as 300-400 years old, to judge from observations of local farmers and from the probable maximum ages of river red gum (Jacobs 1955, Gill 1971, Dr. J. Banks pers. comm.), growing close to the edge of the inner bank suggest that migration rates over a longer time scale are slow (maximum of 1.3 metres/century). Undercutting of banks may have accelerated cut bank retreat in the last 60 years due to sudden dam releases from Wyangala (DLWC 1989).

Bank erosion attributed to the 1952 flood at Meg's Wood was limited to the relatively large scrolled meander identified in Fig. 3.15 as inherited, now under dense eucalypt forest. This bend has also been chuted in several places although chute bars are virtually absent. Numerous deep channels over 3.0 metres deep and 120 metres wide traverse the Erambie terrace; their base is 8 metres above the river bed. In cross-section they are
Fig. 3.15 Geomorphic map of the floodplain and terraces at Meg's Wood. Reach shown appears at the top left of Fig. 3.7. The width of the floodplain (F) and Erambie terrace (E) narrows to 700 metres between bedrock ridges (shaded) and the Crowther terrace (C). The positions of flood channels and in-channel benches (b) are also shown. Sedimentary details for bench MW are given in Fig. 3.18a. JM-1 is a drillcore shown in Fig. 3.27. The location of flood and back channels shown in Fig. 3.16 and 3.17 is shown by symbol ◀ and the surveyed section at A-A' is shown in Fig. 3.27.
asymmetrical, their steep sides towards the floodplain rear (Fig. 3.16). Unlike the inherited reaches, these channels have not developed within existing scroll bar ridges and swales topography and do not appear to be former river courses. Chute bars have not developed at their lower ends although sandy point deposits are often found in the main channel at these locations, presumably supplied with sediment transported through the flood channels. They are interpreted as active flood channels of the present day stream which serve to carry a large proportion of overbank floodwater. Rivers which are highly sinuous are often bypassed during floods when the water takes a more direct and higher gradient route across the floodplain; however, the river here is essentially straight. Flood channels are also found at the rear of the floodplain against bedrock ridges or the escarpment of the Crowther terrace (Fig. 3.17), where they are similar to "back channels" described in semi-confined floodplains in central Australia (Bourke 1995).

In-channel benches

In many places, the main channel cross-section has a stepped appearance produced by the presence of up to three benches within the channel perimeter. Benches are more common on the Meg's Wood floodplain than elsewhere in the Cowra region, and Fig. 3.15 shows the locations of several bench deposits. Their distribution is discontinuous with little consistency either in their position in the meander train, the number of benches, or their height above the river bed. At one location, (unpaired) benches were surveyed at 1.5, 5.3 and 6.1 metres, but different heights were observed elsewhere for in-channel benches, which sometimes lie on the outer, concave bank although they were more commonly observed in point position (on the convex bank). Benches are rarely more than 20 metres wide and some have been partly removed by erosion. Their surfaces are flat or inclined toward the river. Lower benches and point deposits (1-2 metres above the channel floor) are commonly sandy and covered with a veneer of pebbles and coarse sand, which fines downstream over a distance of 30 metres. These features are submerged during mean flow and lack vegetation. Higher benches are well vegetated with grass and trees, some of which may be several hundreds of years old. As shown below, their sediments consist of alternating beds of fresh, coarse sand and mud,
Fig. 3.16. Parallel flood channels >3 metres deep on the floodplain near Meg’s Wood.

Fig. 3.17 Back channel on the floodplain adjacent bedrock ridge at Meg’s Wood, located near JM-1 on Fig. 3.15.
overlying cross-bedded, medium sand. Bedding is horizontal or near horizontal and conforms to the surface morphology.

In-channel benches have been described on several Australian rivers (Riley and Taylor 1978; Taylor and Woodyer 1978, Woodyer et al 1979, Erskine 1999) and elsewhere around the world (Page and Nanson 1982). They are found in diverse environments, from low gradient, suspended load alluvial rivers in western New South Wales to steeper, coastal sand bed streams. Their appearance is discontinuous and irregular, forming on inner or outer banks or along straighter reaches. Their sediments tend to be fine-grained with interbedded thin sand and mud. In-channel benches represent the vertical accretion of sediment within the channel perimeter although the depositional processes involved are not well understood. Woodyer et al (1979) attribute their formation to a combination of deposition from suspended and bedload sediments during conditions of greatly increased energy gradients and turbulence from overbank floods. Concave bank benches described on irregular meanders of the Murrumbidgee River are thought to form under much lower energy conditions (Page and Nanson 1982). Recently, in-channel benches on rivers in the Murray-Darling basin have been considered to represent deposition of alluvium derived from widespread erosion and gullying in farmlands of southeastern NSW (R. Wasson, pers.comm. 1995).

Figure 3.18 shows the sedimentary sequences of several in-channel benches between Cowra and Merriganowry, some 22 kilometres downstream. An excavated bench on the inner bank at Meg's Wood is situated immediately downstream of an active flood channel of the Meg's Wood floodplain. Most of the bench has been eroded and only a remnant remains beneath steep banks (Fig. 3.19 and 3.20), where the top of the bench is three metres above channel bottom and is vegetated with grass. Bench sediments consist of very coarse, loose sand, horizontally bedded, with beds 7-30 cm thick alternating with thinner beds (5 cm) of organic, fine sandy silt or medium sand. The upper sand beds show signs of reverse grading in the lowest 3-5 cm, suggesting deposition during a rising flood. Below 0.5 metres depth, beds are thinner and consist of cross-bedded medium sand, partially cemented and exhibiting strong brown mottling. The
Fig. 3.18  Sedimentary sequences of in-channel benches on the Lachlan between Cowra and Gooloogong. The position of the benches at Meg’s Wood (a) and Farleigh (c) is shown as MW and FB on Figs 3.15 and 3.10 respectively. Bench (b) is located 200 metres downstream from Merriganowry Bridge. Its location can be seen on Fig. 4.23.
Fig. 3.19 Photograph of an eroded in-channel bench in Lachlan River, Meg's Wood, 10 kilometres downstream from Cowra. Dated bench sediments are shown in Figs 3.18 and Fig. 3.20 (below).

