The drivers and consequences of change to the physical character of waterholes on an Australian dryland river.

Photo credit: Western Local Land Services

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CANDIDATE'S CERTIFICATION

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification.

I certify that any help received in preparing this thesis and all sources used have been acknowledged in this thesis.

ABSTRACT

Waterholes are a critical feature of dryland rivers globally, providing geomorphic and ecohydrological complexity. Waterholes typically develop as a series of deep pools that can retain water for extended periods in the absence of surface water connectivity or groundwater inputs. They are often the only source of water in an otherwise arid environment and as such have high ecological, social, and cultural value. From an ecological perspective, waterholes provide refuge to aquatic biota in a drying environment ensuring both their immediate survival and their subsequent recolonisation of the broader river system once flows recommence. Waterholes provide an important water supply to local communities for stock and domestic use and recreation. They are also pivotal to the cultural practise and spiritual beliefs of Indigenous Australians. This study has shown that despite their significance in the landscape, waterholes are increasingly threatened by anthropogenic landscape change. The Barwon-Darling River, an alluvial, dryland river in south-east Australia, is a river where the impact of human activity on waterholes is of concern. This thesis is aimed at understanding (1) if and how the physical character of waterholes on the Barwon-Darling has changed since European colonisation and (2) understanding the drivers and consequences of change to waterholes on the Barwon-Darling River.

In this study, a comparison of historical (1890s) and contemporary (2015) riverbed profiles revealed a substantial change to the depth and spatial distribution of waterholes post European colonisation. The trajectory and magnitude of change is spatially variable and closely aligned with the presence or absence of low-level weirs. These structures create artificially high-water levels immediately upstream of the weir structure, which has increased waterhole depths for approximately 40 % of the river. In contrast, waterholes located outside of the weir pool influence have experienced a significant decline in maximum waterhole depths (median decline of 1.6m). This has resulted in fewer deep waterholes, which is also associated with an increase in the distance between the remaining deep waterholes (i.e., those deeper than 4m). In some cases, those distance have more than doubled. A change to the depth of waterholes and their spatial distribution has serious implications for

hydrological connectivity, water quality, habitat availability and for the long-term presence and persistence of waterholes in the landscape.

The decline in waterhole depths observed on the Barwon-Darling has been attributed to an increase in the rate of sedimentation associated with anthropogenic landscape change. Anthropogenic landscape change has increased the delivery of sediment to the river whilst reducing the capacity of the river system to transport sediment. Although sediment can originate from a range of sources, this study focused on the potential contribution from alluvial floodplain gullies. Floodplain gullies were found to be a prevalent feature within the catchment, with their presence increasing over the past 50 years. Over 4000 gullies were recorded, impacting an area of floodplain of approximately 148 million m^2 and with a combined gully length of 2364 km. The total volume of sediment originating from these gullies is approximately 168 million m^3, which is magnitudes higher than previous estimates for gully erosion in the Barwon-Darling catchment. However, given the gullies in this study have been cut into floodplain alluvium it was assumed that a sizable proportion of the fine sediment exported from the gullies would have remained in suspension and therefore transported some distance from the original source gullies. This was supported through statistical analysis that showed no predictive relationship between the total volume of gully derived sediment delivered to a reach and the magnitude of change to waterhole depth in that reach. The less mobile coarse sediment fraction would, however, be more likely to contribute to the shallowing of waterholes and to the expansion of in-channel feature such as bars and benches.

Like many dryland rivers, the flow regime of the Barwon-Darling River has been modified as a result of water resource development. The abstraction of water, interception of floodplain flows and storage of water within in-stream impoundments has substantially altered the frequency, magnitude, and duration of flows. These changes have compromised the capacity of in-channel flows to entrain and transport sediment, reducing opportunities for sediment to be conveyed throughout the system. The number of events capable of entraining sediment has declined from 23 to 48 % across all sediment calibres (i.e., coarse sand, coarse silt/fine sand, fine silt/clay), whilst the frequency and duration of flows conducive to sediment deposition have increased considerably. Overbank flooding has halved, limiting the opportunities for lateral sediment exchange with the floodplain. During periods of low flow, the longitudinal transport of sediment is limited by low-level weirs. Collectively, these modifications increase the likelihood of sediment being retained within the river channel and, as such, increases the opportunity for within-channel sedimentation and the in-filling of ecologically important waterholes.

Fish populations were used to examine the influence of waterhole depth on dryland river ecology. In particular, the focus was on determining if access to deep water habitat within the broader waterhole setting would influence fish assemblage patterns. Waterhole depth is an ecologically important variable as it influences habitat availability, water quality, density-dependent biotic interactions, and waterhole persistence. As such, waterhole depth was expected to shape fish assemblage patterns in the Darling River, however, its affect was thought to be difficult to isolate given the association that water depth has on creating habitat complexity through the inundation of in-stream wood and other habitat features. As a result, this study investigated the independent and interactive effects of both waterhole depth and habitat complexity on fish assemblage patterns. The presence and size of in-stream wood was used as a surrogate for habitat complexity. The results suggest that waterhole depth does not directly influence fish assemblage patterns, nor does it have an interactive effect with habitat complexity. A significant relationship with in-stream wood was observed, but only when native fish assemblages were considered. The inclusion of exotic species had a homogenising influence due to the relatively even distribution of common carp across sites of varying complexity. Despite this outcome, depth remains a critical factor in dryland rivers as it ensures the presence and persistence of waterholes within the landscape and creates important fish habitat through the inundation of in-stream wood and other habitat features.

The findings in this thesis enhance our understanding of the trajectory and magnitude of geomorphic adjustment that can occur on a dryland river as a consequence of anthropogenic landscape change. This study has shown that the threat to dryland river waterholes is not limited to any one issue but is instead the culmination of a broad range of disturbances within the catchment (i.e., landuse on the adjacent floodplain, modifications to the flow regime, in-stream infrastructure, climate change). Often though, it is difficult to isolate the impact of individual activities given the large spatial and temporal scale at which human disturbance has occurred. As such, it is imperative to establish an integrated approach to managing sediment on dryland rivers, which could include landscape management through gully remediation and grazing management, the provision of environmental flows and the removal of redundant in-stream infrastructure. The results from this study have relevance to dryland rivers globally, highlighting the significance of these important and widespread rivers.

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CHAPTER 1

Introduction

1.1 BACKGROUND

The physical template of a river is a fundamental concept in riverine ecology (Wohl et al., 2015). The physical template is a dynamic, moving mosaic of environmental conditions upon which aquatic biota evolve and adapt (Norris & Thoms, 1999). In an unmodified system, the physical template is controlled by fluvial processes operating at a range of spatial and temporal scales (Figure 1.3) (Thoms, Parsons, & Southwell, 2016). The long-term climatic conditions (precipitation and evaporation) in combination with catchment characteristics (geology, topography, soil type and vegetation) dictate rainfall-runoff relationships (Fryirs & Brierley, 2013b; Meitzen, Doyle, Thoms, & Burns, 2013). Combined these elements govern the shape, size, and slope of the river channel and the drainage network in which the river operates. These features directly influence the distribution of available energy, which is fundamental to the movement of water and sediment throughout the catchment. The presence of sediment and water, in turn, regulates the erosion and depositional processes that are responsible for channel formation (Fryirs & Brierley, 2013b). Natural structural elements within the river channel such as large woody debris, bedrock and/or boulders can influence the physical template by altering flow hydraulics (Wheaton, Fryirs, Brierley, Bangen, Bouwes & O'Brien, 2015). Structural elements promote flow separation leading to the formation of low and high energy zones which force the creation of geomorphic units (Wheaton et al, 2015). A river's longitudinal profile, planform and cross section shape and size, as well as in-channel features such as bars, benches, islands, and waterholes are all recognisable components of a river's physical template (Charlton, 2007). It is these features that provide the habitat heterogeneity that support aquatic organisms throughout their various stages of life (Thoms et al., 2016). The presence and actions of these organisms interacting with the physical template will, in turn, influence the physical character of the river in which they live (Thoms et al., 2016).

Human activities can trigger morphological adjustments to the physical template by altering the way in which water and sediment are conveyed throughout the system (Meitzen et al., 2013; Wohl, 2015, Wheaton et al, 2015). These disruptions arise from the direct alteration to the river channel (e.g., through dams and weirs, channel straightening) and to the surrounding catchment (e.g., on-farm storages, levee banks, land cover change). Indirectly these modifications will affect the physical template by influencing the movement of sediment and water throughout the system (Meitzen et al., 2013; Ta, Xiao, & Dong, 2008; Thoms & Walker, 1993), and by altering flow hydraulics (Wheaton et al, 2015). Human disturbance can drive the physical template of the river to a state beyond its natural contemporary range, having significant implications for channel complexity, lateral and longitudinal connectivity and ultimately the availability of physical habitat in space and time (Grabowski, Surian, & Gurnell, 2014; Meitzen et al., 2013; Petts & Gurnell, 2005). The loss of physical habitat due to human interference is now being recognised as one of the leading factors contributing to the decline in freshwater biota globally (Koehn & Nicol., 2014; Reid et al., 2019). Climate change is expected to further modify the physical template by increasing the frequency of extreme climatic events (i.e., droughts, floods, storms). Droughts are of particular concern, as they are expected to occur more frequently and persist for longer periods of time leading to an increased level of aridity (Larkin, Ralph, Tooth, Fryirs, & Carthey, 2020). As a consequence, surface inflows are expected to decline (Mallen-Cooper, 2020), further disrupting the sediment dynamics (Larkin et al., 2020).

Channel adjustments attributed to human disturbance can be rapid (within 10 years) or can occur over a long period of time (100s of years) and often follow a complex trajectory of change (Petts & Gurnell, 2005). Understanding the nature, magnitude and trajectory of these changes is a critical step in defining the consequences of human intervention and ultimately in guiding the management of river systems (Grabowski et al., 2014). To enable this understanding, long term data sets are required, or a well-established benchmark needs to be derived, both of which are rarely available. Without these, the totality of the system’s response (including recovery potential) to human modification is unlikely to be recognised (Grabowski et al., 2014). In dryland river systems, the lack of data is amplified because they are often in remote and challenging locations, making the collection of long-term time-series data problematic. As such, these systems are frequently data poor (Kingsford & Thompson,

2006) and as a result, management decisions are often made based on either minimal information or in the absence of catchment specific data. Consequently, alternative approaches to assessing geomorphic change are required to fully assess the impact of human disturbance on the physical template of dryland rivers. Historical records for example, are helpful as they provide possible benchmarks against which ongoing temporal change can be assessed (Reid and Ogden, 2006). Such data sets have been used frequently in modern day research and have proven useful for exploring changes to channel morphology over decadal time scales (Gurnell et al., 2016; Rinaldi, 2003). Among these records are the longitudinal profiles, planform maps and channel cross sections (Grabowski et al., 2014; Gurnell et al., 2016) created by engineers and surveyors in the early days of settlement. In more recent decades, the use of remote sensing data and geographical information systems (GIS) has been transformational in capturing data on landscape characterises at unprecedented scales (Fryirs, Wheaton, Bizzi, Williams & Brierley, 2019). Remote sensing and GIS now enable investigations to be undertaken at a much broader scale than what could have done only a few decades ago (Fryirs, Wheaton, Bizzi, Williams & Brierley, 2019).

1.2 DRYLAND RIVERS

1.2.1 The occurrence of dryland rivers globally

Dryland areas encompass approximately 50 % of the global land surface, including the hyper-arid, arid, semi-arid, and dry humid regions (Tooth, 2000). Many thousands of kilometres of streams and large rivers flow through these areas (Kingsford & Thompson, 2006). These rivers are collectively known as ‘dryland’, ‘desert’ or ‘arid-zone’ rivers (Tooth & Nanson, 2011), and they are particularly prevalent on the Australian continent.

Australia is one of the driest continents in the world (Nanson, Tooth, & Knighton, 2002) with approximately 75 % of the land surface classified as being an arid or semi-arid dryland landscape (Kingsford & Thompson, 2006). The bulk of Australia’s dryland landscape is in the continent’s interior, which is surrounded by extensive sub-humid areas (Tooth & Nanson, 2011). Of the 3.5 million kilometres of river channels that flow across the Australian continent 92 % of these are classified as lowland with the bulk of them flowing through a dryland region (Thoms & Sheldon, 2000).

1.2.2 Defining dryland rivers

Dryland rivers exist globally, across a wide range of tectonic, structural, lithological, and vegetative settings and, as such, defining them collectively has proven to be problematic (Nanson et al., 2002; Tooth & Nanson, 2011). Dryland rivers can range from high energy rivers, which drain predominately small, steep catchments (as found in the Mediterranean) to the large, low gradient, low energy rivers typical of the Australian continental interior (Tooth & Nanson, 2011). In further defining the characteristics of a dryland river for the purposes of this document, it is the latter that will form the basis of discussion.

In Australia, a dryland river can be defined as any river flowing wholly or partly through a dryland region. That is an area with an annual rainfall of less than 500 mm/year (Kingsford & Thompson, 2006). Rainfall within these areas can be extremely variable throughout both space and time (Kingsford & Thompson, 2006, Walker et al, 1995). The bulk of the rainfall can result from a single intense storm event followed by extended periods of little to no rain (Young & Kingsford, 2006) creating high inter-annual rainfall variability (Thomas, 2011). As such, many dryland rivers experience decadal-scale cycles of above and below average rainfall (Nanson et al., 2002). In Australia, like many other dryland regions throughout the world, this variability has been linked to the atmospheric circulation phenomenon known as the El Niño Southern Oscillation (ENSO) (Santoso et al., 2016). McMahon and Finlayson, (2003) suggests that ENSO contributes to approximately one third of the variation in regional rainfall within Australia. ENSO cycles between the extreme phases of El Niño and La Niña due to oceanic and atmospheric variability in the Southern Pacific Ocean (Pui, Sharma, Santoso, & Westra, 2012). El Niño events typically occur in Australia every 2-7 years, and they are associated with an increased likelihood of drought (Head, Adams, McGregor, & Toole, 2014). Conversely, La Niña events, which occur intermittently with El Niño, are aligned with periods of above average rainfall (Head et al., 2014). Extremes in rainfall variability are also influenced to a lesser extent by the sea temperatures across the Indian Ocean Dipole (IOC), the Interdecadal Pacific Oscillation (IPO) and the position of the Southern Hemisphere westerlies (the Southern Annular Mode) (Dong & Dai, 2015; Santoso et al., 2016).

Evaporation and transpiration rates in Australia are high and can at times account for up to 95 % of rain falling within the dryland regions (Young & Kingsford, 2006). The high evaporation rates experienced in these areas lead to the minimal conversion of rainfall to runoff (Thoms, Beyer, & Rogers, 2006). In Australia, the mean rainfall to runoff ratio is only 9.8 % compared to the world average of 48 % (Thoms et al., 2006).

1.2.3 Hydrological features of Australian dryland rivers

The defining feature of dryland rivers throughout Australia (and the world) is the high spatial and temporal variability in flows (Walker, Sheldon, & Puckridge, 1995). This variability is symptomatic of the patchy, unpredictable rainfall, extreme rates of evaporation and the low rainfall – runoff ratios experienced in these areas (Thoms & Sheldon, 2000). Discharge in Australian dryland rivers is among the most variable in the world (Puckridge, Sheldon, Walker, & Boulton, 1998). The mean coefficient of variation (Cv) of annual flows for Australian dryland rivers is 1.27, with similar patterns in South Africa (1.14) and the Mediterranean (1.25). These Cvs are twice those experienced in more humid climates (Walker et al., 1995). Mean annual flow variability is typically higher in very large catchments where the river must traverse greater distances (Puckridge et al., 1998).

Dryland rivers can be classified as either allogenic or endogenic based on the origin of their flows (Tooth & Nanson, 2011). Allogenic rivers typically have their headwaters located in the more humid uplands before flowing downstream through a drier lowland catchment. As such, discharge is sourced primarily from rainfall in the upper catchment. The flow in allogenic rivers is typically perennial but can still be variable in nature (Tooth & Nanson, 2011). In contrast, endogenic rivers source most their water from within the dryland region and typically terminate within the dryland interior (Tooth &

Nanson, 2011). Endogenic rivers can be classified as either intermittent (i.e., seasonal flooding followed by little to no flow) or ephemeral (i.e., occasional floods interspersed with periods of no flow) (Nanson et al., 2002). Despite some commonalities between the two types of dryland rivers (i.e., high transmission losses and high flood magnitudes) there are multiple variables that are specific to river type and ultimately influence the way in which water and sediment moves throughout the system. Figure 1.1 is taken from Tooth and Nanson 2011 and demonstrates the extreme variability that can be seen across the spectrum of dryland rivers (i.e., perennial, intermittent and ephemeral).

	EPHEMERAL STREAMS	INTERMITTENT STREAMS	PERENNIAL STREAMS
FLOW OCCUPANCY ***(% of time with linear flow)***	**0 %**	**50 %**	**100 %**
INPUT	Convective storms	Variable combination of convective storms + periodic incursion of moist air (often seasonal)	Predominately springs + wetter mountainous headwaters, snowmelt.
	Highly localised	→	Large supply area, especially headwaters
	Extremely variable	→	Great reliability
THROUGHPUT	Hortonian overland dominant flow	→	Broader mix of surface and subsurface processes
	Rapid initiation of surface runoff	→	Longer response times
	Transmission losses largely through seepage	→	Transmission losses largely through evaporation
OUTPUT	Flash floods likely	Single and multiple peaked floods	Seasonal floods
	Sharply peaked hydrographs	→	Broader based hydrographs
	Considerable variability	→	More (seasonally) dependable
CHANNELS	Poorly connected drainage network	Better integrated drainage networks, commonly high density	Mostly dominated by a single large river
	High magnitude floods commonly a major control on channel adjustment	→	More frequent discharges of greater significance in channel adjustment
	Greater tendency for non-equilibrium channel	→	Greater tendency for channels to attain equilibrium

Figure 1.1: Summary of the hydrology, drainage network and channel characteristics found within dryland rivers (taken from Tooth and Nanson, 2011).

1.2.4 Sediment delivery in Australian dryland rivers

Dryland rivers experience extreme variability in sediment transport characteristics based on the rivers' size, gradient, and location (Nanson et al., 2002). Common to all dryland rivers, however, is that they typically transport large quantities of sediment during flood events, both as suspended sediment and as bed load material (Nanson et al., 2002; Tooth & Nanson, 2011). These high sediment loads reflect the ready mobilisation of sediment from the adjacent catchment and the lack of a protective armour layer making bed material readily available (Nanson et al., 2002). Bed load material is mobilised predominantly on the rising limb of the hydrograph with deposition of a similar amount occurring on flood recession. This process in dryland rivers is commonly known as 'scour and fill' and is fundamental to the formation and maintenance of deep pools (or waterholes) within the system (Tooth, 2000).

Suspended sediment concentrations typically remain high in dryland rivers even under low flow conditions. Suspended sediment concentrations in the range of 30-50 g L^{-1} are common and in extreme events concentrations have been observed in excess of 100 g L^{-1} (Nanson et al., 2002; Tooth, 2000). The movement of suspended material varies depending on the prevailing flow conditions and specifically on water velocity (Tooth, 2000). Water velocity will dictate the size and quantity of sediment that can be physically transported and can therefore limit sediment distribution more so than sediment availability (Tooth, 2000). High sediment yields are typically exported in all dryland rivers. In Australia, the sediment yield is dominated by the suspended sediment component (Olley & Caitcheon, 2000). The highly variable nature of the flow regime in dryland rivers has a substantial influence on the movement of sediment throughout the system. Sediment responds to flow variability by moving as a sequence of waves with bed load and suspended material shifting in a series of short, spasmodic steps (Tooth, 2000). This means that the process of scour and fill is unlikely to be synchronised, meaning any one reach (or waterhole) may be experiencing scouring whilst a neighbouring reach (or waterhole) is filling (Tooth, 2000).

1.2.5 The boom-and-bust ecology of dryland rivers

Hydrological connectivity (or the lack of) is a key feature of dryland rivers, which is governed by the extremes in flow that are common to dryland rivers. It is this variability in connectivity that contributes to the 'boom and bust' ecology often referred to when describing dryland rivers (Bunn, Thoms, Hamilton, & Capon, 2006; Jenkins & Boulton, 2003; Marshall, Lobegeiger, & Starkey, 2021; Sheldon et al., 2010). During flood events dryland rivers experience periods of high lateral and longitudinal connectivity. The magnitude, duration, and rate of rise and fall of these flood events dictate the strength of connectivity throughout space and time (Sheldon et al., 2010). Episodes of extensive flooding (the boom) connect the adjacent floodplain and wetland habitats to the river resulting in periods of intense reproduction and high productivity (Bino, Kingsford, & Porter, 2015; Bunn, Thoms, et al., 2006; Sternberg, Balcombe, Marshall, Lobegeiger, & Arthington, 2012). In contrast, periods of drought result in low levels of connectivity and subsequently high levels of fragmentation (Allen et al., 2019; Stanley, Fisher, & Grimm, 1997; Steward, von Schiller, Tockner, Marshall, & Bunn, 2012). Extended dry periods (the bust) result in the contraction of available habitat (Stanley et al., 1997), often into a series of isolated pools (Allen et al., 2020; Sheldon et al., 2010; Steward et al., 2012). These cycles of boom and bust (or expansion and contraction) are believed to have a profound and fundamental role in shaping the ecological character of dryland rivers (Allen et al., 2019; Hopper et al., 2020; Stanley et al., 1997; Webb, Thoms, & Reid, 2012).

The 'flood pulse' is a fundamental driver for the lateral exchange of energy, nutrients and organic matter between the river channel and the adjacent floodplain (Junk, Bayley, & Sparks, 1989; Junk & Wantzen, 2003; Thoms, 2003; Tockner, Malard, & Ward, 2000). Although the flood pulse on dryland rivers can be intermittent and unpredictable (Puckridge, Walker, & Costelloe, 2000), this exchange is important in that it can facilitate an intense boom in reproduction and productivity in both the river and on the adjacent floodplain (Bino et al., 2015; Bunn, Nungesser, et al., 2006; Thoms, 2003). In the event of a flood pulse, inundated areas are rapidly colonised by fish and invertebrates and large-scale breeding events are often observed (Arthington & Balcombe, 2011; Balcombe & Arthington, 2009;

Chaki, Reid, & Nielsen, 2021). The flood pulse can trigger an increase in primary productivity with the emergence of plants and invertebrates from seed or egg banks residing on the floodplain (Boulton, 2006; Brock, 2006; Capon, 2003; Chaki et al., 2021; Reid & Capon, 2011; Reid, Ogden, & Thoms, 2011). As flood waters recede and habitats contract the boom in productivity is significant in that it ensures that the river enters a period of dry with a diverse, abundant, and healthy population of organisms (Arthington & Balcombe, 2011; Stanley et al., 1997). As the river ceases to flow, often for extended periods of time, the persistence of isolated pools is critical to the survival of aquatic biota and subsequently, to the long-term maintenance of biodiversity in dryland rivers (Marshall et al., 2016; Sheldon et al., 2010). These areas are often referred to as refugia and will be discussed in greater detail in section 1.3 of this document.

Of equal importance to the flood pulse, however, are the in-channel flows (or flow pulses) that occur frequently on dryland rivers in between the major flood events (or flood pulse) and no flow periods (Bunn, Nungesser, et al., 2006; Puckridge et al., 1998; Tockner et al., 2000). These flow pulses ensure that disconnected waterholes are frequently reconnected, and the water lost through evaporation during dry times is replenished (Bunn, Nungesser, et al., 2006). Connection events are critical to maintaining waterholes in dryland rivers. Connection events not only ensure that the physical presence of waterholes is maintained but also mitigate the extreme water quality conditions commonly experienced during low flow periods (Bonada et al., 2020; Fellows, Bunn, Sheldon, & Beard, 2009; Hopper et al., 2020).

1.3 REFUGIA IN DRYLAND RIVERS

1.3.1 Defining refugia

The definition of refugia in the ecological literature adheres to two broad themes (Sheldon, 2010). In the broadest sense, refugia are defined as habitats (or places) that support populations not able to live elsewhere in the landscape (Lancaster & Belyea, 1997). Alternatively, the concept of disturbance can be applied, with refugia being re-defined as a place (or time) where the negative effects of disturbance are lower than in the surrounding place (or time). During unfavourable conditions, organisms utilising refugia have a greater probability of survival and, as such, are critical for the recruitment and recolonisation of the adjacent areas once the disturbance has passed (Lancaster & Belyea, 1997). Disturbance can relate to both abiotic (e.g., droughts and floods) and biotic (e.g., predation) factors.

Refugia are, however, constrained by the spatial and temporal needs of a specific organism. Refugia can range from the smallest (e.g., microhabitat) to the largest (e.g., drainage basin) spatial scale and from the shortest (e.g., hours) to the longest (e.g., millennia) temporal scale (Magoulick & Kobza, 2003). For example, small habitat patches (e.g., centimetres to metres) may have lower temperatures and increased dissolved oxygen concentration that could provide refuge for fish over short periods of time (e.g., minutes to hours). In contrast, large habitat patches (e.g., kilometres) may retain water during an extended drought providing fish with refuge for years to decades (Magoulick & Kobza, 2003). The quality and usefulness of refugia can vary throughout space and time and is species and life stage specific. As an example, a waterhole (or deep pool) that has the ideal physical and chemical conditions for a particular fish species may become intermittently inadequate as flows cease and water levels decline. In such an event, water quality conditions can deteriorate, and the waterhole can become thermally unsuitable for that fish species until flow returns to the system (Fellows et al., 2009). Alternatively, a deep waterhole may provide an ideal refuge for a large-bodied piscivorous fish species, but as a result smaller species or juveniles of large-bodied fish may delay colonising the same waterholes until water levels recede and the shallower water become unfavourable for the larger fish species (Magoulick & Kobza, 2003).

1.3.2 Refugia in dryland rivers

In Australian dryland rivers, the most referred to refugia are known as waterholes. Waterholes typically develop as a string of deep pools that can retain water in the absence of surface flow or groundwater inputs (Knighton & Nanson, 1994). Waterholes form in low gradient channels at locations where flow and erosional energy have concentrated (Knighton & Nanson, 2000). Waterholes are regarded as self-maintaining scour features (Knighton & Nanson, 2000). During periods of low to medium flows these deep pools are natural depositional areas, whilst in higher flows excess energy can induce scour leading to the deposition of sediment downstream (Knighton & Nanson, 2000; Reid, Thoms, Chilcott, & Fitzsimmons, 2016). In alluvial systems, waterholes attain a more permanent status in the landscape once scouring has breached the underlying mud-sand boundary conditions (Knighton & Nanson, 2000). The range of variability between erosion and depositional processes ensures the long-term maintenance of waterholes within dryland regions (Reid et al., 2016). Waterholes are considered contemporary features of the landscape owing to their location within the active channel and the fact that many exhibit downflow splay deposits suggesting ongoing morphological change (Knighton & Nanson, 2000).

Waterholes are often the only source of water in an otherwise arid environment (Sheldon et al., 2010). They are symptomatic of the hydrological extremes experienced on dryland rivers. When surface flow in the river is low or ceases to flow a dryland river becomes highly fragmented and will then only exist as a series of deep pools or waterholes (Hermoso, Ward, & Kennard, 2013; Sheldon et al., 2010). Although some biota have developed adaptations to deal with desiccation in drier times, most aquatic species depend on these remanent waterholes to survive (Hermoso et al., 2013). From an ecological perspective, waterholes provide shelter, habitat, and therefore protection from the drying environment. Once flows recommence the surviving biota form the basis of recolonisation and population recovery in the broader river system (Arthington, Balcombe, Wilson., Thoms, & Marshall, 2005; Marshall et al., 2016; Perry & Bond, 2009; Rolls, Leigh, & Sheldon, 2012). When the river is hydrologically connected waterholes contribute to habitat heterogeneity at the landscape scale by increasing the diversity of available habitat for biota (Boys & Thoms, 2006). From a socio-economic perspective, waterholes are a critical water supply for local communities for stock and domestic use and for recreation. For indigenous Australians, waterholes are critical to their sense of identity, cultural practices, and spiritual beliefs (Jackson, Pollino, Macklean, Bark, & Moggridge, 2015).

1.4 THE RESPONSE OF DRYLAND RIVERS TO HUMAN DISTURBANCE

Dryland rivers and their refugia are increasingly being threatened by human activities, which are altering their physical template and causing serious detrimental effects on refugia function and their biota (Marshall et al., 2021; Sheldon et al., 2010). As dryland rivers are often the only source of water in an otherwise arid environment they can at times be heavily exploited for consumptive use (Thoms et al., 2006). With a rising demand for water by those inhabiting the arid and semi-arid regions of the world the threat to dryland ecosystems will continue to grow (Thoms et al., 2006). This section will focus on the impact of human disturbance on sediment and hydrological connectivity on dryland rivers and will address the more indirect impact of human disturbance though the lens of climate change.

1.4.1 The concept of sediment connectivity and dis(connectivity)

Sediment connectivity can be defined as the mediated transfer of sediment over a range of spatial and temporal scales (Bracken, Turnbull, Wainwright & Bogaart, 2015; Fyrirs, 2013; Heckman, Cavalli, Cerdan, Foester, Javaux, Lode, Smetanova, Vericat, 2018). Sediment connectivity is dependent on the interplay between the structural (morphological) components of the landscape (i.e., landscape topography and vegetation patterns) and the processes that dictate the long-term behaviour of sediment flux (i.e., the flow of energy/transport vectors and materials) (Bracken et al, 2015). Sediment connectivity can be categorised as either structural or functional connectivity (Heckmann et al, 2018, Najaf, Dragovich, Heckmann and Sadeghi, 2021).

Structural connectivity refers to the physical linkage between landscape compartments which is determined by their spatial configuration within the catchment (Heckmann et al, 2018; Najaf et al, 2021). In particular, this refers to the physical contact or adjacency of a sediment source to a store or sink to which sediment can be added or removed throughout time (Fryirs, 2013). However, structural connectivity alone does not enable the transfer of sediment from one landscape unit to another (Heckmann et al, 2018). Of equal importance are the process that drive the continuum of sediment detachment, entrainment, transport, and deposition. This is referred to as functional connectivity (Heckmann et al, 2018; Najaf et al, 2021).

Dis(connectivity) occurs when the efficiency of sediment transfer is constrained by one or more limiting factors (Fryirs, 2013). Fryirs (2103) suggests that the type and strength of linkages within the catchment will determine the level of connectivity or dis(connectivity) observed. Lateral linkages, for example, are charactised by the relationship between the channel network and the broader landscape, which are driven by the magnitude and duration of overbank flow events. Lateral linkages enable sediment to be supplied to the floodplain and stored, or conversely the floodplain can be reworked resulting in the active transfer of sediment to the channel (Fryirs, 2013). In contrast, longitudinal linkages refer to the upstream-downstream connection of a river network, as well as the tributary-trunk stream relationship, whilst surface-subsurface interactions are known as vertical linkages (Fryirs, 2013). A break in any of these linkages through the presence of buffers, barriers or blankets (Fryirs, 2013, Lisenby & Fryirs, 2017) will result in dis(connectivity), these breaks are collectively referred to as blockages.

Buffers are landforms that disrupt lateral connection by preventing sediment from entering the river network. These often take the form of alluvial floodplain pockets and intact valley fill and develop as large sediment sinks which can retain sediment for hundreds to thousands of years (Fryirs, 2013). Barriers more commonly refer to the disruption of longitudinal linkages. Examples include valley constrictions which can promote backfilling and sediment storage and natural bedrock features which limit the downstream transfer of sediment. Sediment storage resulting from barriers is typically for shorter periods with sediment residing in the river for tens to hundreds of years (Fryirs, 2013). Vertical linkages can be constrained by the presence of blankets which smother landforms and prevent the reworking or removal of sediment stores from the sediment cascade (Fryirs, 2013). Understanding the relationship between linkages and blockages and where they are positioned in the landscape can enable a greater understanding of sediment connectivity within a catchment.

1.4.2 The impact of human disturbance on accelerating the supply of sediment to dryland rivers

Landscape change has impacted the supply of sediment to dryland rivers globally (Prosser et al., 2001; Wasson, Oliver, & Rosewell, 1996; Wohl, 2015) and as such has altered sediment connectivity (Heckmann et al, 2018). In Australia's Murray-Darling Basin, land use change dates back to the mid to late 19th century, when European pastoralists first displaced the indigenous people of the basin (Prosser et al., 2003). Throughout this time livestock grazing became the predominant land use across the Basin, and over the past century domestic stocking rates have often exceeded pasture availability (McKeon et al., 2004). Additional grazing pressure has been applied to the landscape from both feral pests (i.e., rabbits and goats) and from native animals such as kangaroos (Prosser et al., 2003; Waters et al., 2012; Waters, Melville, Orgill, Alemseged, & Smith, 2015). Extensive grazing pressure in the early days of settlement has been closely associated with the loss of perennial plant cover, a critical component for mitigating the widespread initiation of soil erosion (Gell et al., 2009; McKeon et al., 2004; Waters et al., 2012).

Perennial plant cover helps to maintain soil porosity, enhances infiltration, and stabilises soil through root cohesion, rain drop interception and by generating surface roughness to slow overland flow (Shellberg, Brooks, Spencer, & Ward, 2013). In the absence of perennial plant cover the critical shear stress needed to initiate erosion is substantially lowered, increasing soil loss within the catchment (Shellberg et al., 2013). The selective grazing behaviour of livestock and their water-centric movement patterns have compounded the issue by compacting the soil and creating deep, well-worn animal tracks (Gell et al., 2009). In such instances, runoff volumes increase, and overland flows concentrate into narrow pathways, increasing the velocity and erosivity of flows as they move overland (Shellberg et al., 2013). The repeated concentration of surface and subsurface flow creates a deep incision in the soil profile, which can eventually lead to gully development (Brooks, Shellberg, Knight, & Spencer, 2009; Shellberg et al., 2013). As gully systems expand, they increase the structural connectivity of the landscape and effectively provide a link for transferring large volumes of sediment from the catchment to the river channel (Frankl, Poesen, Haile, Deckers, & Nyssen, 2013; Lisenby & Fryirs, 2013; Poesen, Nachtergaele, Verstraeten, & Valentin, 2003; Shellberg, Brooks, & Spencer, 2016). In addition, floodplain development, which includes the construction of infrastructure (i.e., roads, pipelines, diversion channels) to support dryland and irrigated agriculture has been responsible for altering the natural drainage lines within the catchment. In combination with the removal of native vegetation for cropping, floodplain development has increased the sensitivity of the floodplain to erosion, resulting in further gully development and the large-scale delivery of sediment to the river system (Downes, Lake, Glaister, & Bond, 2006; Gell et al., 2009).

In lowland rivers, such as those found in the Murray-Darling Basin, sediment delivery via gully erosion consists of both colluvial material originating from the hillslopes of the upper catchment, and alluvial material that has been mobilised on the adjacent floodplain (Prosser et al., 2001; Wallbrink & Olley, 2004; Wethered, Ralph, Smith, Fryirs, & Heijnis, 2015). In Australia, hillslope erosion has received much of the attention, and as such has long been considered a significant driver of land degradation and source of sediment across the continent post European colonisation (Bartley, Hawdon, Post, & Roth, 2007; DeRose, Prosser, Weisse, & Hughes, 2003; Hancock & Evans, 2006; Prosser et al., 2001). Hillslope erosion contrasts significantly to alluvial gullying, which to date has been poorly represented in the literature (Shellberg, Brooks, & Rose, 2013). Alluvial gullying involves the reworking and remobilisation of sediment in what is traditionally recognised as the depositional or sink zone of the catchment (Schumm, 1981; Shellberg et al., 2016). Alluvial gullies often form immediately adjacent to high stream order river channels and are therefore a well-connected source of sediment to the river. In contrast, hillslope gullies can contribute vast quantities of sediment to headwater tributaries, but often have a relatively low sediment delivery ratio to the higher order trunk stream. This is due to the ample opportunity for sediment storage between the upstream source and the main river channel (Shellberg, 2011). Sediment budgets for the Murray-Darling Basin suggest gully erosion is a significant source of sediment to the rivers in the Basin (DeRose et al., 2003). However, to accurately reflect on the impact of gully erosion on the lowland rivers of the Basin a more thorough appraisal of the contribution by alluvial gullying is required, as is a better understanding of the mechanisms driving erosion on the alluvial floodplains.

1.4.3 The impact of human disturbance on the movement of sediment in dryland rivers

Water resource development has substantially influenced the efficiency of sediment delivery in dryland rivers globally (Wohl et al., 2015). The abstraction of water for irrigation and the interception of floodplain flows has reduced the magnitude and duration of flows in many dryland rivers (Graf, 2005; Kondolf & Batalla, 2005; Poff et al., 1997). Consequently, the energy (or flow competence) required to transport sediment has declined (Baker, Bledsoe, Albano, & Poff, 2011; Ta et al., 2008) altering functional connectivity (Bracken et al, 2015). High flow events that would have naturally carried the bulk of the sediment have been reduced, limiting the longitudinal and lateral conveyance of sediment throughout the system (Fryirs & Brierley, 2013b; Wohl et al., 2015). Conversely, the occurrence of low flow (or no flow) events that lack the stream power to sustain sediment in suspension have increased (Wohl, 2015). The deposition and storage of sediment has therefore become more likely (Croke, Fryirs, & Thompson, 2013), particularly for the coarser sediment fraction that has higher entrainment thresholds (Fryirs & Brierley, 2013b). The increase in deposition events is significant as it is often the coarse bedload fraction (i.e., sand/gravel) that shapes the channel morphology in dryland systems (Fryirs & Brierley, 2013b; Hooke, 2003; Tooth, 2000).

In-channel infrastructure, such as dams and weirs have created a physical barrier to the longitudinal conveyance of sediment within dryland rivers (Baade, Franz, & Reichel, 2012; Heckmann et al, 2018; Tamene, Park, & Vlek, 2006; Thoms & Walker, 1993). Additionally, these physical barriers can modify the hydraulic conditions immediately upstream of the barrier by reducing flow velocities (Bice, 2017; Mallen-Cooper, 2020), and thereby further limiting sediment conveyance (Ta et al., 2008). When sediment transport is no longer viable sedimentation occurs resulting in local deposition, which triggers morphological change.

1.4.4 The consequences of altering the supply and movement of sediment

Anthropogenic landscape change has increased the volume of sediment being deposited within dryland rivers, by influencing both the delivery of sediment to the river and the capacity of the river to transport sediment (Brooks et al., 2009; Gobin, Campling, Deckers, Poesen, & Feyen, 1999; Shellberg et al., 2016; Ta et al., 2008; Wohl, 2015). As a result, rates of sedimentation in dryland rivers are now higher than would have occurred naturally (Lobegeiger, 2010; Reid et al., 2016). Sedimentation has been responsible for substantial changes to the physical form, chemical processes and ecological health of dryland rivers and their waterhole features (Figure 1.2) (Fellows et al., 2009; Lobegeiger, 2010; Pearson, Reid, Miller, & Ryder, 2020; Prosser et al., 2001; Reid et al., 2016). Dryland rivers located in lowland environments are particularly vulnerable to the adverse effects of sedimentation due to their low energy and limited ability to recover to their natural form (Kemp, Sear, Collins, Naden, & Jones, 2011).

Sedimentation is often associated with the in-filling of waterholes, leading to a decline in geomorphic complexity and habitat quality (Bartley & Rutherfurd, 2005), whilst also reducing biological diversity (Downes et al., 2006; Kemp et al., 2011; Larsen, Pace, & Ormerod, 2011). The in-filling of waterholes can lead to a decline in ponding depth, which directly influences the presence and persistence of waterholes within the landscape (Costelloe, Shields, Grayson, & McMahon, 2007; Davis & Finlayson, 2000; Hamilton, Bunn, Thoms, & Marshall, 2005; Reid et al., 2016). In the absence of surface flow, waterholes that have declined in depth will dry faster and stay fragmented for longer (Hamilton et al., 2005). In the long term, sedimentation can affect the capacity of a waterhole to act as a refuge for aquatic biota and reduces the availability of water for communities (Hamilton et al., 2005; Lobegeiger, 2010; Reid et al., 2016).

The deposition of sediment can directly smother macrophytes and invertebrates, which can in turn reduce the availability of food to biota positioned at higher trophic levels. In the long term, this can lead to a change in community composition (Henley, Patterson, Neves, & Lemly, 2000; Ogden, 2000).

Likewise, the density and diversity of macroinvertebrates have been directly associated with substrate diversity (Larsen et al., 2011). When fine sediment is deposited, the interstitial space between the coarser substrate is filled, reducing the available living habitat for macroinvertebrates (Kemp et al., 2011). Moreover, the filling of these interstitial spaces can disrupt or block the supply of oxygen to benthic habitat (Kemp et al., 2011). This in turn can alter community composition by creating conditions more favourable to burrowing species that have a higher tolerance for low oxygen levels (Henley et al., 2000). In terms of the fish populations, sediment can smother spawning habitat for those species that spawn on or near the riverbed (Kemp et al., 2011). In parallel, a reduction in the hyporheic oxygen levels can adversely impact developing eggs and the embryonic stages of fish species (Kemp et al., 2011).

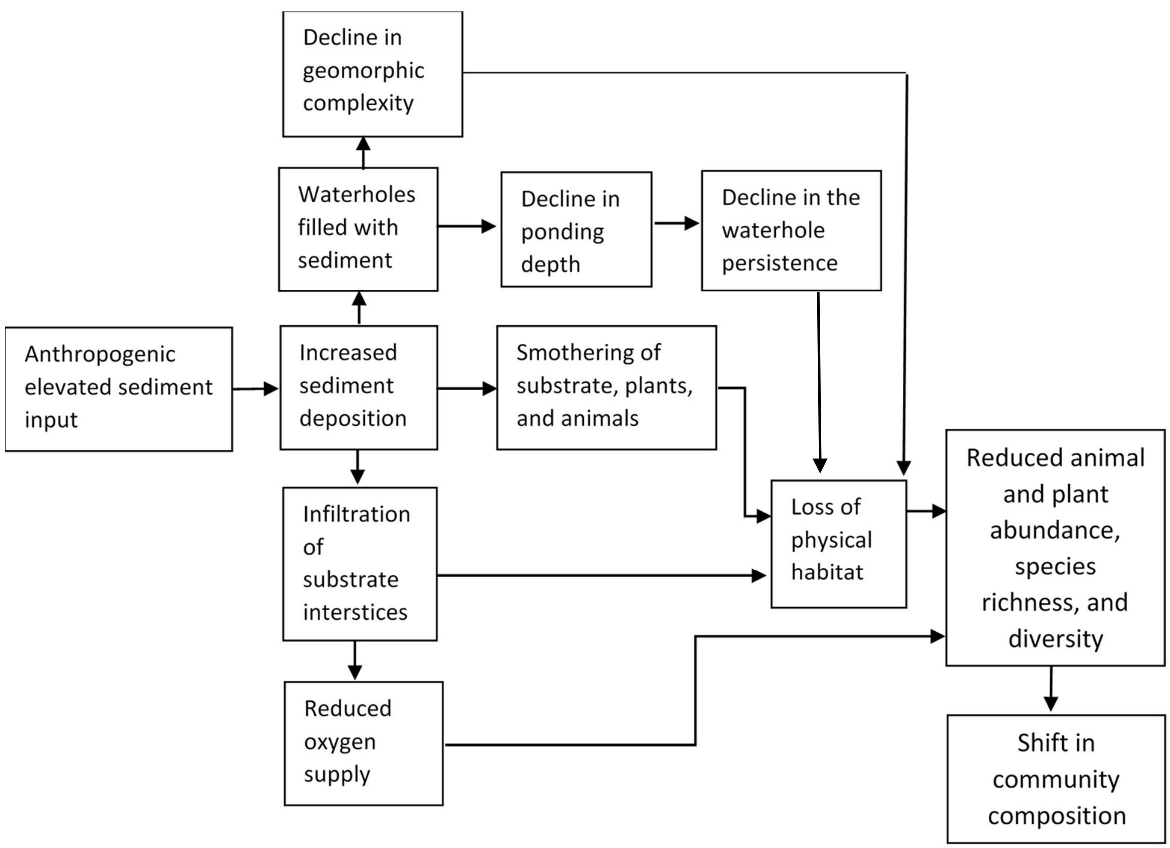

Figure 1.2: The negative impacts of anthropogenically enhanced sedimentation in dryland rivers (adapted from Kemp et al, 2011).

1.4.5 The impact of human disturbance on hydrological connectivity

Hydrological connectivity is being altered globally at unprecedented rates resulting in significant loss to global biodiversity and ecosystem integrity (Pringle, 2003). Alterations to hydrological connectivity can be attributed to the presence of in-stream impoundments (i.e., weirs and dams), the manipulation of the natural flow regime (i.e., the abstraction of water and the capture of floodplain runoff) and landscape change (Elosegi, Díez, & Mutz, 2010; Kondolf et al., 2006; Rolls, Ellison, Faggotter, & Roberts, 2013).

In-stream impoundments create a physical barrier to hydrological connectivity, which can impede the spatial and temporal movement of sediment, nutrients, and organic matter throughout the system (Ward & Standford, 1995). From a biological perspective, the migratory pathways of some species may be blocked or restricted, limiting access to food, shelter, and nursery habitat (Bunn & Arthington, 2002; Rolls et al., 2013; Sheldon et al., 2010). Removing migratory pathways can interfere with the completion of lifecycles resulting in long-term impacts for population dynamics (Bunn & Arthington, 2002; Rolls et al., 2013). With biological dispersal constrained, populations of aquatic biota can decline, and local extinctions can occur (Lake, Bond, & Reich, 2007). This in turn can impact the trophic structure of an ecosystem (Pringle, 2003). Barriers not only provide a physical obstruction to the dispersal of aquatic organisms, but they can also create conditions that are unfavourable for migration. For example, through changes to flow velocity, water depth and the creation of unnatural vertical drops (Bice, 2017; Cote, Kehler, Bourne, & Wiersma, 2008; Mallen-Cooper, 2020; Pearson et al., 2020).

Modifications to the flow regime, as a consequence of river regulation, have disrupted hydrological connectivity and significantly altered the delivery of water within dryland rivers (Elosegi et al., 2010; Kondolf et al., 2006). The storage of water within in-stream impoundments, the abstraction of water for consumptive use and the capture of runoff in floodplain storages has substantially impacted the timing, frequency, duration, volume, and variability of flows on dryland rivers (Hamilton et al., 2005;

Thoms & Sheldon, 2000). In many dryland rivers, flow regulation has led to an increase in the frequency and duration of low flow and no flow events (Mallen-Cooper, 2020; Thoms, 2003). As a result, longitudinal and lateral connectivity have been reduced and dryland rivers have become increasingly fragmented (Stanley et al., 1997). Without regular replenishment flows water quality conditions deteriorate (Sheldon & Fellows, 2010), habitat features (e.g., in-stream wood, overhanging vegetation) become exposed (Boys & Thoms, 2006) and the length of time that a waterhole can persist in the landscape declines (Costelloe et al., 2007; Hamilton et al., 2005).

1.4.6 The impact of climate change on dryland rivers

Over the coming decades the climate is expected to change at unprecedented rates with an average increase in global temperatures of > 1.5 ^{o}C by the end of century (IPCC, 2018). Climate change is expected to reduce precipitation, increase air temperatures, and enhance evapotranspiration rates leading to increased levels of aridity (Cai & Cowan, 2008; Chiew, Young, & Cai, 2011; IPCC, 2018; Larkin et al., 2020; Whetton, 2011). The hotter, drier conditions are in turn expected to cause a decline in surface runoff and a subsequent reduction in streamflow (Fryirs & Brierley, 2013a). In south-east Australia, for example, stream flow is expected to decline by an average of 4 % in response to climate change (CSIRO, 2012). As streamflow declines across dryland rivers, so too will their stream power and their capacity to transport sediment, further exacerbating the impact of water resource development (Larkin et al., 2020).

The implications of climate change on the sediment dynamics and geomorphology of dryland rivers are expected to be profound and long lasting. Larkin et al., (2020) have predicted a dramatic shift in river morphology for 29 dryland rivers in south-east Australia in response to climate change. Of these rivers, 80 % are expected to undergo significant geomorphic adjustment by 2070. A reduction in stream power is expected to lead to an increase in sediment deposition, a downstream decline in channel size and in extreme cases the transition to a terminating river (Larkin et al., 2020). Dryland rivers, as a result, will become more discontinuous leading to a decrease in hydrological and sediment connectivity, and thereby, reducing the distribution of sediment throughout the catchment (Larkin et al., 2020). Accelerated levels of sediment deposition will further contribute to the in-filling of in-channel waterholes, which in the long-term will reduce water depths and waterhole persistence (Larkin et al., 2020).

More directly, climate change will reduce waterhole ponding depth and waterhole persistence through increases in air temperatures and evaporation rates (Cockayne, 2021; Costelloe et al., 2007; Hamilton et al., 2005). In Australia's Lake Eyre Basin for example, evaporation is expected to increase by 35 % in response to climate change, leading to a decrease in waterhole persistence (i.e., the time a waterhole contains water in the absence of surface-flow) of between 16 and 31 % (Cockayne, 2021). Consequently, by 2070 the number of persistent waterholes in the Lake Eyre Basin could be reduced by as much as 67 % following a 12-month period without flow (Cockayne, 2021). The viability of waterholes as a safe haven for both aquatic and terrestrial biota will therefore become compromised under drier climate scenarios.

1.5 THESIS SUMMARY

1.5.1 Study area -The Barwon-Darling River

The Barwon-Darling River is a large, dryland river located in the north-west region of Australia's Murray Darling Basin (Thoms, Hill, et al., 2004) (Figure 1.4). It is an allogenic river with the bulk of the flow contributed by the eastern tributries, which drain the western slopes of the Great Dividing Range. These include: the Condamine-Balonne, Macintyre, Gwydir, Namoi, Maquarie and Castlereagh rivers. The Warrego, Paroo and Culgoa rivers drain from the north, through a more arid environment and provide minor and more intermittent flows (Thoms & Sheldon, 2000). The Barwon-Darling River and its tributaries drain an area of approximately 699 500 km^2 (Thoms, Hill, et al., 2004).

The lowland catchment of the Barwon-Darling is located predominately in arid to semi-arid rangelands and as such is defined by extremes in climatic variability (Thoms & Sheldon, 2000). Median annual rainfall tends to decrease from east to west, ranging from >1200 mm/year to <200 mm. Evaporation rates are high and increase westward, with median evaporation rates of 1250 mm in the upper catchment compared to 2250 mm in the far west (Thoms, Hill, et al., 2004). The flow regime is one of the most variable in the world (Puckridge et al., 1998) with a mean coefficient of variation for annual flows ranging from 1.6 to 3.2 (Thoms, Hill, et al., 2004). For much of the time 'low' flow conditions dominate, with short but intense bursts of rainfall causing periodic flooding and highly variable flow conditions (Thoms, Hill, et al., 2004).

