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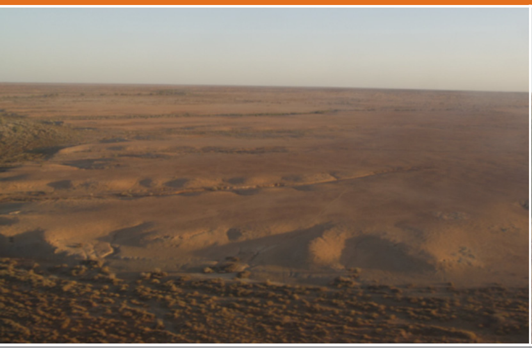


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South Australian Arid Lands Natural Resources Management Board

Geomorphological assessment and analysis of the Neales Catchment

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Executive Summary & Recommendations

Geomorphology is the geology of landscape: in the arid zone, geological processes which govern the distribution of water and sediment ultimately underpin ecology. This report presents the findings of a regional-scale investigation of the Neales River catchment geomorphology, as part of the South Australian Arid Lands Natural Resources Management Board project *"Understanding and managing critical refugia in the arid lands of central northern Australia"* (the Critical Refugia project). Funding was granted through the Australian Government's Caring for Our Country 2009/10 Program. This work contributes to the SAAL Regional NRM Plan Resource Condition Target (RCT) 3: *"By 2020, the extent and condition of at least 50% of priority aquatic ecosystems is improved and other priority aquatic ecosystems are at least maintained in extent and condition"*.

The Neales and Peake Rivers have an extremely variable flow regime, being mostly dry but flowing and flooding regularly. The catchment's processes act to slow the passage of water downstream, such that floodplains are frequently inundated, making the river valleys the focus of biological activity. Channels and allied landforms are generally discontinuous. They collect water at their upstream ends, but then redistribute it across the floodplain from their downstream ends. Floodplain topography and landforms offer substantial barriers to flow, allowing floodwaters time to infiltrate into the alluvial sediments.

The dominant channel types of the Neales and Peake Rivers are anabranching and anastomosing (not braided). The fluvial landforms are generally in good shape, although rilling and gullying are associated with human recreational visitation, and some reaches are very seriously compromised by valley-floor incision (gullies, badlands and arroyos). The Neales Catchment has natural levels of geomorphic activity because of faulting, uplift and downwarping since the Miocene (23 to 5.3 million years ago [Ma]). Therefore, it was not possible to resolve within this study the ultimate causes of the most severe valley-floor incision. It is strongly recommended that further research will benefit local landholders and the wider Australian rangelands community.

Waterholes were a focus of the Critical Refugia project. Waterhole depth is a key determinant of refuge quality. Natural flow variability includes large and extreme floods on a century and multi-century scale. Macroturbulent scour during extreme flood events is needed to create big, deep waterholes. Silt accumulation compromises waterhole depth. Very large flood events, interacting with riparian vegetation, maintain waterhole depth by scouring out accumulated silt. Natural flow variability is therefore critical to the existence of refuge waterholes. Regulating flow or reducing flood peaks would be highly detrimental to waterhole survival. Other threats to waterhole integrity include destruction of riparian vegetation, rabbit warrens undermining banks, rapid gullying delivering excessive silt into waterholes, and possibly cattle promoting connectivity between discontinuous channel segments, via stock pads at the upstream- and downstream-ends. Algebuckina Waterhole has a particular potential threat, in that road development might trigger incision and connect it with West Algebuckina, leading to siltation.

Landforms naturally change over time. In the Neales Catchment, channels and waterholes relocate, are destroyed, or are freshly created on timescales ranging from centuries to millennia. In drafting guidelines and legislation for protecting refuge waterholes it is important to recognise that change is possible. Definitions prioritising refuge waterholes should not be pinned to a specific geographic location; they should be flexible to allow for changing circumstances. Large-scale and probably catastrophic change will occur in the event of an extreme flood. It is important to realise that in that eventuality, what looks like damage is actually landscape renewal: temporarily ugly but ultimately desirable.

Ongoing monitoring of key waterholes is strongly recommended, to ensure the effectiveness of actions taken as a result of the Critical Refugia project. Hydrographic surveys accurately located in coordinate space would monitor siltation, and high-resolution images (LIDAR, aerial photography, or Quickbird) would monitor gullying.

Recommendations:

1. Further investigation into the causes of gullying and valley floor incision at key sites in the Neales catchment using archival aerial photographs to determine the origins and speed of the development of these gully networks. (p.96)

2. Ongoing monitoring (including hydrology and satellite imagery analysis) of key waterholes to determine causes of gullying and siltation at key waterholes. (p.2)

3. Planning of infrastructure development (e.g. causeway at Algebuckina Waterhole) to consider avoiding points of flow concentration (e.g. installing culverts that restrict flow). (p.23)

4. Rabbit control at Algebuckina Waterhole to reduce vegetation loss, gullying, bank-collapse erosion and siltation from run-off. (p.34, 109)

5. Riparian restoration and revegetation at Hookey's Waterhole to restore riparian condition at high use areas. (p.26)

6. Visitor control at Algebuckina waterhole to reduce compaction from vehicles, camping, tree decline and bank de-stabilisation. (p.24)

7. Management guidelines to acknowledge that permanency of waterholes are influenced by geological processes over time and that a broad range of refuge waterholes should be protected. (p.35)

8. Management of total grazing pressure in vulnerable areas so that vegetation can establish on new landforms created after large flood events. (p.35)

9. Further investigation into the origin of Neales catchment hummock fields to determine whether these are formed due to land degradation or are part of natural geological processes. (p.76)

1 Introduction

1.1 Aims, Outcomes, Report Structure

The aim of this Neales River geomorphology study is to provide information on the landscape processes operating in the Neales River and its catchment, in order to support the South Australian Arid Lands Natural Resources Management Board (SAAL NRM Board) project *"Understanding and managing critical refugia in the arid lands of central northern Australia"*. Funding was granted through the Australian Government's Caring for Our Country 2010-13 Program. This study was undertaken by Dr. Gresley Wakelin-King of Wakelin Associates Pty. Ltd, from September 2009 to September 2010. Reconnaissance field work occurred in October 2009, main field work took place in April-May 2010.

Geomorphology is a branch of geology: it is the analysis of landscape processes (such as sediment transport, river behaviour, and the physical and chemical interactions between living things and the Earth). This is relevant to rangeland ecology because in a landscape where water and nutrients are limited, the processes which control water and sediment distribution also control ecosystems. Ecosystem health cannot be fully understood without knowledge of the underpinning landscape processes. Landscape history and processes are identified at a range of spatial scales (from centimetres to scores of kilometres) and time scales (from the weeks and months between flow events, to millions of years of geologic time).

The outcome of the Neales geomorphology project is a better understanding of the natural functioning of this river system. Outputs include a digital dataset, a technical report submitted to the SAAL NRM Board, and source material to include in the report of the larger project "Understanding and managing critical refugia in the arid lands of central northern Australia", for the consideration of a wider audience interested in the SAAL NRM region. Other reports linked to this project are Costelloe (2010), Lee (2010), McNeil et al. (2011), Scholz & Deane (2010).

The findings of this study are presented as a stand-alone report in pages 1-36. However, because geology is not widely understood, and because there is so little previously existing geomorphological information about the Neales Catchment, the report is supplemented by Technical Appendices providing data from this investigation and reviewed literature contributing to this report's findings. Appendix 1 is a glossary of landform terminology, Appendix 2 describes the geology and geomorphology of the Neales Catchment in detail, Appendix 3 considers aspects of methodology, and provides background information on the Neales climate. Appendix 4 is the bibliography. The index will be of assistance to those wishing to link the main body of the report to the supporting data. Several new place names have been created to describe locations in this report, these are described in Appendix 2 and noted in the index.

This study is not designed to identify all locations exhibiting adverse landform outcomes. Such information may be available in Pastoral Board reports. This study is also not addressing change to vegetation communities. Any comments in this report describing the natural, pre-European, or compromised state of some landscape elements, relate to landforms only.

1.2 Post-European Landscape Change

The key issue for any locality is to understand what landscapes, deposits, and processes are natural for the area, and what constitutes "damage" that can be fixed. To ignore such damage is to perpetuate it. Yet to try and rehabilitate something that isn't broken is a waste of resources: money, time, and people’s effort and enthusiasm. It is therefore critical that an informed assessment must be made of post-European change – what kind, how much, or if even there was any. Not all places were impacted equally. While vegetation communities can change over the space of months or years, landscape processes are more robust – up to a point. If the original landscape processes remain in place the foundations of a working ecosystem are there. If the landscape processes are so severely impacted (by grazing, earthworks, or roads and stock routes) that they have changed to something new, then it is hard to go back to the original state. While techniques exist to rehabilitate damaged rangelands, attempting to change or improve on the original landscape processes is usually going to have a poor outcome.

For these reasons, there was a particular focus in the Neales Geomorphology project to assess as far as possible, the degree and nature of post-European change to landscape processes. On the basis that grazing would be most intense close to reliable sources of water, and other human use (e.g. tourism, camping) would be most intense close to vehicle access, field investigations included locations where waterholes were small or non-existent, or which could only be reached by walking. These were compared with areas used more heavily by stock or people. In addition, assessment of landform "naturalness" was based on relationship-driven consideration of whether the landform's context suggested a logical natural landform-creating process. For example, erosion of flat ground along a known major stock route suggests a land-management cause, whereas hillslope erosion on a steep breakaway slope, in the absence of nearby stock routes or watering points, indicates a geological cause. Similarly, to be assessed as natural, a landform's causative process and resulting affect on the landscape would have to contribute to the functioning of the whole system.

Real life does not divide neatly into pigeonholes, and it is not unusual to find circumstances in which human use exaggerates a natural process to the point of landscape damage. In this circumstance, it is quite difficult to assign cause, and it is more realistic to recognise that several factors may be operating (Cooke & Reeves 1976). In some cases the very factors that make some part of the landscape vulnerable (close to the threshold of geomorphic change) are also the factors that make it especially attractive to intense use. In a rugged stony range of hills, the last gentle hillslope remnant from a prior geologic age only remains uneroded by chance; it is also the only slope suitable for droving sheep across the range. The same circumstance that makes the hillslope prone to erosion also makes it a likely stock route. Finally, it is quite possible for landforms of similar appearance to be caused by different processes. This issue (known as **equifinality**) is a continual source of debate and landscape reinterpretation in the geomorphic literature.

1.3 The Neales River Catchment

The Neales River catchment is part of the Lake Eyre Basin in central Australia. The Neales River flows into the north-western part of Lake Eyre at the Neales Delta (Fig. 1). The river is ~270 km long from upstream reaches to the delta apex. Its upstream reaches are divided into two branches (north and south) flowing easterly. Downstream from the confluence, the river follows a reverse-S shaped path, near Oodnadatta (the only population centre on the river). The Neales cuts through the north-northwest trending Peake/Denison Ranges in a narrow gap near Algebuckina Waterhole. Downstream from the ranges, the Neales is joined by the Peake River, which has also come through a gap in the ranges. The Peake River is a larger river than the Neales in both length and catchment; it extends westwards as far as the

Stuart Highway from Cadney Park to Marla. The Peake's main tributaries are Lora and Arckaringa Creeks.

The Neales catchment (including its tributary the Peake River) has an area of 34,600 km^2. Its elevation ranges from 374 m Australian Height Datum (AHD) at the western catchment boundary and 412 m AHD in the Davenport Range, down to -12 m AHD at the mouth of the Neales Delta (Map 1).

Public-road access to the Neales catchment is via the Stuart Highway (bitumen) and the Oodnadatta Track (formed gravel road). Formed gravel roads run between the Stuart Highway and the Oodnadatta Track, from Cadney Park and Coober Pedy (Fig.1). Access to field sites (Map 2) was via private station tracks. All unsealed roads become impassable after only a little rain.

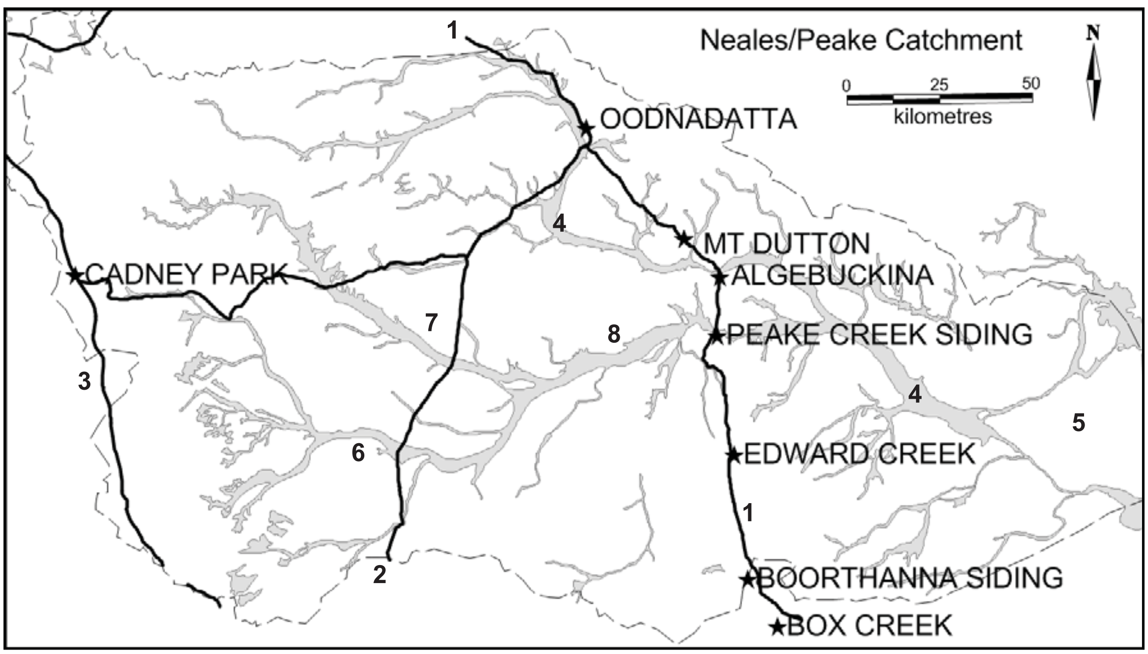


Fig. 1 The Neales Catchment boundary (dashed grey line), drainage network (pale grey), and main roads (black lines). 1 the Oodnadatta Track, 2 the Oodnadatta-Coober Pedy road, 3 the Stuart Highway, 4 the Neales River, 5 the Neales Delta, 6 Lora Creek, 7 Arckaringa Creek, 8 the Peake River.

At the time of European settlement the Neales River area was occupied by the Arabana (Arabunna) Aboriginal peoples with the Wanggangurru (Wangkanguru) to the north east and the Gugada (Kokata) to the south west (McBryde 1987). Aboriginal interests are currently represented by the Dunjiba Community Council, Oodnadatta. Since early European settlement travel between Adelaide and the

Northern Territory has relied heavily on water supplies from permanent or semi-permanent waterholes and the Great Artesian Basin springs, and there has been particularly heavy use of Algebuckina Waterhole, Old Peake, Hookeys Waterhole (Oodnadatta), and similar locations.

Cattle pastoralism has been the major land use since European settlement, and waterholes were important sources of stock water. After rain, when minor waterholes and channels were full of water, stock would be spread along the length of the rivers, but as smaller watering points dried up stock were moved to the major long-term waterholes such as Algebuckina (Lee 2010). In consequence, there has been stock movement along the major river valleys, as well as static grazing. The development of bore-drilling technology decreased stock reliance on waterholes. At present, the two major industries are cattle pastoralism and tourism. Cattle pastoralism's activities include creation of stock pads, grazing, and trampling (especially near intensely used areas e.g. watering points, yards). Tourist activities include fishing and swimming (which involves creating paths to the waterholes) and camping (which involves driving vehicles near waterholes, collecting firewood, creating fireplaces, and digging toilet and refuse pits).

Vegetation in the catchment is described in Scholz & Deane 2010. Generally, the hillslopes surrounding the river valleys are extremely poorly vegetated or barren. In comparison, the river valleys may be well-vegetated, with trees, shrubs, chenopods, and (after rain) grasses and herbs.

Although one might expect that the defining climate characteristic for the arid zone is lack of rain, in fact the variability of rainfall is equally significant (see Technical Appendix 3). As a result, spatial and temporal flow variability is a defining characteristic of arid-zone rivers. A flow event in a drylands river may occur at any scale, and may start and finish almost anywhere in the drainage network, depending upon the size and location of the rainfall event, and the nature of antecedent landscape conditions. Extreme floods are an expected part of the flow pattern.

The Neales catchment has an extreme level of rainfall variability (Bureau of Meteorology 2010). Lake Eyre full episodes are likely to be related to La Niña years in the ENSO cycle (Kotwicki & Allen 1998). Since the effects of the ENSO cycle on Australian weather are reinforced or diminished according to the state of the Interdecadal Pacific Oscillation (McKeon et al. 2004) and other weather cycles, the basin hydrology will be variable on a multi-year and on a decadal cycle. The Neales River undoubtedly has an extremely variable flow pattern, including the chance of extremely large floods. The post-European data record is small and incomplete, and it is certain that we haven't seen a really big flood yet. The 1984 floods, the biggest in recent decades, have a recurrence interval of only ~25 years (based on records 1979-2003) (J. Costelloe *pers. comm.* 2010).

1.4 Acknowledgements

Assistance in the field was cheerfully and ably provided by geologist Jay Stafford. I would like to thank Henry Mancini, the SAAL NRM Board water projects officer, for project management and breadth of vision. The landholders and managers of Allandale, The Peake, and Todmorden Stations, and the Dunjiba and Arabunna people, are thanked for permission to work on their lands. I was grateful for the hospitality and help of managers and staff of the Pink Roadhouse in Oodnadatta, the William Creek pub, and accommodation and tyre-fixing businesses in Coober Pedy. Special thanks goes to SAAL NRM Board staff and the other members of the Neales Catchment critical refugia project team for many interesting and fruitful discussions: Justin Costelloe, Gini Lee, Brooke Madill, Henry Mancini, Dale McNeil, David Schmarr, Glen Scholz and Janet Walton.

2 Landscape Processes of the Neales Catchment

2.1 Geology Influences Landscape

The river valleys of the Neales Catchment are set within a rocky landscape dominated by fine-grained sedimentary rocks (siltstones, mudstones, fine sandstones) overlain by gibber plains of hard silcrete and ferricrete (occurring as pebbles, cobbles, and boulders). Most of the sedimentary rocks belong to the Cretaceous-age Eromanga Basin (part of the Great Artesian Basin) (see Map 1, Geology). The silcretes and ferricretes are younger rocks, formed as chemical precipitate layers within the existing rocks during the Tertiary geological age. Uplift and erosion during the geological past has stripped back overlying soils and sediments, revealing the fine-grained rocks and gibber plains that we see today.

The gibber plains are resistant to erosion, and protect the underlying soft sedimentary rocks. Gibber plain surfaces may show wide shallow dendritic drainage networks, or patterned ground (stony gilgai), or dense desert pavement. Gibber distribution is patchy. Where this is thin or non-existent, the underlying rocks are exposed to the forces of weathering and erosion which break them down into fine sediments, which are then washed into the alluvial valleys. Where the rocks are uplifted into relatively high hills, the hard silcrete capping forms a well-defined edge, and the rapidly eroding soft sedimentary rock forms a relatively steep scarp. The most spectacular example of this is The Jumpup on Arckaringa Creek.

This is the origin of the sediment transported down the Neales and Peake rivers in the present day. Where the flat hilltops are still mostly protected by gibber (most of the upper Neales River) the supply of sediment is slow but steady, whereas scarp slopes (much of the Peake) shed sediments in pulses related to intense rainfall or large floods.

Deep weathering during the geological past has emplaced considerable amounts of gypsum (calcium sulphate) within the surface rocks. In some places small crystals of gypsum replace whole layers of the previously existing rock, and elsewhere dinner-plate-sized transparent sheets of gypsum are set within the rock. Gypsum dissolves in water and its presence in the landscape contributes to "hard" water, but by itself it doesn't taste salty or lead to saline scalds.

Near the Mt. Dutton and Peake/Denison Ranges, coarse Eromanga Basin sedimentary rocks are exposed (coarse sandstone, conglomeratic sandstone). These are the dominant aquifer (water-bearing) units of the Great Artesian Basin. The artesian water is very hard, containing salt (NaCl) as well as gypsum, and where artesian water comes to the surface the area is marked by white patches of salt-crusted soil, and diminished plant vigour. Waterhole salinity and floodplain salinity is ultimately associated with outcrops of artesian water.

Australia is widely regarded as a quiet landscape, without the vigorous tectonic (faulting and seismic) activity that occurs elsewhere in the world, however this is not actually true. Several parts of Australia are actively (though mildly) tectonic, with uplift, subsidence, and faulting of sufficiently recent age to affect landforms and therefore influence human management. The Neales Catchment is one such area (Fig. 2). There is evidence of tectonic activity during the Tertiary geological age, during the Pleistocene, and possibly during the present day.

Faulting has cut through the Eromanga Basin strata, allowing artesian waters to come to the surface as springs and saline seeps. This directly affects fish and vegetation habitats; and by affecting the density and vigour of vegetation, this also affects those geomorphic processes which rely on vegetation to trap sediment.

Faulting has uplifted the Peake/Denison Ranges and Mt. Dutton. This influences the downvalley slope of the drainage networks (Table 1), forming an intermediate base level halfway between the uplands and the river's end. The uplifted ranges also force the Peake and Neales Rivers into narrow valleys, concentrating the force of the flows. This is instrumental in creating the large waterholes characteristic of Algebuckina and Peake Gap. At Mt. Dutton, the uplift is sufficiently recent that the fluvial systems have not yet adjusted to it: the Neales River and Ockenden and Hann Creeks circle around it (Fig. 2, Map 2). Ockenden and Hann Creeks have relatively steep downvalley slopes (Table 1), probably predisposing them towards erosion and valley-floor incision.

Another form of tectonic activity is broad undulation, where uplift and subsidence take place. The scale is ~100-200 m of elevation across ~100-200 km of landscape. In the Neales Catchment, the western and possibly northern edges have been uplifted, and subsidence is occurring in the Lake Eyre Basin. The uplift creates a situation where erosion is likely to be a dominant landscape force; in the Neales Catchment, the gibber plains have partially preserved the uplifted areas from erosion. The subsidence creates a lower base level (Lake Eyre), predisposing the lower Neales towards the development of an inset valley within the broader pre-existing alluvial valley. That being the case, somewhere between the Peake/Denison ranges and the lower Neales there is likely to be an area of geomorphic instability. This is consistent with the observation in this report that the Peake-Neales confluence shows severe gullying and badlands development.

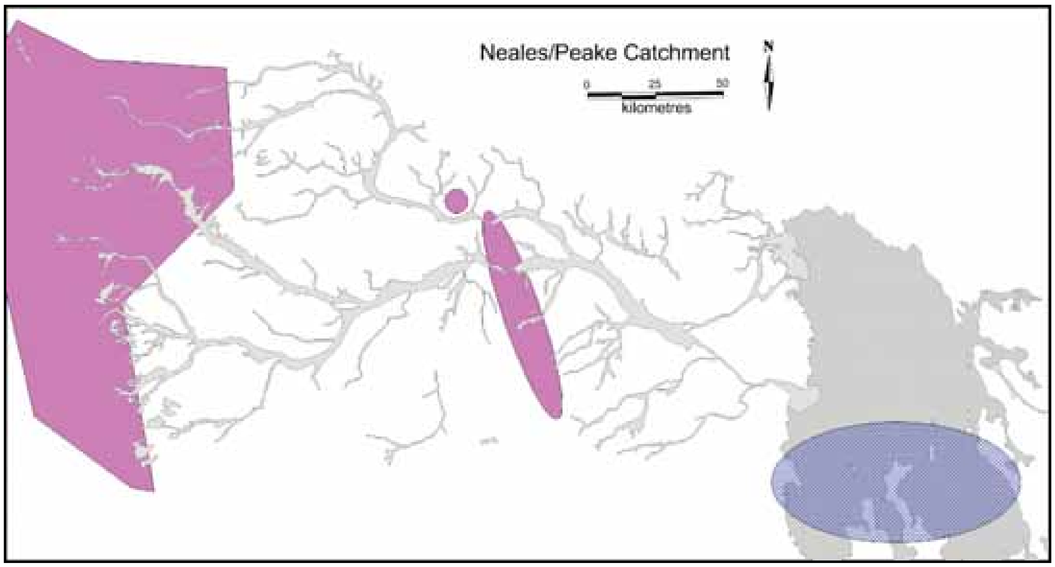


Fig. 2 Sketch map of neotectonic activity relevant to the Neales Catchment. Pink, uplift; blue hatching, subsidence.

The combination of uplift with rock types that produce flat erosion-resistant hilltops and soft, easily-eroded scarps produces an environment in which stream piracy is likely to take place. A developing river network at a lower elevation cuts through the edge of a flat-top hill and "captures" the drainage network above. The Neales shows several examples of stream piracy, the most spectacular of which is the Oodnadatta “S”. Almost all the upper Neales used to flow to the northeast. The consequence of this geomorphic process is that the Oodnadatta South area (from Stony Creek to Elbow Bend) is a relatively steep knickpoint reach (Table 1 p.70). The stream power here is therefore higher, and it is in this reach that Stewarts and Cramps Camp Waterholes are found. They are unexpectedly deep, compared to their length and width.

2.2 The Neales and Peake Rivers

2.2.1 Landforms and Processes

The high degree of flow variability within the Neales Catchment means that although the rivers are usually dry, floods are a common part of the hydrological cycle. In addition, most channels in the Neales Catchment are discontinuous. If looked at from above (air-photos or Google Earth) there will be a clearly-defined channel marked by a double line of trees (the riparian coolibahs), however this channel will change to some kind of poorly-defined flow path at its upstream or downstream ends (Fig. 3).

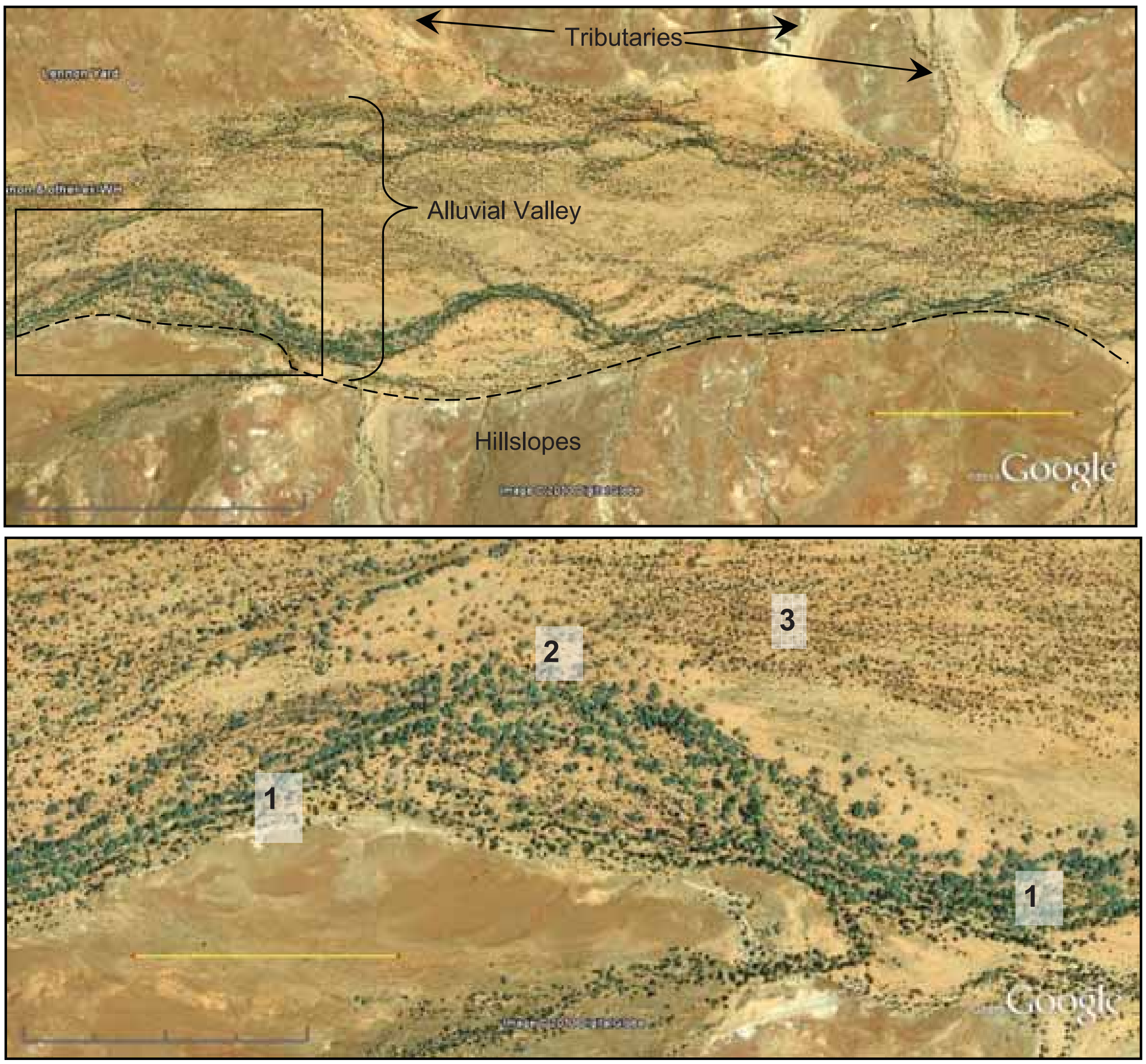


Fig. 3. Discontinuous channels in the south branch of the upper Neales River. Top: The south branch of the Neales River has a primary meandering channel along the valley south, and an anabranching secondary channel along the valley north. North to top, scale bar = 1 km, box shows locations of detailed view. Bottom: the primary channel, while more continuously well-defined (1), also has poorly defined reaches (2). Floods will cover the whole alluvial valley. Flood pathways are marked by alignment in the hummock fields (3). Scale bar = 0.5 km.

This is in contrast to a "normal" (perennial) river, where channels are continuous, clearly-defined, and the place for normal water flow. For both these reasons, the Neales floodplains frequently carry water. Management of the river has to include management of above-floodplain level flow.

Above-floodplain level flow paths are visible on Google Earth by lines of trees, and the alignment of hummock fields (Fig. 3). Hummocks occur where vegetation impedes the flow of water across the floodplain, trapping vegetation as a shadow bar (Fig. 4). In the Neales, hummocks are usually centred around nitre bush, although they may also be found behind Acacia trees and various elements of riparian vegetation. Elsewhere in the world, similar landforms are known as coppice dunes, and arise through overgrazing and erosion. This study does not find conclusive evidence for widespread land degradation as the origin of these hummock fields. This study does find good geological reasons for their existence in the Neales as a natural feature which contributes positively to the fluvial processes. The resemblance of hummocks to coppice dunes is an example of equifinality. This is a contentious result and further research may be warranted.

Fig.4 Hummocks: looking upstream at the silty tails of large hummocks centred around nitre bush, near the Algebuckina northwestern bank. Jay for scale.

Floodplains look flat, but their topography is actually very irregular. Gentle undulations (changes in elevation of ~1-2 m over distances of ~20-200 m) are where floodplain has been created by channel relocation (see section 2.2.2 below). Low areas mark filled-in channels, and raised areas are old splays or high silt plains. Other elements of irregular floodplain topography include dry swamps (wide, shallow discontinuous flow paths) and small isolated channel segments, created by turbulent scour during floods. In some reaches (Hookeys, Peake Gap), rocky outcrops stick up as little hills, and high-level shadow bars on their downvalley sides indicate the water level of the last megaflood.

The trees, hummock fields, and irregular topography of the floodplain are all roughness elements which serve an important function in the Neales River. They impede flow, decreasing its erosive power and allowing floodwaters time to infiltrate into the alluvial sediments. This is a key process for the ecological richness which characterises most of the alluvial valleys. Without this roughness, floodplain-level flow would be fast and erosive, channel downcutting would be triggered, and valley-floor incision would take place. At that point water would drain efficiently down the channel, bypassing the floodplain. Floodplain vegetation would die (Fig. 5).

Fig. 5 Dead trees near the incised channel of the Neales just downstream of Ockenden Ck. Jay for scale.

Most reaches are anabranching (have several different channel threads, which interconnect but are hydraulically independent). There is a wide variety of channel types in the Neales Catchment. The largest and most clearly-defined are waterholes: linear to gently curved, with high steep banks and a deep scoured bed which sometimes contains a narrow inset lowest-elevation channel (misnamed a "low-flow channel", however its depth is well below cease-to-flow depth, therefore it cannot be flowing when the water level is so low). Waterholes are discontinuous, although they usually link to some kind of shallower channel at one or both ends. Typically there is a splay at the waterhole downstream end; sometimes the downstream channel leading out of the waterhole diverts sharply around the outside of the splay (Fig. 6). Waterholes are characterised by their ability to retain water for some time after rain. Other channel types include ordinary channels (which do not retain water, and are shallower and narrower than nearby waterholes), short channel segments, small-channel complexes (clusters of small channels which combine to make a swampy biologically rich area), distributary channels (dispersing water through the splays at the downvalley ends of larger waterholes), "sideways" channels (oriented at right-

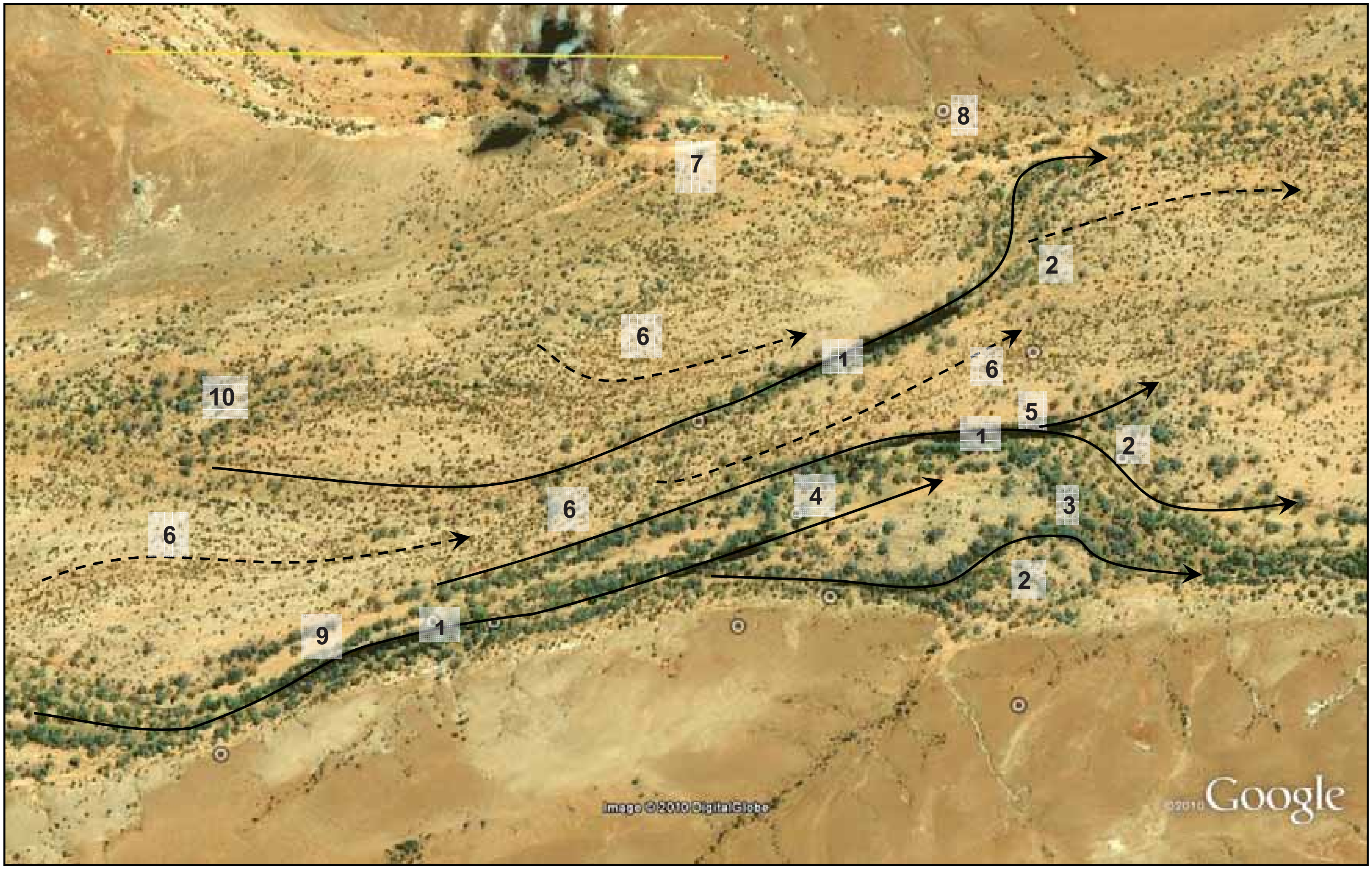


Fig. 6 Google Earth image of floodplain and channel elements at the Neales south branch; white circle are geology sites, north to top, yellow scale bar = 1 km. Flow is from left to right, black lines show main flow paths, dashed black lines show the most prominent floodplain-height flow paths. 1 waterholes (lines of dark water, flanked by green trees), 2 riffles formed on downstream splays, 3 a dry swamp, 4 small channel complexes, 5 silty high plain, 6 hummock fields, 7 tributary channel and floodplain, 8 valley margin, 9 two abandoned channels run parallel to the present waterhole, 10 lines of large trees along frequently-inundated flow paths.

angles to the general downvalley flow direction). The summary of all these channel types is that the dominant fluvial process is gathering water together from the floodplain flow into a short discontinuous channel, from which it is distributed across the floodplain again at the downvalley end. Like the roughness elements, this diversity and discontinuity of channel types impedes water flow and allows floodwaters to be retained in the floodplain. Continuity between channels would be detrimental to this process.