Fig. 3.20 Point bench at Meg's Wood located downstream from flood channel mapped in Fig. 3.15. Sedimentary sequences are logged in Fig. 3.18a.
adjacent flood channel may be the source of the coarse sand that now lies
within the upper profile of the bench.

The bench at Merriganowry is one of several similar features
developed on the river's convex bank within a more sinuous reach of the
river. The highest point of the bench top is approximately 4 metres above
the river bed and the river side is eroded, exposing 1.5 metres of the bench.
Several prominent scour scars along its back edge suggest erosion may also
have removed some of the surface sediments. The upper beds feature
similar bedding to the bench at Meg's Wood. A thin veneer (5-7 cm) of
organic silty sand overlies interbedded medium sand and silt, pale brown,
partially cemented and mottled, with coarse sand. Below 1 metre depth,
near-horizontal beds of coarse, loose sand are cross-bedded.

The ephemeral behaviour of in-channel benches is illustrated by an
element on the Farleigh floodplain, where a 1.2 metre deep pit was
excavated in a bench deposit at the intersection of the main channel and an
active flood chute (FA on Fig. 3.10). Freshly cut banks apparent in the 1954
aerial photos suggest that substantial erosion of the floodplain occurred
during the 1952 flood, implying that part, if not all of the bench
accumulated after this event. The top of the bench is roughly 2 metres
above the river bed. The exposure revealed a poorly organised deposit with
structureless beds of organic, yellowish brown fine sandy silt with
occasional large pebbles, interspersed with thin lenses (1-5 cm) of medium-
coarse sand (Fig. 3.18c). Beds dip around 5-7° toward the river, paralleling
the slope of the bench surface. Sediments at the base of the pit
(approximately 0.5 m above the river bed) are medium silt, considerably finer
than the adjacent channel bed material of large pebbles and coarse sand. A
thin veneer of very fine sand was deposited on the surface of this bench
during a high flow a few days before the pit was excavated (August, 1998).

In-channel benches on the Lachlan between Cowra and Gooloogong
are similar in many respects to those described elsewhere except that they
lack the fining upward sequence found on low gradient rivers in the central
western Murray-Darling, described by Riley and Taylor (1978); Woodyer et al
(1979) and Taylor and Woodyer (1978). The benches are clearly bedded but
lack the fine-coarse-fine alternation or couplets representative of individual flood events. Bench sediments are derived from a mixture of coarse, overbank flood sediments and finer sediments deposited during lower flows and bankfull floods. Their limited lateral extent and the fact that they have been eroded in several places suggest they are ephemeral features with limited potential for preservation and may be periodically removed by some of the larger floods. In this respect, they may be more similar to benches on some Hunter Valley streams which have been described as recovery landforms formed by moderate floods within the void eroded by catastrophic floods (Erksine 1999).

3.7 Sediment characteristics

Samples for particle size analysis were collected in order to determine the sedimentological differences between palaeo-alluvium and the active floodplain, and to attempt to characterise active and relict surfaces. Variations of particle size within the floodplain deposits also were expected to reflect floodplain depositional events. Furthermore, bed and bank samples were collected for a larger scale analysis of downstream changes in channel geometry and sediment characteristics between Cowra and Kiacatoo (Chapter Four).

A total of 48 channel and floodplain sediment samples were taken from a set of five sites over a 15 kilometre reach downstream from Cowra. In general, three samples were collected during low flow from relatively flat sections from the channel bed at equal intervals across the river, and one to four samples from each bank, avoiding mud drapes. In some places, the channel banks are cut into palaeochannel sediments, identifiable as quartz cobbles in a red clay/sand/silt matrix up to 5 metres above the floor of the present channel bed. These areas were avoided for channel perimeter sediment samples. Floodplain samples were collected using a spade or from shallow auger holes.

Samples were dried, lightly pounded and reduced to measurable quantities using a sample splitter. Coarser sediments with less than 20% silt-clay content were separated into samples of at least 100g (dry weight) and sieved into half-phi size classes for detailed assessment of sediment
fractions. Finer samples (>20% silt-clay content) were chemically dispersed and 62.5 g were analysed using the hydrometer technique (Allen 1981, K. Fitchett, pers.comm. 1996). The organic content appeared to be low and was not measured. Calculations of the graphic mean, sorting, kurtosis and skew* of particle size distributions are derived from Folk (1961).

Figures 3.21 and 3.22 show particle size distributions for landforms on the Cowra, River Park, Farleigh and Meg's Wood floodplains. Sample groupings are based on morphostratigraphic units.

Particle size and sorting were found to vary considerably between different morphostratigraphic units. Chute bars contain the best sorted sediment with a high level of consistency between reaches: three samples were analysed from chute bars several kilometres apart and yielded virtually identical moderately sorted coarse sand with a near-symmetrical and peaked distribution (Fig. 3.21a). In contrast, chute fill sediments produced a range of cumulative particle size curves (Fig. 3.21b), many with a sandy component indistinguishable from chute bar sediments but the presence of small pebbles gives a bi-modal distribution. Fresh sand deposits mantling stripped sections of the floodplain are similar to chute bar sediments but tend to be coarser and included large pebbles. Surface samples from elliptical scour scars produce a higher concentration of large pebbles and coarser, very poorly sorted sand.