The physical character of the Barwon-Darling River is defined by low bed slopes (0.00005 m/m), high sinuosity (>2) and low stream power (<5 Wm^{-2}). It has a deeply incised river channel with depths reaching up to 25 m. Channel widths range from 40 to 80 m (Thoms, Sheldon, Roberts, Harris, & Hillman, 1996) and discharge capacities range from 46 m^3/s to 925 m^3/s (Boys & Thoms, 2006). The river bed substratum consists predominately of a uniform mix of fine silts and clays interspersed with coarser sand (Woodyer, Taylor, & Crook, 1979). The bulk of the sediment (i.e., 95 %) is transported as fine suspended sediment. The in-channel environment consists of a nested series of large depositional features referred to as benches. These depositional features form between the channel bank and the main floodplain surface and act as temporary sediment stores. The subsequent re-working of these sediment stores is an important source of sediment to the river (Thoms & Olley, 2004). The river channel includes few physical features, with large in-stream wood being one of the few hard substrates available, along with the occasional lateritic outcrop (Thoms et al, 1996). Additional in-channel habitat is available through the presence of overhanging vegetation, undercut banks and the root masses of riparian vegegtation (Boys & Thoms, 2006; Matheson, Thoms, Southwell, & Reid, 2017).

Since European settlement the surrounding catchment has been used predominately for livestock grazing (Crabb, 2004). The grazing industry was well established in the catchment by the 1870s, but at the time it was confined to properties with river frontage or bore water access due to the lack of farming infrastructure (i.e., water tanks, dams and roads) (McKeon et al., 2004). A history of overstocking is well documented for this early period of settlement with high stocking rates being associated with the widespread loss of perennial plant cover and intiation of soil erosion (McKeon et al., 2004). Irrigated agriculture and dryland cropping on the Barwon-Darling floodplain have emerged in more recent times (CSIRO, 2008). Land use in the upper catchment is dominated by a mixture of grazing and dryland farming (e.g. wheat, cereals) (Crabb, 2004), whilst irrigated agriculture (predominately cotton) makes up a smaller percentage of the total farm area (Barma, 2005). Large scale water infrastructure development commenced on the tributaries in the 1960s resulting in 11 major headwater storages with a combined capacity of 5149 GL (Thoms, Sheldon, & Crabb, 2004). Whilst there are no large reservoirs on the main channel of the Barwon-Darling, 15 low levels weirs have been built incremently for the provision of stock and domestic use (Thoms & Sheldon, 2000). The oldest weir, at Bourke, dates back to 1897, whilst the most recent was constructured in 1983 upstream of Louth. The majority of weirs, however, were built during the 1960s and 1970s (NSW Department of Primary Industries, 2006). Due to the low gradient of the Barwon-Darling River a single weir can impound and influence the hydraulic character of many kilometres of river creating deeper, more perennial conditions immediately upstream of each structure (Chessman, Jones, Searle, Growns, & Pearson, 2010; Mallen-Cooper, 2020; Pearson et al., 2020).

Water abstraction combined with the capture of floodwaters in off-river reservoirs has substantially altered the hydrology of the Barwon-Darling River (Thoms & Sheldon, 2000). Median annual runoff has been reduced by 42 %, whilst median daily flows has been reduced by as much as 73 %, with the downstream locations the most severly impacted (Thoms & Sheldon, 2000). The greatest impact has been on the magnitude of small flood events (i.e., with an ARI < 2 years), which have declined in the order of 40 to 61 %. Low flows are now frequently below lotics thresholds (i.e., 250 ML/day) and the magnitude of the near annual flow pulse that would have occurred historically has been reduced by over 90 % (Mallen-Cooper, 2020).

This thesis will focus on the Barwon-Darling River from Mungindi in the north to the township of Wilcannia in the south-west, spanning approximately 1400 km of river (Figure 1.4). From a water management perspective this section of the river is defined as unregualted with no large head water reservoirs on the main stem of the river (*New South Wales Water Sharing Plan for the Barwon-Darling Unregulated and Alluvial Water Resources 2012 s. 4.1*). This differs to further downstream where the Menindee Lakes Storages regulate flows to the Lower Darling (*Water Sharing Plan for the New South Wales Murray and Lower Darling Regulated Rivers Water Sources 2016 s. 4.1)*. To reduce complexity this thesis will concentrate only on the unregualted section of the Barwon-Darling River.

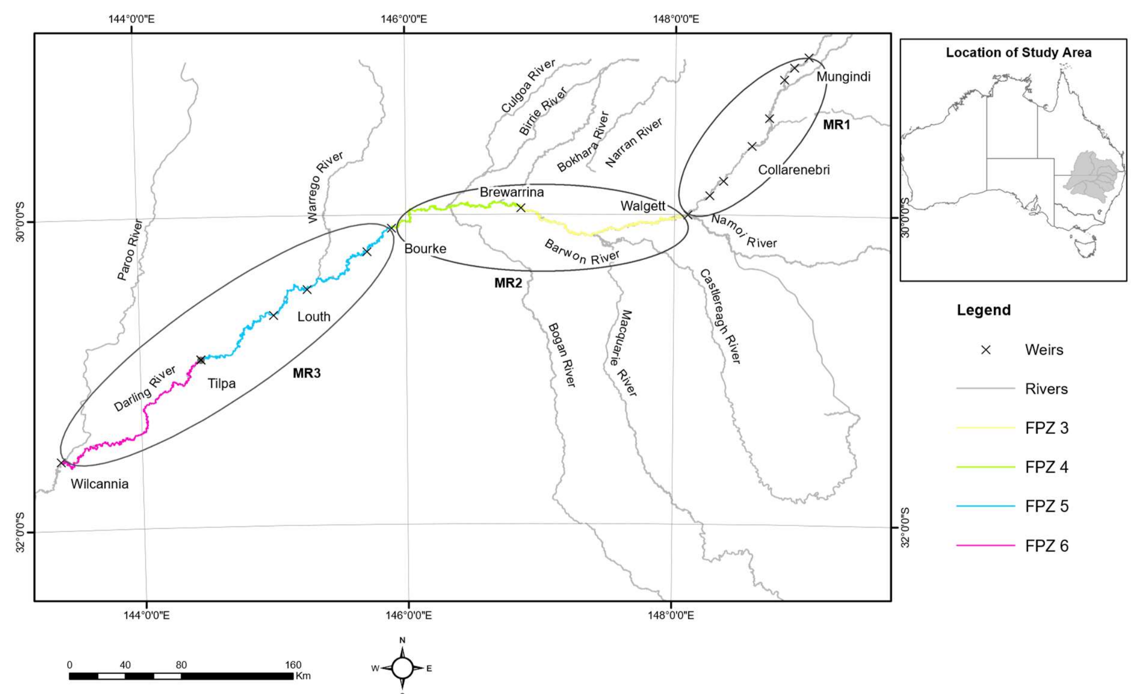

Figure 1.3: Part of the Barwon-Darling River Catchment (Coordinate system: GDA/MGA Zone55). MR1 to MR3 represent macro reaches which are defined by the degree of structucal control influencing the floodplain and river channel environment. Nested within each macro reach are functional process zones (FPZ 3 to FPZ 6), which are defined by river sections that are geomorphically similar and have a relatively uniform discharge and sediment regime.

1.5.2 Conceptual model of the impact of human disturbance on the Barwon-Darling River

The Barwon-Darling River is just one example of a dryland river that has experienced substantial modifications since European settlement. Figure 1.3 provides a conceptual model for the Barwon-Darling Catchment highlighting the modifications that have occurred within the catchment since European settlement. As previously outlined, these changes include: the construction of low levels weirs (Thoms and Sheldon, 2000), the abstraction of water for town water supply and irrigation (Barma, 2005), the introduction of irrigated and dryland farming (Crabb 2004) and the introduction of domesticated animals (i.e., sheep, cattle) and feral species (i.e., goats, rabbits) (McKeon et al., 2004). The model identifies the physical response to these changes that are currently understood and are well documented within the literature. For example, a reduction in perennial plant cover (McKeon et al., 2004), which can increase runoff, and reduced infiltration caused by the compaction of soil by hard hooved sheep and cattle (Gell et al, 2009). Combined these changes lead to an increased sensitivity to soil erosion within the catchment (Gell et al, 2009). The model also captures changes related to the presence of instream infrastructure. It highlights changes to the flow hydraulics that have resulted from the creation of large, deep weir pools, shifting the Barwon-Darling from a free-flowing lotic system to a series of disconnected lentic weir pools (Mallen-Cooper et al., 2020). In parallel to the observed changes to the physical landscape, the model highlights the ongoing changes associated with climate change, such as, reduced precipitation and increased evaporation across the catchment (Cai & Cowan, 2008; Chiew, Young, & Cai, 2011).

In addition to the known consequences of landscape change, the model also captures physical responses that have not previously been observed but are expected to be identified in this thesis. For example, alterations to waterhole morphology and distribution, prevalence of floodplain gullies and changes to flow and sediment connectivity. This model will underpin the discussion throughout this document.

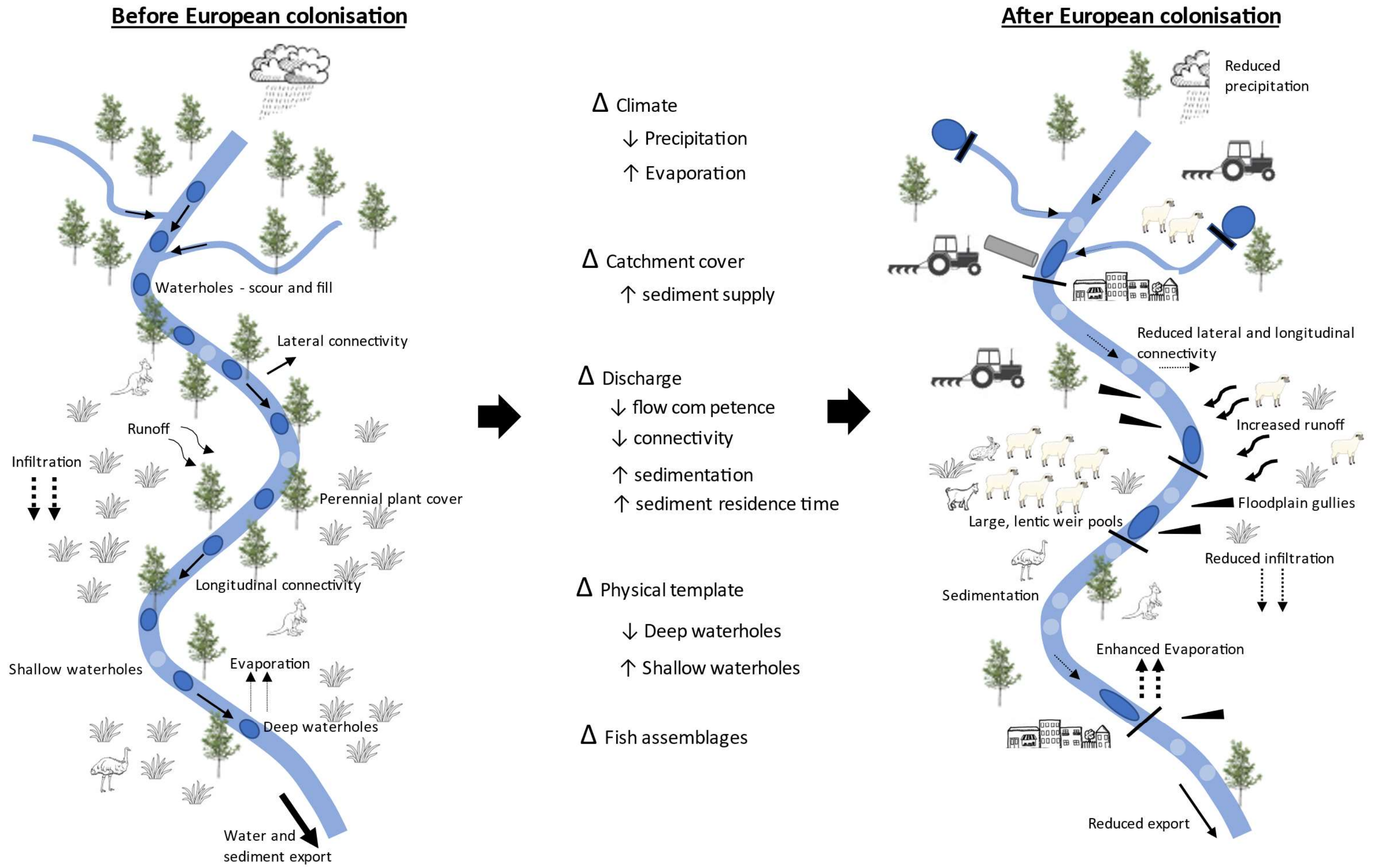

Figure 1.4: Conceptual model illustrating the known and expected response to landscape change in the Barwon-Darling River catchment since European colonisation

1.5.3 Research Aims and Objectives

The overall aim of this thesis is to examine if and how the physical template of the Barwon-Darling River has changed over the last 120 years and to explore the ecological consequences of these changes. In examining changes to the physical template, the specific focus of this study will be on investigating changes to waterhole depth under cease to flow conditions. Although waterholes are just one component of the physical template they have been chosen for this study because of their ecological, social, and cultural significance to Australian dryland rivers. Modifications to waterhole morphology, in particular a decline in waterhole depth can have significant implications for their persistence and connectivity within the landscape and can limit their accessibility for water dependent biota (Sheldon et al., 2010). With cease to flow conditions on the Barwon-Darling becoming more frequent and persisting for longer periods of time (Mallen-Cooper 2020) the implications of declining waterhole depths could have serious and irreversible consequences for the river and its biota.

Based on evidence from neighbouring rivers a decline in waterhole depth and therefore a change to the physical template was anticipated due to changes in the supply of sediment to the system (Lobegeiger, 2010; Reid et al., 2016). In lowland rivers, an accelerated supply of sediment can be attributed to a combination of sources. These being: (1) the redistribution of sediment within the channel; (2) the influx of sediment from upstream source areas, including the major tributaries; (3) the influx of bank material; and (4) the influx of sediment from the adjacent floodplain via alluvial gullying. Of these, there is substantial evidence of the first three mechanisms operating on the Barwon-Darling River (DeRose et al., 2003; Olley & Caitcheon, 2000; Thoms, 1997; Thoms & Olley, 2004). The fourth mechanism, the contribution of sediment from the adjacent floodplain has for the Barwon-Darling remained largely unquantified in the literature. In fact, past modelling of sediment budgets for the Murray-Darling Basin have not recognised floodplain gully erosion as a source of sediment to the Barwon-Darling, and as such its contribution has not been accounted for in basin wide sediment modelling (DeRose et al., 2003). This is despite floodplain gully erosion being long regarded as a significant management issue in other parts of south-east Australia (Prosser et al., 2001, Wethered et al., 2015). Furthermore, with anecdotal evidence from local land managers and property owners suggesting that gully erosion is a prevalent feature of the Barwon-Darling floodplain, this potentially important source of sediment warrants further investigation. As such, this study will investigate the role of floodplain gully erosion as a mechanism for sediment delivery to the Barwon-Darling and will attempt to quantify its impact on waterhole depth.

Floodplain alluvial gullies are significant in the broader context of sediment connectivity. When alluvial gullies form within the floodplain they increase the connectivity of the landscape and provide a conduit for transferring large quantities of sediment from the catchment to the river channel (Frankl, Poesen, Haile, Deckers, & Nyssen, 2013; Poesen, Nachtergaele, Verstraeten, & Valentin, 2003; Shellberg, Brooks, & Spencer, 2016). However, changes to the supply of sediment as a consequence of increasing connectivity and the role it has in driving morphologocal change cannot be considered in isolation. Of equal importance, are the limitiations or barriers to functional connecitvity that dictate where morphological change is likely to occur. This study will investigate the impact of water resource development on sediment connectivity. It will determine how modifications to the flow regime has altered the capacity of the river to transport sediment, which is critical to maintaining sediment connectivity within the system. Likewise, the impact of instream infrastructure on creating a physical barrier to sediment connectivity will be explored.

The final component of work in this thesis will be to assess the ecological consequences of an altered physical template. This will be done by exploring the relationship between fish populations and waterhole depth to determine the importance of accessibility to deep habitat for native fish. This is a critical consideration given the substantial changes to the Barwon-Darling flow regime that have occurred because of water resource development. These changes have resulted in a more hydraulically disconnected river (Mallen-Cooper, 2020) with waterholes drying more frequently and staying dry for longer. Such conditions have at times led to poor water quality conditions and catastrophic fish deaths in the lower Darling River (Sheldon et al., 2022; Vertessy et al., 2019).

Understanding the association between flow regime, sediment connectivity, waterhole morphology and fish response will inform a more integrated, multidisciplinary approach to managing the Barwon-Darling River.

This thesis is split into four data chapters (Chapters 2-5) each with their own specific aims and objectives, which are outlined below. Chapter 6 provides an overall summary of the research findings and their implications, along with a critical appraisal of the approach used throughout this study.

Aim 1 (Chapter 2): Determine if and how the physical character and location of waterholes on the Barwon-Darling River have changed over a period of 120-years. The following objectives were established to achieve this aim:

- Quantify changes to the median and maximum waterhole depths.
- Document the spatial patterns in changes to waterhole depths.
- Compare the spatial organisation of waterholes between two survey dates (1800s and 2015).
- Demonstrate the need for a robust, analytical approach to assess temporal geomorphic change using historical data.

Aim 2 (Chapter 3): Quantify the contribution of sediment derived from alluvial floodplain gully erosion to the Barwon-Darling River and understand the implications for dryland river waterholes. The following objectives were established to achieve this aim:

- Characterise the spatial and temporal distribution of gully erosion on the Barwon-Darling River floodplain.
- Quantify the contribution of sediment to the Barwon-Darling River from alluvial gully erosion.
- Compare the volume of sediment removed from alluvial gullies with previous estimates from the SedNet model for the Darling River Catchment.
- Quantify the relationship between gully erosion and change to waterhole depth.

Aim 3 (Chapter 4): Investigate the role of water resource development on influencing the river's capacity to transport sediment and influence sediment dynamics within the Barwon-Darling system. The following objectives were established to achieve this aim:

- Quantify the impact of antecedent sediment concentrations on sediment transport capacity.
- Quantify the impact of water resource development on the capacity of flows to entrain and transport sediment.
- Quantify the impact of water resource development on the lateral exchange of sediment with the floodplain.
- Quantify the impact of in-stream infrastructure on the trapping of sediment in-stream.

Aim 4 (Chapter 5): Examine the role that waterhole depth has on shaping fish assemblage patterns in the Barwon-Darling River and in doing so understand the ecological consequences of changing waterhole depths. The following objectives were established to achieve this aim:

- Characterise the effects, including the interactions, of waterhole depth and in-stream wood on fish assemblage patterns.

- Characterise how these effects differ for exotic and native fish species.

1.5.4 A nested approach to studying the Barwon-Darling River

For the purposes of this study a nested approach was used to stratify the river. A the broadest scale, the river was broken into three macro reaches (Figure 1.4), which are assocaited with the degree of structual control influencing the floodplain and river channel environment (Thoms, et al., 2004). In this study, the macro reach scale has been used in Chapter 3, which focuses on floodplain alluvial erosion. Contrasting valley floor dimensions across the three macro reaches were expected to influence the presence and extent of alluvial gullying. Between Mungindi and Walgett (Macro Reach 1) the floodplain and river channel are contained within the Cobar structural lineament, which has resulted in limited floodplain development particularity on the western margins. The eastern margin has a weaker structural control and has to some extent been influenced by the Macintyre-Gwydir fan complex. South of Bourke (Macro Reach 3), the river is constrained by the Darling structural lineament and here the floodplain extent is at its minimum. Furthermore, several calcrete and silcrete bedrock outcrops within this reach act as local bed controls for the river. The river between Walgett and Bourke (Macro Reach 2) is not constrained but it is influenced by the mega scale alluvial fan emanating from the Gwydir, Namoi, and Macquarie-Bogan systems to the east and south, and the Culgoa-Balonne to the north. The lack of structural influence in this part of the river has meant that valley dimensions and floodplain development have not been limited in this part of the river (Thoms et al., 2004).

At a finer scale, the three macro reaches can be broken into six functional process zones (FPZs) (Thoms, et al., 1996). FPZs are characterised as large sections of river (>200 km) that are geomorphically similar and have a relatively uniform discharge and sediment regime (Boys and Thoms, 2006). As such, their definitions relate more closely to the character of the in-stream environment as opposed to the broader floodplain. For this reason, FPZs was used as the primary scale of investigation used in Chapter 2, which investigates changes to the in-stream physical template of the Barwon-Darling River. However, data limitations with the historical data set meant that only four of the six FPZs (FPZ 3 to 6) could be incorporated into this study with these FPZs forming part of macro reach 2 and 3.

Modelled data was obtained from the most upstream location of each FPZ to investigate temporal change to sediment transport dynamics (Chapter 4). This enabled changes to sediment dynamics to be explored at the boundary of each FPZ. However, in doing so it is recognised that there would be substantial variation in sediment movement within each FPZ based on cross sectional shape and size, channel roughness, slope and morphology, presence of aquatic vegetation, transmission loss, organic content, the clustering of grains, and differences in particle geometry, imbrication, armouring, compaction and packing along the reach.

The ecological reponse to human modification to the Barwon-Darling is examined in Chapter 5. Sampling of fish populations focused on the stretch of river below Bourke (macro reach 3). Waterholes in this section of river frequently contract to a series of shallow, disconeected pools when no flow or low flow conditions pervail. During periods of extreme dry only the deepest waterholes (which are typically associated with the weir pools) maintain water for extended periods of time. As a result, this section of river offered a wide selection of waterholes with a broad range of waterhole depths.

1.5.5 Thesis outline

This thesis is made up of six chapters. Following this introductory chapter, the research aims are addressed in four data analysis chapters developed as stand-alone manuscripts.

Chapter 2 examines the change to the physical template of the Barwon-Darling River over a 120-year period. Historical longitudinal profiles from the late 1800s were compared to contemporary bed profiles derived from high-definition side scanning sonar. Comparisons focused on waterhole features such as changes to waterhole depth and distance to neighbouring waterholes. Chapter 2 has been published in the journal *Geomorphology.*

Chapter 3 examines the spatial and temporal distribution of alluvial gullies on the Barwon-Darling River floodplain using a combination of light detecting and ranging data (LiDAR) and digital air photos. LiDAR derived digital elevation models were used to estimate the volume of sediment removed from alluvial gullies and comparison made with previous estimates from the SedNet model for the Darling River catchment. The relationship between alluvial gullying and change to waterhole depth is investigated. Chapter 3 has been prepared for submission to *Earth Surface Processes and Landforms*.

Chapter 4 examines the role of water resource development on influencing the Barwon-Darling River's capacity to transport sediment and influence sediment dynamics. It will compare pre-development flow scenarios with present day flow scenarios and determine how the frequency and duration of flows capable of entraining and transporting sediment (longitudinally and laterally) have changed. The impact of in-stream infrastructure (i.e., low level weirs) on inhibiting the transport of sediment is examined. Chapter 4 has been prepared for submission to *Geomorphology.*

Chapter 5 investigates the ecological consequence of changing water depth. Specifically, it examines the role that waterhole depth in combination with in-stream wood has on shaping fish assemblage patterns on the Barwon-Darling River and determines if their role differs between native and exotic fish assemblages. Chapter 5 has been prepared for submission to *Marine and Freshwater Research.*

Chapter 6 provides a synthesis of the major research findings. This includes a discussion regarding the significance of the research findings to the broader field of geomorphology and the management implications for dryland river waterholes. The synthesis ends with a critical appraisal of the methods used in this study and proposes several pertinent questions for future research.

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CHAPTER 2

Comparison of historical and modern river surveys reveal changes to waterhole characteristics in an Australian dryland river.

ABSTRACT

Human activities are known to impact the physical template of river channels. These impacts can result from deliberate, direct modifications as well as via indirect processes linked to broadscale landscape change. This study examined changes in the physical template of the Barwon-Darling River, a dryland river in south-eastern Australia. Historical longitudinal profiles from the late 1800s were compared with contemporary profiles derived from high-definition, side scanning sonar. Comparisons focused on characterising waterhole features as they are a critical biophysical component of dryland rivers. The use of historical data presented several challenges related to small sample size and suspected sampling bias in the historical survey. However, this study demonstrates that these issues are not insurmountable providing the limitations and uncertainties with the data are acknowledged and data analyses are limited to parameters that can distinguish genuine landscape change. The findings revealed a dramatic change in the physical template of the Barwon-Darling River over a 120-year period. Waterhole depths and distances between waterholes have been altered significantly. The magnitude and trajectory of change was found to be scale-dependent, with the greatest observable change aligned with the presence or absence of low-level weirs. Waterholes influenced by low-level weirs have increased in depth because of localised impoundment, whilst the distance between deep waterholes (>4 m in depth) has declined substantially. In contrast, the maximum depths of waterholes located outside the influence of weir pools has declined by 1.6 m and the distance between deep waterholes has more than doubled in several reaches. These declines are likely to be caused by sediment accumulation in waterholes associated with anthropogenic increases in sediment flux and a decline in the river's capacity to entrain and transport sediment throughout the system.

2.1 INTRODUCTION

In a natural context, a river's physical template is primarily controlled by long-term climatic conditions and the character of its catchment (Meitzen et al, 2013; Tooth, 2000). Catchment features such as the underlying geology, topography, soil type and vegetation, in conjunction with precipitation and evaporation, dictate rainfall-runoff relationships (Fryirs and Brierley, 2013a). Combined, these elements govern the shape, size, and slope of the channel and the density of the drainage network in which a river operates. In turn, these factors influence the distribution of available energy and, in doing so, regulate the movement of water and sediment throughout the system, which is fundamental to channel formation (Fryirs and Brierley, 2013a). A river's longitudinal profile, planform and cross-sectional shape and size, as well as in-channel features such as bars, benches, islands, and waterholes, are all components of the physical template that are influenced by these landscape scale interactions (Charlton, 2007).

Human activities can disrupt natural channel-forming processes by altering the way in which water and sediment are conveyed throughout the system (Meitzen et al., 2013; Prosser et al., 2001; Thoms and Walker, 1993). These disruptions can arise from the direct alteration of the river channel (e.g., dam and weir construction, channel straightening) or indirectly by the influence that these modifications have on the movement of sediment and discharge within the system (Meitzen et al., 2013). These changes can drive the physical template of a river to a state beyond its natural range, having significant implications for channel complexity, longitudinal and lateral connectivity, and subsequently habitat availability for riverine biota (Grabowski et al., 2014; Petts and Gurnell, 2005).

Anthropogenic channel adjustments can occur over long periods of time and will often follow a complex trajectory of change (Petts and Gurnell, 2005). Understanding the nature, magnitude and trajectory of any morphological adjustment arising from human activity is a critical step in defining the consequences of human intervention and ultimately in guiding the management of river systems (Grabowski et al., 2014). To do this, long-term or historical records of channel form are helpful as they provide possible benchmarks against which ongoing temporal change can be assessed (Reid and Ogden, 2006). Particularly valuable sources of historical data are the land and river surveys created by the engineers and surveyors responsible for assessing localities for early settlement and, later, for exploring options to regulate the river for water supply or navigation. Among these surveys are longitudinal profiles, planform maps and channel cross sections (Grabowski et al., 2014; Gurnell et al., 2016). Each of these have been used frequently in modern day research and have proven useful for exploring changes to channel morphology over decadal time scales (Gurnell et al., 2016; Rinaldi, 2003).

Historical data can, however, have inherent uncertainties. Although invaluable for providing a snapshot of historical conditions, historical datasets of river physical form often have limited resolution, are of unknown accuracy, and frequently lack background information on the context for data collection and data collection methods (Gurnell et al., 2016). When using historical data, the limitations and uncertainty must therefore be recognised, and robust and statistically valid approaches used to compensate for these issues. Caution must also be applied when interpreting results (Grabowski et al., 2014; Gurnell et al., 2016).

This study uses historical data to quantify changes to the physical template of the Barwon-Darling River, a dryland river in western New South Wales, Australia. Like most Australian dryland rivers, the Barwon-Darling has been affected by anthropogenic catchment modification, hydrological change through flow regulation and extraction, and in-channel structural modification (Thoms et al., 2004a; Thoms and Sheldon, 2000). Australian dryland rivers, such as the Barwon-Darling, are commonly large, low-gradient, alluvial rivers that have relatively low energy and experience slow moving, long duration floods (Thoms etal., 2006; Tooth and Nanson, 2011). As such, in a natural context, they typically undergo low rates of geomorphic change (Tooth and Nanson, 2011). This is particularly so where well-defined riparian vegetation communities, indurated sediments, and cohesive muds provide channel boundary strength (Nanson et al., 2002; Tooth and Nanson, 2011). In contrast, the initial response to profound human disturbance may be rapid in these systems. However, it is not possible to be sure that the totality of the system response (including potential recovery) has propagated fully throughout the system within a few years or even decades without long-term datasets or a well-established benchmark. Yet, because of their remote locations these rivers are frequently data-poor and as such long-term time-series data are rarely available (Kingsford and Thompson, 2006). Consequently, an alternative approach to assessing geomorphic change is required.

In examining changes to the physical template, the specific focus of this study is on changes to waterhole features on the Barwon-Darling. Although waterholes are just one component of the physical template, they have been chosen as the focus for this study because they are a critical feature of many Australian dryland river systems (Lake, 2003; Sheldon et al., 2010). Waterholes typically develop as a string of deep pools capable of retaining water for long periods in the absence of flows (Knighton and Nanson, 1994; Reid et al., 2016). They are often the only source of water in what is an otherwise arid environment. From an ecological perspective, they provide shelter, habitat, and protection for aquatic biota during the extended periods of low flow or no flow commonly experienced in dryland rivers (Sheldon et al., 2010; Walker et al., 1995). In the context of local communities, waterholes provide a supply of water for stock and domestic use and recreation. Not all waterholes are permanent. It is therefore important to understand any natural and anthropogenic factors that influence the character, persistence, and quality of waterhole features. In this study, a benchmark is established using rare examples of historical longitudinal profiles to identify and characterise waterholes from the late 1800s. Comparisons are made to a modern profile to determine if and how the physical character and location of waterholes have changed over a period of 120-years. These comparisons aim to (1) quantify changes to the median and maximum waterhole depths between the 1890s and the present, (2) document the spatial patterns in changes to waterhole depths, (3) compare the spatial organisation of waterholes between the two survey dates, and (4) demonstrate the need for a robust, analytical approach to assess temporal geomorphic change using historical data sources.

2.2 STUDY AREA

The Barwon-Darling River and its tributaries drain an area of approximately 699,500 km^2 (Thoms et al., 2004a) (Figure 2.1). It is an allogenic river with most flows contributed by the eastern and northern tributaries: principally the Condamine-Balonne, Macintyre, Gwydir, Namoi, Castlereagh and Macquarie rivers, all of which originate in a well-watered upper catchment (Thoms and Sheldon, 2000). Smaller and more intermittent contributions are made by the Warrego and Paroo rivers, which have headwaters located in more arid environments (Thoms and Sheldon, 2000).

The lowland catchment of the Barwon-Darling River is predominately arid to semi-arid and defined by extremes in climatic variability (Thoms and Sheldon, 2000). Annual average rainfall varies between 200 to 1000 mm, decreasing east to west, but most often remains below 600 mm (Thoms and Sheldon, 1997). Evaporation increases to the west with median annual evaporation rates of 1250 mm in the upper catchment compared to 2250 mm in the semi-arid lowlands (Thoms et al., 2004b). The hydrology is dominated by 'low' flow conditions, which are periodically interrupted by major widespread flood events that are often associated with short but intense periods of rainfall (Thoms et al., 2004b). The flow regime of the Barwon-Darling is considered to be one of the most variable in the world (Puckridge et al., 1998) with the mean coefficient of variation for annual flows ranging from 1.6 to 3.2 (Thoms et al., 2004b).

The physical character of the Barwon-Darling River is defined by low bed slope (averaging 0.00005 m/m), high sinuosity (>2) and low stream power (<5 Wm^{-2}) (Thoms et al., 1996). Ninety-five percent of its sediment is transported as fine suspended sediment (Olley and Caitcheon, 2000). It has an extremely variable in-channel environment made up of a series of morphological features known as inset benches. These large, flat, depositional features form between the channel bed and main floodplain surface (Thoms et al., 2006; Thoms and Sheldon, 1997). Channel capacities range from 46 m^3/s to 925 m^3/s with flows predominately confined within a highly incised river channel. Channel depths can reach up to 25 m whilst channel widths range from 40 to 80 m (Thoms et al., 1996).

Since European settlement in the mid-1800s, the surrounding catchment has predominately been used for livestock grazing (Crabb, 2004). The grazing industry in this area was well established by the 1870s (McKeon et al., 2004), but because of the lack of infrastructure (i.e., water tanks, dams and road transport) stock were largely confined to properties with river frontage or access to bore water (McKeon et al., 2004). A history of overstocking during this early settlement period is well documented. Peak sheep numbers were recorded in 1891, with an estimated stock population of 15.4 million across western NSW (Beadle, 1948). These stocking rates led to considerable grazing pressure, resulting in a loss of perennial plant cover and the widespread initiation of soil erosion (McKeon et al., 2004).

In more recent times, irrigated agriculture and dryland cropping have become more common (CSIRO, 2008). Large scale water infrastructure development commenced on the tributaries in the 1960s, resulting in 11 major headwater reservoirs with a combined capacity of 5149 GL (Thoms et al., 2004a). Although no large reservoirs exist on the main channel of the Barwon-Darling River, 15 low-level, fixed crest weirs have been constructed to assist with maintaining a series of large pools which could be used for the provision of stock and domestic use (Thoms and Sheldon, 2000). Because of the low gradient of the Barwon-Darling River, a single weir can impound and influence the hydraulic character of many kilometres of river upstream (Chessman et al., 2010). The construction of low-level weirs has been an incremental process. The oldest weir was constructed at Bourke in 1897, while the most recent was constructed in 1983 upstream of Louth. The majority of weirs were, however, built during the 1960s and 1970s (NSW Department of Primary Industries, 2006).

Between the 1960s and 1995 there was a marked increase in the number of water licenses issued for irrigation on the Barwon-Darling (Thoms and Sheldon, 2000). However, in 1995 a Cap on water diversions was introduced to protect and enhance the riverine environment and to protect the rights of water users (Thoms and Sheldon, 2000). Despite these changes the abstraction of water and the capture of floodwaters within off-river reservoirs has substantially altered the hydrology of the

Barwon-Darling River (Chessman et al., 2010; Thoms and Sheldon, 2000), with annual diversions over the past 30 years fluctuating between 100 GL/yr and 500 GL/yr (CSIRO, 2008). Since early European settlement, the average daily flows have been reduced by 32 %, and median daily flows have been reduced by as much as 73 %, with the downstream locations being the most severely impacted (Thoms and Sheldon, 2000).

This study focusses on the Barwon-Darling River between the townships of Walgett in the north and Wilcannia in the southwest, spanning approximately 1000 km of river channel (Figure 2.1). This is an area that was extensively surveyed in the late 1800s as part of a proposal to establish a series of locks along the length of the river in order to facilitate riverboat navigation. These surveys provide benchmark data against which comparisons can be made regarding changes to the river's physical template over time.

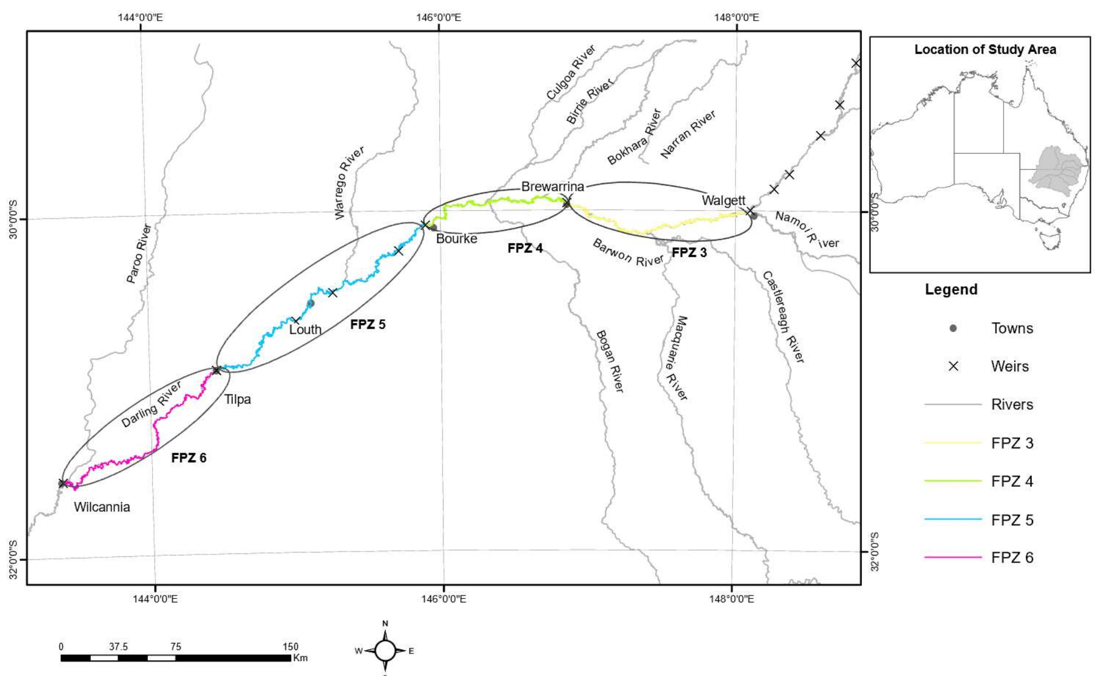

Figure 2.1: Part of the Barwon-Darling catchment. FPZ 3 to FPZ 6 highlight river sections of similar geomorphic character. (Coordinate system: GDA/MGA Zone 55).

2.3 METHODS

2.3.1 Defining the physical template of the Barwon-Darling River

For the purposes of this study waterholes were defined as any segment of river that exceeds 0.5 m in depth for a minimum of 50 m in length at cease-to-flow conditions. A depth threshold of 0.5 m was selected because below this threshold water quality can deteriorate rapidly, with water temperatures becoming thermally unsuitable for fish survival (Wallace et al., 2017).

Waterhole distribution and character were assessed based on a historical (late 1890s) and modern day (2015) river profile. The historical river profile represents the profile prior to the construction of weirs (except for Bourke Weir), headwater dams, significant water abstraction and the introduction of floodplain infrastructure for irrigation. In contrast to the historical profile, the modern profile represents the landscape after substantial water resource development and land-use change within the catchment. The historical river long profiles were created by the Department of Public Works, Water Conservation Branch in 1897/1898 (Department of Public Works - Water Conservation Branch, 1898a: Department of Public Works - Water Conservation Branch,1898b). The bed profiles provided information on the locations and depths of a sample of waterholes based on flow conditions at the time of survey (Figure 2.2). Waterhole depths at cease-to-flow were estimated by identifying natural barriers to downstream flow on the historical profile, from which an inference to cease-to-flow water levels was made (Figure 2.2). Modern day waterhole locations and depths were obtained from high-definition, side scanning sonar conducted by the NSW Department of Primary Industries in 2015 (NSW Department of Primary Industries, 2015). Waterhole depths were again adjusted to represent cease-to-flow conditions, but these were based on the stage height of the nearest gauge at cease-to-flow. The continuous nature of measurement used for the modern survey means that the profile represents the complete population of waterholes present at the time of sampling rather than a sample of that population.

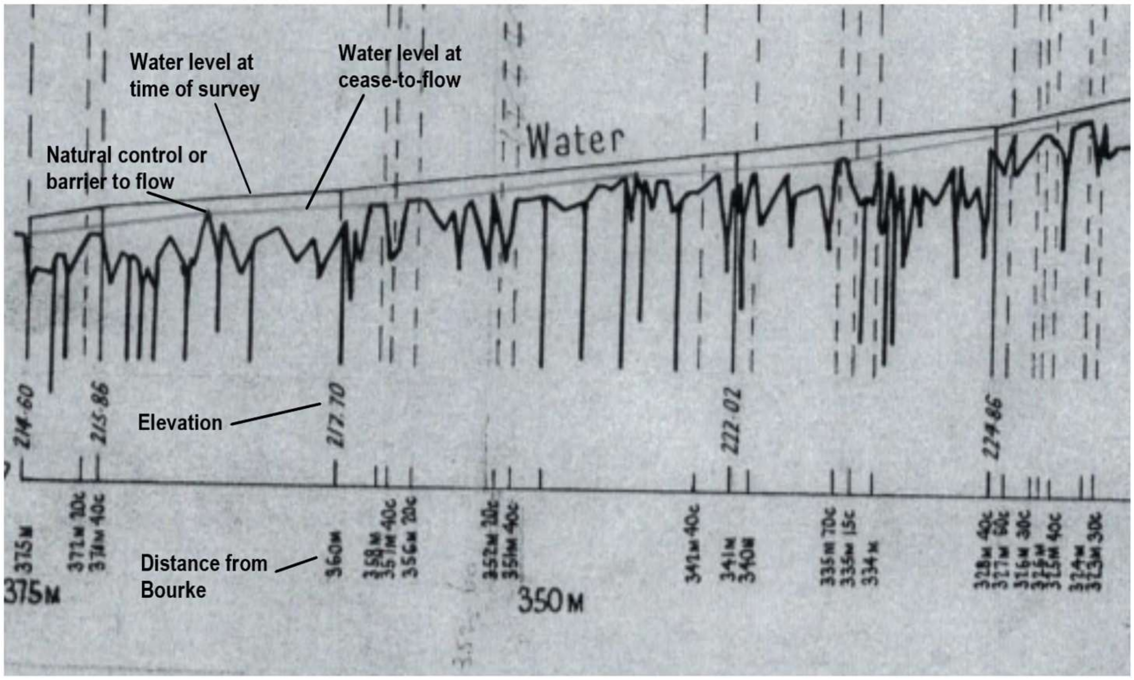

Figure 2.2: Snapshot of an historical longitudinal profile showing the water level at the time of surveying and the inferred water level at cease-to-flow.

2.3.2 A hierarchical approach to investigating changes to the physical template of the Barwon-Darling River

A hierarchical approach based on three spatial scales was used to compare the two datasets. At the largest scale, the historical and modern channels were compared for the full length of river between Walgett and Wilcannia. Nested within the river at the intermediate spatial scale, comparisons were made across four 'functional process zones' (FPZs) (Figure 2.1) (Boys and Thoms, 2006). FPZs are characterised as large sections of river (>200 km) that are geomorphically similar and have a relatively uniform discharge and sediment regime (Boys and Thoms, 2006). These groupings provide a useful hydro-geomorphic framework, with respect to scale and process, to explore patterns in the degree of change to the physical template. At the smallest spatial scale, a comparison of the historical and modern profile was made for reaches that were characterised as either weir pool or non-weir pool, as identified by the shape of the riverbed on the modern profile (Table 2.1). The influence of low-level weirs on bed form and stage height has been well documented in the literature (Thoms and Sheldon, 1997; Walker et al., 1993) and preliminary analysis of data from this study suggested it may be a useful scale for revealing patterns of change.

Table 2.1: River distances relating to weir pool and non-weir pool reaches based on 2015 river survey.

FPZ	Combined length of weir pool (km)	Combined length of non-weir Pool (km)	Total pool length (km)	% of reach in weir pool influence
3	85	185	270	32
4	60	150	210	29
5	275	90	365	75
6	45	235	280	16

2.3.3 Preliminary exploration of the historical and modern datasets

An exploratory approach to data analysis was initially undertaken to examine differences between the two datasets considering the different survey methods used for data collection. This step identified several inconsistencies between the datasets, which impacted on the ability to directly compare data between the two time periods and consequently drove the selection of subsequent data analyses. Figure 2.3 outlines the identified issues and the approach used to address or resolve these issues to ensure greater confidence in the overall analysis and interpretation of data.

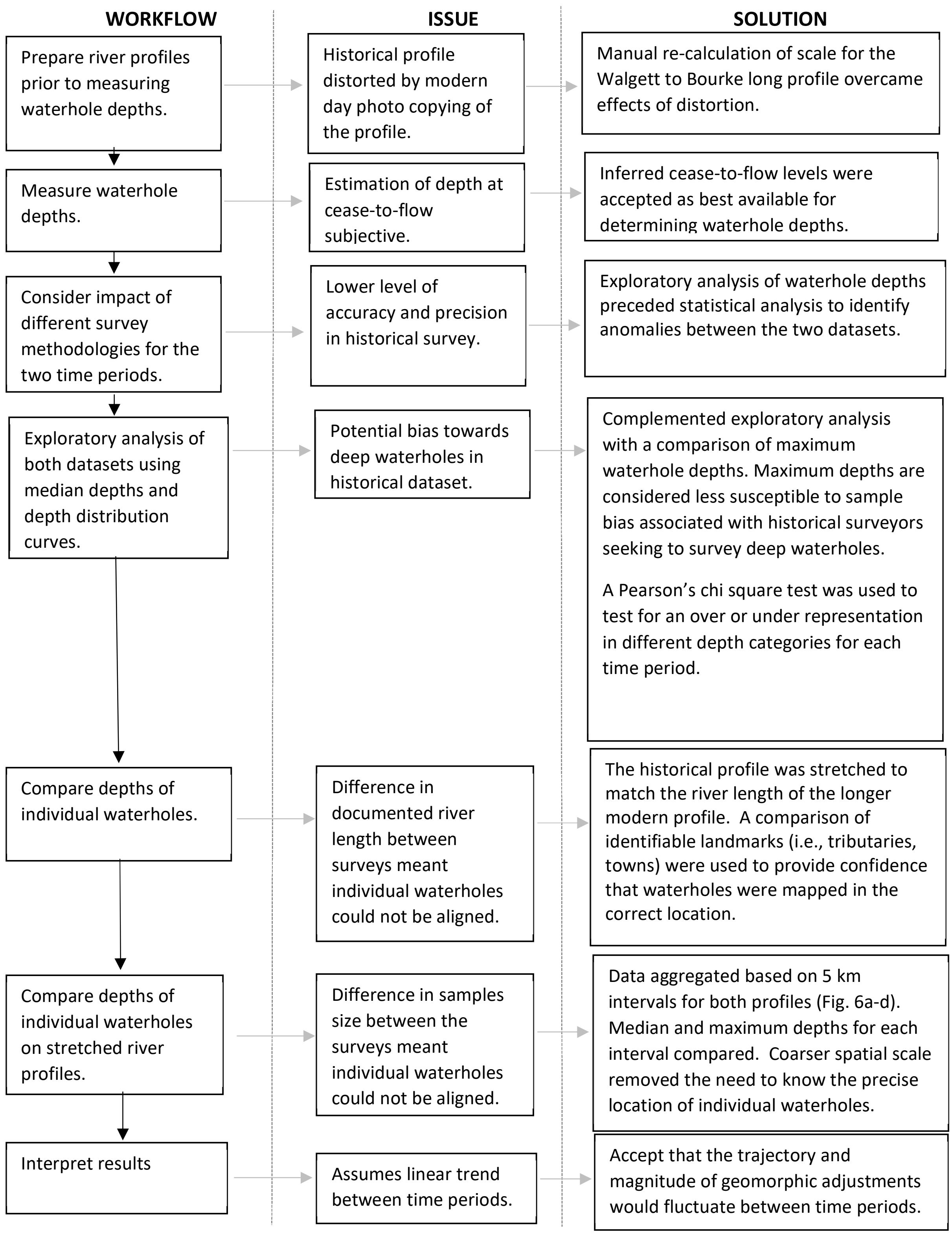

Figure 2.3: Workflow highlighting the issues associated with the historical dataset and the steps used to resolve these issues and improve confidence in data analysis and interpretation.

2.3.4 Quantifying temporal and spatial changes to waterhole depth

Median depths were investigated in combination with kernel density plots to characterise and compare the datasets for each time period. However, the preliminary data analysis flagged issues with potential sampling bias in the historical data (Figure 2.3). The historical survey was conducted with the intent of finding suitable locations for lock and weir development and as such it may not have objectively characterised the full long profile for the river. Historical government records suggest that the nineteenth century surveyors may have targeted a number of isolated, natural rocky outcrops embedded in the alluvium for lock development (New South Wales. Parliament. Legislative Assembly, 1891). As such, sampling efforts may have been directed towards these shallow, hard rocky surfaces and more specifically the natural deep pools that formed immediately upstream. This approach to sampling would result in a biased sample of waterhole depths that could skew or fatten the upper tail of distributions. In turn, this could lead to the systematic over estimation of the median waterhole depths. Importantly though, the postulated bias toward sampling deep waterholes would have less impact on maximum water depths (targeting deep pools in a survey cannot result in higher maximum depths being recorded than exist in the full population of depths), making maximum depth an appropriate summary statistic to complement the comparison of median water depths.

Maximum water depths were compared across location (FPZs), sampling period (historical and modern) and treatment (weir and non-weir) using a three-way analysis of variance in R statistical software (R Core Team, 2018). In addition, the output from the ANOVA provided context for investigating the impact of each of the main effects and two-way interactions on maximum water depths.

2.3.5 Quantifying the spatial organisation of waterholes throughout time

Distances between waterholes exceeding a range of depths were determined to establish if the spatial organisation of waterholes has changed between the two surveys. A series of thresholds were identified based on the depths of waterholes matching the 50th, 60th, 70th, 80th and 90th percentiles in the historical dataset. Separate thresholds were established for weir pool and non-weir pool locations so that the influence of weirs on waterhole depth could be identified (Table 2.2). For each threshold, waterholes exceeding the specified depth were identified in each dataset and the distance downstream to the next waterhole exceeding the same depth was calculated.

By using a series of depth thresholds, patterns and trends in changes to spatial organisation could be investigated in relation to the depth gradient. This approach was taken because there is no single waterhole depth that can be objectively identified as critical for all biotic components or processes relying on waterhole habitat, or for the connection between waterhole habitats. Thus, by establishing patterns and trends in changes to connectivity across a range of waterhole depths, general comments can be made about the effects on connectivity across this range.

Table 2.2: Waterhole depths at cease-to-flow based on the historical bed profile.