Anastomosing reaches are characterised by a different fluvial style. In these, multiple channel threads are more or less continuous. Channels and floodplains are fairly uniform: they do not display the diversity that is the case elsewhere in the Neales. In these reaches the small size and tortuous flow paths of the channels, and roughness of the hummocky and well-vegetated floodplains act to slow flow and allow flood water infiltration. Anastomosing reaches are most likely to form in reaches where the boundary topography does not promote macroturbulence, and which are to some extent buffered from the region's natural flow variability. In the Neales, these include Farley's and Eaglehawk reaches and the Peake, Blyth and Wood Duck floodouts.

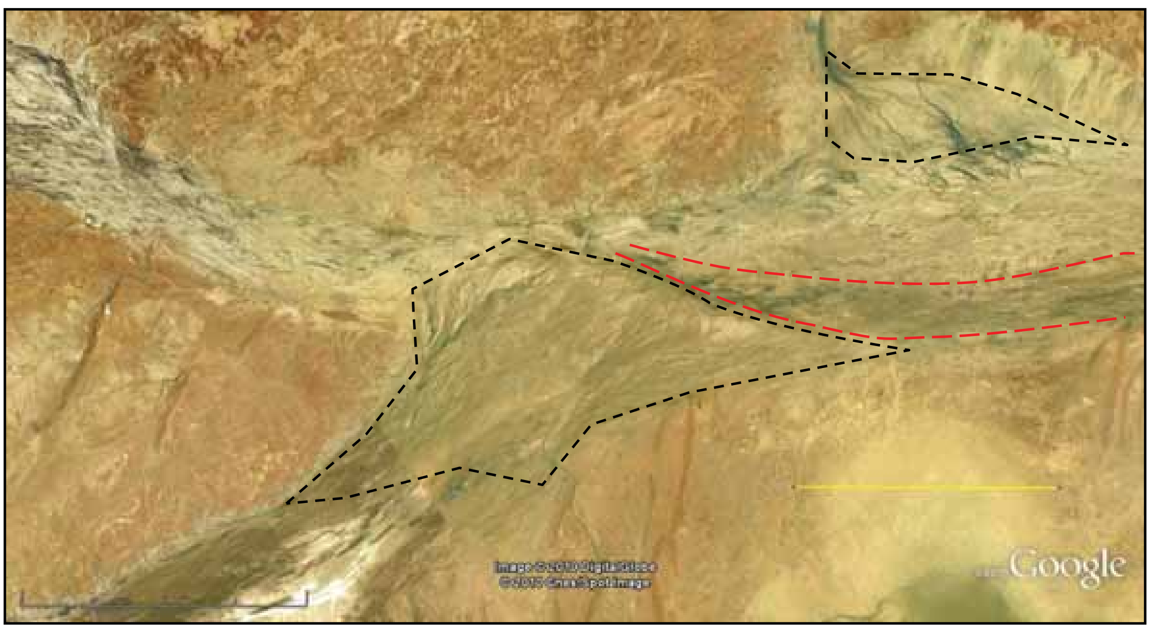


Fig. 7 Google Earth image of tributary-junction floodouts in the Neales-Peake confluence area. Floodouts outlined by dashed black lines at Wood Duck (top right) and Peake-Blyth (centre). Dashed red lines outline a diffuse flow path. Flow is from bottom left (Peake), top left (upper Neales), and top (Wood Duck) to right. Yellow scale bar = 5 km, north is ~20° counterclockwise from top.

A floodout is a wide low-gradient area, typically occurring at a valley's entry into the wider valley of the main trunk stream. The river's flow ceases to be focused and instead spreads out as sheetflood or a wide network of anastomosing channels (Fig. 7). Floodouts are often valuable productive land. They are prone to the development of erosion gullies at their downstream edges where there is usually a zone of increased slope.

All waterholes and most of the larger channels are associated with high silt plains: slightly elevated landforms along one or both banks, or immediately downvalley from the channel. The high silt plains are naturally poorly vegetated owing to their constituent material (extremely well-sorted quartzose silt, which packs down hard, lacks organics, and is poor at retaining moisture). High-level shadow bars and many downstream splays are made of the same material. High silt plains are deposited during waterhole formation, and continue to develop with successive floods. Hummock fields are found on some of the high silt plains of larger waterholes

Waterholes and channels have steep to vertical banks, crowned at the bank-top by dense riparian vegetation. In some larger waterholes the riparian vegetation promotes the development of a narrow riparian ridge, like a single long thin hummock. During large floods, above-floodplain level flow interacts with riparian vegetation to

- focus higher-velocity flow down the centre of the waterhole, scouring it clean of accumulated silt
- create a line of shear along the banks, maintaining bank steepness
- intercept sediment excavated from the waterhole, trapping it within the riparian zone and spreading it over the high silt plain.

The presence of riparian vegetation is therefore critical for waterhole landform and habitat maintenance.

2.2.2 Waterhole Formation and Evolution

Waterholes, dry swamps, and most of the different kinds of channels are created by macroturbulent scour during very large floods and megafloods. Imagine a tornado in the flowing water – a powerful vortex whirling around as it travels downstream. The base of the vortex touches down and carves a long straight groove into the floodplain. Dislodged sediment spits out of the groove and settles nearby (forming the high silt plains). Eventually, its power used up in this work of creation, the vortex weakens and lifts off the floodplain, dying away in a swirling eddy. The last burst of sediment, mixed with gravelly sand, is dragged out of the groove and settles immediately downstream (forming the splay). After the flooding, water remains in the groove and a waterhole is formed. Vegetation germinates along the banks and on the downstream splay.

The "tornado" image is an oversimplification of the behaviour of turbulent water, however it is a good description of the relationship between floods, turbulence, and landforms in the Neales Catchment. Macroturbulent scour in South Africa has been observed to create landforms very similar to the Neales waterholes, including the straight banks and the inset "low-flow" channel. The turbulence cells are scaled to water depth, and so are the width, depth, and length of the resultant grooves. The biggest waterholes therefore occur where water from many tributaries is constrained into narrow floodplains, making deep, powerful flow: the gaps through the Peake/Denison Ranges at Algebuckina and Peake Gap. Where a waterhole is wide but shallow (West Algebuckina, or the unnamed channel segment near Peake Gap, Fig. 8), this is an indication of a once-deep waterhole, now silted up.

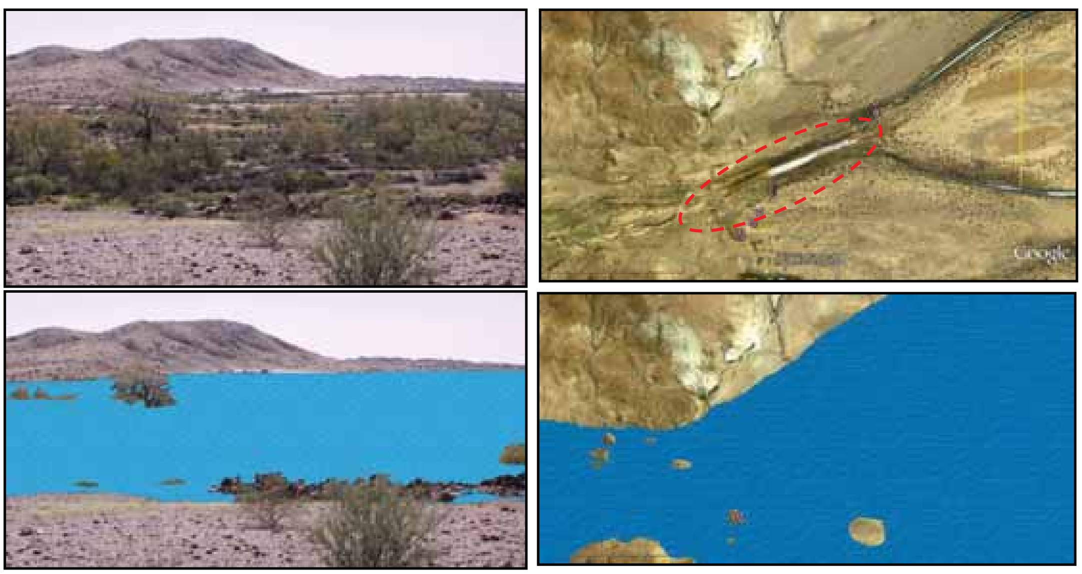


Fig. 8 The flood height and extent of floodplain inundation in Peake Gap's last megaflood. Left, looking across the Peake Gap valley, right Google Earth image of the same area, north to top, scale bar = 1 km., Top: as the area is today, bottom: as it was during the last very large flood. The wide but shallow waterhole remnant is circled in red.

The Neales Catchment's flow regime is known to be extremely variable, even without having yet observed century-scale flooding (the so-called 1-in-100 flood). Elsewhere in arid Australia, millennial-scale floods (occurring every thousand years or so) have left indelible marks on the landscape. Deposits left by deep, wide inundation at Peake Gap (boulder beds and high-level shadow bars) indicate the scale of relatively recent flooding. (Fig. 8). In the Neales, it is likely that the biggest waterholes are created by extreme levels of flooding with a recurrence interval of ~500-1000 years. (These time intervals are estimates based on the scale of landform development and flood histories elsewhere in arid Australia.)

In the Neales Catchment waterholes often occur in clusters. Some reaches have many waterholes, and are associated with a rich variety of other landforms: short channel segments, small channel complexes, dry swamps (e.g. Fig. 6); whereas others have few or none (e.g. Fig. 3). Waterholes are most likely to occur in reaches likely to carry deep water where the topography promotes macroturbulence: rough, irregular boundaries where rocky outcrop protrudes through the floodplain (Hookeys, Peake Gap); valley margins (Mathieson, Cliff, Afghan); or complex flow conditions where two bodies of water meet (Angle Pole). Geomorphically complex reaches with a diversity of landforms are likely to have a diversity of habitats for non-aquatic plants and animals, and a range of options for migrating fish.

Very large floods are smaller than megafloods and occur a little more often (~100-300 years). They maintain and develop the fluvial landforms. Small turbulence may cut small channel segments or create little scours on the high silt plains. Deep water flowing over the waterhole and its surrounding floodplain scours the waterhole base, trims the banks, and renews silt across the high silt plains and the downvalley splays. In the larger waterholes distributary channels may cut through and extend beyond the original splay, sometimes developing their own high silt plains. With time, the high silt plains may develop to such an extent that the waterhole banks are some of the highest landforms of the alluvial valley.

Fine sediments will be transported through the river system by flows and floods of all scales. However, while large floods may flush available sediments out to the Lake, smaller flows and floods (1-10 year recurrence intervals) may transport sediments for only short distances. Silt and fine sand eroded from the uplifted hillslopes will naturally accumulate in channels and waterholes, and be trapped behind and amongst floodplain vegetation (forming hummock fields).

The gradual accumulation of alluvial sediments will lead to some landforms becoming likely to change, especially within the context of the variable flow pattern. A small channel which has silted up during small flows, for example, is not an efficient pathway for the next annual flood; the flood will cut a new channel, and the old channel will be abandoned. In similar ways, all the fluvial landforms are subject to change. The frequency and scale of the change depends on the size of the landform. Small channels and anastomosing channels may change frequently (sub-century timescale) but the changes may go unnoticed. Medium-scale channels and waterholes may relocate, and new waterholes be created (century timescale), most likely in association with larger-than-annual floods. Very large waterholes, such as Algebuckina, will undergo avulsion (sudden and usually catastrophic relocation) on a multi-century timescale. This is likely to be associated with very large to extreme floods.

Fig. 9 Google Earth image of a remnant of an avulsed large waterhole at Peake Gap. 1 rocky Peake Gap, 2 the main channel, currently very shallow in comparison to its width, 3 Baltucoodna and Warrarawoona Waterholes in low-elevation parts of the valley, 4 abandoned path of the previous main waterhole, 5 old high silty plains flanking the previous waterhole. North to top, yellow scale bar = 1 km, flow left to right.

One possible trigger for channel or waterhole avulsion is the deposition of sediment pulses, blocking flow and diverting the next floodwaters down some other path. This was the likely cause of the abandonment of the Peake Gap waterhole at some pre-historical time. Originally, the waterhole was of a similar size to Algebuckina (Fig. 9). It was flanked by a very large high silt plains. A pulse of sediment from Arckaringa Creek was transported by a small flow but blocked the channel ~2 km downvalley from Peake Gap. The next floodwaters diverted around the blockage, switching to the low ground on either side of the high silt plains, and forming the current waterholes Baltucoodna and Warrarawoona.

The final factor influencing channel and waterhole evolution is two-way erosion. This relates directly to flow variability, and effects the development of gullies, distributary channels through splays, and odd "hook" shapes in waterhole banks. Although we normally consider flow to occur in the downvalley direction only, ephemeral rivers also have the situation during waning floods where water from the floodplain drains back into channels and waterholes. As it does so, it can be erosive. This may promote the development of distributary channels and sideways channels. Where gullying through waterhole banks is a problem, this waning-flow drainage is likely to seriously exacerbate gully development.

Fig. 10 At a part of Algebuckina visited by vehicles, dendritic rill systems (**R**) extend out across the high silt plain. They lead to gullies (**G**) which cut through the riparian ridge and drain into the waterhole. Vehicle for scale.

2.2.3 Rills, Gullies, Badlands, and Arroyos

A different channel type is dominated by the process of erosion. Unlike other fluvial styles (which construct the floodplain through which they flow), rills, gullies, badlands and arroyos are entirely erosional in their nature.

Rills are cm-scale erosion networks, the smallest-scale landform of this type. Rills can coalesce to form gullies (Fig. 10), deeper and larger channels which cut through waterhole banks or into valley floors. Gullies erode headwards (expanding in an upvalley direction) as well as cutting down. Gullies can spread out to form networks (badlands), which can migrate rapidly across floodplains, removing substantial sediment and capturing all the above-floodplain flow. Downvalley, badlands expand into arroyos: deep, steep-sided flat-bottomed channels, from which water does not overflow, even during big floods. They do not have the same relationship with their floodplains as the waterholes do. Waterholes are associated with flourishing riparian vegetation; arroyos are associated with dead floodplains (Fig. 11).

Algebuckina, Stewarts, and other recreational waterholes have many rill networks which lead to gullies that cut through the waterhole banks (Fig. 10). Rill and gully erosion delivers sediments into the waterholes. At the Peake/Neales confluence, badlands near Wirriarrina Dam have delivered sediments into Tardetakarinna waterhole, contributing to its destruction. Several other sets of badlands in that area lead to two large arroyos (Fig. 11) which cut into the floodplain and have led to loss of biological productivity.

Fig. 11 Erosion in the Two Arroyos reach. Top, a wide arroyo near 6-Mile Bore, showing flat floor, steep sides, and dead trees at the bank top. Jay (circled) for scale. This wide channel is half the size of the same channel further downstream. Bottom, floodplain into which the badlands and arroyo are incised. This photo taken after good rain: elsewhere, floodplains were covered with waist-high grass. The original hummock field is now starved of flow: its hummocks are not being replenished by sediments bought down during flow events, and its vegetation is dead or dying. Hat for scale.

3 Key Areas

3.1 Algebuckina Waterhole, Alge Pinch, West Alge

There's three distinct parts of the Algebuckina area: Algebuckina Waterhole, Algebuckina Pinch, and West Algebuckina (Fig. 12).

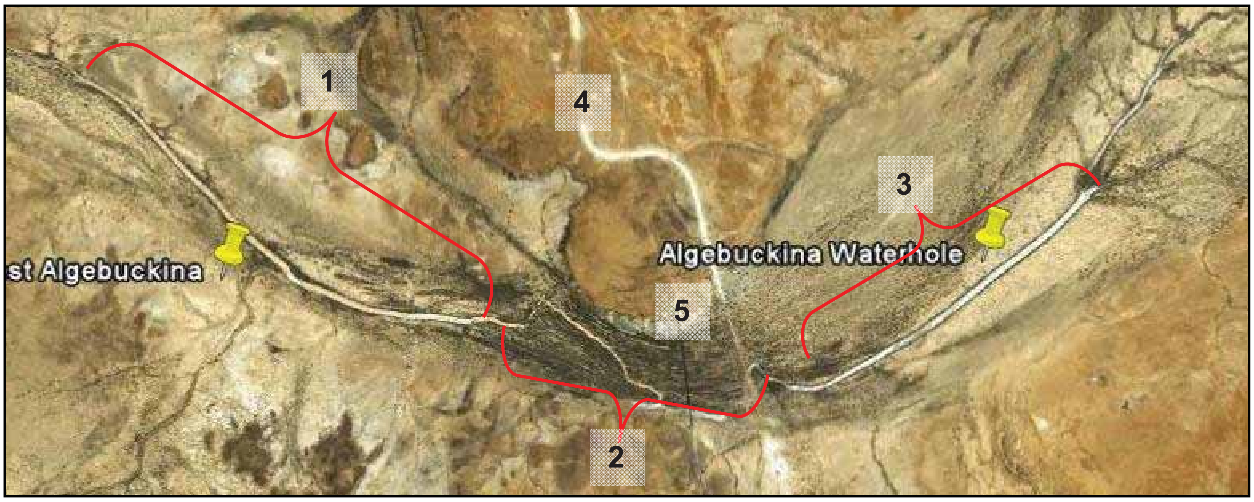


Fig. 12 Google Earth image of the Algebuckina area, north to top. 1 West Algebuckina, 2 Algebuckina Pinch, 3 Algebuckina Waterhole, 4 white line is the Oodnadatta Track, 5 dark line is the Algebuckina Railway Bridge.

West Algebuckina, a long stretch of channel, is not regarded as a "waterhole" by locals, as it is too shallow to retain water for very long. However its length and width are of a similar scale to Algebuckina Waterhole, so the geomorphic indications are that it used to be much deeper. A finding of this report is that West Algebuckina is likely to have been silted up as a result of valley-floor incision upstream near Ockenden Creek.

Algebuckina Pinch is where the causeway and rail bridge go across the Neales River. The floodplain is narrowest here, constrained between hills of erosion-resistant rock. The Pinch is vegetated by dense scrubby trees, which are a valuable protection against erosion. A channel cutting through the trees looks to be small and inefficient. It crosscuts the major flow direction and may have developed from an old track. It would be detrimental if an efficient channel developed through Algebuckina Pinch, as this would allow silt accumulating in West Algebuckina to be flushed into Algebuckina Waterhole, reducing its depth and destroying its refuge value. It is critically important that any infrastructure development (e.g. the road crossing of the Oodnadatta Track) must avoid points of flow concentration (e.g. culverts).

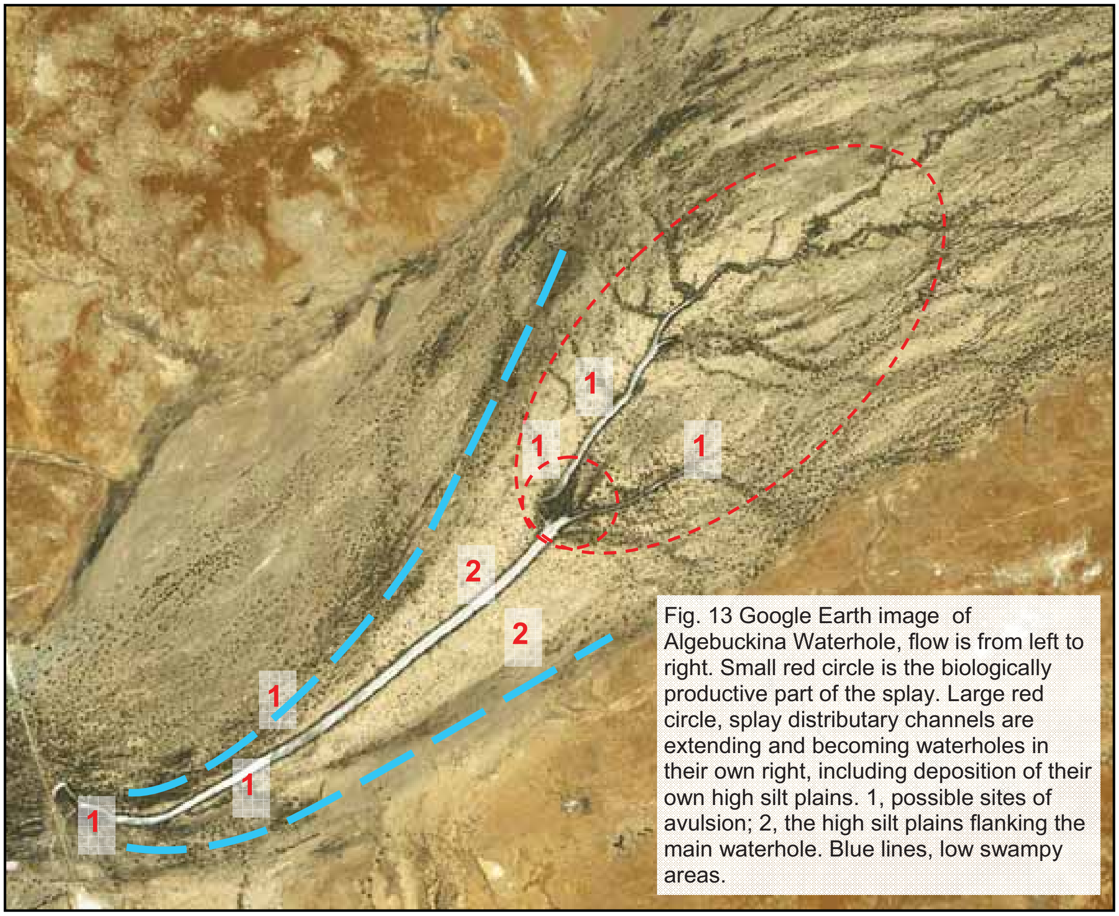


Fig. 13 Google Earth image of Algebuckina Waterhole, flow is from left to right. Small red circle is the biologically productive part of the splay. Large red circle, splay distributary channels are extending and becoming waterholes in their own right, including deposition of their own high silt plains. 1, possible sites of avulsion; 2, the high silt plains flanking the main waterhole. Blue lines, low swampy areas.

Algebuckina Waterhole is a key ecological refuge and popular tourist spot, long known for its depth and ability to retain water through the longest dry spell. The waterhole is long, wide, and deep. Its flanking high silt plains are very narrow at the upstream ends and widen downstream (Fig. 13). On either side of the high silt plains are narrow zones of low elevation which are swampy after rain. At the downstream end of the waterhole the main channel splits into many small channels: this area is the splay, and the nest of small channels makes it ecologically productive. Several distributary channels extend through the splay, one of which is extending and forming a secondary waterhole. A number of sideways channels extend through the high silt plains of this secondary waterhole. Remnant traces of other large channels, now abandoned, can be seen on the floodplain.

Since depth is a key determinant in a waterhole's ability to store water, anything that allows sediment to accumulate in the waterhole is detrimental. Rilling and gullying in the high silt plains, from vehicle traffic and waterhole access respectively, are currently delivering sediment into the waterhole. Rabbit warrens in non-tourist areas promote gullying and bank collapse, and so also contribute to the problem. There is no current indication that excess silt is being washed into the waterhole from upstream, however if channel incision connects Algebuckina with West Algebuckina, then the risk of siltation will be high.

No waterhole is permanent, and it is likely that flood-driven channel avulsion will remove Algebuckina Waterhole in some future century. (It is equally likely that the same large flood will create a new waterhole nearby.) For that reason, Algebuckina Waterhole should not be the only protected refuge waterhole, and management considerations should allow flexibility in defining which waterholes are to be managed for their refuge qualities. After avulsion, it is likely that the relocated channel will flow down one or both of the low swampy areas (Fig. 13).

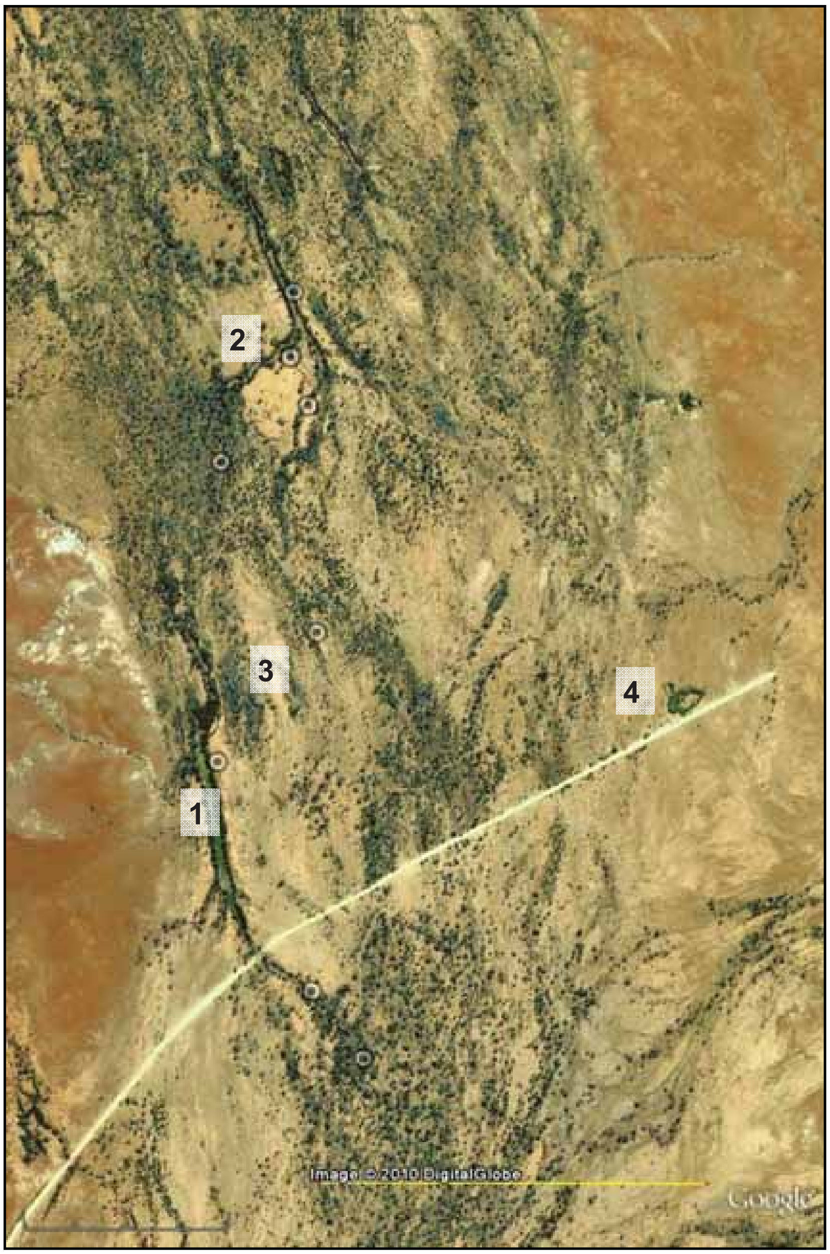


Fig. 14 Google Earth image of Hookey's reach of the Neales River south of Oodnadatta. 1 Hookeys Waterhole, 2 another moderately large waterhole which has high silt plains downvalley from sideways channels, 3 rocky outcrop here promotes turbulence, 4 the lowest parts of the valley are here, not where the waterholes are. North to top, yellow scale bar = 1 km, flow is from top to bottom, pale line is the Oodnadatta – Coober Pedy road

This kind of large-scale landscape change cannot be prevented (nor should it be). However, there is no reason to encourage avulsion to happen prematurely. Areas where floodwaters seeking avulsion might break through are shown in Fig. 13. It is desirable that gullying be prevented and natural vegetation be preserved in these areas. A possible avulsion trigger would be accumulation in the waterhole of enough silt to seriously impede flow, followed by a large rapidly-rising flood. Under these circumstances, a hydraulic dam would be created and floodwaters would be likely to divert at the waterhole's upstream end. This is another reason to discourage silt accumulation in the waterhole, and preserve its natural self-maintaining processes.

3.2. Hookey's Waterhole and the Oodnadatta South Reach

The Neales River between Oodnadatta and the confluence with Stony Creek has many opportunities for turbulent flow during floods, and consequently the area is rich in waterholes and channels of all shapes and sizes. The many landforms (Fig. 14) gives a diversity of habitat for plants and land animals, and will offer many options of habitat for migrating fish during floods.

Figure 15 The downstream splay at Hookeys Waterhole. 1, this large tree is isolated from the bank by splay distributary channels. 2, The root mass is exposed but not actively eroding, and looks the same as in an old photograph in a book at the Oodnadatta Roadhouse. Photograph taken from the opposite bank, looking southeast.

There are areas of bank erosion and severe bank retreat in the waterhole's downstream splay, which is close to the road and subject to frequent recreational use. However, the erosion is not widespread – for example, a nearby tree isolated between splay distributary channels (Fig. 15) is the same now as it was during earliest European settlement. The indications are that landforms around Hookeys are generally stable and in reasonably good condition (with the exception of the erosion noted above). There do not appear to be any particular threats to waterhole or landform integrity in this area. Preservation of riparian vegetation, restoration of riparian vegetation in eroded high-use areas, and maintenance of the river's natural flow variability will allow these waterholes to self-maintain their depth.

3.3. Angle Pole Waterhole and Oodnadatta North

The upstream reaches of the Neales River are split into North Branch and South Branch. The North Branch has few waterholes. The South Branch has more and larger waterholes than the North Branch, but they are still relatively small and shallow in comparison with the rest of the Neales River. This is consistent with the relatively small catchments of these lower-order systems. It is not until downstream from the confluence of North and South Branch that the Neales River generates enough discharge to make bigger waterholes.

The Angle Pole Waterhole complex is downstream of the confluence. It owes its existence to the turbulence generated by the interface between two streams of water (Fig. 16). Like Hookey's, it is a cluster of waterholes, small channel complexes, and other landforms. It is likely to offer a variety of habitats to both aquatic and non-aquatic organisms.

Angle Pole has been used in pre-European as well as European times. There has been some post-European ground surface lowering and bank retreat in places, however there is no conclusive evidence of a causal link with European settlement. The area is geomorphically active with respect to fluvial landforms: in the South Branch some waterholes have diminished while others have been created, channels

Fig. 16 Google Earth oblique image of Angle Pole waterhole, left arrow, South Branch, right arrow, North Branch. A complex of small channels has formed where the two flows meet (green oval). A possible megaflood deposit at the confluence is shown by the black dashed outline. Eye altitude 270 m, looking upstream, yellow scale bar = 0.3 km.

have avulsed and flow pathways shifted. Overall the geomorphology appears to be in good shape. There are vehicle tracks along the high silt plains. Preservation of the riparian vegetation and continuance of the natural flow variability will allow waterhole depths to be self-maintaining. Preservation of the floodplain vegetation will prevent undesirable connectivity between waterholes.

A less-vegetated triangle in the floodplain near the North and South Branch confluence (Fig. 16) may be a tributary-confluence megaflood deposit. If so, its surface would be slightly above the general floodplain surface, so it would be less well-watered. The lack of vegetation may be either because it was never well-vegetated, or because being less well-watered, it is less likely to recover from grazing pressure.

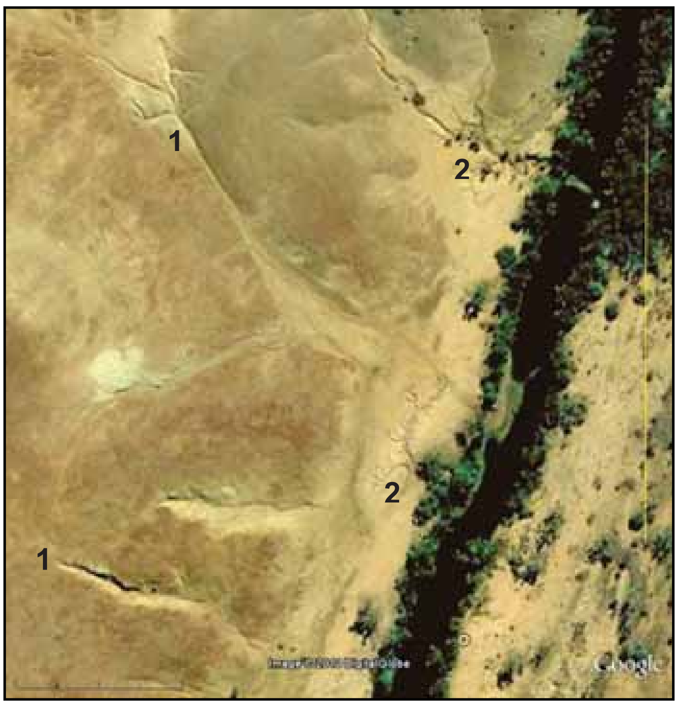


Fig. 17 Google Earth image of Stewart Waterhole. 1 gullying cutting into gibber hillslope edges, 2 gully networks (badlands) cutting into silty high plains. North to top, yellow scale bar = 0.2km, flow top to bottom.

3.4. Knickpoint Reach: Stewarts and Cramp's Camp Waterholes

The reach containing Mathieson's, Stewarts, and Cramps Camp Waterholes is the neck where the original stream capture occurred between upper and lower Neales River drainage networks. It has the steepest and narrowest floodplain; stream power is higher here (floods are more erosive), the blanket of alluvial sediment is thinner. Some of these waterholes are deeper than might be expected from their width, which is consistent with a high stream power. Despite their depth, they do not retain water for very long. One possibility is that they are "leaky" at the bottom, which would be consistent with the waterhole having been scoured through thin alluvial sediments into basal gravel.