The calibre of bed material is extremely variable and often bi-modal, both along the reach and in individual sections (Fig. 3.22f). Around Cowra, the bed material is composed of moderately to poorly sorted very coarse sand with a fine-skewed distribution. Further downstream at Megs Wood the bed is dominantly poorly sorted pebbles with a second mode of fine-skewed, very coarse sand. Low-level point bar sediments tend to be better sorted than the bed material and somewhat finer, being composed of

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*Graphic mean, \( M_2 = (\phi_{16} + \phi_{50} + \phi_{84})/3 \)
Sorting is given by graphic standard deviation, \( \sigma_g = (\phi_{84} - \phi_{16})/2 \)
Inclusive graphic skewness, \( Sk_g = \phi_{16} + \phi_{84} - 2\phi_{50} + \phi_{5} + \phi_{95} - 2\phi_{50} \)
\[ 2(\phi_{84} - \phi_{16}) \]
\[ 2(\phi_{95} - \phi_{5}) \]
Graphic kurtosis, \( K_g = \frac{\phi_{95} - \phi_{5}}{2.44 (\phi_{75} - \phi_{25})} \)
moderately sorted medium or coarse sand, with a fine tail and markedly peaked distribution (Fig. 3.21c). The similarity between some point bar and bench sediments and those of the chute bars reflects the transport and reworking of sand from flood chutes into point bars immediately downstream. Individual point bars fine in a downstream direction and some are mantled with a veneer of coarse pebbles and cobbles, consistent with winnowing of fine material at the surface (Leopold et al. 1964).

Low-level benches adjacent to coarse-grained point bars in areas which are regularly stripped by large floods generally are considerably finer grained, grading from poorly sorted medium silt to medium sand and may contain pebbles or medium cobbles (Fig. 3.22e). Two of the samples shown in Fig. 3.22e were taken from bench deposits shown in Fig. 3.18 (a,c). Texturally, the finer grained component of channel benches cannot be distinguished from low-level bank sediment although larger cobbles are not commonly encountered in cut bank exposures. Samples FA-E1 and FAB1 were obtained from bank and bench deposits less than three metres above channel bottom and located immediately downstream of active chutes bars. The samples have similar particle size characteristics and are coarser than bank and bench sediments elsewhere except for sample (MWPS-BO), which consists of moderately well sorted very coarse sand that more closely resembles chute bar sediments and supports the interpretation that the coarse-grained component of certain channel benches is sometimes supplied directly via flood and chute channels. In most benches, the supply of sand through the chutes is mixed with, or appears in alternating beds with finer sand and silt deposited from the main channel; the variety of curves for bench and low bank sediments tends to indicate different sediment sources and/or depositional processes.

Bank and levee sediments in general are coarser than those of many low banks and benches (Fig. 3.22d). Most samples are poorly sorted medium to fine sand with a strongly fine-skewed, platykurtic distribution. The fine tail of RP-G 480 is more characteristic of low bank and bench sediment but was sampled from an area of stripped floodplain and is several metres below true banktop. Where levees could be identified, they typically
Fig. 3.21 Cumulative particle size curves for samples from various physiographic units on the floodplain and Erambie terrace between Cowra and Gooloogong, namely chute bar (a), chute fill (b), and point bar (c) sediments. On the legend, FA = Farleigh floodplain; RP = River Park floodplain; MW = Meg's Wood floodplain.
Fig. 3.22 Cumulative particle size curves for samples from bank top and levee sediments (d), in-channel benches and low banks (e), and bed sediments (f). On the legend, CB = Cowra floodplain, shown in the centre of Fig. 3.8; FA = Farleigh floodplain; RP = River Park floodplain; and MW, MWPS samples are from the Meg's Wood floodplain.
contained beds of moderately sorted, loose medium sand underlying 30 cm of dark yellowish brown fine sand and silt that was 1.5 phi units finer. The depth of coarser, loose sand could not be determined in all cases and may be a surface veneer.

Some of the variability of grain size characteristics in individual landforms, especially chute fill and levee banks reflects the wide range of flows involved in their deposition. Figure 3.23 shows cumulative grain size curves for selected samples from individual physiographic units and reveals the considerable range of textures from channel to floodplain. Graphic means, sorting, skews, and kurtosis of these samples are given in Table 3.3. Poorly sorted fine silt analysed from the outer margin of the floodplain is the finest sediment encountered and gravel from the channel bed, the range of which is illustrated by the shaded envelope in Fig. 3.23, is coarser than representative samples from the other morphostratigraphic units. Between these two extremes, there is no consistent relationship between sediment texture and height above the channel bed (Fig. 3.24), which is unexpected, as sediment texture normally becomes finer with height above the bed (Walling et al 1992).

Overbank flood deposits in chute bars below Cowra tend to be better sorted, coarser and less fine-skewed and more leptokurtic than the deposits of in channel benches, which result from more normal flows. This is the reverse of characteristics of flood deposits described by Knox (1987). Normally, concentrations of coarse silt and sand decrease with height and distance from the channel bed, as contact of shallow water with a wide floodplain slows water velocities and reduces competence (Allen 1985, 98-102, Pizzuto 1987). In the upper Lachlan Valley, flood flows achieve considerable depths on the floodplain and in some reaches the flood competence is also enhanced by steeper floodplain gradients than in the main channel.