Percentile	Depth (m) Weir Pools	Depth (m) Non-Weir Pool
50th	3.36	3.36
60th	3.9	4.08
70th	4.4	4.64
80th	5.58	5.28
90th	6.69	6.24

2.4 RESULTS

2.4.1 A visual comparison of waterhole depths for the historical and contemporary profiles

Figure 2.4 provides a visual comparison of waterhole depths taken from the historical and modern river profiles. An increase in waterhole depths relating to the presence of low-level weirs is clearly visible at the downstream end of each FPZ. In the case of FPZ 5, waterhole depths increase at four individual locations corresponding with the location of the four low-level weirs present within this zone. By contrast, Figure 2.4 shows that there are fewer waterholes deeper than 3 m in the modern dataset in areas outside of the weir pool influence.

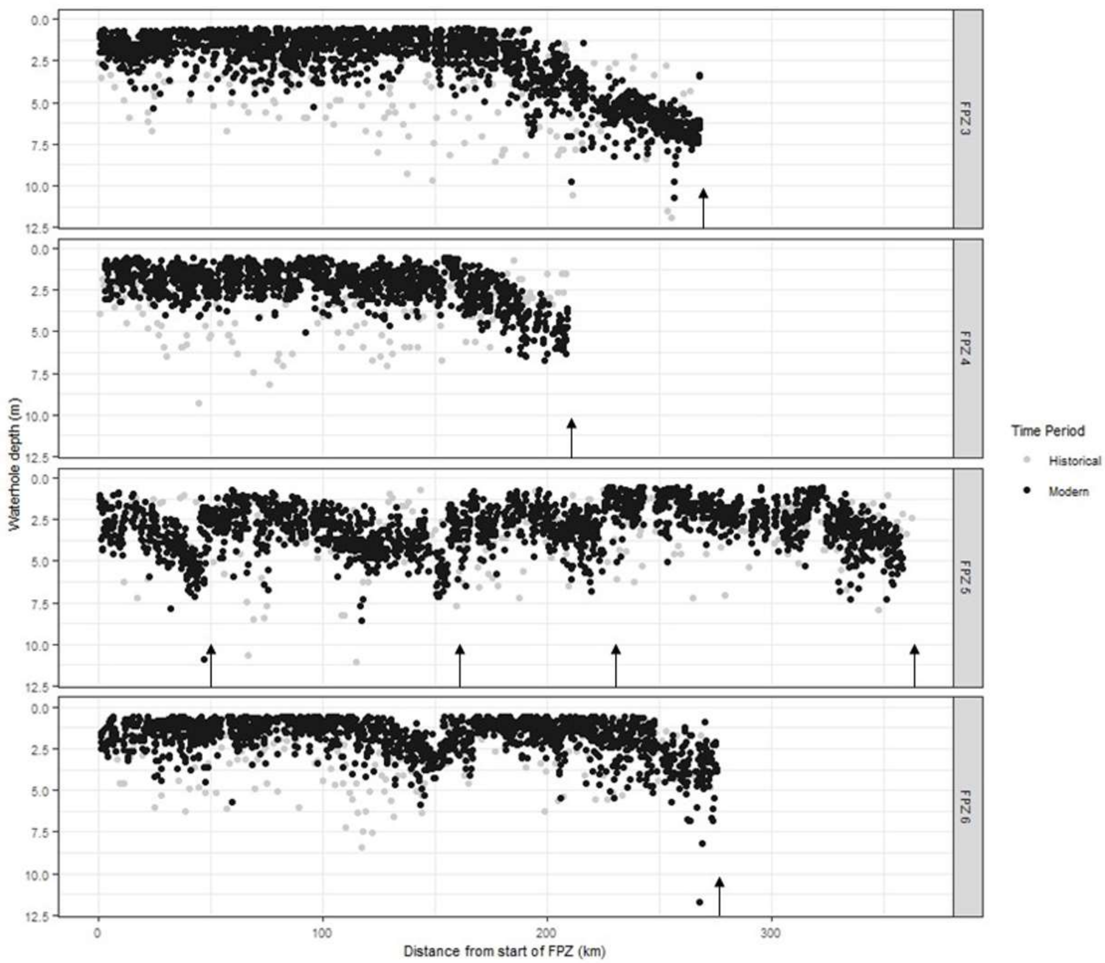

Figure 2.4: The longitudinal distribution and depth of waterholes on the Barwon-Darling River taken from the historical and modern river profiles (each row represents an FPZ and the location of weirs are shown as an arrow).

2.4.2. Quantifying temporal and spatial changes to waterhole depths

2.4.2.1 Exploration of the historical and modern datasets using median waterhole depths

Median waterhole depths were consistently lower in the modern dataset (range = 1.5 – 2.8 m) compared to the historical dataset (range = 2.9 to 4.5 m) across all four FPZs (Figure 2.5). However, only minor differences were observed between the two time periods when exploring the data independently for reaches influenced by low-level weirs (Figure 2.5). In these reaches, median depths differed by no more than 0.4 m in any FPZ. In contrast, a noticeable difference was observed in non-weir pool locations, with median depths ranging from 1.4 to 2.1 m in the modern dataset compared to 2.8 to 4.1 m in the historical dataset.

In the historical dataset, the most upstream FPZ (i.e., FPZ 3) had the highest median depths for both the weir pool and non-weir pool locations, with median depths up to 1.5 m greater than the other FPZs. No other longitudinal trend was evident in the historical dataset. In the modern dataset, FPZ 3 again had the highest median depth for the weir pool locations, but in the non-weir pool locations median depths were relatively consistent between FPZs.

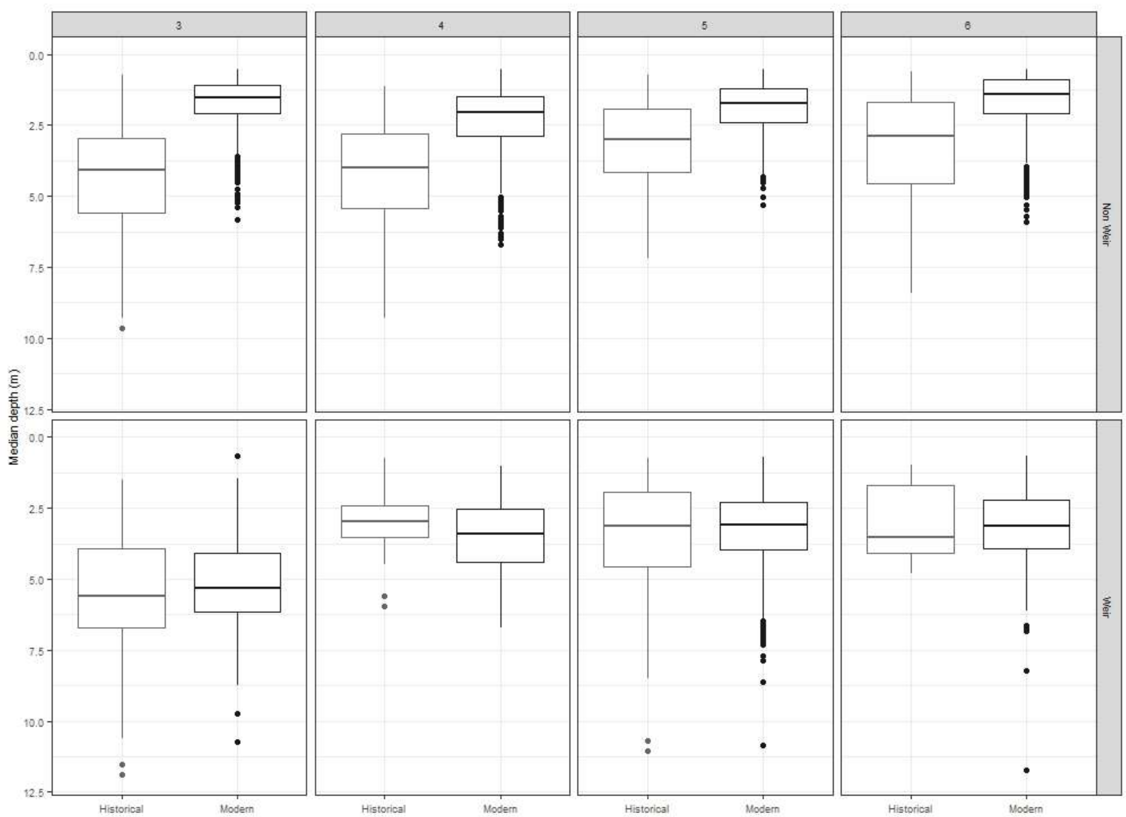

Figure 2.5: Median depth of waterholes on the Barwon-Darling River between Walgett and Wilcannia in the historical and modern datasets as grouped by FPZ and weir pool influence. The centre line of the box represents the median or 50 % quantile, whilst the lower and upper hinges represent the 25

% and 75 % quantiles. The upper whisker is equivalent to the largest observation that is less than or equal to the upper hinge plus 1.5 times the IQR. Conversely, the lower whisker represents the smallest observation greater than or equal to the lower hinge minus 1.5 times the IQR. Outliers are represented by the black dots. n = 269 (historical/weir), n = 447 (historical/non-weir), n = 2489 (current/weir), n = 4226 (current/non-weir).

2.4.2.2 Characterising the distribution of waterhole depths

Overall, waterhole depths in the modern dataset were positively skewed (SK = 1.23) with a greater proportion of shallow waterholes being represented (Figure 2.6). In contrast, the historical dataset had a greater spread of waterholes across the depth spectrum, which resulted in a more symmetrical distribution (SK = 0.83) (Figure 2.6). A Pearson's chi square test indicated that there was a higher than expected number of deep waterholes (i.e., >3 m) in the historical dataset (X^2 = 462, df = 8, p-value <0.001) and the same was observed across all FPZs (Table 2.3)

Table 2.3: Pearson's chi square test results for waterhole depths in each FPZ

FPZ	X^2	df	p-value
3	187	8	<0.001
4	234	8	<0.001
5	80	8	<0.001
6	236	8	<0.001

Distribution curves showed a different pattern when the datasets were split based on weir and non-weir pool locations. In the full datasets, the distributions were more skewed in the modern datasets (Figure 2.6a-b), but in the weir pool locations the opposite was observed (Figure 2.6c-d). In these areas, the distribution of waterhole depths for the historical dataset were positively skewed (SK = 1.13), whilst the distributions for the modern dataset were close to symmetrical (SK = 0.70). In contrast, in non-weir pool locations (Figure 2.6e-f), the historical dataset was close to symmetrical (SK = 0.53), which is similar to that observed for the full dataset. The modern dataset was again positively skewed as it was in the full dataset, yet the relative skew was stronger (SK = 1.28).

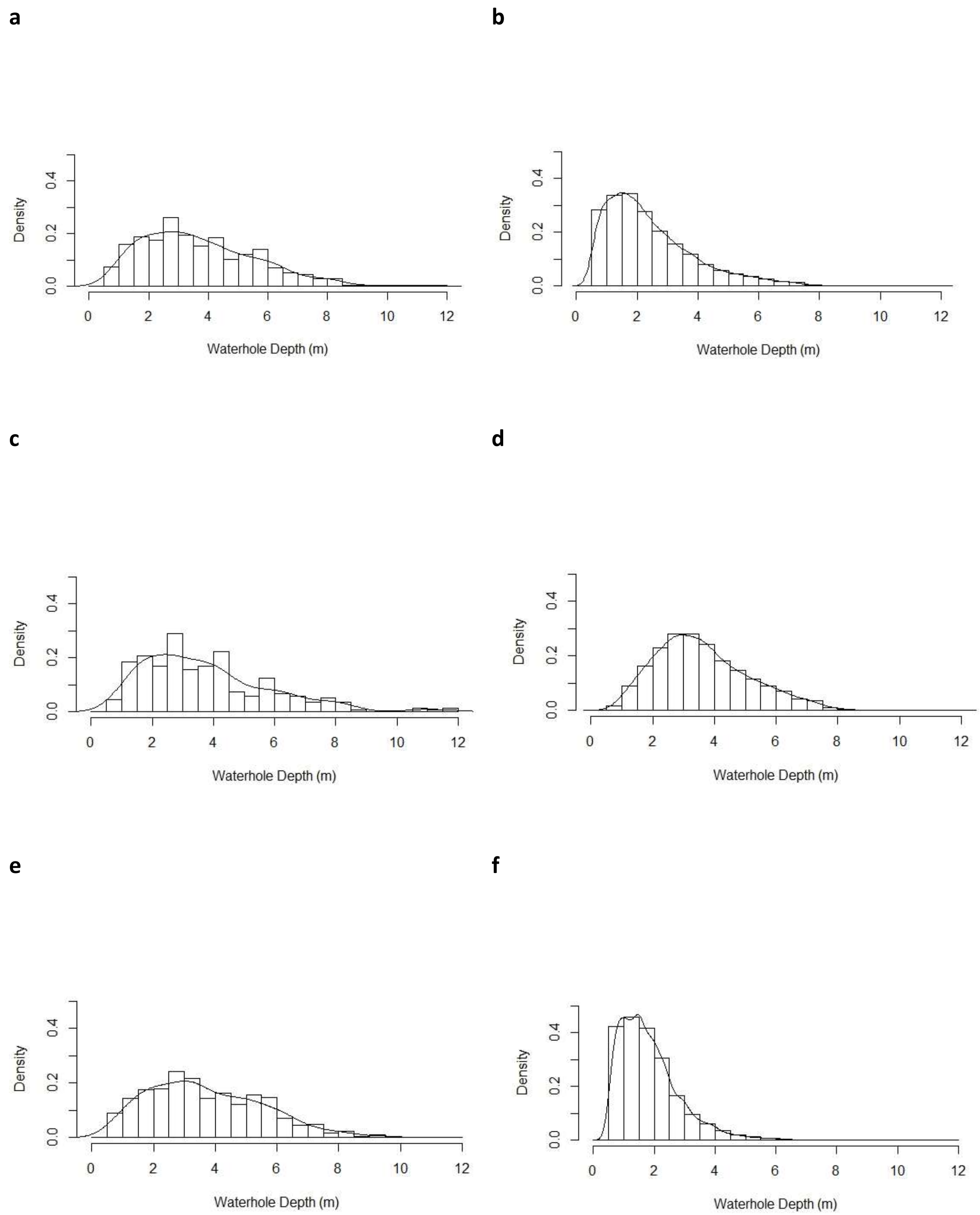

Figure 2.6 (a-f): Distribution of waterhole depths grouped by dataset and weir pool influence. (a – historical – all waterholes, b – modern – all waterholes, c – historical – within weir pool influence, d – modern – within weir pool influence, e - historical – outside of weir pool influence, f - modern – outside of weir pool influence)

2.4.3 Changes to maximum waterhole depths

Maximum water depths varied significantly between FPZs (ANOVA $p < 0.001$), time periods ($p < 0.05$) and weir versus non-weir pools ($p < 0.001$). Significant two-way interactions between each of the factors were observed ($p < 0.05$ for each combination). However, no three-way interaction was detected between the three main effects ($p = 0.69$) (Figure 2.7).

Overall, maximum water depths were greatest in the historical dataset with 59 % of the 5 km intervals having a maximum depth greater than its corresponding modern 5 km interval (Table 2.4). A similar trend was observed across all FPZs, except FPZ 5. Longitudinal profiles for each FPZ provide a visual comparison of maximum water depths across the 5 km intervals and are particularly useful for highlighting the influence of low-level weirs (Figure 2.8a-d). Contrasting results were again observed for weir and non-weir pool locations. Reaches within weir pool locations had maximum waterhole depths that were consistently higher in the modern dataset. The increase in depths across the 5 km intervals ranged from 1.6 to 8.7 m, with a median increase in maximum water depths of 1.4 m (Figure 2.7). In contrast, the maximum depths in the non-weir pool locations were consistently lower for the modern dataset. The decline in maximum depths ranged from 0.02 to 7.3 m, with a median decrease of 1.6 m. The greatest decline was observed in FPZ 3 (median = 1.4 m, max = 4.3 m), whilst the most downstream FPZ (FPZ 6) experienced the smallest decline (median = 1.3 m, maximum = 4.25 m).

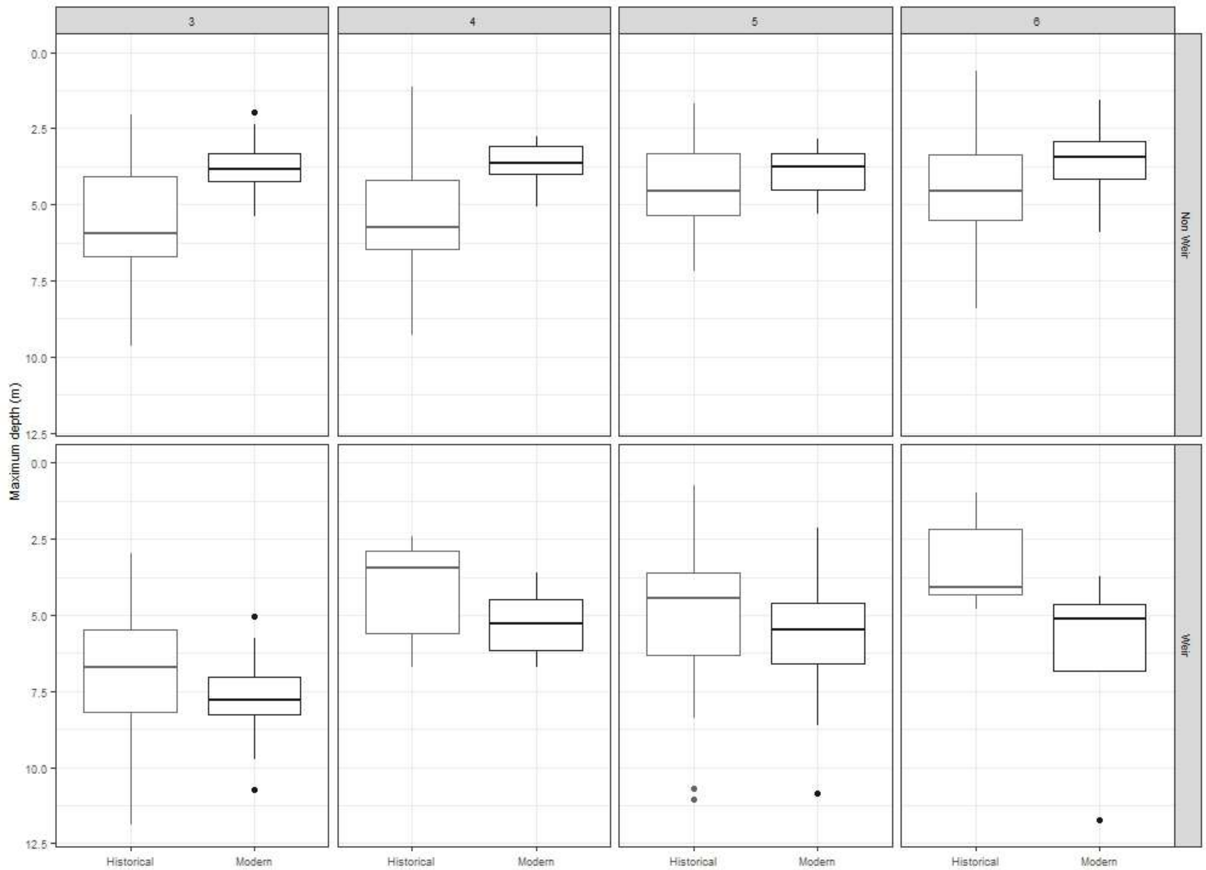

Figure 2.7: Maximum water depths of waterholes on the Barwon-Darling River between Walgett and Wilcannia in the historical and modern datasets as grouped by FPZ and weir pool influence. The centre line of the box represents the median or 50 % quantile, whilst the lower and upper hinges represent the 25 % and 75 % quantiles. The upper whisker is equivalent to the largest observation that is less than or equal to the upper hinge plus 1.5 times the IQR. Conversely, the lower whisker represents the smallest observation greater than or equal to the lower hinge minus 1.5 times the IQR. Outliers are represented the black dots.

Table 2.4: Frequency of 5 km intervals observed with the highest maximum depth across FPZs

	ALL	FPZ 3	FPZ 4	FPZ 5	FPZ 6
No of 5 km intervals in zone	235	54	42	73	56
No. of intervals with the highest max. depth in historical dataset	138 (59%)	37 (69%)	31 (73.8%)	31 (42%)	39 (69.6%)
No. of intervals with the highest max. depth in modern dataset	97 (41%)	27 (31%)	11 (26.1%)	42 (58%)	17 (30.4%)

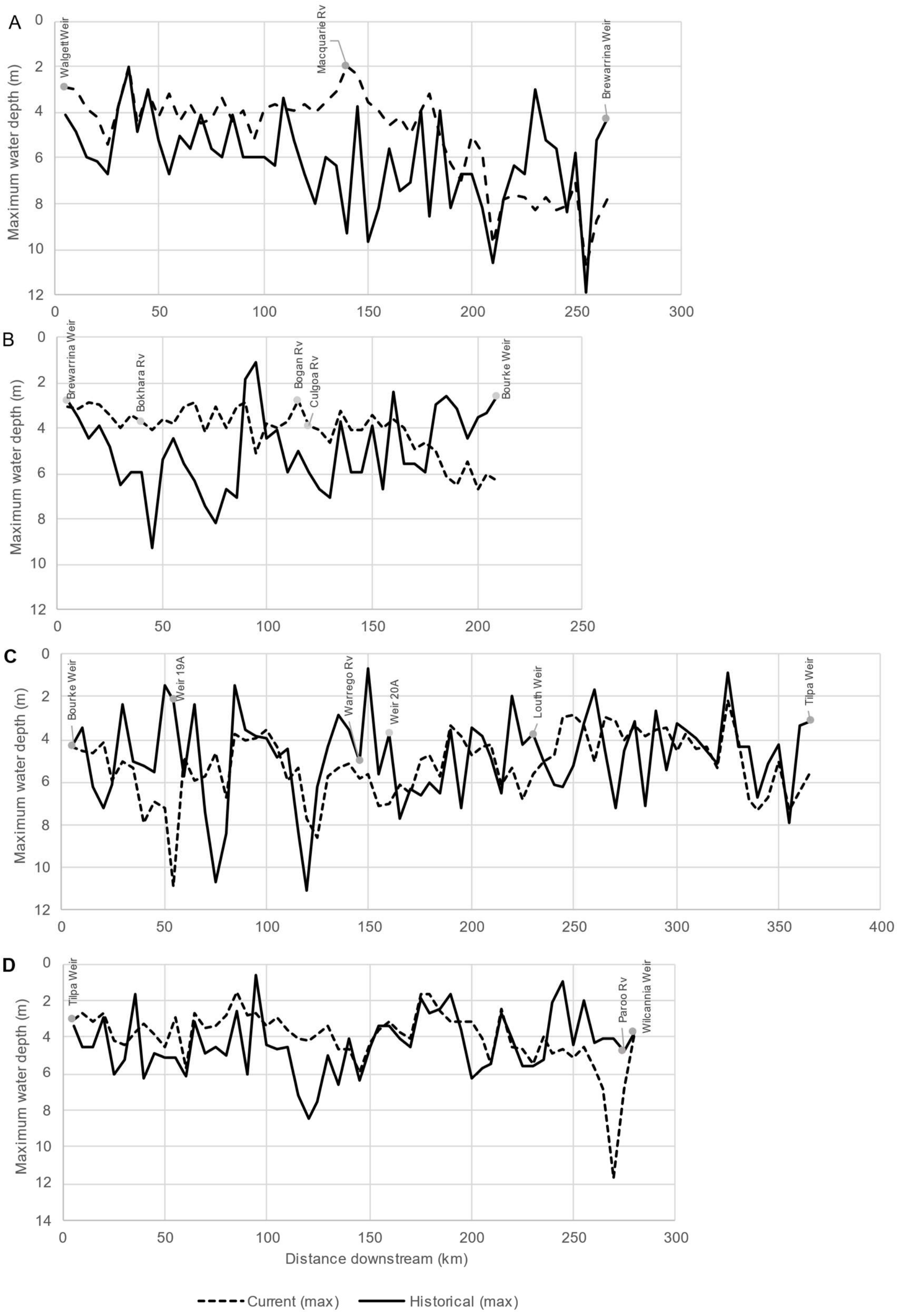

Figure 2.8(a-d): Longitudinal profiles showing maximum waterhole depths for each 5 km interval in each FPZ for the historical and modern datasets (a - FPZ 3, b - FPZ 4, c- FPZ 5, d – FPZ 6).

2.4.4 Quantifying changes to the distance between waterholes from historical and modern surveys

The change in distance between the waterholes varied substantially between the two surveys with the trajectory of change (i.e., an increase or decrease in distance) being dependent on weir pool influence (Table 2.5).

The distance to the next downstream waterhole of the same or greater depth has declined for waterholes located within the weir pool influence in all FPZs (Table 2.5). This trend was consistent across all waterhole depth thresholds (Table 2.5). Median distances ranged from 1.5 to 23.2 km in the historical dataset and declined to a range of 0.18 to 2.64 km in the modern dataset, equivalent to a reduction in distance ranging from 21-98 %.

In contrast, waterholes located in non-weir pool locations experienced a less consistent trajectory of change (Table 2.5), but for water depths exceeding the 60th percentile (~4 m) distances increased in most scenarios. Median distances ranged from 1.2 to 21 km in the historical dataset and increased to 0.93 to 42.3 km in the modern dataset. However, waterholes in the modern dataset started to disappear above the 80th percentile (5.28 m) in FPZ 4 and 5 and above the 85th and 90th percentile in FPZ 3 and 6, respectively. In these cases, a measure of distance was not calculated as the next closest waterhole was in the adjacent FPZ.

Table 2.5: Percentage change in the median downstream distance to waterholes meeting the depth threshold within weir and non-weir pool areas.

FPZ	50th	60th	70th	80th	90th
WEIR POOL					
3	36%↓	90%↓	90%↓	92%↓	91%↓
4	89%↓	88%↓	96%↓	*	*
5	92%↓	92%↓	94%↓	86%↓	73%↓
6	93%↓	93%↓	98%↓	*	*
NON-WEIR POOL					
3	5%↓	161%↑	286%↑	*	*
4	79%↑	975%↑	1815%↑	*	*
5	69%↓	15%↓	93%↑	*	*
6	53%↓	2%↓	64%↓	629%↑	*

*No waterholes meeting threshold requirements in modern dataset for FPZ

2.5 DISCUSSION

2.5.1 Changes to the physical template of the Barwon-Darling River

The results of this study suggest that the physical template of the Barwon-Darling has been substantially altered over the past 120 years. Along the entire study reach (Walgett to Wilcannia), both the median and maximum waterhole depths have declined significantly since the 1890s. Associated with this decline has been a considerable increase in the distances between deep waterholes (>4 m) in most locations. Despite potential concerns relating to sampling bias in the earlier survey, the observed decline in both the median and maximum waterhole depths suggest that the observed differences are real, at least in direction, even if not in the precise magnitude of change.

Although the overall pattern is one of declining waterhole depths, the trajectory and magnitude of change is scale dependent and varies across the three spatial scales of investigation (i.e., the entire study area, FPZs and weir pool vs non-weir pool). The largest observable difference in the trajectory and magnitude of change for waterhole depths occurs at the smallest scale of observation. That is, median and maximum waterhole depths increased in reaches influenced by low-level weirs, whilst in non-weir pool locations, waterhole depths declined. At the scale of FPZs, a declining trajectory in waterhole depth is consistent across all FPZs, yet the magnitude of change is far greater in the upstream FPZs (FPZ 3 and 4).

Increasing waterhole depths is not unexpected at the weir pool locations. Localised impoundment in these reaches mean that water levels are held at a more stable and artificially high stage height than would have occurred naturally (Jones, 2007). On lowland rivers like the Barwon-Darling, the effects of weirs are compounded by their low bed slope (Chessman et al., 2010). A single low-level weir can impound the river for many kilometres upstream, transforming some river sections into large, deep, static pools that are almost permanently inundated. As a result, it is not surprising in this study to find an association between increasing waterhole depths in the weir pool locations and a decrease in the distance between deep waterholes - i.e., those waterholes exceeding 4 m in depth. The decline in distance between deep waterholes within weir pool sections is inevitable given the overall increase in waterhole depth, but it is worth noting that this pattern means that the deep waterholes within weir pool sections are now more connected than they were prior to weir construction. In contrast, the decline in waterhole depths in the non-weir pool locations resulted in a substantial increase in distance (at times more than double) between the deeper waterholes despite the modern dataset having a significantly larger sample of waterholes than the historical dataset. The consequence for the non-weir locations is a reduction in waterhole connectivity.

The decline in waterhole depths and the reduced connectivity observed in this study is likely a consequence of increasing sedimentation within the system. This situation is commonly found on large lowland rivers throughout the Murray-Darling basin in south-eastern Australia (Gell et al., 2009). On the Barwon-Darling River, sediment cores taken from the channel bed and from in-channel benches in FPZ 3 indicate that in the last 100 - 150 years, 0.5 - 2 m of sediment has accumulated (Olley and Caitcheon, 2000). Such accumulation, if replicated at other locations, would account for the decline in waterhole depths and is consistent with the median decrease in maximum water depths of 1.6 m.

On lowland rivers the supply of sediment can be attributed to a combination of three principal mechanisms: (1) the redistribution of sediment within the channel, (2) the influx of sediment from upstream source areas, including the major tributaries, and (3) the influx of sediment from the adjacent floodplain. Of these, there is substantial evidence of the first two on the Barwon-Darling River operating over significantly different temporal scales. In the longer term, the partial reworking of in-channel bench deposits is a significant source of sediment to the river at intervals up to 95 years (Thoms and Olley, 2004). The contemporary supply of sediment is, however, dominated by contributions from upstream tributaries and will vary throughout time depending on the prevailing flow conditions in each of the tributaries (Olley and Caitcheon, 2000). The third mechanism, the contribution of sediment from the adjacent floodplain, has for the Barwon-Darling remained largely unquantified in the literature. However, based on research in neighbouring catchments it is likely to be significant (Lobegeiger, 2010; Reid et al., 2016). The combination of floodplain development and extensive grazing pressure has reduced perennial plant cover on the Barwon-Darling floodplain, increasing its sensitivity to erosion (Gell et al., 2009; McKeon et al., 2004). Alluvial gullying has increased on the Barwon-Darling over the past 50 years with 3-4 gullies/km contributing significant quantities of sediment to the river (Pearson *et al*, 2021).

The increasing supply of sediment to the Barwon-Darling has occurred in parallel with a likely decline in the river's capacity to entrain and transport sediment through the system. The extraction of water for irrigation since the 1960s has substantially reduced the magnitude of small flood events on the Barwon-Darling (i.e., those floods with an average reoccurrence interval <2 yr) by as much as 70 % (Thoms and Sheldon, 2000). Under natural flow conditions these smaller flood events are critical for maintaining the natural equilibrium between sediment deposition and the longitudinal conveyance of sediment (Reid et al., 2016). In the absence of these flows, sediment is more likely to be retained close to its source leading to an eventual decline in waterhole depths (Knighton and Nanson, 1994). On the Barwon-Darling, this issue is compounded by the presence of 15 low-level weirs that would not only create an effective barrier to trap sediment but would also lower flow velocities, inducing sediment deposition (Fryirs and Brierley, 2013b; Ward and Standford, 1995).

Waterholes in this study experienced the greatest decline in water depths (i.e., a decline of 2.2 m) in the most upstream FPZs (FPZ 3 and 4), which corresponds with the confluence of all but two of the major tributaries. This pattern is consistent with the notion that the upstream tributaries are an important source of sediment to the Barwon-Darling. However, other mechanisms driving sediment accumulation should not be dismissed. It is possible, for example, that floodplain contributions may be more significant in the upper part of the catchment (FPZ 3 and 4) because of higher levels of floodplain development adjacent to this part of the river. Alternatively, it is possible that the channel dimensions, bed slope, and discharge capacity may create hydraulic conditions that are more conducive to the reworking and redistribution of sediment in the upper two FPZs (FPZ 3 and 4). However, without further investigation we can only speculate as to what mechanisms are driving sedimentation and the subsequent changes to the river's physical template.

A combination of sediment tracing, the more widespread collection and dating of sediment cores, and detailed hydraulic modelling would provide greater clarity on how sediment interacts within the Barwon-Darling River. By understanding how the supply and movement of sediment is influenced by periods of major disturbance (natural or anthropogenic) we can more accurately predict how sediment may behave in the future. This knowledge will be critical to the on-going and targeted management of sedimentation and the subsequent protection of waterholes in dryland rivers (Olley and Caitcheon, 2000; Reid et al., 2016; Thoms and Olley, 2004).

2.5.2 Implications of a changing physical template

Modifying a river's physical template can have significant implications for longitudinal connectivity and subsequently for the availability and quality of habitat for riverine biota (Jacobson and Galat, 2006; Sheldon and Thoms, 2006; Walker and Thoms, 1993). The impact of low-level weirs in creating deeper, more stable conditions is well known and various examples exist in the literature regarding the compensatory adjustments made by biota following a shift towards more permanent levels of inundation (Jones, 2007; Walker et al., 1993). However, of perhaps greater significance in this study is evidence indicating extensive shallowing of waterholes and a substantial increase in distance between those waterholes in non-weir pool locations. These areas outside of the weir pool influence constitute approximately 660 km of river channel or 59 % of the entire study area.

Declining waterhole depths can have significant implications for water quality, waterhole persistence, and ultimately for longitudinal connectivity (Sheldon et al., 2010; Sheldon and Fellows, 2010). Shallow waterholes will remain wet for shorter periods of time during low and no-flow events, creating a more fragmented and less connected river system (Lobegeiger, 2010; Puckridge et al., 1998; Reid et al., 2016). As waterholes dry, the exposed riverbed creates a physical barrier to longitudinal connectivity. At the landscape scale, this means that the well-connected weir pool sections become increasingly isolated, not only by the physical barrier of the weir itself, but also by the drier sections of riverbed present on either side of the weir pool. As a result, the spatial and temporal movement of sediment, nutrients, and organic matter through the system is compromised (Ward and Standford, 1995). From a biological perspective, the migratory pathways of some species may be blocked or restricted, limiting access to food, shelter, and nursery habitat (Bunn and Arthington, 2002; Rolls et al., 2013; Sheldon et al., 2010). As water levels decline, the quality of water can deteriorate and temperatures can become thermally unsuitable for fish survival. Competition and predation increase, and protective habitat can become exposed (Fellows et al., 2009; Sheldon and Fellows, 2010).

On-going water extraction has been shown to significantly reduce the magnitude, frequency, and duration of flows on the Barwon-Darling River, particularly in the low to medium flow range, which is critical for the replenishment of dryland waterholes (Thoms and Sheldon, 2000). Of even greater concern, however, is the potential impact of climate change on already impacted waterholes. Climate change can be expected to cause waterhole depths to decline further because of declining inflows exacerbated by a reduction in precipitation, increasing air temperatures, and enhanced evaporation (Hamilton et al., 2005). Under climate change scenarios, shallow waterholes would be expected to dry more rapidly and stay fragmented longer (Hamilton et al., 2005).

2.6 CONCLUSION

The historical data used in this study presented several challenges particularly in relation to sampling bias and low sample size in the historical dataset. However, this study demonstrates that such issues are not insurmountable providing the limitations with the data are recognised so that methods can be devised and results interpreted with these limitations in mind. Despite the inherent flaws, historical data are an invaluable resource for extending our temporal perspective of our river systems.

This study has shown a substantial change to the character and spatial organisation of waterholes on the Barwon-Darling River over a 120-year period. Although depths increased in areas under the influence of weir pools, outside of these areas (constituting nearly 60 % of the river) waterholes have become substantially shallower and distances between deep waterholes have increased. These changes, combined with the effects of climate change and ongoing water extraction, have the potential to reduce the persistence and quality of waterholes and to create a more fragmented landscape of aquatic refugia within the river system.

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CHAPTER 3

Floodplain gully erosion – An overlooked source of sediment and the implications for dryland river waterholes.

ABSTRACT

Dryland alluvial rivers are naturally complex systems with a range of in-stream and floodplain geomorphic units that provide habitat for aquatic and terrestrial biota. However, these systems are increasingly being threatened by accelerated rates of sedimentation leading to a decline in geomorphic complexity, habitat quality and ponding depth. The implications of sedimentation on waterholes, or deep pools, is of particular concern as they are often a critical source of water in otherwise arid environments. In dryland rivers, the source of sediment is however not well understood. This study has is focused on the potential for sediment derived from alluvial floodplain gullies to influence geomorphic change. Alluvial floodplain gullies are often overlooked in comparison to the more widely documented hillslope, or colluvial, gullies. This study shows that alluvial gullying is a prevalent feature of the Barwon-Darling River, a dryland system located in the northern half of the Murray-Darling Basin (MDB). The estimated volume of sediment derived from these gullies far exceeds the estimates used in past sediment budgets for the Barwon-Darling River. Gully size and complexity varied from small, linear features to large, complex, branching gullies. However, the more recent episodes of gullying (i.e., post 1960s) are limited to smaller gullies, which are likely to yield less sediment than the side walls of the larger, complex, older gullies. The combined length of these newer gullies is just 25 km, which is equivalent to 1 % of the total gully network. A predictive relationship between gully volume and change in waterhole depth was expected in this study but one was not observed. Nevertheless, the role of alluvial floodplain gullies as a significant source of sediment should not be overlooked when assessing dryland river forms and processes.

3.1 INTRODUCTION

Dryland rivers are shaped by a combination of sediment erosion and deposition which can yield a complex arrays of geomorphic units, depending on the valley setting and flow regime. Sedimentation has been responsible for substantial changes to the physical form, chemical processes and ecological health of dryland rivers and their waterhole features (Bartley & Rutherfurd, 2005; Fellows, Bunn, Sheldon, & Beard, 2009; Pearson, Reid, Miller, & Ryder, 2020; Prosser et al., 2001; Reid, Thoms, Chilcott, & Fitzsimmons, 2016). Dryland rivers in low-gradient, unconfined alluvial settings are particularly prone to sedimentation due to their inherently low and/or declining discharge and stream power, which limits sediment transport capacity (Larkin, Ralph, Tooth, Fryirs, & Carthey, 2020; Ralph & Hesse, 2010). Sedimentation can lead to the creation of in-channel features such as bars and benches and to the formation of levees adjacent to the river (Fryirs & Brierley, 2001). Sedimentation is often associated with the partial or complete in-filling of channels and waterholes, leading to a decline in geomorphic complexity and habitat quality (Bartley & Rutherfurd, 2005), whilst also reducing biological diversity (Downes, Lake, Glaister, & Bond, 2006; Kemp, Sear, Collins, Naden, & Jones, 2011; Larsen, Pace, & Ormerod, 2011). The filling of waterholes with sediment can lead to a decline in ponding depth and waterhole persistence (Costelloe, Shields, Grayson, & McMahon, 2007; Davis & Finlayson, 2000; Reid et al., 2016), whilst excess sediment can alter water quality and nutrient supply (Henley, Patterson, Neves, & Lemly, 2000; Wohl, 2015).

Anthropogenic landscape change has exacerbated the effects of sedimentation by influencing both erosional processes that affect the delivery of sediment to the river (Brooks, Shellberg, Knight, & Spencer, 2009; Gobin, Campling, Deckers, Poesen, & Feyen, 1999; Olley & Wasson, 2003; Shellberg, Brooks, & Rose, 2013), and the capacity of the river to transport sediment (Everitt, 1993; Ta, Xiao, & Dong, 2008). On many dryland rivers, extensive grazing pressure in combination with floodplain development has led to the loss of protective perennial plant cover and has altered natural flow paths increasing the sensitivity of the banks and floodplain to erosion (Gell et al., 2009; McKeon et al., 2004).

Thus, a significant increase in mobilised sediment has been observed, accelerating the supply of sediment to dryland rivers (Olley & Wasson, 2003; Wallbrink & Olley, 2004; Wethered, Ralph, Smith, Fryirs, & Heijnis, 2015; Wilkinson, Hancock, & Hawdon, 2013). Once in the river, the conveyance of sediment is often compromised by a modified flow regime, reducing the rivers capacity to transport sediment (Pearson, Reid, & Ryder, 2021). In-stream infrastructure (i.e., low level weirs common to lowland rivers) can act as a physical barrier to the movement of sediment (Chitata, Mugabe, & Kashaigili, 2014; Lobera, Batalla, Vericat, Lopez-Tarazon, & Tena, 2016; Thoms & Walker, 1993), and they can alter hydraulic conditions by reducing flow velocities (Bice, 2017; Mallen-Cooper, 2020), further inhibiting the transport of sediment (Pearson et al., 2021). Together, these catchment modifications can lead to a higher volume of sediment being deposited within the river channel and subsequently retained locally within the waterhole features (Reid et al., 2016).

Waterholes are an important biophysical feature of dryland rivers, providing both geomorphic and ecohydrological complexity (Arthington, Olden, Balcombe, & Thoms, 2010; Knighton & Nanson, 2000; Marshall, Lobegeiger, & Starkey, 2021; Sheldon et al., 2010). They typically develop as a series of deep pools capable of retaining water for extended periods during the absence of surface water connectivity and groundwater inputs (Knighton & Nanson, 1994). In dryland rivers, waterholes are often natural deposition zones under low to moderate flow conditions (Nanson, Tooth, & Knighton, 2002). However, waterholes often form at points of lateral confinement where flows concentrate under high flow conditions, producing the requisite stream power for scour to occur (Knighton & Nanson, 1994). This process ensures deep pools are retained within the river system, although not always in the same location (Reid et al., 2016). As they are often the only source of water in an otherwise arid landscape, waterholes provide a critical water supply for local communities for stock and domestic use and recreation. Waterholes are also critical to the sense of identity, cultural practices, and spiritual beliefs of indigenous communities, (Jackson, Pollino, Macklean, Bark, & Moggridge, 2015). From an ecological perspective, waterholes provide refugial habitat for aquatic biota during prolonged periods of low flow or no flow that commonly occur in these semi-arid landscapes (Arthington & Balcombe, 2011; Bunn, Thoms, Hamilton, & Capon, 2006; Marshall et al., 2021; Rodgers & Ralph, 2011). When the river is hydrologically connected, waterholes contribute to habitat heterogeneity at the landscape scale increasing the diversity of available habitat for biota (Boys & Thoms, 2006). Despite the importance of waterholes, these critical features are increasingly threatened by growing levels of sedimentation (Lobegeiger, 2010; Negus, Blessing, Clifford, & Steward, 2015). Sedimentation can affect the capacity of a waterhole to act as a refuge for aquatic biota and reduces the availability of water for communities (Lobegeiger, 2010; Reid et al., 2016).

In Australia's Murray-Darling Basin (MDB), gully erosion has emerged as the main source of anthropogenic sediment impacting rivers within the Basin (DeRose, Prosser, Weisse, & Hughes, 2003; Hughes & Prosser, 2012; Prosser et al., 2003, Wallbrink & Olley, 2004, Wasson, Mazari, Starr & Clifton, 1998). Modelled data indicates that gully derived sediment contributes approximately 8 million $m^3 yr^{-1}$ to the MDB and is responsible for 40 % of all sediment supplied to the MDB rivers (DeRose et al., 2003). A further 6 $m^3 yr^{-1}$ is attributed via bank erosion and 5.5 $m^3 yr^{-1}$ by hillslope erosion (via sheet or rill erosion). In alluvial systems, such as those found in the MDB, gully erosion typically develops as a deep incision within the alluvium (referred to as valley-bottom alluvial gullies) or on nearby hillslopes (referred to as valley-side hillslope gullies) in response to the repeated concentration of surface and subsurface flows along the same narrow flow paths (Brooks et al., 2009; Thwaites, Brooks, Pietsh, Spencer, 2021, Shellberg et al., 2013). As gully networks develop the bulk of the sediment derived from the gully originates from the headward retreat of the gully into the surrounding alluvium (Brooks et al, 2009). Asgully systems networks expand, they increase the connectivity of the landscape and effectively provide a link for transferring large volumes of sediment from the hillslopes and the floodplain to the river channel (Frankl, Poesen, Haile, Deckers, & Nyssen, 2013; Poesen, Nachtergaele, Verstraeten, & Valentin, 2003). Throughout the process of expansion vast quantities of sediment can be derived from sidewall erosion rather than from the initial headcut (Blong, Graham & Veness, 1982, Crouch, 1987, Crouch & Blong 1989, Hughes & Prosser, 2012). In the MDB much of the sediment supplied to the river system is however not transported downstream but is deposited or lost along the way (DeRose et al., 2003; Hughes & Prosser, 2012, Olive & Rieger, 1986). Of the total sediment supplied to the MDB only 1 % of modelled sediment is exported from the basin, with the remainder deposited on either the floodplain (46 %), in reservoirs (20 %) or as riverbed deposits (33 %) (DeRose et al., 2003). As such, it has become accepted that the MDB is a basin in which sediment redistribution dominates rather than one of net sediment export (DeRose et al., 2003, Fryirs & Brierley, 2001, Wasson, Oliver & Rosewell, 1996).

This study focuses on the Barwon-Darling River, the main arterial dryland river in the northern MDB. Over the past century waterhole morphology on the Barwon-Darling River has changed substantially with 57 % of the river containing waterholes that have declined in depth (Pearson et al., 2020). This contrasts with the remaining 43 % of the river, which is influenced by contemporary weir pools that have artificially increased waterhole depths due to the effects of weir impoundment (Pearson et al., 2020). This paper will test the assumption that alluvial floodplain erosion is contributing to the accelerated rates of sedimentation observed in the Barwon-Darling waterholes. Gully erosion on the Barwon-Darling floodplain has previously been thought to be limited due to the drier climate and low relief of the catchment (Hughes & Prosser, 2012). Previous modelling for the Barwon-Darling has estimated gully erosion within the catchment to contribute approximately 134,000 m^3 of sediment per year to the river, which equates to only 2 % of gully derived sediment in the entire basin (DeRose et al., 2003). However, these estimates do not account for gully erosion on the adjacent floodplain but are instead indicative of hillslope, or colluvial, gullies present higher in the landscape (I. Prosser, personal communication, April). Past sediment modelling has been compromised by the scarcity of gully data in the lowland part of the basin, resulting in the use of very coarse resolution gully mapping for model development (Hughes & Prosser, 2012). In doing so, the authors recognised that the reliability of the data is compromised by a very small sample window, which was unlikely to detect all of the gullies in the project area (Hughes & Prosser, 2012).

This study aims to improve the resolution of gully data and in doing so refine the estimate of gully derived sediment for the Barwon-Darling River between Mungindi and Wilcannia. Understanding the relative contribution of gully derived sediment is an important first step in mitigating or eliminating the negative effects of gully erosion on dryland rivers. The information from this study will facilitate targeted landscape management aimed at reducing the volume of gully derived sediment contributing to sedimentation in dryland river waterholes. This paper aims to use a desktop analysis to: (1). characterise gully erosion on the Barwon-Darling River floodplain and quantify its spatial and temporal distribution; (2). Use a statistical approach to quantify the relationship between gully-derived sediment and change to waterhole depth; and (3). estimate the contribution of gully-derived sediment to the Darling River Catchment and make comparisons with estimates from past modelling.

3.2 LANDSCAPE SETTING

This paper will focus on the main stem of the Barwon-Darling River and the adjacent floodplain extending from the township of Mungindi in the north-east to Wilcannia in the south-west, spanning approximately 1400 river kilometres (Figure 3.1). Anecdotal evidence on this part of this river suggests that alluvial gully erosion is a prevalent feature of the floodplain despite its lack of recognition in sediment budgets for the MDB. The Barwon-Darling can be split into three macro reaches the are indicative of the degree of structural control influencing the evolution of the drainage network (Thoms, Sheldon, Roberts, Harris, & Hillman, 1996) (Figure 3.1).

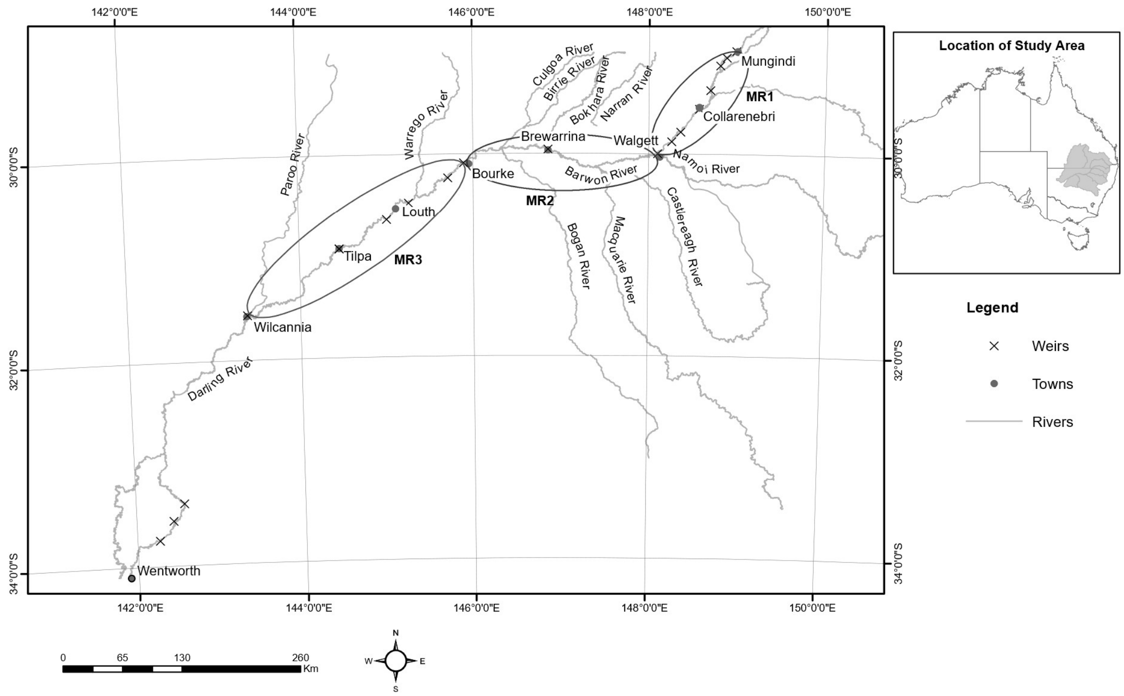


Figure 3.1: Part of the Barwon-Darling catchment. The Barwon-Darling River has been split into three macro reaches (i.e., MR1, MR2 and MR3), which are indicative of the degree of structural control influencing the evolution of the drainage network (Thoms et al., 1996) as defined in Section 3.2.2. (Coordinate system: GDA/MGA Zone 55).