Stewarts waterhole is a very popular spot for local recreation. Vehicle tracks along the west silt floodplain are associated with very severe gullying. The floodplain is narrow, and gullying has extended right across the floodplain and up the steep hillslopes (Fig. 17). This site is visibly popular but only with locals, and it is not visible from the main road. It is unlikely that the use is as intense here as it is in Algebuckina, yet the erosion is every bit as bad. It is likely that the steep hillslope gradients and strong stream power make this an especially vulnerable area for erosion. Rehabilitation here would ideally include hillslope gullies as well as floodplains. Examination of archived aerial photography would provide more information about the inception and development of these gullies

3.5. Peake/Neales confluence: Tardetakarinna ex-Waterhole

Further investigation is recommended, but this report finds a strong likelihood

- that there was once a large reliable waterhole (Tardetakarinna) just upstream of the Blyth floodout, where the Peake River empties into the Peake/Neales confluence
- that a system of gullies and badlands, extending from Tardetakarinna Waterhole and expanding headwards towards Wirriarrina Dam, incised into the floodplain and delivered quantities of sediment into Tardetakarinna Waterhole
- that the waterhole was silted up and destroyed.

It is possible that stock pads extending between Wirriarrina Dam and the uphill entrance of Tardetakarinna Waterhole were the initiating trigger for the gullying. In addition, downstream channel continuity discussed in the paragraph below may also have originated from stock pads going downstream to the next waterhole.

A continuous channel has been established between the Tardetakarinna Waterhole splay's northern distributary channel (Fig. 18), and the next small waterhole downstream (Small Tarde). The Google Earth image indicates that another continuous channel is established from the downvalley splay of Small Tarde, extending through a short channel segment (Hydro Tarde, where the hydrology data logger for the Critical Refugia Project is installed). This small channel is continuous all the way downstream to Wood Duck Arroyo (discussed further below), and from there to Lake Eyre. This indicates that in this reach the normal functioning of the river, in which the discontinuous nature of the waterhole and channel segments returns water to the floodplain, is severely compromised. Water flowing down this continuous channel is likely to increase the incision and form an arroyo.

Fig. 18 Google Earth image of the channels extending downvalley from old Tardetakarinna Waterhole. 1 Old Tardetakarinna Waterhole's downstream splay (1A the northern distributary channel, 1B the southern distributary channel), 2 the channel linking Tardetakarinna Waterhole with Small Tarde, 3 Small Tarde, 4 Small Tarde's downstream splay, 5 a channel between Small Tarde and the Wood Duck Arroyo contains the small waterhole Hydro Tarde, 5 the diffuse Neales flow path. North is ~30° counterclockwise from photo top, yellow scale bar = 1 km.

The Wirriarrina Badlands capture virtually all the water coming down the Neales River and feed it into the remnants of Tardetakarinna Waterhole. Currently most of that water bypasses the continuous channel to Small Tarde and Hydro Tarde. Instead, it flows through Tardetakarinna Waterhole splay's southern distributary channel into a diffuse flow path which is productive land. It is likely to be desirable to the land managers that water flow continue to bypass the northern distributary channel, in order that 1) the diffuse flow path continues to receive water and 2) the continuous channel extending through Small Tarde and Hydro Tarde be deprived of water that will promote more incision.

The amount of incision occurring around the Peake/Neales confluence indicates that this is a geomorphically active area, vulnerable to erosion. One consequence is that the area is prone to gullying along roads. For example, the road extending south-southwest from Hydro Tarde (Fig. 18) has developed actively extending gullies despite being perpendicular to the direction of flow. Great caution should be exercised in doing anything that cuts down into the floodplain, as this will focus stream power and may trigger valley-floor incision.

Whether this vulnerability is a consequence of increased discharge in this reach, its tectonic setting, its geomorphic setting, land management actions, or all four, is not clear from this investigation. This is a complex landscape and it is strongly recommended that further research will be of benefit to the landholders and be a valuable addition to range management knowledge generally.

3.6. Neales-Peake Confluence: Arroyos

The continuous channel extending from the remnants of Tardetakarinna Waterhole becomes wider and increasingly deeply incised with distance downstream. It develops into a large arroyo that runs across the downstream side of the Wood Duck Floodout. Gullying extending laterally from this arroyo is extending into the floodout and is likely to compromise its productivity. A separate set of gullies and badlands is extending into the diffuse flow path, near 6-Mile Bore. These coalesce downvalley into another very large arroyo. Together, these two arroyos capture the entire flow of both the Peake and the Neales Rivers, depriving the lower Neales floodplain of all the water it might otherwise receive (Fig. 19).

It seems unlikely that anything can be done to rehabilitate the arroyos, because of their size. It may be possible and would certainly be desirable to prevent the gullies extending any further in to Wood Duck Floodout, Blyth Floodout, or the diffuse flow path. Specialist advice should be sought. As discussed previously, further investigaion is needed into the causes of this incision.

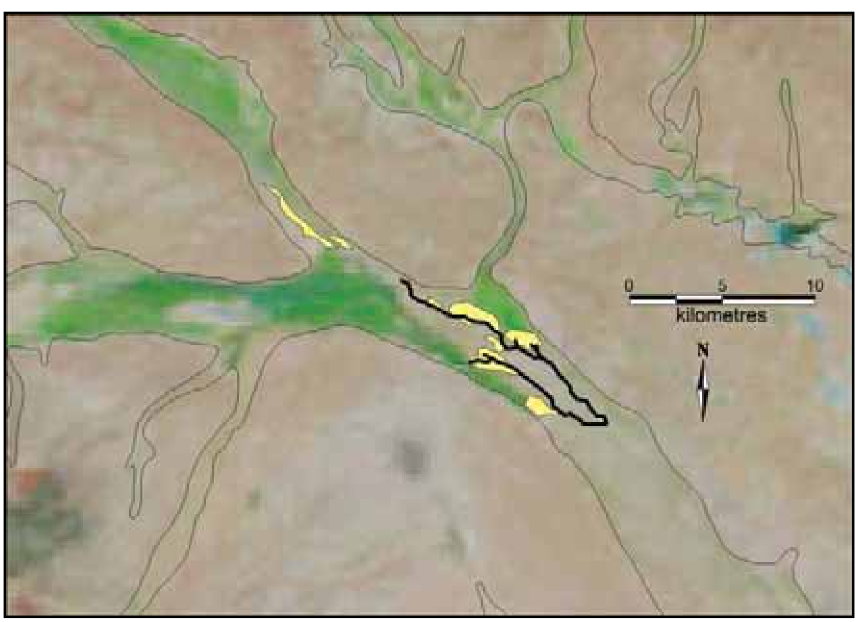


Fig. 19 MODIS satellite image of the Peake-Neales confluence, after a ~1:10 flow event. The vegetation response (green) demonstrates areas of floodplain inundation. Absence of floodplain inundation corresponds exactly to arroyos (thick black lines) and badlands (yellow areas). The river valley is outlined in grey, flow is from left and top left, to bottom right.

4 Management Implications

4.1 Opportunities

The landforms and geomorphic processes in the Neales Catchment are in reasonably good shape (except for localised areas of gully erosion or valley-floor incision). This catchment therefore presents an opportunity to preserve a unique landscape.

Other reports for the Critical Refugia project describe the role of the large waterholes as ecological refugia for aquatic biota. Land-based plants and animals are also well served by refuge waterholes. The river valleys are the primary source of biological productivity in this otherwise harsh landscape. Even though this project was primarily designed to look at aquatic refugia, it is important to also acknowledge the importance of refuge waterholes for non-aquatic biota. Riparian zones are widely acknowledged to mediate erosion and provide ecological services. Their significance is reflected in the amount of Landcare and other funding available for riparian projects. In the arid zone, floodouts and waterhole downvalley splays are equivalent to riparian zones, and funding for riparian works should be equally applicable to them.

Refuge waterholes provide shelter for feral plants and animals as well as desirable species. Periods of hard drought, when populations of e.g. rabbits have retreated to a few sheltered areas, may be opportunities for targeted pest control.

The Neales Catchment is a significant place for earth-science research. Some elements of the geomorphic processes and landforms described in this report have not previously been described in the scientific literature. Also, it is a modern-day analogue for some things which are better known from their geological deposits. Scientific research funded by academic sources can be designed to be relevant to landholders. This is best achieved by fostering communication between landholders and earth scientists.

4.2 Threats

The Neales Catchment rivers have evolved in response to the area's extremely variable rainfall and flow patterns. Any regulation of these rivers will be detrimental to the landforms. Particularly, any decrease in the frequency or scale of floods will inevitably lead to silting-up of waterholes, destroying habitats and eliminating their refuge value and amenity.

The riparian vegetation of the waterholes plays a vital role in concentrating the stream power of floodwaters along the sides and bed of the waterholes, scouring out accumulated silt and maintaining the steep banks. As such, the riparian vegetation is vital in maintaining the waterholes' habitat and refuge values. Riparian vegetation is directly threatened by human use in firewood and tinder collection. It is also threatened by deterioration of the landforms which the riparian vegetation grows on (banks, riparian ridges, hummocks, floodplains), as the landforms are dug into, trampled over, or driven over so frequently that tracks form and promote erosion. Revegetation or allowing natural recruitment and restoration processes along the riparian margin will re-establish geomorphic function.

Rill and gully networks in high silt plains and banks of large waterholes represent substantial episodes of erosion, delivering sediments into the waterholes. This risks waterhole shallowing, decreasing their refuge value. Rilling is strongly associated with high human visitation, particularly vehicle use.

Waterhole banks support the riparian vegetation. Gullies which cut through the banks compromise the density of the vegetation, promote erosion, and may create conditions favouring avulsion. Contrary to expectations, cattle seem to have few links with gullies through the banks of larger waterholes. Gullies seem to be most associated with intense human visitation: people gaining access to the water by going straight down the steep banks. It appears that cattle use gullies to gain access to waterholes after the gullies have been created by people. This finding is contentious and warrants further investigation.

Expanding networks of gullies and badlands which incise into floodplains are a threat in three ways. Firstly, they capture and rapidly transport away the water that should be infiltrating into the floodplain. Widespread death of vegetation is the result, for example at the Neales near Ockenden Creek, or in the lower Neales near the Wood Duck Floodout. Secondly, incision of gully networks releases considerable amounts of sediment to be transported downstream. The sediment is likely to accumulate in the next waterhole silting it up and either destroying its refuge value (West

Algebuckina) or completely destroying the waterhole itself (Tardetakarinna). Thirdly, where gully and badlands networks extend across the full width of the floodplain, it may constrain fish migration to a downvalley-only direction.

Fig. 20 This erosion gully in the non-tourist part of Algebuckina drains into a rabbit hole at some distance from the bank edge. Water emerges at the base of the bank, leading to undercutting and bank collapse. Rabbit hole is behind hammer (circled).

Rabbits are an unexpectedly strong threat to waterhole bank integrity. Their warrens focus waning-flow erosion towards the bank at water level (Fig.20), encouraging basal sapping and wholesale bank collapse tens of metres in extent. Bank collapse is atypical of these fluvial landforms and will dump considerable sediment into the waterhole. As well as the generally detrimental effect of shallowing, sediment blockages in a downstream splay may create hydraulic damming and promote avulsion.

Channel discontinuity is an important part of good river function in the Neales. Anything that connects one waterhole to the next by a permanent channel is likely to be detrimental. It is possible that stock pads between the Tardetakarinna downstream splay and the next waterhole's upstream end contributed to the loss of Tardetakarinna waterhole. An area of particular threat is at Algebuckina Pinch. If a channel is established between West Algebuckina and Algebuckina Waterhole, the silt accumulated in West Algebuckina will move downstream, and destroy the refuge value of Algebuckina Waterhole. The most likely management action to create such a channel through Algebuckina pinch would be if the Algebuckina road crossing was raised and the flow directed through culverts. Such an action would concentrate the force of the flow and create valley-floor incision. Ideally Algebuckina crossing should remain a low-level causeway. If a raised road is considered necessary in the future, the road should be on a bridge high enough to allow the full flow of water.

The earliest European settlers in Australia often followed best-practice farming techniques which worked well in England. Only much later was it realised that those practices were inappropriate here. In the same way, there may be a desire to "restore" or "revegetate" Neales Catchment landforms in a way that is best practice elsewhere in Australia. The Neales River is different from other Australian rivers, and its landforms won't look the same as the Murray, the Todd, or the Barwon. Some parts of Australia had rivers that were chain-of-ponds before European settlement, but that was not the case here. Cautious investigation should take place before deciding that Neales landforms should somehow look different than they currently do.

4.3 Recommendations

Management guidelines should be written in a way which recognises that no waterhole is permanent, and that new refuge waterholes may be created. The definition of refuge waterholes should not be in terms of a fixed geographic point, but should be flexible to account for the changes that time may make to the landscape.

Large floods and megafloods are inevitable, although they may not occur for a very long time. When they do occur, they will look like massive destruction. It is important to remember that they are a natural force of landscape renewal. Rather than trying to "fix" the scouring or sediment dumps they have created, it would be best practice to manage total grazing pressure in vulnerable areas, so that vegetation may establish on the new landforms.

Management actions instituted as a result of the Critical Refugia project are likely to aim to reduce gully erosion and rehabilitate gully networks. It is important to monitor ongoing landform development to assess if management actions have been effective. Hydrographic surveys of the key waterholes need to be properly located in 3-D coordinate space. Aerial photography, LIDAR, or Quickbird imagery is necessary to monitor erosion gullies (Landsat and SPOT are not of sufficiently high resolution).

It is possible that some of the gullying and valley-floor incision have occurred in geomorphically vulnerable areas. The possibility that either 1) the erosion existed already or that 2) relatively mild land use merely hastened an inevitable change, is likely to make a difference to management priorities. This is a difficult question to resolve and further investigation is recommended. A small-scale project investigating archival aerial photography will provide valuable information about the inception and speed of development of gully networks, and is strongly recommended. It is also strongly recommended that a doctoral-level investigation of the Peake-Neales confluence be undertaken to investigate the origin and management responses to the arroyos and badlands.

5 Index

(**bold** page numbers indicate definition)

A1 Technical Appendix 1: Glossary of Fluvial Landforms

This report's fluvial landform terminology is defined below. Note that many of the existing words first described temperate-zone landforms, and so carry implications for landform function which don't apply in the Neales Catchment. For example, the word "river" is defined in Australia's own Macquarie Dictionary as "a considerable natural stream of water flowing in a definite course or channel" – clearly not the case here.

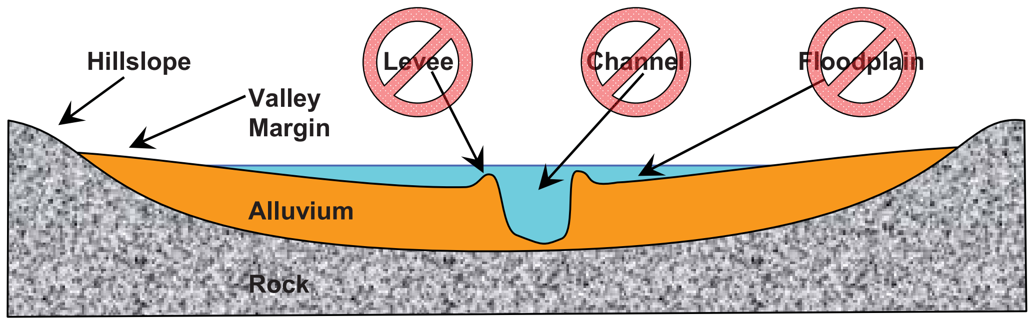


Fig. A1.1 Valley-scale and reach-scale fluvial landforms. The red crossed circles are a reminder that the terms levee, channel, floodplain, have different implications in the Neales River in comparison to their meanings in temperate-zone geomorphology.

A1.1 Valley-Scale Features

Alluvium is sediment which has been transported and deposited by the river (Fig. A1.1). The **alluvial valley** is the wide flat patch of alluvium within which the river sits. Alluvial valleys are flanked by **hillslopes** (Fig. A1.2), which in this report specifically refers to slopes not deposited by fluvial action. The **valley margin** is that part of the alluvial valley which is close to the hillslope base, where the alluvium can be expected to be very thin. A **reach** is a unit of scale expressing the amount of river valley that holds a substantial bit of channel or landform; usually a reach is several kilometres, but in a small creek it may be hundreds of meters. A reach usually has some defining common feature: geography (e.g. "the Oodnadatta north reach"), or landform ("this reach contains no waterholes").

A **bedrock river** or **bedrock channel** is one in which the river is cut into exposed rock, rather than sitting in a layer of its own alluvium. The most familiar examples of bedrock rivers are mountain streams or rivers cut through gorges, with rocky cliffs on either side, and bedrock and boulders exposed in the channel. However, a bedrock

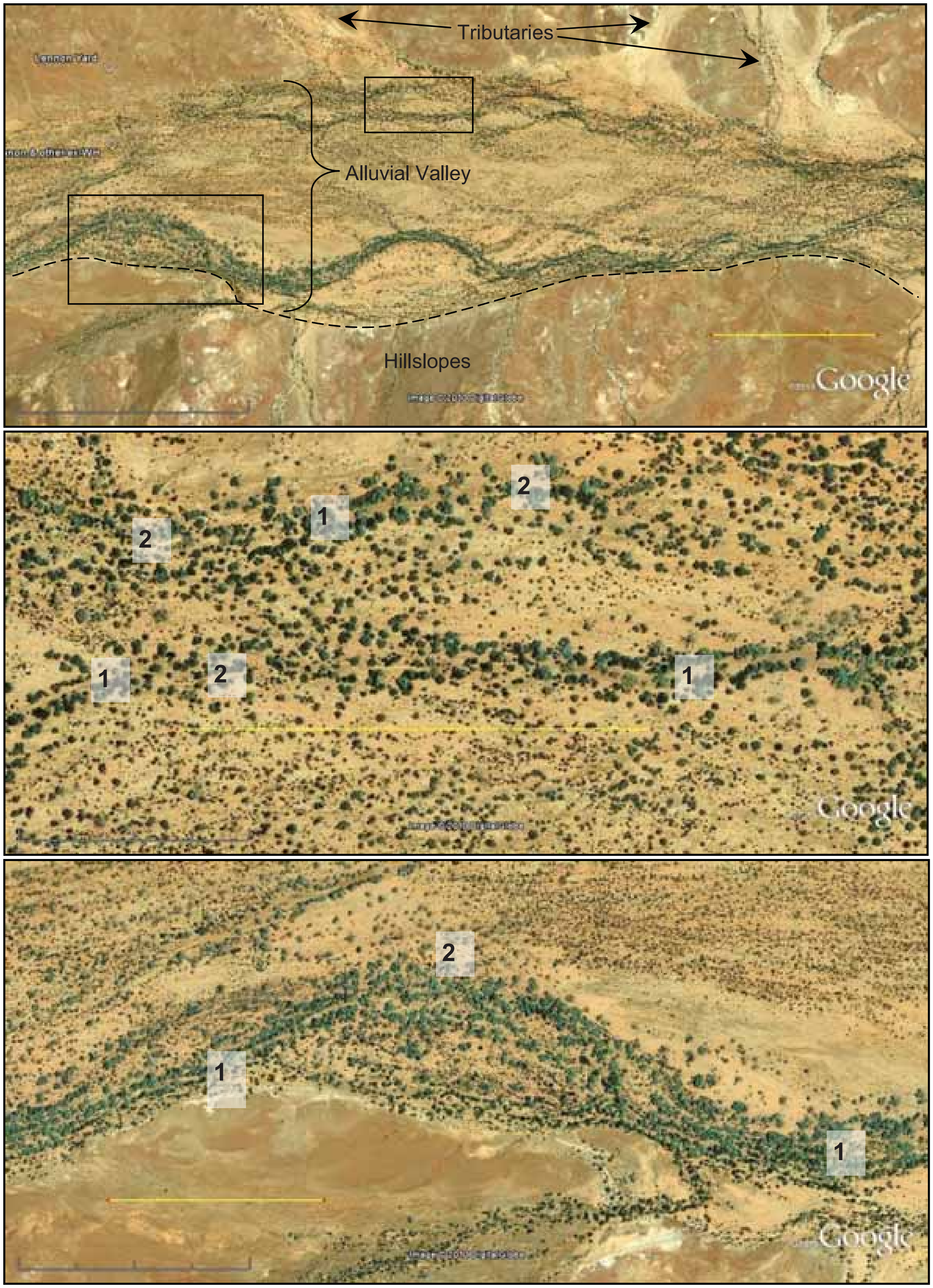


Fig. A1.2. Channels in the south branch of the Neales River. Top: Downstream from Lennon ex-waterhole, the south branch of the Neales River appears to be a “normal” assemblage of floodplain and continuous creek channel, in this case a primary meandering channel along the valley south, and an anabranching secondary channel along the valley north. North to top, scale bar = 1 km, boxes show locations of detailed views. Middle: However, the secondary channel is discontinuous, with alternate well-defined (1) and poorly-defined (2) reaches. Yellow scale bar = 0.5 km. Bottom: the primary channel, while more continuously well-defined (1), also has poorly defined reaches (2). Scale bar = 0.5 km.

river can also be one in which the bedrock is "covered by an alluvial veneer which is largely mobilised during high flows..." (Tinkler & Wohl 1998). The Neales River alluvial valleys are wide and shallow everywhere upstream of the lower Neales (there was insufficient field time to investigate the lower Neales in detail). Given the Neales' flow variability and the certainty of megafloods through this system, at least some Neales reaches will operate as bedrock channels at least some of the time. Bedrock rivers have different features and processes to alluvial rivers (Tinkler & Wohl 1998) and this is discussed further below.

In the Neales, the **primary flow path** is the line down which water most often flows, the first continuous path of inundation once the river has risen above cease-to-flow depth. It is usually marked by a belt of large trees (coolibahs, river gum, or acacias). It is not necessarily along the lowest part of the alluvial valley.

In "normal" (temperate-zone perennial) rivers, channel and floodplain are clearly separate entities. The channel is the relatively narrow and deep landform which is the primary flow path, and ordinarily contains all the water. The wide flat floodplains accommodate excess water during flood events; they are not part of the normal flow path. In the Neales River these things are different. Parts of the primary flow path occur over the floodplain; while there are some places where a channel is clearly defined, there are many places where it is not. In this report the terms **channel** and **floodplain** broadly retain the physical description (narrow/deep versus shallow/wide) but it is important to note that the "normal" process definition (ordinary flow versus flood flow) is completely meaningless here. In the Neales, a process definition probably relates to floodplain inundation and cease-to-flow depth: possibly a channel retains water after the system as a whole has ceased to flow. However the boundaries are so fuzzy that it is probably better to deal with each landform on a case-by-case basis.

A1.2 Types of Channels

The Neales River has a wide variety of channel types: ordinary channels, channel segments, riffles, waterholes, small channels, and small-channel complexes. There is no clear-cut difference between small channels, channels, and waterholes: there are many things that might be a large channel or a small waterhole. To some extent it depends whether you see them dry or full of water.

Ordinary **channels** are usually visible in the Google Earth images as a double line of trees (the riparian fringe), flanking a relatively clear space which is where the water flows. Although "normal" (temperate-zone perennial) river channels are continuous, in the Neales River the primary flow path is dominantly discontinuous, alternating between clearly-defined channels (or short **channel segments**) and poorly-defined areas of more diffuse flow (Fig. A1.2). These poorly-defined areas may be **riffles** (wide and gravelly) or they may just be wider and shallower channels. In either case, large trees growing all over the channel bed rather than just along the riparian fringe are characteristic of these poorly-defined areas. Where the primary flow path is clearly visible (for example, see Fig. A1.2) but does not consist entirely of channels, it might be referred to generally as the **creek bed**.

Fig. A1.3 The small-channel complex to the north west of Angle Pole Waterhole.

The small channels are similar to ordinary channels, but smaller: not visible on Google Earth unless the view is from very close in, and only several metres wide. Small channels seem to be more likely to silt up between big flows, but then small flows cut into silted-up channel bed. **Small channel complexes** are groups of small torturous channels, usually linking other, larger flow path elements. Typically they are small, and deep for their size, and densely vegetated – they look to be biologically quite rich (Figs. A1.3, A1.4).

Channels come in different planforms (like a plan, the way they look from above). Each planform reflects a certain type of fluvial process, in response to specific conditions of slope, stream power, and sediment load. **Meandering** channels are sinuous, their channels migrate sideways incrementally, and they form in response to excessively steep downvalley slopes for the scale of their discharge. The lower Neales River is meandering for part of its length. **Arroyos** are steep-sided, flat-bottomed channels. Unlike the other fluvial styles, arroyos do not construct the

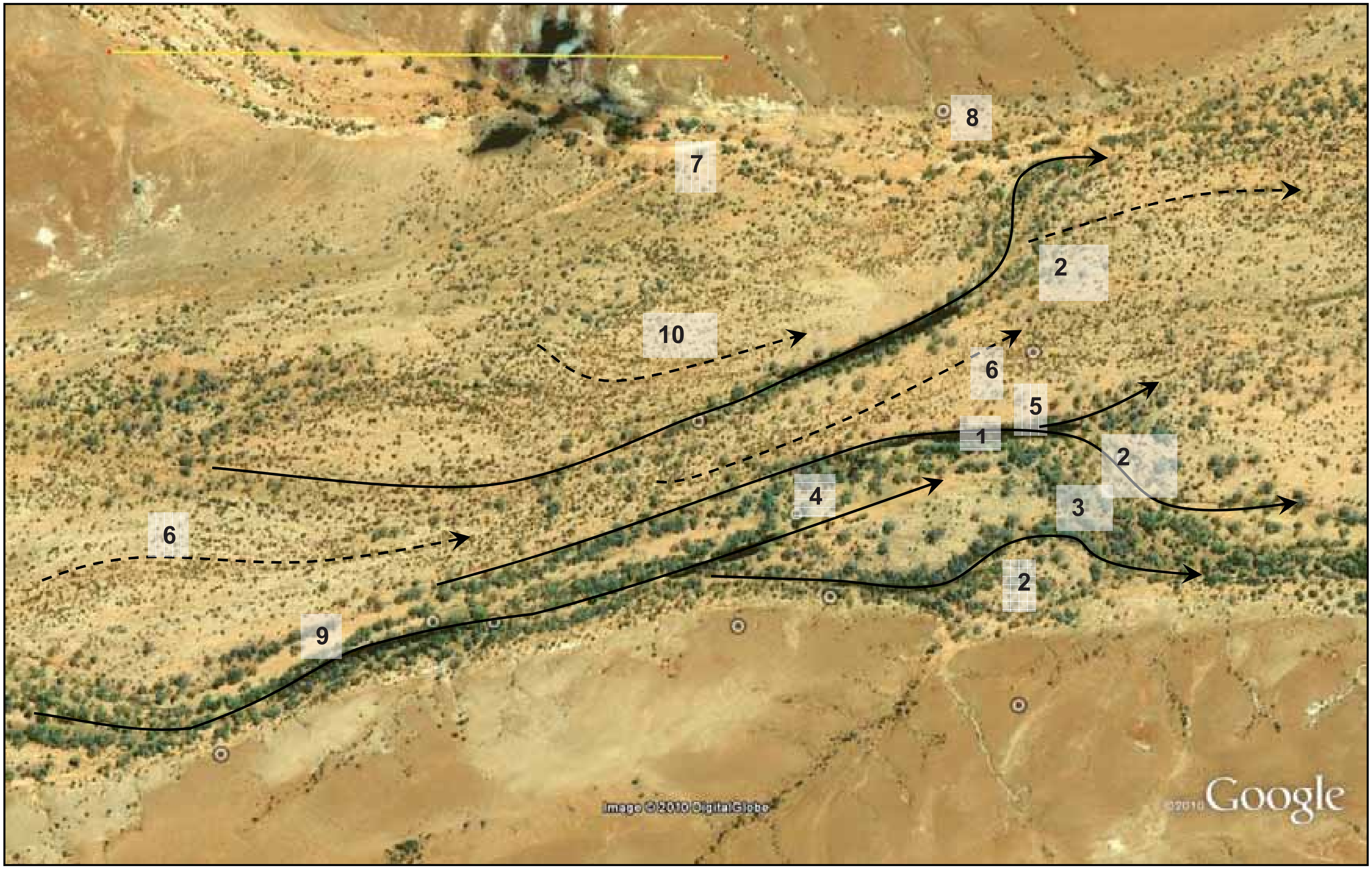


Fig. A1.4 Google Earth image of floodplain and channel landforms in the 4-Waterholes area of South Branch, ~4 km WSW of Lennon's Yard; white circle are geology sites, north to top, yellow scale bar = 1 km. Flow is from left to right, black lines show main flow paths, dashed black lines show the most prominent floodplain-height flow paths. Numbers indicate landform examples: 1 waterholes, 2 riffles formed on downstream splays, 3 a dry swamp, 4 small channel complexes, 5 silty high plain, 6 hummock fields, 7 tributary channel and floodplain, 8 valley margin, 9 two abandoned channels run parallel to the present waterhole, 10 lines of large trees along frequently-inundated flow paths.

floodplain through which they flow: they are entirely erosional in their nature. The upstream end of an arroyo is usually a head-cut **gully**, or a complex of gullies (**badlands**). The Neales River downstream from the Peake-Neales confluence is badlands and arroyos.

Braided channels are multi-thread (have many primary flow paths in the same reach), contain frequently-overtopped unstable bars, and no floodplain. Old references describe Australian inland rivers as braided however this is now known not to be the case. The Neales River is **not braided**. Anabranching rivers are also multithread, and have a number of hydraulically independent channels (**anabranches**) separated by floodplain-height stable vegetated bars. Each anabranch can have its own fluvial style (for example, Fig. A1.4). Anabranching forms in response to insufficient stream power to carry the sediment or fluid load. The Neales is anabranching in many of its reaches. Much of the Neales floodplain is covered by a fine network of flow paths and small channels, and this is best described as an **anastomosing** planform. This is also a multithread type of river. The differences between anabranching and anastomosing are the subject of current academic debate. In the Neales, it's probably best thought of as anabranching being something large-scale that the primary flow path (major channels) might do, whereas the valley-wide flow of floodplain inundation by many small waterways is anastomosing.

Channel continuity is that quality where a channel is continuous all the way down the primary flow path – like a "normal" river. Continuous channels are efficient in transporting their discharge downstream. The more efficient a channel is, the less chance water has to infiltrate into the floodplain. Channel continuity is not a desirable characteristic in arid-zone streams. **Discontinuous streams** have alternating channelised and unchannelled reaches (Bull 1997, Wakelin-King & Webb 2007, and Fig. A1.4). Many Australian arid-zone discontinuous streams alternate between arroyos and **floodouts** (reaches where the river is 100% floodplain, see Tooth 1999), however in the Neales the alternation is between channels and floodplain-level flow.

Waterholes are particularly large and deep channel segments (Figs. A1.4, A1.5). Neales waterholes are typically long and straight but characterised by irregular features such as hooks and curves. There is a gradation of form between channels and waterholes, and a big grey area in the middle, where something can be either a large channel or a small waterhole. In part the definition is physical: ka waterhole is a channel segment which retains water for a long time (whereas a channel goes dry fairly quickly). This physical definition implies two things, firstly a certain depth such that the water takes a long time to evaporate (Costello et al. 2005), secondly a lack of channel continuity such that the water doesn't drain out. The definition of waterhole is also cultural: useful sources of water tend to be given names and called "Waterhole", even if in other circumstances they are actually fairly small and not likely to be long-lasting. An example of this would be Afghan Waterhole, which is quite small and looks quite shallow on the Google Earth image. Afghan is located in an area with many other waterholes, most of which don't have names recorded on the 1:250,000 topographic map. Its name and significance may derive from being the water source used by a particular (possibly isolated) community segment in early days of settlement.

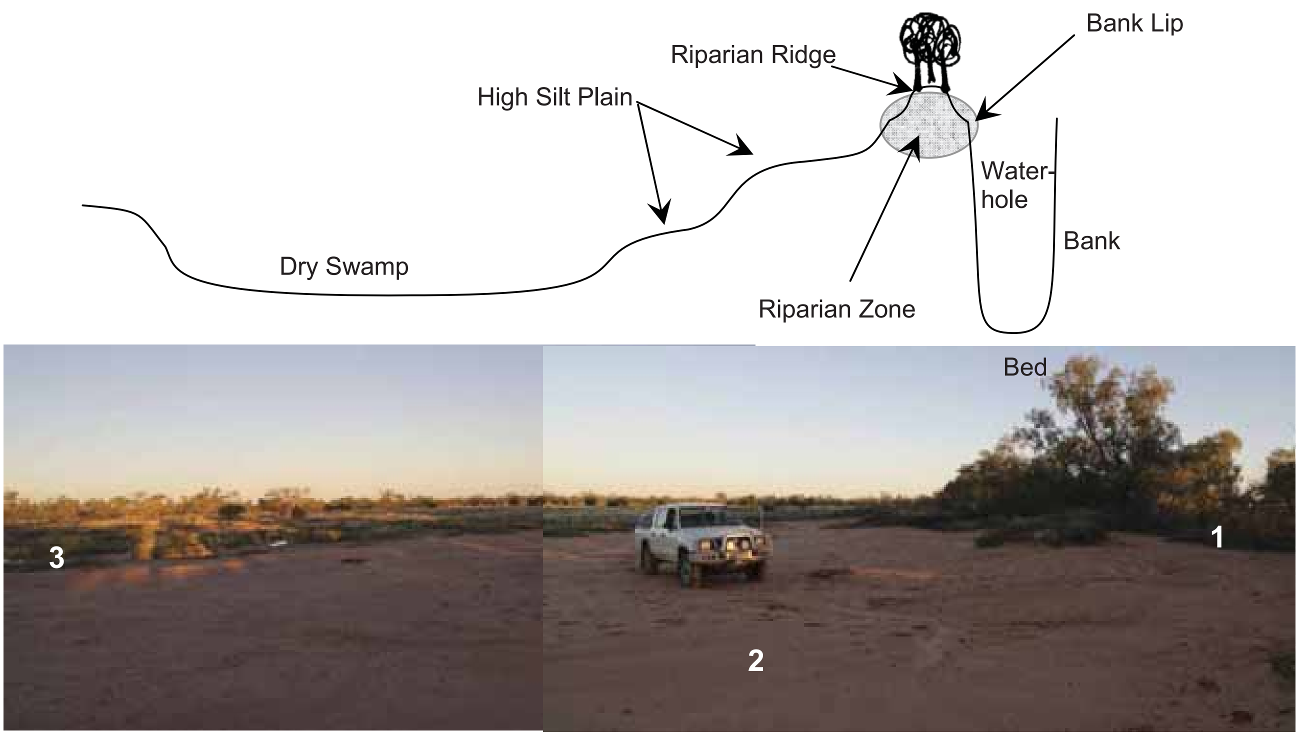


Fig. A1.5 Channel and floodplain landforms at Hookeys Waterhole, looking south towards the road from a camping area ~0.5 km away from the road. Waterhole is to the right. Top: sketch of landform relative elevations (not to scale). Bottom: photo, corresponds to the sketch. 1, a belt of trees along the riparian zone, the waterhole is out of sight beyond them; 2, the high silt plains, 3, a dry swamp.

A1.3 Landforms of the Channel and Channel-Margin

A waterhole or channel has a **bed** (the floor of the channel) and **banks** (the sides). At the top of the banks is the **bank top**, and there is often a **lip** or edge (Fig. A1.5). Sometimes "banks" is used to mean bank tops, but it's usually clear from the context.

Typically a channel or waterhole has a **riparian zone** along the banks, where vegetation benefits from extra moisture. In the Neales the riparian zones are characterised by a belt of large trees (mostly coolibah) and dense understory (grasses and chenopods). The trees growing along the bank lip often lean over the water, or have branches extending out almost horizontally, with an "elbow" dipping towards the water (Fig. A1.6). Commonly the lower parts of the "elbow" will have no leaves or small branches, or a few broken-off stubs, whereas there will be normal foliage above.

Fig. A1.6 Mt Carulinia Waterhole, on a tributary to the Neales South Branch. Riparian trees lean over, or have branches extending over the water. Branches have "elbows" which dip down to the water surface.