3.8 Facies models of meandering rivers

Fig. 3.25 shows an alluvial facies model for active reaches of the floodplain downstream from Cowra. Proximal to the channel, lateral migration deposits are coarse textured gravels at the base, grading up to
Fig. 3.23 Average cumulative particle size curves of various physiographic units on the floodplain at Cowra.

### Tab. 3.3 Statistics for particle size analyses for representative samples from various physiographic units shown in Fig. 3.23.

<table>
<thead>
<tr>
<th>Landform</th>
<th>height above bed (metres)</th>
<th>$M_3$</th>
<th>StDev</th>
<th>Skl</th>
<th>Kg</th>
<th>Description</th>
</tr>
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<tr>
<td>bed</td>
<td>0.0</td>
<td>-3.70</td>
<td>1.48</td>
<td>0.65</td>
<td>1.55</td>
<td>Poorly sorted pebbles, strongly fine-skewed, very leptokurtic</td>
</tr>
<tr>
<td>bed</td>
<td>0.0</td>
<td>-1.58</td>
<td>1.20</td>
<td>0.22</td>
<td>0.84</td>
<td>Poorly sorted very coarse sand, fine-skewed, platykurtic</td>
</tr>
<tr>
<td>low bench</td>
<td>0.9</td>
<td>5.47</td>
<td>3.24</td>
<td>0.05</td>
<td>0.71</td>
<td>Very poorly sorted medium silt, near symmetrical, platykurtic</td>
</tr>
<tr>
<td>low bank</td>
<td>2.3</td>
<td>6.33</td>
<td>2.47</td>
<td>0.11</td>
<td>0.84</td>
<td>Very poorly sorted medium silt, fine-skewed, platykurtic</td>
</tr>
<tr>
<td>chute bar</td>
<td>5.5</td>
<td>0.37</td>
<td>0.58</td>
<td>-0.10</td>
<td>1.26</td>
<td>Moderately well sorted coarse sand, coarse-skewed, leptokurtic</td>
</tr>
<tr>
<td>chute fill</td>
<td>6.0</td>
<td>0.17</td>
<td>0.84</td>
<td>-0.13</td>
<td>1.04</td>
<td>Moderately sorted coarse sand, coarse-skewed, mesokurtic</td>
</tr>
<tr>
<td>high bank</td>
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<td>2.55</td>
<td>0.97</td>
<td>0.32</td>
<td>0.89</td>
<td>Moderately well sorted fine sand, strongly fine-skewed, platykurtic</td>
</tr>
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<td>7.37</td>
<td>1.90</td>
<td>-0.01</td>
<td>0.64</td>
<td>Very poorly sorted fine silt, symmetrical, very platykurtic</td>
</tr>
</tbody>
</table>
medium-fine textured bank and floodplain sediment, that may be partially removed owing to floodplain stripping or buried beneath coarser grained levee and chute levee sediment. The channel itself may contain fills of medium-fine sand and silt in benches but these are periodically removed by floods and are unlikely to be a significant component of floodplain sediments. Some distance from the channel, the floodplain is subject to cut and fill by flood chutes, stripping and scour scars with fills of mixed textures including coarse flood deposits from coarse sand, pebbles and cobbles deposited during large floods in chute fills, chute bars and crevasse splay deposits, with a finer matrix of fine sand, silt and clay deposited during shallow overbank flows. Areas distal to the channel vertically accrete fine-textured sediment in back channels, flood channels and as a surface mantle. Slow lateral migration allows pedogenesis of floodplain sediments and reworking and disturbance of sedimentary structures.

Both inherited and free reaches of the river below Cowra reflect a floodplain adjusted to repeated, high magnitude, overbank flows. The disparity between mean annual flow and mean annual or larger floods has resulted in an irregularly stepped morphology with alternating floodplain stripping and deposition operating at several levels above the channel bed. In both sinuous and straighter reaches, flood flows are physically separated from lower flows. Inherited reaches are dominated by flood chutes, chute bars and scour scars, forms which have been attributed elsewhere to the effect of low frequency, high magnitude floods. Coarse sediment is transported during larger floods through chutes and supplies sediment to chute bars, point deposits, in-channel benches and islands immediately downstream. In the main channel, finer grained material is deposited during lower, within channel flows, resulting in an inversion of the normal fining upwards sequence. Benches develop in places of major stripping or bank erosion, at the intersection between flood chutes and the main channel. In the straighter reaches, where the terraces have been cut back and the floodplain is relatively wide, subsidiary flood channels convey larger flood flows and chute bars are subdued or absent. Coarse-grained levees are prominent on the channel banks at various heights above the river. In-channel benches are more numerous and commonly developed above small point bars as temporary sediment stores. Their alternating beds of fine and
Fig. 3.24 Plot showing the relationship between silt-clay percentage (solid diamonds) and sand percentage (open points) of sediment samples in the Cowra area, with height above the river bed.

Fig. 3.25 Alluvial facies model for active floodplain reaches downstream from Cowra showing limited lateral migration deposits within broader zone of chutes, chute fill, back channel fill, coarse-textured levees and overbank flood deposits. Benches are generally ephemeral features that are rarely preserved in the floodplain.
coarse sediment reflect the changing source of sediments deposited during large floods and during bankfull and lower flows.

The cut and fill on the floodplain surface resembles high energy floodplain described by Nanson and Croke (1991) although such floodplains are usually entirely composed of coarse, uncohesive sediments. On the other hand, slow growth of fine-grained point bars and accumulation of muddy, in-channel benches more closely resembles fine-grained, meandering or stable streams described by Jackson (1981) that are characterised by relative stability and low energy conditions. In terms of stream power and shear stress, the floodplain at Cowra is a high-medium energy surface which contains a low energy channel.