3.2.1 The Barwon-Darling drainage network

The Barwon-Darling River is an allogenic river draining an area of approximately 699 500 km^2 in the northern region of Australia's Murray-Darling Basin (Figure 3.1). Perennial flows are contributed primarily from the regulated eastern and northern tributaries, which originate in a dry sub-humid catchment (Larkin et al., 2020). These include: the Condamine-Balonne, Macintyre, Gwydir, Namoi, Castlereagh, and Macquarie Rivers (Thoms & Sheldon, 2000). More intermittent contributions are made by the unregulated Warrego and Paroo Rivers, which have headwaters located in more arid environments (Thoms & Sheldon, 2000). The lowland reaches of these tributaries are significant contributors of fine sediment (<10 µm) to the Barwon-Darling River (Olley & Caitcheon, 2000), with contributions from each tributary varying depending on prevailing flow conditions. Discharge in the river channel increases between Mungindi and Bourke (macro reaches 1 and 2), before declining downstream of Bourke, due to a lack of tributary inflow and higher rates of evaporation (Thoms, Sheldon, et al., 2004).

The lowland catchment of the Barwon-Darling River is located predominately in the semi-arid area of south-east Australia. Annual average rainfall varies between 200 to 1000 mm, decreasing east to west. Evaporation rates are high across the catchment but particularly so in the south-west where evaporation rates can reach 2250 mm/yr. Like many lowland rivers the Barwon-Darling River is defined by low bed slopes (averaging 0.00005 m/m), high sinuosities (>2) and low stream power (5 Wm^{-2}) (Thoms et al., 1996). It has a deeply incised river channel with depths reaching up to 25 m. Channel widths range from 40 to 80 m (Thoms et al., 1996) and discharge capacities range from 46 m^3/s to 925 m^3/s (Boys & Thoms, 2006).

3.2.2 Geology

The Barwon-Darling catchment is characterised by low relief ranging from just 50 m above sea level in the southwest of the catchment to 600 m on the eastern margins (*NSW Digital Elevation Map 1:1 500 000*, 2016). However, sixty percent of the catchment is below 300 m (Thoms et al., 2004). The geology of the Barwon-Darling is dominated by a large intercratonic Cainozoic basin, which has been infilled with alluvial sediments originating from erosion in the eastern highlands (Thoms et al., 2004; Triantafilis & Buchanan, 2009). In the lower reaches of the Darling River, downstream of Tilpa, the Cainozoic alluvium is interspersed with large tracts of aeolian sand (Kearle, Gosper, Achurch, & Laity, 2012). The contemporary Barwon-Darling channel is largely controlled by several structural contortions in the basement rock (Thoms et al., 2004). North of Walgett (Macro Reach 1) the floodplain and river channel are contained within the Cobar structural lineament, which has resulted in limited floodplain development particularity on the western margins. The eastern margin has a weaker structural control and has to some extent been influenced by the Macintyre-Gwydir fan complex. Channel planform varies from sinuous to tortuous with sinuosities ranging from 1.8 to 2.3. Likewise, south of Bourke (Macro Reach 3), the river is constrained by the Darling structural lineament and here the floodplain extent is at its minimum and lateral mobility is limited. Furthermore, several calcrete and silcrete bedrock outcrops within this reach act as local bed controls for the river. River planform in macro reach 3 is less sinuous with sinuosities ranging from 1.7 to 1.8. The river between Walgett and Bourke (Macro Reach 2) is not constrained but it is influenced by the mega scale alluvial fan emanating from the Gwydir, Namoi, and Macquarie-Bogan systems to the east and south, and the Culgoa-Balonne to the north. The lack of structural influence in this part of the river has meant that valley dimensions and floodplain development have not been limited in this part of the river (Thoms et al., 2004). River planform throughout the whole reach is tortuous with sinuosities generally greater than 2.3.

3.2.3 Soils

Soils of the Barwon-Darling floodplain are predominately made of a mixture of deep (>1.5 m), uniform, grey, brown, and red cracking clays which are often characterised by a gilgai microrelief (Kearle et al., 2012; Triantafilis & Buchanan, 2009). Downstream of Tilpa these clays are interspersed with calcareous or siliceous sands, collectively referred to as rudosols (Triantafilis & Buchanan, 2009). Coarse red sediments along with brown and red duplex soils have been deposited on higher levees bordering the floodplain (Kearle et al., 2012; Walker & Alchin, 2004). Severe scalding is common on these duplex soils, which have historically been extensively grazed (Kearle et al., 2012). The riverbed substratum is mud dominated and made up of a relatively uniform mixture of fine sand, silt, and clay particles (Woodyer, 1978). Fine suspended sediment makes up 95 % of the Barwon-Darling sediment load (Olley & Caitcheon, 2000). The adjacent floodplain comprises of a series of paleo-channels dating from 3.2 ka to 85 ka, most of which carried a greater discharge and higher proportion of bedload material than the modern river (Hesse et al., 2018; Lawrie et al., 2012).

3.2.4 Catchment land use

Since European colonisation the surrounding catchment has been used predominantly for livestock grazing (Crabb, 2004), and today it continues to utlilise 79 % of the total land area of the Barwon-Darling valley (Crown Lands and Water Division, 2018). The grazing industry was introduced into the catchment in the mid to late 1800s and at the time it was limited to properties with river frontage due to the shortage of water infrastructure on the floodplain (i.e., water tanks and dams). In more recent times irrigated agriculture (3 % of land area) and dryland cropping (9 % of the land area) have developed, although it is mostly confined to the floodplain between Mungindi and Bourke (Crown Lands and Water Division, 2018). The 1960s saw the commencement of large-scale infrastructure development on the tributaries resulting in 11 major headwater reservoirs. While there are no large reservoirs on the Barwon-Darling River, 15 low-level, fixed crest weirs have been constructed to provide for stock and domestic use and to support irrigated agriculture. Water abstraction combined with the capture of floodwaters in off-river reservoirs has substantially altered the hydrology of the Barwon-Darling River since the 1960s (Chessman, Jones, Searle, Growns, & Pearson, 2010; Mallen-Cooper 2020; Thoms & Sheldon, 2000). Median annual runoff has been reduced by 42 % whilst the median daily flow has been reduced by as much as 73 % with the downstream locations being the most severely impacted (Thoms & Sheldon, 2000). Modifications to the flow regime has altered flow hydraulics on the Barwon-Darling with the river changing from a near-perennial system to a river characterised by low flows and a shift to more lentic (still-water) conditions (Mallen-Cooper, 2020). The magnitude of the near-annual flow pulse that was once a regular feature of the Barwon-Darling have been reduced by more than 90% (Mallen-Cooper, 2020).

Figure 3.2 presents a conceptual model of the relationship between the modifications that the Barwon-Darling catchment has experienced and the expected impact these modifications would have on the systems structural and functional connectivity. This model provides the thought process behind why waterholes depths on the Barwon-Darling would be expected to decline with an increase in the supply of sediment from alluvial gullies.

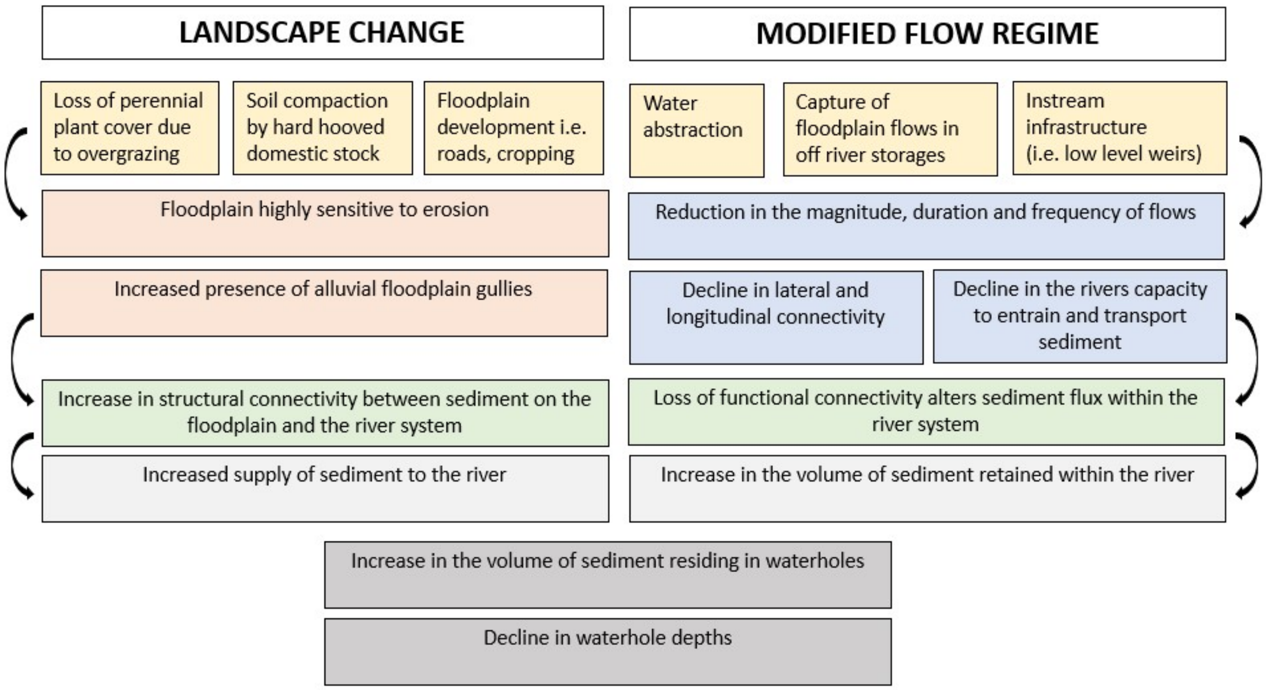


Figure 3.2: Conceptual model showing the relationship between the modifications that the Barwon-Darling catchment has experienced and the expected impact these modifications would have on the systems structural and functional connectivity and how this could modify waterhole depths.

3.3 METHODS

This project was developed to investigate the prevalence of floodplain gully erosion on the Barwon-Darling River and its contribution to declining waterhole depths. Due to the large spatial scale of the project area the methods were limited to a desktop approach utilising remote sensing techniques. As such, the inherent uncertainties associated with a desktop approach are acknowledged. However, the finer resolution of data captured in this desktop study in comparison to past modelling within the catchment (DeRose et al, 2003, Hughes & Prosser, 2012) is expected to yield a higher level of accuracy with respect to gully occurrence and sediment contribution to the Barwon-Darling River.

3.3.1 The definition of gully erosion

For the purposes of this study gully erosion refers to incisional features that form on the alluvial floodplain immediately adjacent to the main channel of the Barwon-Darling River (Figures 3.2a-c).

Gullies can consist of a single incision in the floodplain (Figure 3.3a-b) or they can develop into a complex, branching network of drainage channels (Figure 3.3c-d). Gullies often have a visible deposit of sediment at the base of the gully where the gully intersects with the river (Figure 3.2b). The floodplain in which these gullies develop consist predominately of red, brown, and grey cracking clays.

(a).

(b).

(c).

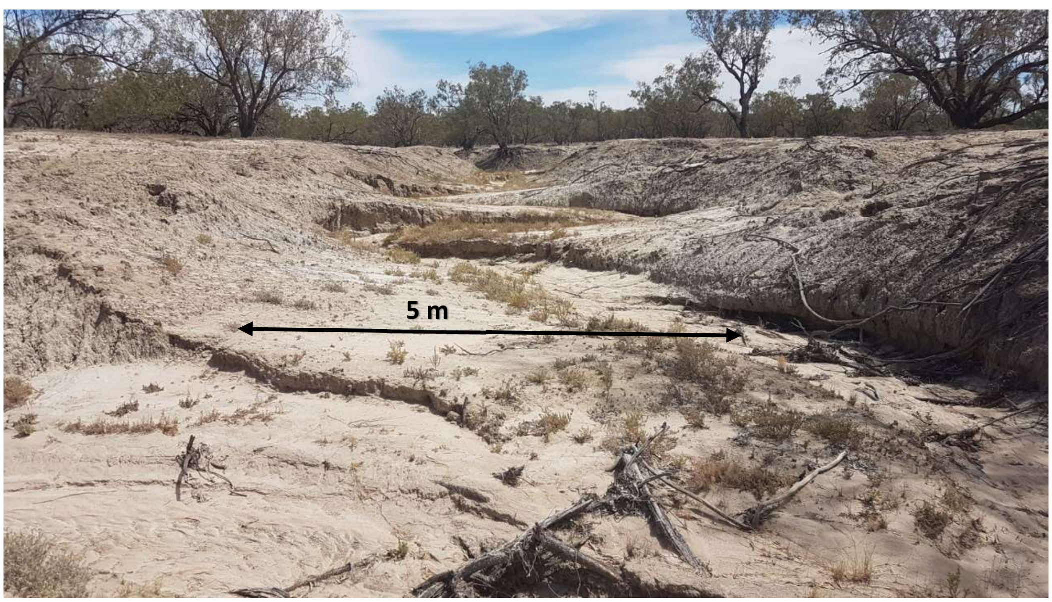
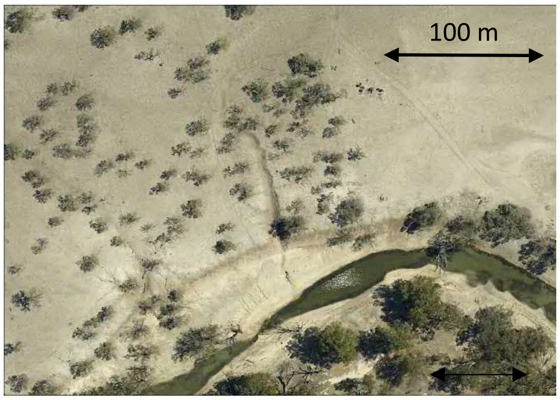


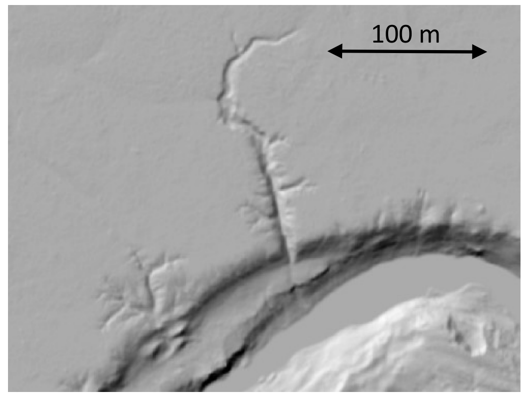
Figure 3.3: Photos of gully erosion on the Barwon-Darling River (in macro reach 3): (a) gully entering the main channel of the Barwon-Darling River, (b) an example of a visible sediment deposit at the exit

of the gully into the river, (c) example of gully on the Barwon-Darling floodplain. All gullies are incised into floodplain alluvium consisting of red, brown and grey cracking clays.

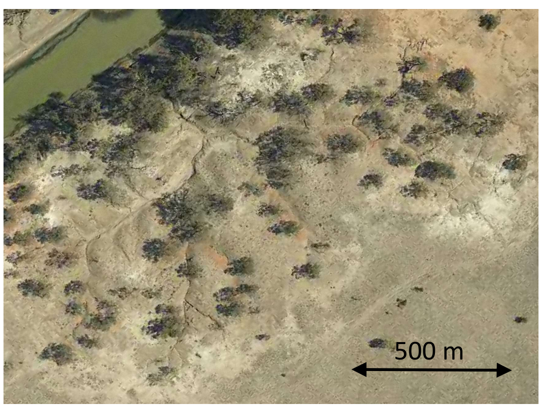
(a).



(b).



(c).



(d).

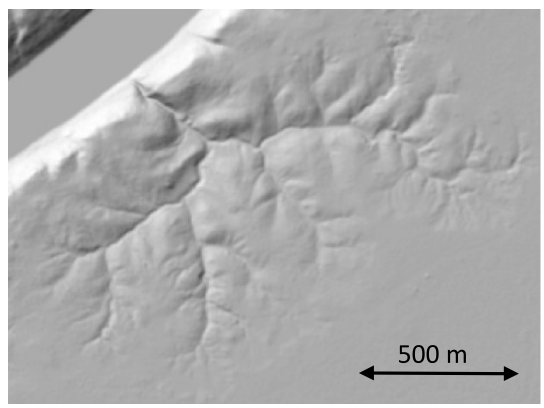


Figure 3.4: Examples of gully erosion on the Barwon-Darling River floodplain: (a) aerial image of a single, linear incisional gully; (b) LiDAR-derived DEM of the single, linear incisional gully shown in (a); (c) aerial image of a branching gully; (d) LiDAR-derived DEM of the branching gully shown in (c).

3.3.2 Gully detection and mapping

LiDAR (light detection and ranging) data captured across the Barwon-Darling Catchment in 2005 -2014 was used to generate a series of 1 m^2 ground surface digital elevation models (DEMs) and corresponding 1 m^2 hillshades (Geoscience Australia, 2020). The LiDAR derived data had a 0.3 m vertical accuracy and a 0.8 m horizontal accuracy. The combination of DEMs and hillshade images facilitated the identification of floodplain gullies and the manual digitisation of surface area and gully length for individual gullies between Mungindi and Wilcannia. The manually digitised area was later refined using ArcGIS modelling (Section 3.3.3). The length of the gully represents the most visible channels within the gully itself, and these were mapped from the confluence with the main channel of the Barwon-Darling to the gullies headcut position. The location of each gully with respect to the river was recorded in terms of whether it was on an inside bend, outside bend or a straight stretch of river. Location is an important variable as it has the potential to influence channel scour, lateral migration and the base level to which the gully network could incise (Fryirs & Brierley 2013). Gully order was used to provide a simple representation of gully complexity (i.e., simple, linear to complex, branching) and was based on the Strahler method for stream order. The simplest gullies were assigned a score of 1 and are indictive of gullies in the early stages of incision, whilst the most complex gullies were assigned a score of 4 and represent gullies that have undergone extensive expansion across the floodplain. Gully complexity was explored as it can provide an insight into the evolution of a gully network and can provide an indication of the processes driving gully initiation and gully expansion (Brooks et al., 2009, Thwaites et al., 2021). To ensure a consistent approach to gully mapping a key set of parameters was established to define a gully. For a gully to be included in the analysis it was required to: (1) intersect with the main channel of the Barwon-Darling River and therefore contribute sediment directly to the river; (2) appear as a visible incision in the riparian zone/floodplain on the DEM at a scale of 1:5000; and (3) have only one entry point to the river (i.e., the entry/exit points from natural oxbows or cut-off features associated with bends were excluded). Natural features such as paleochannels and anabranches were excluded as they do not meet the criteria typically used to define a gully and, they are fundamentally formed through a different suite of processes (Daley et al., 2021, Thwaities et al., 2021). However, natural drainage hollows that had become actively eroded were included when an active incision could be identified. In these situations, it was the area of the active gully incision that was mapped rather than the broader area of the natural hollow.

3.3.3 Capturing gully area and volume

The manual digitisation of surface area for individual gullies was based coarsely on what appeared on the LiDAR to be the area of floodplain impacted by the gully. ArcGIS (ArcMap 10.4.1) was then used to develop an automated model that would more accurately reflect gully area based on the edge of the incised gully channel. At each gully location the pre-erosion surface was estimated by interpolating across the top of the original digitised gully using the natural neighbour algorithm in ArcGIS (Baker, Bledsoe, Albano, & Poff, 2011; Ledoux & Gold, 2005). A difference image was then generated between the DEM and the new interpolated surface known as a DEM of Difference (DoD) (Goodwin, Armston, Muir, & Stiller, 2017). Any area that fell within a specified 'difference' threshold (i.e., anything with a positive value) was defined as gully providing a more accurate estimate for gully extent. Gully volumes were then calculated by subtracting the LiDAR DEM elevation from the interpolated surface elevations within each of the new gully extents.

3.3.4 Gully distribution, character, and sediment contribution

A hierarchical approach was used to explore spatial patterns in gully distribution (count), gully size (area and length) and sediment contribution to the river (volume). At the highest-level gullies were grouped (or stratified) into three macro reaches (MR) as defined in section 3.2.2 based on the degree of structural control influencing the evolution of the river channel (Figure 3.1). Contrasting valley floor dimensions across the three macro reaches were expected to influence the degree of alluvial gullying. At a finer scale of observation, spatial patterns were explored based on the location of gullies in relation to low level weirs, with gullies being further stratified into weir pool and non-weir pool locations. This comparison was made due to observed differences in the magnitude and trajectory of change in waterhole depth between the two locations since European colonisation (Pearson et al., 2020). A Welch ANOVA was used to compare the area, length, and volume of gullies across macro reaches and between weir and non-weir pool locations.

3.3.5 Temporal changes to the distribution of gully erosion

Digital historical air photos were used to compare the number of gullies present historically with the number of gullies observed on the contemporary LiDAR data. Air photo images were sourced from State of New South Wales Spatial Services Unit for the 1950s and 1960s, covering the entire river channel within the study area, and from those a subset of images was randomly selected. Enough images were selected to represent 10 % of the entire river channel which was deemed an adequate sample size based on the number of images available. On each image a 1 km stretch of river channel was identified for comparison with the same location on the contemporary data. Images that had poor clarity or thick tree cover were removed from the selection process. Gullies connecting with the main river channel within each 1 km reach were manually counted and compared with the number of gullies identified from the LiDAR imagery. Additional images were sourced for the 1970s, 1980s, and 1990s for two sections of river between Brewarrina and Wilcannia so that an analysis of decadal change to gully abundance could be undertaken.

3.3.6 The accumulation of sediment in the Barwon-Darling waterholes

The volume of sediment that has accumulated in each of the Barwon-Darling waterholes over the past 120 years was estimated for the non-weir pool locations where water depths have declined, based on waterhole length and depth data from a previous study (Pearson et al., 2020). The volume of sediment was calculated based on the length of the waterhole at cease to flow, the width of the waterhole and the depth of sediment believed to have accumulated over the past 120 years (i.e., volume = length x width x depth). The length of individual waterholes had previously been estimated for the Barwon-Darling using high-definition side-scanning sonar (Pearson et al., 2020). A depth of 1.6 m was used as an estimate of sediment accumulation across all the waterholes, as this reflects the average decrease in maximum waterhole depths over a 120-year period, as observed by Pearson et al*.,* (2020). However, the decline in waterholes by Pearson et al., (2020) varied substantially (i.e., ranging from 0.02 m to 7.3 m). For this reason, comparisons were made between the volume of sediment accumulating based on the average decline in waterhole depth (i.e., 1.6m) with estimates based on the minimum and maximum decline. The width of the waterholes was kept constant at 20 m, which was estimated as the average wetted area of the waterholes at cease to flow. These dimensions allowed coarse estimates to be made regarding the total volume of sediment that may have accumulated in the waterholes since the late 1800s. However, the limitations of this approach are acknowledged. For example, the standard calculation for volume (volume = length x width x depth) as used in this study assumes that all waterholes have the same morphology. It also assumes that the longitudinal profile of the waterhole is rectangular, which does not account for the tapering in water depth that would occur at either end of the waterhole.

The potential contribution of gully-derived sediment to waterhole aggradation was investigated by comparing the estimated volume of sediment accumulating in the waterholes with the volume of sediment lost from the gullies as determined from the LiDAR data. It was assumed that the coarse sediment fraction coming out of the gullies is what has driven the loss of waterhole depth. In this study, the ratio of coarse to fine sediment was assumed to be 60:40 based on the approach used in the MDB SedNet model (DeRose et al., 2003). However, the 60:40 ratio used in the SedNet model was a Basin wide average and as such it may not be applicable to the alluvial floodplain gullies mapped in this study. The gullies in this study have been cut into floodplain alluvium, which is predominately made up of grey, brown, and red cracking clays. It is therefore more likely that the fine sediment fraction would dominate and for this reason a ratio of coarse to fine sediment of 80:20 was also explored to illustrate the range of possible outcomes for different sediment profiles. The higher percentage of fine sediment is consistent with several large alluvial gully systems located in far north Queensland (Brooks et al., 2021) where the fine sediment fraction can range from anywhere between 30 and 80 % (A. Brooks, personal communication, April 2021).

3.3.7 The relationship between gully derived sediment and change in waterhole depths

To identify change in waterhole depth, Pearson *et al.* (2020) split the main channel of the Barwon-Darling between Walgett and Wilcannia into a series of 5 km intervals. The change to the maximum waterhole depth in each of the 5 km intervals was then quantified. This study has used those same 5 km intervals to assess the influence of gully derived sediment on the magnitude of change to waterhole depth. The total volume of sediment lost from the floodplain gullies that intercept with the river in each of the 5 km reaches was determined. An analysis of covariance (ANCOVA) was then used to quantify the variance in waterhole depths (i.e., the dependent variable) over time resulting from gully-derived sediment in the non-weir pool locations. The ANCOVA incorporated several covariates including: the total sediment volume contributed to the river in each 5 km interval, the distance of a waterhole from the nearest upstream tributary, and the distance of the waterhole downstream from the top of the study area to assess any cumulative impacts. A step wise approach was used to eliminate covariates and identify the model of best fit for predicting change in waterhole depth.

3.3.8 Comparing past and present modelling for gully derived sediment

The estimated volumes of gully derived sediment delivered to the Darling River catchment has been compared between past modelling of sediment delivery for the MDB using the SedNet model (DeRose et al., 2003) and the volume estimates taken from the contemporary LiDAR data. Comparisons were only made for the Darling River (as opposed to the combined Barwon-Darling) because in the SedNET model the estimates for the Barwon River are amalgamated with estimates for the adjacent tributaries making the data incomparable. However, to do this several assumptions were made regarding the data. These being: (1). a bulk density of 1.5 was applied to the SedNet data to enable the conversion of data into comparable units as used in the present study (i.e., tonnes to m^3), (2). the age of gullies identified on the LiDAR was assumed to be 100 years old, consistent with the estimated age used in the SedNet model, (3). sediment was removed from the gullies at a constant, linear rate though time.

3.4. RESULTS

3.4.1 The character and spatial distribution of gully erosion

Based on contemporary LiDAR a total of 4855 gullies were mapped on the 1390 km section of the Barwon-Darling between Mungindi and Wilcannia (Figure 3.4). The length of the gully network is 2364 km in total and is impacting an area of floodplain of 148 million m^2 which represents the combined area of individual gullies. A total of 168 million m^3 of sediment is estimated to have been removed from the gullies. The size of individual gully networks varied substantially ranging from just 0.02 km to 11 km in length and with areas ranging from 37 m^2 to 181 000 m^2. The median volume of sediment removed from the gullies was 3873 m^3, yet gully volumes ranged from 4 m^3 to 4.5 million m^3. Most gullies formed on the higher terrace of the outside bend (i.e., 38 % of gullies) or on straight sections of the river (i.e., 60 % of gullies) where the banks are at its steepest (up to 25m). This pattern was observed across all three macro reaches (Figure 3.5). Simple, linear gullies made up the bulk of the gullies (57 %). Few large, complex, branching gullies were observed (order 4 = 1 %, order 3 = 9 %) (Figure 3.5), all of which were located on either the outside bend or on the straights. Order 4 gullies were absent from macro reach 1.

The number of gullies was relatively consistent across the three macro reaches. In macro reach 1, there were 3.1 gullies/km of river, which is marginally fewer than in macro reach 2 (3.8 gullies/km) and macro reach 3 (3.4 gullies/km). Median gully length, area and volume were all greatest in macro reach 3, however, a Welch ANOVA indicated that the difference between macro reaches was not significant (supplementary material - Figure 3.11, Table 3.2). Overall, gullies located within the weir pool influence were significantly longer (Welch ANOVA $F = 24.85$, $df = 1$, $p < 0.001$), covered a greater area of floodplain (Welch ANOVA $F = 19.34$, $df = 1$, $p < 0.001$) and have lost a higher volume of sediment (Welch ANOVA $F = 21.74$, $df = 1$, $p < 0.001$) than those located outside of the weir pool influence. However, this trend was not consistent when the data was split based on macro reach with significant differences only observed in macro reach 3. Gully volumes in macro reach 3 were significantly higher in non-weir pool locations, whilst gully length and area were significantly lower (Figure 3.6).

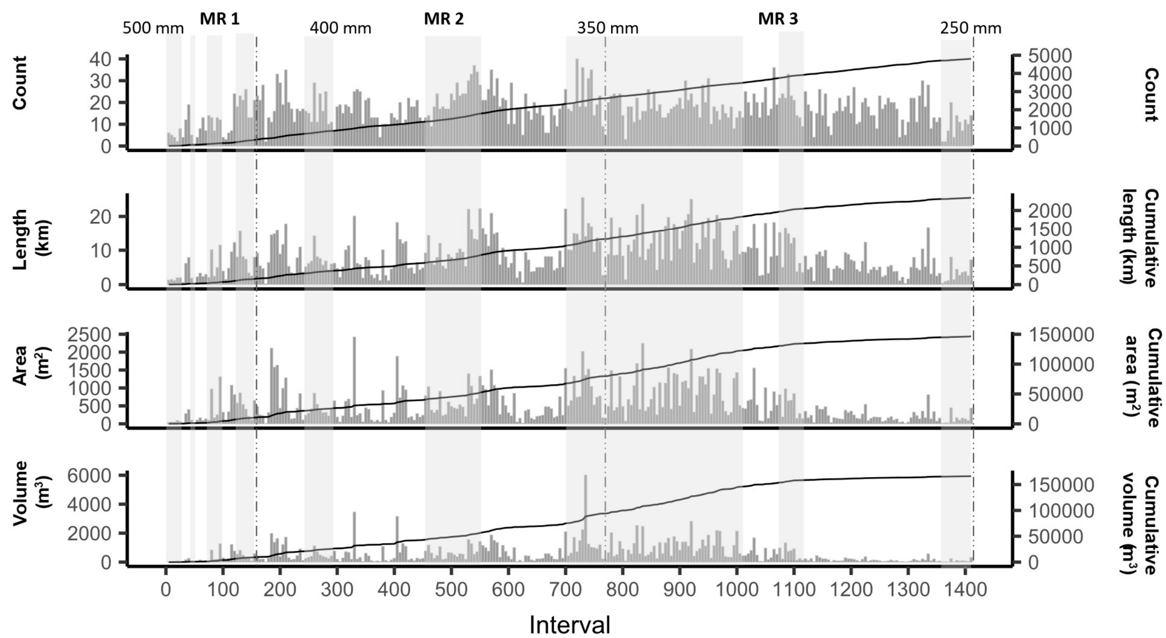


Figure 3.5: Longitudinal profile of floodplain gullies showing gully count and total length, area, and volume for each 5 km interval. Macro reach (MR) boundaries are illustrated with the dashed line and weir pools are highlighted in grey. Average annual rainfall is listed at the top of the figure for each location. (Area and volume x '000)

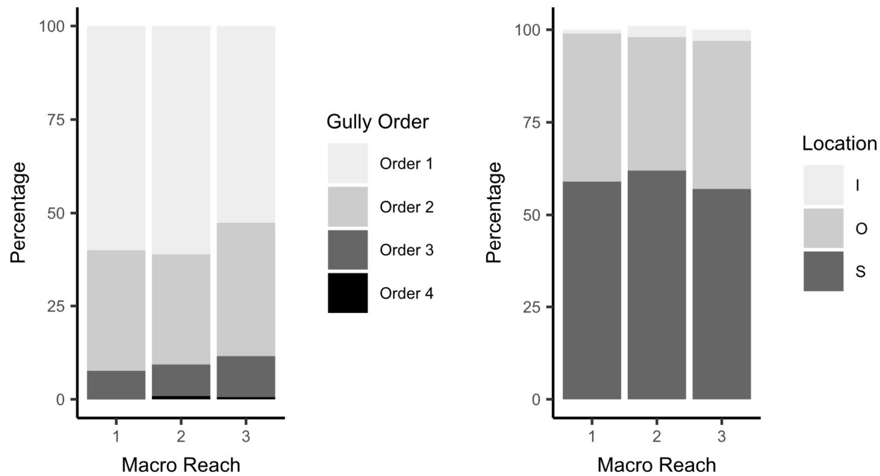
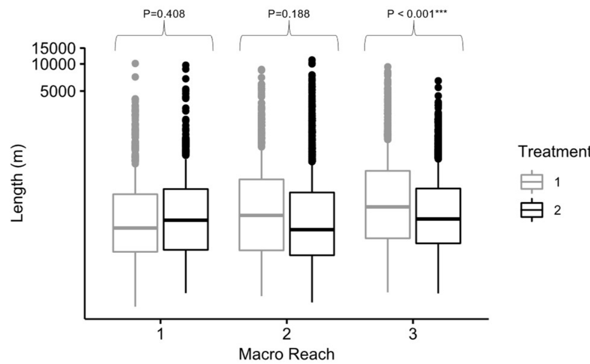
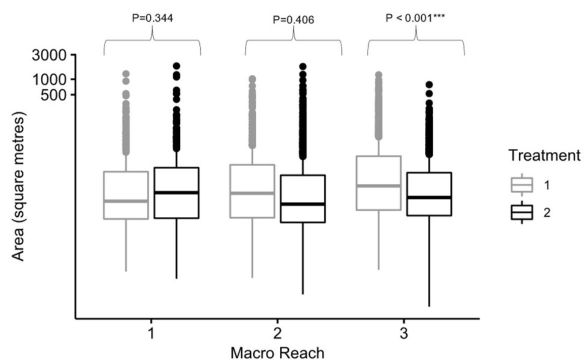


Figure 3.6: Proportion of gullies assigned to (a) gully order and (b) Gully location (I – Inside bend, O – Outside bend – S – Straight)

(a)



(b)



(c)

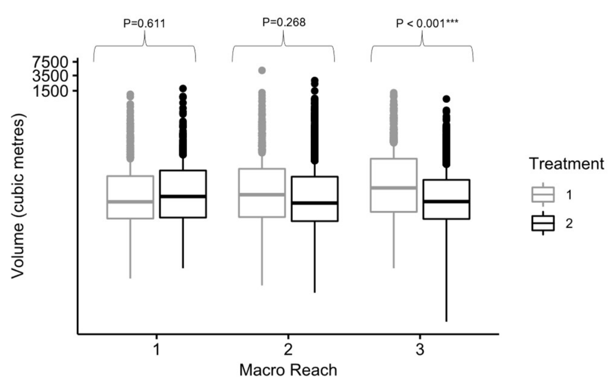


Figure 3.7: Comparison of: (a) gully length, (b) gully area and (c) gully volume for gullies within the weir pool influence and those outside of the weir pool influence for each macro reach. *p-values* from the Welch ANOVA tests are included at the top of each figure. Statistical differences were only observed for variables in macro reach 3 as indicated by ***. (Area and volume x '000)

3.4.2 Temporal changes to the distribution of gully erosion

Air photo analysis identified an increasing number of gullies over the past 60 years. In the 1960s a total of 353 gullies were present in the reaches where gully numbers were counted compared to 494 in 2005. This equates to a 40 % increase in gully numbers. For those reaches that had images available from each decade a gradual but continuous increase was observed with an average of 7 new gullies per decade across the selected images (Figure 3.7). However, of these new gullies 72 % were simple, linear gullies (order 1). A further 25 % are categorised as order 2 and the remaining 3 % as order 3. The combined length of new gullies that have emerged since the 1960s is just 27 km, which is equivalent to 1 % of the total gully network. The greatest length of new gullies was found in macro reach 2 (14km) followed by macro 3 (10km) and macro reach 1 (2km).

(a). (b).

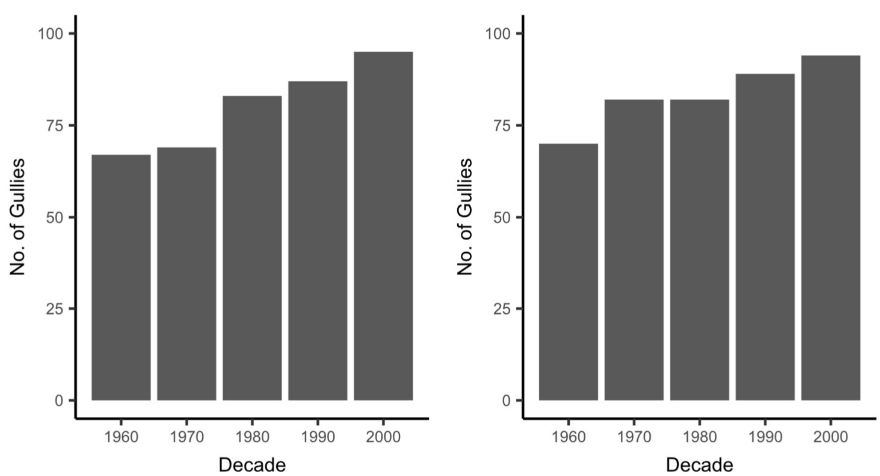


Figure 3.8: Decadal change in gully numbers between the 1950s and 2000s: (a). Brewarrina to Bourke, (b). Tilpa to Wilcannia.

3.4.3 The accumulation of sediment in the Barwon-Darling waterholes

Based on waterhole dimensions in the non-weir pool locations and the average decline in waterhole depths of 1.6 m, it is estimated that 19 million m^3 of sediment has accumulated in the waterholes over the past 120 years, or 158,333 m^3 yr^{-1}. 10 million m^3 of this sediment accumulated in macro reach 2 between Walgett and Bourke and the remaining 9 million m^3 in macro reach 3 downstream of Bourke. Floodplain gully erosion has likely been a significant contributor. In the non-weir pool locations, a total of 70 million m^3 of sediment have been removed from the gully systems over time.

Based on the 60:40 ratio for coarse to fine sediment as used in the SedNet model it is estimated that approximately 42 million m^3 of the gully derived sediment would have been made up of coarse sediment and 28 million m^3 of fine sediment (Figure 3.8). The estimated volume of bedload contributing to waterhole aggradation (i.e., the coarse sediment fraction) is therefore more than double the total volume of sediment that has been estimated as accumulating in the waterholes. This suggests that either the coarse bedload fraction has been overestimated using the 60:40 ratio and/or not all of the bedload material leaving the gullies has been retained within the waterholes but has instead been deposited elsewhere in the river channel. In contrast, if we flipped this ratio and assumed that being an alluvial system the fine sediment fraction dominates the gully contribution (e.g., 20:80) then the estimate for bedload material (14 million m^3) more closely resembles the total volume of sediment accumulated with the waterholes (19 million m^3) over the past 120 years. Using estimates from the SedNet model, bank and hill slope erosion would have contributed a further 2.3 million m^3 of coarse sediment if using the same 20:80 split. In the 20:80 scenario the bulk of the fine sediment would most likely have been flushed downstream.

It is important, however, to note that the margin of error around the estimates for sediment accumulation are very large. If the same calculations are done based on the minimum and maximum decline in maximum waterhole depth (i.e., 0.02m and 7.3m) then the volume estimates over the same period range from 247 000 $m^3$and 90 million m^3. Highlighting the need for more targeted, site-specific investigations at each of the waterholes.

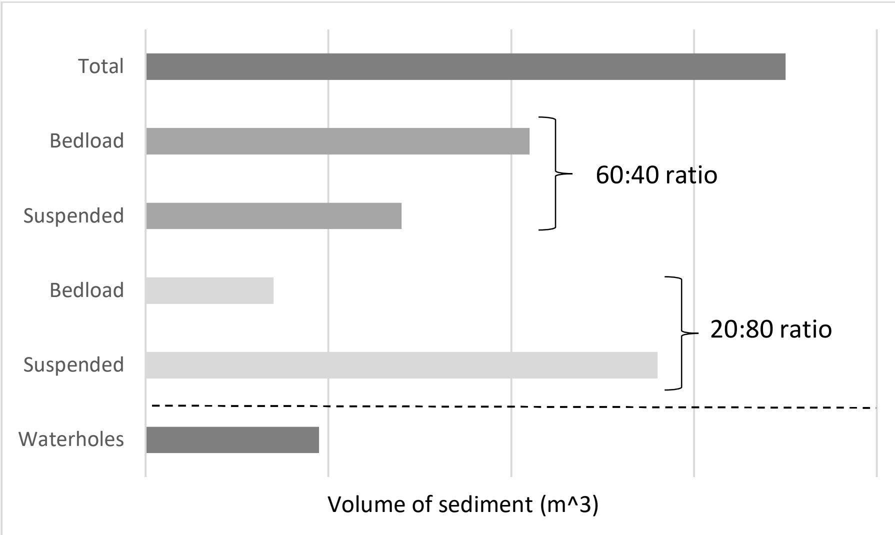


Figure 3.9: Contribution of gully derived sediment to the Barwon-Darling River showing the total volume of sediment and the estimated bedload and suspended load fraction using a 60:40 ratio and a 20:80 ratio. The volume for waterholes is the estimated volume of sediment accumulation in the waterholes.

3.4.4 The relationship between gully derived sediment and the change in waterhole depths

The magnitude of change to the maximum waterhole depth in the non-weir pool locations was not significantly related to the total volume of gully-derived sediment (ANCOVA, $p > 0.05$ in all model combinations) (Figure 3.9). In fact, an inverse relationship was often observed with the largest gullies coinciding with locations that had experienced an increase in waterhole depth (e.g., between the 700 and 1000 km intervals), whilst in the most downstream sections of the river where sediment supply has decreased, waterhole depths have become shallower (Figure 3.10). In contrast, a two-factor ANCOVA yielded a significant predictive relationship between change to waterhole depth and the distance of a waterhole to the nearest upstream tributary ($p = 0.0002$). However, the predictive power for the model was very low ($R^2 = 0.1109$). Scatterplots indicate that the greatest change in waterhole depth occurred when waterholes were located close to a tributary confluence (Figure 3.9). However, a high degree of scatter between points supports the low R^2 for the model fit. A significant relationship also exists between change in waterhole depth and the downstream distance of a waterhole (two factor ANCOVA, p = 0.002), with the most upstream waterholes experiencing the greatest change (Figure 3.9). However, a three-factor ANCOVA removed downstream distance as a parameter suggesting that distance to the nearest tributary is a more influential factor in driving change to waterhole depth.

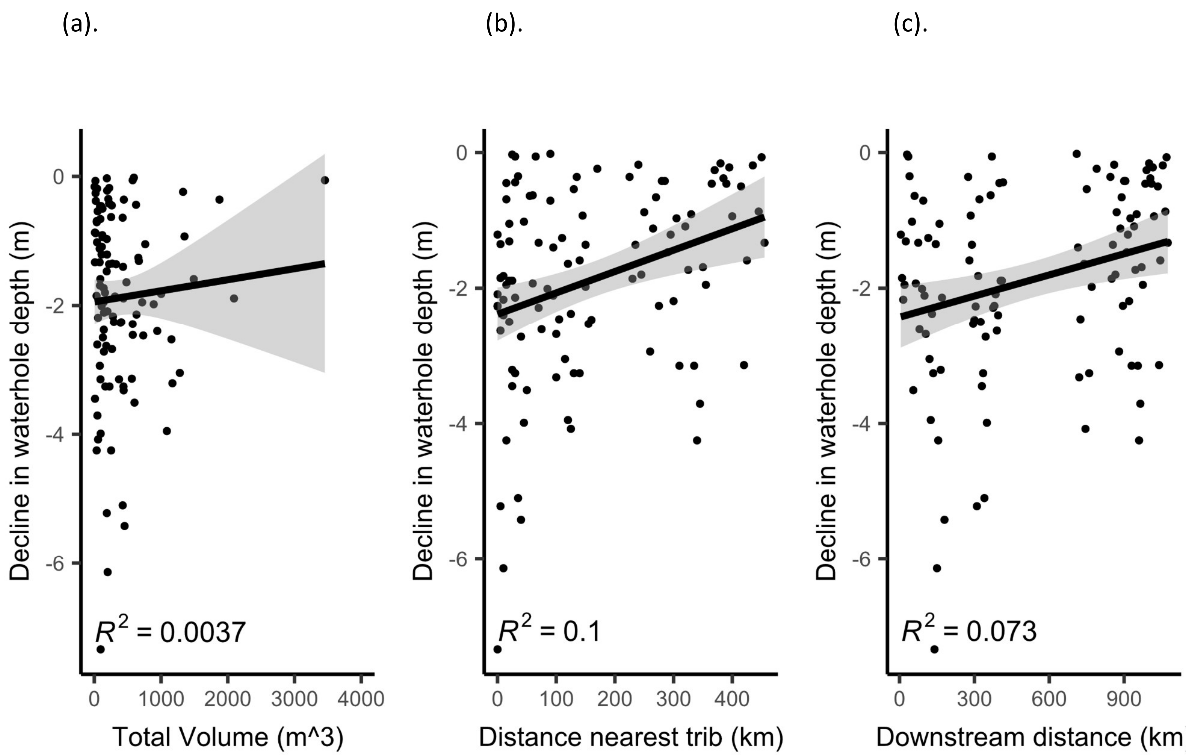


Figure 3.10: Factors influencing the decline in waterhole depths in non-weir pool locations (a). Total volume for 5 km interval, (b). distance of waterhole to nearest upstream tributary, (c). distance of waterhole downstream

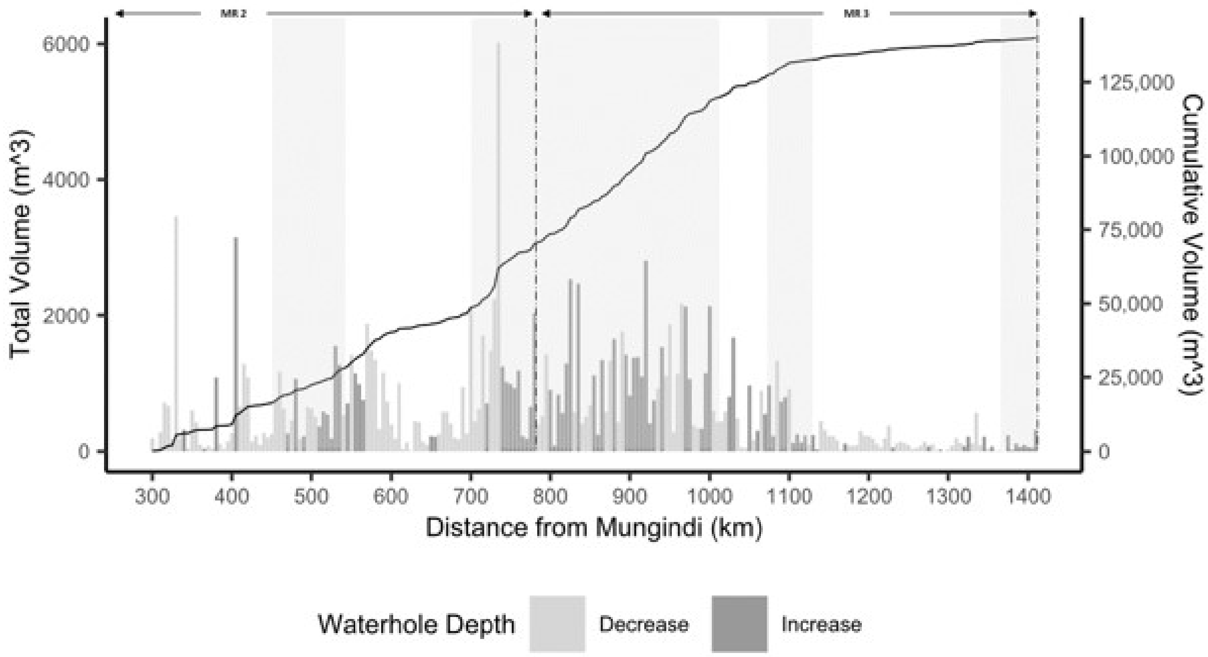


Figure 3.11: Relationship between change in waterhole depth, total gully volume per 5 km interval and the cumulative gully volume. Macro reach (MR) boundaries are illustrated with the dashed line and weir pools are highlighted in grey. (Total volume and cumulative volume x '000)

3.4.5 Comparing past and present modelling for gully derived sediment

Gully estimates based on the contemporary LiDAR suggest that sediment derived from alluvial gullying on the Barwon-Darling has been underestimated in the past. Results from the SedNet model suggests that gully erosion on the Darling River between the Culgoa River junction and Wentworth has contributed 13 million m^3 of sediment to the Darling River over a 1510 km section of river (Table 3.1). In contrast, estimates for gully volume based on the contemporary LiDAR suggests a total contribution of 95 million m^3, however, this estimate is for a section of river that is almost half the distance (~689 km). When the differences in river distance are accounted for the contribution of sediment per year is almost 13 times higher based on the LiDAR estimates (1377 m^3 km^{-1} yr^{-1}) compared to the SedNet model (89 m^3 km^{-1} yr^{-1}) (Table 3.1).

Table 3.1: Comparison of gully derived sediment to Darling River based on the SedNet modal (DeRose et al., 2003) and the LiDAR estimates (2013-2017).

	Total (m^3)	**Annual** ($m^3\ yr^{-1}$)	**Annual/km** ($m^3\ km^{-1}\ yr^{-1}$)
Gully contribution[1] (LiDAR estimates)	94,867,223	948,672	1377
Gully contribution[2] (SedNet model)	15,600,000	156,000	103
Bank erosion (SedNet model)	29,733,333	297,333	197
Hill erosion (SedNet model)	2,600,000	26,000	17

Note: [1]LiDAR contribution measured for the Darling River between the Culgoa River Junction and Wilcannia (~689 km). [2]SedNet contribution measured for the Darling River between the Culgoa River Junction and Wentworth (~1510 km).