In the Neales the smaller channels and waterholes (those which were dry and could be examined) had steep to vertical and sometimes embayed sides. Transported sediments were only present as small end-flow mud drapes, or sometimes a little silty channel-fill from small short flows; bedload is hardly ever present and the beds are generally scoured into the floodplain. The beds in small channels had gently undulating floors, without a continuous thalweg (the line defining the lowest points along the length of a river bed). The larger waterholes have more pronounced irregularity on the bed surface. The fish monitoring team report that there is commonly a "low-flow channel", a narrower and deeper inset channel within many waterhole floors (D. McNeill pers. comm. 2010). Waterhole cross-section data collected by the hydrology team confirms the presence of an inset channel in some waterholes (J. Costelloe pers. comm. 2010). The inset channel has a complex topography: its levels are uneven and it can cross from one side to the other (Fig. A1.7), it is not merely a smaller narrower version of the waterhole.

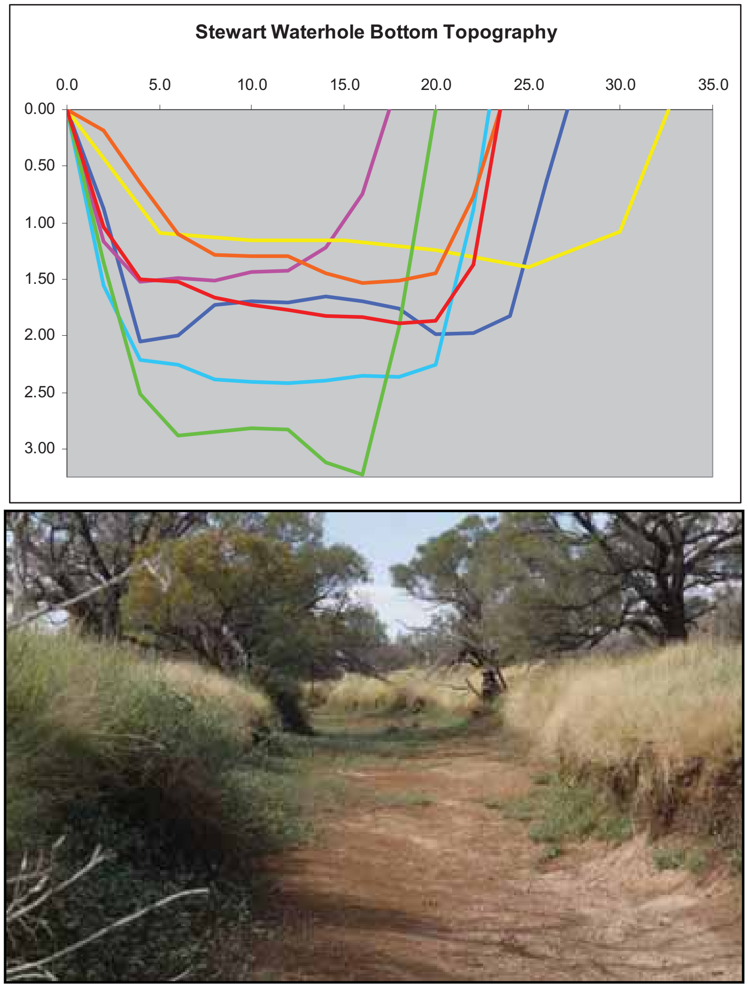


Fig. A1.7 Channels and waterholes have scoured, irregular bed topography. Top: Surveyed Stewart Waterhole cross-sections (raw data from J. Costelloe, pers. com. 2010). Because of survey logistics, the sections on this graph are all artificially right-bank aligned. From upstream to downstream, the section order is red-orange-yellow-green-light blue-blue-violet. Bottom, embayed banks and a scoured uneven bed of a small channel near Farley dam, east of Elbow Bend.

Many rivers have a raised area of sandy or silty sediments along the banks, known as a **levee**. In "normal" rivers the levee is formed by floodwaters overtopping the river banks, and depositing the coarser elements of the river's suspended sediment load along the bank top closest to the river. In the Neales there are many waterholes without levees. However, many channels and waterholes have **high silt plains** next to them (Figs. A1.5, A1.8). These are high flat plains of hard, quartzose silt, usually bare or with little vegetation (unless a hummock field is developed upon them). In some, the high silt plains are a narrow band along the bank top, exactly as classic levees, but more typically they occur on the downflow side of the waterhole or channel (Fig. A1.8). They are also different to levees in that they often do not occur on both sides of the channel. In some waterholes there is a further bank top landform, the **riparian ridge**, a very narrow (~2 m) but relatively long and high (tens of metres, ~0.75 m) ridge of sediment, usually heavily colonised by nitre bush (Fig. A1.5). In a few of the largest waterholes, the riparian ridge is set back a little way from the bank top.

In the Neales River it is common that the most prominent channels and waterholes are not located in the lowest part of the alluvial valley. Rather, they tend to occur on the side slope of a slight rise in the valley, and the larger waterholes tend to be perched in the middle of pronounced linear rises. These rises are the high silt plains.

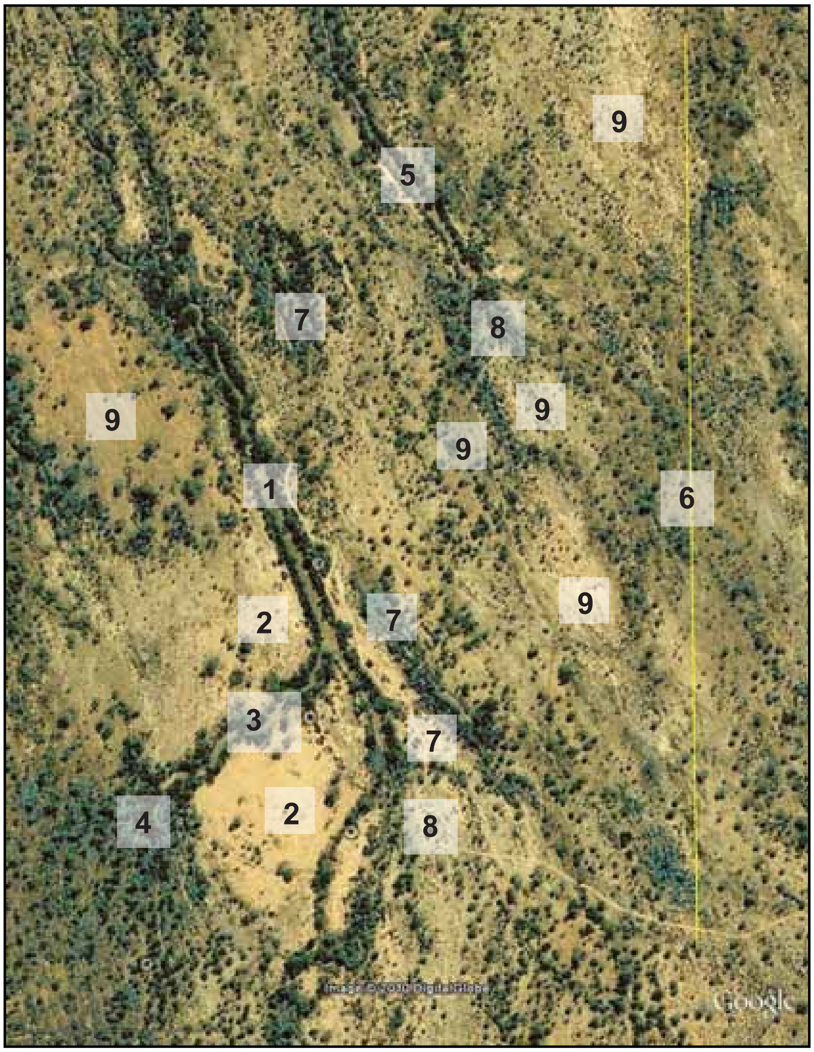


Fig. A1.8 Google Earth image of the smaller waterholes 1 km NNE from Hookeys'; north to top, yellow scale bar = 1 km, flow top to bottom. Numbers: 1 main waterhole, 2 high silt plains, 3 a "sideways channel", 4 the sideways channel finishes downstream in a biologically rich floodout area, 5 the smaller waterhole, 6 a complex floodplain of small channels, hummock fields, and poorly-defined flow paths, 7 small scours, 8 splays, 9 high silt plains from previous waterholes and channels.

The upstream ends of waterholes are sometimes blunt, with no obvious channels going into them, though more often there are small channels or other flow paths that deepen and widen abruptly. The downstream ends of waterholes and channel segments must necessarily have a reverse gradient (where the downvalley direction has an uphill slope), since the bed has a lower elevation than the floodplain. Waterhole and channel ends have characteristic terminations:

- the smaller ones tend to shallow abruptly, with the bed rising in a series of undulations to a floodplain-height finish
- some medium-sized ones finish in gravelly riffle reaches, with very coarse sediment, large bars, and large channel capacity (all indicators of substantial discharge)
- many medium-sized waterholes and all large waterholes finish in **splays**: a pod of silty and sandy sediment, roughly the same elevation as the high silt plains (that is, slightly above the level of most of the floodplain). Downstream splays are also a feature of Cooper Creek waterholes (Knighton & Nanson 1994). Splays are important in protecting waterhole integrity (by acting as a barrier to connectivity).

The riffles and splays form a barrier across the downstream end of channels and waterholes, and for that reason there is a great tendency for downstream channels to go around corners at this point (Fig. A1.4). Characteristically, splays are cut by a

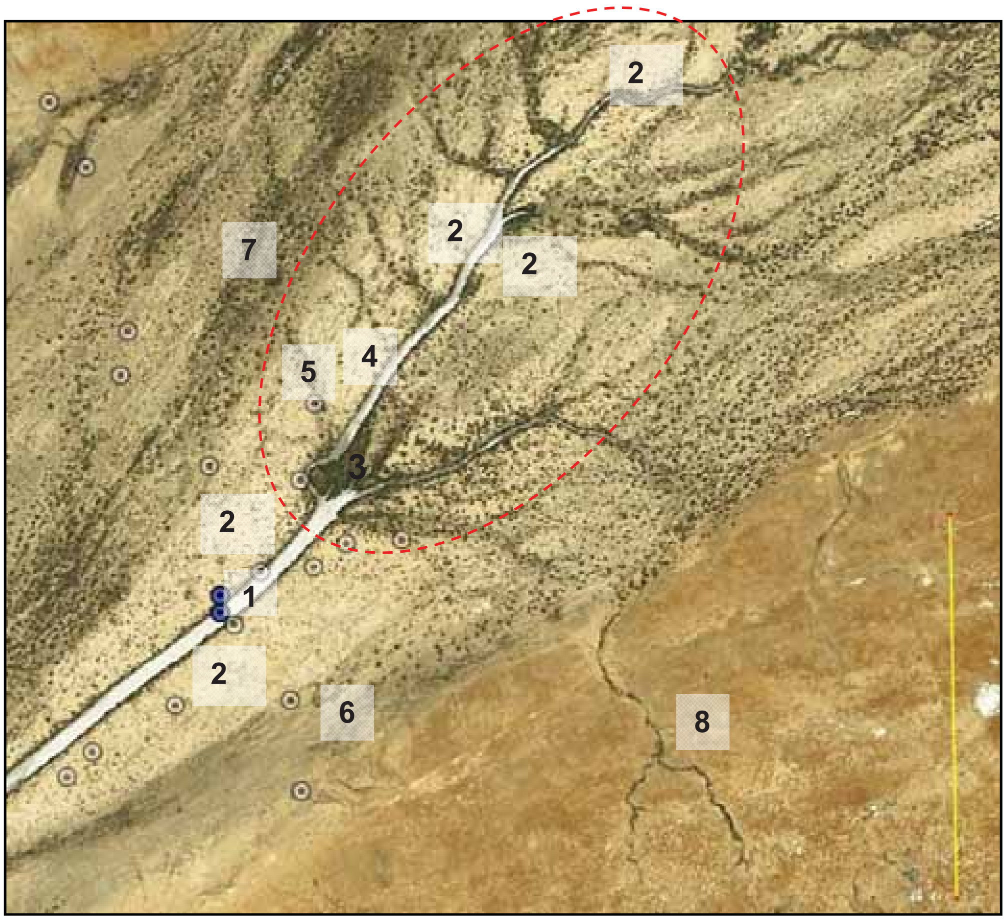


Fig. A1.9 Google Earth image of the downvalley part of Algebuckina Waterhole, and its very large splay complex (circled); north to top, yellow scale bar = 1 km, white dots are geomorphology field sites, blue dots are hydrology sites. Numbers: 1 the waterhole, 2 high silt plains flanking waterhole and splay channels, 3 a densely vegetated part of the splay, 4 the biggest distributary channel becoming a waterhole in its own right, 5 a small channel cutting across the high silt plain 6 south bank low area, 7 north bank low area, 8 rocky hillslope.

number of smaller **distributary channels** fanning out from the waterhole or channel end. The beds of these distributary channels also have reverse gradient. The concentration of small channels, in which water is trapped after cease-to-flow, creates a biologically rich area (Fig. A1.9); these landforms are ecologically and geomorphically equivalent to riparian zones, although they are not technically riverbanks. Some distributary channels extend downstream to become waterholes in their own right with their own high silt plains (Fig. A1.9).

Some waterholes have a "**sideways channel**", in which a substantial channel leads from the waterhole at a direction almost perpendicular to the general flow direction (Fig. A1.8). They do not appear to be just an extreme example of a splay channel going off at an angle; they look to be a separate feature in their own right. Small channels draining the Algebuckina splay channel (Fig. A1.9) have a similar configuration.

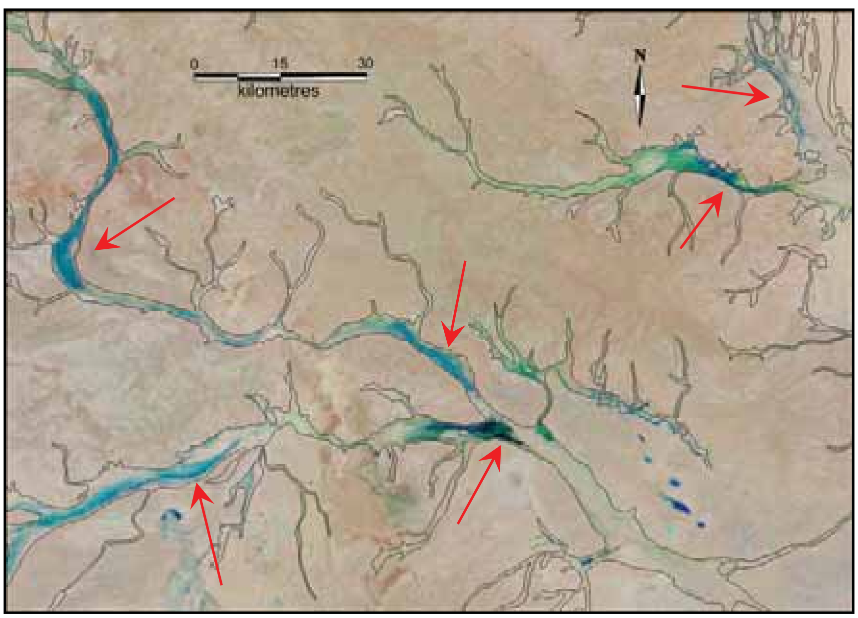


Fig. A1.10 MODIS satellite image showing the Neales River from Afghan Waterhole to the delta apex, during a ~1:10 flow event December 2009. The floodplain is outlined in black, vegetation shows as green, and water is blue. There are six separate flood pulses (red arrows) and in several places they occupy the entire alluvial

A1.4 Floodplains

In the Neales River the floodplains carry a substantial component of the flow – unlike "normal" rivers, flow across the floodplain is not an unusual event. The December 2009 flow (which had a 1 in ~10 recurrence interval, J. Costelloe, pers. comm. 2010), for example, inundated the whole Neales floodplain in the Oodnadatta, Elbow Bend, Farley's, Mount Dutton, Eaglehawk, and Wirriarrina reaches, as well as most of the Peake and Macumba floodplains (Fig. A1.10).

The Neales floodplains are strongly marked by flow paths, often right to the valley margins and often very complex, deviating strongly from the general downvalley direction. The flow paths are most visible in the lines of trees and shrubs oriented in

Fig. A1.11 Hummocks and hummock fields. Top: Google Earth image of a small-channel complex just upstream from Angle Pole Waterhole, flow direction (red arrows) is shown by vegetation lines and small waterway alignment. The left red arrow points to a white circle indicating location of the middle photo. Centre: In the main flow path a miniature scour is flanked by steep silt hummocks, each of which are vegetated by a straight line of trees. Jay, sitting beneath tree on photo right, for scale. Bottom: Looking upstream at the silty tales of large hummocks with nitre bush; near the Algebuckina north-western bank. Jay for scale.

the flow direction, visible on Google Earth images (Figs. A1.4, A1.11). **Lines of large trees** (mostly coolibahs, some eucalyptus or very large acacias) are mostly associated with small channels or dry channel segments (landforms which are on the borderline between one thing and the other: they carry above-floodplain flow, but look like channels).

Hummocks are mounds of fine sand and silt deposited in and around woody bushes such as nitre bush. Hummocks are streamlined in shape, oriented according to flow direction across the floodplain, and hummock height is scaled to flow depth. Other researchers have referred to these as coppice or coppice dunes (Croke et al. 1998) however that term is not used here because it has specific connotations of formation during grazing-induced degradation (McKee 1967, Rango et al. 2000). Some hummocks may be tens of metres long consisting of a train of bushes. Typically hummocks occur in groups: **hummock fields** (Figs. A1.4, A1.11), occurring where above-floodplain anastomosing flow has been strong enough to transport silt and sand, despite the great roughness of the flow path. These flows are at least equal in depth to the height of the hummock sediment: up to 1.5 m in places (Fig. A1.11). Many hummock fields are not associated with defined channels, however hummocks also occur flanking isolated valley-margin floodplain scours (these are some of the biggest hummocks), and flanking channels in small-channel complexes (Fig. A1.11).

Dry swamps are very wide and shallow scours into the floodplain (Fig. A1.4, A1.5). They collect water but it soaks in or evaporates fairly soon. Dry swamps are boggy when they are wet, and moderately well vegetated, but the vegetation may not contain any large trees, or the trees may be dead (having germinated and grown after some good flows, but dying when the water supply dries up). There is a degree of overlap between small-channel complexes and dry swamps, here defined on a functional basis (small-channel complexes transfer water downvalley, dry swamps are less likely to do that).

Many floodplains are marked by **small scours** (Fig. A1.8), which are exactly similar to channels and waterholes (straight planform, scoured bed, edged by dense vegetation) but on a much smaller scale. The smallest one seen in fieldwork was only 1 m long and was located on the crest of a high silt plain. They occur in all sizes grading up to small channel segments.

In some reaches the floodplain has no strongly-marked primary flow path, no single channel bigger than the others, no waterholes. In these **anastomosing reaches** flow is distributed across the width of the alluvial valley in a network of small channels, channel segments, and hummock fields (Figs. A1.11, A1.12). These reaches include the Wurley-Breadon reach in the Neales South Branch, the Andy Camp reach in the Neales North Branch, the Elbow Bend area, Cliff-Wirriarrina reach and Eaglehawk reach. Most of these reaches are characterised by very wide valleys, and a few have extra-low slopes. In addition, Eaglehawk and Cliff-Wirriarrina reaches are downstream from Algebuckina (and therefore somewhat buffered from flow variability).

A **floodout** is where a river ceases to flow between banks, and the channel disappears: flows spread out across the whole floodplain as sheetflow (Tooth 1999). The processes which give rise to floodouts, and which sustain them, make arid-zone floodouts biologically productive and valuable ecological refugia (Bull 1997, Wakelin-King & Webb 2007). Floodouts are equivalent in ecological and geomorphic function to riparian zones along river banks (Wakelin-King 2006, Wakelin-King 2008). In the Neales Catchment, large floodouts occur in the Peake Floodout (upstream from the Denison/Davenport Ranges), and in the tributary junctions where Wood Duck Creek and the Peake River enter the Neales (Wood Duck Floodout and Peake-Blyth Floodout respectively) (Fig. A1.12). In these areas, the channels do not entirely disappear, but rather concentrated channelised flow entering the floodout spreads out as many small distributary channels. The floodouts look similar to the anastomosing reaches, however their context, geomorphic processes, and management implications are different.

At the Peake-Neales junction, water is carried by **a diffuse flow path** (Fig A1.12): an elongate area of slightly lower elevation than the rest of the floodplain. It lacks clear large channels, but has a few isolated channel segments, flanked by silty hummocks. It has a network of thickly vegetated small channels, and some hummocky areas, but does not resemble the anastomosing reaches. Its sediments (heavy cracking clays) are finer than the rest of the Neales floodplain.

A shadow bar is a block of sediment deposited behind some obstacle in the middle of the flow path. As the flowing water goes past the obstacle, downstream turbulence allows the deposition of sediment. The hummocks described above are a type of shadow bar. In the Neales Catchment, two **high-level shadow bars** were observed,

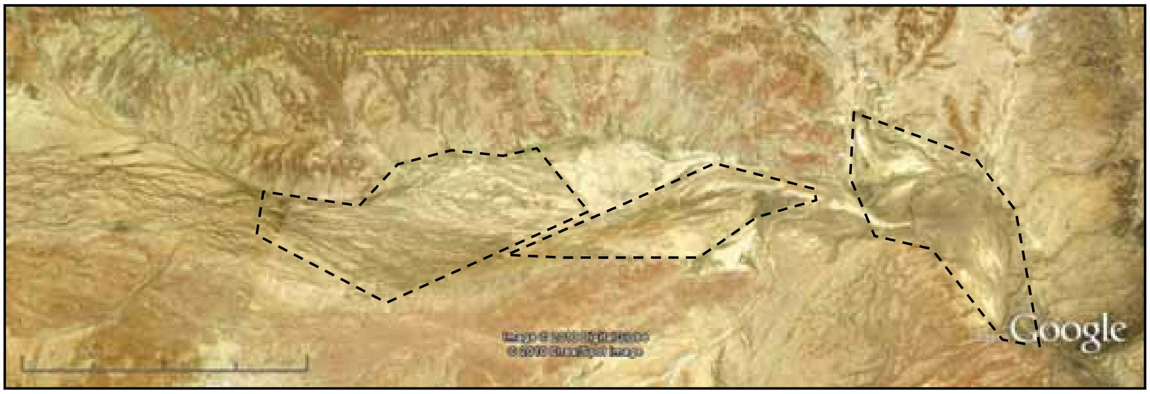
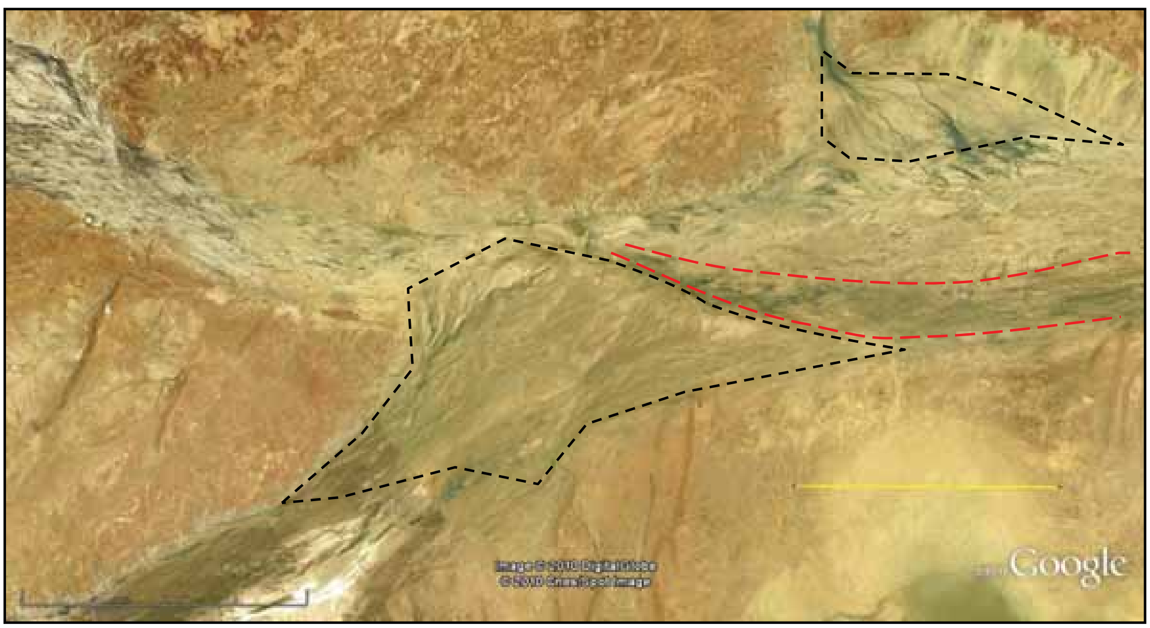


Fig. A1.12 Google Earth images of floodouts in the Neales Catchment. Top, the Peake Floodout, upstream from the ranges; Peake Siding is near the “G” of the Google logo. Yellow scale bar = 10 km, north is ~10° clockwise from top, flow left to right. Dashed lines outline floodout lobes resulting from episodic sediment delivery into the area. An anastomosing reach is to the west (left). Bottom, tributary-junction floodouts outlined by dashed black lines at Wood Duck (top right) and Peake-Blyth (centre). Dashed red lines outline the diffuse flow path. Flow is from bottom left (Peake) and top left (upper Neales) to right. Yellow scale bar = 5 km, north is ~20°



one in the Peake Gap (where the Peake river flows through the Denison/Davenport Ranges, just near Freeling Springs), and another not far from Hookeys Waterhole. There are undoubtedly more. In the two observed high-level shadow bars, low hills of rocky outcrop rising above the floodplain accumulated sediments downstream from them. The sediments were similar to the high silt plains (bare, quartzose fine sediment) but their elevation was visibly above normal fluvial processes.

A **rill** (or rill network, or **rilling**) is a shallow (0.5-2 cm deep) set of erosive mini-channels, typically cut into gently-sloping landforms on floodplains and hillsides. Rills collect runoff and feed it downslope into small channels, which increases the erosive power of the flow. In the Neales reaches where erosion is a problem, rill networks lead downslope to gullies cutting through waterhole banks, or to badlands dissecting valley floors.

A2 Technical Appendix 2: Detailed Geology & Geomorphology

A2.1 Geology

A2.1.1 Rock Units and Surface Lithologies

The geology of the Neales catchment shown in Map 2 is derived from the Geoscience Australia Geological Dataset, and unless otherwise referenced unit information is from Geoscience Australia (2010).

The oldest rocks in the catchment are Proterozoic shales, quartzites, phyllites, metasediments, granites and vein quartz, referred to collectively in this report as "basement" (brown on the geological map). They crop out most prominently in the Denison/Devonport ranges; smaller outcrops also occur at Mount Dutton and near Levi Creek.

The most widespread units in the catchment are the sedimentary rocks of the Jurassic to Cretaceous age Eromanga Basin (shades of green on the geological map). From oldest to youngest these are:

- the Algebuckina Sandstone and the Cadna-owie Formation, quartz sandstone with pebbles, conglomerates, siltstone and shale; these are important aquifers, carrying the slightly salty water of the Great Artesian Basin; they are also a source of sandy sediment, such that creeks flowing past these outcrops are much sandier than most creeks in the Neales catchment;
- the Bulldog Shale, which is impervious to water and confines the aquifers beneath it, thus creating the artesian properties of the water; where the "seal" of the Bulldog Shale is cracked by a tectonic fault or by onlap onto basement, the artesian water leaks to surface creating springs or salty surface deposits (Habermahl 1982, Krieg et al. 1991, Costelloe et al. 2005, Costelloe et al. 2008);
- the Oodnadatta Formation (claystone, siltstone, fine-grained sandstone) and the Winton Formation (lithic and feldspathic sandstone) overlie the Bulldog Shale.

A thin cover of Tertiary age sedimentary rocks (mostly grey on the geological map) occurs around the outer upstream 60 km of the catchment, most notably in the Oodnadatta area. A number of different claystones, dolomites, limestones and other lithologies were deposited ~45 Ma (million years before present) and ~15 Ma, including:

- the Yardinna Claystone, the upper layer of which is dense gypsum, forming buff coloured flat-top hills near Oodnadatta (Fig. A2.1)

- the Eyre Formation sheds distinctive highly rounded, very smooth pebbles and cobbles into the river in the Algebuckina area
- the Mirackina Conglomerate (orange on the geological Map 1) is a 140 km long ribbon of fluvial sediments

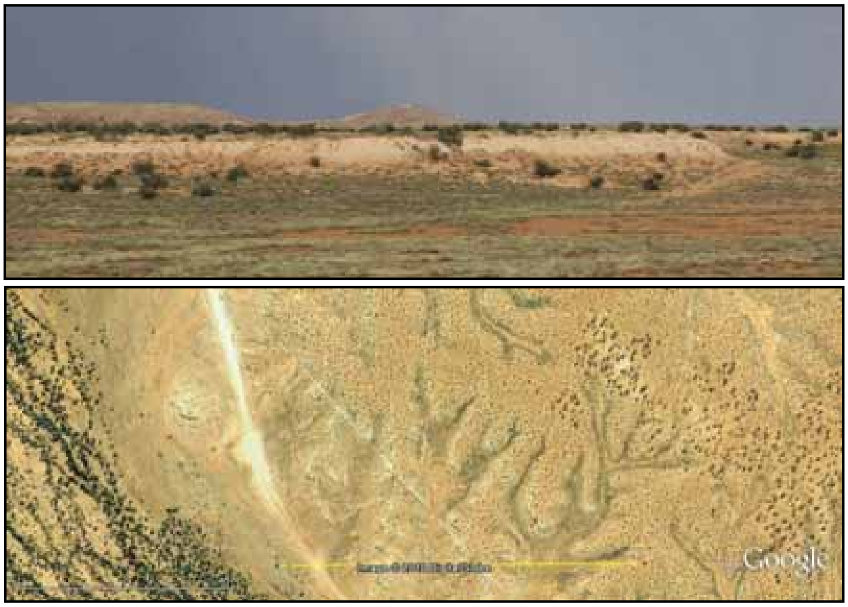


Fig. A2.1 Top: low flat-top hills, pale buff in colour, are gypsum layers of the Yardinna Claystone (red arrow). In the background, higher hills of dark ironstone. Bottom, Google Earth image of the gypsum hills (centre and right). Oodnadatta Track and the Neales River to the left, north to top, yellow scale bar = 1km.

Younger sedimentary rocks and sediments include limestones, colluvium, sand sheets and sand dunes, and sheet wash surfaces. The alluvium (pale blue on the geological map) outlines the drainage network and shows which river valleys have accumulated alluvial sediments.

These rocks have been near the earth's surface beneath a wide, flat plain for an immensely long time – in some cases, since the close of the age of dinosaurs (~65 Ma). During that time, there have been three episodes of intense weathering, during which the abundant groundwater filtering through the rocks leached them and precipitated silica or iron in the soil's capillary zone (Alley 1998). The result is that many of the less-resistant rocks (e.g. shales) are now relatively soft and prone to erosion, often showing bright white and dark reddish-brown mottling. On the other hand, the silica and iron groundwater deposits are now erosion-resistant capping stone on many flat-topped hills (silcrete and ferricrete, speckled pale brown and reddish-brown on the geological map), The hard rounded gibber which mantles most of the hillslopes – the gibber plain – is derived from the breakdown of silcrete boulders in a process that may take as long as a hundred thousand years (Asma 2008).

During the weathering, sulphate-rich groundwater deposited gypsum was widely deposited throughout the rocks of the weathering profile (Thiry et al. 2006). The Eyre Formation and the Coorikiana Sandstone are pyritic (Alley 1998) and may have been the source of the sulphate. As well as the Yardinna Claystone's upper layer of gypsum, all near-surface rocks in the basin contain gypsum plates, veins, or void fills of gypsum; soil gypsum is associated with the gibber plains, and a gypsite crust up to 3 m thick is widespread (Freytag et al. 1967, Williams 1976, Thiry et al. 2006, Asma 2008).

Fig. A2.2 Top: stony gilgai on the Flood Road near Hookey's Waterhole. Stony runoff surfaces shed rainwater, which is caught and held by less stony run-on surfaces (here, full of water from rain the previous week). Bottom, on this Google Earth image the stony gilgai is the pale and brown patterned ground. The red-brown ground without pattern is gibber plain without gilgai. Pale double line is the track, white dot is site of photo above, and yellow scale bar = 100m.

Some of the rocks in the Neales Catchment contain swelling clays (similar, but in a lesser degree, to clays of Australia's black soil plains). Where such clays accumulate in alluvial valleys, they form vertic soils (crumbly "self-mulching" soils which show very deep cracks when dry and are extremely boggy when wet). Where swelling clays are associated with gibber they form stony gilgai, a runoff-run-on land type in which rainfall is shared by sloping bare stony areas and intercepted by vegetated clayey flat areas which are characteristically centred around a very deep macropore ("crabhole") (Wakelin-King 1999). Stony gilgai is very distinctive in Google Earth because of the roughly contour-parallel arcuate patterning (Fig. A2.2). It can be quite biologically productive. Stony gilgai is widespread in the Neales Catchment. Its distribution is likely to be controlled by the thickness of the regolith overlying the clayey sediment: where the regolith is too thick, the swelling clays are not able to engage in gilgai processes; where regolith is too thin or absent, the swelling clays are rapidly eroded leaving only bare shale.

Tectonic movement (see below) during the Tertiary domed and uplifted the silcrete crusts, promoting erosion and removal of eroded material (Alley 1998).

The modern day hillslope surfaces:

- are almost entirely sites of erosion rather than sediment accumulation
- are exposed rock in many places, including basement rock, weathered shale, silcrete and ferricrete, all of which are likely to be high-runoff surfaces
- bare rock of the breakaways (steep scarps around the edges of mesas and flat-top hills) is likely to be the highest runoff surface
- are dominated by closely-packed gibber as a thin layer overlying fine silty sediment ("desert pavement", Fig. A2.3). Desert pavements originate in part from the upward migration of rocks through the soil profile, and in part from the accumulation of windblown sediments beneath those rocks. Such a hillslope is robust against erosion as long as the desert pavement is not disrupted, but can be prone to gullying otherwise. Desert pavement is a high-runoff surface
- in some places, hillslopes are mantled by a coarse poorly-sorted regolith overlying weathered rocks (Fig. A2.3), resulting from preferential removal of fine sediments
- hillslope fine sediments, where present, are generally likely to be nutrient-poor and gypsum-rich
- are commonly covered by stony gilgai, which is likely to be a relatively low-runoff surface (until the soil macropores are saturated)
- include sand dunes and sheet sand, which will be very low-runoff surfaces; however some areas shown as sand on the geological maps are actually high-runoff regolith surfaces.

Fig. A2.3 Left: The packed stones of a desert pavement are underlain by soft swelling clays and silts; footprints (above the hammer head) and wheel tracks sink in. Right: Sandy gravel regolith (red-brown) overlying white Bulldog Shale. Hammer for scale.

The alluvial valleys are opposite in character to the hillslopes surfaces in that –

- they are sites of sediment accumulation, at least between megafloods (see geomorphology below)
- the fine sediments are likely to contain nutrients and organic material
- the fine sediments are unlikely to contain crystalline gypsum, except in specific locations (6-Mile Arroyo, and near-spring floodplain salts as described in Costelloe et al. 2005)
- they are generally low-runoff surfaces (described in geomorphology section below).

The generally high-runoff nature of the hillslope surfaces, and the variation between high-runoff and relatively low-runoff surfaces, are important contributors to the flow variability of the Neales River. It is possible to roughly characterise land system units into high- and low-runoff groups (Fig. A2.4) however the disposition of different land surfaces is intricate, and more detailed mapping would be required to characterise runoff relationships accurately.