3.9 Channel ages and rates of change

Two radiocarbon dates on sediments of the Cumberoona Floodplain Formation were obtained from an exposed section on the Farleigh floodplain (Fig. 3.26). Details of radiocarbon dates are given in Tab. 3.4. The location is shown on Fig. 3.10. Charcoal preserved within weakly pedogenised fine sand and silt, 4.5 metres below the floodplain surface and close to low water level of the stream yielded dates of 2420±80 years BP (ANU-11093) (2300-2750 years calBP) and 2600±60 years BP (ANU-11092) (2460-2790 years calBP). The sediments are weakly horizontally bedded and mostly structureless pebbly sand, overlain by fine, pebbly medium sand, resembling the structureless sediments encountered in stripped floodplain sections further upstream also assigned to the Cumberoona Floodplain Formation. The abundance of silt and carbon fragments and the lack of flow structures suggest a well-vegetated floodplain built by vertical accretion but could equally represent cohesive lateral accretion deposits that have been disturbed by pedogenesis, including bioturbation, and deeply rooted trees. The exposure is located on the convex bank, 20 metres from a major flood chute - channel intersection and immediately downstream from an area of stripped floodplain and aggrading, inset bench formation. The width of the floodplain between the Erambie terrace is around 150 metres; 40 metres separates the bank from sediments of the Erambie terrace behind, indicating a minimum rate of channel migration of 5.7±0.36 cm/year since deposition. The sediments are very similar to those of the actively accreting banks of the
<table>
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<th>Sample</th>
<th>Location</th>
<th>Age (yr BP)</th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>ANU-11124</td>
<td>Merriganowry</td>
<td>450±110</td>
<td>charcoal in sandy point bar</td>
</tr>
<tr>
<td>ANU-11126</td>
<td>Megs Wood</td>
<td>730±110</td>
<td>charcoal in coarse sands of bench deposit</td>
</tr>
<tr>
<td>ANU-10763</td>
<td>Meg's Wood</td>
<td>1740±140</td>
<td>peaty channel infill of cut-off meander, present river phase</td>
</tr>
<tr>
<td>ANU-11093</td>
<td>Farleigh</td>
<td>2420±80</td>
<td>charcoal in fine silty sand, Cumberoona Floodplain Formation</td>
</tr>
<tr>
<td>ANU-11092</td>
<td>Farleigh</td>
<td>2600±60</td>
<td>charcoal in fine silty sand, Cumberoona Floodplain Formation</td>
</tr>
</tbody>
</table>

Tab. 3.4 Radiocarbon dates on floodplain sediments in the Cowra region.

Fig. 3.26 Section exposed in bank near centre of Fig. 3.10 showing aggrading bench deposit against stripped bank opposite an active chute bar. Details of dates are given in Tab. 3.4.
present river and are considered to have been deposited under a channel regime very similar to the present. Therefore the dates suggest that the present regime has been active for at least 2500 years.

Rates of lateral channel movement have been estimated earlier from the age of trees on convex, inner meander bends at a maximum rate of 1.3 cm/year. These can be compared with rates over longer periods based on radiocarbon dating of floodplain sediments. Estimates of meander migration rates can be gauged from the cutoff meander reach with similar dimensions to the present channel preserved towards the northern end of the floodplain at Meg's Wood, which show that a floodplain 700 metres wide has developed since the river has been in its present phase (site MW, Fig. 3.15). Assuming the present channel has been active since 2600 years ago, an average maximum rate of channel migration can be estimated of 27±1.7 cm/year.

A well preserved meander neck cutoff was investigated at the northern, downstream end of the Meg's Wood floodplain (JM-1 in top left of Fig. 3.15). The meander belt is inset within fine sandy scrolls of large, meandering palaeochannel and is separated from the modern channel by a large, compound natural levee two metres high (Fig. 3.27). The cutoff has infilled with silt and sandy silt to within two metres of the floodplain surface. Power auger drilling extracted samples to a depth of 12 metres near the meander apex at what was considered to be the deepest point. Peaty channel infill, 9.6 metres below the floodplain surface and 1 metre above coarse sand and gravel of the old channel bed was radiocarbon dated and returned an age of 1740±140 years BP (ANU-10763) (1,300-1950 years calBP) (Fig. 3.27), which is taken as approximately the time of meander abandonment. Since cutoff, the river has migrated 100 metres from the ends of the abandoned loop; thus assuming that migration has been unidirectional, the channel migration rate in the last 1700 years was about 6.4±1.3 cm/year. Together with the estimate for the present channel of 1.3 cm/year, the radiocarbon results suggest that migration has diminished in the last ∼2000 years.

The bed of the cut-off channel is some 3.8 metres lower than that of the present channel, suggesting that aggradation of the channel bed and
Fig. 3.27 Surveyed cross-section of the floodplain at Meg's Wood showing compound levee, in-channel benches, back channel and sediments in cutoff meander augered to 12 metres at JM-1. Position of radiocarbon dated sample is marked with a triangle. Location of section is shown on Fig. 3.15.
possibly the floodplain has occurred in the last 1700 years. Recent aggradation of the floodplain surface near Cowra is apparent in burial of palaeochannels on the Erambie surface by 5 metres of organic, fine overbank silt (stratigraphic section is given in Chapter 5). The location of the section is marked as DL in Fig. 3.7. Thus, the most recent episode of the river's evolution may have been characterised by a shift in the dominant mode of floodplain formation from lateral to vertical accretion.