3.5 DISCUSSION

3.5.1 The spatial and temporal distribution of gully erosion on the Barwon-Darling floodplain

The results from this study suggest that floodplain gullies are a prevalent feature of the contemporary Barwon-Darling River. The formation of gullies on the Barwon-Darling floodplain is driven by a combination of natural and anthropogenic factors. The natural geomorphic character of the Barwon-Darling River and its adjacent floodplain is conducive to gully formation. The main river channel is deeply incised within the floodplain creating steep banks (up to 25 m), which means the elevational relief between the riverbed and the high floodplain is substantial (Boys & Thoms, 2006). We would expect that when water from overland flow, groundwater seepage, overbank flood discharge or receding backwater move over these steep banks enough energy would be generated to initiate gully erosion (Brooks et al., 2009; Shellberg, Brooks, & Spencer, 2016). This would be particularly evident on the steep straight sections of the Barwon-Darling where the bulk of the gullies occur. Widespread gullying is also common on the outside bends of the Barwon-Darling, where bend curvature would increase thalweg scour, lateral migration and the lowering of base levels, leading to gully erosion (Fryirs & Brierley, 2013). The spatial distribution of gullies was relatively consistent across the three macro reaches and although the length, area and volume of the gullies were higher in macro reach 3 the differences were not significant. This is perhaps surprising given the geological controls that were used to define the macro reaches are influential in driving valley floor dimensions (Thoms et al., 2004), which could in turn influence runoff volumes and the erosivity of water as it moves across the floodplain. For example, the narrower floodplain in macro reach 3 and macro reach 1 may return overland flows to the river faster, generating more erosive flows on the floodplain (Power, Parker, Dietrich, & Adrian, 1995). The longitudinal profiles for gully length, area, and volume shows a notable difference in the size of gullies within macro reach 3. The upper reaches between Bourke and Tilpa appear to have substantially larger gullies than the lower half of the macro reach (i.e., downstream of Tilpa). This is likely driven by the fact that the upstream section is almost completely influenced by a series of connected weir pools, which appear to have an influence on gully size, as will be discussed later. However, we also speculate that climatic variables may be an influencing factor, with a reduction in gully size at the downstream end of the reach where average annual precipitation is lower and evaporation rates are higher. A drier climate at the downstream end of the reach would reduce overland flow and therefore erosion potential (Hughes & Prosser, 2012). However, differences in rainfall intensity, timing and vegetation cover may result in localised variability in sensitivity to gully erosion across the reach.

The number of gullies were similar across weir pool and non-weir pool locations, yet the size, length, and volume of sediment loss, were all significantly greater in the weir pool locations. The most likely reason being that the presence of low-level weirs has concentrated activity (both human and animal) on the land adjacent to the weir pools where the water levels are higher and where water is more persistent in the landscape. Grazing pressure may intensify in these locations, as would infrastructure development for irrigation, and recreation is likely to be more common. Field and desktop observations suggest that on the Barwon-Darling floodplain gullies are often associated with unnatural linear features in the landscape. For example, roads, tracks, pipelines, fences, and well-worn animal tracks, which are all known to contribute to gully erosion through the concentration of overland flows (Aby, 2017; Boardman, 2014; Brooks, Spencer, & Knight, 2007; Carey, Stone, Norman, & Shilton, 2015a, 2015b; Valentin, Poesen, & Li, 2005). A higher frequency of these features on the land adjacent to the weir pool areas could potentially enable a greater expansion of gullies in these locations.

Over the past 50 years new gullies have continued to develop on the Barwon-Darling floodplain with a gradual increase in gully numbers. There are now 40 % more gullies than were present on the floodplain in the early 1950s. However, of significance is the fact that most of these new gullies are small, linear incisions in the floodplain, whilst the larger, more complex gullies appear to have formed prior to the 1950s. This early expansion of gullies is likely to be a legacy affect from the grazing industry which was well established in the catchment by the 1870s (McKeon et al., 2004). In the early days of settlement the lack of infrastructure (i.e., water tanks, dams and road transport) meant that stock were largely confined to properties with river frontage or access to bore water (McKeon et al., 2004). A history of overstocking during this early settlement period is well documented (Beadle, 1948), which lead to considerable grazing pressure, resulting in a loss of perennial plant cover and the widespread initiation of soil erosion (McKeon et al., 2004).

The implications of gully size and age on sediment yields have not been explored in this study but is an issue that requires further investigation. In south-east Australia, where the focus of research has been on colluvial gullies, there is evidence to suggest gullies experience an exponential decay in erosion rates and sediment production over time (Shellberg, 2011). This means that often the highest rates of erosion occur in the initial stages of gully incision before slowing or stabilising once the gully reaches it maximum extension (Hughes & Prosser, 2012; Olley & Wasson, 2003; Rustomji & Pietsch, 2007; Whitford, Newham, Vigiak, Melland, & Roberts, 2010). However, anecdotal evidence from land managers in the Barwon-Darling Catchment suggests that the large, complex, branching alluvial gullies observed in this study are still expanding within the floodplain. This is consistent with observations of alluvial gullies in northern Australia where the gullies are unconfined both vertically and horizontally due to the abundant store of dispersible soil on the floodplain (Brooks et al., 2009, Shellberg, 2011; Shellberg et al., 2016). This contrasts with colluvial gullies that are often limited in growth by the presence of bedrock, which limits the volume of unconsolidated sediment available for erosion, leading to an exhaustion in sediment supply (Shellberg, 2011). In the context of the Barwon-Darling River, this may mean that the large, complex, older gullies that predate the 1950s may still be producing significant quantities of sediment. Furthermore, side wall erosion is now likely to be the dominant process, which is typically the case in established gullies (Blong, Graham, & Veness, 1982; Casasnovas-Martinez, Ramos, & Poesen, 2004; Crouch, 1987, Crouch, 1990; Whitford et al., 2010). If this is the case, then the sheer length of the gully network in these older gullies may mean that they are still producing more sediment than the combined volume of sediment from the newer, smaller gullies. Understanding the relationship between gully size and the volume of sediment yielded from different parts of the gully network is an important factor for understanding the rate and timing of sediment contribution to the river. This is an area which requires further investigation on the Barwon-Darling River.

The other important factor with respect to the timing of gully development, is that the bulk of the gullies have formed prior to the construction of most of the low-level weirs, indicating that gully development has occurred independently to the presence of weirs. This is consistent with the finding that showed that the spatial distribution or number of gullies was consistent across weir pool and non-weir pool locations. However, as discussed previously, the presence of weirs do appear to influence the size and growth of gullies once they have established, albeit indirectly through the more intense use of the floodplain.

3.5.2 The contribution of gully derived sediment to declining waterhole depths

This study has shown that floodplain alluvial gullies have contributed large quantities of sediment to the Barwon-Darling River. It has also suggested that based on declining waterhole depths the volume of sediment that has accumulated in the waterholes of the Barwon-Darling River is substantial. Based on this information we hypothesised that there would be a close association between the observed decline in waterhole depth and the total volume of gully derived sediment entering a reach. The greatest change in waterhole depth was expected to occur in the proximity of the large, alluvial gullies. However, this study did not find a clear, predictive relationship between gully volumes and change in waterhole depths. Instead, change to waterhole depth was more closely aligned with the distance of a waterhole from its nearest upstream tributary. A lack of response to total gully volumes may be attributed to several factors. The first being that there is simply no association between the quantity of gully derived sediment entering a reach and the observed change in waterhole depth in that reach. This may be a consequence of the gully sediment being highly mobile, as is the case with the finer sediment fraction which is easily moved in suspension both longitudinally and laterally before being deposited. As such, it is more likely that the sediment would settle some distance from its source, which could accelerate sedimentation in a downstream reach (and hence a downstream waterhole) or it may move out onto the floodplain (Woodyer, 1978). In contrast, the coarser sediment fraction may be limited in its mobility and is more likely to be deposited on the gully floor or at the exit of the gully where visible sediment fans are often observed. On the Barwon-Darling River the high presence of in-channel benches suggests that the lateral accretion of sediment is a common geomorphological process (Thoms & Olley, 2004; Woodyer, Taylor, & Crook, 1979). These large depositional features may account for some of the gully derived sediment deposited within the river. Secondly, a lack of response in waterhole depth to gully volume is that the sediment contributed by the gullies may have been masked by contributions from alternative sources of sediment. The SedNet modelling has, for example, identified bank erosion and, to a lesser extent, hillslope erosion as an additional source of sediment within the Darling catchment. This finding is supported by the ANCOVA results in the present study, which identified upstream tributaries as a likely source of sediment filling waterholes. It may therefore be difficult to isolate the impact of gully derived sediment on waterhole morphology without a more comprehensive consideration of the overall sediment budget. Third, the lack of response could be attributed to the desktop approach taken in this study. A more targeted investigation is needed that could validate the change in waterhole depth at specific waterholes (rather than across a 5km interval) and then explore these changes in association with sediment derived from gully networks immediately upstream of each individual waterhole.

3.5.3 Comparing past and present modelling for gully derived sediment

Sediment budgets derived from the SedNet model for the Murray-Darling Basin suggested that there has been minimal gully erosion in the Darling River catchment with gully derived sediment from the Darling River contributing just 2 % of the total sediment delivered to rivers in the MBD (DeRose et al., 2003; Hughes & Prosser, 2012). This value is predominately in reference to colluvial gullying (pers comm I. Prosser, 2021). Alluvial floodplain gullying, as defined in this study, was largely unaccounted for in the SedNet model. This study is significant in that it demonstrates that alluvial gully erosion is an important process on the Barwon-Darling floodplain, and as such, it is a key source of sediment missing from previous basin wide sediment budgets.

Past research on the Barwon-Darling River has indicated that 95 % of the fine sediment fraction (<10 µm) in suspension originates from subsoil material (i.e., derived from banks and gullies) (Prosser et al., 2001). However, there has been no evidence to suggest whether this material was originating from headwater gullies, colluvial gullies positioned higher in the landscape, or, if it was from bank and/or gully erosion occurring locally along the main trunk of the Barwon-Darling River itself (Prosser et al., 2001). This study suggests that the latter certainly has a substantial contribution although the relative proportion in comparison to other subsoil sources has not been quantified.

Estimates from the SedNet model have indicated that 79 million m^3 of sediment has been exported from the tributaries to the Barwon-Darling over the past 100 years, whilst only 16 million m^3 of sediment were exported from gullies located within in the Barwon-Darling catchment. In comparison, for the same historical period, this study has estimated that 94 million m^3 of sediment has been contributed to the river from the Barwon-Darling floodplain. However, this assumes that the alluvial gullies mapped in this study are of a similar age (i.e., 100 years old) and that the sediment removed from these gullies has occurred within that 100-year window and not before. Based on these calculations the estimates for gully erosion in the SedNET model are 86 % lower than the estimates made in this study. This in part is a result of the Sednet model focusing on colluvial gullies positioned higher in the landscape. These gullies would be less connected with the river and, as such, much of the eroded material has likely been deposited on the valley floor before reaching the river system (Wethered et al., 2015). This contrasts with alluvial gullies that develop on the adjacent floodplain and are therefore highly connected to the main trunk of the river. Furthermore, the use of higher resolution mapping in this study has proven critical for identifying these large alluvial gullies on the Barwon-Darling floodplain.

The prevalence of alluvial gullies observed in this study suggests that alluvial gullies may be a significant source sub soil material on the Barwon-Darling. This is consistent with findings from other parts of the MDB that has shown subsoil erosion to be a significant contributor of sediment to rivers in the south-east of Australia (Olley & Wasson, 2003; Prosser et al., 2001; Wallbrink & Olley, 2004; Wethered et al., 2015). For example, in the lower reaches of the Coolbaggie Creek (a sub catchment of the Macquarie River, catchment area 1000 km^2) subsoils account for 100 % of the fine sediment fraction (Wethered et al., 2015). Evidence from radionuclide studies in combination with downstream changes in channel morphology and sediment size suggests that on the Coolbaggie Creek the dominance of sub material is indicative of a higher presence of alluvial gullies in the lower reaches of the river (Wethered et al., 2015). Similar trends of subsoil dominance and gully erosion have been observed on other large trunk steams within the MDB, and, on some of the smaller tributaries (Wethered et al., 2015). For example, the Murray River (Prosser et al., 2001), Murrumbidgee River (Wallbrink & Olley, 2004), Namoi River (Olley & Scott, 2002), Jerrabomberra Creek (Wasson et al.,

1998) and Jugiong Creek (Wallbrink & Olley, 2004) all highlighting the importance of floodplain gullies as a source of sediment to the MDB.

3.5.4 Future research direction and the relevance to dryland rivers globally

Gully erosion is considered a major land degradation issue in dryland catchments globally (Casasnovas-Martinez et al., 2004; Oostwoud Wijdenes & Bryan, 2001; Vandekerckhove et al., 2000). As such it is important that we understand the mechanisms and processes driving gully erosion and the implications that gully erosion can have on dryland river waterholes. This study has revealed many gaps in what we know about alluvial floodplain gullying in the Barwon-Darling River Catchment. The following section provides recommendations for future research, which although specific to this study, would have relevance to research pertaining to alluvial gullies globally. First, the automated GIS modelling undertaken in this study to determine gully volumes needs validating so that the reliability of volume estimates can be determined. A targeted approach that involves defining the dimensions of select gullies using a combination of remote desktop analysis and ground truthing is needed to test the accuracy of the automated modelled data. Consideration should also be given to the vertical accuracy (i.e., +/- 0.3m) of the LIDAR data to determine the margin of error associated with gully volume estimates and provide a more accurate reflection of the range of volumes that could be expected from individual gullies. Second, a more accurate description of gully age is required particularly for those larger gullies that pre-date the aerial images. This would provide better predictive capability regarding the historical rate of sediment yield and enable comparisons to be made for pre and post European colonisation. Likewise, gully evolution and the current level of erosion activity should be considered. Whether a gully is in the initial stages of development or in the later stages of expansion, stabilisation, or accretion, will influence the contemporary rate at which sediment is lost from the gully network. Third, a more accurate description of particle size distribution for gully derived sediment is required. Particle size is important as it can dictate the potential for sediment to be mobilised once it is within the river system. An analysis of particle size would provide an indication of the proportion of sediment that is likely to be deposited and therefore contribute to sediment accumulation with the waterhole features (i.e., the coarser bedload material or possibly aggregates of the fine material). Fourth, a more accurate estimate for the volume of sediment that has accumulated in the waterholes should be obtained, building on the coarse estimates made in this study. The use of a consistent width across all waterholes has likely resulted in an overestimate of sediment accumulation as this approach does not account for differences in channel morphology. Likewise, this study has demonstrated an issue with using a consistent depth for estimating the volume of sediment accumulation. The volume of sediment accumulation based on the average change in waterhole depth (i.e., 1.6m) was shown to differ greatly to the volume of sediment accumulation based on minimum and maximum change to waterhole depths. The reality is that individual waterholes have experienced differences in the degree of change and this should be reflected in the estimates for sediment accumulation. A more targeted, field-based approach to measuring sediment accumulation would improve predictive capability with respect to the rate of future sediment accumulation, which may be critical for understanding waterhole longevity and their future persistence within the landscape. Finally, in the northern Australia tropics, Brooks (2009, 2021) and Shellberg (2011, 2013, 2016) have comprehensively described alluvial gullies and the suite of factors that drive gully initiation and growth, which differentiates them from hillslope colluvial gullies. Factors range from catchment controls such as regional hydrology, connection with the groundwater aquifer and catchment morphology including valley bottom width, to local scale controls, including the depth of alluvium, local topography/elevation, channel geometry and discharge, the proximity to neighbouring gullies and/or natural paleochannels or anabranches, and the presence of dispersive soils. Mechanisms that drive gully initiation and perpetuate gully growth include flow concentration, fluvial scour, the presence groundcover vegetation, overbank flooding and local rainfall intensity amongst others. The relevance of these factors to alluvial gullies in arid and semi-arid locations should be explored as an understanding of the mechanisms driving alluvial gullying is important for ensuring that the remediation of gullies is targeted towards minimising the factors that contribute to gully success.

3.6 CONCLUSION

Alluvial floodplain gullying is a prevalent feature of the Barwon-Darling catchment that has in the past been overlooked and unaccounted for in sediment modelling for the Barwon-Darling River catchment. This study has shown that the volume of sediment removed from alluvial gullies far exceeds the contribution of sediment from alternative sources, such as colluvial gullies positioned higher in the landscape, upstream tributaries, and bank erosion. As such, alluvial floodplain gullying warrants serious consideration in future sediment budgets. Alluvial gullies in this study were observed to be larger in length, area and volume in locations influenced by low-level weirs, which we speculate is a result of more intense land use on the adjacent floodplain in these areas. Gully numbers have increased over the last 50 years, however, most of the new gullies are limited to simple, linear features, whilst the large complex gullies pre-date the 1950s. With anecdotal evidence suggesting that these large gullies are continuing to expand on the floodplain it may mean that through side wall erosion these older gullies are still providing vast quantities of sediment to the river. This study did not reveal a strong predictive relationship between alluvial gully erosion and change in waterhole depth. However, alluvial gullying would still be expected to have implications for channel morphology and for the functioning of aquatic habitats and their biota. To enable the targeted remediation of gully erosion it will be imperative to (1) develop a greater understanding of the mechanisms driving gully initiation and gully growth in arid to semi-arid environments and (2) understand the rate of sediment delivery and the behaviour of that sediment once in the river system.

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3.8 SUPPLEMENTARY MATERIAL

3.8.1

Figure 3.11 shows a series of boxplots comparing the gully volume, area and length between macro reaches.

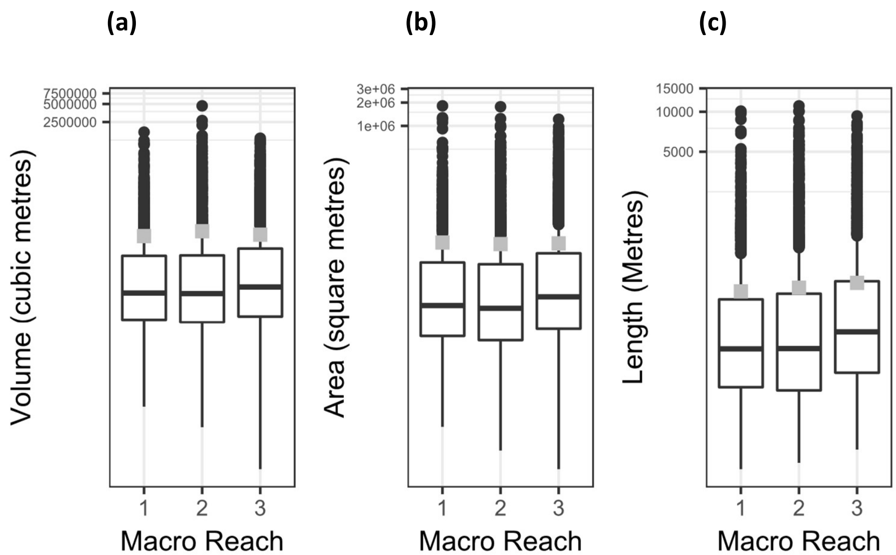

Figure 3.12 Comparison of gully volume (a), area (b) and length (c) between macro reaches. The mean is represented by the grey square. The centre line of the box plot represents the median or 50th percentile, whilst the lower and upper hinges represent the 25th and 75th quantiles. The upper whisker is equivalent the largest observation that is less than or equal to the upper hinges plus 1.5 times the IQR. Conversely, the lower whisker represents the smallest observation greater than or equal to the lower hinge minus 1.5 time the IQR. Outliers are represented by the black dots. n= 839 (MacroReach 1), 1830 (MacroReach 1), 2184 (MacroReach 1).

3.8.2

Table 3.2 shows the results from the Welch ANOVA comparing gully volume, area, and length for each macro reach.

Table 3.2 Results of Welch ANOVA comparing gully volume, area, and length for each macro reach.

Measure	**Welch ANOVA result**		
	Df	*F-value*	*P-vale*
Volume	2	0.9	0.409
Area	2	0.07	0.932
Length	2	2.13	0.119

Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	**% of contribution**
Candidate	Marita Pearson	75
Other Authors	Dr Michael Reid	15
	Tim Ralph	5
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Name of Candidate: Marita Pearson

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Candidate Date: 26/11/2021

Principal Supervisor Date: 26/11/2021

Higher Degree Research Thesis by Publication - University of New England

STATEMENT OF ORIGINALITY

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

Type of work	Page number/s
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Name of Candidate: Marita Pearson

Name/title of Principal Supervisor: Dr Michael Reid

Candidate Date: 26/11/2021

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CHAPTER 4

Water resource development reduces sediment transport capacity and increases the potential for sedimentation in a dryland river channel.

ABSTRACT

Sedimentation poses a serious threat to the persistence of waterholes in dryland rivers. Sedimentation can lead to the in-filling of waterholes and has been associated with substantial change to the physical form, chemical processes, and ecological character of dryland rivers. Modifications to the river channel and flow regime associated with water resource development has altered the capacity of rivers to move sediment from source to sink. On the Barwon-Darling, a dryland river in south-east Australia, alterations to the flow regime have on average resulted in a 35 % decline in the number of events capable of entraining coarse sand. Additional declines in the number of events capable of entraining coarse silt/fine sand (23 %) and fine silt/clay (48 %) have also been observed. In contrast, the frequency and duration of events conducive to the deposition of coarse sediment has increased at almost all sites. At the most impacted site the number and duration of events enabling deposition has increased by as much as 154 % and 72 % respectively, substantially increasing the number of days where deposition is likely. This is significant as it is often the coarse sediment fraction that governs channel morphology in dryland rivers. Overbank flooding has halved limiting the potential opportunities for lateral sediment exchange across the channel-floodplain interface. During periods of low flow, the longitudinal conveyance of sediment is limited by in-stream infrastructure. Collectively, these modifications increase the likelihood of sediment being retained within the river channel, increasing the opportunity for within-channel sedimentation and the in-filling of ecologically important waterholes.

4.1 INTRODUCTION

Sedimentation poses a significant threat to dryland rivers as it is often associated with substantial change to the physical form, chemical processes, and ecological character of the river (Prosser et al., 2001). Sedimentation can reduce habitat complexity and habitat heterogeneity (Bartley & Rutherfurd, 2005), which together can influence the diversity and composition of aquatic biota (Downes, Lake, Glaister, & Bond, 2006; Kemp, Sear, Collins, Naden, & Jones, 2011; Larsen, Pace, & Ormerod, 2011; O'Conner & Lake, 1994). Sedimentation reduces the ponding depth of natural pools and subsequently the persistence of water in those pools in the absence of flow (Costelloe, Shields, Grayson, & McMahon, 2007; Davis & Finlayson, 2000; Reid, Thoms, Chilcott, & Fitzsimmons, 2016). Accelerated rates of sedimentation are increasingly being observed in dryland rivers globally (Gomez et al., 2003; James, 1999; Simms & Rutherfurd, 2017; Ta, Xiao, & Dong, 2008). This is often the result of anthropogenic modifications to the flow regime, which can affect the connectivity of sediment within a river system (Heckmann, 2018, Ta et al., 2008; Wang, Wu, & Wang, 2007).

Sediment connectivity can be defined as the mediated transfer of sediment over a range of spatial and temporal scales (Bracken, Turnbull, Wainwright & Bogaart, 2015; Fyrirs, 2013; Heckman, Cavalli, Cerdan, Foester, Javaux, Lode, Smetanova, Vericat, 2018). Sediment connectivity is dependent on the interplay between the structural (morphological) components of the landscape (i.e., landscape topography and vegetation patterns) and the processes that dictate the long-term behaviour of sediment flux (i.e., the flow of energy/transport vectors such as water) (Bracken et al, 2015). In dryland systems, sediment connectivity is influenced by the interaction of multiple variables (e.g., sediment volume and accessibility, grain size, bed slope, channel geometry and roughness, and transmission loss), however, it is the flow regime that ultimately governs where, how much and for how long sediment is transported and stored in the river system (Fryirs & Brierley, 2013; Wohl et al., 2015). The potential energy created by flow (i.e., the stream power) drives the detachment of sediment from its surrounding surface and enables the entrainment and transport of sediment throughout the system (Fryirs & Brierley, 2013). In the absence of flow, the deposition of sediment is more likely, enhancing the storage of sediment within the channel or on the adjacent floodplain (Croke, Fryirs, & Thompson, 2013; Everitt, 1993; Ralph & Hesse, 2010; Wethered, Ralph, Smith, Fryirs, & Heijnis, 2015; Wohl et al., 2015). In such situations, sediment connectivity is constrained and dis(connectivity) occurs (Heckmann et al, 2018, Fryirs, 2013).

The presence of flow facilitates the connectivity of sediment, thus enabling the delivery of sediment from source to sink (Hooke, 2003, Wohl et al., 2019, Poeppl, Fryirs, Tunnicliffe & Brierley, 2020) (Figure 4.1). However, the delivery of sediment can become impeded by any factor that constrains the capacity of flows to transport sediment. This can occur when: (1) the supply of sediment exceeds the capacity of the channel to carry that sediment (i.e., when antecedent sediment concentrations are hyper concentrated) (van Maren, Winterwerp, Wu, & Zhou, 2009; Winterwerp, 2001), (2) the channel lacks the available energy (or flow competence) to transport the calibre of sediment in supply (Baker, Bledsoe, Albano, & Poff, 2011; Everitt, 1993; Ta et al., 2008) and (3) the transport of sediment is interrupted by a natural or artificial barrier limiting its longitudinal or lateral conveyance (Chitata, Mugabe, & Kashaigili, 2014; Fryirs, 2013; Lobera, Batalla, Vericat, Lopez-Tarazon, & Tena, 2016). The downstream delivery of sediment is therefore dependent on the lowest transport capacity of any reach along the river continuum (Fryirs, Brierley, Preston & Kassai, 2007). If sediment transport is limited, then any increase in sediment supply will result in higher rates of deposition in those reaches that have a low transport capacity, potentially altering channel morphology (Prosser et al., 2001).

Water resource development has had a significant role in influencing sediment delivery globally. The abstraction of water for irrigation, the interception of floodplain flows and the impoundment of flows by dams and weirs have reduced the magnitude and duration of flows in many rivers (Graf, 2005; Kondolf & Batalla, 2005; Poff et al., 1997). As a consequence, the frequency of higher energy flows that would have naturally carried the bulk of the sediment have been reduced (Wohl et al., 2015). In-stream infrastructure (i.e., dams and weirs) create a physical barrier to the longitudinal conveyance of sediment (Baade, Franz, & Reichel, 2012; Petts & Gurnell, 2005; Tamene, Park, & Vlek, 2006; Walker & Thoms, 1993) and they can modify the hydraulic conditions immediately upstream by reducing flow velocities (Bice, 2017; Mallen-Cooper, 2020), and thereby further limiting sediment conveyance (Ta et al., 2008; Wang et al., 2007). In contrast, flows downstream of instream infrastructure are often high in energy and low in sediment yield, producing highly erosive conditions immediately below the structure (Kondolf, 1997).

Dryland rivers are significant as they drain almost 50 % of the earth's surface (Tooth, 2000) and support approximately 28 % of the world's population (Larkin, Ralph, Tooth, Fryirs, & Carthey, 2020). Dryland rivers globally have, however, been subjected to substantial modification and exploitation as the demand for water in these arid environments has increased (Barnes, 2017; Best, 2019; Thoms, Beyer, & Rogers, 2006; Xu, 2005). The morphological consequences of these modifications are now being realised (Abate et al., 2015; Casado, Peiry, & Campo, 2016; Everitt, 1993; Gaeuman, Schmidt, & Wilcock, 2005; Richard & Julien, 2003). For example, waterholes, which are just one component of dryland rivers, are increasingly being threatened by sedimentation, which can in part can be associated with a modified flow regime (Reid et al., 2016). Waterholes, which develop as a series of deep pools are a critical feature to dryland rivers as they can retain water for extended periods of time in the absence of surface flow water connectivity and groundwater inputs (Hermoso, Ward, & Kennard, 2013). Waterholes provide refugial habitat for aquatic biota and are an important supply of water for remote communities (Arthington & Balcombe, 2011; Bernardo & Alves, 1999; Pires, Pires, Collares-Pereira, & Magalhaes, 2010). Sedimentation is, however, compromising the value of these important features in dryland rivers (Costelloe et al., 2007; Hamilton, Bunn, Thoms, & Marshall, 2005; Pearson, Reid, Miller, & Ryder, 2020; Reid et al., 2016).

This study investigates the degree to which water resource development modifies a river's capacity to transport sediment and subsequently how this influences sediment dynamics within the system as conceptualised in Figure 4.1. The study focuses on a large, alluvial dryland river (the Barwon-Darling

River) in the south-east of Australia, where sedimentation is thought to have contributed to a decline in waterhole depth (Pearson et al., 2020). The study will investigate the impact of four key variables (as identified in Figure 4.1) which are expected to influence sediment connectivity and sedimentation in large, alluvial floodplain rivers. In doing so, the following hypotheses will be tested: (1) antecedent sediment concentrations do not affect the transport capacity of flows on the river, (2) water resource development has reduced the capacity of flows to entrain and transport sediment, (3) water resource development has reduced the frequency and duration of overbank flow events required to transfer sediment laterally into floodplain sinks, and (4) in-stream infrastructure has the capacity to trap sediment particularly under low flow scenarios. The impact of a modified flow regime on sediment dynamics is an understudied aspect of water resource development. As such, the results from this study will not only have relevance to dryland rivers within Australia, but they will also contribute to understanding the impact that water resource development has had on the sediment regime of dryland rivers globally . The results are expected to reiterate the need to consider sediment dynamics as part of the water resource planning process and in particular the provision of targeted environmental flows to manage sedimentation.

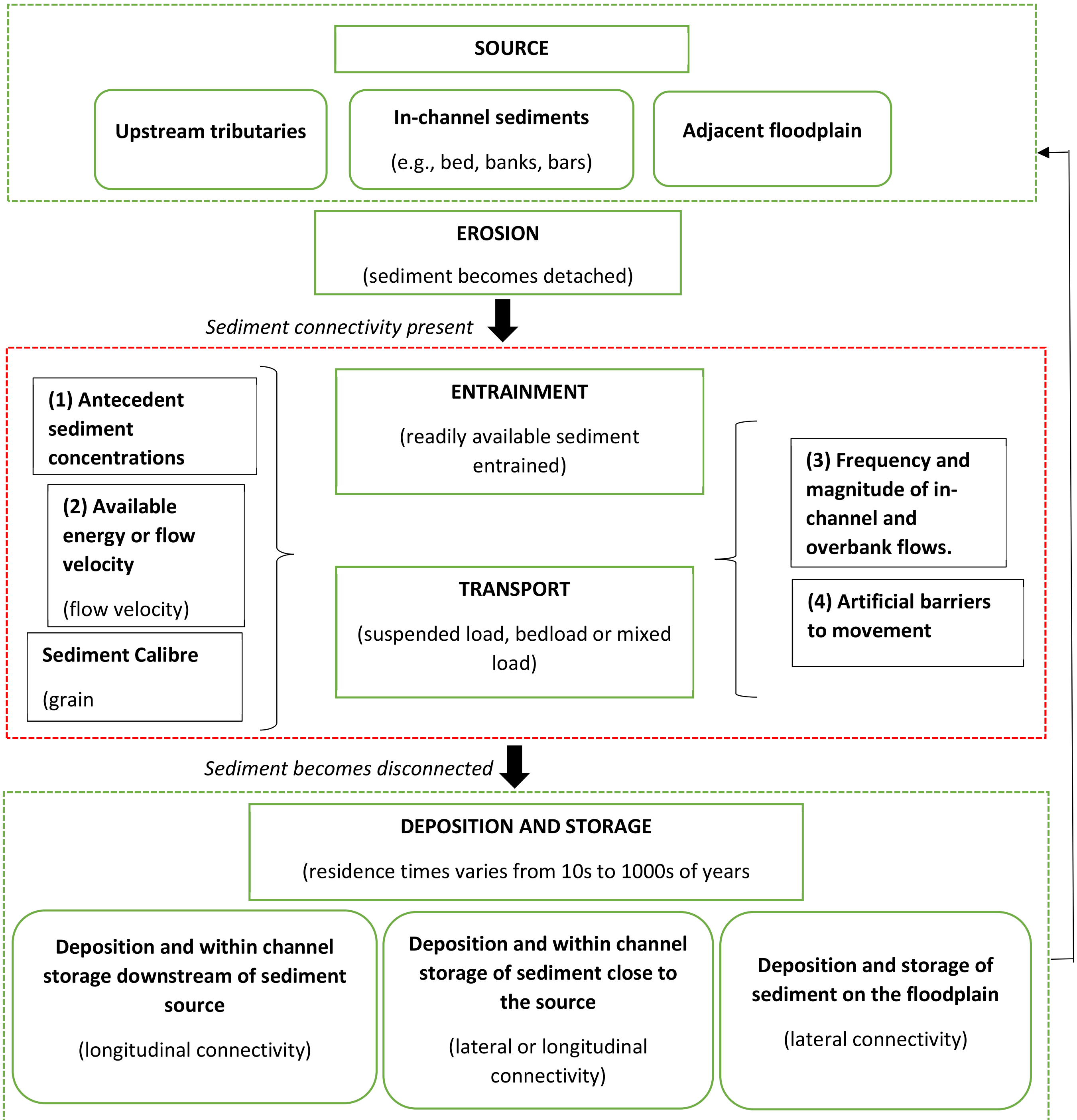


Figure 4.1: A conceptual representation of the sediment dynamics of a lowland, dryland river with a focus on the factors (1-4) driving the entrainment and transport of sediment (Bracken, Turnball, Wainwright, & Boggart, 2015; Brune, 1953; Croke et al., 2013; Fryirs, 2013; Fryirs & Brierley, 2013; Najafi, Dragovich, Heckman, & Sadeghi, 2021, van Maren et al., 2009; Winterwerp, 2001; Hooke, 2003).

4.2 STUDY AREA

The Barwon-Darling River is a large lowland river located in the north-west region of the Murray Darling Basin, in south-east Australia (Figure 4.2). The river and its tributaries drain an area of approximately 699 500 km^2 (Thoms, Hill, et al., 2004). It is an allogenic river with most of its tributaries draining a well-watered upper catchment on the western margins of the Great Dividing Range. The bulk of the flow is contributed from the Condamine-Balonne, Macintyre, Gwydir, Namoi, Macquarie, and Castlereagh Rivers. The Warrego and Paroo Rivers make smaller and more intermittent contributions from their headwaters located in more arid environments (Thoms & Sheldon, 2000).

The catchment area is predominately arid to semi-arid rangelands and as such is defined by extreme climatic variability (Thoms & Sheldon, 2000) with low rainfall, high evaporation and minimal runoff (Thoms, Sheldon, & Crabb, 2004). Annual median rainfall tends to decrease westward from >1200 mm/year in the headwaters to <200 mm/year in the far west (Thoms & Sheldon, 2000). Evaporation rates are high across the catchment but particularly so in the south-west where median annual potential evaporation rates can reach 2250 mm (Thoms, Sheldon, et al., 2004). The flow regime is one of the most variable in the world with a long-term coefficient of variation of annual flows ranging from 0.04 % to 911 % (Thoms & Sheldon, 2000). 'Low' flow conditions dominate the flow regime with periodic interruptions by major widespread flood events, often associated with short but intense periods of rainfall (Thoms, Sheldon, et al., 2004). Discharge capacities range from 46 m^3/s to 925 m^3/s (Boys & Thoms, 2006). Flow volumes increase between Mungindi and Bourke, before declining downstream of Bourke, due to a lack of tributary inflow and higher rates of evaporation (Thoms, Sheldon, et al., 2004).

The riverbed substratum is dominated by a relatively uniform mixture of fine sand, silt, and clay particles with little variation along most of its length (Woodyer, Taylor, & Crook, 1979). 95 % of its sediment is transported as fine suspended sediment (Olley & Caitcheon, 2000). Sediment concentrations range from 5 to 500 mg/L. The flocculation of sediment in the Darling River is, however, common when flows are low and particularly when there is an increased influx of saline groundwater (Oliver, Grace, Olley, & Cooper, 2004). Large, flat, depositional features known as in-channel benches are commonly formed between the channel bed and main floodplain surface (Sheldon & Thoms, 2006; Thoms & Olley, 2004). These benches act as temporary sediment stores with deposition rates ranging from 9-64 mm/year (Woodyer et al., 1979).

Livestock grazing has been the dominate land use within the catchment since European colonisation and currently utilises 79 % of the total land area within the Barwon-Darling valley (Crown Lands and Water Division, 2018). Irrigated agriculture (3 % of the land area) and dryland cropping (9 % of the land area) have emerged in more recent times, but it is mostly confined to the floodplain between Mungindi and Bourke. Eleven major reservoirs have been constructed on the tributaries from the 1960 onwards with a combined capacity of 5 billion m^3 (Thoms, Sheldon, et al., 2004). Whilst there are no large reservoirs on the main channel of the Barwon-Darling, 15 low level weirs have been constructed for the provision of stock and domestic use (Thoms & Sheldon, 2000). Due to the low gradient of the Barwon-Darling River (averaging 0.000005 m/m), a single weir can impound and influence the hydraulic character of many kilometres of river (Chessman, Jones, Searle, Growns, & Pearson, 2010). The construction of low-level weirs has been incremental with the oldest weir constructed at Bourke in 1897 and the most recent constructed in 1983 upstream of Louth. However, the bulk of the weirs were built during the 1960s and 1970s (NSW Department of Primary Industries, 2006). The capture of floodwaters within off-river storages on private property has steadily increased since the 1960s and has a combined storage capacity of 284 gigalitres (CSIRO, 2008).

This paper will focus on the Barwon-Darling River between the townships of Collarenebri in the north-east and Tilpa in the south-west, spanning approximately 1000 km of river channel (Figure 4.2). This paper will focus on the period of time between 1895 and 2009, for which modelled hydrological data are available.

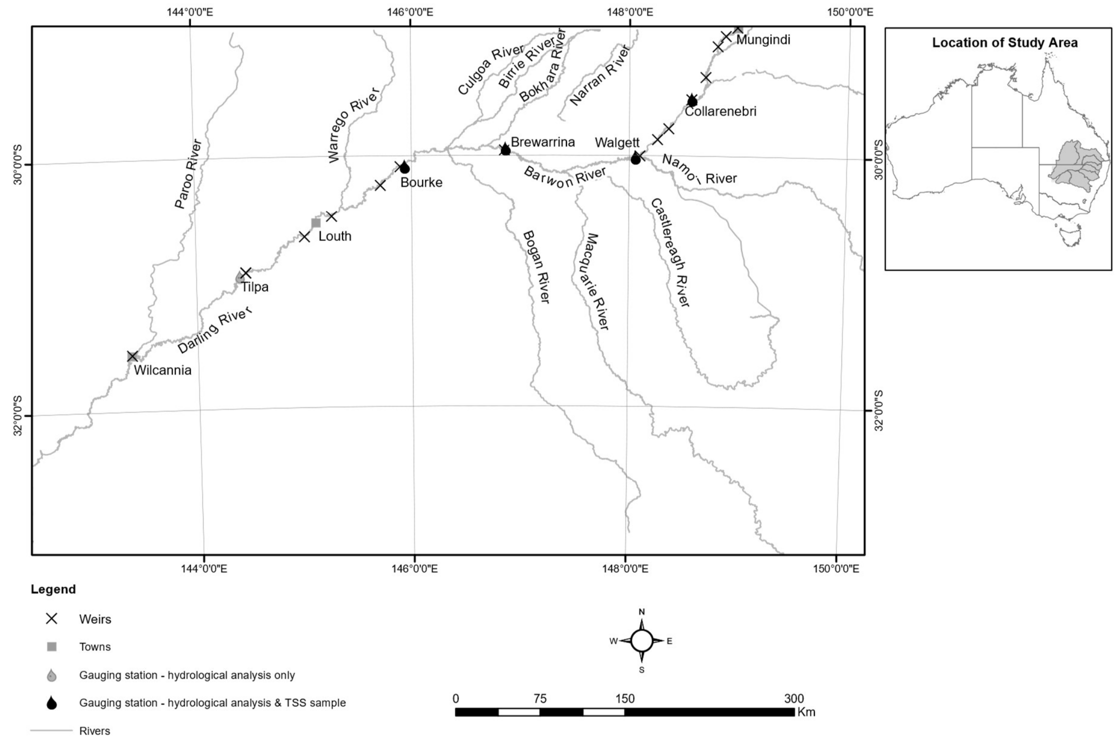


Figure 4.2: Part of the Barwon-Darling River catchment in western, New South Wales, Australia (Coordinate system: GDA/MGA zone 55).

4.3 METHOD

The methods used in this study have been designed to investigate the four key variables identified in Figure 4 as being influential to sediment movement and connectivity in a large, alluvial dryland river. Given the large spatial scope of the study area and the limited resources available, this study has utilised a desktop approach to investigate which of these factors may be influencing sedimentation within the Barwon-Darling waterholes.

4.3.1 The influence of antecedent sediment concentrations on sediment transport capacity

Sediment transport can be limited when the supply of sediment exceeds the capacity of the channel to carry that sediment. This occurs when the antecedent sediment concentrations are hyper concentrated and exceed a threshold of 200 km/m^3 or 200000 mg/L (van Maren et al., 2009;

Winterwerp, 2001), although this value can vary based on particle size and densityTo determine if sediment concentrations are a factor limiting sediment transport on the Barwon-Darling, data for total suspended solids (TSS) was obtained from the New South Wales Office of Water. Data availability was limited to monthly data spanning a 12-year period between 2007 and 2019. Sample collection was part of a routine monthly sample collection program and samples were taken under a range of flow conditions reflecting intra and inter-annual variation in discharge. TSS values are inclusive of both inorganic and organic material. TSS data was only available for the Collarenebri, Walgett, Brewarrina, and Bourke gauging stations (Figure 4.2). Distribution curves were generated for the four sites to capture the range of total suspended solids over the sampling period.

4.3.2 Quantifying the impact of water resource development on the river's capacity to entrain and transport sediment

4.3.2.1 Hydrological modelling

The temporal change to the river's flow regime and its capacity to entrain and transport sediment as a result of water resource development was examined at five gauging locations using two modelled flow scenarios: (1) without development (WoD) and (2) with development (WD). Simulated daily discharge data (ML/day) was provided by the Murray Darling Basin Authority for the period 1895-2009 for both scenarios. The 'without development' scenario provides the best representation of 'natural' flow conditions. The 'without development' scenario simulates what flow would have looked like between 1895 – 2009 if all aspects of water resource development were removed. That is the removal from the system of all flow regulating structures, all consumptive water users and all existing rules governing flows and water use. The inflow data for the 'without development' scenario has not, however, removed the impact of land use change and therefore does not truly represent pre-European conditions (Murray-Darling Basin Authority, 2016a). Despite these limitations, it is currently the best available representation for natural conditions on the river system. In contrast, the 'with development' scenario simulates the best estimate of what flow conditions between 1895-2009 would have looked like based on the water management operations that were in place as of 2009. This includes any water entitlements, water allocation policies, water sharing rules, operating rules, and infrastructure such as dams, locks and weirs that were operational in 2009 (Murray-Darling Basin Authority, 2016a). All modelled data were based on the 114-year climate history recorded between 1895-2009 (Murray-Darling Basin Authority, 2016a). The modelled data used in this study underpins water resource planning across the Murray-Darling Basin, and as such, it has been the subject of rigorous calibration, testing, and refinement over several decades (Murray-Darling Basin Authority, 2016b). It is however important to note that at the time of writing modelled flow data was unavailable beyond 2009 and therefore more recent flow scenarios could not be explored in this study.

The modelled data was input into the easily accessible and freely available River Analysis Package (RAP) designed to investigate trends in time series data (Marsh, Stewardson, & Kennard, 2003). RAP was used to produce summary statistics (i.e., mean, mean and coefficient of variation) for daily discharge data, which enabled comparisons of the flow regime between the with and without development scenarios.

4.3.2.2 Identification and comparison of entrainment thresholds

The Hjulstrom Curve (Fryirs & Brierley, 2013) was used to estimate the flow velocities required for the entrainment, transport and deposition of sediment across a range of sediment calibres – fine silt, coarse silt/fine sand, coarse sand (Table 4.1). The minimum discharge associated with these flow velocities was estimated at five gauging stations (Figure 4.2). Utilising existing stage to discharge tables and stage to area tables for each gauging station, the average cross-sectional velocity was determined for respective stage heights and flows. The standard formula for discharge (i.e., Q=AV) was reversed to enable a calculation for velocity (i.e., V=Q/A), where Q is discharge (or flow), A is area and V is velocity. Once this relationship was established the minimum discharge thresholds associated with the velocities required for entrainment, transport, and deposition could then be determined for each gauging location. These minimum discharge thresholds are central to the comparison of the river's transport capacity with and without development.

The frequency and duration of flow events exceeding the minimum discharge thresholds required for entrainment were determined for each modelled scenario using the 'high spell' function in the River Analysis Package (Marsh et al., 2003). A high spell analysis calculates statistics based on when a flow equals or exceeds a pre-defined flow threshold (Marsh et al, 2003). In this study, a high spell event occurred when the discharge thresholds for entrainment were exceeded. Each event was assigned a minimum event duration of one day to correspond with the data format (i.e., daily discharge) of the modelled data. However, it is recognised that an entrainment threshold may only be breached for a small proportion of the day before flows dip back below the critical threshold. Daily fluctuations in discharge above and below entrainment thresholds cannot be accounted for without looking at a finer resolution of data. Given the temporal scale investigated in this study (i.e., a period of 114 years) the comparison of daily discharge is deemed fit for purpose.

A 'low spell' analysis was also undertaken to compare the frequency and duration of flow events that would enable the deposition of coarse sediment under each flow scenario. A 'low spell' event occurred when flows fell below the discharge threshold for deposition. However, the hydrological model used in this study is known to have issues with providing an accurate representation of low flows (Murray-Darling Basin Authority, 2018) and for this reason comparisons were limited to the coarse sediment fraction, which had higher deposition thresholds than the coarse silt/fine sand fraction. Fine sediment was also excluded from the comparison as it would be expected to remain in suspension whilst the river is flowing, no matter the size of the flow.

Distribution curves were generated for each development scenario to compare temporal changes in the distribution of flows across each category of the sediment cycle i.e., erosion, entrainment, transport, and deposition. These are accessible in the supplementary information (Figures 4.10 - 4.14).

Table 4.1: Flow velocities required for erosion, entrainment, transport, and deposition based on sediment calibre (values taken from the Hjulstrom Curve).

Process	Velocity band (ms^{-1})		
	Fine silt/Clay (0.006 mm)	Coarse Silt/Fine Sand (0.006 mm)	Coarse Sand (2 mm)
Entrainment	0.8 – 2	0.30 – 0.65	0.4 – 0.6
Transport	0 - 0.8	0.004 – 0.30	0.09 – 0.4
Deposition	Not applicable	0 – 0.004	0 – 0.09

4.3.3 Quantifying the impact of water resource development on the river-floodplain sediment exchange

Examining change to overbank flow regimes allows inferences to be made regarding the likelihood of lateral sediment movement and hence the loss of sediment from within the channel. When thresholds for bank full channel capacity are exceeded floodplain inundation occurs resulting in the lateral connection between the channel and floodplain. Lateral connectivity disrupts the downstream conveyance of sediment leading to a reduction in within-channel sediment and a reduction in end of catchment sediment yield (Croke, 2013). However, when the floodplain becomes disconnected from the river, floodplain storage becomes limited and the volume of sediment retained within the channel boundary is increased (Croke et al., 2013). The 'high spell' function of the River Analysis Package (Marsh et al., 2003) was again used to investigate the temporal change to the frequency and duration of flow events that could initiate overbank flooding. In this case a high spell event was defined as any event exceeding the threshold for overbank flooding at each gauging location. Overbank flow thresholds were adopted from the literature (NSW Department of Planning, Industry and Environment, 2020, Sheldon, 2019). Although this study is focusing on the lateral movement of sediment from the river onto the floodplain it is recognised that some of this sediment (or new sediment) may return to the river as floods recede.

4.3.4 Investigating the influence of in-stream infrastructure on the river's capacity to trap sediment

The trap efficiency (TE) or the proportion of sediment that is deposited in the weir pools was estimated by calculating the capacity/average annual inflow ratio for each weir pool and applying it to the trap efficiency curves developed by Brune (1953) and later modified by the United States Natural Resources Conservation Service (NRCS) (Verstraeten & Poesen, 2000). The average annual inflow was calculated from the with development scenario, whilst the capacity of weir pools was adopted from the literature (Thoms, Sheldon, Roberts, Harris, & Hillman, 1996). Estimates for trap efficiency were determined based on the NRCS sediment categories – fine sediment (silts and clays), mixed sediment and coarse sediments (sand and gravel). This method was, however, limited in that the Brune curve was developed for a river system that has a regular and predictable flow regime (Revel, Ranasiri, Rathnayake, & Pathirana, 2015; Tebbi, Dridi, & Morris, 2012). As such it is thought to be less applicable to systems like the Barwon-Darling River that has a highly variable and highly unpredictable flow regime. In these systems, the annual trap efficiency can vary substantially from the long-term trap efficiency due to year-to-year hydrological variation making the value for trap efficiency less predictable (Revel et al., 2015; Tebbi et al., 2012). In this study, a range of flow scenarios were explored that enabled estimates to be made for the trap efficiency of weirs on the Barwon-Darling across a range of flow scenarios. In addition to using the average annual inflow, this study looked at trap efficiencies using the 25th, 50th and 75th percentiles for annual flows and also compared these to the trap efficiency of weirs throughout the Millennium Drought (2001-2008) one of Australia's worst droughts on record (Cai, Purich, Cowan, van Rensch, & Weller, 2014). In the absence of data relating to actual sediment deposition rates in weir pools, as is the case for the Barwon-Darling, TE calculations provide an indication of the frequency to which weirs act as a barrier to sediment connectivity throughout the system.

4.4 RESULTS

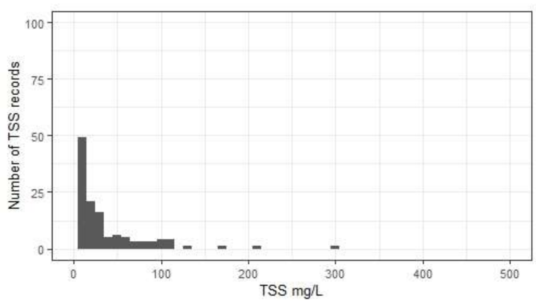
4.4.1 The influence of antecedent sediment concentrations on sediment transport capacity

TSS levels ranged from 5 mg/L to 500 mg/L (Figure 4.3a – 4.3d). However, TSS levels typically remained low for much of the sampling period with distribution curves being positively skewed towards the lower end of the TSS scale at all four sites. Median TSS levels were well below 500 mg/L at all sites with the lowest median measured at Bourke (13 mg/L) and the highest measured at Walgett (46 mg/L). These TSS levels are well below the threshold (200000 mg/L) that would limit sediment transport, suggesting antecedent sediment concentrations do not influence sediment behaviour on the Barwon-Darling River. As such no further analysis was undertaken.