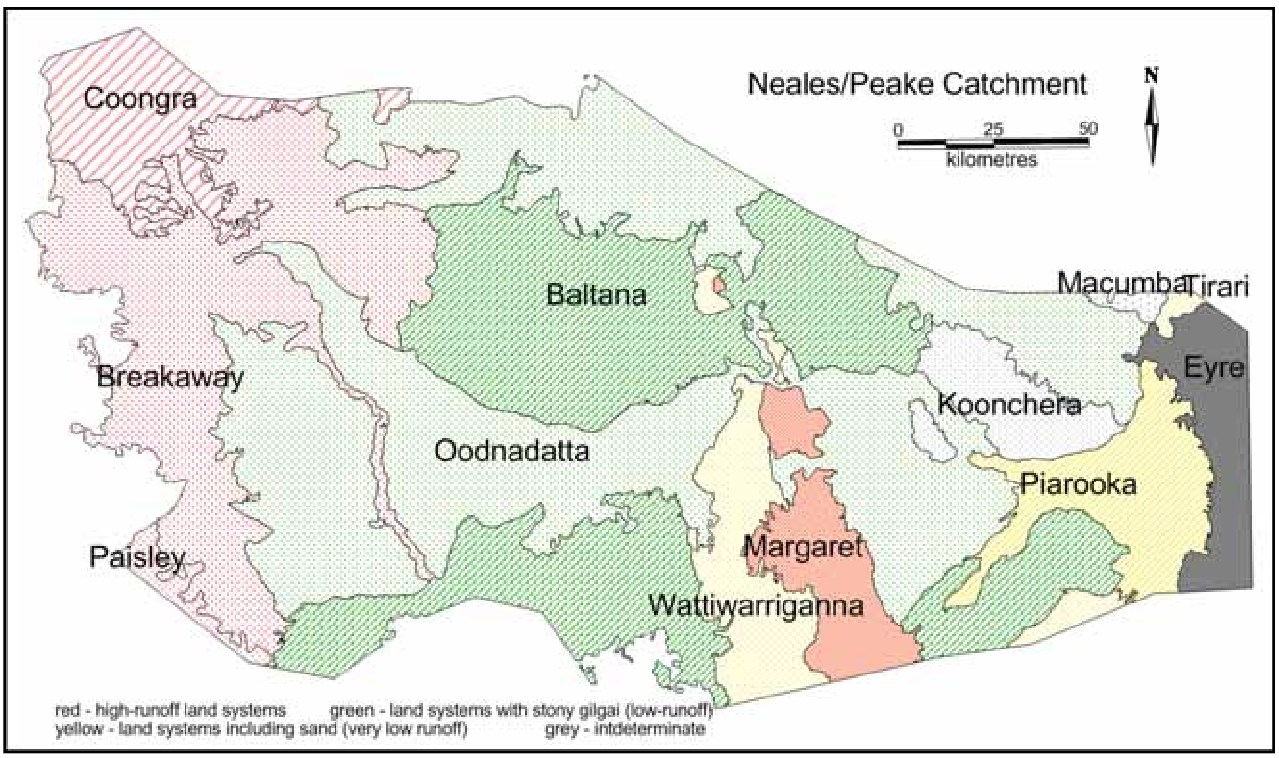


Fig. A2.4 Land systems map of the Neales Catchment, with the land systems grouped according to likely runoff characteristics. Land systems unit maps from SA Dept. Water Land Biodiversity & Conservation (sourced 2010).

A2.1.2 Tectonic History Creates the River Network

The centre of the Australian continent has a low level of tectonic activity in comparison to the rest of the world. For the last 65 million years, while the Neales catchment has been sitting under the sun, entire mountain ranges have been thrust from deep in the earth's crust up to the peaks of the Himalayas. The Neales Catchment had already accumulated all its sediments and undergone most of its weathering and silcrete development 5 million years ago, when New Zealand's mountains were only just poking their heads above sea level.

However, a relatively low level of tectonic activity doesn't mean that nothing happens. Mild faulting occurs in most Australian Cainozoic basins, and in Central Australia a widespread expression of Cainozoic tectonism is undulation, where the land surface flexes with a vertical range of hundreds of meters over areas hundreds of kilometres wide (Sandiford et al. 2009). Faulting and tectonic movements create or modify landforms, but the effects can be subtle: instead of vaulting mountain ranges, there are slope changes which control river networks (Crone et al. 2003, Twidale & Bourne 2004). In the Neales Catchment episodes of tectonism in the Miocene (~45 MA) and mid-Pleistocene (<~2MA) have domed and faulted the Cainozoic sediments (Alley 1998, Waclawik & Lang 2004).

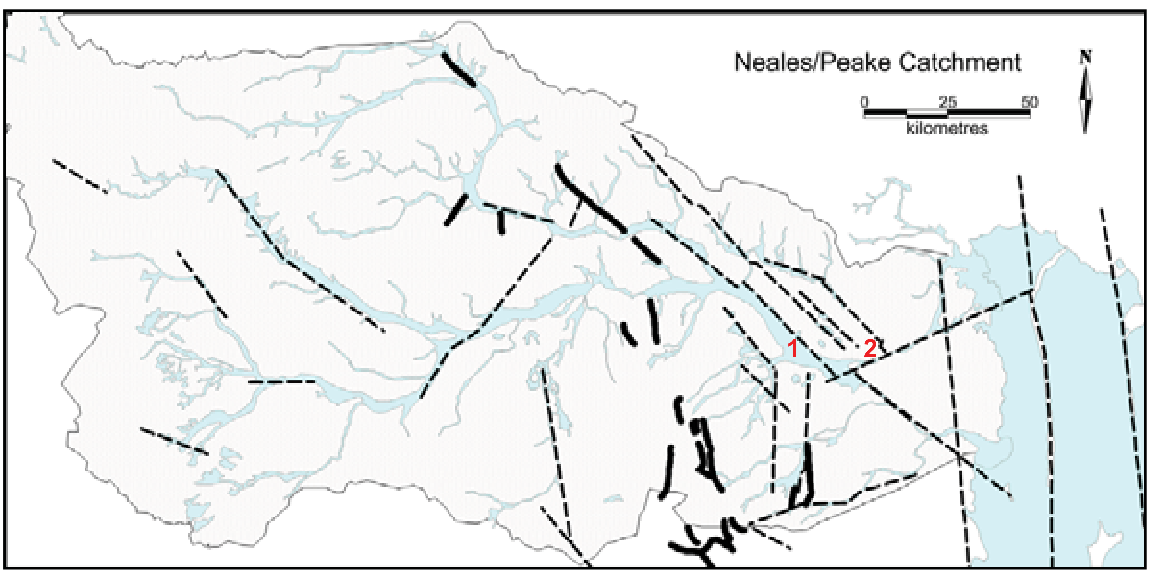


Fig. A2.5 Faulting in the Neales Catchment. Heavy black lines, faults shown on the Geoscience Australia Geological Dataset; dashed black lines, faults shown in Waclawik & Lang (2004) Waclawik et al. (2005) Waclawik et al. (2008), or inferred in this report on the basis of the preceding references and the author's experience in regional geological mapping. 1 The Lake Eyre Fault, 2 the probable fault along Browns Creek.

Mid-Miocene uplift of the fault-bounded Peake/Denison Ranges (Waclawik & Lang 2004) created a mid-catchment barrier for the Neales and Peake Rivers, through which they flow at Algebuckina and Peake Gap. The geological map also shows other faults near Mount Dutton and Oodnadatta (Fig. A2.5). Early to mid-Pleistocene faulting has affected the Neales River, creating converging and diverging stream paths, closed basins, aligned alluvial valleys (Browns Creek, the lower Neales and to the valley in which Lambing Creek meets Hawker Creek), and promotion of overbank flooding (Waclawik & Lang 2004, Waclawik et al. 2005, Waclawik et al. 2008). In particular, where the lower Neales River crosses the Lake Eyre Fault, the Oodnadatta Formation is exposed in the channel, the floodplain is elevated, and the downvalley slope promotes overflow into the Umbum channel. In the Neales Delta, faulting has created a meandering planform in the Neales River and Umbum Creek, and is coincident with the location of the Neales overflow. That fault line is parallel to lineaments controlling drainage into Lake Eyre (including the Warburton groove).

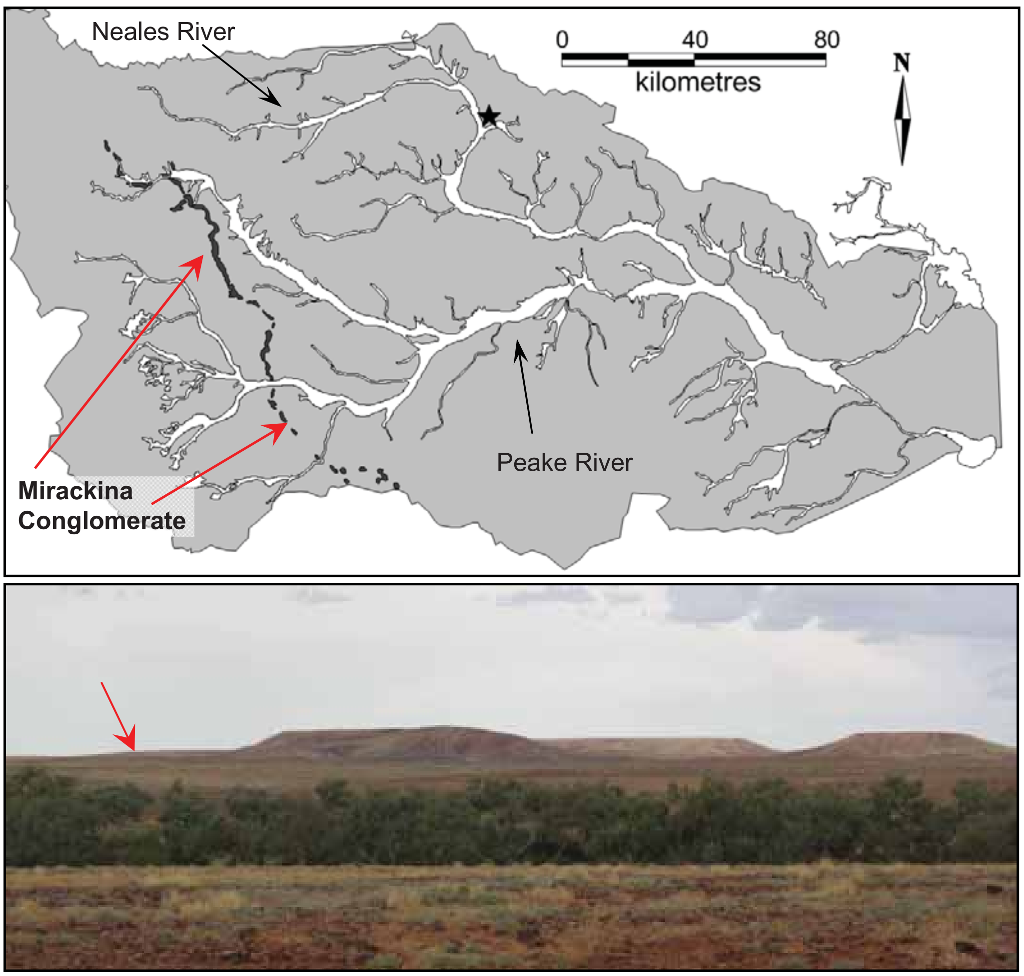


Fig. A2.6 Topographic inversion of the Mirackina Conglomerate, a 45 Ma-age river channel preserved as a narrow band of gravelly rock. Top, the catchment map shows that the ancient river (red arrows) cuts across modern catchment boundaries. Bottom, once river gravels occupying the lowest parts of a valley, now the Mirackina Conglomerate forms the highest hills in the area. The roughly planar level (red arrow) below the conglomerate's flat hilltop is an etch surface.

Crustal warping and subsidence formed a proto-Lake Eyre (~52 million years, Alley 1998), but the location and flow direction of the rivers was not the same as it is now. The Mirackina Conglomerate (age ~23 Ma, Miocene) shows palaeodrainage (Barnes & Pitt 1976, Geological Survey of South Australia 2008) going in quite a different direction from the modern river system; once occupying the bottom of the valley, these sediments now form the highest points on the landscape (Fig. A2.6). Tectonic activity has lifted up the land surface and relocated the deepest part of the lake since the time of the ancient Mirackina river. A similar movement, lifting the palaeolake Billa Kallina to form the current drainage divide between Lake Torrens and Lake Eyre (Sandiford et al. 2009), shows this scale of topographic inversion is widespread in central Australia.

The Neales catchment is uplifted along its western edges, and in the central Peake/Denison area. The catchment is subsiding at its eastern edge (Lake Eyre). Base level (the equivalent of the coastal plain's "sea level", which is "bottom" for river flows, and to which river profiles are graded) is currently approximately -6m AHD, but when Lake Eyre has been permanently full in the past base level has been as much as +35m AHD (see Section A2.1.4). What this means for the Neales geomorphology is that the overall regime is erosive, the valleys tend towards deepening and/or widening, the downstream valley is likely to have accumulated sediment to a level of +35m AHD during the geological past when Lake Eyre was permanently full, and that now Lake Eyre is empty the downstream valley sediments will be prone to incision down to the new base level. This type of landscape is well-researched in that field of geology which analyses basin development (sequence stratigraphy; for example, Zaitlin *et al.* 1994, Ardies *et al*. 2002), and would be described as a lowstand, with complex fill within incised valleys.

In summary, Cainozoic tectonic activity has strongly influenced the drainage network in the Neales Catchment. This includes faulting so recent as to be still affecting floodplain sedimentation and channel behaviour, and uplift/subsidence imposing an overall erosive regime on the catchment. Valley-fill sediments which have accumulated within the lower Neales will be predisposed towards incision.

Stacks of Flats

In the Neales Catchment, tectonic undulation of the land surface, creating broad domes and areas of subsidence, is expressed as a landscape with three stacked more-or-less planar surfaces. The lowest and youngest land surface is the modern one: the floodplains of the Neales below Elbow Bend, equivalent levels along the Peake, the flanking peneplain; elevations from ~150 m upstream, to the base level at the Neales Delta (-6 m AHD).

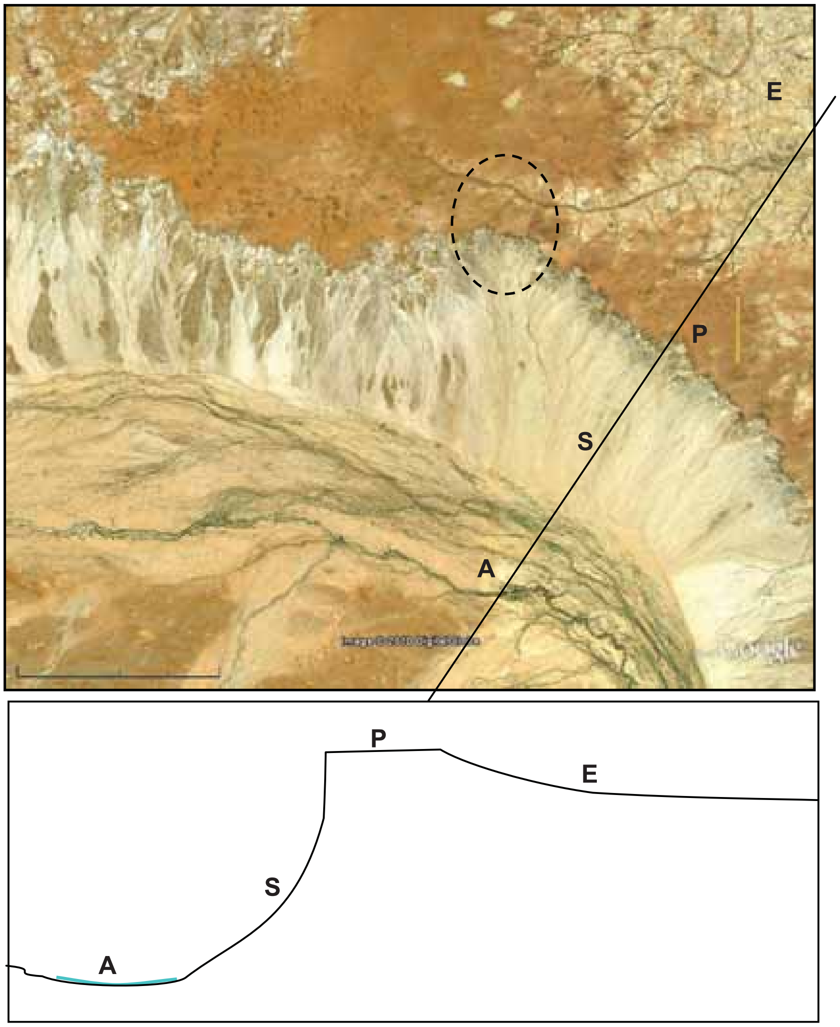


Fig.A2.7 Top: Google Earth image of The Jumpup, a 60 m scarp; yellow scale bar = 1km, north to top, black line is trace of the cross-section. Bottom: cross-section of The Jumpup topography, not to scale.

A Arckaringa Creek, **S** the bare weathered shale of the scarp face, vertical in its top several meters, **P** intact remnants of the old land surface (peneplain) are brown when viewed from above, **E** The etched surface shows the incised drainage, and the white of exposed weathered shale.

The highest and oldest land surfaces in the Neales Catchment are the old peneplain, and the topographically inverted silcretes and Mirackina Conglomerate. Around and beyond the western margins of the Neales Catchment (for example, from Marla southwest along the Stuart Highway for ~40 km) there is an intact land surface characterised by red earths, banded vegetation, and broad, gentle swales without definite watercourses. It is uplifted relative to modern baselevel. This wide flat surface (a peneplain) once extended across much of the Neales Catchment, but has now been dissected by erosion (see discussion below). Intact remnants form tablelands, particularly in the western catchment along Arckaringa Creek. In the Neales Catchment silcretes which were formed within the soil profile have also been uplifted, and their resistance to erosion while the softer shales decay around them has created a distinctive tableland and breakaway landscape. At least some of these silcretes are coeval (originating or existing during the same period) with the marginal old peneplain. The silcretes, along with the Mirackina Conglomerate, are described as “topographically inverted” because what was once low is now elevated.

The old peneplain, and the soft rocks which once surrounded the silcretes and the Mirackina conglomerate, is being eroded 1) as an etch surface, and 2) by scarp retreat. In the etch surface, a dendritic drainage network of small channels, laid like a flat hand over the ground, etches into the landscape over a wide area. The gibber plains are slowly thinned and worn away, while drainage becomes incised. The result is a broad gently sloping landscape which imperceptibly merges down to the modern land surface. The etch surface forms the middle more or less planar level in the landscape (Figs. A2.6, A2.7). Scarp retreat takes place when the older peneplain, capped by a upper hard layer, is juxtaposed to the modern land surface, which lower in elevation (Fig. A2.7). Erosion of the upper old surface is slow, but the soft underlying shale exposed in a cliff can be eroded rapidly, so the cliff face retreats. Scarp retreat is widespread in the Neales Catchment, and the most spectacular example is The Jumpup, a ~60 m cliff facing southwards into the Arckaringa Creek. Typically, Neales Catchment scarps have a steep to vertical upper face, where the hardest rocks are located, a moderately steep middle section of crumbly soft rock, and a wide fan of weathering product leading down to the creek or valley.

The two different weathering styles have implications for fluvial processes. Firstly they will respond to rain events in different ways. The scarps are high-runoff surfaces with small catchments: they will contribute little volume but will generate runoff fairly rapidly. The etch plains are broad and can collect a lot of rain, but (especially where they are associated with stony gilgai) they will generate runoff only slowly; however that runoff is likely to be sustained, if the rainfall event is extended. Scarps will therefore promote flashy flow, whereas etch plains are more likely to promote longer, steadier flows. Together, they constitute runoff variability which promotes flow variability.

Secondly, scarps and etch plains will contribute to the creeks' sediment load differently. Scarps are likely to be transport-limited (generate more weathered rock than can be transported away); there will be a good deal of sediment in floodplain storage, promoting valley fill and (probably) anabranched systems. However, where scarps experience high- intensity rainfall, pulses of sediment are likely to be liberated

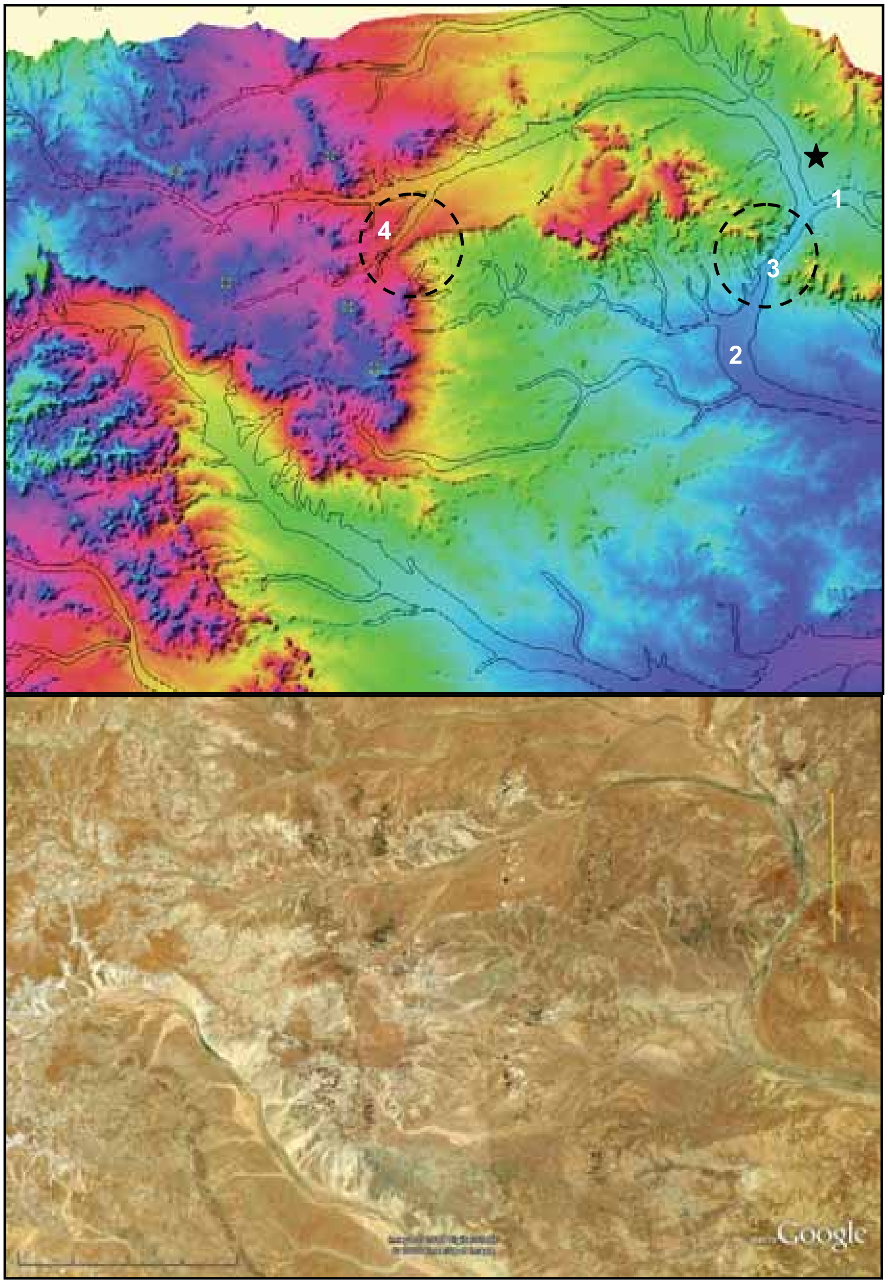


Fig. A2.8: Stream capture has created the Oodnadatta “S” (dashed circle #3), and the next likely stream capture is in the Neales south branch (dashed circle #4). Top: DEM of the Neales and Arckaringa catchments. Modern floodplain is outlined in black, north to top, scale as for bottom image; star = Oodnadatta, 1 Stony Creek 2 Elbow Bend, 3 the knickpoint reach (Oodnadatta south), 4 Wurley Hole creek. Remnants and etch plains of the older, higher peneplain (pink, red, yellow and light green) surround the floodplains of the upper Neales as far as Oodnadatta. Flat areas fringed by scarps are intact old land surfaces (there are small yellow cross-hairs on some examples). The developing modern peneplain surrounds Arckaringa Creek, and the Neales south of Elbow Bend (light green, light blue, dark blue). Black crossed lines mark Wurley Hole and Breadon Bore creeks. Bottom: Google Earth image of land surfaces in the same area; north to top, yellow scale bar 20 km.

into the system, and therefore contribute to the variable nature of the sediment load. The Peake River derives much of its sediment load from scarp weathering, and discreet sediment pulses can be seen in the Peake Floodout (Nilpinna area), and large volumes of sediment in floodplain storage in the Peake Floodout have discouraged coherent channel formation from the Peake Floodout all the way through to Peake Gap. Etch plains on the other hand will have more rain and runoff available to transport their sediments, so less of their sediment will be stranded in floodplain storage, and more will be routed through the fluvial system.

Stream Capture

Scarp retreat can be rapid in a particular direction, if the surface runoff conditions are favourable, and it erodes down to base level rapidly, but its extent is not wide. Etching occurs over a wide area but takes a long time to lower the ground surface to base level. Therefore, where the peneplain and the lower modern land surface are close together, separated by a steep scarp, it is likely that scarp retreat will capture drainage from the upper surface to the lower (Fig. A2.8). This is visible in several places in the Neales/Peake, most notably at the Neales' "S" bend near Oodnadatta. The Neales upstream of Oodnadatta was once part of the Macumba or Manarrina catchments. There was previously a scarp similar to The Jumpup extending east-west from Mt Albany to Hann Hill; it was breached by scarp retreat and the drainage of the upper etch plain was captured by the proto-Neales. The Oodnadatta south reach, from Stony Creek to Elbow Bend, joins the upper and lower surfaces.

A2.1.3 Downvalley Slopes, Valley Width

DEMs from the NASA Shuttle Radar Topography Mission (SRTM) were used to measure downvalley slope, using Global Mapper software and Microsoft Excel graph tools. Alluvial valley width was measured using Google Earth Pro. Data is presented in Table 1.

The slope and valley width data indicate no correlation between valley width and the presence of waterholes. Surprisingly, waterhole reaches tend to have slightly lower downvalley slopes than non-waterhole reaches. This indicates that the conditions of waterhole formation are more complex than a simple valley width: depth flow relationship. The steepest reach in the Neales River is the Mathieson-Stewarts reach, and this corresponds to the knickpoint between the upper etch plain, and the lower modern surface. Stewart and Cramps Camp Waterholes are anomalously deep for their size (Costelloe 2010), and this occurs within the steeper reach. Floodplain

Table 1: Downvalley slopes and valley widths of the Neales River (continued next page).

Location	Reach	Slope (%)		Alluvial Valley Width (m)	
		WH	no WH	WH	no WH
South Branch	Wurley tributary		0.174		
	Breadon tributary		0.097		
	Eucalyptus-Barney	0.136		200	
	d/str from Euc-Barney		0.162		300
	u/str from 4-Waterhole		0.116		520
North Branch	4-Waterhole	0.116		740	
	Wurley reach		0.133		1570
	Breadon reach		0.126		1880
	Mt Carulinia reach		0.104		860
	Confluence w/ North Branch		0.108		1050
	Jam Tin reach		0.135		200- 500
	Andy Camp to Yardinna		0.131		900
	Yardinna to confluence		0.102		400-1430
	Slate to Afghan		0.104	420-690	1210
	Upstream from Angle Pole		0.093		840
Neales: Oodnadatta	Angle Pole	0.099		2080	
	Downstream from Angle Pole		0.103		2320
	Angle Pole to Hookeys		0.093	1540-2260	
	Shepherd's to Hookeys	0.080		1500	
	Downstream from Hookeys		0.068		1350
	Mathieson	0.042		1120	
	Math-Stewart knick point		0.206		680
	Stewart-Cramps	0.160		830	
	Elbow Bend		0.068		3560
	Cramps Turnoff Ck (tributary)		0.411		250
West of Alge	Farley reach		0.068		1580
	Dutton reach		0.036		1610
	Hann Ck (tributary)		0.184		840
	Ockenden Ck (tributary)		0.122		370
The Algebuckinas	west Algebuckina	0.035		440	
	Algebuckina pinch	0.059		370	
	east (true) Algebuckina	0.065		1750	
	Eaglehawk reach		0.067		2500
Peake	Floodout upstream from gap		0.049		4380
	Peake Gap overall	0.047		780	
	Peake Gap (rocky)	0.090		700	
	Peake Gap (channels)	0.008		3600	
	Pke-Neales junction floodout		0.069		3770

Table 1: Downvalley slopes and valley widths of the Neales River (continued from previous page).

Location	Reach	Slope (%)		Alluvial Valley Width (m)	
		WH	no WH	WH	no WH
The Tardes	Old Tardetakarinna		0.036		1530
	Small+HydroTarde, badlands		0.061		3300
	Two arroyos		0.044		3300
Lower Neales	Single channel		0.029		4300
	Meandering channel		0.050		5000
Whole Neales Catchment	Upstream from Denison R.	0.083			
	Downstream from Denison R.	0.053			

geomorphology in this reach is dominated by scouring, and the alluvial cover is very thin; relatively high stream power occurs in this area.

The downvalley slope in Mount Dutton and West Algebuckina is relatively low, which is consistent with bedrock exposed in the alluvial valley acting as a local base level for the upper Neales. The overall downvalley slope of the upper Neales and the Neales downstream of the Ranges also indicate that Algebuckina Pinch and Peake Gap are acting as local base level.

The almost flat gradient immediately downstream from Peake Gap indicates that the sudden valley widening promotes immediate sediment deposition as sediment-laden flows leave the gap. Variable downvalley slopes in the Tardes and lower Neales reflect a complex landform assemblage including at least three floodouts (see below), in an area with strong tectonic influence; further investigation is suggested.

A2.1.4 Lake Eyre Hydrology: Ice Ages (Quaternary) to Now

Tertiary to Quaternary

The Earth's climate changes over time. During the early Tertiary the Lake Eyre basin was warm and wet: rainforests clothed the hills, the lake basin had permanent water, and the animal life included dolphins and crocodiles (Alley 1998, Croke et al. 1998). During the late Tertiary the Lake Eyre basin climate became much drier and moved towards the present arid condition. Worldwide cooling ~2.6 million years ago was accompanied by the beginning of the glacial cycles, and the Quaternary period (Pleistocene, 2.6 Ma to 12,000 years ago, and Holocene, 12,000 years to present) has been characterised by strongly fluctuating climatic conditions between glacial and interglacial periods. In the Lake Eyre basin during geologically recent times, there is evidence for enhanced river flow from the north at ~120 ka, ~85 ka, ~68 ka, and during the Last Glacial Maximum ~18 ka (Cohen et al. 2010). Lake Eyre has been filled to a level 25-35 m AHD some time before 59 ka, and beach ridges at a level of 6-7 and 10-12 m AHD have been visited several times since 59 ka (Nanson et al. 1998).

A lake-full level at ~35 m AHD would bring the water's edge up to the area of 6-Mile Bore, a location which corresponds with observations of large solid masses of crystalline gypsum exposed at gully-floor level in the 6-Mile Arroyo. While soil gypsum is common throughout the catchment hillslopes, visible crystalline gypsum was not observed in the alluvial sediments elsewhere. A lake-full level at ~12 m AHD would cover the Neales Delta nearly to the apex, with water encroaching a little distance up Brown's Creek. The Ghost Yard Beds, which were probably deposited from standing water (Croke et al. 1998), may correspond to this lake-full level.

Megafloods Since the Last Glacial Maximum

Although overshadowed in the human imagination by the greater climatic variations of the Ice Ages, the Holocene has also been a period of climatic variability worldwide, encompassing as many as six episodes of rapid climate change, including the Holocene Climatic Optimum (~9-6 ka), the Medieval Warm Epoch (1000-1400 AD, 1-0.6 ka) and the Little Ice Age (1500-1800 AD, 0.5-0.2 ka) (Williams et al. 1998, Mayewski et al. 2004). During that time inland Australia has experienced a number of rare but extremely large flow events (**megafloods**), which have left a strong imprint behind. In Central Australia, various megafloods in the Ross, Todd, and Finke Rivers created slackwater deposits, sand sheets, high-level bars, and km-scale fields of low-amplitude bedforms deposited across the floodplain (Kochel & Baker 1988, Pickup et al. 1988, Pickup 1991, Patton et al. 1993, Bourke 1994, Bourke & Pickup 1999). In western New South Wales, megafloods on scales of millennia and several hundred years have imprinted the fluvial landscape (Jansen & Brierley 2004). The Neales and Peake Rivers will undoubtedly have experienced such extreme flow events over similar timeframes, traces of which will be preserved in the landscape.

A2.2 Geomorphology: Modern Landscape Processes

In this section the sediment and landform distributions are examined in the context of the catchment's geological and climatic history, revealing the process relationships between the landforms, and showing how the river works. The degree and type of post-European change will also be addressed. (Note that this study, which is on such a wide scale, does not intend to document all areas of intense use. There are undoubtedly some intensely-used areas not visited during this project; they are likely to be recorded in Pastoral Board reports.)

A2.2.1 Marks of Megafloods

The high-level shadow bars at Hookeys and Peake Gap indicate the approximate height of rare, large floods which have occurred in (geologically) recent time. Other indicators of flood height include valley-margin gravel and boulder deposits, stripping-back of valley margin hillslope surfaces, and streamlining of low hills. Without further research it is not possible to be precise about the flood discharge levels. However, it is possible to indicate visually the flood levels that would have created these features (Fig. A2.9). Sediment dating would be necessary to know exactly when the last of these megafloods was, however it can be estimated that it was not very long ago (perhaps several hundred years), as the landforms are in reasonably intact condition.

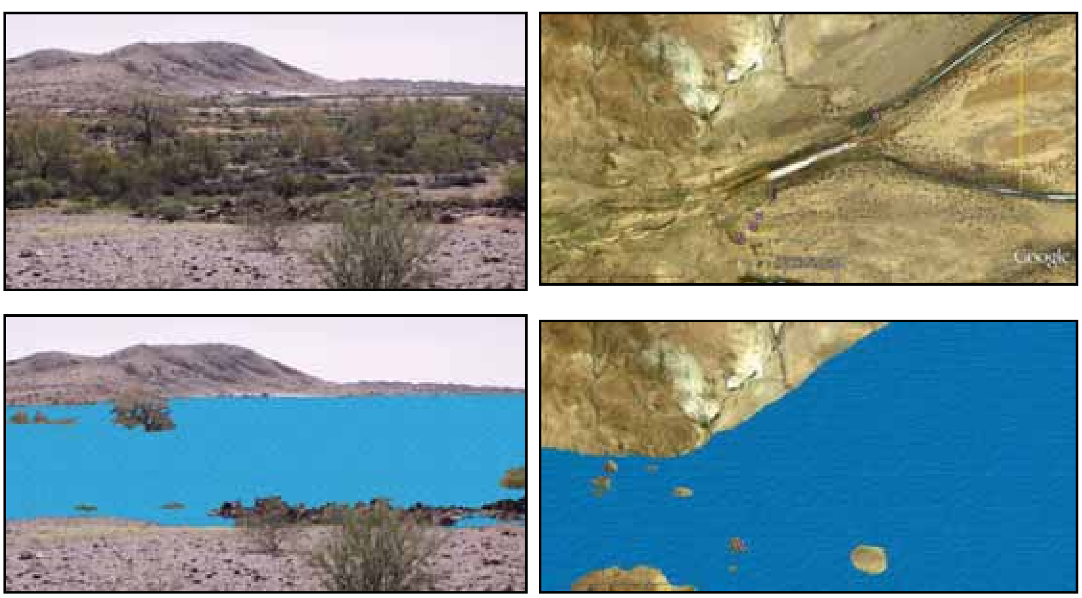


Fig. A2.9 The flood height and extent of floodplain inundation in Peake Gap's last megaflood. Left, looking across the Peake Gap valley, right Google Earth image of the same area, north to top, scale bar = 1 km., Top: as the area is today, bottom: as it would be flooded to the gravel-bar level at 61.5 m AHD.