Further evidence of recent channel stability comes from two radiocarbon dates from coarse-textured beds within vertically aggrading, in-channel benches shown in Fig. 3.18. An age of 450±100 years BP (ANU-11124) (280-570 years calBP) was obtained from cross-bedded sand beneath finer, horizontally bedded sand at a depth of 1.4 metres below the surface in bench sediments at Merriganowry, 20 km downstream from Cowra. Assuming uniform sedimentation, the result indicates aggradation of 0.37±0.13 cm/year. A second dated point bench is located at Meg's Wood, where charcoal from within loose, coarse sand 85 cm below the bench surface, yielded an age of 730±110 years BP (ANU-11126) (510-840 years calBP). A substantial portion of the bench has been laterally eroded although the remnant is actively aggrading at present. Net aggradation rates on this bench are apparently lower, around 0.13±0.03 cm/year. Both dates indicate relatively slow rates of vertical accretion but the possibility of periodic stripping of bench surface sediments cannot be excluded, and these are regarded as minimum accretion rates. However, these ages for benches within the channel do indicate that negligible lateral channel migration has occurred over the last c. 425 years and 680 years in these locations.

Periodic stripping of sediments within the channel does not appear to have affected the channel form. The recurrence interval of stripping episodes could not be determined from the evidence available; however, other evidence suggests that large floods are likely to have been a feature of the river for some time. The cutoff channel infill JM-1 at Meg's Wood contains at least four lenses of coarse sand or gravel deposited >5 metres above the old bed, probably during large floods capable of transporting coarse sediments as suspended load, suggesting that at least four highly competent floods have occurred in the last c.1600 years.
Summary

A good chronology of floodplain sedimentation requires a greater number of radiocarbon dates; however, the relative sequence of recent alluvial changes is outlined here, for comparison with the more detailed discussion of palaeochannel morphologies, sediments and chronologies presented in Chapter 5.

Episodic incision into the Crowther terrace in the Cowra area of around 15 metres produced the Mulyan terrace, now mostly reworked by later streams. A floodplain 1-5 km wide was excavated by sinuous and laterally migrating palaeochannels with channel dimensions much larger than the present river, producing the Erambie terrace. Scallops in the scarp of the Crowther terrace are similar in wavelength to palaeo-meanders preserved on the tread of the Erambie terrace. A subsequent reduction in discharge resulted in a change to a much smaller meandering river, examples of which are preserved on the Erambie surface at River Park (Fig. 3.11) and on the Meg's Wood floodplain (Fig. 3.15) where it occasionally influences the course of the modern stream. This had dimensions roughly twice that of the present river and produced scrolled floodplains through lateral migration. No obvious incision or aggradation accompanied the change.

A change in river style accompanied a further reduction in discharge to a river with channel dimensions similar to present. The channel migrated laterally but did not produce scroll-patterned floodplains. A change from lateral migration to vertical aggradation occurred some time after 1700 years ago, burying the Erambie terrace in places beneath a broadly convex drape of overbank silt. The lack of well-developed, sinuous meanders on the river today, except in areas of active chute bar deposition, suggest that a change towards lower sinuosity and channel straightening, through chute development, has occurred in the last 2000 years.

3.10 Flood competence and peak discharge estimates

Major floods have both erosional and depositional effects. One of the most commonly used indicators of large flood events is textural reversals or discontinuities in the normal fining-upward alluvial sequence caused by the
increase in competence of large flood flows (Knox 1987). However, this can be difficult to distinguish on a floodplain characterised by variable and/or poorly sorted sediments and a general lack of preserved sedimentary structures. An indication of the competence of large floods, i.e. the largest particle that a given flow can transport, can be gauged from the size of boulders and cobbles deposited away from the river bed, which are assumed to have been transported in traction. Although the calibre of sediment deposited by a flood may be limited by the size of available sediment, minimum flow depths can be calculated from empirical relationships between entrainment and flow velocity.

Large cobbles on the floodplain at River Park were identified as flood deposits rather than a palaeoalluvial lag, based on their location on the surface of flood chutes, within scour scars and on stripped floodplain of recent origin. A representative measure of the largest particle size was obtained from individual measurements of the B-axis in the field, taking the average of the five largest gravels, following the method of Costa (1983). Costa's relationship between flow velocity and particle size, developed for gravels 50-3200 mm diameter, is given below:

\[ V = 0.18d^{0.49} \]  

where \( V \) is the mean flow velocity and \( d \) is the particle size in millimetres. The largest River Park gravels have an average intermediate axis of 115.5 mm, therefore, using Costa's relationship, they require a mean velocity of at least 1.8 m s\(^{-1}\) to initiate transport.

Estimates of velocity and peak discharge for the largest floods at Cowra were also derived from the Manning equation. A cross-section of the valley was surveyed close to the location of the streamflow gauge at Cowra. The largest gauged flood in 1952 reached a stage 0.7 m below the maximum flood height reached in 1870 and shown on Fig. 3.28. In 1870, the surface water width perpendicular to the flow measured 1180 metres and mean flow depths over the Erambie terrace and floodplain averaged 3.2 and 6.1 metres respectively, increasing to 5.9 and 7.6 metres at section 1, two km downriver (Fig. 3.8). Because of the relatively large depths of floodplain flow and the
Fig. 3.28 Surveyed cross-section of Lachlan Valley near the streamflow gauge at Cowra, showing 1870 peak flood stage and cross-section. Floodplain and channel segments with various roughness coefficients are calculated using methods given in Acrement and Schneider (1989), and are for discharge estimates given in Tab. 3.5. Location is shown as section 2 on Fig. 3.8.
irregular surface topography, and because floodplains typically have very
different roughness coefficients to channels (Acrement and Schneider 1989),
values of Manning's $n$ were calculated separately, following the methods
given in Acrement and Schneider. This is similar to the simple additive
method of Cowan (1956), in which values for surface irregularities, channel
shape and size, obstructions to flow, vegetation and degree of meandering
are added to a base value judged from sediment size. For floodplains, the
base value is based on the surface sediment of the floodplain (or terrace) and
correction factors are made only for surface irregularities, obstructions and
vegetation. Using this method, roughness coefficients for the floodplain
sections, $n_1$ and $n_2$, were judged to be 0.030 and 0.071 respectively. A
channel roughness coefficient of 0.08 was derived from the Manning
equation, using DLWC estimates of velocity. (The channel $n$ value is high
compared with results reported from other suspended-load or mixed-load
rivers (Leopold et al 1960, Barnes 1967, Hicks and Mason 1991), and
physical obstacles such as logs and riparian tree roots may contribute
hitherto unrecognised roughness.) The Manning equation is given below:

$$\nu = \frac{R^{2/3}s^{1/2}}{n}$$  \hspace{1cm} (3.2)

where $\nu$ is the mean velocity in ms$^{-1}$, $R$ is the hydraulic radius of the channel
in metres, $s$ is the slope and $n$ is Manning's roughness coefficient (Leopold et
al 1964). The floodplain slope is known from a survey of the floodplain two
kilometres downstream; the relative difference in elevation of back channels
was used to avoid the surface irregularities found closer to the river. The
lower channel gradient of 1 in 1640 was used to calculate velocity along the
main channel. Mean depth, calculated as cross-sectional area of the flow
divided by the surface width, was used in place of the hydraulic radius.

Applied to the 1952 flood, separate calculations of flood discharge for
floodplain and channel segments gives velocities of 0.4 ms$^{-1}$ and 0.9 ms$^{-1}$ for
the floodplain and 1.7 ms$^{-1}$ for the channel, and discharges of 20 m$^3$s$^{-1}$, 1440
m$^3$s$^{-1}$ and 3150 m$^3$s$^{-1}$ giving a total peak discharge of totals 4610 m$^3$s$^{-1}$ (Tab.
3.5). The same method can be used on the largest historical flood in 1870,
which reached a stage height of 15.9 metres. Mean velocities over the
Erambie terrace were calculated at 1.0 ms$^{-1}$ with 1.8 ms$^{-1}$ in the main channel and total discharge is calculated as 6730 m$^{3}$s$^{-1}$.

Estimates using the Manning equation are slightly lower those obtained from DLWC (1996), who estimated a discharge of 5380 m$^{3}$s$^{-1}$ for the 1952 flood, while velocities are consistent with those obtained from estimating minimum transport requirements of the cobbles on the floodplain at River Park. Given that the velocity estimates using the competence method can involve errors of 25-100% (Williams and Costa 1988), the large cobbles deposited on the floodplain could have been transported during most of the larger historical floods.

Studies of catastrophic response are usually more concerned with the erosional impact of large floods on apparently stable, well-adjusted floodplains. Erosional effects are the result of a combination of hydraulic factors (mostly slope and discharge) and resistance to scour of the floodplain itself. The hydraulic expression of flood power is normally given by the boundary shear stress ($\tau$) in N m$^{-2}$ and unit stream power ($\omega$) in W m$^{-2}$ (Baker and Costa 1987). Boundary shear stress is normally calculated as

$$\tau = \gamma RS$$

where $\gamma$ is the specific weight of water, normally 9807 N m$^{-3}$, $R$ is hydraulic radius, although mean depth (m) is often substituted in wide channels and valleys, and $S$ is valley slope. Unit stream power ($\omega$) is

$$\omega = \gamma DVS$$

where $D$ is water depth (m) and $V$ is velocity (ms$^{-1}$).

Using velocities and depths estimated over the Erambie terrace gives bed shear stresses of 33 N m$^{2}$ and 26 N m$^{2}$ for the 1870 and 1952 floods respectively, and unit stream powers of 32 W m$^{2}$ and 22 W m$^{2}$ (Tab. 3.5). Greater depths over the floodplain increase these values to 77 N m$^{2}$ and 70 N m$^{2}$ with unit stream power of 140 W m$^{2}$ and 120 W m$^{2}$. Shear stresses and stream power values for the smaller historical floods shown in Tab. 3.5.
are based on DLWC estimates of peak flood discharge divided by the surveyed cross-sectional area. The variability in results, e.g. calculated velocities of 1.9 m\textsuperscript{s} for smaller floods in 1900 and 1925, suggests their methods were not consistent.

<table>
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<tr>
<th>Year</th>
<th>Peak stage (m)</th>
<th>Peak discharge (m\textsuperscript{3}s\textsuperscript{-1})</th>
<th>Mean velocity (m\textsuperscript{s})</th>
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<th>Floodplain</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>bed shear stress (N m\textsuperscript{2})</td>
<td>unit stream power (W m\textsuperscript{2})</td>
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<td>32</td>
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<td>1.4</td>
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<td>4163*</td>
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Tab. 3.5 Estimates of bed shear stress and stream power on Erambie terrace and floodplain at Cowra based on velocities derived from the Manning equation (*) and DLWC estimates (•).