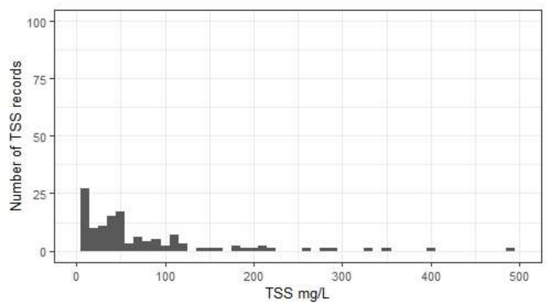
4.4.2 Hydrological change between the historical and current modelled flow scenarios

The comparison of modelled flow scenarios indicates that the flow regime has been altered substantially due to water resource development (Figure 4.4, Table 4.2). The 'with development scenario' indicates that the mean daily discharge has decreased on average by 43 % across the five gauging locations when compared to the 'without development scenario'. A similar result was observed for median daily discharge with an average decline of 65 %. The impact of water resource development on median daily discharge has increased with distance downstream. A 43% decline in median flows was observed at Walgett, the most upstream site, compared to a 77% decline in median flows at Tilpa. Flow variability has increased across all sites with the Cvs in the current scenario ranging from 2.4 to 4.0, up from 2.0 to 2.3.

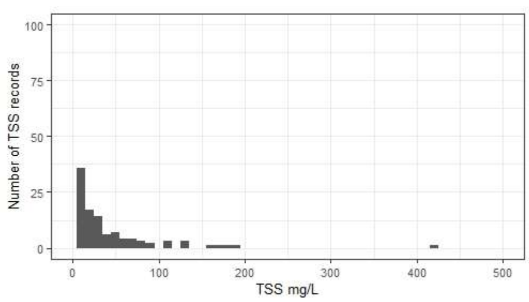
(a) Collarenebri



(b) Walgett



(c) Brewarrina



(d) Bourke

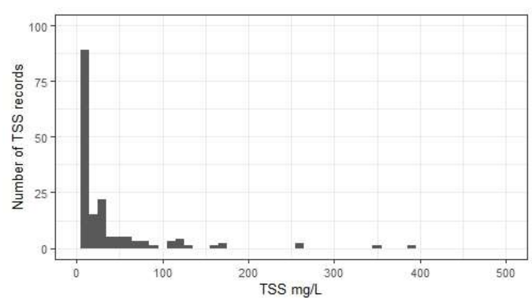
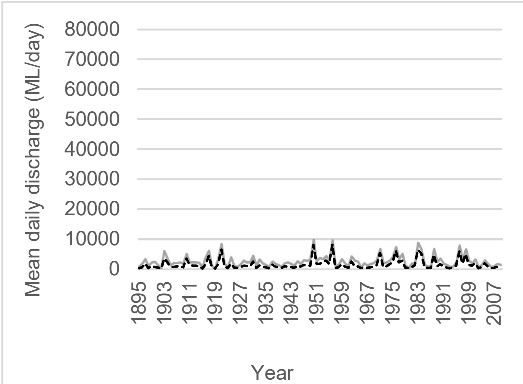


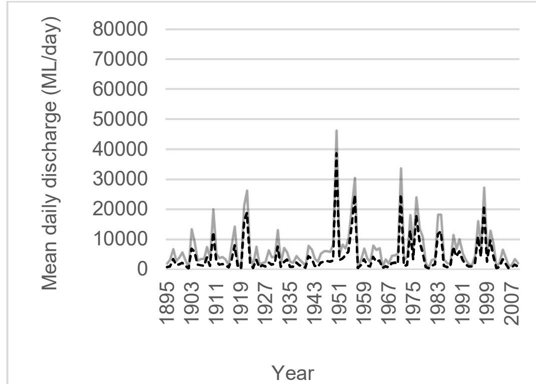
Figure 4.3a – 4.3d: Frequency distribution of recorded values for total suspended solids (mg/L) for monitoring stations on the Barwon-Darling River (note: to allow conisistency in the x-axis scale across the four figures a single outlier of 1000 mg/L was removed from the Walgett data)

Table 4.2: Summary statistics for daily discharge (ML/d) for the 'without development' (WoD) modelled flow scenario and the 'with development' (WD) modelled flow scenario (Cv = coefficient of variation).

	Collarenebri		**Walgett**		**Brewarrina**		**Bourke**		**Tilpa**	
	WoD	**WD**	**WoD**	**WD**	**WoD**	**WD**	**WoD**	**WD**	**WoD**	**WD**
Mean	2616	1487	7016	4104	6254	3782	10436	5871	9976	5459
Median	547	313	1233	489	1772	638	2688	823	2719	637
Cv	2.0	2.6	3.1	4.0	2.3	3.0	2.4	3.2	2.3	3.1

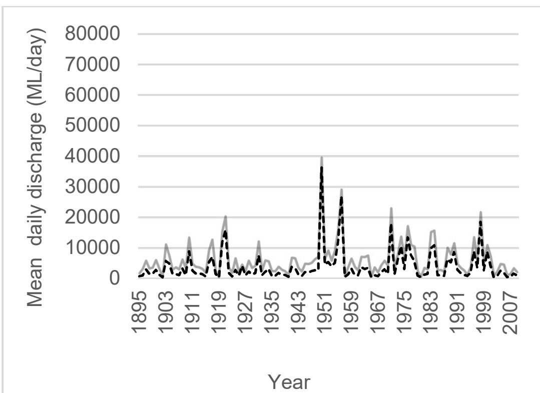
(a) Collarenebri (b) Walgett

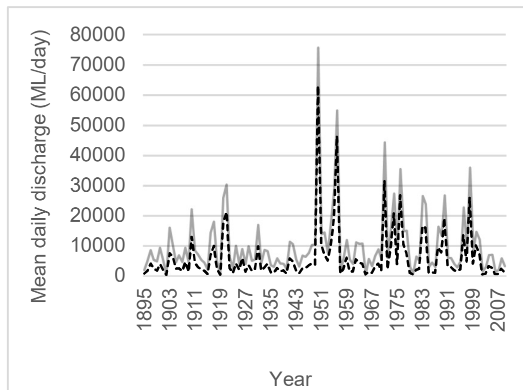




(c) Brewarrina

(d) Bourke





(e) Tilpa

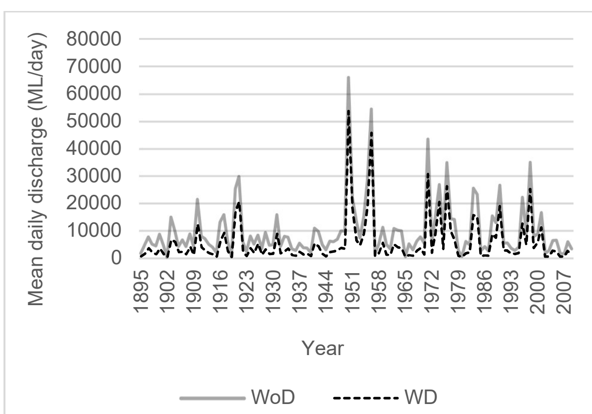


Figure 4.4: Mean daily discharge for the without development (WoD) and with development (WD) flow scenarios (ML – megalitre)

4.4.3 The impact of water resource development on the river's capacity to entrain sediment

The high flow spell analysis showed a substantial decline in the total number of events (Figure 4.5, Table 4.3) and the total duration of flow events exceeding the minimum discharge thresholds for sediment entrainment across all sediment calibres (Figure 4.6, Table 4.3). On average the total number of events with the capacity to entrain coarse sand has declined by 39 %. There have also been declines of 35 % and 49 % in events capable of entraining coarse silt/fine sand and fine silt/clay respectively. Flows at Bourke have been the most heavily impacted with an average decline in the number of events of 49 % across all sediment calibres, whilst Tilpa, the most downstream site, has been impacted the least, with an average decline of 34 % across sediment calibres. Likewise, the total duration of events has declined on average by 47 % for coarse sand, 46 % for coarse silt/fine sand and 43 % for fine silt/clay. The average number of days between flow events meeting entrainment thresholds have increased by as much as 124 % at Bourke, with all five sites heavily impacted (i.e., ranging from 76 % to 110 % increases).

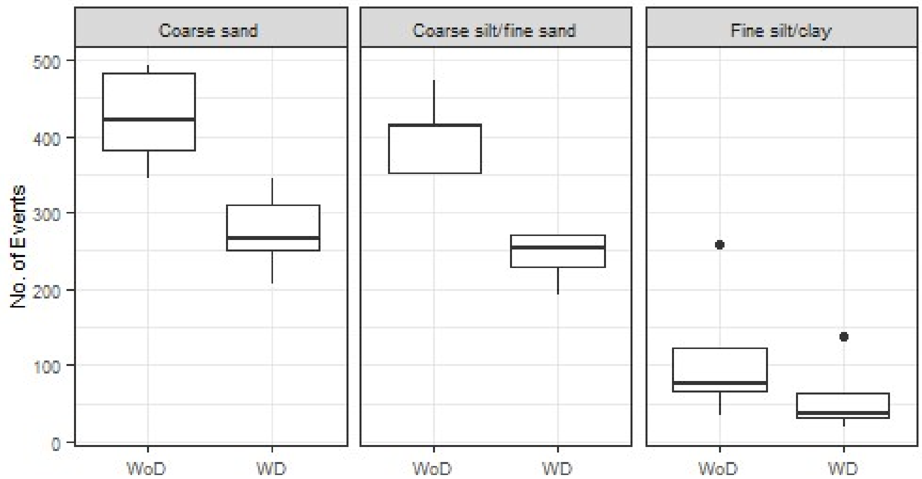


Figure 4.5: Total number of events exceeding discharge thresholds for sediment entrainment combined across all gauging stations for the without development (WoD) and with development (WD) flow scenarios (tests of significance are in the supplementary material – Table 4.7).

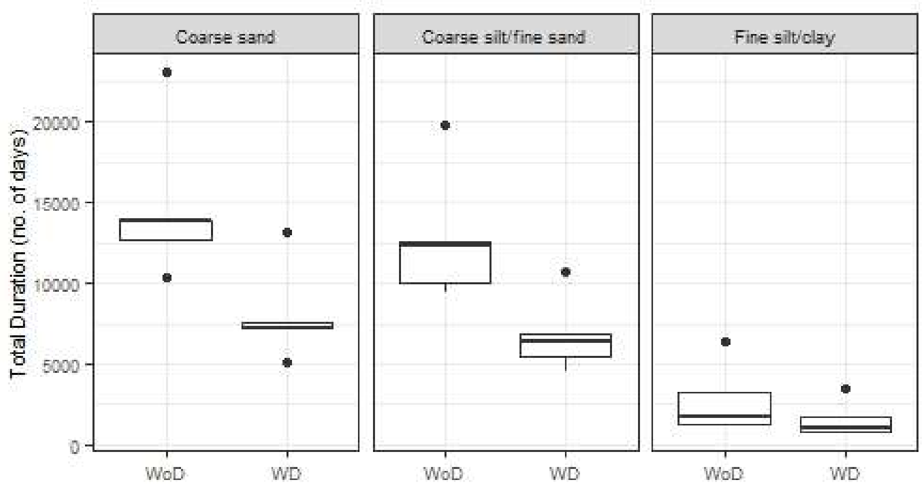


Figure 4.6: Total number of days exceeding discharge thresholds for sediment entrainment combined across all gauging stations for the without development (WoD) and with development (WD) flow scenarios (tests of significance are in the supplementary material - Table 4.8).

Table 4.3: Percentage change from the without development to with development scenario in the number events and the total duration of events with the capacity to entrain sediment (ML – megalitre, Na. data unavailable)

		Collarenebri	Walgett	Brewarrina	Bourke	Tilpa
Fine silt/clay (0.006 mm grain – 0.08 ms^{-1})	**Flow threshold (ML/day)**	**Na.**	**43890**	**10445**	**40450**	**53133**
	No. of events	**Na.**	-50 %	-46 %	-55 %	-46 %
	Total duration	**Na.**	+42%	−47 %	+46 %	+37 %
Coarse Silt / Fine Sand (0.06 mm grain – 0.30 ms^{-1})	**Flow threshold (ML/day)**	**2628**	**3756**	**3901**	**6277**	**2007**
	No. of entrainment	-37 %	+29 %	-40 %	-45 %	-23 %
	Total duration of	-51%	-43 %	-45 %	-48%	-43 %
Coarse Sand (2 mm grain – 0.05 ms^{-1})	**Flow threshold (ML/day)**	**3084**	**5523**	**4546**	**7487**	**3084**
	No. of events	-43 %	-39 %	-44 %	-46 %	-32 %
	Total duration	-52 %	-45 %	-45 %	-48 %	-46 %

In contrast to the entrainment thresholds, the total number of events and the total duration of events falling below the discharge thresholds that enable deposition have increased at all but one site (Figure 4.7, Table 4.4). The total number of events enabling the deposition of coarse sediment have on average increased by 33 %, however the magnitude of change varied between sites. The greatest impact on the deposition of coarse sand occurred at Walgett with a 158 % increase in the number of deposition events and a 72 % increase in the duration of events enabling deposition. Tilpa was the only site to experience a decline in both the number of events and the duration of deposition events (i.e., a decrease of 57 % and 83 % respectively).

More detailed information on the changes to the distribution of flow events in relation, entrainment, transport, and deposition thresholds are available in the supplementary material (Figure 4.10 - 4.14). These figures highlight a notable shift in sediment dynamics between development scenarios. A higher frequency of events enabling the deposition of the larger sediment fraction (i.e., coarse silt/fine sand and coarse sand) was observed for the with development scenario across all sites. Simultaneously, there has been a decline in the number of events with velocities capable of the entraining sediment.

(a) (b)

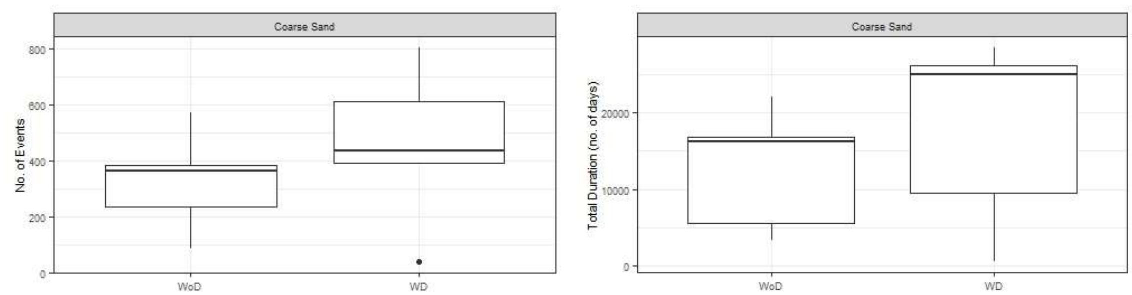


Figure 4.7 a-b: Total number of events (a) and total duration of events (b) dropping below thresholds for coarse sediment deposition combined across all gauging stations for the without development (WoD) and with development (WD) flow scenarios (tests of significance are in the supplementary material – Table 4.9).

Table 4.4: Percentage change from the without development to with development flow scenario in the number events and the total duration of events that enable deposition of coarse sediment (ML – megalitre)

		Collarenebri	Walgett	Brewarrina	Bourke	Tilpa
Coarse Sand	**Flow threshold (ML/Day)**	**634**	**164**	**999**	**1561**	**114**
	No. of events	+41 %	+158 %	+13 %	+8 %	-57 %
	Total duration	+29 %	+72 %	+54 %	+55 %	-83 %

4.4.4 The impact of water resource development on the river-floodplain exchange

Results indicate that there has been a decline in the total number and the total duration of overbank flow events on the Barwon-Darling under the with development (WD) flow scenario (Figure 4.8, Table 4.5). The number of events resulting in overbank flows has declined on average by 53 % across gauging stations, whilst the duration of events has declined by an average of 45 %.

(a) (b)

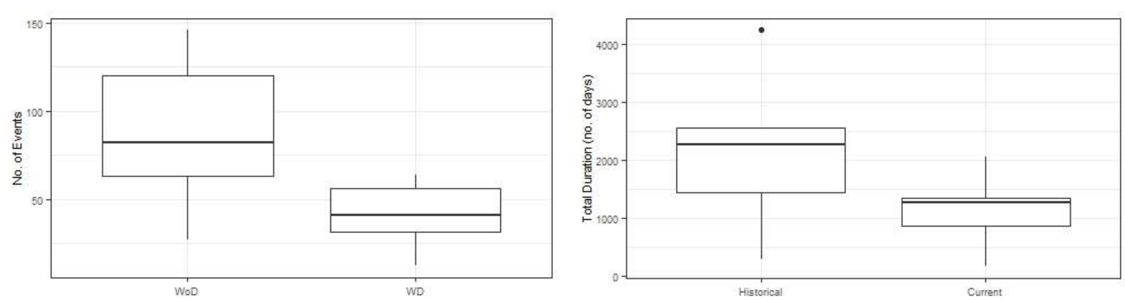


Figure 4.8 a-b: Total number of events (a) and total duration of events (b) exceeding thresholds for overbank flows combined across gauging stations for the without development (WoD) and with development (WD) flow scenarios.

Table 4.5: Percentage change from the without development to with development flow scenario in the number of overbank flow events (ML – megalitre)

	Collarenebri	Walgett	Brewarrina	Bourke	Tilpa
Flow threshold (ML/day)	**>30100**	**>27000**	**>32000**	**>35500**	**>25480**
No. of events	-56 %	-56%	-51%	-50%	-53%
Total duration	-41%	-44%	-39%	-47%	-52%

4.4.5 The influence of in-stream infrastructure on the river's capacity to trap sediment

Based on average annual inflows the low-level weirs on the Barwon-Darling River have low trap efficiencies, limiting their capacity to trap sediment. The capacity/average inflow ratio for each of the weir pools is less than one, indicating that in an average flow year the entire volume of the weir pool should be replenished within the year. As a result, the likelihood of sediment being trapped is low. When using the average annual inflow to calculate TE, results indicated that only two of the five weirs are capable of trapping sediment (Table 4.6). The Bourke Weir would be the most effective and it would be expected to trap sediment across all sediment calibres, whilst Walgett would trap coarse and mixed sediment but would be unable to trap fine sediment. These results do, however, vary substantially when the average annual inflow is replaced by the 25th, 50th or 75th percentile annual inflows or when considering the average annual inflows during the Millennium Drought. For example, under these alternative scenarios the trap efficiency for the Bourke and Tilpa weirs are highest when flow conditions are low, resulting in a large proportion of the coarse sediments being trapped (i.e., 50 – 86 % T.E) (Figure 4.9). Similar trends were found at the remaining the three remaining sites (refer to supplementary material, Figure 4.15).

Table 4.6: The trap efficiency (TE) of low-level weirs on the Barwon Darling River based on a modified Brune efficiency curve (Verstraeten & Poesen, 2000) (ML – megalitre).

Site	Weir pool capacity (ML)	Average Annual Inflow (ML)	C/I	TE (%) Fine sediments	TE (%) Mixed sediment	TE (%) Coarse sediment
Collarenebri	560	543235	0.001	0	0	0
Walgett	4000	1499052	0.003	0	12	28
Brewarrina	1500	1381511	0.001	0	0	0
Bourke	30000	2151928	0.014	36	50	63
Tilpa	300	2007175	0.001	0	0	0

(a) Bourke weir pool (b) Tilpa weir pool

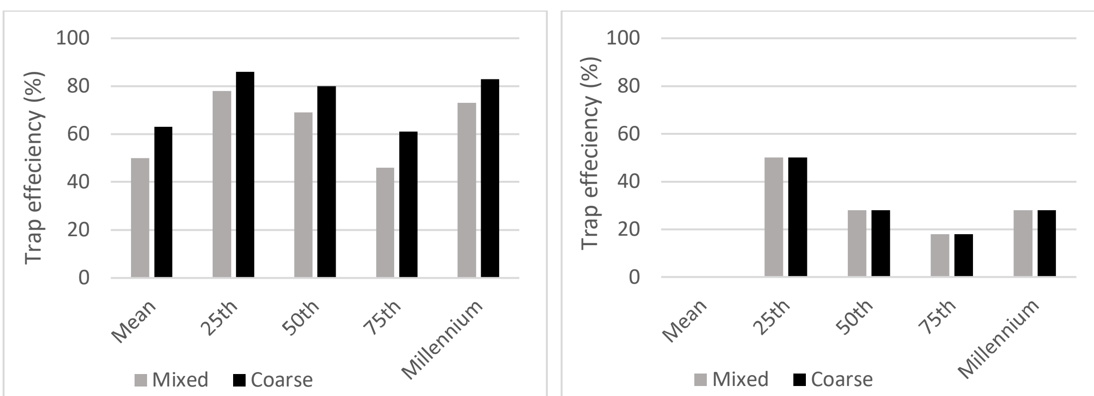


Figure 4.9: Trap efficiency values for the Bourke and Tilpa weirs based on variable annual inflows (i.e., the mean annual inflow, the 25^{th}, $50^{th}$and 75^{th} percentile annual inflows and the mean annual inflow for the Millennium Drought (2001-2008)). Note: The lack of data for the mean annual flow at Tilpa reflects a 0 % trap efficiency for both mixed and coarse sediment.

4.5 DISCUSSION

The flow regime of the Barwon-Darling River has been modified substantially due to water resource development leading to a reduction in the river's capacity to transport sediment. With the lateral and longitudinal transfer of sediment compromised, the retention of sediment within the river channel would be expected to increase. An increase in sediment retention corresponding with changes to the capacity of flows to move sediment could explain the accelerated rates of sedimentation observed on the Barwon-Darling since European settlement (Pearson et al., 2020; Thoms & Olley, 2004).

4.5.1 The influence of antecedent sediment concentrations (sediment supply) on the river's capacity to transport sediment

The concentration of suspended sediment in the Barwon-Darling River remained low over the 12-years of data examined in this study and well below the sediment concentration that would inhibit the entrainment of sediment (i.e., 2000 mg/L) (van Maren et al., 2009; Winterwerp, 2001). This indicates that despite evidence of ongoing sediment input from the tributaries (Thoms & Olley, 2004), bank erosion (DeRose, Prosser, Weisse, & Hughes, 2003) and alluvial gullies on the adjacent floodplains (Pearson et al., 2020), the water column is unlikely to reach a concentration where sediment could not be transported in suspension. Antecedent sediment concentrations are therefore not considered a limiting factor for sediment transport in the Barwon-Darling River and for that reason are not considered any further in this discussion.

4.5.2 The impact of water resource development on sediment entrainment and the lateral and longitudinal conveyance of sediment

Flow competence, a critical factor in the transport and connectivity of sediment, has been substantially altered because of water resource development on the Barwon-Darling River. This study has shown that under a modified flow regime the entrainment of sediment is less likely across all sediment calibres (i.e., clay – silt – sand). Conversely, a higher frequency and duration of low flows means that there has been an increase in the number of days where the deposition of coarse material (i.e., coarse sand) would be expected. The increase in deposition events is significant because, although the Barwon-Darling is predominately a suspended load system, it is often the coarse bedload fraction (i.e., sand/gravel) that shapes the channel morphology in dryland systems (Fryirs & Brierley, 2013; Hooke, 2003; Tooth, 2000). With reduced flow competence, a higher proportion of coarse sediment would be retained locally with net deposition more likely. Cease to flow events would further exacerbate within-channel deposition by enabling deposition across all sediment calibres, including the fine silts/clays that would otherwise remain in suspension. Cease to flow events have not been considered in this study due to limitations with the model in predicting low flows (Murray-Darling Basin Authority, 2018). However, temporal comparisons based on gauged data from the Barwon-Darling suggest that the frequency and duration of cease to flow events have increased (Mallen-Cooper, 2020; Sheldon, 2017). Furthermore, a decline in overbank flooding as observed in this study has reduced the hydrological connectivity between the river and the adjacent floodplain. Without overbank flooding the opportunity for the lateral transfer of sediment from the river to floodplain is reduced, increasing the likelihood of within channel deposition (Croke et al., 2013).

In dryland systems, where waterholes are a critical feature, the potential for increasing levels of deposition (sedimentation) is of significant concern. Waterholes are self-maintaining scour features in that under low to moderate flow conditions they act as a natural deposition zone for sediment (Nanson, Tooth, & Knighton, 2002). However, during periods of high flow the stream power can exert enough stress on the riverbed and banks to initiate scour, which is critical for maintaining the deep pools which constitute a waterhole feature (Knighton & Nanson, 2000; Nanson et al., 2002). Modifications to the flow regime as demonstrated in this study have the potential to amplify deposition rates and reduce opportunities for sediment entrainment, disrupting the natural conveyance of sediment throughout the system (Reid et al., 2016). The result may be that waterholes are increasingly filled with sediment, which over time can lead to a decline in waterhole depth (Reid et al., 2016). In the absence of surface flows, shallower waterholes will dry faster reducing their capacity to persist within the landscape (Costelloe et al., 2007; Hamilton et al., 2005). This has serious consequences in an arid environment where waterholes are at times the only source of water for local communities and are critical for sustaining the aquatic and terrestrial biota (Perry & Bond, 2009; Rolls, Leigh, & Sheldon, 2012). In the long term, sedimentation can affect the capacity of a waterhole to act as a refuge and it reduces the availability of water for stock and domestic use, recreation, and the maintenance of water for indigenous cultural practice (Hamilton et al., 2005; Jackson, Pollino, Macklean, Bark, & Moggridge, 2015; Lobegeiger, 2010; Reid et al., 2016).

4.5.3 The influence of in-stream infrastructure on the river's capacity to trap sediment

This study found that the trap efficiencies of low-level weirs on the Barwon-Darling River is highly variable depending on the inflow used to calculate the capacity/inflow ratio. Based on the conventional use of the Brune curve (i.e., using the average annual inflow) the trapping of sediment would be limited and thus minimal disruptions to downstream sediment conveyance would be expected. However, this study has shown that when the variability and unpredictability of a dryland river flow regime is considered, the applicability of the Brune curve in its original format is somewhat questionable. Results revealed that as the annual average inflow was reduced the trap efficiency of the low-level weirs increased. This is significant given the dominance of low flow conditions on the Barwon-Darling River (Thoms, Sheldon, et al., 2004) and the fact that in drought conditions low-level weirs can capture 100 % of the flow for prolonged periods of time (Mallen-Cooper, 2020). During events such as the Millennium Drought, when the river experienced low or no flows for extended periods (van Dijk et al., 2013), the retention of sediment in the weir pools would be expected to be quite high. However, how much of this sediment remains within the weir pool once flows recommence is unknown. Further investigation of bed level change would provide a useful indication of the full extent of the impact of low-level weirs on sediment trapping and any change to channel morphology. For example, on the Murray River, also in south-east Australia, bed level elevations have been found to differ markedly post weir development with bed levels aggrading by as much as 2.2m upstream of the weir (Thoms & Walker, 1993). Similar results have been observed on dams and weirs globally (Baade et al., 2012; Ta et al., 2008; Yang & Lu, 2014). The Brune curve, despite its limitations in a dryland environment, has value in that it can easily provide an estimate for trap efficiency using limited data. This is an important factor for dryland rivers which are often in remote, arid landscapes where minimal data collection occurs (Sultana & Naik, 2015).

4.5.4 Implications of climate change and land use change

Over the coming decades the climate is expected to change globally at unprecedented rates (Cai & Cowan, 2008; Chiew, Young, & Cai, 2011). In south-east Australia, climate change projections suggest that there will be an increase in the level of aridity (Larkin et al., 2020) resulting from lower precipitation, higher temperatures, and higher evapotranspiration rates (Cai & Cowan, 2008; Chiew, Young, & Cai, 2011; Whetton, 2011). The hotter, drier conditions across south-east Australia are expected to result in a decline in surface runoff and a subsequent reduction in streamflow of around -4 % (CSIRO, 2012). In the Barwon-Darling catchment, a 1^{o}C increase in temperature is expected to elicit a median decline in rainfall of -4 % (ranging from -11 % to 4 % for the dry extreme through to the extreme wet climate scenario) (Post, Chiew, Teng, Wang, & Marvanek, 2012), whilst median runoff is expected to decline by -8 % (ranging from -25 % to 13 %) (Post et al., 2012). As catchments become more arid and streamflow declines so too will the stream power and the capacity of rivers to transport sediment (Larkin et al., 2020). A reduction in discharge associated with climate change is likely to result in more zero flow days, less overbank flooding, and more frequent and longer duration flows that remain below the critical levels for sediment entrainment and transport. The net impact would be even greater levels of deposition and sediment retention within the river channel, having serious implications for aquatic habitats, water depth and waterhole persistence (Costelloe et al., 2007; Hamilton et al., 2005). However, despite projections for increasing levels of aridity, climate change models also indicate that in some regions where annual rainfall is expected to decline, individual rainfall events may intermittently become more intense. In such instances, high volume runoff events may be initiated (Post et al., 2012), creating short-term (hours to days) opportunities for sediment movement and sediment connectivity throughout the catchment.

The implications of climate change on the sediment dynamics of dryland rivers are expected to be profound and long-lasting with significant geomorphologic adjustment expected, and in extreme cases a change to river type (Larkin et al., 2020). For example, climate projections for 29 alluvial, dryland rivers in south-east Australia, predict that there will be a dramatic shift in river morphology with rivers becoming more discontinuous. As rives become more intermittent hydrological and sediment connectivity will decline, thereby reducing sediment distribution (Larkin et al., 2020). The implications of climate change on the channel morphology of the Barwon-Darling have not been investigated to date. However, this study has gone some way in providing a link between how the sediment dynamics of the Barwon-Darling have changed in response to a modified flow regime. It also provides an insight into how the Barwon-Darling and similar dryland rivers may continue to change in response to a modified flow regime regardless of the cause.

4.5.5 Research limitations and further research needs

The use of the Hjulstrom curve in this study has enabled inferences to be made regarding the impact that water resource development has had on sediment movement through the Barwon-Darling River. However, the Hjulstrom curve is limited by its simplicity. The Hjusltrom curve conceptualises the circumstances under which sediment entrainment, transport and deposition occur based on particle size. However, particle size is just one of the factors under which these three phases operate. The ease at which sediments move into motion will vary depending on a range of factors. For example, within channel resistance created through bed roughness (i.e., vegetation or wood), whether the grain is loose or embedded, and in fine grained systems, particle cohesion (Fryiers and Brierley, 2013). Before entrainment can occur, these additional resistance forces must first be overcome and as a result higher velocity flows would be needed for entrainment. An understanding of the within channel environment and its influence on entrainment is therefore critical for validating the conclusions made in this study based on the Hjulstrom curve.

Of particular interest in suspended load systems like the Barwon-Darling are the electrochemical cohesive properties of fine-grained sediment (i.e., the silt-clay fraction) which can bind particles together to form flocs or aggregates (Fryirs & Brierley, 2013). This process changes the size, shape, density and porosity of the particle, which can in turn influence the hydrodynamics of the newly formed particle, thereby affecting its transport and deposition (Droppo, 2001). When particles bind together, larger, heavier particles are created, increasing their settling velocity, and thereby accelerating deposition (Droppo, 2001; Fryirs & Brierley, 2013). The influence of flocculation on the rate of deposition/sedimentation needs further exploration particularly in the context of how it could influence the presence and maintenance of waterholes within alluvial, dryland rivers.

On the Barwon-Darling there is strong evidence of particle cohesion and the flocculation of fine silt/clay sediments. This is particularly evident when there are no flows or very low flows in the river (Woodyer, 1978), and is further enhanced in locations where there has been an influx of saline groundwater (Donnelly, Grace, & Hart, 1997; Grace, Hislop, Hart, & Beckett, 1996). Modifications to the flow regime that result in low flow, low velocity conditions are more conducive to the deposition of larger, heavier flocs (Wenjie, Wang, Yang, Zhang, 2015). Given the frequency at which these lower flows are now being observed on the Barwon-Darling it will be important to consider the relationships between flow regime, flocc or particle size and sedimentation rates in future research.

Also, limiting in this study was the use of an average cross-sectional velocity for interpretating the behaviour of sediment (i.e., entrainment, transport, deposition) on any one day. The reality being that the velocity of flows at each gauging station will vary throughout the cross section based on water depth, proximity to bank (Mallen-Cooper, Koehn, King, Stuart & Zampatti, 2008), channel shape, sinuosity and roughness, and the presence or absence of in-stream obstructions (i.e., large woody debris, rocks/boulders, vegetation). This means that even on days where a high flow dominates there may still be patches or pockets of low velocity flows throughout the cross section which are enabling deposition. Additionally, the average velocity as used in this study could be markedly different to the velocity nearer the riverbed where entrainment occurs. A more sophisticated approach such as the use of an acoustic doppler would provide a greater understanding of the variance in velocity throughout the water column enabling more accurate estimates of sediment entrainment.

At a broader scale, the thresholds for flow competence used in this study were based on the discharge and velocity of in-channel flows. However, the capacity of a reach to transport sediment is dependent on not just stream power but on a suite of interconnected factors that include: channel roughness, slope and morphology, presence of aquatic vegetation, transmission loss, organic content, the clustering of grains, particle geometry, imbrication, armouring, compaction and packing (Reid, Lane, Berney, & Holden, 2007). These factors have not been considered in this study but need recognition as each of these factors can also be impacted by human modification to the river channel. For example, the construction of in-stream infrastructure (Thoms & Walker, 1993) or the removal of large woody debris (Davidson & Eaton, 2013) can alter channel roughness, slope, and morphology. The extent to which these factors have been modified on dryland rivers and how those modifications could influence the capacity of the river to transport sediment should be explored further.

4.6. CONCLUSION

Water resource development has substantially impacted the capacity of flows to move sediment throughout the Barwon-Darling River system. This study has shown that modifications to the flow regime have severely compromised sediment connectivity by limiting the river's capacity to entrain and transport sediment, whilst also creating conditions more conducive to sediment deposition. A reduction in overbank flooding has reduced the opportunity for the lateral exchange of sediment between the river and floodplain, which could further contribute to within-channel deposition. In addition, in-stream infrastructure has been shown to impede the longitudinal conveyance of sediment under low flow conditions. Collectively, these modifications have serious implications for the health and persistence of waterholes on the Barwon-Darling River. As the sediment supply to the river continues via upstream tributaries (DeRose et al., 2003) and the adjacent floodplain (Pearson, Reid, Ralph, & Miller, 2021) the potential to shift sediment away from these critical features has declined. The observed changes in waterhole depths on the Barwon-Darling as described in Pearson et al. (2020) can in part be attributed to the impact that water resource development has had on reducing the rivers capacity to move sediment throughout the catchment. As the opportunities for sediment connectivity have declined the retention and storage of sediment within the waterholes of the Barwon-Darling has likely increased. Further modifications to the flow regime in response to climate change and an expansion in water resource development is expected to exacerbate the threat of sedimentation on the Barwon-Darling.

By exploring the impact of a modified flow regime on sediment dynamics this study has addressed an important and understudied aspect of water resource development on dryland rivers. This study will complement the plethora of research relating to the impact of dams on water discharge, sediment flux and geomorphic adjustment (Casado et al., 2016; Richard & Julien, 2003; Ta et al., 2008; Wang et al., 2007). However, with a focus on a lowland environment this study has demonstrated the combined impact of water abstraction, the interception of floodplain flows and the storage of water within in-stream impoundments. The results from this study suggest that there is a need to consider sediment dynamics and sediment connectivity as part of the water resource planning process. The provision of targeted environmental flows specific to the management of sediment flux are useful in riverine systems, and in the dryland river context, could prove useful for the long-term maintenance of waterhole depth. The findings from this study will have relevance to large, alluvial, dryland rivers globally as they highlight the need to manage flows and therefore sediment dynamics in these important and widespread rivers. The results will, however, be equally important across all climatic settings where rivers have been subjected to a change in sediment regime and a potential shift in morphological character.

4.7 REFERENCES

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Woodyer, K. D., Taylor, G., & Crook, K. A. W. (1979). Depositional processes along a very low-gradient, suspended load stream: The Barwon River, New South Wales. *Sedimentary Geology, 22*, 97-120.

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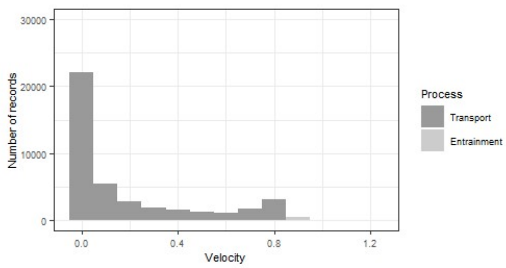
4.8 SUPPLEMENTARY MATERIAL

4.8.1 Distribution curves

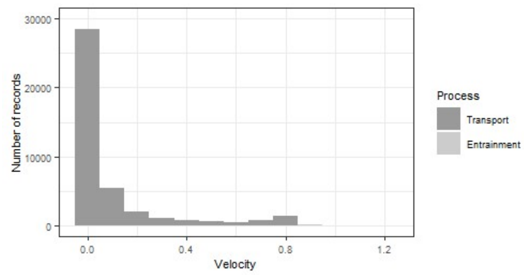
Figures 4.10 to 4.14 compare the distribution of flows for two modelled scenarios. These being the historical without development flow scenario compared to the current with development flow scenario. The figures illustrate how the capacity of a river to entrain, transport and deposit sediment has shifted between the two temporal scales. The modelled flow scenarios were supplied from the Murray Darling Basin Authority.

Collarenebri – Fine silt

a. Historical

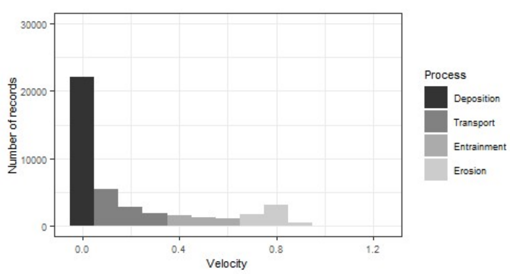


b. Current

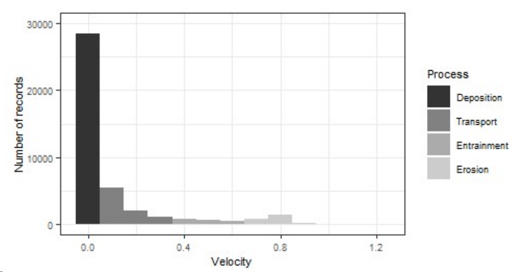


Collarenebri – coarse silt/fine sand

a. Historical

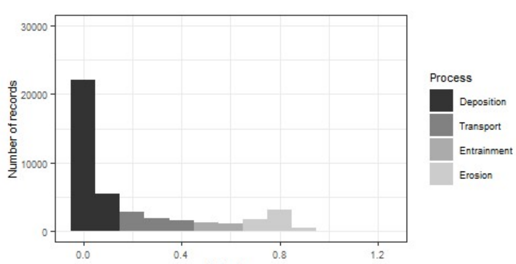


b. Current



Collarenebri – coarse sand

a. Historical



b. Current

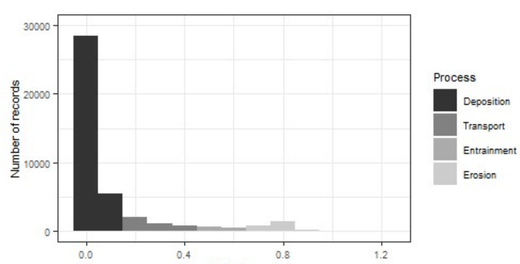
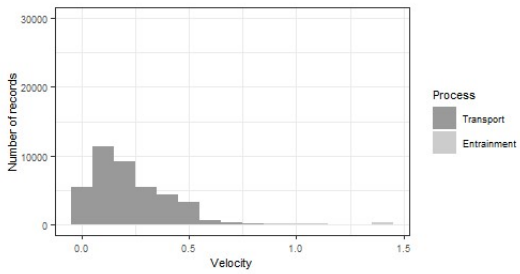


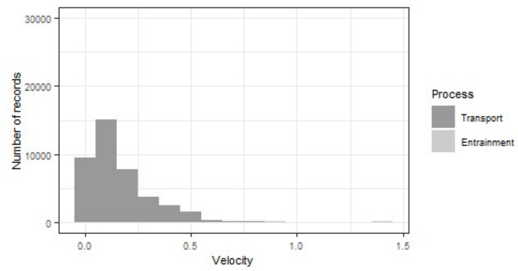
Figure 4.10 The distribution of flows for the historical and current modelled flow scenarios at Collarenebri in relation to sediment processes (erosion, entrainment, transport, and deposition).

Walgett – Fine silt

a. Historical

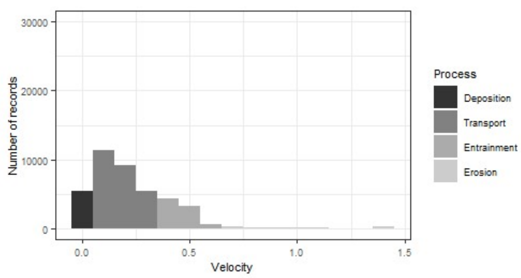


b. Current

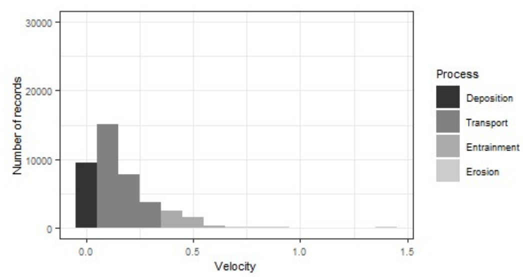


Walgett – Coarse silt/fine sand

a. Historical

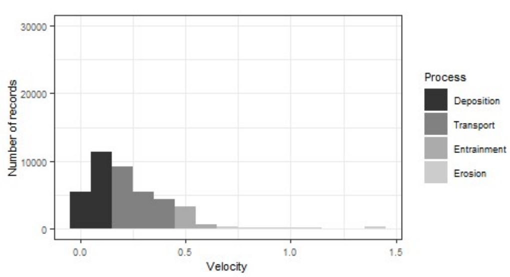


b. Current



Walgett – Coarse sand

a. Historical



b. Current

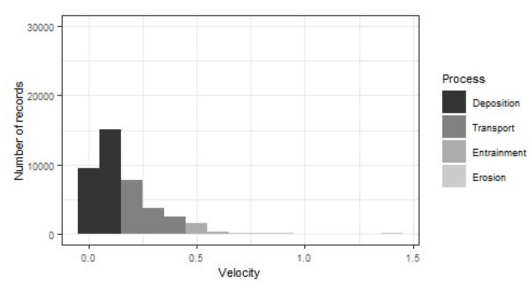
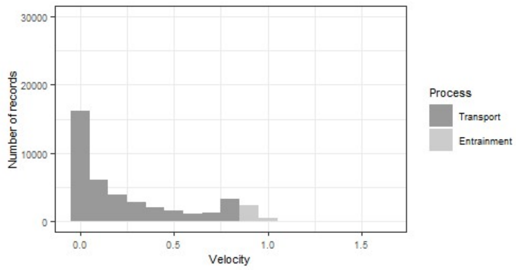
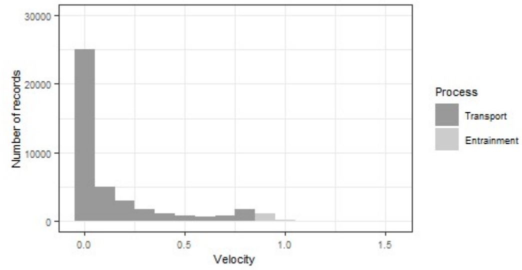


Figure 4.11 The distribution of flows for the historical and current modelled flow scenarios at Walgett in relation to sediment processes (erosion, entrainment, transport, and deposition).

Brewarrina – Fine silt

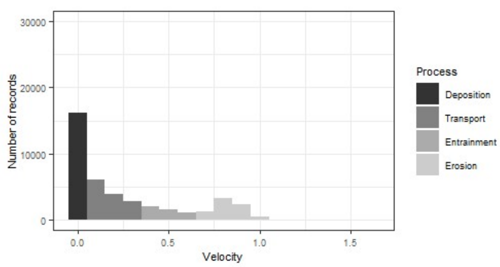
a. Historical b. Current

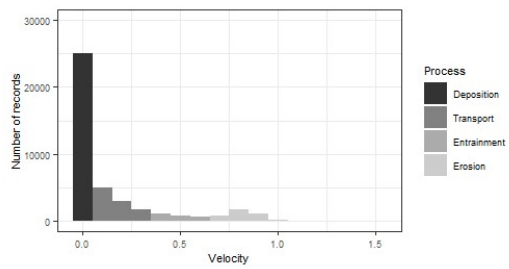




Brewarrina – Coarse silt/fine sand

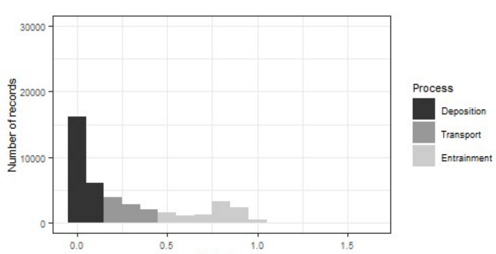
a. Historical b. Current





Brewarrina – Coarse sand

a. Historical b. Current



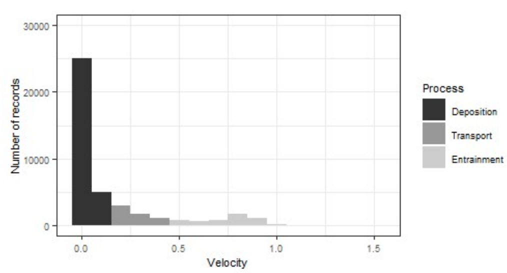
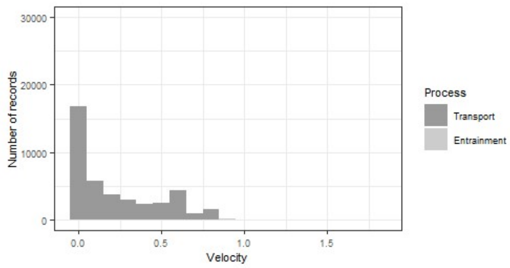


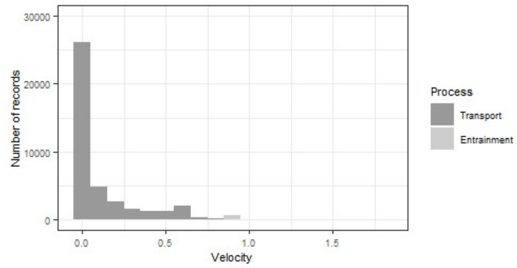
Figure 4.12 The distribution of flows for the historical and current modelled flow scenarios at Brewarrina in relation to sediment processes (erosion, entrainment, transport, and deposition).

Bourke – Fine silt

a. Historical

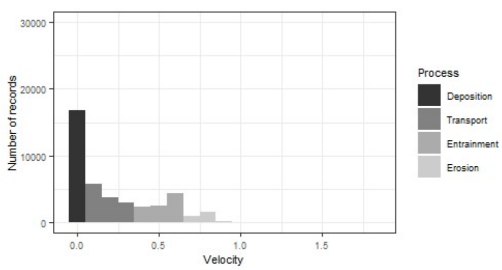


b. Current

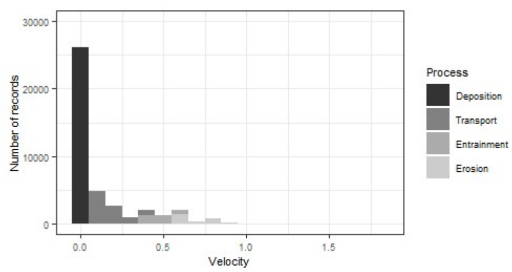


Bourke – Coarse silt/fine sand

a. Historical

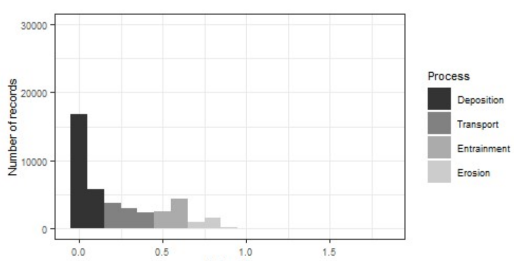


b. Current



Bourke – Coarse sand

a. Historical



b. Current

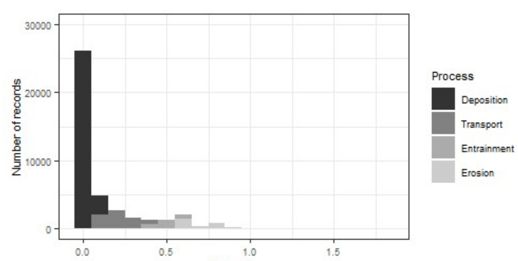
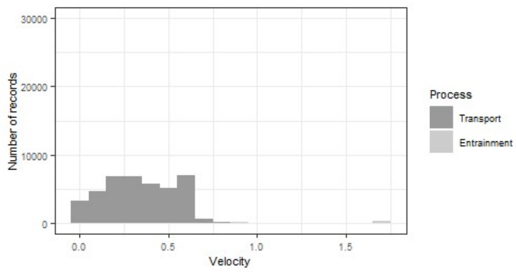
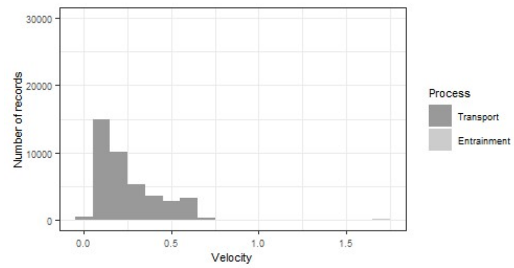


Figure 4.13 The distribution of flows for the historical and current modelled flow scenarios at Bourke in relation to sediment processes (erosion, entrainment, transport, and deposition).

Tilpa – Fine silt

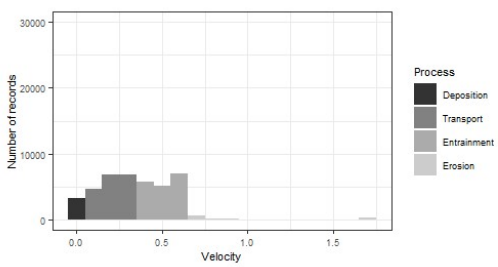
a. Historical b. Current

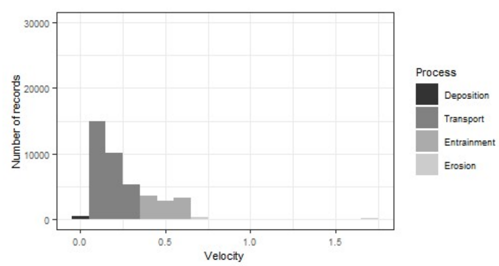




Tilpa – Coarse silt/fine sand

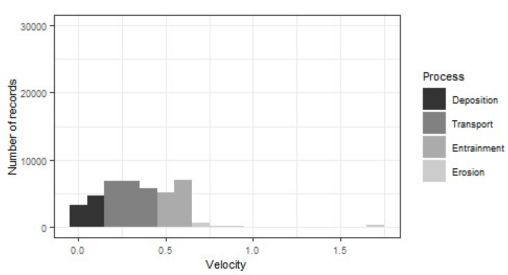
a. Historical b. Current





Tilpa – Coarse sand

a. Historical b. Current



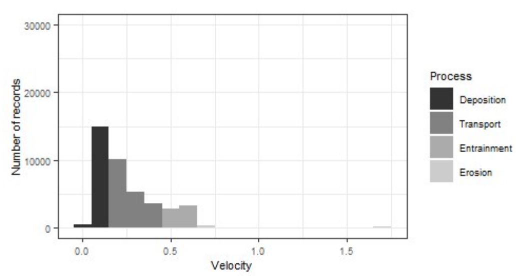
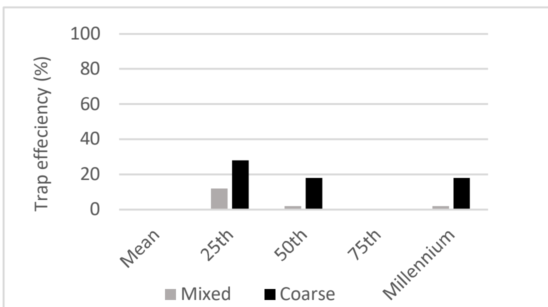


Figure 4.14 The distribution of flows for the historical and current modelled flow scenarios at Tilpa in relation to sediment processes (erosion, entrainment, transport, and deposition).