Elsewhere on the Neales, likely megaflood landforms include the tributary-confluence floodouts where the Peake River and Wood Duck Creek enter the Neales (similar to the formation process of floodouts in western New South Wales, Wakelin-King & Webb 2007), and high-level gravel flood bars at and immediately downstream from the North Branch and South Branch confluence (similar to the junction bar and side bars from gravelly flood deposits described in Mosher & Martini 2002).

A2.2.2 Hillslope Erosion and Sediment Transport

Because of the Neales Catchment's uplifted tectonic context, it is characterised by long-term erosion, very slow in world terms but nonetheless widespread and active in the present day. The bare rock of the Eromanga Basin shales, the silcrete and ferricrete of the Tertiary soil profiles, are exposed in slow etch plains and dramatic scarp retreat (see Geology Section). The sediments are dominantly quartzose silt, clay, and very fine sand, reflecting the generally fine-grained provenance; only creeks immediately downstream of aquifer outcrops have sandy bedloads. The sediment is transported down the fluvial network in pulses, finding temporary floodplain storage in the wide anastomosing reaches and in the tributary-junction floodouts. The episodic nature of sediment transport (and consequently the high degree of floodplain storage, despite the essentially erosional setting) relates to the infrequent and highly variable rainfall regime. (The Neales River is transport-limited: there is usually more sediment ready to be moved, than there is water of sufficiently high energy to erode and remove it.) Longer-term sediment storage takes place in the Neales Delta. Ultimately, sediment is deposited in Lake Eyre, to be preserved in the rock record by subsidence, or to be relocated downwind by deflation.

A2.2.3 Hummock Fields: Land Degradation or Natural Feature?

Most hummocks in Neales River hummock fields are shadow bars, formed around woody bushes. The low branches and leafy stems produce local turbulence, promoting sediment deposition within, below, and just downstream from the bush. Germination is favoured there, so some hummocks may consist of a train of bushes.

Elsewhere in the world, similar structures are known in range research circles as coppice dunes. In New Mexico, they are documented to result from a process which begins with overgrazing, followed by replacement of palatable grasses by unpalatable shrubs. Erosion then liberates sediment which is blown by wind and trapped by the new shrubs, creating a new dune field (Rango et al. 2000). In the New

Mexico sedimentary record, coppice dunes are only present within the last hundred years (Blair et al. 1990). From Rango et al. (2000), it can be inferred that the process of coppice dune formation involves one ecological process and two separate geomorphic processes. Ecologically, preferential grazing depletes grass and the vegetation community switches to shrubs. Geomorphically, loss of groundcover decreases the sediment's resistance to wind erosion, so sediment is transported, and the shrubs change the aerodynamic landscape, promoting sediment deposition around shrub bases.

The Neales Catchment hummocks are definitely deposition from floodplain-level flow. They are not aeolian. In this report they are considered to be a natural landscape feature.

- Their geographic distribution is independent of grazing-industry infrastructure, and they are present as far upstream as could be investigated in the field and by Google Earth (and therefore, as far as possible from the heavily-used major waterholes).
- Hummock fields are less prominent where there are also indications of less above-floodplain level flow (in the Neales North Branch, see below). Where present, they are oriented to flow direction and scaled to flow depth. That is, their geographic distribution is related to landscape processes.
- The geographic distribution of hummocks and hummock fields is coherent over a landscape scale, and relates cleanly to the wider fluvial processes. Generally, post-European landscape degradation landforms look confused and incoherent with respect to their landscape context.
- The link between coppice dunes and land degradation is in overgrazing, which reduces vegetation, which allows sediment to be available for transport. However in the Neales Catchment, the geological context (uplift and weathering) is such that erosion is constant and sediment transport down the fluvial system is to be expected. The fact that bushes are accumulating sediments around them is not *per se* evidence of overgrazing. Sediment accumulation in the lee of flow obstructions is well-documented (they are known as shadow bars). The possibility should be considered that wherever rangeland scientists see shrubs accumulating sediments in the presence of known areas of overgrazing and degradation, the term "coppice dune" is applied, whereas where other geologists see similar things in other settings, the term "shadow bar" is applied. The terminology difference prevents rangeland scientists from seeing literature on shadow bars in a non-degraded setting.

An example of these relationships is the sparse occurrence of hummock fields in the North Branch of the Neales. The North Branch does not appear (on Google Earth) to be any more grassy than that of the South Branch. There is a string of yards and a station track along the North Branch, suggesting that it was grazed. There does not appear to be any land management reason for the sparseness of hummock fields. On the other hand, other geomorphic indicators indicate that (in contrast to the rest of the Neales) above-floodplain level flows and strong flows are minimal to absent in the North Branch, and this is consistent with its relatively small catchment. There are therefore good geomorphic reasons for the sparseness of hummock fields.

In this report the hummock fields are interpreted as having a role in the larger fluvial system: they are a substantial roughness element, slowing above-floodplain level flow, therefore promoting wide floodplain inundation. Without the hummock fields, large flows would be more likely to incise into the valley floors, establish channel connectivity, and starve the floodplain of water. Far from being a problem that needs solving, it is likely that the hummock fields are a feature which needs preserving.

This is not to say that the hummock fields are in pristine condition with respect to their vegetation. It might be that there would once have been more grasses amongst the hummocks; such vegetation analysis is not within the scope of the geomorphology report.

These differing interpretations of the origin of Neales Catchment hummock fields (land degradation versus geological context) have important implications for land management. If the hummocks are a degradation feature, then the river's ecosystem is widely compromised. On the other hand if the hummocks are a natural feature, then the river is in quite good condition and any attempt to interfere with the nitre bush may lead to valley-floor incision and channel connectivity, and ultimately to widespread landscape degradation. The origin of the hummock fields might be investigated by determining the palynology (pollen content) of sediments in the Neales Delta outflow (investigating the relative abundance over time of grasses and shrubs). A doctoral project on this topic would be technically challenging but would be a valuable contribution to the discourse on post-European landscape change in central Australia.

Shadow bars and hummock trains also form in the lee of floodplain trees, and in amongst riparian vegetation. Some of the larger waterholes have a riparian ridge along their bank tops (Fig. A1.5). Their low width relative to height and length indicates firstly that these ridges form in relation to the riparian vegetation, and secondly that they form in response to active above-banktop flow moving in the downvalley direction (as opposed to simple overflow moving in a direction from the waterhole and away across the floodplain).

The more complex waterholes may have a combination of features. Algebuckina has a riparian ridge set back slightly from the bank top, with trees growing on the bank top, hummocks along the riparian ridge, and a second hummock field at some distance at a lower elevation on the high silt plains.

A2.2.4 Channel and Waterhole Distribution: Related to Scouring

In the Neales Catchment erosion as a fluvial process is visible at the human scale in the generally scoured nature of the channel beds. On a landscape scale, it is shown by the widespread distribution of floodplain scour resulting in various types of channel-like landforms. These occur in an incredible range of sizes, from tiny scours on the bank top or floodplain (see Fig. A2.29), to channel segments to channels to waterholes. In each case the landform is roughly straight lines, with a central low-elevation area (which becomes the channel or waterhole), flanked by silty ridges. Dry swamps are also related to floodplain scours, but the scouring was weaker, and the landforms wider and more shallow.

Evidence for the scour origin of these landforms includes

- their discontinuous nature: the channel-forming process is not associated with in-channel flow, like other rivers; it is spatially intermittent
- the ridges flanking the channel don't originate in channel overflow (see Fig. A1.11); they are associated with the creation of the linear scour. This is particularly clear where scour/ridge sets are isolated from other landforms
- the spatial distribution of these landforms is clustered (e.g. 4-Waterholes, Fig. A1.4) indicating reaches in which flow conditions are predisposed to scouring.

Fig. A2.10 A Kelvin-Helmholtz instability in the atmosphere creates vortexes along the boundary between two wind layers. Water vapour condenses in the low-pressure areas, and the resultant clouds outline the vortexes. A similar process happens when two bodies of water, both flowing in the same direction, merge. Image from WikiCommons, Wavecloudsduval.jpg.

Diverging flow paths around obstacles create turbulence. One type of turbulence is a vortex or eddy called a kolk. It can be imagined as a little tornado in water, and it can be capable of strong erosion. Kolks are created at a location of flow instability, then they break free of that location and move downstream. Reaches in which channel-forming turbulent scour occurs include those with complex topography (Hookeys and Peake Gap, with rocky outcrop in the floodplain Fig. A1.8), or reaches of relatively high stream power because of their steeper downvalley slope (Stewarts, Cramps Camp), flow concentration (Algebuckina), or flow convergence (Angle Pole). Valley margins (Afghan, Cliff) can be a locus for high shear or turbulence when the valley is full wall-to-wall (Waitt 2002).

As turbulent water interacts with nearby flows it will tend to create further turbulence. Also, turbulence creates landforms which are themselves sources of disruption to above-floodplain flow. In this way, reaches with waterholes or large channel segments are likely to have many such landforms, on a range of scales. A particular kind of turbulence (a Kelvin-Helmholtz instability) is created where two flows of different speeds merge. The friction between the two layers creates a series of vortexes (Fig. A2.10, and see www.youtube.com/watch?v=FYCTpnp1I4Q).

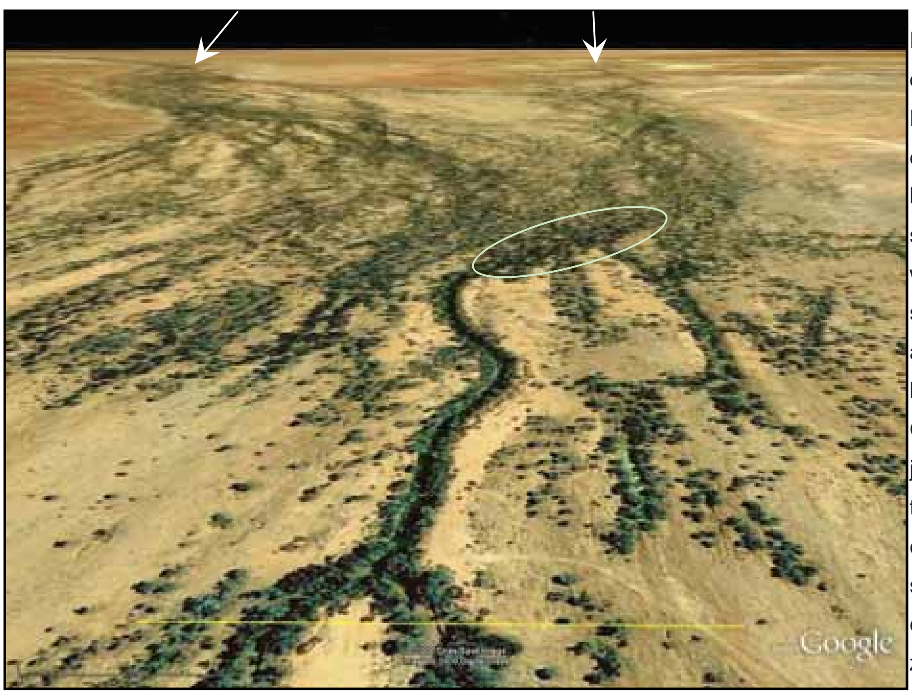


Fig. A2.11 Google Earth oblique image of Angle Pole waterhole from an eye altitude of 270 m, looking upstream, yellow scale bar = 0.3 km. Left white arrow, Neales River south branch; right white arrow, Neales River north branch. Vehicle track from Oodnadatta road comes in just left of the Google trademark (bottom right). A complex of en-echelon small channels (green circle) marks the turbulent zone where the two flows meet.

The Angle Pole Waterhole reach is an example of complex flow conditions that will create a waterhole complex. The North and South Branches of the Neales come together here. Tributary asynchronicity alone is likely to create discharge differences between the two branches, and in addition the North Branch has a smaller catchment and its geomorphology indicates lower discharges than the South Branch. Where the two flows join, a Kelvin-Helmholtz instability has created a complex of short, parallel, en-echelon short channels (Fig. A2.11). Just downstream is a complex landform assemblage including the major waterhole, several short waterholes, scours, and dry swamps, with attendant high silt plains (Fig. A2.12).

Fig. A2.12 Google Earth image of Angle Pole waterhole. North to top, yellow scale bar = 0.5 km, flow top left to bottom right. Pink numbers: 1 main waterhole (longest, deepest. most continuous channel segment), 2N & 2S north and south extent of the nest of en-echelon small waterholes, 3 various silty high plains, 4 dry swamps, 5 minor waterholes, 6 a sideways channel. Flow is shown by white arrows, and double dashed-line arrows for less deeply scouring flow.

On the other hand, reaches with low stream power (wider alluvial valleys or smaller discharge), less topographic irregularity, or less experience of flow variability (anything downstream from very large waterholes which capture the entire upstream flow component, will be protected from most flow variability) lack the formative conditions for waterholes or significant channels. In these reaches, the river is usually anastomosing, with the flow more evenly distributed across the valley width.

A2.2.5 Waterhole and Channel Formation: Megafloods and Macroturbulence

Megafloods, with a recurrence interval of centuries to millennia, will have deep strong flows in which turbulent vortices are also unusually large: these structures are called **macroturbulence**. While these can also be imagined as little tornadoes, a more correct description of their movement is that they are downstream-moving eddies, consisting of high-speed downwelling sweeps and burst-like upwelling ejections, producing flow-parallel ridges and troughs along which sediment is transported (Shvidchenko & Pender 2001). Macroturbulent scour is scaled to flow depth (vertical scale approximately equal to flow depth, length ~ 5 depths, width ~2 depths) and is an important contributor to sediment transport (Shvidchenko & Pender 2001).

In the Neales River the scale of the largest waterholes and channels indicates that they formed during megafloods. The geomorphology, with deep central channels, flanking ridges, and downstream splays which are often gravelly indicate formation by macroturbulent scour. Reaches whose boundary conditions (topography) promoted flow instability during megafloods were subject to giant eddies which travelled downvalley, scouring deep channels into the floodplain surface as they went. The silty fine sand pulled up from the floodplain was deposited beside or just downstream of the new channel (forming the high silt plains), while heavier larger sediments (gravel and boulders) were flushed downstream. As it travels the energy of the eddy is dissipated. At some point the eddy ceases to have enough energy to proceed; it scours less deeply into the floodplain, eventually lifting off the valley floor altogether; it dumps the heavy large sediments as a wedge of bouldery gravel at the downstream end of the new waterhole (forming the splays). The macroturbulence may also create a narrower and deeper inner channel. Macroturbulent scour during a single flow event in South Africa created funnel-shaped, steep-sided channels up to 30 m wide and 1-3 m deep; some channels were bifurcate or graded downstream into a series of scour holes (Zawada & Smith 1991).

The Neales and Peake Rivers are likely to behave as bedrock rivers during very large floods and megafloods. Flow conditions are likely to include transcritical flow (in which a single reach will have contiguous bodies of water travelling under subcritical, critical, and supercritical flow regimes), standing wave trains, and roll waves (Tinkler & Wohl 1998). These observations explain a number of things of Neales River geomorphology, and have some implications.

With transcritical flow, flow dynamics within a reach becomes very complicated, and when calculating discharge or employing hydrologic modelling for large-scale flows, "the cross-sectional focus for calculation of cross-sectional Froude numbers must be replaced by a view along the thalweg" (Tinkler & Wohl 1998). An additional complication is that there is little to no quantitative research into roughness values (Manning's n, a measure of flow impedance) for flow through really substantial vegetation. The implication of these two things is that discharge modelling which works acceptably well for flows with low recurrence intervals (a 1 in 20 flood, for example), is unlikely to be directly scalable upwards into multi-century or millennium level floods.

Roll waves are scaled to channel depth, and can appear to be "walls of water". They appear to be likely under conditions of very high supercritical flow (Froude number > 1.6). Their most likely initiating point is in wide shallow steep systems and over gravel surfaces, and from there they travel downstream (Tinkler & Wohl 1998). Roll waves are very rare but undoubtedly quite dangerous. Infrastructure planning, which will of course be recognising the possibility of large destructive floods in the Neales River, should take into account the existence of roll waves. Another implication of roll waves is that their residual deposits may complicate palaeoflood reconstruction (Tinkler & Wohl 1998),

Standing wave trains are where a central flow zone of critical (high-energy) flow is contained between water of lower flow energy, forming a zone of persistent power extending down to the river bed. Such wave trains can extend for hundreds of meters and be several metres wide. The result is an inner channel within the stream bed (Tinkler & Wohl 1998). This explains the Neales waterhole inset "low-flow channels": they can't really be carved during low-flow, because when the water is at that depth, the river has ceased to flow and has no energy for channel incision. These inner channels reflect high energy flow during flood conditions.

Cavitation, which is the formation and collapse of vapour bubbles in flowing water, can generate powerful shockwaves with an extremely high potential for initiating erosion (Thompson & Wohl 1998). Scour holes tens of metres deep and long have been observed to form over a period of only months in concrete dam spillways as a result of cavitation (Falvey 1982). Although usually discussed in terms of high velocity flows, cavitation can be associated with macroturbulence in relatively low velocity flows (Fattor et al. 2001). It is possible that cavitation plays a role in channel and waterhole initiation in the Neales River.

Although these processes have been discussed separately as if existing in isolation, it is probable that many of them happen at the same time in the same reaches. Megaflood hydrology will be complex, and this is reflected in the landform complexity.

Megafloods are extremely rare on a human timescale, but they are inevitable. They are not something that can be prevented by engineering works. (Standard engineering is designed against the 1:100 flood event, for the good reason that that covers most eventualities, and to design for the Probable Maximum Flood is usually prohibitively restrictive and expensive.) However it is possible to stay out of their way by not building critical infrastructure (including human habitation) in megaflood pathways. The Neales and Peake Rivers alluvial valleys should be regarded in this way. It is also important to recognise the role of megafloods in creating new waterholes, since even the biggest waterholes now present in the landscape will one day cease to exist (see below).

A2.2.6 Waterhole and Channel Maintenance: Banks, Deep Beds, and Large Floods

The new channel or waterhole created by the macroturbulent scour during the megaflood has high silt plains along or near its banks. Being well-sorted fine quartzose silt, they pack down as the flow recedes, and their well-preserved form in the present day indicates they were never a welcoming environment for seeds to germinate in. However, the channel or waterhole banks are clearly a welcoming environment for germination, since channel edges are so closely associated with dense vegetation. This may have occurred either immediately after the formative flow event, or at some later time. By the time of the next big flood, then, it can be expected that the new channel or waterhole has a line of bushes and trees growing along its banks.

The riparian vegetation plays three important roles during large floods (where flood level is well above bank level, and water is moving downvalley).

1. Riparian vegetation is an important protector of bank integrity during floods, even quite major floods (Zawada & Smith 1991, Hubble & Rutherfurd 2010.).
2. Water encountering the roughness of vegetation will lose velocity, and its sediment carrying capacity will thereby be decreased. The muds and silts it carries will be deposited as shadow bars behind the vegetation, eventually forming a riparian ridge along the bank top (see Fig. A1.5). The riparian ridge, containing loose wet sediments and rich in organics and seeds, will be an increasingly favourable site for vegetation to germinate and establish. In this way the riparian ridge becomes self-maintaining. It probably also plays a role in intercepting sediment and deflecting it across the near-channel areas. Riparian vegetation intercepting high-level flood flow creates a shear zone between bank and channel (Zong & Nepf 2010) and this is likely to play a role in maintaining the steep sides of waterholes and channels. It may also explain the setback of some riparian ridges from bank top edges.
3. During large floods in Channel Country waterholes, the slower bank top flow has the effect of forcing a narrow band of high-energy, more erosive flow down deep along the middle of the channel (Knighton & Nanson 2000). This may be in the form of standing wave trains. This channel-centre strong flow will have the effect of scouring out and deepening the existing channel.

In this way, large channels and waterholes are maintained by the combination of flow variability giving the occasional large flood, and dense riparian vegetation. Bank integrity is maintained, and the slow silting-up of the waterhole (which is probably inevitable during smaller flows) is reversed. It is critically important for the Neales River waterholes that flow variability remain at its natural level, and that riparian vegetation be protected.

During waterhole scouring, silty sediment excavated from the bed will be redeposited across downstream high silt plains, and also over the splays at the downstream waterhole terminations (see Fig. A1.9).

There is a waterhole-sized large channel segment (here named Blyth Scour), upstream from the Peake-Blyth confluence (and upstream from where saline bore water from Big Blyth Bore enters the Peake). It looks like it ought to be a waterhole but instead has lateral gully erosion and is anomalously poorly vegetated. Possibilities include:

- This is a normal process of waterhole initiation by scouring, and that riparian vegetation normally comes at a later stage, or that riparian vegetation has greater difficulty in establishing in the reaches are affected by saline groundwater. This seems unlikely, as other waterholes within the influence of

- the Great Artesian Basin groundwater seem to have riparian vegetation (e.g. Cliff and South Cliff Waterholes).
- This is a normal process of waterhole initiation by scouring, but the processes which allow riparian vegetation to develop has been short-circuited by stock grazing the emerging growth after the first scouring event, and by cattle pads promoting erosion which in turn discourages riparian ridge and riparian vegetation establishment. This is possible, given its proximity to Big Blyth Bore. Depending on the age of establishment of the bore, it may be possible to check this on old aerial photography.
- This reach's topography may promote shallow scour but not deep (macroturbulent) scour, impeding full waterhole development.

A2.2.7 Waterhole and Channel Adjustment: Banks, Variable Flows, and Gullying

During a flow event as the flood height rises and falls, so does the locus of geomorphic activity. Riparian belts which will be accumulating sediments during flood stage will be subject to erosion during lower stages. Also, during waning flow, as well as water flowing downvalley, there will be water draining from the floodplain back into the channel. While the geomorphic features created by these late-stage flows are not large, they do provide foci for erosion and deposition during later flow events. In this way, the "hooks" and "sideways channels" which are characteristic landforms in this catchment are created.

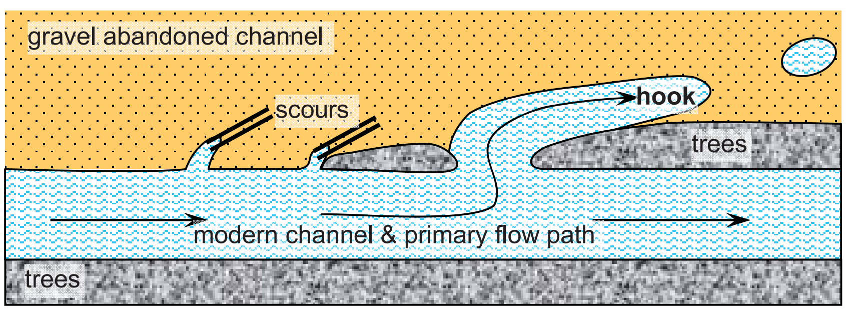


Fig. 29. Sketch of a hook creating a secondary flow path near a waterhole. Not to scale, but the width of the hook entrance is ~3 m, and the channel downflow from the hook is ~15 m long.

At 4-Waterhole, for example, overbank waters have cut across the riparian ridge, creating scours oriented almost perpendicular to the flow direction (that being the most direct downslope direction for the overbanking waters). Those overbank waters then flowed downstream along an abandoned channel (#9, Fig. A1.4). During waning flow, floodwaters draining back into the channel re-occupied these low points, eroding along the same path but in the opposite flow direction (in rather than out). Later flows reoccupied one of these scours, creating a "hook" (Fig. A2.13). In larger waterholes (Figs. A1.8, A1.9) the "sideways channels" are likely to result from similar rising-flood breaches of the high silt plains, followed by waning-flood and later flood excavation (on both rising and falling flow stages) to create a new channel.

This process of "sideways" erosion is particularly important in waterholes with high human visitation, as the small “sideways gullies” may be used to access the water. These footpaths, leading across the riparian ridge, down the bank, and to the water's edge will become foci for rill erosion during rising and falling river stages. This is doubly the case where there is removal of riparian vegetation near the tracks. The gullying breaches the riparian ridge, and the removal of vegetation hampers its natural rehabilitation. (Note that these “sideways” gullies in their early stages are only likely to give access to steep banks, which in large waterholes may be easy for people to climb down but possibly difficult for cattle to get down).

Waning-flow erosion is an important factor in the damage done by rabbits to Algebuckina Waterhole. The north-western Algebuckina bank, which has little human visitation, has many rabbits. They evidently prefer to dig their warrens into gullies near the riparian ridge. Their burrows act as foci for flow, so that dendritic rill networks extend out into the high silt plain from rabbit warrens. Sediment distribution indicates that burrows extending from the high silt plain down to the water's edge undermine the bank and can lead to bank collapse extending for tens of metres. Rabbits create paths along the bank tops and from bank top down to water’s edge, and these are also flow concentration pathways which become eroded.

A2.2.8 Ecological Riches: Floodplain and Channel Process During Normal Flows

From their upstream reaches to their confluence, the Neales and Peake Rivers are characterised by landforms which act to maximise the retention of water on the floodplain, which leads to sustained growth of vegetation. Other important roles for above-floodplain level flow are allowing fish migration from and between refuge waterholes, and giving them the access to new food resources which leads to the huge increases in fish biomass which are significant ecological events (D. McNeill, D Schmarr pers. comm. 2010). The anastomosing reaches spread water in many little channels, with the result that there is a maximum exposure of the flowing water to transmission loss (where water infiltrates into the alluvial sediments). In the other reaches,

- the discontinuous nature of the channels and waterholes, in which water collected at the upstream ends is re-distributed across the floodplain at the downstream end, acts to spread water across the floodplain
- the patches of trees and the hummock fields are substantial roughness elements which impede flow and allow floodplain-level water to infiltrate into the floodplain surface
- the complex landforms, including the small-channel complexes and dry swamps, also impede flow and encourage infiltration.

During ordinary (up to ~20 year recurrence interval) flows and floods, therefore, the normal river process results in substantial water retention within the alluvial sediments, leading to the relatively rich ecology present in the alluvial valleys (Fig. A1.10). It is important to note that the hummock fields, and (in high-energy reaches such as the Algebuckina Pinch) belts of scrubby trees, are important elements in this process. Reducing the amount of trees or hummock fields risks allowing valley floor incision and increases in channel connectivity, with consequent decreases in productivity.

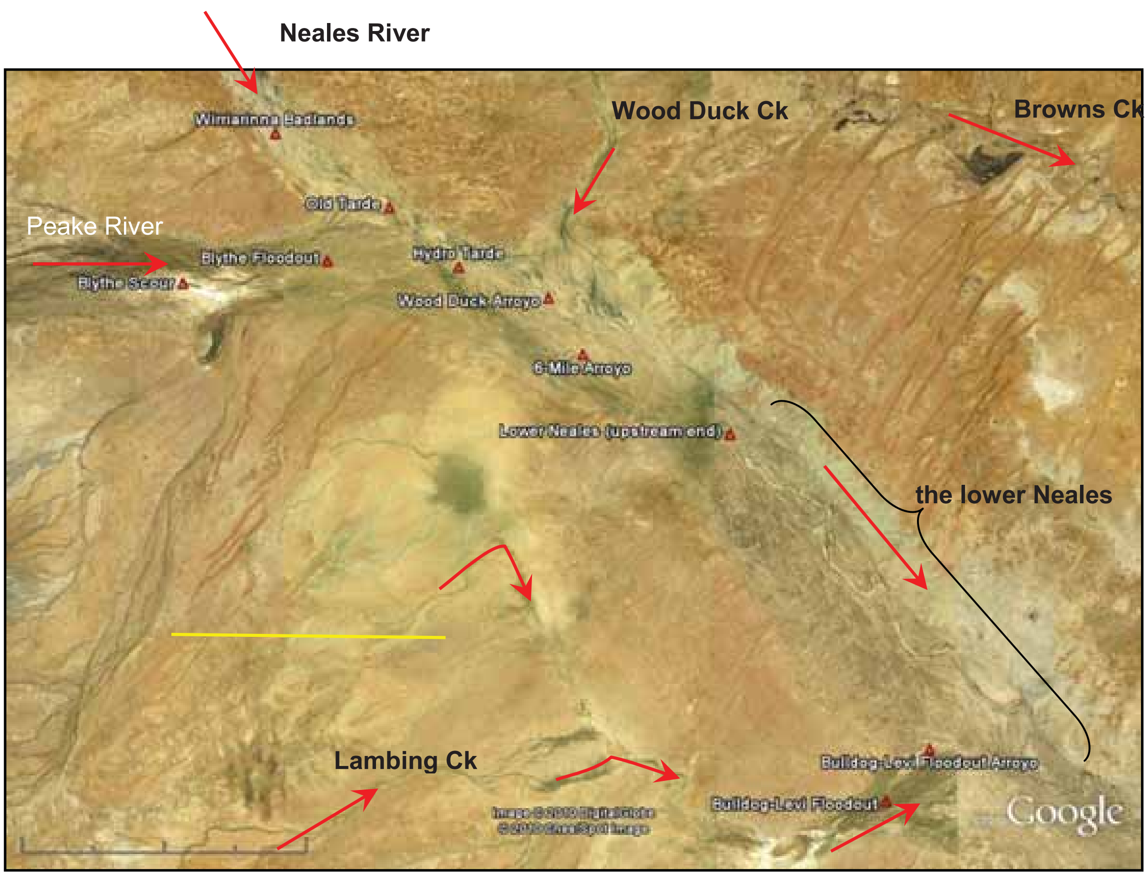


Fig. A2.14 Google Earth image of place names along the Neales-Peake confluence and the lower Neales. Red arrows indicate flow directions, north to top, yellow scale bar = 10 km.

Within this broad context there are specific areas that are particularly rich ecologically: the small-channel complexes, the splays downstream from most waterholes (Figs. A1.8, A1.9, A2.12), the occasional small floodout (Fig. A1.8), and the large Wood Duck Creek and Peake-Blyth Floodouts (Fig. A1.12). The waterholes themselves are of course ecologically rich, and the larger waterholes will be refugia for aquatic biota, however it is important to note that the splays and small-channel complexes in particular are likely to be important refugia for plants and non-aquatic animals. Riparian zones along channel banks are traditionally regarded as very important ecologically; in dryland rivers, floodouts, splays and similar landforms are equally important.

A2.2.9 Ecological Poverty: Badlands and Arroyos at the Neales-Peake-Wood Duck Confluence

(**new names*) The Peake River flows through the Peake-Denison Ranges at *Peake Gap**, near the Peake Creek railway siding, and the Neales flows through the Ranges at *Algebuckina Pinch**, near the Algebuckina Rail Bridge. Where the Peake flows into the Neales, downstream from the Ranges, Wood Duck Creek and Blyth Creek also

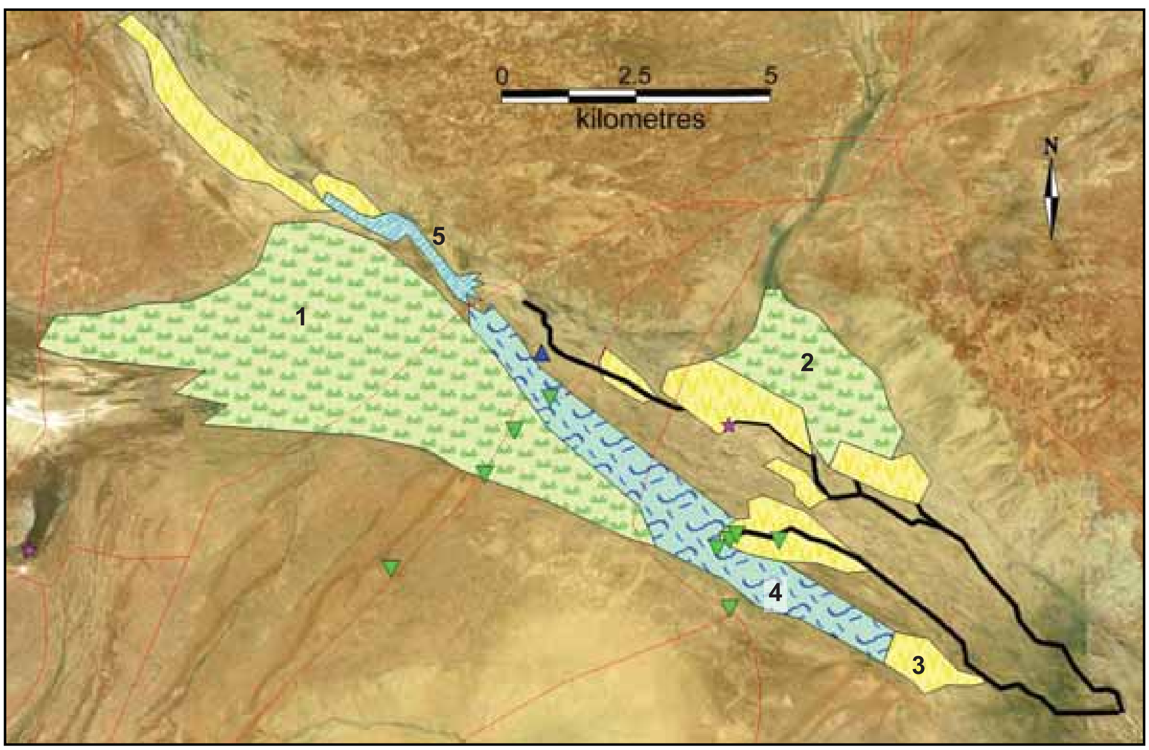


Fig. A2.15 Geomorphology of the Peake-Neales-Blyth-Wood Duck confluence. 1 low-angle fan of the Peake-Blyth Floodout, 2 low-angle fan of the Wood Duck Floodout, 3 (yellow areas) badlands and gullies, 4 (blue, wavy lines) the diffuse flow path, 5 (blue, short lines) Old Tarde. Thick black lines are arroyo channels, green triangles are geomorphology sites, blue triangle is hydrology site (Hydro Tarde).

enter the Neales, forming a wide valley (the Peake-Neales confluence). The confluence receives (at the time of this study) flow from the open Big Blyth Bore, as well as normal river flows. Some new names (*italics*) are assigned to features in this report and described below (Figs. A2.14, A2.15, A2.16):

- near Big Blyth Bore, *Blyth Scour* and *Peake-Blyth Floodout*
- near Wirriarrina Dam, *Wirriarrina Badlands*, a 5.4 km long linear belt of gullies and badlands, linked by a single continuous arroyo;
- the mapped location of Tardetakarinna Waterhole is here referred to as *Old Tarde* (its visible expression on the land) and *Map Old Tarde* (on the 1:250K topographic map, the coordinates of the right-bank distal edge); downstream of that, near the station track, is a small waterhole where the flow meter is installed, here referred to as *Hydro Tarde*; between these is a small waterhole here referred to as *Small Tarde*
- at the downstream end of Wood Duck Creek is the *Wood Duck Floodout*, and nearby is the *Wood Duck Arroyo*
- near 6-Mile Bore, is the *6-Mile Arroyo*
- the reach of the river where both arroyos run parallel to each other is referred to as the *Two Arroyos reach*
- downstream from where the Two Arroyos join to form a single channel is the lower Neales; it finishes at the apex of the Neales Delta
- in the lower Neales, opposite Primrose Spring, four creeks flowing down from the Davenport Range (Lambing, Bulldog, Levi, Hawker Creeks) join in a poorly organised drainage (near Outside Springs) which enters the Neales via the *Bulldog-Levi Floodout*; the *Bulldog-Levi Arroyo* cuts through the floodout.