Magilligan (1992) defines minimum stability thresholds for significant alteration of floodplain surfaces in gentle-gradient, alluvial rivers in humid and sub-humid environments with catchments from 10 km\textsuperscript{2} to 3000 km\textsuperscript{2} as being 100 N m\textsuperscript{2} and 300 W m\textsuperscript{2}. Such forces are not achieved at Cowra by even the largest recorded floods. However, major morphologic adjustments with both major erosion and deposition on the floodplain and adjacent terrace occur here during lower stream power and shear stress thresholds than reported elsewhere in the world. Maximum flood velocities, bed shear stresses and unit stream powers calculated for the floodplain and terrace of 1.5 m\textsuperscript{s}, 33-70 N m\textsuperscript{2} and 50-115 W m\textsuperscript{2} respectively, are higher than those generated at bankfull stage for the main channel of 1.1 m\textsuperscript{s}, 30 N m\textsuperscript{2} and 60 W m\textsuperscript{2} respectively. Costa and O'Connor (1995) suggest peak flow duration is an important determinant of geomorphic effectiveness on alluvial rivers in northern United States and it is possible that a long duration of peak flow discharge seen on Lachlan floods (11 hours in the 1952 flood), may allow more significant floodplain modification than larger flash floods that maintain peak flow conditions for only a couple of hours. The local stability
threshold on the Lachlan may also be reduced when riparian and floodplain vegetation dies back during times of drought, which may terminate with a flood.

The frequency of flood discharges causing major morphologic adjustments to the floodplain is also higher on the Lachlan than on other temperate, alluvial rivers. The high flood competence of floods with a recurrence interval of 12 years suggests that the local minimum stability threshold is regularly exceeded on the Lachlan. In typical basins analysed by Magilligan (1992), stability thresholds were exceeded by floods with a magnitude of 2-18 times that of the 100 year flood.

3.11 Discussion

The main channel at Cowra has an anomalously large channel capacity, which is reflected in unusually long return periods of bankfull flows of 4.2 years (2.5 years on the partial series) compared to the global median of 1.58 (1.0) cited by Dury (1973). No evidence was found for Holocene or post-settlement incision, which has been suggested as a cause of lower than normal bankfull frequencies on some Australian rivers (Dury et al 1963). Indeed, the Lachlan appears to have aggraded its channel over the past 1700 years. Longer return periods of bankfull flows are also predicted for rivers with dominantly vertically accreting floodplains because the floodplain is not regularly consumed by cut-bank and point bar migration, which would otherwise keep it to a consistent level (Wolman and Leopold 1957, Nanson 1986). The large channel capacity at Cowra is attributed to greater confinement of large flood flows, increasing the water depth and concentrating bed shear stress and stream power within a narrow floodplain. As shown in Chapter Four, the relationship the influence of flooding width consistently influences channel capacities between Cowra and Gooloogong. Rutherfurd (1994) reported a similar situation on semi-confined reaches (<3 km wide) of the lower Murray River, where high velocities attained during overbank stages produced a larger capacity channel than found in unconfined reaches.

In most situations, rivers develop their bankfull channel to cope with the normal range of flows (Leopold et al 1964). While abnormally high flows
have been reported to pass almost unnoticed on some channels and floodplains (McKee et al 1964, Gardner 1970), others experience significant geomorphic modification. The typical catastrophic flood response is considered to be the destruction of vegetation and massive channel widening, often accompanied by braiding or a decrease in sinuosity (Schumm and Lichty 1963, Ostercamp and Costa 1987) and normally followed by several decades of recovery with vegetation re-establishment and channel infilling. In flood-prone areas where large floods recur at intervals shorter than the recovery time of the stream, quasi- or non-equilibrium river forms tend to develop (Stevens et al 1975). Such responses have been documented on steeper coastal streams in Australia (Nanson 1986, Erskine 1996). The Lachlan between Cowra and Gooloogong flows over gentler gradients than the coastal streams described by Erskine and Nanson, and has a stable channel similar to low gradient streams in the western Murray Darling basin, yet it possesses a variety of features on the floodplain normally attributed to rare, high magnitude flood events and which here are observed to be forming under the natural flood regime of the river. During large floods, the channel is bypassed and the main effects of the floodwaters are transferred to the floodplains. The inability of the channel to rework flood deposits to any considerable degree has resulted in an essentially flood dominated floodplain which is relatively stable but does exhibit a number of high-energy features that become slowly subdued by sediment accretion. The stability of the main channel is such that many late Pleistocene palaeochannels have survived and continue to exert a direct influence on the morphology of the present river, which remains in an inherited state in some reaches. "Flood-dominated systems" have been associated with highly variable rivers where the modal flow is far lower than bankfull discharge (Brackenridge 1988). The flood response on such rivers is geared toward overbank flooding rather than channel enlargement. On the Lachlan, the wide range of flows combined with the effects of partial confinement of the floodplain have resulted in a high energy floodplain which contains a stable, low energy channel.

This kind of compound channel, in which flood flows are physically separated from smaller flows, has been recognised in several climatic environments. The channel country in arid central Australia features
separate channel networks for high and moderate flows although this is largely the result of sedimentological changes (Nanson et al 1986). Floodplains in which there is more than one level of geomorphic activity have been described in the ephemeral desert streams of central Australia, where processes operate at a variety of scales but cannot be said to achieve any degree of equilibrium (Pickup 1991). Tiered floodplains are found in the seasonal and monsoonal tropics in which features relating to large floods are a persistent feature of the landscape. A large part of the work of these stream is carried out during high magnitude floods (Rajaguru et al 1995, Gupta 1995). Alluvial rivers in humid, temperate climates have been considered unlikely to develop enough flood power to substantially modify their floodplains (Magilligan 1992), although McGowan and Garner (1970) considered that "the type of discharge (flashy or continuous) is also a critical factor controlling the channel pattern and hence the types of sedimentary structures present in the larger accretionary features". Erskine (1999) also ascribes the compound channel form of many Australian rivers to the differential impacts of catastrophic and smaller floods and the highly variable character of Australian hydrology.