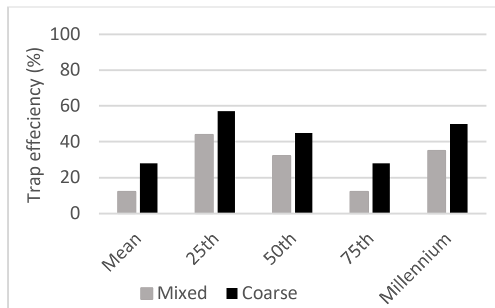
4.8.2. Trap efficiency figures Collarenebri, Walgett, and Brewarrina weirs

Figure 4.15 shows the sediment trap efficiency for the Collarenebri, Walgett, and Brewarrina weirs based on variable annual inflows i.e., the mean annual inflow, the 25th, 50th and 75th percentile annual inflow and the mean annual inflow for the Millennium Drought (2001-2008). Trap efficiencies were based on the Brune Curve (Brune, 1953) and modified to suit the different inflow scenarios.

a. Collarenebri



b. Walgett



c. Brewarrina

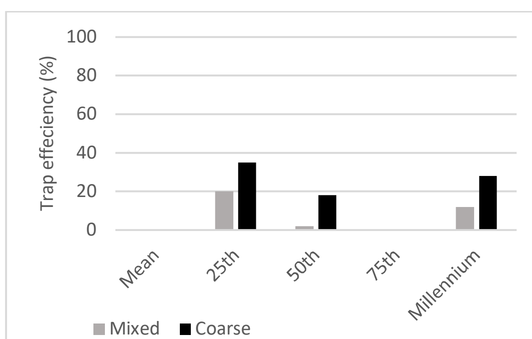


Figure 4.15. Trap efficiency values for the Collarenebri, Walgett, and Brewarrina weirs based on variable annual inflows (i.e., mean annual inflow, the 25th, 50th and 75th percentile annual inflows and the mean annual inflow for the Millennium Drought (2001-2008).

4.8.3 Reference for section 4.8.1

Brune, G. M. (1953). Trap efficiency of reservoirs. *Eos, Transactions American Geophysical Union, 34*(3), 407-418. doi:https://doi.org/10.1029/TR034i003p00407

4.8.4 ANOVA results

Table 4.7 are the results from a one-way ANOVA comparing the total number of events and the total duration of events exceeding minimum discharge thresholds for sediment entrainment combined across gauging stations for the without development and with development flow scenarios.

Table 4.8 are the results from a one-way ANOVA comparing the total number of events and the total duration of events dropping below thresholds for sediment deposition combined across gauging stations for the without development and with development flow scenarios.

Table 4.9: are the results from a one-way ANOVA comparing the total number of events and the total duration of overbank flows combined across gauging stations for the without development and with development flow scenarios.

Table 4.7: One-way ANOVA results comparing the total number of events and the total duration of events exceeding minimum discharge thresholds for sediment entrainment combined across gauging stations for the without development and with development flow scenarios (* denotes a significant result).

Sediment calibre	**Number of events**			**Total duration of events**		
	df	*t-value*	*p-value*	*df*	*t-value*	*p-value*
Coarse sand	8	4.023	0.0038*	8	2.630	0.030*
Coarse silt/fine sand	8	5.79	0.0004*	8	2.846	0.022*
Fine silt	6	0.946	0.3805	6	0.891	0.407

Table 4.8: One-way ANOVA results comparing the total number of events and the total duration of events dropping below thresholds for sediment deposition combined across gauging stations for the without development and with development flow scenarios.

Sediment calibre	**Number of events**			**Total duration of events**		
	df	*t-value*	*p-value*	*df*	*t-value*	*p-value*
Coarse sand	8	4.276	0.0027	8	3.877	0.0047

Table 4.9: One-way ANOVA results comparing the total number of events and the total duration of overbank flows combined across gauging stations for the without development and with development flow scenarios.

	df	*t-value*	*p-value*
Total number of events	8	2.046	0.0750
Total duration	8	1.407	0.1970

Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name (please print clearly)	**% of contribution**
Candidate	Marita Pearson	80
Other Authors	Dr Michael Reid	15
	Dr Darren Ryder	5

Name of Candidate: Marita Pearson

Name/title of Principal Supervisor: Dr Michael Reid

Candidate   Date: 26/11/2021

Principal Supervisor   Date: 26/11/2021

Higher Degree Research Thesis by Publication - University of New England

STATEMENT OF ORIGINALITY

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

Type of work	Page number/s
Journal article Prepared for submission to *Geomorphology*.	133-184

Name of Candidate: Marita Pearson

Name/title of Principal Supervisor: Dr Michael Reid

Candidate Date: 26/11/2021

Principal Supervisor Date: 26/11/2021

CHAPTER 5

The influence of water depth and in-stream wood on native fish assemblages in waterholes of a large, dryland river.

ABSTRACT

Waterholes (or deep pools) are an important feature of fish habitat in dryland rivers. They provide a critical refuge to fish populations as they are often the only source of permanent or semi-permanent water available to fish during extended periods of low or no flow. The depth of a waterhole is an important variable as it can not only drive the presence and persistence of a waterhole in the landscape, but it can also influence a range of abiotic and biotic process that can shape fish assemblage patterns. This study is aimed at understanding the influence of waterhole depth on fish assemblage composition, abundance, and biomass in the Darling River (Murray-Darling Basin). The focus is on determining if proximity and access to deep water habitat within the broader waterhole setting influences fish assemblage, and, if fish respond to any interaction between waterhole depth and habitat complexity. For the purposes of this study, habitat complexity was defined by the presence and complexity of in-stream wood, which is just one component of fish habitat in dryland rivers. The results indicated that maximum waterhole depth and therefore access to deep water habitat did not affect native and exotic fish assemblage patterns at the reach scale (kms). Native fish populations did, however, respond positively to the presence and complexity of in-stream wood. The interaction between water depth and in-stream wood is an important one within the riverine landscape where the inundation of wood is vital for sustaining fish populations.

5.1 INTRODUCTION

Human activities have had a profound impact on fish habitat in large dryland rivers (Bice, 2017; Mallen-Cooper, 2020; Pearson, Reid, Miller, & Ryder, 2020; Wedderburn, 2017). The features that define fish habitat, which include in-stream wood, substratum type, depth, and hydraulic diversity are increasingly being lost or modified in dryland systems (Koehn & Nicol., 2014; Mallen-Cooper, 2020; Pearson et al., 2020). These changes are due to the direct modification of the river channel (i.e., the construction of dams and weirs and the removal of natural physical structures) and the flow regime which alters hydrological and sediment connectivity, and the indirect impact of landscape change on the surrounding catchment and riparian zone (i.e., damage to overhanging vegetation by livestock, removal of riparian vegetation and sedimentation) (Koehn, 2009; Mallen-Cooper, 2020; Marshall, Lobegeiger, & Starkey, 2021). Loss of riverine fish habitat is now recognised as one of the leading factors contributing to the decline in freshwater fish populations globally (Dudgeon et al., 2006; Reid et al., 2019). In Australia's Murray-Darling Basin (MDB), for example, native fish populations are estimated to be at approximately 10 % of pre-European levels and have undergone significant reductions in their abundance and distribution across the basin (Koehn & Nicol., 2014).

The Darling River in the MDB is an example of a dryland river that has experienced substantial change in response to human disturbance (Matheson, Thoms, Southwell, & Reid, 2017a; Pearson et al., 2020; Thoms & Sheldon, 1997, 2000). One such change is associated with the depth of waterholes (or deep pools) within the river system (Pearson et al., 2020). Waterholes in much of the Darling River have experienced a decline in maximum depth in since European colonisation (Pearson et al., 2020). This has resulted in fewer naturally deep waterholes within the system, with the deepest waterholes now confined to weir pools, which constitute approximately 40 % of the river (Pearson et al., 2020). Further declines in waterhole depths are expected in the coming years as waterholes continue to be filled by an elevated supply of sediment from the adjacent floodplain (Pearson, Reid, Ralph, & Miller, 2021) and from upstream tributaries (DeRose, Prosser, Weisse, & Hughes, 2003). Additionally, a decline in the river's capacity to entrain and transport sediment, means that any new sediment supplied to these waterholes will likely be deposited and without the stream power required for entrainment that sediment could reside for longer than what would have occurred naturally (Pearson, Reid, & Ryder, 2021). As climate change reduces surface water inflows within the catchment (CSIRO, 2012; Post, Chiew, Teng, Wang, & Marvanek, 2012) shallow waterholes will dry faster and stay disconnected for longer, altering the movement of aquatic biota between the disconnected waterholes (Costelloe, Shields, Grayson, & McMahon, 2007; Hamilton, Bunn, Thoms, & Marshall, 2005). With an increased understanding regarding the extent of physical change to waterhole depth it is now timely to shift the focus to investigating the ecological consequences of these changes.

Waterhole depth is an important variable in dryland rivers as it can influence fish assemblage patterns directly or indirectly through a range of abiotic and biotic processes (Balcombe et al., 2006). The availability, diversity, and quality of fish habitat, for example, is directly associated with waterhole depth (Boys & Thoms, 2006; Magoulick & Kobza, 2003), as is the persistence of waterholes as a habitat feature in the landscape (Hamilton et al., 2005; Marshall et al., 2021; Reid, Thoms, Chilcott, & Fitzsimmons, 2016). Deeper waterholes not only incorporate both deep and shallow areas, but due to their greater volume they are more likely to contain a larger range of in-channel structures, for example, in-stream wood, in-channel benches, overhanging vegetation, and the root masses of riparian vegetation (Arthington, Balcombe, Wilson., Thoms, & Marshall, 2005; Balcombe et al., 2006; Boys & Thoms, 2006; Pusey & Arthington, 2003). Deep waterholes are also more effectively buffered against the critically high water temperatures that are often recorded in shallow waterholes and can lead to low levels of dissolved oxygen (Magoulick & Kobza, 2003; Marshall et al., 2021). Indirectly, waterhole depth can influence density-dependent biotic interactions such as predation, competition, and resource availability (Arthington et al., 2005; Balcombe et al., 2006; Basu, 1996; Harvey & Stewart, 1991; Lonzarich, 1995). Thus, waterhole depth has the potential to regulate fish assemblage patterns, food web interactions and the likely success and persistence of native and exotic species within dryland river waterholes (Arthington et al., 2005; Balcombe et al., 2006). While shallow habitat can offer fish some benefit, often supporting more food resources (Balcombe et al., 2006; Bunn, Davies, & Winning, 2003; Richardson & Cook, 2006), it is assumed that waterholes offering both shallow and deep habitat would support a more abundant and diverse fish assemblage.

This study explores the influence of waterhole depth on fish assemblage patterns in the Darling River. The focus will be on maximum waterhole depth to determine if proximity and accessibility to deep habitat within a waterhole influences fish assemblages. Waterholes on the Darling River can extend for several kilometres and offer a range of water depths, both within and between waterholes (Pearson et al., 2020). The maximum depth is important as it is this habitat and its associated complexity that remains inundated during periods of low or no flow. The question, therefore, is whether fish will favour waterholes with deep habitats over waterholes that do not have deep habitat when the river is hydrologically connected, despite both having similar shallow water habitat. We anticipate that the influence of water depth will be difficult to isolate given the interaction between waterhole depth and habitat availability. Similarly, we assume that habitat availability and complexity will be enhanced in deeper waterholes due to a greater abundance of submerged in-stream wood, which is known to have a significant positive influence on fish assemblages in lowland rivers (Crook & Robertson, 1999; Koehn & Nicol., 2014; Nicol, 2004). As such, our primary hypotheses are that fish assemblage composition, abundance and biomass will be influenced by: (1) maximum waterhole depth as an independent variable, with larger bodied species preferring waterholes that offer the protection of deeper habitat (cf.Harvey & Stewart, 1991; Power, 1984; Schlosser, 1988) and (2) the interactive effect between maximum waterhole depth and habitat complexity, where habitat complexity is defined by the presence and size of in-stream wood. Understanding the interaction between waterhole depth and in-stream wood is important given the evidence of physical change to waterhole depth in the Darling River and the likely continued decline in coming years.

5.2 STUDY AREA

The Darling River is a large, alluvial dryland river draining an area of approximately 699 500 km^2 in the north-west region of the Murray-Darling Basin, in south-east Australia (Thoms et al., 2004) (Figure 5.1). The physical character of the Darling River is defined by low bed slope (0.00005 m/m), high sinuosity (>2) and low stream power (<5 Wm^{-2}) (Thoms, Sheldon, Roberts, Harris, & Hillman, 1996). The bed substratum consists predominately of fine silts and clays interspersed with coarser sand (Boys & Thoms, 2006). In-stream wood is the one of the few solid substrates available, along with the occasional lateritic outcrop. Overhanging vegetation, undercut banks, and the root-masses of riparian vegetation provide additional in-channel habitat. In-channel benches, gullies and anabranches provide geomorphic complexity (Boys & Thoms, 2006). Channel depths can reach up to 25 m and channel capacities extend from 46 m^3/s to 925 m^3/s (Boys & Thoms, 2006).

A series of six low-level weirs has been constructed along the length of the Darling River to provide water for towns and stock and domestic use in farms (Thoms & Sheldon, 2000). Due to the gentle stream gradient of the Barwon-Darling a single weir can impound and influence the hydraulic character for many kilometres of river (ranging from 20-80 km) creating deeper, more perennial conditions immediately upstream of each structure (Chessman, Jones, Searle, Growns, & Pearson, 2010; Mallen-Cooper, 2020; Pearson et al., 2020). None of the weirs provide adequate fish passage. Water abstraction commenced in the 1960s and, in combination with the capture of floodwaters in off river reservoirs, has had a profound impact on the hydrology of the Darling River (Mallen-Cooper, 2020; Thoms & Sheldon, 2000). Low flows that are critical for connecting and replenishing waterholes have been altered substantially. Low flows are now frequently below lotic thresholds (<250 ML/day) and the magnitude of near-annual flow pulses have been reduced by over 90 % (Mallen-Cooper, 2020). The removal of in-stream wood in the mid to late 1800s to facilitate navigation has significantly impacted the characteristics and availability of in-stream habitat (Matheson, Thoms, Southwell, & Reid, 2017b). Additionally, the supply of large woody debris to the river was reduced through the removal of riparian trees to fuel the paddle steamer industry (Westbrooke, 2004). Extensive grazing pressure has caused the widespread loss of understorey vegetation in the riparian zone and prevented overstory species regenerating further reducing the supply of woody debris into the river (Westbrooke, 2004). (Pearson et al., 2020).

This paper will focus on the Darling River between the townships of Bourke and Wilcannia, spanning approximately 630 km (Figure 5.1). Waterholes in this section of river frequently contract to shallow disconnected pools with only the deepest waterholes (which are typically associated with weir pools) maintaining water throughout periods of extreme dry. As a result, this section of river offered a wide selection of waterholes across a range of water depths.

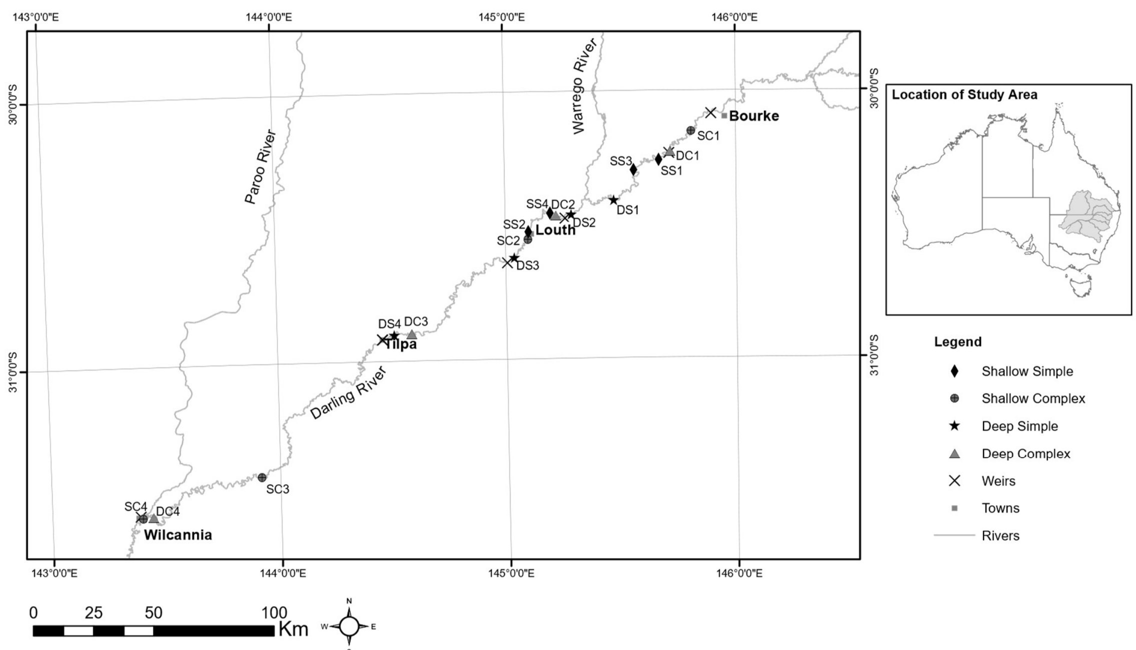


Figure 5.1: Part of the Darling Catchment showing locations of fish sampling. (Coordinate system GDA/MGA Zone 55).

5.3 METHODS

5.3.1 Study Sites

Waterholes between the townships of Bourke and Wilcannia were categorised based on waterhole depth and habitat complexity using pre-existing waterhole data (NSW Department of Primary Industries, 2015; Pearson et al., 2020). Waterholes with a maximum depth greater than 6m at cease to flow were categorised as 'deep', whilst waterholes with a maximum depth less than 4m at cease to flow were categorised as 'shallow'. The depth threshold for shallow sites reflect the accessibility of sites at the time of sampling. Sites that were shallower than 4 metres were typically disconnected under cease to flow condition limiting boat access. It is, however, important to note that the maximum waterhole depth does not reflect the depth across the entire waterhole, but it does provide an indication of whether deep habitat is available within the waterhole. Table 5.1 provides the maximum waterhole depth and the mean depth and range of depths that were sampled at each location. Waterholes were also categorised based on whether they had a 'complex' or 'simple' in-stream environment, which was defined by the total number of pieces of in-stream wood present and the complexity of individual pieces of wood. In-stream wood complexity ranged from class 1 to class 4 (Hughes et al., 2008). A class 1 piece of in-stream wood represents a single tree trunk or branch, whilst a class 4 piece of in-stream wood is either a complete tree with extensive branching or an accumulation of smaller snags in which an individual snag could not be resolved (Matheson et al., 2017a). Complex sites had a higher overall abundance of in-stream wood and a higher abundance of class 3 and class 4 pieces of in-stream wood relative to the simple sites. In stream wood was used as a measure of complexity in this study as it is the predominant source of habitat heterogeneity in the Barwon-Darling River. Additionally, the importance of in-stream wood to native fish population has been previously demonstrated on the Barwon-Darling (Boys & Thoms, 2006) and its inclusion in this study enables its interaction with water depth to be investigated. Sixteen sites were selected to represent the four possible combinations of treatment and treatment groups: deep/simple, deep/complex, shallow/simple, shallow/complex (DS, DC, SS, SC) (Table 5.1, Figure 5.1). Each site was 1 km in length.

Table 5.1: Site information for fish sampling. Maximum depth refers to the maximum depth of the waterhole at the centre point of the 1 km sampling reach. The mean depth is the average depth of water at the locations where the electrofishing operations were undertaken, whilst the range is the range of depths sampled at any one site.

Site	Max Depth (m)	Mean Depth (m)	Range of Depth (m)	Total no of pieces of in-stream wood	No. of in-stream wood (complexity 4)	No. of in-stream wood (complexity 3)	No. of benches
				DEEP COMPLEX			
DC 1	10.7	na	na	63	1	5	0
DC 2	6.5	1.3	0.8 - 2.5	54	1	4	0
DC 3	6.7	1.9	1.0 – 3.0	77	2	5	1
DC 4	7.3	1.9	0.8 – 3.0	47	2	3	2
				DEEP SIMPLE			
DS 1	7.3	1.3	0.7 – 1.5	40	0	0	0
DS 2	6.3	1.4	1.0 – 2.0	39	0	0	0
DS 3	6.8	1.4	0.3 – 4.0	36	0	0	0
DS 4	7.3	1.7	0.8 - 2.5	52	0	1	0
				SHALLOW COMPLEX			
SC 1	3.0	1.6	0.5 – 2.5	59	1	3	0
SC 2	3.2	1.9	0.5 – 3.0	61	2	3	1
SC 3	2.9	2.5	0.5 – 3.0	41	1	2	0
SC 4	2.1	1.5	1.0 – 2.0	40	1	3	0
				SHALLOW SIMPLE			
SS 1	2.1	na	na	34	0	1	0

Site	Max Depth (m)	Mean Depth (m)	Range of Depth (m)	Total no of pieces of in-stream wood	No. of in-stream wood (complexity 4)	No. of in-stream wood (complexity 3)	No. of benches
SS 2	3.8	1.3	1.0 – 2.0	30	0	0	1
SS 3	2.1	0.9	0.5 – 1.5	52	0	0	0
SS 4	2.0	1	0.5 – 2.0	39	0	1	0

5.3.2 Fish Sampling

Fish sampling was undertaken at each of the sixteen 1 km reaches over an 8-day period in November/December 2017. The point at which waterhole depth was recorded formed the centre point of each 1 km reach. Sampling was undertaken using boat mounted electrofishing during daylight hours. Fishing was undertaken using a 5 m, aluminium boat mounted with a 7.5 kw Smith-Root Model GPP H/L electrofishing unit. Two anodes were suspended from the bow of the boat with the hull acting as the cathode. Electrofishing was conducted with a single pass in a downstream direction with 12 fishing operations being performed. Each fishing operation consisted of intermittent pulsing for a period of 90 seconds per operation as the boat was moved adjacent to the selected habitat. A total of 1080 seconds of fishing was performed. Fishing was alternated from the left to right bank between operations to reduce any herding effects. Electrofishing has previously been shown to be the most effective method for sampling fish populations in the Barwon-Darling River Boys & Thoms, 2006; Faragher, 1997). All available mesohabitats within the study reach were sampled proportional to their availability within the reach. Mesohabitats included: in-stream wood, smooth bank, rocky outcrops, matted bank, point bars, and vegetated bank. Fish immobilised by the electric current were removed from the water using large dip nets, identified, measured, weighed, and inspected for abnormalities. All fish were measured to the nearest millimetre using fork lengths. Only fish greater than 100 mm in length were weighed due to expected inaccuracies in measuring smaller individuals. Fish that were observed during an operation but could not be netted were identified and included in the total catch count for statistical purposes. All native fish were returned to the waterhole following observations.

5.3.3 Water quality and Habitat Assessments

Water quality parameters were measured at the centre point of each 1 km reach where waterhole depth was at its maximum. Measurements were taken using a TPS FL90 water quality meter. Water temperature, electrical conductivity, dissolved oxygen, and pH readings were taken near the surface (i.e., at a depth of 0.25m) and just above the bed profile. A water quality sample was taken 25cm below the surface and later used to measure turbidity using a transparency tube. A habitat assessment was undertaken at the reach scale. For each 1 km reach the percentage availability of mesohabitats were estimated based on visual inspection and categorised based on percentage cover (i.e., low < 25%, low moderate 25-50%, high moderate 50-75%, abundant >75%). The longitudinal connectivity of the riparian vegetation was determined from aerial photography. The abbreviations used throughout this document for each of the water quality, habitat and hydraulic variables are outlined in Table 5.2.

Table 5.2: Abbreviations for the water quality and habitat variables used.

Abbreviation	Description
Water Quality Variables – (25cm below surface)	
S_DO	Dissolved Oxygen
S_pH	pH
S_Temp	Temperature
S_EC	Electrical conductivity
S_Turb	Turbidity
Water Quality Variables – (immediately above the riverbed)	
B_DO	Dissolved Oxygen
B_pH	pH
B_Temp	Temperature
B_EC	Electrical conductivity
Habitat Variables	
RipConn	Connectivity of riparian vegetation
Smooth	Smooth bank
Irregular	Irregular bank
Rocky	Rocky outcrop present
Matted	Matted roots present
EmergeVege	Emergent vegetation present
FloatVege	Floating vegetation present
Vegetated	Vegetated bank
Backwater	Backwater present
Point	Point bar present
Comp4	Abundance of class 4 snags
Comp3	Abundance of class 3 snags
TotalSnag	Total number of snags in 1 km reach
Bench	Within channel benches present
Hydraulic Units	
WaterPersist	Persistence of water within waterhole – derived from Landsat imagery(Fisher, Flood, & Danaher, 2016)
DepthHole	Maximum depth of waterhole
DepthAve	Average depth at electrofishing sites
WidthAve	Average width of river channel at electrofishing sites

5.3.4 Statistical analysis - Water chemistry and habitat variables

A comparison of sites based on water chemistry and habitat variables was undertaken using a factor analysis of mixed data (FAMD) in the R statistical software with the FactoMine and Factoextra packages (Kassambara & Mundt, 2020; Le, Josse, & Husson, 2008; R Core Team, 2018). This allowed similarities between sites to be identified based on both qualitative and quantitative data. FAMD plots were generated to visualise the similarities and differences between treatment groups (DS, DC, SS and SC), site complexity (complex, simple) and waterhole depth (deep, shallow).

5.3.5 Statistical analysis – Total abundance, total biomass, and species presence/absence

All statistical analysis used catch per unit effort (CPUE) as the response variable to ensure consistency in effort per unit of electrofishing time. Electrofishing at 15 of the 16 sites was based on a total of 1080 seconds. The one exception to this was the final sampling location which was only fished for 540 seconds due to dangerous weather conditions. A two-way ANOVA was used to determine the effects, including interactions, of waterhole depth and in-stream wood, on total abundance, biomass, and species presence/absence. All univariate statistics were undertaken in the R statistical software (R Core Team, 2018).

5.3.6 Statistical analysis - Fish assemblage patterns

Non-metric multidimensional scaling ordination plots (nMDS) were used to visualise the separation between sites according to treatment, complexity, and depth. The nMDS plots were generated from Bray-Curtis similarity matrices for abundance, biomass, and species presence/absence. Similarity matrices for abundance and biomass were calculated using fourth root transformed data aimed to reduce the contribution of highly abundant species, whilst ensuring the less abundant species also contributed to the similarity matrix (Anderson, Gorley, & Clarke, 2008). A two-factor PERMANOVA based on the same similarity matrices was used to test for differences in fish assemblage patterns in relation to waterhole depth and complexity, as well as interactions between these factors. The contribution of a given species to the dissimilarity between fish assemblages according to depth and complexity was determined using a SIMPER analysis. The two-factor PERMANOVA was undertaken on the full data set that included both the exotic and native species and was then repeated for a dataset that included native species only.

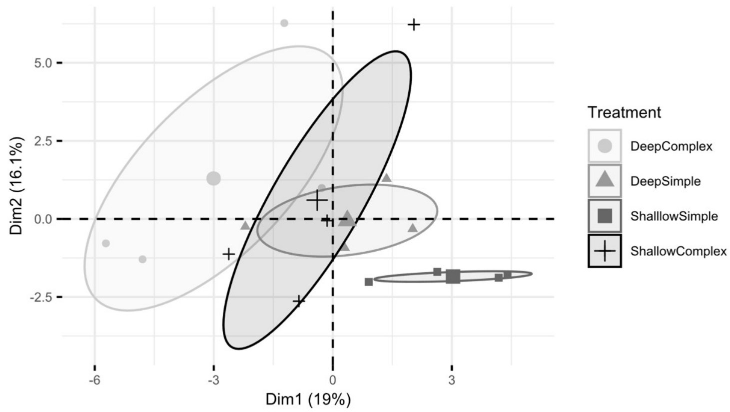
The associations between water chemistry, habitat variables and fish assemblage patterns were explored using BIO-ENV (Clarke, Gorley, Somerfield, & Warwick, 2014). BIO-ENV tests which combination of environmental variables produces a resemblance matrix (based on normalised Euclidean distance, with pairwise similarities between sites) that best matches, the resemblance matrix produced for fish assemblages (based on Bray-Curtis similarities), with comparisons made based on rank correlations. All multivariate analyses were undertaken in the PRIMER 7 software package (Clarke & Gorley, 2015). The association between individual fish species and the water chemistry and habitat variables was determined using Spearman rank correlation in the R statistical software (R Core Team, 2018). A Bonferroni correction was applied to the critical p value to account for multiple tests and thereby reduce the risk of type 1 error. Given the high number of water quality and geomorphological variables, statistical significance was accepted at $p \leq 0.002$.

5.4 RESULTS

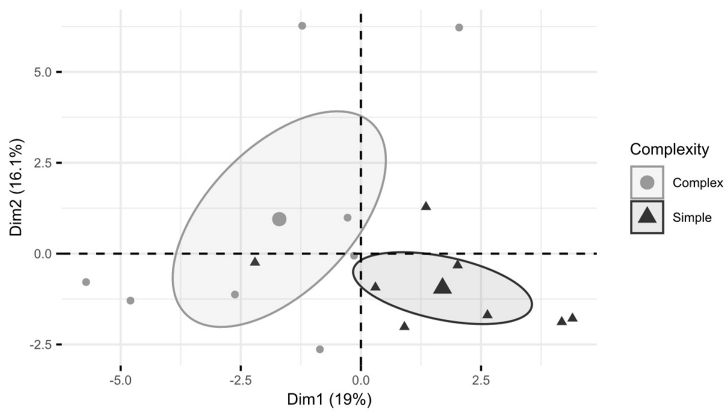
5.4.1 Water chemistry and habitat variables

The four treatment levels (DC, DS, SC, and SS) displayed some grouping in ordination space based on water quality and habitat variables (Figure 5.2). The most tightly grouped treatment level was the shallow, simple sites, which were predominately influenced by water temperature (surface and benthic)(Figure 5.3). A visible separation was apparent between the complex and simple sites, whilst the deep and shallow sites displayed considerable overlap.

(a)



(b)



(c)

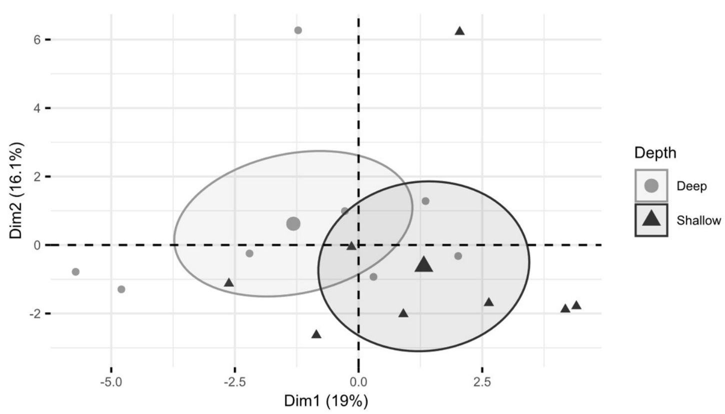


Figure 5.2: FAMD plot of monitoring sites based on (a) treatment levels, (b) habitat complexity, (c) water depth. The larger symbols depict the centre point of the ellipse in ordination space for each treatment.

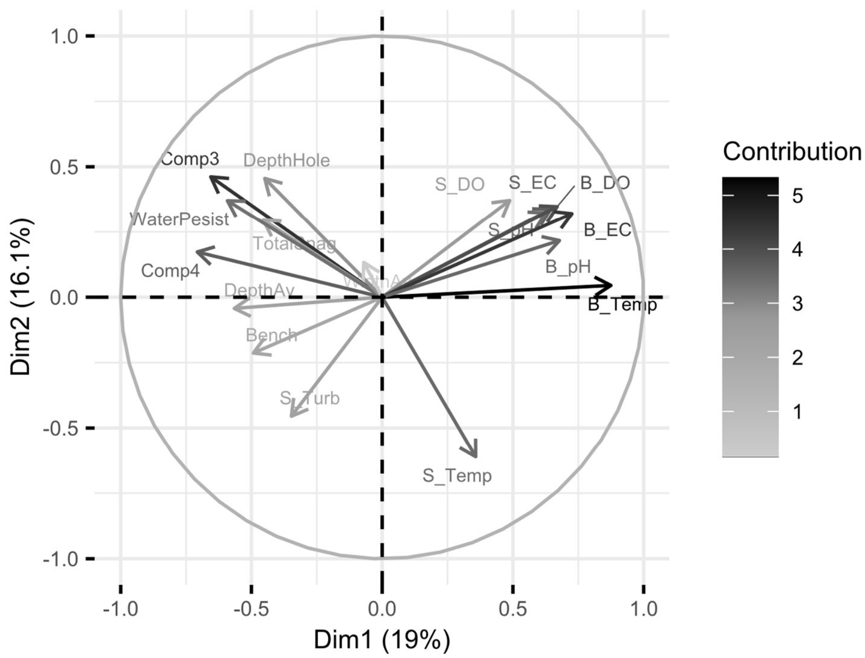


Figure 5.3: Biplot highlighting the key variables contributing the FAMD plots. The legend illustrates the contribution of each variable to the FAMD plot with the darker shades providing the greatest contribution (Table 5.2 defines the abbreviations for the water quality and habitat variables).

5.4.2 Catch Summary

A total of 1159 fishes were caught across the 16 sites, comprising five native species and two exotic species (Table 5.3). Bony bream (*Nematolosa erebi*) was the most abundant and widespread species; it accounted for 74 % of the total catch and was found at all 16 sites but made up only 20 % of the total biomass. Common carp (*Cyprinus carpio)* was the only other species found at all 16 sites and was the second most abundant species (i.e., 19 % of the total catch) and contributed to 59% of the total biomass. Golden perch (*Macquaria ambigua*) was found at 14 of the 16 sites, but was much less common, contributing to 3 % of the total catch and 7 % of the total biomass. The Murray cod (*Maccullochella peelii peelii*) was found at 6 of the sites but only made up 1 % of the total catch. Murray cod did, however, contribute to 13 % of the total biomass. The least common taxa were the spangled perch (*Leiopotherapon unicolor*) and western carp gudgeon (*Hypseleotris spp.*), which were found at only 3 sites. Notable absences from the catch included Australian smelt (*Retropinna semoni*) and the freshwater catfish (*Tandanus tandanus*), although the former is less likely to be captured using electrofishing. These are just two of the more common species that have been historically recorded on the Barwon-Darling River that were not observed in this study (refer to supplementary material - Table 5.7 for full list). More detailed species catch data can also be found in the supplementary material (Table 5.8).

Table 5.3: Fish species caught across all 16 sites.

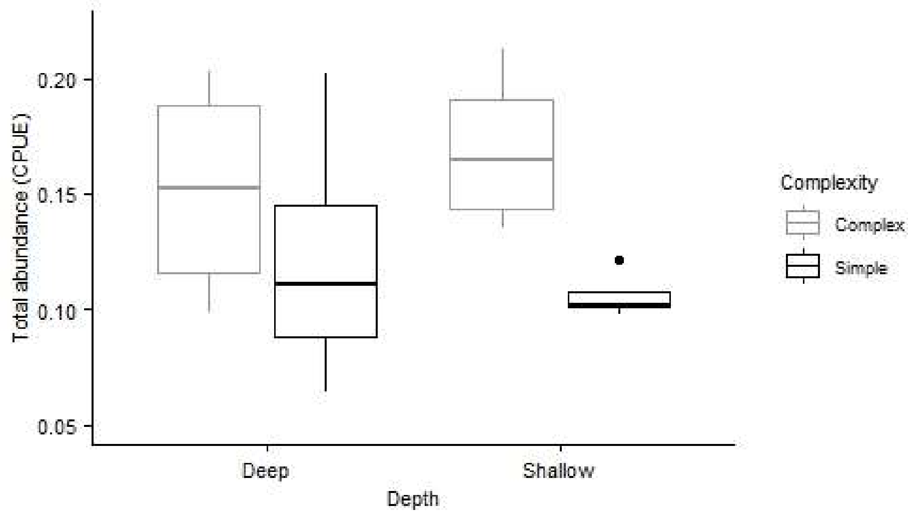
Fish species – Scientific name	Fish species – Common name
Nematolosa erebi	Bony bream
Macquaria ambigua	Golden perch
Maccullochella peelii	Murray cod
Leiopotherapon unicolor	Spangled perch
Hypseleotris spp.	Carp gudgeons
*Cyprinus carpio**	Common carp
*Carassius auratus**	Goldfish

*indicates an introduced species

5.4.3 Total abundance, biomass, and species richness

Depth was not found to have a significant effect on total abundance, biomass, or species richness. In contrast, the presence of in-stream wood did affect fish abundance ($F_{1, 12} = 4.75, p = 0.05$), with a greater abundance recorded at the more complex sites across both the shallow and the deep waterhole treatments (Figure 5.4a). In-stream wood did not significantly affect biomass or species richness. Although the median, 25th and 75th percentile for biomass were all higher at the deep, complex sites and the overall variability in biomass for individual fish was far greater than at the remaining sites. There were no interactions between the main effects.

(a)



(b)

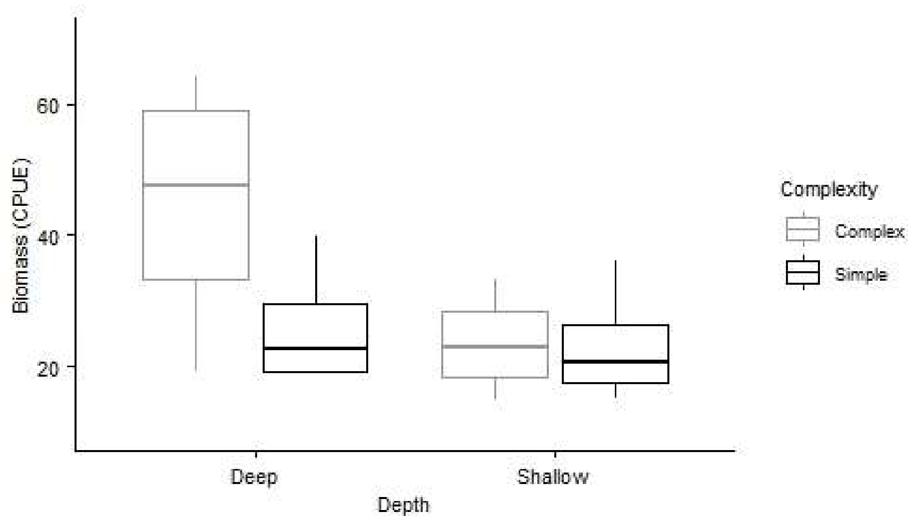


Figure 5.4: Difference in (a) total abundance and (b) total biomass (g) between treatments.

5.4.4 Fish assemblage patterns

No difference in fish assemblage patterns were observed based on biomass for depth ($p = 0.63$), complexity ($p = 0.20$) or for the interaction effect ($p = 0.86$) when considering all species (i.e., exotics and natives combined). Likewise, when considering the biomass of native species alone there was also no difference in depth ($p = 0.63$), complexity ($p = 0.22$) or for the interaction effect ($p = 0.86$). Neither depth ($p = 0.60$) nor complexity ($p = 0.1$) was found to influence fish assemblages based on abundance. However, when only native fish were included, significant differences were detected between the complex and simple sites ($p = 0.05$) due to a higher abundance of Murray cod and golden perch in the complex sites (Table 5.4). The extent of separation between the complex and simple sites for native species can be visualised in the nMDS plot (Figure 5.5a). Fish assemblage patterns based on species presence/absence showed no significant difference for depth ($p = 0.31$) and complexity ($p = 0.15$) and no interaction effect ($p = 0.82$) (Figure 5.5b). Although the separation of assemblages by depth ($p = 0.09$) and complexity ($p = 0.07$) based on presence/absence were greater when only native fishes were considered these differences were still not significant. The difference between the complex and simple sites for presence/absence was again driven by Murray Cod and golden perch (Table 5.5).

Table 5.4: Taxa contributing to the dissimilarity in CPUE between the complex and simple sites based on native fish assemblage patterns. (1) Average CPUE for each taxa, (2) The ratio of the average contribution divided by the standard deviation. The higher the value the greater consistency of the taxa contributing to the dissimilarity between sites, (3) Indicates the average contribution that each species makes to the dissimilarity between the simple and complex sites, (4) Indicates the cumulative contribution of taxa to the dissimilarity between the simple and complex sites (Clarke & Gorley, 2015).

Species	**Mean[1] Simple**	**Mean[1] Complex**	**Mean[1] Dissimilarity**	**Consistency ratio[2]**	**Contribution[3] %**	**Cumulative[4] %**
Murray cod	0.02	0.13	6.68	1.17	30.28	30.28
Golden perch	0.17	0.23	5.64	0.94	25.58	55.86
Bony bream	0.54	0.58	3.91	1.26	17.73	73.60
Spangled perch	0.05	0.02	3.00	0.67	13.61	87.21
Gudgeon	0.02	0.04	2.82	0.66	12.79	100

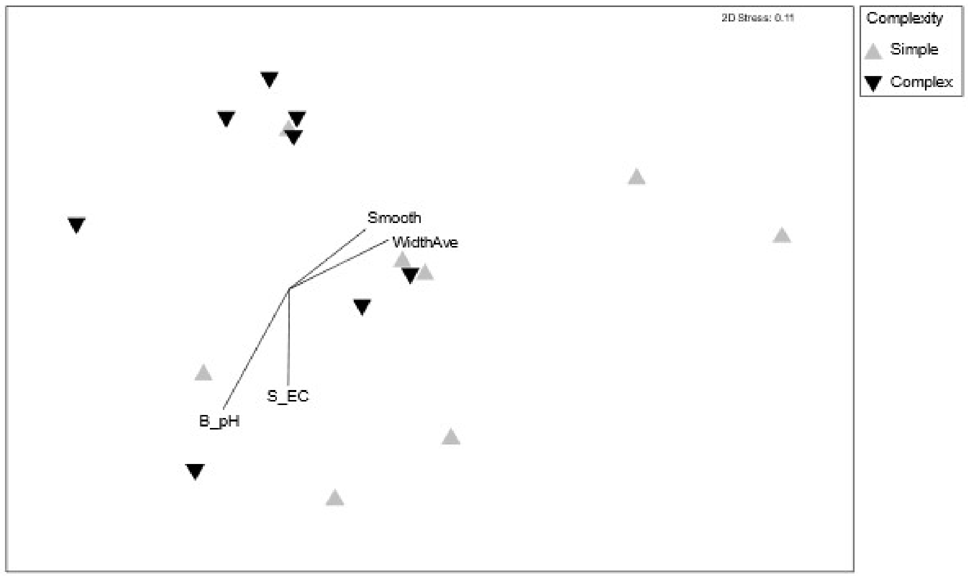
Overall mean dissimilarity = 22.06 (i.e., the average of the Bray-Curtis dissimilarities between all pairs)

Table 5.5: Taxa contributing to the dissimilarity in species presence/absence between the complex and simple sites based on native fish assemblage patterns. (1) Average for each taxa, (2) The ratio of the average contribution divided by the standard deviation of those contributions. The higher the value the greater consistency of the taxa contributing to the dissimilarity between sites, (3) Indicates the average contribution that each species makes to the dissimilarity between the simple and complex sites, (4) Indicates the cumulative contribution of taxa to the dissimilarity between the simple and complex sites (Clarke & Gorley, 2015).

Species	**Mean[1] Simple**	**Mean[1] Complex**	**Mean[1] Dissimilarity**	**Consistency ratio[2]**	**Contribution[3] %**	**Cumulative[4] %**
Murray cod	0.13	0.63	11.41	1.15	39.99	39.99
Golden perch	0.75	1.00	6.46	0.56	22.63	62.62
Spangled perch	0.25	0.13	5.37	0.66	18.82	81.44
Gudgeon	0.13	0.25	5.30	0.66	18.56	100
Bony bream	1.00	1.00	0.00	na	0.00	100

Overall mean dissimilarity = 28.54 (i.e., the average of the Bray-Curtis dissimilarities between all pairs)

(a)



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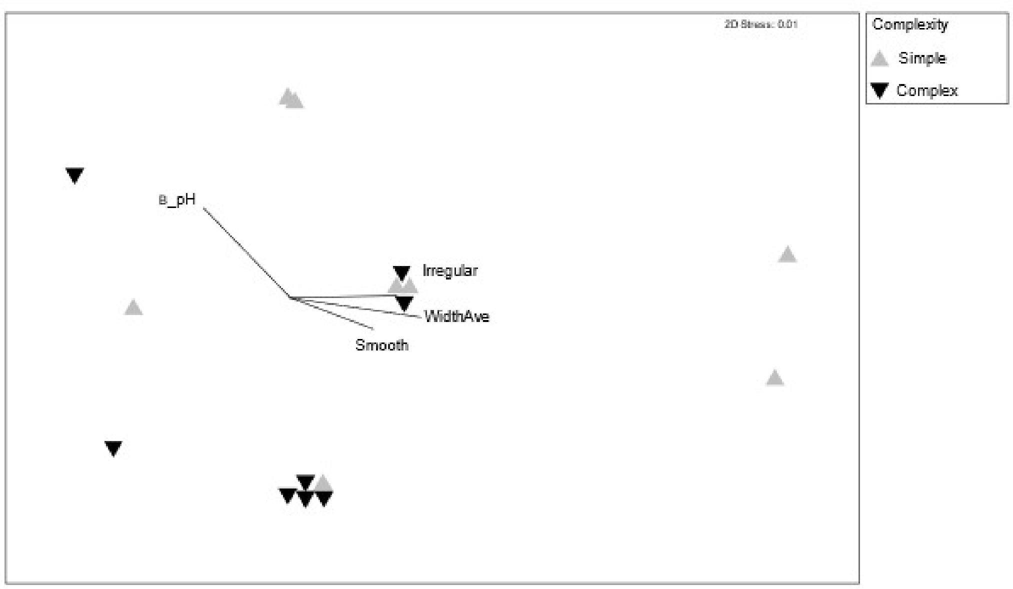

Figure 5.5(a-b): Native fish assemblage patterns based on (a) abundance (CPUE) (b) presence/absence. Resemblance matrices were based on S17 Bray-Curtis similarity on fourth root transformed data. The simple/complex labels refer to site complexity with respect to the availability and complexity of in-stream wood. The water quality and habitat features that were identified by BIOENV as contributing to abundance and presence/absence analysis are displayed on each figure.

5.4.5 Relationships between fish assemblages and environmental variables

BIO-ENV analysis indicates that there is only a weak to moderate correlation between fish assemblage patterns and the water chemistry and habitat variables. The strongest correlation and only significant result (i.e., a significance level of 3.2 %) was for species abundance with all species included and a combination of 8 water chemistry and habitat variables (Table 5.6, Figure 5.5a-5.5b). Similar variables influenced the fish assemblage patterns for the full complement of species compared to the fish assemblage patterns for the native species alone. However, turbidity was notably absent from those factors contributing to native species fish assemblage patterns. Several correlations were observed between the abundance and biomass of individual species with water chemistry and habitat variables. However, once the Bonferroni correction was applied only two significant correlations were observed. Goldfish abundance had a significant positive correlation with surface turbidity ($p = 0.002$, rHo = 0.708) whilst the biomass of bony bream had a significant positive correlation with surface pH ($p = 0.002$, rHo = 0.702).

Table 5.6: Summary of BIO-ENV results based on Spearman rank correlations (r_S) between fish assemblage structures, water chemistry and habitat variables. (Results presented for best possible solutions only).

Variable	Rho	Selections
All species		
Abundance	0.549	Smooth, Irregular, Backwater, Width, S_EC, B_EC, S_pH, S_Turb
Presence/Absence	0.419	Smooth, Irregular, Width, S_Turb, B_Temp
Biomass	0.454	Backwater, Bench, S_EC, S_pH, B_pH
Native species only		
Abundance	0.406	Smooth, Width, S_EC, B_pH
Presence/Absence	0.374	Smooth, Irregular, Width, B_pH
Biomass	0.454	Backwater, Bench, S_EC, S_pH, B_pH

5.5 DISCUSSION

This study tested whether waterhole depth and habitat complexity influence fish assemblage patterns in waterholes along a 630 km length of the Darling River. The results indicate that the presence of deep habitat within the broader waterhole setting does not influence the characteristics of fish assemblage. The composition, abundance, and biomass for both native and exotic species were similar in both the deep and shallow waterholes. Habitat complexity did, however, influence native fish species with a greater abundance of natives associated with the presence of in-stream wood.

5.5.1 The role of complexity in influencing fish assemblage structure

In this study, the total abundance of fish was significantly higher at the complex sites. This result was not unexpected given previous evidence from the Darling River (Boys & Thoms, 2006) and other inland waterways (Crook & Robertson, 1999; Lieschke, Lyon, Moloney, & Nicol, 2016; Pettit, 2012). In-stream wood, which has been used in this study as the indicator of complexity has been shown to have a positive correlation with the abundance of several key fish species caught in this study; Murray cod, golden perch, and common carp (Boys & Thoms, 2006; Crook, Robertson, King, & Humphries, 2001; Jones & Stuart, 2007; Koehn, 2009; Koehn & Nicol., 2014; Koster, Dawson, Kitchingman, & Moloney, 2020; Nicol, 2004; Raymond et al., 2019). In-stream wood is a significant feature in inland rivers providing resting, shelter and foraging habitat for fish. In-stream wood can conceal individuals from predators and conversely hide predatory fish from prey, whilst helping to delineate territories and individual spawning sites (Arthington et al., 2005; Crook & Robertson, 1999; Crook et al., 2001; Kalogianni et al., 2020; Koehn, 2009; Nagayama, Nakamura, Kawaguchi, & Nakano, 2012).