The main landform elements are (Figs. A1.12, A2.15):

- There are two tributary-junction floodouts at Wood Duck Creek and the Peake River; the distal edge of the tributary fans has a slightly greater slope than the rest of the fan surface, and areas like these are prone to erosion (Bull 1997, Wakelin-King & Webb 2007).
- The Neales primary flow path is Old Tarde, then the diffuse flow path that skirts the edge of the Peake-Blyth Floodout.
- Finally, there are gullies, badlands (gully networks), and arroyos, all representing various degrees of valley-floor incision.

This part of the Neales is strongly influenced by its geological history. Ancient faulting determines spring distribution. More recent tectonic activity has disarranged drainage, creating the small enclosed drainage basins and creeks with right-angled bends in them. Lake Eyre subsidence, combined with valley fill during higher palaeolake levels, predisposes the Lower Neales to incision.

The fact that Tardetakarinna Waterhole ("Old Tarde") is named, and displayed as a shape (not a single line) on the 1:250,000 topographic map sheet, indicates that it was a large and reliable source of water in recent (post-1945) times. Today however it no longer exists. In its place is a 240 m wide channel, gullied and mobile, which lacks riparian vegetation. This area was accessible during geomorphology fieldwork, however the Google Earth image indicates that this channel is more shallow than the much smaller channels downstream (Small Tarde and Hydro Tarde).

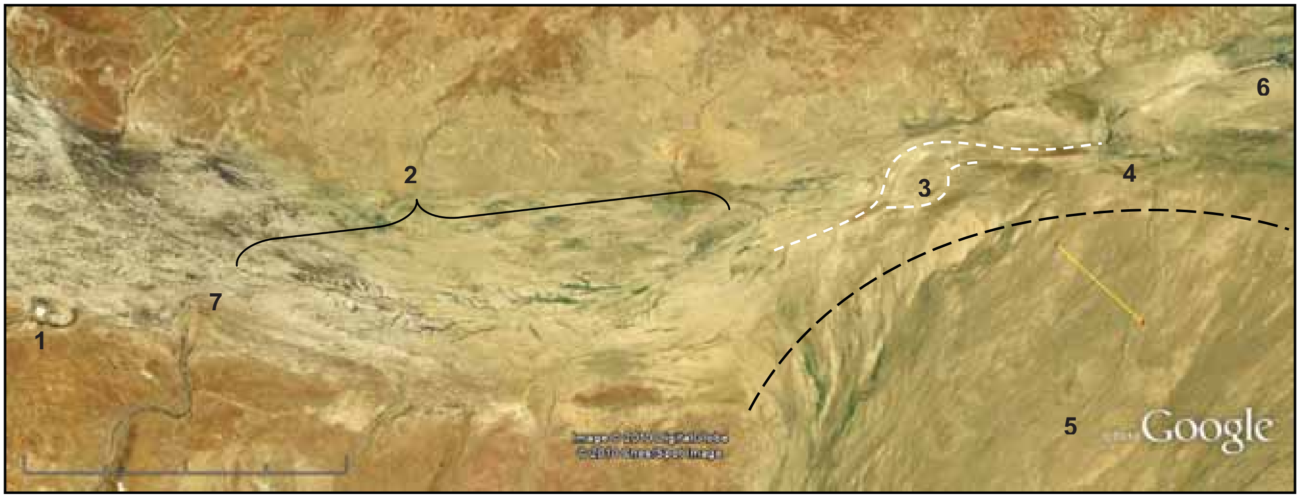


Fig. A2.16 Google Earth image of the Old Tarde reaches; north is ~45° counterclockwise from the photo top, yellow scale bar = 1 km. 1 Wirriarrina Dam, 2 Wirriarrina Badlands, 3 (white dashed line) the channel of Old Tarde waterhole, 4 the Old Tarde downstream splay, 5 the Peake-Blyth floodout, black dashed line, the downstream edge of the Peake-Blyth floodout, 6 Small Tarde, 7 the only part of the Neales floodplain in this reach which (at the time of these images) is not upstream from either badlands or Old Tarde.

Upstream from Old Tarde is the Wirriarrina Badlands (Fig. A2.16), which cut obliquely across the Neales floodplain, extending nearly as far as Wirriarrina Dam. Only a narrow neck (0.5 km) along the floodplain margin is unaffected (according to the Google Earth image, Fig. A2.16; that image is several years old, so the unaffected neck may be smaller by now). The sediment from the gully erosion near Wirriarrina Dam must be being delivered into Old Tarde. This would promote channel aggradation and account for Old Tarde's present shallow state.

Fig. A2.17 Google Earth image of Old Tarde's downstream splay, and Small Tarde; north is ~30° counterclockwise from photo top, yellow scale bar = 1 km. 1 Old Tarde's downstream splay (1A the northeastern channel, 1B the southwestern channel), 2 the channel linking Old Tarde with Small Tarde, 3 Small Tarde's downstream splay, 4 a relatively recently developed channel between Small Tarde and the Wood Duck Arroyo, 5 the diffuse Neales flow path.

The downstream end of Old Tarde is a well-vegetated splay with smaller distributary channels around it. The northeastern channel (#1A, Fig. A2.17) continues down to Small Tarde, which has its own downstream splay; Small Tarde's splay channel leads to Hydro Tarde and is continuous with Wood Duck Arroyo (and thereby, fully continuous right to Lake Eyre). The southwestern channel from Old Tarde (#1B, Fig. A2.17) empties into the Neales diffuse flow path (Figs. A1.12, A2.15, A2.17). Several station tracks cross the valley around here, and it looks like the boggy condition of these tracks during wet spells has led to the development of multiple tracks, and possibly also excavation of nearby floodplain sediment for road repairs.

Fig. A2.18 Google Earth image of the Two Arroyos reach of the Neales River; north is ~20° from photo top, yellow scale bar = 1 km. 1 Wood Duck Floodout, 2 Wood Duck Arroyo (the off-white, slightly sinuous thick line extending from left to right across the floodplain), 3 6-Mile Arroyo (the off-white slightly sinuous line), 4 the diffuse flow path, 5 sand dunes on the hillslope above the floodplain margin, ~3 km east from 6-Mile bore, 6 high-runoff slopes extending from the old land surface down to the floodplain margin. Red arrows indicate flow direction. White circles are geology field sites. The pink square (obscured by the text "Wood Duck Arroyo" is the fish site "Not-Tarde". The diagonal line where the floodplain changes colour, to photo Wright, is the boundary between two different satellite images.

Downstream from Hydro Tarde is the Two Arroyos reach, where the floodplain is dominated by two very large arroyos and their associated badlands (Figs. A2.14, A2.15, A2.18). The largest, Wood Duck Arroyo, is continuous all the way up to Old Tarde. The smaller 6-Mile Arroyo was the biggest channel seen on the river system seen during fieldwork ((Fig. A2.19) (20 m wide, 3-4 m deep, in a location upstream from the channel's largest dimensions). The bed was mobile sand, clay, and gypsum, with very high dissolved gypsum in the remnant pools of water. The arroyos proceed parallel down the floodplain, joining ~7 km downstream from 6 Mile Bore. Between them, the arroyos and their badlands extend across the full width of the floodplain.

Fig. A2.19 Erosion in the Two Arroyos reach. Top: The wide **arroyo**, showing flat floor, steep sides, and dead trees at the bank top. White patches of salinity are visible in the bed. Jay (circled) for scale. This channel is half the width of the same channel further downstream. Bottom: **Badlands** with dense scrub growing close to the gully walls, where vegetation benefits from water captured from the floodplain above. Jay (circled) for scale.

The smallest upstream tributaries of the arroyos are gullies, which extend in an upstream direction by erosion at the gully head, this being the location of greatest erosive power (Fig. A2.20). Individual gullies coalesce to form gully networks (badlands), and the badlands form small arroyos that merge with the larger arroyos (Fig. A2.21). Bushy scrub growing in many gully heads is benefiting briefly from the gully’s interception of floodplain water (Fig. A2.19). However, this vegetation will die as the gully extends headwards. Large solid masses of crystalline gypsum at gully-floor level were observed in gully heads at 35m AHD, a location corresponding to the >59,000 year palaeolake level.

Fig. A2.20 A gully headcut capturing sheetflow in the USA (Bull 1997, his Fig. 12 A, the label M is a mesquite bush).

The few remnant Two Arroyos reach floodplain surfaces available to this field work were characterised by low hummocks, a few small gum trees and a few moderately large coolibahs. The hummocks, the gravelly to cobbley patches amongst the generally silty floodplain sediments, and the few short mini-waterholes, all indicate this floodplain was capable of substantial above-floodplain level flow. However in the present day the hummocks are starting to erode (have not been renewed by further flood-borne sediment), and most of the floodplain trees are dead or dying (Figs. A2.19, A2.22). This change is fairly recent: the hummocks are only a little eroded, and the trees haven't been dead long (many small twigs remaining). In contrast to the rest of the Neales during this visit, the small plants were sparse and dry (Figs. A2.19, A2.22). The floodplain has lost its water to the gullies, badlands and arroyos, which have captured the surface water (the local lower base level of the incised channel provides a much steeper gradient for the water to go down) and the groundwater (the lower base level draws down the piezometric surface).

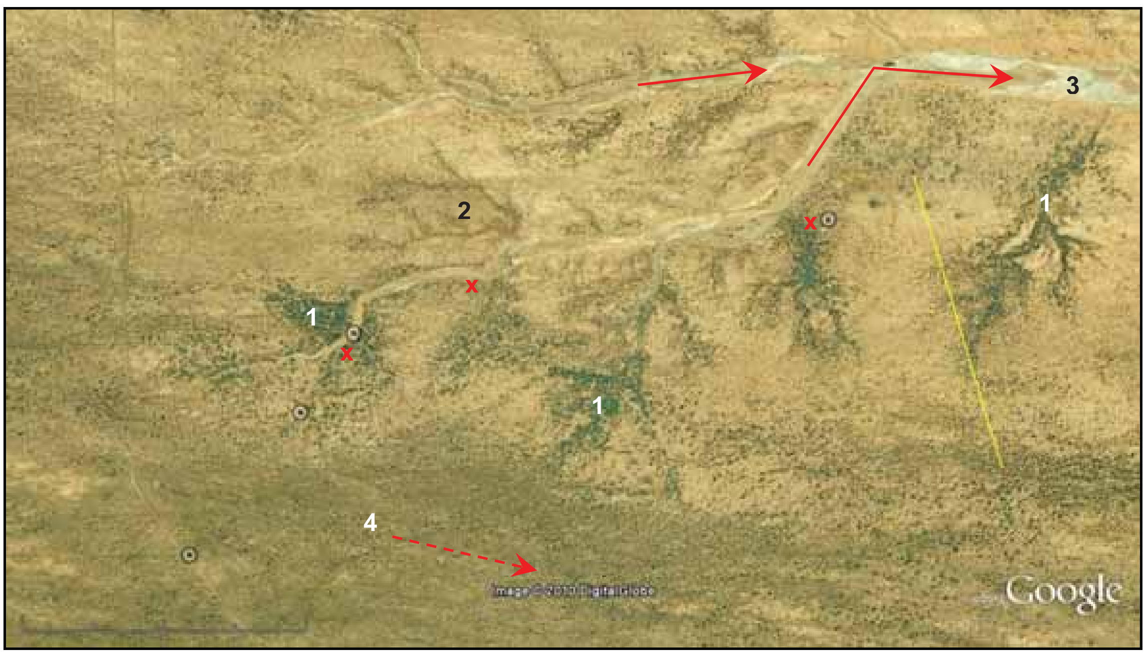


Fig A2.21 Google Earth image of the upstream section of 6-Mile Arroyo; north is ~10° counterclockwise from photo top, yellow scale bar = 0.5 km. 1 three examples of badlands with scrub vegetation growing in the gully floors, 2 an unvegetated badlands network, 3 the arroyo channel showing white chemical sedimentation, 4 the diffuse flow path (note that it is intercepted by another badlands downstream from this image). Red arrows indicate flow direction, solid-line arrows are flows confined to arroyo, dashed arrow is above-floodplain flow. White circles are geology field sites. Red "x" marks the location of photos in Fig. 35.

Whereas the rest of the Neales river landforms act to slow flow and spread water across the floodplain, the badlands and arroyos are brutally efficient in transporting flow downstream. This means that unless there is a very large flood, there is no possibility of a flow being big enough to overtop the arroyo channels. Also, the conditions under which the amount of water flowing into the arroyos is sufficiently large to overcome the arroyo efficiency and allow sufficient connectivity for fish to swim upstream (that is, to look like Fig. A2.20) is limited in time and space. Such connectivity is only likely to be achieved at flood peak discharges, and in locations where the gully heads are shallow and rough: scrubby badlands (Fig. A2.19 bottom, and Fig. A2.21 #1). Overall this suggests that fish will be able to migrate downstream into the badlands/arroyos, but upstream migration will be disadvantaged.

Fig. A2.22 Floodplain vegetation during the field work, photos taken within 14 days of each other. Top: Rich grass in the intact (unincised) floodplain upstream from the Neales-Peake confluence (Gresley for scale, photo: Jay Stafford). Bottom: Floodplain into which the badlands and arroyo are incised. The original hummock field is now starved of flow: its hummocks are not being replenished by sediments brought down during flow events, and its vegetation is dead or dying. Hat for scale.

A sequence of images from the MODIS satellite for the ~1:10 year event December 2009-January 2010 demonstrates the arroyos in action capturing floodplain water, and also shows the current flow pathways through the Peake-Neales confluence reaches (Fig. A2.23). During this flow event, rain was widespread (>10 mm from Coober Pedy to Oodnadatta to Marree) and fell under conditions of substantial antecedent moisture. Flood pulses extending the width of the alluvial valleys can be observed travelling downvalley (images not shown here, but see Fig. A1.10). There is no reason to believe that the halting of the flood fronts, described below, is related to transmission loss.

The MODIS images show the following flow patterns:

- Flow from the Peake Gap area splits around the Blyth Scour and then extends across the full width of the Peake-Blyth Floodout; from there water goes into the diffuse flow path (see Figs. A2.15, A2.17 A2.18, A2.23).
- Flow from the upper Neales enters an arroyo incised into the valley floor near Ockenden Creek; from there it flows into west Algebuckina, where it may eventually overflow into Algebuckina.
- Flow from Algebuckina is spread across most of the Eaglehawk and Cliff reaches floodplains until it gets to Wirriarrina Dam, at which point it enters the Wirriarrina Badlands; they empty into Old Tarde. Old Tarde drains out into the diffuse flow path via its southwestern splay channel (see Figs. A2.15, A2.16 A2.17, A2.23).
- Note that if Old Tarde was instead to drain via its northeastern splay channel (see Figs. A2.15, A2.17), the whole Neales flow would be channelled straight down into Wood Duck Arroyo (through Small Tarde and Hydro Tarde).

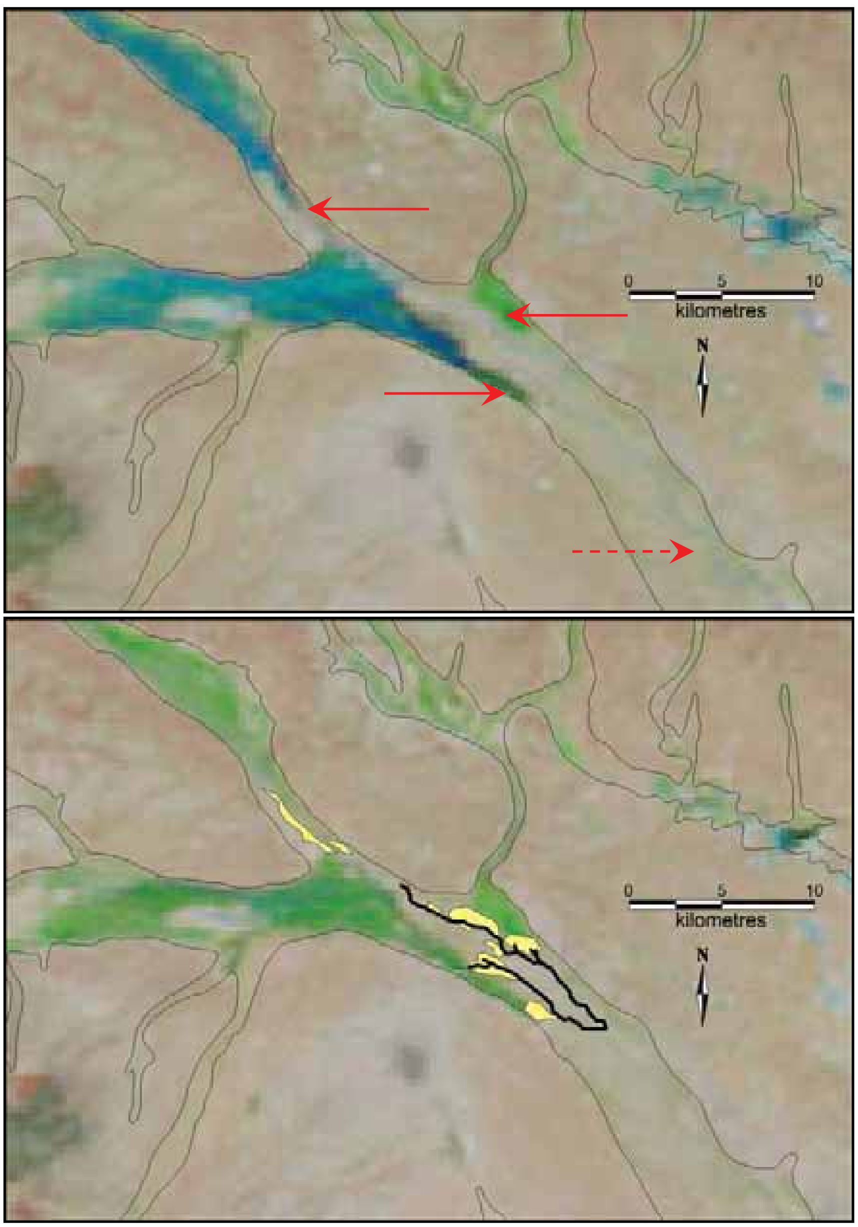


Fig. A2.23 MODIS satellite image showing the Peake-Neales confluence, during a ~1:10 flow event. The floodplain is outlined in black, vegetation shows as green, and water is blue. Flow is from left and top left, to bottom right. Top: On day 8 after rain, the flood fronts (red arrows) have been seemingly frozen in place since Day 3, despite the fact that the upstream parts of each pulse are still flowing. The lower Neales is flowing (red dashed arrow). Bottom: the vegetation response demonstrates areas of floodplain inundation. Absence of floodplain inundation corresponds exactly to arroyos (thick black lines) and badlands (yellow areas).

- The diffuse flow path is captured by the badlands of the 6-Mile Arroyo.
- The two arroyos have now captured the entire flow from the Peake, Neales, Blyth, and Wood Duck waterways. This water all goes down the lower Neales channel.
- (There is another small arroyo and badlands system incising into the Bulldog-Levi Floodout, which feeds into the lower Neales.)

These arroyo systems have serious implications for land managers.

1. The arroyos and gullies as they presently exist represent a serious loss of productivity over the entire Neales below the Peake-Neales confluence.
2. This type of system advances headwards quite rapidly and some very productive areas are directly in the path of gully extension: the diffuse flow path, the Wood Duck and Blyth-Peake Floodouts (with their vulnerable downstream edges), and the Neales floodplain upstream from Wirriarrina Dam. The Google Earth image suggests that Wood Duck Floodout is already compromised. Within the Peake-Neales confluence, management of the downstream splay at Map Old Tarde is critical to avoid further loss of productive floodplain.
3. Gully heads typically have stepped walls with near-vertical risers, see Fig. A2.20. While Neales fish can swim upstream against quite steep slopes (D. McNeil pers. comm. 2010), the arroyos are a potential barrier to upstream fish migration from Lake Eyre or the lower Neales into the Peake or into Algebuckina, or from Peake upstream into Algebuckina. To a certain extent this conclusion depends on the state of the Wirriarrina Badlands, which was not investigated during this study. More field work, and data on present-day fish migration patterns, is desirable. Nonetheless, if the gully systems extend, this prediction becomes more and more certain.

The important question as to whether these arroyos are entirely a response to post-European land use, or entirely natural, or something in between, is presently unresolvable. Alternate possibilities are presented in the next three paragraphs.

1) The case for a natural cause for these arroyos and badlands lies in the Peake-Neales confluence's position in a tectonically active zone, at the interface between active uplift (the Peake/Denison Ranges) and active subsidence (Lake Eyre). At the very downstream end of the Neales Delta, the Neales River was almost certainly always a single continuous channel. Somewhere between the delta apex and the Peake-Neales confluence there must have been a transition between the discontinuous, highly vegetated valley floor fluvial style (typical of the Neales upstream from the confluence), and the continuous channel style now present in the lower Neales. That transition is likely to have always involved some form of erosion. Elsewhere in Australia, the pre-European sedimentary record of some rivers shows alternating periods of long, slow sediment aggradation, and rapid gully incision (Prosser 1991), and that may be the case here. Geological investigations of

sedimentary basins show that base-level lowering can lead to valley incision, and repeated cut-and-fill of valley sediments (see *Section A2..2, Tectonic History Creates the River Network*). In this area the spatial relationship between the Peake-Blyth Floodout, the Wood Duck Floodout, and a floodout that may once have existed from the Neales may have led to a vulnerable area somewhere between Small Tarde and the two arroyos reach. (Floodouts, by their very nature, are prone to erosion at their downstream edges; Bull 1997, Wakelin-King & Webb 2007.) An erosion threshold may have been crossed during natural flow variability.

2) The case for a land management origin for these arroyos is that grazing-driven devegetation is a very common cause of valley-floor incision, as are other linear disturbances such as stock routes (e.g. Wasson & Galloway 1986, Grant 1994). Often an arroyo can be traced back upstream where it can be seen to originate in a vehicle track: the track both clears vegetation (decreasing valley floor strength) and concentrates flow (increasing erosive power), and so triggers erosion. That does not appear to be the case here, as the tracks are perpendicular to the valley direction, however the upstream lip of an inset track can be a focus for turbulent erosion during overland flow, so these station tracks may indeed be triggering factors.

3) Another scenario is that several causes reinforce each other. In the Nogoa River in Queensland, Finlayson & Brizga (1993) found that valley-floor trampling and vegetation thinning by cattle impacted on a fluvial system which was sensitive to disturbance due to its high flow variability. In the Neales, this landform configuration (the multi-creek confluence, with floodouts narrowing the valley) is particularly vulnerable to repeated episodes of gully erosion. The present episode of gullying may have been triggered by a combination of

- pastoral land use, and/or
- climate variability (switching between flood-dominated and drought-dominated regimes, Warner 1987), and/or
- large flood events (such as 1974).

This is not a simple question, and it is not a simple landscape. Further research is strongly recommended. A geomorphological analysis of the Neales-Peake confluence and the Lower Neales would be a doctoral-scale project, and would benefit landholders by addressing the natural-vs.-human question. A quick and easily achievable project, using aerial photograph archives to document the development of the badlands, would investigate the speed of landform change, and contribute to strategic management decisions.

A2.2.10 A Different Kind of River: the Lower Neales

It was not possible to visit these areas during the field study, and these comments are based on the remote study.

The lower Neales is a continuous, fully-connected channel extending from the junction of the Two Arroyos all the way down to Lake Eyre. The first 2.8 km of channel is a meandering thalweg set into a low-sinuosity arroyo or incised channel belt. From that point, the whole channel meanders, and there is evidence of normal meandering river behaviour: floodplain creation and channel migration (shown by scroll plains), floodplain-level overbank flow (flow paths in floodplain vegetation) For the first time in the Neales River, the riverbed is likely to be depositional instead of erosional; in consequence, waterholes will be relatively mobile and impermanent. Waterhole mobility down this reach of the Neales is likely to be on a smaller timescale, responding to less extreme flow events than elsewhere in the Neales.

There is no evidence of gully networks or badlands, so it is possible these reaches are behaving in their normal fashion. However, it is also possible that this incised channel is of recent development, and that channel aggradation from "sand slugs" (derived from badlands gullying in the upstream reaches) has allowed water to escape onto the floodplain.

Further investigation would clarify this picture, although (given the limited mobility of fish populations from this part of the Neales) this may not be a high priority. This reach might be assessed by investigation of archival aerial photography; and comparison of the age (relative size) of channel trees between reaches which are likely to have been channelised forever (downstream from the delta apex), and reaches which may be newer. This approach may be complicated by high levels of floodplain salinity, affecting eucalypt growth.

A2.2.11 Rivers that Change: Variable Flow and Landform Tipping Points

It is the nature of humans to assume stability in something which hasn't changed for a generation or two. Nonetheless it is evident that Neales River channels and waterholes can change, substantially, and sometimes very rapidly. The Neales Catchment is full of stochastic influences (almost-random inputs into the system). The variable rainfall and runoff, leading to extremely variable flow patterns in both time and space, are one set of stochastic forces. The irregular landform topography and irregular floodplain surface (see Appendix 3.2) is another – at any one place the downvalley slope may be less than the slope across- or even up-valley. For this reason the Neales River is likely to be substantially threshold-driven: in response to some event (a tipping point) landforms can switch abruptly from one state to another. The triggering event might be a particularly large flow, which in a particular location cuts a new path across the floodplain; or a slow steady accumulation of sediment over many flows, which eventually becomes large enough to divert the primary flow path somewhere else. For example in Fig. A1.2 (top) the primary flow path might diminish in importance, and the secondary flow path expand to carry the bulk of the flow in that reach. It should be noted that human land management activities can bring a reach's tipping point within the reach of a normal flow event: for example a well-vegetated valley floor might only incise for a 1:100 year rainfall – but the same valley floor, devegetated and with a road down the middle, may incise after a much smaller rain event.

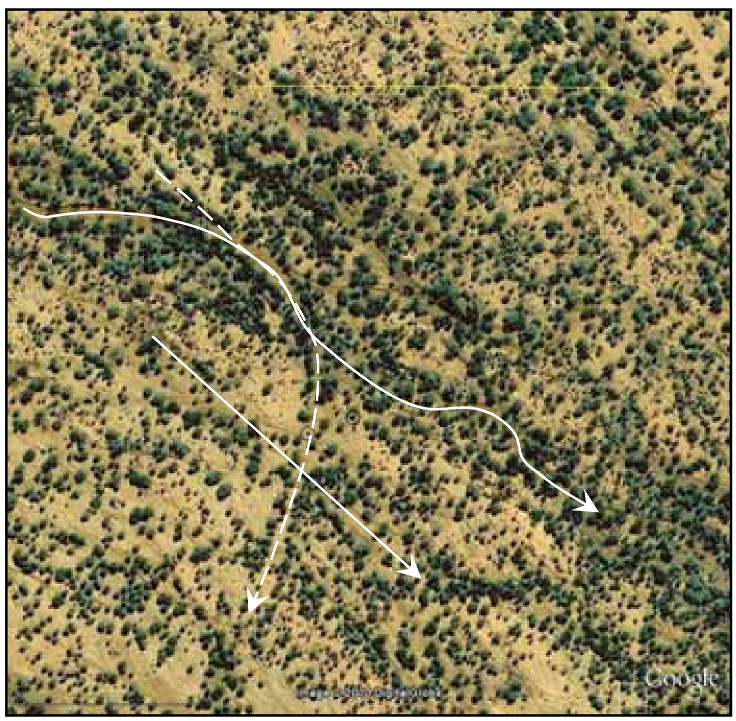


Fig. A2.24 Google Earth image of an old channel (now abandoned), visible in the paired tree lines (dashed white line). It is crosscut by modern flow from the south branch (white line). North to top, yellow scale bar = 0.3 km, arrows show flow direction, location near Angle Pole Waterhole.

The most observable change to channels on a human timescale is probably the delivery of silt into waterholes, eventually causing them to become shallow. Under pre-European conditions, this might occur after a long series of low flow events, and the waterholes would be scoured again after the next large flow event. In the modern day, rilling and gullying near popular swimming and fishing holes delivers sediment to

Fig. A2.25 Google Earth image of the Lenin-Bulletin Waterholes area (right) and the 4-Waterholes reach (left); north to top, yellow scale bar = 1 km, white circles = geology sites. The two ex-waterholes (asterisks) near Lennon Yard are located along a flow path (black dashed line) which was once, but is no longer, the primary flow path of these reaches. The modern primary flow path is shown by double line of dark green trees on the south side of the alluvial valley). Bulletin ex-waterhole is also marked with an asterisk; the main flow has bypassed it due to chute cut-off. Also see Fig. 16.

the waterholes, contributing to waterhole shallowing (Costelloe 2010). Another cause can be upstream valley-floor incision. For example, the shallowness of West Algebuckina (in comparison to its width) is likely to be the result of the relatively recent incision of the upstream valley floor at Ockenden Creek, releasing silt to accumulate in West Algebuckina.

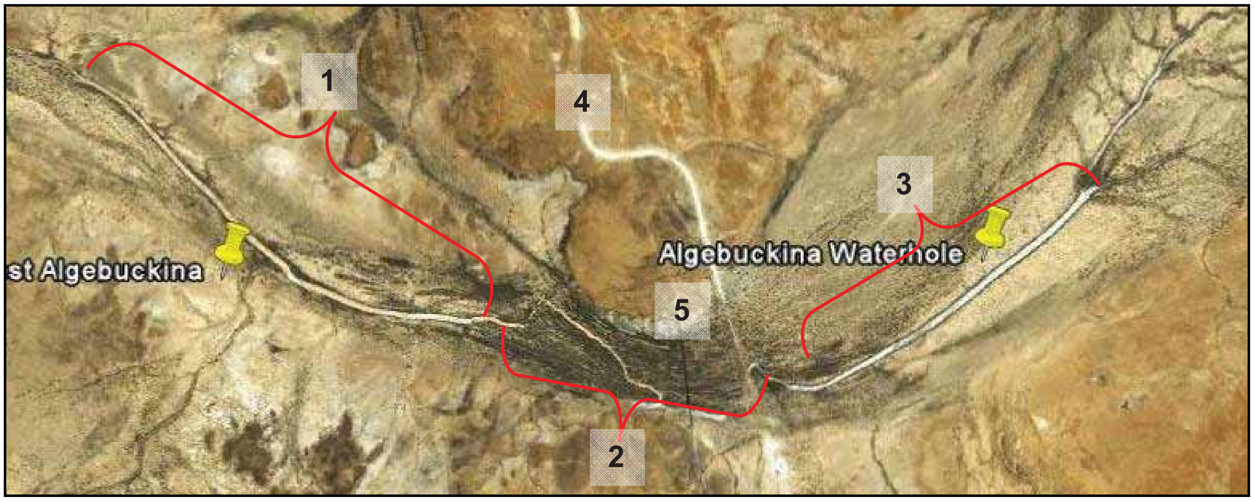


Fig. A2.26 Google Earth image of the Algebuckina area, north to top. 1 West Algebuckina, 2 Algebuckina Pinch, 3 Algebuckina Waterhole, 4 white line is the Oodnadatta Track, 5 dark line is the Algebuckina Railway Bridge.

The shallowing of West Algebuckina highlights a potential risk to the depth (and thus, refuge qualities) of Algebuckina Waterhole. At the moment, West Algebuckina is separated from Algebuckina Waterhole by Algebuckina Pinch, a narrow floodplain hemmed in by resistant hills and vegetated by a thick belt of scrubby trees (Fig. A2.26). Only a small irregular channel threads through the trees. If a substantial channel was to develop, linking West Algebuckina to Algebuckina Waterhole, it is likely that flow events would flush substantial silt into Algebuckina Waterhole, effectively destroying it. A similar sequence of events probably led to the loss of Tardetakarinna Waterhole (page 89). Algebuckina Pinch is where the railway bridge and Oodnadatta Track cross the river. If infrastructure development leads to a new road crossing, very great care should be taken that the flow is not concentrated. This would create a point source of gullying, connecting the two waterholes and moving silt from West Algebuckina to Algebuckina Waterhole. A common arid-zone situation leading to flow concentration and gullying is where flow is passed under the roadway in culverts which are only designed to match channel size. When overbank flow happens (as is invariably the case in variable-flow arid-zone systems), the floodwaters become erosive where they emerge from the culverts. Ideally, the

Algebuckina road crossing should remain a bed-level causeway. If a new elevated road crossing is installed, the elevated structure should encompass the whole valley.

The smaller channels in the upstream Neales sometimes change or are abandoned in favour of other channels. All that might be left is a double line of trees oriented at an angle to the current flow direction: the actual channel has been filled in by the sediment moving down the river system (Figs. A1.4, A2.24). In the anastomosing reaches (Farley, Eaglehawk, etc), the small scale of the landforms and the anastomosing fluvial style indicates the channel relocation will happen reasonably frequently (sub-century recurrence interval). These small changes are unlikely to be noticed.

Waterholes diminish and disappear and new ones are created. The Tardetakarinna Waterhole was substantial enough to be named; its name is Aboriginal, suggesting it was a fairly old waterhole; but it does not exist anymore. In the south branch of the Neales Lennon and Bulletin Waterholes were given European names, and roads and yards constructed nearby; these waterholes were useful after European settlement but are now minor, whereas nearby bigger waterholes (in this report called 4-Waterholes) are unnamed and without yards (Fig. A2.25).

The medium-sized waterholes which are important habitats in most years (such as Hookeys, Angle Pole, Stewart's) look to have been stable since before European settlement: they have signs of Aboriginal and European occupation, and no change has been noticed in those (such as Hookeys) which have been a resource for whole communities (and so would not have undergone change without some historical record). Nonetheless, waterholes on these scales do change (probably on a century timescale). The high silt plains which are such a feature of these waterholes are visible by their pale colour, slight elevation above other floodplain landforms, and lesser degree of vegetation (see Figs. A2.11, A2.12). It is possible to see places where the high silt plains have been modified by subsequent channel development and vegetation establishment (Fig A1.8. #2). With closer examination it becomes clear that the entire floodplain is covered by the remnants of old silt plains (#9 Fig. A1.8, and see Figs. A1.2, A1.4, A2.24, A2.25, A2.27). This explains floodplain topographic irregularity observed on the 1-second DEM (see Technical Appendix 3).