Interestingly, the response of fish assemblage structure (specifically the abundance of individual taxa) to complexity varied based on the inclusion or exclusion of exotic species. Complexity was found to have a significant effect on patterns of native fish assemblage, with both the Murray cod and golden perch exhibiting a preference for sites with complex habitats. However, when native and exotic species were aggregated fish assemblage patterns did not differ significantly between the complex and simple habitats due to the relatively even distribution of common carp among waterholes. Carp were present at all sixteen sites with a negligible difference in the average abundance between the complex and simple sites. This is a notable observation given the positive correlation that carp has previously shown towards in-stream wood (Boys & Thoms, 2006; Koehn & Nicol., 2014). However, like previous studies it also demonstrates that carp distribution is not limited by the availability or complexity of in-stream wood (Boys & Thoms, 2006; Jones & Stuart, 2007; Koehn & Nicol., 2014; Nicol, 2004). Carp will typically utilise a larger proportion of available habitats than native species as both adults and juveniles (Boys & Thoms, 2006; Crook et al., 2001; Jones & Stuart, 2007; Nicol, 2004). In a simplified river where the supply of in-stream wood has been removed, reduced, or exposed (through loss of flows) carp are therefore likely to have a competitive advantage over the native species (Koehn, Brumley, & Gehrke, 2000). The exception to this is bony bream, which is an ubiquitous native species in the Darling River. As in previous studies on the Darling River (Balcombe, Arthington, Thoms, & Wilson, 2011; Boys & Thoms, 2006; Gehrke & Harris, 2000), bony bream dominated the abundance in this study, making up 74 % of the total catch. The bony bream is a habitat generalist and is the most widespread lowland fish species in Australia (Wedderburn, 2017). Therefore, like carp, the presence and complexity of in-stream wood is not critical to their distribution, persistence, and success.

5.5.2 The role of waterhole depth in influencing fish assemblage composition and its interaction with habitat complexity

In this study, maximum waterhole depth did not influence total fish abundance, total biomass, or total species richness, and it only had minimal impact on fish assemblage composition at the waterhole scale. This finding does not, however, mean that depth is not important for sustaining fish populations, as it clearly is at larger spatial and temporal scales, as will be discussed later. The results from this study though, suggest that on the Darling River, access to deep water habitat within a waterhole is not as influential as habitat complexity in driving fish assemblage composition, abundance, and biomass. Water depth has previously been thought to drive fish assemblage patterns by influencing fish behaviour and habitat preference in response to predation risk (Power, 1984;

Schlosser, 1988). Observations on smaller streams have suggested that large-bodied species show a preference for deeper habitat where the risk of predation from wading and diving birds/animals is reduced (Power, 1984; Schlosser, 1988). The presence of large-bodied piscivorous species in deeper habitat is, in turn, a deterrent for small bodied species and the juveniles of some large bodied species, which as a result show a preference for shallower habitat (Harvey & Stewart, 1991). In this study, however, the lack of difference in fish assemblage composition between the deep and shallow sites suggests that on the Darling River the perceived risk of predation is not an influential factor for fish when choosing between deep or shallow habitat at the reach scale, or at least not for the water depths considered in this study. In large, lowland rivers like the Darling, the inherent risk of predation may be reduced by both the river's size (Harvey & Stewart, 1991) and its high turbidity levels which can reduce the visibility of prey (Kemp, Sear, Collins, Naden, & Jones, 2011; Koehn, 2009).

In this study, we hypothesised that the effect of waterhole depth on fish populations would be modified through the presence of in-stream wood. If in-stream wood was available to offer shelter and protection, then water depth alone would be less critical to fish populations. Large-bodied species, for example, would not need to select deeper water if the threat of overhead predation could be reduced by selecting a more complex environment with an abundance of in-stream wood, regardless of the depth. This hypothesis is consistent with more recent studies concerning depth-size relationships for freshwater fish. These studies have indicated that while depth alone may influence the distribution of an individual species (Lonzarich, 1995) or an individual size class (Koehn, 2009; Koehn & Nicol., 2014), the overall fish densities and species richness within a community are driven by the interaction between habitat complexity and water depth (Lonzarich, 1995). Results in this study were, however, inconsistent with these studies in that we found no interaction between waterhole depth and habitat complexity in the response of fish. It is however acknowledged that this study has asked a different question in relation to depth than these previous studies. The focus here has been on 'access to deep habitat' in a waterhole of varying depths. While this study did not show that access to deep holes at the meso-scale is an important factor influencing fish, it has shown that complexity at the same scale is important. This highlights the importance of considering habitat across a range of scales.

This study found no evidence that the fish assemblages within waterholes were influenced by maximum depth. However, the potential that differences do exist, and that sampling methodology and site selection contributed to limiting the capacity to detect those differences should be acknowledged. In relation to sampling methodology, electrofishing in this study focused on sampling across all available mesohabitats. This meant that most of the fishing was undertaken closer to the banks where the water was shallower and the bulk of the habitat (undercut banks, vegetated bank, rocky outcrops, in-stream wood) occurred. Habitat was sparse within the open channel where water is generally deeper, and it was limited to the occasional piece of in-stream wood. This approach meant that sampling depth did not always reflect the maximum depth of the waterhole. As a result, electrofishing across both treatments (deep, shallow) was ultimately undertaken across a similar range of water depths close to the bank. However, it is important to note that the scale of this study was concentrated on the use of a waterhole in its entirety and was not trying to differentiate fish assemblage based on a single mesohabitat use. This study focused on determining if fish assemblage would differ based on proximity and accessibility to a deep patch of habitat within the waterhole and all the advantages that a deep waterhole may provide. The assumption being that a deep waterhole would offer access to a greater range of protective habitat features, a more persistence and reliable source of water and better water quality conditions.

There are also potential biases associated with the use of boat-mounted electrofishing gear. Boat-mounted electrofishing is the most efficient method and the least selective for sampling across fish species and size class in the lowland rivers of the MDB (Boys & Thoms, 2006; Faragher, 1997). Nonetheless, it is acknowledged that electrofishing can be biased against small-bodied fish, which may explain the lack, or absence of some of the smaller species (i.e., carp gudgeons, Australian smelt, crimson spotted rainbow fish) (Dolan, 2003; Zalewski, 1985). Furthermore, the effectiveness of electrofishing is believed to be reduced in deeper waters (>3m), which may have resulted in an underestimation of fish at the deepest sites (Boys & Thoms, 2006). The most likely result being an underestimation of adult Murray cod and golden perch, which typically favour sites that have deeper water, with a mean depth preference of 2.8m and 2.6m respectively (Koehn & Nicol., 2014). So, although the presence/absence data for these two large bodied species may be accurately reflected in the results, the adult populations of Murray Cod and golden perch may be under-represented in the abundance and biomass figures. The use of complementary methodology (i.e., bait/light traps, fyke nets) in this study may have provided a different perspective on the influence of depth and complexity on fish assemblage. However, despite the depth limitations of electrofishing we can at a minimum compare fish assemblage within the top three metres of surface water. Therefore, the results with respect to the significance of habitat complexity remain valid with the deep and shallow simple sites differing from the deep and shallow complex sites. Similarly, based on the expected species list for the Darling River (supplementary material - Table 5.7) we cannot identify any species that would solely utilise water depths greater than 3m and therefore would not have been sampled in this study.

In relation to site selection, the selection of shallow waterholes for this study was limited by the prevailing conditions influencing river access. As a result, the difference in maximum depth between shallow and deep waterholes were relatively, though necessarily, small. Shallow waterholes were defined as waterholes less than four metres in depth at cease to flow, whilst the deep waterholes all exceeded six metres in depth. As such, the magnitude of difference in depth tested in this study may not have been enough to elicit a response in fish populations, particularly in relation to predation risk. A more pronounced gradient of waterhole depths may have produced a more noticeable difference in fish assemblages.

Finally, most of the deep treatment sites used in this study fell within the influence of a weir pool rather than being located within a naturally deep waterhole. The implications of this relate to flow hydraulics and the lack of flow variability that these weir pools experience (Mallen-Cooper, et al., 2020). The presence of weir pools on the Barwon-Daring have altered what was once a naturally free flowing lotic system into a series of fragmented, lentic weir pools with more stable and permanent water conditions (Mallen-Cooper, et al., 2020). The compensatory adjustments made biota following a shift towards more permanent levels of inundation are well document within the literature (Jones, 2007., Walker 1993, Sheldon & Walker, 1997). For example, on the Barwon-Darling River the spatial partitioning of freshwater mussel species has been observed based on flow hydraulics within the weir pools (Jones, 2007). Whist, on the Murray River, there have been a loss of freshwater species with the Murray crayfish (*Euastacus armatus*), trout cod (*Maccullochella macquariensis*), river blackfish (Gadopsis marmoratus), Macquarie perch (*Macquaria australasica*), and river snail (*Notopala sublineata)* now extinct in the lower Murray where weir pools dominate (Mallen-Cooper and Zampatti, 2018). Likewise, on the Murray River, the abundance of some native fish species including the Murray cod (Maccullochella peelii peelii) and silver perch (Bidyanus bidyanus) have declined in the weir pools with populations now more heavily concentrated in areas with free-flowing water (Mallen-Cooper and Zampatti, 2018). These examples reiterate the significance of lotic environments and demonstrate the impact that altered flow hydraulics can have on freshwater biota. So, although deep waterholes may provide access to a greater array of physical habitats, the hydraulics conditions that native fish require to cue important life stages such as migration and spawning may be lacking. The interactive effect of water depth and flow hydraulics is a significant variable that has not been considered as part of this study.

5.5.3 The importance of waterhole depth for maintaining fish habitat

Although a direct association between water depth and fish assemblage pattern at the waterhole scale has not been observed in this study, it is important to note that water depth remains a critical variable in dryland rivers such as the Darling River. Water depth has value for two distinct reasons. First, due to their greater volume, large, deep waterholes are likely to contain a greater number of structural habitat features compared with small, shallow waterholes. This would not only include in-stream wood, but also in-channel benches, overhanging vegetation, and the root masses of riparian vegetation, creating a more complex in-stream environment (Arthington et al., 2005; Bond & Lake, 2003; Boys & Thoms, 2006; Pusey & Arthington, 2003). Deep waterholes would therefore provide greater range of habitat opportunities for fish communities. At the landscape scale, a loss of deep waterholes would be significant, as it would likely signify a decline in habitat heterogeneity within the broader river system. Second, in the absence of surface flow, the presence and persistence of waterholes in the landscape is directly associated with waterhole depth (Costelloe et al., 2007; Hamilton et al., 2005). During periods of low flow or no flow deep waterholes will retain water for longer periods making them a critical refuge for fish populations (Hermoso, Ward, & Kennard, 2013; Marshall et al., 2021). These refuge waterholes not only facilitate fish survival through the physical presence of water, but they also mediate the extremes in water chemistry that can often occur in shallow waterholes (Sheldon & Fellows, 2010) and can be lethal to fish populations (i.e., high water temperatures, low dissolved oxygen) (Stocks, Ellis, van der Meulen, Doyle, & Cheshire, 2021; Vertessy et al., 2019). The presence of deep waterholes within a dryland river is critical to the long-term survival of fish populations across the hydrological extremes experienced in dryland rivers. For that reason, it is important to understand how waterhole depth has changed and if the loss of deep waterholes as observed by Pearson et al. (2020) has influenced the availability of fish habitat, particularly as the river starts to dry.

If waterholes continue to decline in depth in response to anthropogenic landscape change and loss of surface flows, their value as a refuge in an otherwise arid environment could be lost. This is particularly pertinent in relation to climate change where reduced inflows are likely to lead to waterholes drying faster and staying fragmented for longer. The worst-case scenario being that in a hotter, drier environment, waterholes could be completely lost from extensive reaches of the river. The consequences of losing one or more deep waterholes in a river (particularly those with a complex habitat) is likely to be significant in dryland rivers where waterholes provide critical refuge to the aquatic biota. The provision of environmental flows could play a significant role in not only maintaining the presence of waterholes but also in enabling the inundation of structural habitat features. In combination with habitat restoration activities, environmental flows could provide opportunities for native fish to thrive in the Darling River system. This study has reiterated the significance of in-stream wood (regardless of depth) for supporting native fish populations, particularly the less ubiquitous, iconic Murray Cod. As such its protection, maintenance and enhancement should continue to be the focus river restoration activities in dryland rivers.

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5.7 SUPPLEMENTARY MATERIAL

5.7.1 Expected fish species

Table 5.7 provides a list of species that have historically been captured in the Darling River but were not captured as part of this study.

Table 5.7 – Fish species expected to occur in the Barwon-Darling River (Balcombe, Arthington *et al.* 2011; Boys and Thoms 2006; Davies, Stewardson *et al.* 2012; Litermans 2009)

Fish species – Scientific name	Fish species – Common name	Status
Retropinna semoni	Australian Smelt	Common
Philypnodon grandiceps	Flat headed gudgeon	Common
Tandanus tandanus	Freshwater catfish	Declining
Neosilurus hyrtlii	Hyrtl's tandan	Uncommon
Melanotaenia fluviatilis	Murray-Darling rainbow fish Crimson spotted rainbow fish	Uncommon
Ambassis agassizii	Olive perchlet	Threatened
Mogurnda adspersa	Purple spotted gudgeon	Threatened
Craterocephalus stercusmuscarum fulvus	Un-speckled hardyhead Fly-speckled hardyhead	Threatened
Bidyanus bidyanus	Silver Perch	Threatened

5.7.2. References for section 5.7.1

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5.7.3 Species catch data

Table 5.8 provides species catch data for the Darling River.

Table 5.8: Species catch data - Total weight (g) and length (mm) per species, per site.

Site	Bony bream		Golden perch		Murray cod		Spangled perch		Carp gudgeons		Common carp		Goldfish	
	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)	Weight (g)	Length (mm)
DC1	5385	6417	1596	431	0	0	0	0	0	0	13836	2596	0	0
DC2	13823	18301	7166	2132	0	0	0	0	0	0	41006	11578	34	125
DC3	3225	7088	4108	924	45156	3479	0	0	0	0	16934	5041	90	1252
DC4	5145	8350	2108	765	11586	915	0	0	0	0	22046	4823	0	0
DS1	6922	7442	2040	766	2834	566	0	0	0	0	16240	4020	0	0
DS2	3480	3710	0	0	0	0	0	0	0	0	17459	3905	0	0
DS3	8512	13385	8026	2664	0	0	142	305	0	0	26476	5814	0	0
DS4	5057	7703	0	0	0	0	0	0	0	0	15222	3758	na	73
SC1	7590	16827	0	0	0	0	0	0	na	34	21186	4594	0	0
SC2	7570	11228	4032	1519	0	0	72	164	0	0	9250	4235	0	0
SC3	4719	6504	224	251	0	0	0	0	0	0	11052	3161	20	190
SC4	4024	4195	2472	1032	5270	522	0	0	0	0	6112	3768	na	612
SS1	5772	7149	988	623	0	0	0	0	0	0	12808	2720	0	0
SS2	6883	7459	2894	1120	0	0	0	0	0	0	29330	8397	0	0
SS3	8240	10371	870	973	0	0	0	0	0	0	15598	5174	0	0
SS4	1162	4060	0	0	0	0	48	135	0	0	15056	4713	36	275

na – fish <100mm where not weighed

5.7.4 Summary of species catch data

Table 5.9 provides a visual representation of the spatial distribution in species catch across sites and the percentage catch of each species at each site.

Table 5.9: Catch summary depicting species presence (shaded grey) and percentage of total catch at each site (%)

Treatment	NATIVE					EXOTIC	
	Bony Bream	Golden Perch	Murray Cod	Spangled Perch	Gudgeon	Carp	Goldfish
Deep Complex							
DC1	83	2				15	
DC2	72	4				23	1
DC3	60	2	5			17	16
DC4	80	3	1			16	
Deep Simple							
DS1	75	4	2			20	
DS2	65					35	
DS3	79	6		2		13	
DS4	82					17	2
Shallow Complex							
SC1	93				1	6	
SC2	78	4		1		16	
SC3	75	2				20	3
SC4	39	6	2			39	14s
Shallow Simple							
SS1	81	5				14	
SS2	58	5				38	
SS3	76	5				19	
SS4	66			2		27	5

Higher Degree Research Thesis by Publication

University of New England

STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

	Author's Name **(please print clearly)**	**% of contribution**
Candidate	Marita Pearson	70
Other Authors	Dr Michael Reid	20
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Higher Degree Research Thesis by Publication - University of New England

STATEMENT OF ORGINALITY

We, the Research Master/PhD candidate and the candidate's Principal Supervisor, certify that the following text, figures and diagrams are the candidate's original work.

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CHAPTER 6

Synthesis

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6.1 Introduction

The aim of this thesis was to examine how and why the physical template of the Barwon-Darling River, a dryland river in south-east Australia, has changed over the past 120 years post European colonisation. The research has found that there has been a substantial change to the physical template of the Barwon-Darling River with significant changes to waterhole depth observed (Chapter 2). The role of sediment in modifying the rivers' physical template has been investigated with a particular focus on alluvial floodplain gullies and their potential impact on waterhole depth (Chapters 3). However, this study found that despite alluvial gullies increasing structural connectivity, the large volume of sediment that has been removed from these gullies have not influenced waterhole depth (Chapter 3). Water resource development has, however, compromised the river's capacity to convey sediment longitudinally and laterally, thereby reducing functional connectivity. As a result, there has been an increase the potential for sediment to be retained within the river channel, potentially reducing waterhole depth (Chapter 4). Fish populations, which were used as a primary indicator to assess the ecological consequences of an altered physical template, did not show a direct association with waterhole depth (Chapter 5).

This synthesis will begin by providing a brief summary of the intent and research findings from each chapter (Chapters 2 to 5). This leads into a discussion regarding the significance of the research findings to the broader field of geomorphology and the management implications for dryland river waterholes. The synthesis ends with a critical appraisal of the methods used in this study and proposes several pertinent questions for future research

6.2 Modifications to the physical template of the Barwon-Darling River

Waterholes (or deep pools) are just one component that makes up the physical template of a dryland river. They were chosen as the focus of this study because they are recognised as a critical feature of dryland rivers and are one of the few features that are common across the broad spectrum of dryland rivers globally (Nanson, Tooth, & Knighton, 2002; Sheldon et al., 2010). Waterholes are important as they are often the only source of water in an otherwise arid environment, and as such they have a high ecological, social, and cultural value (Arthington, Balcombe, Wilson., Thoms, & Marshall, 2005; Jackson, Pollino, Macklean, Bark, & Moggridge, 2015). This study has shown that despite their significance in the landscape, waterholes are increasingly threatened by anthropogenic landscape change. A comparison of historical and contemporary riverbed profiles has revealed substantial and significant change to the depth of waterholes and their spatial distribution within the river channel post European colonisation (Chapter 2). The magnitude and direction of change to waterhole depth observed in this study has been closely aligned with the presence or absence of low-level weirs, of which there are many on the Barwon-Darling River. Low-level weirs by design create artificially high-water levels immediately upstream of the weir structure (Mallen-Cooper, 2021), which has led to an increase in waterhole depths in those areas. In contrast, outside of the weir pool influence, an area that constitutes around 60 % of the study area, maximum waterhole depths have declined by as much as 7.3 m, with a median decline of 1.6 m. Associated with these changes in waterhole depth has been a change in the spatial distribution of waterholes. Deep waterholes (i.e., those deeper than 4m) within the weir pools are now connected by surface water more than they would have been pre-development. The higher frequency of deep waterholes in the weir pools has meant that the distance between those deep waterholes has declined. However, the loss of deep waterholes outside of the weir pool influence has led to a substantial increase in the distance between deep waterholes and in some cases these distances have more than doubled. These changes were thought to be related to a combination of an increased supply of sediment from the adjacent floodplain and a decline in the rivers capacity to entrain and transport sediment throughout the system. These questions were investigated, and the results are detailed in chapters 3 and chapter 4 of this document.

Modifications to the physical template of the nature observed in this study are likely have a profound and long-lasting effect on dryland river waterholes. The creation of deeper, more stable lentic conditions by low-level weirs is well known within the literature with evidence of biota making compensatory adjustments to cope with the shift towards more permanent levels of inundation

(Jones, 2007; Walker & Thoms, 1993). However, in this study it is the evidence of extensive shallowing of waterholes outside of the weir pool influence that is of real concern. From a biological perspective declining waterhole depth can lead to the exposure of in-stream habitat, deteriorating water quality conditions and biotic interactions can intensifying as the area of habitat availability is reduced (Boys & Thoms, 2006; Lonzarich, 1995; Magoulick & Kobza, 2003; Sheldon & Fellows, 2010). Evaporation from shallow waterholes is typically higher, meaning that the in the absence of surface or groundwater flow the persistence of waterholes within the landscape will decline (Costelloe, Shields, Grayson, & McMahon, 2007; Hamilton, Bunn, Thoms, & Marshall, 2005). Shallow waterholes will dry faster and because they dry faster, they stay fragmented for longer resulting in a less connected river system. As waterholes dry the riverbed is exposed creating a physical barrier to longitudinal connectivity, which can compromise the spatial and temporal movement of sediment, nutrients, and organic matter throughout the system (Sheldon & Fellows, 2010). Likewise, the migratory pathways of some species may be blocked or restricted when the river dries, limiting access to food, shelter, and nursery habitat (Bunn & Arthington, 2002; Rolls, Ellison, Faggotter, & Roberts, 2013; Sheldon et al., 2010).

6.3 The influence of alluvial floodplain gully erosion on modifying the physical template of the Barwon-Darling River.

Sedimentation was identified as a potential driver of morphological change on the Barwon-Darling River (Chapter 3). The observed decline in waterhole depths detailed in Chapter 2 was suspected to be associated with an accelerated supply of sediment filling the waterholes post European colonisation. This study has investigated the potential contribution of gully erosion as one possible source of sediment to the river, and in particular, it has focused on alluvial floodplain gullying. The contribution of sediment from alluvial gullying has not previously been recognised or accounted for in the Barwon-Darling Catchment (DeRose, Prosser, Weisse, & Hughes, 2003). Digital elevation models derived from LiDAR imagery were used to identify and map alluvial gullies and to predict the volume of gully-derived sediment that has been exported to the river. Estimates of gully contribution from historical models (i.e., the SedNET model) (DeRose et al., 2003) could then be compared with the contemporary data, which was collected at a much finer spatial scale. Results from this study suggest that the volume of sediment contributed from alluvial floodplain gullies is 13 times higher than previously estimated by the SedNet model for gully erosion in the Barwon-Darling River catchment (DeRose et al., 2003). These results reflect: (1) the coarse spatial cover of available of data used in the SedNet model; and (2) the focus of the SedNet modelling on colluvial, hillslope gullies that are less connected to the river system than those that have developed on the floodplain immediately adjacent to the river. The inclusion of alluvial gullying into sediment budgets is important for predicting future sediment yields and for anticipating their potential impact on the in-channel environment.

The size of gullies on the Barwon-Darling floodplain appears to be influenced by the presence of weir pools, with the overall length, area, and volume greatest in these locations. This is likely a result of the more intense land-use on the adjacent floodplain in locations where weir pools provide a more reliable and permanent source of water to the community. Gully numbers have steadily increased over the past 50 years, however, most of the new gullies are limited to simple, linear features, whilst the larger complex gullies pre-date the 1950s. Anecdotal evidence suggests that these large gullies are continuing to expand on the floodplain, which may mean that through side wall erosion they can continue to provide larger quantities of sediment to the river than the combined volume of the newer, smaller gullies. Understanding the source of sediment contributing to our dryland rivers is an important first step in the maintenance and protection of key waterhole features. An awareness of the source and the magnitude of sediment contribution will ensure landscape management is targeted appropriately and will assist in predicting future sediment generation.

This study did not find a clear predictive relationship between the decline in waterhole depth within a reach and the total volume of gully derived sediment contributing to that reach. This could be linked to sediment mobility, with the fine sediment fraction being easily mobilised and subsequently stored some distance from the original source (Woodyer, Taylor, & Crook, 1979). Conversely, the coarse sediment fraction may be limited in movement and may therefore remain either on the gully floor or it may contribute to the lateral accretion of sediment within the channel. This is particularly evident at the point of entry to the trunk stream where sediment fans are often observed. Alternatively, a relationship between gully volume and the magnitude of decline in waterhole depth may have been difficult to detect as the gully derived sediment could not be isolated from alternative sources of sediment. Finally, the results may simply be a reflection of the methods used and with a more targeted, field based approach, a different result may be obtained.

6.4 The role water resource development in modifying the physical template of the Barwon-Darling River.

Water resource development has had a significant impact on dryland rivers globally (Graf, 2005; Kondolf & Batalla, 2005; Poff et al., 1997). Yet, the impact of water resource development on the sediment regime has remained a largely understudied area of research in dryland rivers. Water resource development has modified the flow regime of dryland rivers through the abstraction of water for irrigation, the interception of floodplain flows and the impoundment of flows by dams and weirs (Poff et al., 1997; Wohl et al., 2015). Consequently, the magnitude, frequency and duration of flows have been compromised, which has serious implications for dryland river waterholes. Waterholes are characterised as self-maintaining scour features that are governed by the flow regime (Nanson et al., 2002). Under low to moderate flow conditions waterholes become a natural deposition zone in which sediment accumulates. Yet, under periods of high flow, the stream power generated can exert enough stress on the riverbed to initiate scouring enabling the removal of sediment from the waterholes (Nanson et al., 2002; Reid, Thoms, Chilcott, & Fitzsimmons, 2016). This is a critical process for maintaining deep waterholes within the system. Anthropogenic modifications to the flow regime can, however, disrupt this natural pattern of erosion and deposition, which can lead to a change in the waterhole morphology (Wohl et al., 2015).

This study has investigated how alterations to the flow regime have impacted the Barwon-Darling River's capacity to entrain and transport sediment both longitudinally and laterally (Chapter 4). The results have indicated that modifications to the flow regime have resulted in a decline in the frequency and duration of flow events capable of entraining sediment across a range of sediment calibres (i.e., clay – silt – sand). In parallel, the number of low flow, low velocity events that enable the deposition of sediment have increased substantially. In addition, overbank flooding has halved, limiting the potential opportunities for the lateral exchange of sediment with the floodplain. These modifications increase the likelihood of sediment being retained within the river channel and, as such, increase the potential for sedimentation and the in-filling of waterholes. This process is further exacerbated by the presence of low levels weirs, which, under low flow conditions, have the potential to trap large volumes of sediment within the weir pools. In the longer term the accumulation of sediment directly upstream of the weir structures could reduce the overall capacity of the weir pool. Low-level weirs can also modify hydraulic conditions immediately upstream by reducing flow velocities (Bice, 2017; Mallen-Cooper, 2020) and thereby further limiting sediment conveyance (Ta, Xiao, & Dong, 2008).

Previous research investigating the impact of water resource development has largely focused on the hydrological and ecological implications of an altered flow regime. Although there is a plethora of research on the implications of infrastructure (dams and weirs) on the sediment regime (Baade, Franz, & Reichel, 2012; Ta et al., 2008; Tamene, Park, & Vlek, 2006; Thoms & Walker, 1993), few studies have looked at the overall impact of a modified flow regime. This study is significant in that it goes some way in providing a link between how the sediment dynamics of a dryland river responds to a modified flow regime, regardless of the cause (i.e., water resource development, land use change and climate change). The results from this study provide justification for the consideration of sediment dynamics in future water resource planning. The provision of environment flows specific to the management of sediment have not previously been incorporated into water resource plans for the Barwon-Darling River. Targeted environmental flows, which on the Barwon-Darling are primarily delivered by placing limitations on the extraction of natural flows, could prove useful for the long-term management of sediment and maintenance of waterhole depth. This is particularly pertinent given the current climate change projections, which suggest inflows into the Barwon-Darling could be reduced as a result of declining precipitation, higher evaporation rates, and reduced surface runoff (Cai & Cowan, 2008; Chiew, Young, & Cai, 2011). Likewise, an increase in on-farm storages and a growth in groundwater extraction on the tributaries to meet water demand are also expected to reduce inflows into the catchment (Chiew et al., 2011). These scenarios are expected to further reduce the capacity of the river to remove sediment from key waterhole features, which could lead to further shallowing of these critical habitat features.

6.5. The ecological consequences of a modified physical template

This study was aimed at understanding the ecological consequences of modifying waterhole depth (Chapter 5). Waterhole depth is ecologically important in dryland river systems as it can influence habitat availability, water quality, density-dependent biotic interactions, and waterhole persistence (Balcombe et al., 2006; Boys & Thoms, 2006; Magoulick & Kobza, 2003). As such waterhole depth was expected to influence fish assemblage patterns in the Barwon-Darling River. The focus for this study was on maximum waterhole depth to determine if fish assemblages would differ based on accessibility to deep habitat within the waterhole, and all the advantages that deep water may provide (i.e., a greater range of protective habitat, a more persistent and reliable water source and better water quality conditions). However, this study found that maximum waterhole depth did not influence fish assemblage patterns, nor did it have an interaction effect with habitat complexity. Habitat complexity in this study referred specifically to the presence and size of in-stream wood. In-stream wood has a well-established relationship with fish assemblage patterns as it can provide important habitat for several fish species (Koehn & Nicol., 2014; Nicol, 2004). In this study, a significant relationship with habitat complexity was observed, but only when native fish assemblage patterns were considered in isolation. The inclusion of exotic species in the data set had a homogenising influence due to the more even distribution of common carp across sites of varying complexity. Carp are an ubiquitous exotic species across the Murray-Darling Basin, which can typically utilise a larger selection of habitat than the native species (Nicol, 2004). This gives them a competitive advantage over most native species in river systems where in-stream wood has been removed, reduced, or exposed. The exception to this being the native bony bream, which are also prevalent across a range of habitat features. This study highlights the need for the continued protection, restoration, and inundation of in-stream woody habitat in our dryland rivers.

Although accessibility to deep water did not appear to influence fish assemblage patterns directly the importance of deep waterholes in a dryland river should not be underestimated. Waterhole depth remains a critical variable in dryland rivers in terms of ensuring the presence and persistence of aquatic habitat during periods of low flow or no flow in the river (Costelloe et al., 2007; Hamilton et al., 2005). Waterhole depth should also be recognised as a significant factor in increasing habitat availability for fish populations, with deeper waterholes providing a greater array of habitat features (Boys & Thoms, 2006). Specifically, deeper water is more likely to contain a higher abundance of in-stream wood creating a more favourable environment for native fish species.

6.6. Significance of research

This study is significant in that it demonstrates the trajectory and magnitude of morphological change that is possible on an alluvial dryland river system in response to human activity. This understanding is important as the threat to dryland river waterholes globally is ongoing, and as such, further changes to the physical template of dryland rivers is expected. This study has provided a process by which morphological change can be assessed. The impact of human activity on the physical template is often difficult to identify and isolate without access to long-term data sets against which ongoing temporal change can be assessed. Yet these long-term datasets are often lacking in the remote and arid locations in which dryland rivers are found (Kingsford & Thompson, 2006). This study has demonstrated that in the absence of a long-term data set an isolated historical record such as a longitudinal bed profile can be of value in extending our temporal perspective of dryland rivers. This, however, is not without risk as historical datasets often have inherent flaws such as limited resolution, are of unknown accuracy and frequently lack the background context required to interpret the data (Grabowski, Surian, & Gurnell, 2014; Gurnell, Peiry, & Petts, 2016). However, this study has shown that these issues are not insurmountable and has demonstrated a process by which these issues can be identified, acknowledged, and overcome, enabling statistically valid conclusions to be drawn. The key message from this study is that when using historical data, acknowledge the limitations of the data early in the research process. Based on these limitations it is then important to ensure that data analysis is limited to parameters that can then distinguish genuine landscape change without being compromised by the flaws or uncertainties in the data.

In the context of the broader field of geomorphology, this study has demonstrated the need for a multidisciplinary approach for understanding and demonstrating sediment connectivity or dis(connectivity) within the landscape. In this study, mapping the prevalence of alluvial gullies has revealed the significance of gullies in expanding structural connectivity between the floodplain and the river channel. The implications of which were large volumes of sediment being supplied to the river channel. However, the role of flow and the interaction it may have with gully derived sediment is equally important for understanding the potential consequences to a river system, in this case to dryland river waterholes. Modifying the flow regime through the abstraction of water or through the capture of floodplain flows has been shown to reduce the rivers capacity to covey sediment, thereby reducing functional connectivity. In dryland rivers, the focus is increasingly shifting to, how can we maintain these critical waterhole features as both a refuge to aquatic biota and as a water supply for rural and indigenous communities. This study is significant in that it reiterates the need for a targeted, multidisciplinary approach to both research and to management to ensure we can maximise the environmental benefits to dryland rivers. However, this message does not just apply to dryland rivers, but it is equally relevant to rivers in other climatic settings.

6.7 Management options for the protection and maintenance of dryland river waterholes

This study has shown that the threat to the long-term maintenance and protection of waterholes on the Barwon-Darling is not the result of any one issue but is instead the result of a broad range of disturbances within the catchment (i.e., land use on the adjacent floodplain, modifications to the flow regime, in-stream infrastructure and climate change). Collectively, these disturbances have altered the supply and distribution of sediment throughout the catchment, which has had significant implications on channel morphology. The focus in this study has been on the decline in waterhole depth, which has the potential to seriously compromise the ongoing presence and persistence of waterhole within the landscape, reducing their value as a refuge for aquatic biota. Given the spatial and temporal scale of human disturbance within the catchment it has been is difficult in this study to isolate the consequences of individual activities. As such, it will be imperative to take an integrated approach to managing sediment within the Barwon-Darling Catchment.

Based on the findings from this study management options for the Barwon-Darling can be divided into two categories. The first deals with managing the increasing supply of sediment to the river by minimising gully erosion on the adjacent floodplain. Maintaining groundcover and minimising soil disturbance is a key component in reducing gully erosion and the mobilisation of sediment within the catchment (Carey, Stone, Norman, & Shilton, 2015a; Gell et al., 2009; McKeon et al., 2004). To do this, grazing pressure should be reduced on the floodplain and in the riparian zone by utilising stock rotation, riparian fencing, and the provision of off-stream watering points. In cropping systems, conservation farming practices such as stubble retention, reduced tillage, direct drilling, and controlled traffic will help to maintain groundcover and minimise soil disturbance (Carey et al., 2015a; Carey, Stone, Norman, & Shilton, 2015b). The volume and speed of overland flows should also be managed to minimise its erosivity. This is particularly critical where gullies already exist within the floodplain. This can be done through a combination of earth works (i.e., diversion banks and/or champagne banks) and/or the use of soft filters (i.e., logs/branches/rocks) to slow or redirect flows into a more stable waterway or natural depression from which it can then flow into the main channel without causing sedimentation (Carey et al., 2015a, 2015b).

The second management option deals with managing flows and infrastructure in the river to enable the transport of sediment and to ensure the natural process of scouring can occur. The removal of weirs that no longer serve a purpose should be considered to enable hydrological connectivity within the system, allowing for the longitudinal movement of sediment. The provision of environment flows specific to the management of sediment has not previously been incorporated into water resource plans for the Barwon-Darling River (Department of Planning, 2020). However, targeted environment flows could prove useful in managing the distribution of sediment throughout the system. This study has identified the discharge thresholds that would enable the entrainment and transport of sediment across a range of sediment calibre as well as the discharge requirements for overland flow. Through a combination of water delivery from upstream tributaries and through placing limitations on the extraction of natural flows within the Barwon-Darling, these discharge thresholds could be obtained more frequently and for longer durations. Aside, from the benefits to sediment management, environmental flows will also contribute to inundation of critical fish habitat such as in-stream wood, undercut or vegetated banks and the root mass of riparian vegetation (NSW Department of Primary Industries, 2015).

6.8 Limitations of research

This study has utilised a combination of data sources (i.e., historical surveys, modelled data, remote sensing) to quantify morphological change on the Barwon-Darling River, and, to investigate the factors that have contributed to this change. Although each of these data sets are valuable, each one comes with their own limitations and challenges for use. This section will provide further insight into the issues that emerged throughout this study and the implications for data analysis. This section will inform similar studies in the field of geomorphology and riverscape ecology.

6.8.1. Use of historical data

The use of historical data was fundamental throughout this project for exploring changes to the physical template of the Barwon-Darling River. Of particular interest in this study was the use of historical longitudinal profiles, which have been used globally for decades to investigate and visualise changes to riverbed profile in response to anthropogenic disturbance (Peiry, 1987; Rinaldi, 2003; Rinaldi & Simon, 1998; Sear, Darby, Thorne, & Brookes, 1994). However, whilst geomorphologists have recognised the potential value of these data sets, they have also identified their inherent flaws. The challenges associated with the use of longitudinal profiles centre around sampling bias, data accuracy and precision, uncertainty in relation to the purpose and methods of data collection, assumptions in interpretation of data and the side effects of data treatment (Gurnell, Peiry, & Petts, 2016; Hooke & Kain, 1982), all of which have been encountered in this study (Figure 2.3).

The original purpose for which an historical record was compiled exerts a profound influence on what was recorded and the nature of recording (Hooke & Kain, 1982). In chapter one for example, the historical profile that was used, was created as part of a program of works to find suitable locations for the construction of weirs and locks to facilitate navigation on the river. The method behind the collection of data and the positioning of data collection points were unknown. However, it was clear from the profile that data collection was not equally spaced along the length of the river profile. Historical documents did, however, suggest that the nineteenth century surveyors may have targeted natural rocky outcrops for lock development (New South Wales. Parliament. Legislative Assembly, 1891; Poole, 1897). This was a critical piece of information that provided some context around data collection and flagged the potential for sampling bias towards the natural deep pools that formed immediately upstream of these hard, rocky surfaces. This information influenced the approach to data analysis used in this study and ensured that if there had been a systematic over estimation of water depths then this could be accounted for in the comparison with the contemporary river profiles.

Differences in channel length is another common challenge when comparing historical long profiles to contemporary data river profiles (Gurnell et al., 2016; Simon & Rinaldi, 2016). This is often a result of a shift in planimetric position due to changes in river sinuosity over time (Gurnell et al., 2016; Simon & Rinaldi, 2016) or can simply be an error in data collection or instrumental accuracy (Hooke & Kain, 1982). In this study, the historical profile for Bourke to Wilcannia was 28 kilometres shorter than what contemporary mapping would tell us. As a result, imposing historical waterhole locations over a modern-day GIS layer created some challenges. Previous mapping by Woodyer, Taylor & Crook (1979) indicates that the Barwon-Darling River has not shifted significantly in plan since 1848 suggesting an alternative cause for discrepancies in river distance. To overcome this issue, the historical layer in this study was stretched so that identifiable points along the river (i.e., the townships of Bourke and Wilcannia, the Warrego confluence and well-known homesteads) fell in the correct locations. This process provided greater confidence that the historical waterholes were mapped close to their correct location in the GIS platform.

Variance in sampling intensity between the historical and contemporary data sets was unavoidable in this study given the markedly different technologies used for data collection. The continuous nature of measurement by the side-scanning sonar meant that the contemporary profile represented the complete population of waterholes present at the time of sampling, whilst the historical data only captured a sample of the waterholes present in the late 1800s. This made it difficult to align individual waterholes on both data sets with any degree of confidence. For this reason, the decision was made to aggregate waterholes based on a series of 5km intervals before any statistical comparison of change to waterhole depth was undertaken. This coarser spatial scale removed the need to know the precise location of individual waterholes whilst still enabling some conclusions to be made regarding the trajectory of change to waterhole depth.

When using historical data temporal comparisons are often limited to just two observations in time as was the case in this study (i.e., 1898 and 2015). The use of only two points means that estimating the direction and the extent of change can only assume a linear transition in the intervening period (Gurnell & Downward, 1994; Hooke & Kain, 1982). However, it is feasible that geomorphic adjustments may have fluctuated, with the trajectory of change reversing several times throughout the period in question (Gurnell & Downward, 1994; Hooke & Kain, 1982). Furthermore, the rate of change is unlikely to have been consistent throughout time and instead would have fluctuated with periods of intense geomorphic change followed by relative quiescence (Gurnell & Downward, 1994; Hooke & Kain, 1982). An incomplete picture of the rivers evolution is therefore obtained which could result in a misinterpretation of the events or factors that are driving morphological change.

The treatment and storage of historical data has implications for data accuracy (Grabowski, Surian, & Gurnell, 2014; Hooke & Kain, 1982). This can be a problem for topographic data where the original material can experience shrinkage or stretching of paper affecting planimetric accuracy (Hooke & Kain, 1982). However, in this study the issue was more around the distortion of the profile due to modern day photocopying. It was evident that the profile created for the river between Walgett and Bourke had at some point been enlarged. As a result, the quality and resolution of the profile was poorer, and the scale needed to be re-worked to ensure the measurements for longitudinal distance and water depth were accurate.

Chapter two highlighted many challenges of working with historical topographic data and flagged the importance of acknowledging the limitations early so that methods can be devised, and results interpreted with the limitations in mind. Despite the challenges historical data remains invaluable in providing temporal information on our river systems (ref). Historical data not only provide a reference against which the magnitude and trajectory of change can be measure but it can also shed light on contemporary geomorphic processes which may not be well understood without an appreciation of the past (Trimble & Cooke, 1991).

6.8.2. Remote sensing (LiDAR), automated modelling and the need for ground truthing

The use of LiDAR has increased in recent decades due to the growing availability of high-resolution imagery (Yousefi, Ralph, Farebrother, Chang, & Hesse, 2018), and the fact that it can provide data at unprecedented scales (hundreds of kilometres) (Bartley et al., 2016) compared to traditional methods (i.e., field-based mapping or aerial photography). In this study, LiDAR in combination with GIS modelling has enabled the mapping of alluvial floodplain gullies and the associated DEMs have allowed estimates to be made with respect to gully volumes. This approached provided an overview of the prevalence of alluvial gullies and the magnitude of the sediment that has been delivered to the Barwon-Darling River. However, as discussed in Chapter 3, a significant limitation of this study has been the lack of validation of the data used. The LiDAR used in this study had a vertical accuracy of +/- 0.3m which may mean that the gully volume estimates could be either an under or over-estimate. Sensitivity analysis associated with the minimum and maximum volumes that could be measured for individual gullies is needed to provide greater confidence in the reliability of data.

The large geographical extent of the study area (i.e., 1400 km of river channel) combined with a limited budget and timeframe meant that this study was limited to the desktop analysis of LiDAR data. Ground truthing to validate this analysis is a critical component that is missing from this study. A more targeted, field-based approach would enable the dimensions of individual gullies to be verified which would then enable the efficacy of the automated GIS model to be tested for predicting gully extent and gully volume. A field-based approach would also enable data collection regarding sediment particle size and gully stability, as well as information on waterhole dimensions and depth of sedimentation, all of which were critical knowledge gaps identified in chapter 3.

6.8.3. Use of modelled data for hydrological analysis

Modelled outputs are only as reliable as the model from which they originate. The modelled data used in this study underpins water resource planning across the Murray-Darling Basin, and as such, it has been the subject of rigorous calibration, testing, and refinement over several decades (Murray-

Darling Basin Authority, 2016). However, this study was limited by the temporal scope of the data. At the time of writing modelled flow data was unavailable beyond 2009 and therefore more recent flow scenarios could not be explored in relation to the river's capacity to transport sediment. Likewise, the hydrological model used in this study is known to have issues with providing an accurate representation of low flows (Murray-Darling Basin Authority, 2018). This created limitations when undertaking the low flow analyis with respect to the likehood of sediment depostion. Future studies should consider, where available, the use of 'actual' flow data obtained from local gauging stations to complement and reinforce the findings from data modelling.

6.9 Directions for further research

This research has explored the impact of anthropogenic landscape change on the physical template of a dryland river and the subsequent ecological consequences. In doing so, it has contributed to our understanding of dryland rivers, particularly in relation to how sediment dynamics respond to landscape change and to a modified flow regime. However, throughout the course of this research several pertinent research questions have been identified that if answered could refine our understanding of dryland rivers even further.

This study has demonstrated the extent of alluvial gullying and its likely impact on the Barwon-Darling River (Chapter 3), but it has not addressed in any detail the factors that are driving gully initiation and subsequent gully expansion. However, a framework for such work does exist in the literature, with extensive research having been undertaken in the northern-Australian tropics with respect to alluvial gullies (Brooks, Shellberg, Knight, & Spencer, 2009; Shellberg, 2011). The applicability and transferability of the knowledge gained in the tropics to arid and semi-arid regions warrants further investigation. This would involve looking at the impact of catchment controls (e.g., regional hydrology and connection with groundwater aquifers and catchment morphology including valley bottom width), local controls (e.g., vegetation, topography, channel geometry and discharge, backwatering, depth of alluvium, the proximity to neighbouring gullies and/or natural paleochannels, and the presence of dispersive soils) and climatic conditions (i.e., overbank flooding, local rainfall, and drought) on the initiation and growth of gullies. Factors associated with land-use that could drive gullying should also be explored further. In this study, for example, field observations suggest that gully development is often associated with a linear disturbance on the floodplain (i.e., roads, fence lines, pipelines). Likewise, grazing intensity (historical and current) which is often associated with soil compaction and the presence or absence of scalds on the floodplain would also be expected to contribute to erosion potential (Gell et al., 2009; Waters et al., 2012).

Moving forward, more detailed information regarding the character of sediment that has been removed and continues to be removed from the gully systems on the Barwon-Darling floodplain should be obtained. Particle size is an important factor as it can dictate the mobility of sediment once it enters the river system. The less mobile, coarser sediment fraction is assumed to drive morphological change through ongoing sediment deposition within the river channel. In this study, the volume of coarse sediment exported from alluvial gullies and contributing to waterhole accumulation was estimated. However, the accuracy of those estimates should be confirmed and refined if necessary. Based on the SedNet modelling for the Murray Darling Basin a ratio of 60:40 (coarse:fine sediment) was initially used for estimating the likely accumulation of sediment within the waterholes. However, it was acknowledged that this ratio would likely overestimate coarse sediment. The reason being that the gullies identified in this research were predominately cut into floodplain alluvium that is dominated by grey, brown, and red cracking clays, which contain a higher proportion of fine sediment. Understanding the relative proportions of coarse and fine sediment entering the river will enable greater predictive capacity with respect to the impact of sediment on in-stream features. Consideration should also be given to gully evolution and the current level of active erosion throughout the Barwon-Darling catchment. The magnitude of sediment delivery to the river will to some extent be dependent on whether a gully is in the initial stages of development or if it is in the later stages of expansion, stabilisation, or accretion. If we can predict the likely future contribution of sediment, we can anticipate the rate at which waterholes would be filled, and we can anticipate when the waterholes may no longer be viable as a refuge for biota or a reliable supply of water for the community. To enable a targeted approach for managing sediment delivery to the Barwon-Darling we also need to understand the complex combination of source material. Sediment fingerprinting has proven to be a useful tool in isolating the contribution of sediment from multiple sources and a range of techniques have been used globally with success (Haddadchi, Ryder, Evrard, & Olley, 2013). Sediment fingerprinting could assist with quantifying the contribution of sediment to the Barwon-Darling waterholes from the upstream tributaries, colluvial gullies and the alluvial gullies identified in this study.

Analysis of aerial photography in this study suggests that over the past fifty years new gullies have continued to develop on the floodplain (Chapter 3). However, the larger, more complex gullies appear to have developed prior to the 1950s. Detailing the age of gullies would again improve predictive capability regarding the historical rate of sediment yield and would enable comparisons to be made for pre and post European colonisation. The use of sediment cores have been used successfully in waterholes in the upper MDB to establish the age of sediment filling waterholes post European colonisation (Reid et al., 2016). Similar techniques could be applied to the Barwon-Darling. Understanding gully age may also assist to identify the anthropogenic or hydrologic triggers of gully erosion within the catchment. There has always been speculation that gully development is related to the early days of settlement (i.e., in the late 1800s) when stocking rates were vastly higher than what is currently held on the floodplain. However, the impacts of more contemporary land-use on both gully initiation and on gully growth should be explored in more detail. Understanding the historical triggers for gully erosion will assist with targeting remediation works on the floodplain to minimise sediment export to the river.

Perhaps one of the largest area of uncertainty going forward is the impact of climate change on inflows into the Barwon-Darling River and the subsequent impact on sediment dynamics. Projections for climate change as summarised in Chapter 4 indicate that a reduction in precipitation, higher temperatures, and higher evapotranspiration are expected to result in a decline in surface runoff and a subsequent reduction in streamflow (CSIRO, 2012). Consequently, we would anticipate more zero flow days, less overbank flooding, and more frequent and longer duration flows below entrainment thresholds, all of which would exacerbate sedimentation. This study has demonstrated the impact of water resource development on modifying the flow regime and to impact the capacity of flows to transport sediment laterally and longitudinally. It has not, however, made any projections for how the entrainment and deposition of sediment may change because of climate change (nor land use change), which is again critical for understanding the potential future threat of sedimentation on the Barwon-Darling waterholes. The challenge, however, will be to develop hydrological models that reflect climate change scenarios, in particular low flow scenarios, whilst also anticipating the likely response of policy makers and water users to climate change, both of which could further dictate water availability (Murray-Darling Basin Authority, 2016).

The ecological implications of a modified physical template were considered in this study by exploring the response of fish assemblage patterns to differences in waterhole depth (Chapter 5). Results indicated that waterhole depth as a habitat variable at the reach scale did not influence fish assemblage composition. However, it was acknowledged that water depth remains a critical variable in dryland rivers through its influence on the long-term persistence of waterhole features in the landscape, the buffering against extreme and undesirable water quality conditions and through the inundation of significant woody habitat and other habitat features. What is currently lacking is an understanding of how waterhole availability at the landscape scale influences fish assemblage patterns. The results from this study indicate that there has been a loss of naturally deep waterholes in the Barwon-Darling River and as a result the distance between the remaining deep holes has increased substantially (Chapter 1). The ecological consequences of changing the spatial distribution of deep waterholes are a significant gap in our understanding of dryland rivers. Future research should consider how a sequence of deep waterholes in a stretch of river influences the long-term survival of fish populations and metapopulations. In doing so, it should consider the implications of losing deep waterholes (particularly complex ones) at the landscape scape on fish populations.

6.10 References

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