The very largest waterholes are stable for longer (change in any one place occurring on a multi-century timescale). Their likely sequence of landscape development is:

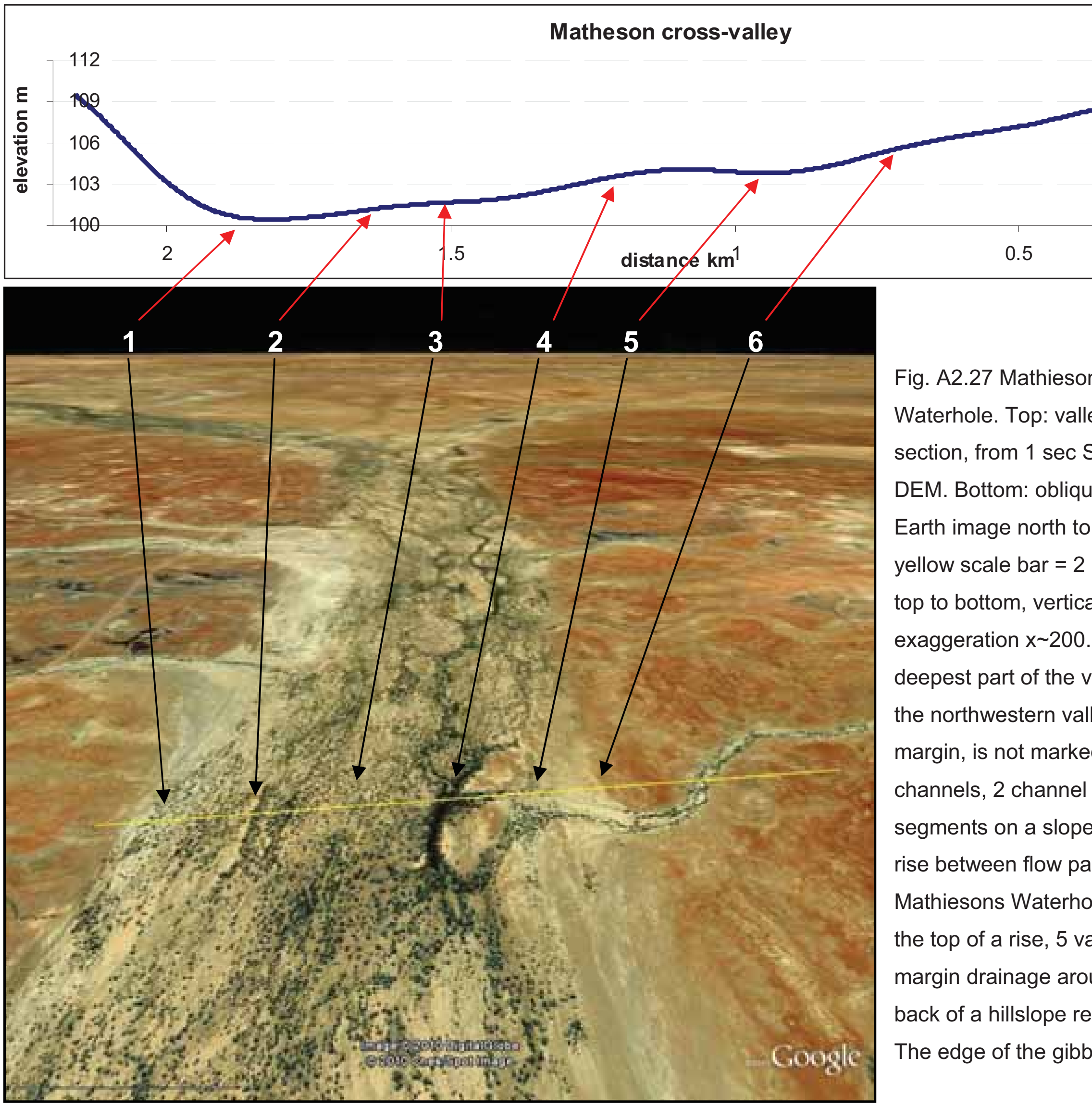


Fig. A2.27 Mathieson Waterhole. Top: valley cross-section, from 1 sec SRTM DEM. Bottom: oblique Google Earth image north to top left, yellow scale bar = 2 km, flow top to bottom, vertical exaggeration x~200. 1 the deepest part of the valley, at the northwestern valley margin, is not marked by any channels, 2 channel segments on a slope, 3 slight rise between flow paths, 4 Mathiesons Waterhole is near the top of a rise, 5 valley-margin drainage around the back of a hillslope remnant, 6 The edge of the gibber plain.

- The large waterholes accumulate high silt plains along their banks and across their downstream splays. So much sediment accumulates that the waterholes are now occupying elevated positions within the alluvial valley (Fig. A2.27).
- A really big waterhole like Algebuckina accumulates wide high silt plains on either side. The increase in width with distance downstream indicates that the plains are being constructed from silt removed from the waterhole only a few metres upstream (Fig. A1.9).
- Under the right conditions, the downstream splay is breached and one of the small splay channels extends to become a substantial channel in its own right. It also accumulates flanking high silt plains (Fig. A1.9).
- The big waterhole is now confined between high banks, while the alluvial valley margins are of considerably lower elevation.
- A tipping point occurs when flow entering the upstream end of the waterhole overwhelms the channel capacity. Likely causes include hydraulic damming, an extra-large flood or roll wave, or because the channel mouth has been blocked by a pulse of sediment stranded during previous flow event. In any case, the flow is diverted around or over the high banks, and flows down the

lower elevation pathways along the valley margins. This is the origin of the landforms at Peake Gap (Fig. A2.28): the dry and relatively shallow channel near Freeling Springs is the original channel (its width is not in the scale of its depth, indicating it was once much deeper); Baltucoodna and Warrarawoona Waterholes are relatively new, and the remains of the previous waterhole's old channel and high silt plains can be seen between Baltucoodna and Warrarawoona. Baltucoodna and Warrarawoona are the only waterholes in the study which are not perched on high silt plains.

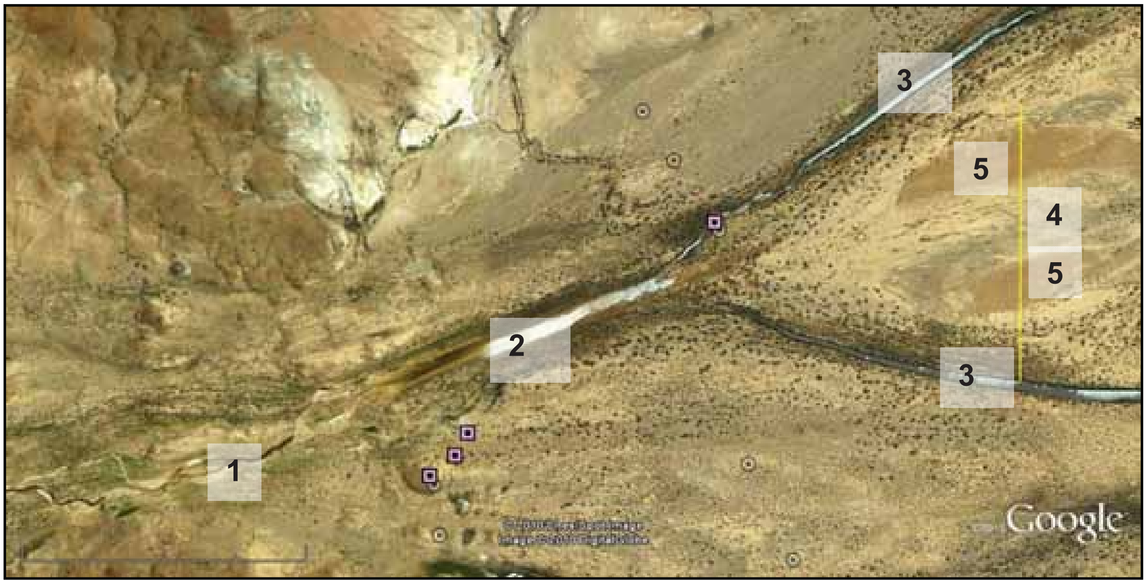


Fig. A2.28 Google Earth image of Peake Gap, north to top, yellow scale bar = 1 km, flow left to right. Numbers: 1 the rocky gap, 2 the main channel, currently very shallow in comparison to its width, 3 Baltucoodna and Warrarawoona Waterholes in low-elevation parts of the valley, 4 abandoned path of the previous main waterhole, 5 older high silty plains flanking the previous waterhole.

The management implications of waterhole and channel mobility are:

- Channel relocation (avulsion) or waterhole abandonment are part of the natural river behaviour, a response to the threshold-driven nature of the landforms and the variable flow regime. The variable flow regime is necessary for ecological health and landform maintenance. It will have effects that look like destruction but which are actually part of a natural cycle of landscape renewal.
- When drafting guidelines or legislation to protect the critical refugia waterholes, it is extremely important 1) not to restrict protection to a specific waterhole, because it may change and cease to be a viable refuge, and 2) to allow for the possibility that new important refuge waterholes might be created.
- It would be wise to protect several refugia rather than just one.
- Algebuckina Waterhole is vulnerable to avulsion by the same sequence of events as happened at Peake Gap (Fig. A2.29). Management actions to protect against avulsion should include protecting and restoring the riparian vegetation, protecting and restoring the dense scrub of trees just downstream

from the road crossing, and rehabilitating the gullies through the banks. However, avulsion will happen at some future time (possibly hundreds of years in the future).

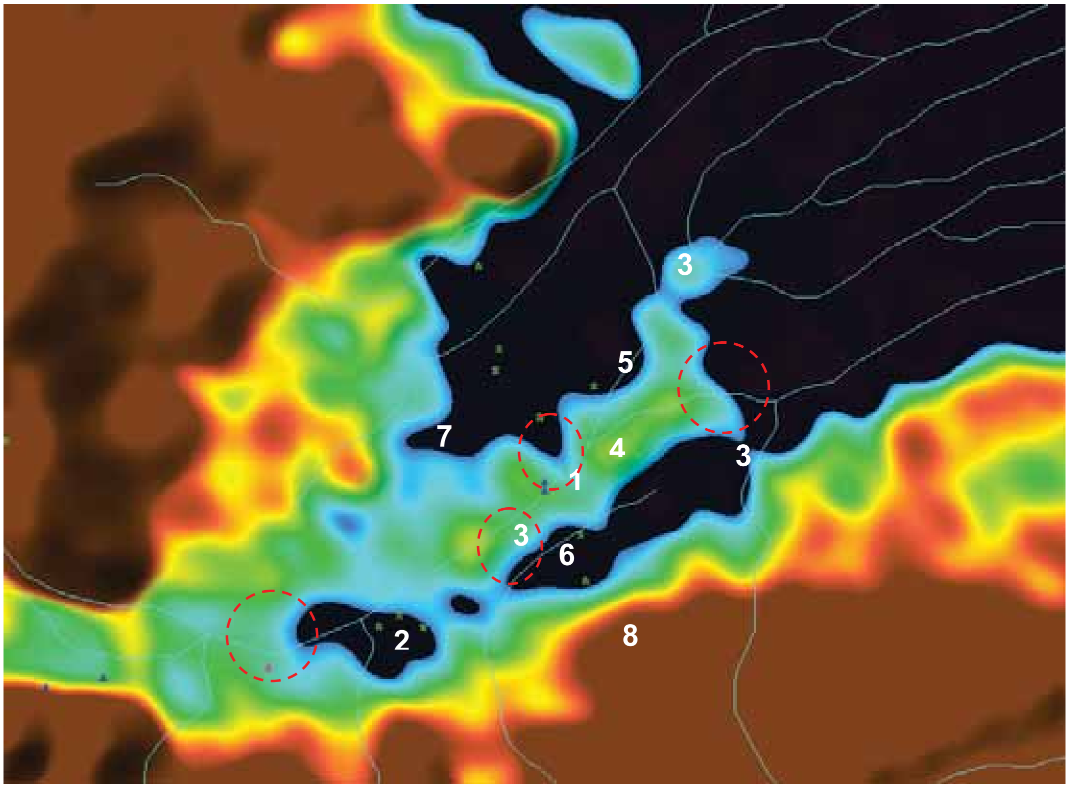


Fig. A2.29 Digital Elevation Model image of Algebuckina Waterhole, showing risk avulsion areas (red dashed circles) flanking the present waterhole. North to top, green stars are geomorphology field sites, blue triangles are hydrology sites, pink star is fish site. Elevation gradations at 1 m intervals, in the sequence brown (66+ m), red (65 m), yellow, green, light blue (62 m); black simulates a flood level at 61.5m (the highest elevation of modern flow events). SRTM 1-sec data. Numbers: 1 the waterhole, 2 the Allendale/Peake fence location, 3 silty high plains flanking waterhole and splay channels, 4 downstream splay , 5 biggest splay channel becoming a waterhole in its own right, 6 south bank low area, 7 north bank low area, 8 rocky hillslope.

A2.3 Landforms and Ecology

A2.3.1 Tourism and Local Recreation

The high silt plains are extremely desirable in terms of tourist visitation and local inhabitants' recreation. They are close to scenic waterholes for swimming and fishing, they are not boggy to drive on (Fig. A2.30), they make comfortable camping. In the more popular tourist waterholes (Algebuckina, Stewarts, Hookeys, Angle Pole) the high silt plains are where the vehicle tracks are, and where most camping occurs.

During this study the spatial relationships between rilling, vehicle access, and cattle sign were actively investigated. There was no relationship between intense stock use and rill/gully networks (see below). There was a strong correlation between vehicle access and the development of rill/gully networks in the high silt plains. All the popular human visitation sites showed dendritic gully networks (Fig. A2.31) on the high silt plains, connected to narrow deep gullies through the riparian ridge and bank tops. Where the rill networks are most strongly developed, it is evident that there is considerable sediment transport from the high silt plains into the waterhole. This matches observations made during the hydrology investigation that the waterholes are becoming shallower at these points (Costello 2010).

It is probable that there are two separate processes at work: 1) gullying develops through the riparian ridge and the bank lip as a result of people going down to the water, and 2) rill networks, which develop in response to the gullies, are promoted or exacerbated by vehicles driving over the high silt plains.

Fig. A2.30 The silty high plain at Angle Pole waterhole is bare along its flank, providing easy vehicle access. Its crest is colonised by nitre bush with trees along the waterhole bank (right). Left, a small scour into the top of the silt is a waterhole in miniature: bed (dark mud showing between banks), banks (red arrows) and bank vegetation mimic waterhole landforms, while its orientation matches the orientation of the main channels. Jay for scale.

Rehabilitation will be best achieved by revegetating the riparian zone, even within gully notches. Re-establishing vegetation along the riparian zone will promote the waterhole's natural self-healing processes (sediment deposition within the vegetated zone during high flows). In the popular tourist areas the depletion of riparian vegetation by trampling, woodcutting and deadwood gathering is marked, and should be of substantial concern given the absolutely critical role that riparian vegetation plays in waterhole maintenance. Revegetation of the riparian ridge, and visitor management, should be high priorities.

A common and effective method of dealing with gully erosion is stabilising the gully head by re-vegetation. There may be some difficulties with this where the rill networks are cutting into the high silt plains (e.g. Fig A2.31). The high silt plains are naturally poorly vegetated, suggesting that when the plains formed, they were unfavourable to plant growth. This is consistent with their material: well-sorted quartzose silt would pack down hard, providing little opportunity for seed lodgement or root growth, and it would not contain nutrients or retain moisture. On the other hand, very old high silt plains eventually host some vegetation, so perhaps planting may succeed if the hard packing is loosened, and some organic material is supplied. However, riparian revegetation should be a higher priority than gully head planting.

Fig. A2.31 Rills and gullies at Algebuckina. Top: One of the dendritic rill systems (**R**) extending out across the high silt plain of in a part of Algebuckina visited by vehicles. It leads to a gully (**G**) which cuts through the riparian ridge and drains into the waterhole. Vehicle for scale. Bottom: This erosion gully in the non-tourist part of Algebuckina drains into a rabbit hole at some distance from the bank edge. Rabbit hole is behind hammer (circled).

In the popular tourist area at Algebuckina camping activities were also impacting the hummock plains, thinning the vegetation, and reducing the height and width of the hummocks. (Ideally this would be confirmed by more fieldwork.) It is likely that the detrimental activities include breaking off bush twigs for kindling, digging toilet and refuse pits in the soft silt, and driving and walking on the edges, causing the hummocks to erode. Loss of the hummocks may be undesirable if it promotes faster overbank flow during large floods. However, this is a lower priority than bank vegetation rehabilitation.

In the unofficial camping area east (downstream) of the Algebuckina Causeway, the small-channel complex has many tracks amongst the channels, and there is considerable ground surface lowering. It would be desirable to investigate a reference area nearby that has no vehicle access, but from this study it appears that this area is heavily modified by vehicle tracks depleting vegetation and causing erosion. This is undesirable as reducing this vegetation, or allowing flow pathways to develop through it, may increase the likelihood of avulsion (Fig. A2.29).

In Stewart Waterhole gully networks from the floodplain are extending up into the nearby hillslopes along pre-existing but previously unincised zero-order drainage lines. While these have almost certainly developed in response to heavy local use, it is unlikely that the intensity of use here is greater than at Hookeys or Algebuckina. The greater extent of erosion at Stewart's relates to two factors: its location in the knickpoint reach, and therefore greater local gradients, bringing hillslopes closer to the threshold of gully incision; and the close connection between the floodplain and the nearby hillslopes, such that the hillslopes immediately feel the effect of erosion on the nearby floodplain.

A.2.3.2 Cattle

In some locations (Farley dam, west Algebuckina) which were obviously heavily used by cattle (tracks, cattle pads, dung, depleted vegetation) there were no extensive rill networks, and very little gullying. This indicates that human visitation may be the more dominant factor in rilling and gullying around large waterholes.

At these larger waterholes there were surprisingly little sign of cattle going down the banks to drink. The single cattle pad that was seen went obliquely down the bank, not straight through like the tracks at the tourist sites. All the waterholes have very steep banks, and it is likely that these were too steep and too deep for cattle to access easily. However, after something (such as human visitation) had allowed a gully line to develop through the banks, cattle would then have access to the waterhole via an easier pathway. (Note that these comments are not applicable to smaller waterholes, whose banks would be steep but shallow, so possibly more accessible to cattle. However, a site heavily used by cattle, where several stock pads cut through hummocks and floodplain topography and led straight to a small waterhole, showed no gullying. Also, note that this wide-scale study was never intended to map all areas of intense stock use, so it is quite possible that cattle tracks down steep banks existed in places not visited during this field work. If there are such tracks, it is worth considering whether these are, like Algebuckina, places that were also frequently visited by humans.)

Due to access difficulties during this wet year, it was not possible to examine the waterhole ends. However, it is likely that in the larger waterholes, cattle use would be more intense on the upstream and downstream waterhole ends, where access to the water would be along the gently sloping splay channels. These would be a more reliable access to water, than the steep banks. Stock use at waterhole downstream terminations could be a concern. If cattle pads trigger breaching of the downstream-end splays at waterholes, this would lead to a lowering of the cease-to-flow depth of the waterhole. This is a potential part-cause for the draining of Tardetakarinna Waterhole, and may also be a factor in the development of Algebuckina Splay sideways channels (Fig. A1.9).

With the exception of areas close to watering points and dams there did not appear to be substantial change to geomorphic processes of the Neales River as a result of grazing pressure. (Note that these comments absolutely do not refer to changes to vegetation communities, which lie outside the scope of this report.) Some workers might regard the hummock fields as evidence of substantial change, in which grassland is depleted by grazing and replaced by shrubland, which then develops coppice dunes. In this report, this is not considered to be the case for the reasons given in Section A2.2.3 above. The effect of grazing pressure on the thinly-vegetated the hillslopes, and the effect of cattle pads on the desert pavements, was not investigated in this study, and is worth consideration in its own right.

A.2.3.3 Rabbits

On the north-western bank of Algebuckina Waterhole, near the splay and opposite one of the fish sites, there was some sign of human presence (a few old camping places) and some sign of cattle. There were a lot of rabbits. The rabbits are currently the most active force promoting erosion in that area. Rabbit burrows focus runoff and waning-flow drainage via burrow holes (Fig. A2.31), directing it toward the bank at water level, undermining the bank and leading to bank collapse. It is not clear from this investigation whether the gullies and rill networks are primarily caused by the rabbits, or whether the rabbits have exacerbated pre-existing gullies. However it is certain that they are currently extremely detrimental to the geomorphic processes of this part of Algebuckina. In addition, as a refuge waterhole Algebuckina also provides refuge for rabbits, where they can wait out a drought. Rabbit control should be an immediate priority. Note that warren ripping would be equally detrimental to the waterhole banks (as promoting erosion) and control should be by poison or similar means.

A2.3.4 Landforms as Habitat

Aquatic Biota

The deepest waterholes are refugia for aquatic life, preserving fish populations during drought, and medium-sized waterholes are habitats during times of fish population expansion (Costelloe 2010, McNeil & Schmarr 2010). Turbulent scour during large and very large floods creates waterholes and maintains waterhole depth. Large flow events are therefore very important for the ecological wellbeing of this river system.

Waterhole beds will have quite different physical characteristics at different flow stages. During small flow events, flow conditions will be relatively tranquil. There may be some sediment transport but there is very little evidence of bedforms (such as sand waves), such as may be more common in other sorts of rivers. During large flow events the waterhole beds are likely to be highly turbulent, and in extremely large flow events the waterholes may experience supercritical flow. Turbulence is likely to extend from bank to bank and along the whole length of a waterhole. There will be a central high-velocity zone, and also be shear zones along the banks. The geomorphology gives very little evidence for sheltered patches in the main parts of the waterholes.

During no-flow and small flow events, the downstream splays are likely to have a variety of topography and boundary conditions, offering a range of habitat types. Their high degree of vegetation is likely to be beneficial to waterhole fauna, as both protection from birds and as a source of organic material. During large and very large flow conditions there may be more sheltered areas within the downstream splays, although there would also be the risk of being moved out into the above-floodplain level flow. Perhaps that's not a risk, perhaps that's an opportunity for fish to move out to the floodplain without using much energy.

Across the floodplain there will be a wide variety of flow conditions, ranging from flow separation (with sheltered areas of low-energy), to turbulence around objects, to rapid flow down channels. Flow speeds and turbulence levels will vary across the floodplain.

At the beginning of a flow event, food resource availability may be very low for most fish in refuge waterholes; when they escape to the floodplain they find new resources (D. McNeill pers. comm. 2010). It is worth considering then that waterhole complexes such as Angle Pole or Hookeys, which will have nearby waterholes with presumably intact invertebrate fauna, may have a special value. While Algebuckina may give refuge for longer, there may not be much on the floodplain when the fishes get out there.

Floodplain landforms which are too small to shelter fish after cease-to-flow (for example, anastomosing reaches), are nonetheless important contributors to the ecosystem because they grow vegetation, some of which eventually contributes to organic material washed into downstream waterholes.

Gully heads in badlands-arroyo complexes are likely to limit the upstream movement of fish, because there would be only a brief time during peak flow when there would be sufficient water to establish connectivity (see Figs. A2.19, A2.20). The badlands-arroyo complexes at the Neales-Peake confluence and in the Lower Neales may already be, or may soon become, a barrier for upstream fish migration (for example, from Peake Gap to Algebuckina, or from Lake Eyre to Algebuckina)

Land Plants and Animals

While the focus of this project is on aquatic biota in waterholes, it should be noted that the Neales River is also the major habitat for a substantial proportion of the catchment's land plants and animals (in comparison to the relatively barren hillslopes). The refuge waterholes are no less important for them, providing seed bank and animals in breeding condition to repopulate the rivers after long drought..

Riparian zones are well-known to be valuable in river systems generally, promoting river health and providing ecosystem services to biota. The Neales Catchment riparian zones obviously fall into this category. The downstream splays should also be counted as riparian zones: they provide the same ecosystem services (and also landscape services such as erosion mitigation). That riparian zones are usually envisaged as occurring along river banks is an artefact of the perennial-river centricity of geomorphic discourse. Discontinuous rivers are more characteristic of dryland settings, and in discontinuous rivers floodouts and downstream splays are riparian (Wakelin-King 2006, Wakelin-King 2008).

Refuge waterholes can also shelter feral plants and animals. This makes them an opportunity for targeted pest control during long drought.

A 2.3.5 Further Investigation and Essential Monitoring

Erosion gullies at Algebuckina Waterhole, Stewart waterhole, Ockenden Creek, Wirriarrina reach, and the Peake-Neales confluence are of particular concern to both landholder interests and ecological services. A question not resolved by this investigation is the timing and speed of development of these erosion gullies. A relatively small investment in examination of archived aerial photography would provide more information, and assist in prioritising rehabilitation works.

Ongoing monitoring of erosion networks is essential to see if the management actions arising from this project are having the desired effect. The rehabilitation works, changes to management policy, or infrastructure designed to control intensity of usage at key sites, will be based on an idea of what caused the issues at a particular site. Without monitoring, it will be impossible to determine whether management actions have been correctly targeted.

- Depths of key waterholes should be monitored by hydrographic surveys which are accurately located with respect to the Australian Height Datum and also with respect to key landforms which are themselves accurately surveyed-in.
- Monitoring of erosion at key waterholes and at the Peake-Neales confluence should be a priority. The present low-cost options such as Landsat and SPOT are of insufficient resolution, and LIDAR, orthophotography, or Quickbird should be commissioned (see Technical Appendix 3).

These landscapes are complex and under-researched. The findings of this report are that there are multiple factors promoting landscape change. Predisposing factors include neotectonic activity and the geomorphic context of a particular site. Land-use factors include not only stock, but vehicles, people getting to waterholes, and rabbits. Academic earth-science research aimed at a better understanding of the many factors influencing this landscape would be of long-term benefit to the stakeholders and would be a valuable addition to Australia's understanding of itself.

- A doctoral-level investigation of the Peake-Neales confluence is highly recommended in order to investigate the origin and management responses to the arroyos and badlands. The project would be relevant to land managers but would also be of interest to hydrocarbon industry basin analysis research groups (who might provide funding).
- An Honours-level project using Optically Stimulated Luminescence to estimate the time since the last megaflood would be relevant to flood forecasting.
- A doctoral-level investigation of the palynology of sediment in the Neales Delta outflow areas (looking at the relative abundance of grasses and shrubs over time) would aim to resolve whether the hummock fields are, or are not, Invasive Native Scrub and an indication of fluvial system breakdown. The project would be technically difficult but the results could be very important to land managers and Quaternarists.

A2.4 Key Points from Technical Appendix 2

Long Weathering and Barren Rocks

- Shales, limestones, and other sedimentary rocks have been exposed to three episodes of strong weathering, leaching the rocks, mobilising calcium and sulphate, and creating silcrete and ferricrete layers.
- Fine sediments exposed on hillslope surfaces often contain crystalline gypsum and swelling clays. Shales are soft and easily weathered, silcretes are hard and barren.
- Crystalline gypsum is uncommon in the alluvial sediments, except in the gullies of the 6-Mile Arroyo, where masses of crystalline gypsum at ~35 m AHD represent near-shore groundwater from a relatively recent lake-full stage (>59,000 years ago).
- White patches of salinity in creeks and floodplains are groundwater outcrop, which along with springs have their location governed by local geology (rocks, faulting, and erosion). Geology also influences which springs are currently active (as does groundwater extraction).

Tectonism, Erosion, and Sediment Supply

- The tectonic setting of the Neales Catchment is one of slow but steady warping since the Miocene, with uplift in the catchment west and subsidence in Lake Eyre. Consequently the hillslopes around the Neales River are predominantly erosional and supply sediment into the fluvial system.
- Etch plains are a slow steady source of sediment, whereas areas of scarp retreat are transport limited, supplying sediment in pulses. Most of the Neales has a steady supply of sediment in transport, whereas Arckaringa Creek moves sediment in discrete pulses.
- The Neales valleys are largely erosional; thin layers of alluvial sediments have accumulated in the valleys because the system as a whole is transport-limited.
- Valley-fill sediments which accumulated in the lower Neales (during a previous Lake Eyre highstand) will be predisposed towards incision (because the basin is currently in a lowstand state).
- Sediment supply (amount and grainsize) is a significant driver of fluvial process.

Tectonism and Development of the Drainage Network

- Miocene (~23 Ma) and early to mid-Pleistocene (~2 Ma) folding and faulting have strongly influenced the drainage network and continue to have an active effect on present-day fluvial processes.
- The tectonic setting governs downvalley slope, which is a significant driver of fluvial process.
- Drainage networks “compete” with each other for catchment area. Etch surfaces cover more area but scarps have more slope advantage. A scarp that erodes back can “capture” drainage from an etch surface. The Oodnadatta “S” was created this way. Stream capture changes slope and sediment supply, influencing downstream fluvial processes.

Sources of Flow Variability

- Climate change over geological time and normal 100-year to 1,000 year climate variability have produced lake-full episodes, and megafloods.
- The hillslopes are dominated by high-runoff rocks (duricrusts, gibber, and weathered shale) but also include low-runoff sand and stony gilgai.
- Variability in surface runoff characteristics, combined with the likely differences in rainfall capture of scarp (rare but flashy) versus etch plain (more frequent, sustained) will be one of two major drivers of Neales River flow variability (the other being the climate).

Flow Variability: All Types of Flow are Important

- Waterholes and channels are created and maintained by scouring during flow events.
- A high degree of flow variability is natural to the Neales Catchment, including floods, large floods, and megafloods. Infrastructure development within the alluvial valleys should be subject to an informed risk management process.
- Megafloods, with multi-century to millennial recurrence interval, are highly destructive but nonetheless play an important role in landscape renewal. Megafloods are responsible for the creation of the major waterholes.
- Megafloods or large floods are responsible for creating the narrow inset "low flow channel" found in many waterholes.

- Macroturbulent scour is scaled to depth, therefore waterholes that are very shallow in comparison to their width (west Algebuckina, and the Peake Gap channel) have been infilled by some process subsequent to their formation. West Algebuckina was silted up after valley floor incision near Ockenden Creek. Peake Gap's wide but shallow waterhole relates to sediment pulses and channel avulsion.
- Large channels and waterholes are maintained by large floods (with multi-decade to century-scale recurrence interval), and dense riparian vegetation. Bank integrity and waterhole depth is maintained by scouring as high-level flows move through riparian vegetation. Bank and vegetation configuration create a high-intensity flow down the middle of the waterholes, scouring the waterholes clean of accumulated silt and maintaining bank steepness. The action of riparian vegetation on silt-laden floodwaters promotes deposition in the riparian zone, across the high silt plains, and across the downstream splays.
- During ordinary flow events (yearly to decadal recurrence interval) flow over the floodplain is promoted the discontinuous channels and the anastomosing reaches. Floodplain flow is slowed by roughness elements such as hummocks, irregular topography, trees, small scours. The slow advance of the floodplain-wide flow front allows water time to infiltrate into the alluvial sediments, promoting ecological richness.
- Some reaches are more likely than others to promote the creation of waterholes during large flow events. This relates to the degree of alluvial fill, and the topographic boundary conditions. Waterhole clusters may be more ecologically valuable than single waterholes, by virtue of providing more ecological niches.
- In this report, the hummock fields characteristic of the Neales are seen as naturally-occurring, and having an important role in river process during the common episodes of floodplain-level flow. Hummock fields (and other substantial vegetation) are a roughness element, preventing valley floor incision and promoting infiltration of water into the floodplain. A different view of hummock fields is that they are an Invasive Native Scrub and evidence of degradation, however the only evidence for this interpretation is their resemblance to some landforms in the USA. These differing views have significant management implications, and further research is indicated.

Neales Catchment Landscape Processes

- The present-day Neales River is a product of its tectonic context, governing downvalley slope and sediment supply.
    - Low downvalley slopes encourage floodplain storage of sediment pulses, leading to wide alluvial valleys, shallow channels, and anastomosing primary flow paths (e.g. Elbow Bend). All other things being equal, stream power will be relatively low in these reaches.
    - Steeper downvalley slopes encourage sediment transport, leading to more narrow valleys and more strongly marked flow paths (channels). The steepest downvalley slope along the main river axis is near Mathieson-Stewarts. All other things being equal, stream power will be relatively high in these reaches.
    - There is no direct correlation between waterhole formation and alluvial width, or steeper downvalley slope. Waterhole formation will therefore arise from more complex circumstances of flow conditions.
- The river has a complex flow pattern in which the primary flow path is in some places is clearly distinguishable, as channels, waterholes, or creek beds

marked by trees; in other places the primary flow path is spread across the entire valley width as anastomosing small channels.

- The division of fluvial landforms into "channel" and "floodplain", which is so fundamental to temperate-zone rivers, is almost meaningless here. Neales River fluvial process works to divert flow from channels onto the floodplain wherever possible, and the floodplain is an integral part of the flow pattern.
- Channel types include channels, channel segments, small channel complexes, and waterholes. The channel planforms are often anabranching, and usually discontinuous. Some reaches lack waterholes and are characterised instead by anastomosing channels.
- Badlands complexes and arroyos are present downstream of the Peake-Neales junction.
- The lower Neales is meandering, inset within the channel belt. Unlike the rest of the river its bed is likely to be depositional, and its waterholes will be relatively impermanent and mobile.
- Channel landforms include high silt plains, riparian ridges, and splays cut by distributary splay channels at the downstream terminations of waterholes.
- Floodplain landforms include dry swamps, hummock fields, and no-waterhole reaches of anastomosing small channels. Downstream of the Peake-Neales junction, a poorly-defined flow path is evident in a wide belt of slightly lower elevation floodplain.
- There are floodouts on the Peake River upstream of Peake Gap, and at the confluences between the Peake and the Neales, and Wood Duck Creek and the Neales. Floodouts are usually biologically rich, and also play an important role in mediating erosion. They are geomorphically robust up to a point, but sensitive to erosion at their downstream ends.
- The Neales Catchment is generally an area of erosion, and there is a constant sediment supply being fed into the alluvial system. Most parts of the Neales catchment are transport-limited, and sediment travels in pulses. This contributes to stochastic flow processes, and promotes channel avulsion.
- Channels and waterholes are impermanent.
    - Larger channels, channel segments, and small waterholes will accumulate silt over many small flows. In some cases they may be silted right up and abandoned.
    - Anastomosing channels probably move on a decadal scale, but the changes are small and unnoticed.
    - Medium-sized waterholes move and are abandoned, probably catastrophically, during ~century-scale flow events. The remnants of these old waterholes can be seen in many parts of the Neales floodplain, as the floodplain topographic irregularity which is the remnant of the old waterholes' high silt plains.
    - The largest waterholes build up silt around themselves and downstream, allowing other parts of the alluvial valley to maintain a lower elevation. Eventually (on a multi-century timescale) flow will bypass the large waterholes and they will be abandoned in favour of new flow paths.

Management Implications

- The local landforms must be understood and managed in terms of their own local landscape processes, rather than being treated on the basis of their resemblance to similarly-shaped landforms in other settings. This comment is relevant to multithread (anastomosing) reaches (which are not braids), hummock plains (which are not coppice dunes), and high silt plains (which are not classical levees).

- Floodouts, and the clusters of distributary channels cutting through splays at waterhole downstream terminations, function as riparian zones in terms of their ecological and geomorphological function (refuge habitats, mediators of erosion and buffers to fluvial function). Classically, the definition of riparian zones (based on perennial temperate-zone rivers) is that they are found along river banks. It is recommended that floodouts and splay distributary channels in the Neales River be recognised as refuge habitats equivalent to riparian zones so that they may have equal access to funding targeted towards riparian zone management.
- The value of waterhole banks, floodouts and downstream splays as refugia for non-aquatic biota, should be recognised. They also shelter pest animals and offer opportunity for targeted pest control during drought.
- Flow conditions during large floods and megafloods will be complex, with transcritical flow and extreme degrees of roughness. Hydrological models which work well for ordinary floods will not be scalable up to these extreme conditions.
- Riparian vegetation (both trees and understory) is vital in waterhole landform maintenance. Activities which reduce vegetation in the riparian zone should be avoided. Revegetation of degraded riparian areas (including in gullies through riparian areas) should be a priority: vegetation will allow the riparian zones to fix themselves during subsequent flow events.
- It is critically important that flow variability remain at its natural level, so that refuge waterhole depths can be maintained.
- Valley-floor incision, leading to channel connectivity and efficient water transfer downstream, is a substantial cause of degradation. In particular, the entire Peake-Neales confluence is very highly compromised. Arroyos and badlands are extending upstream, and without remediation they are likely to affect the Wood Duck Floodout, the Peake-Neales Floodout, and extend further up the Neales.
- The Peake-Neales confluence is a geomorphological a complex area, tectonically active and at the interface between the uplifted Peake/Denison Ranges, and the subsiding deposcentre (Lake Eyre). The relative importance of land management versus landscape processes in creating these arroyos is not clear from this investigation. Further research is strongly recommended.
- The badlands and arroyos might prove a barrier to upstream fish migration. While fish may easily move downstream into arroyos, they will be unable to move laterally out again, due to the deep vertical banks. They might move upstream again via the upstream stepped gully-head edges, which are shallow enough for fish to jump up. However they are very limited in their extent, and flow continuity over those edges may be temporally restricted to the flood peak. Therefore there are likely to be few opportunities for fish to move upstream from arroyos to badlands to the wider floodplain. There is little chance that Lake Eyre fish will be able to re-occupy Algebuckina, and it is likely that fish migration upstream from Peake to Algebuckina is either compromised now, or will be compromised in the near future.
- Management guidelines and surface water legislation which is written to protect significant waterholes should recognise that no waterhole is permanent; guidelines and legislation should be drafted in such a way as to be able to be applied flexibly to new locations in the landscape.
- Algebuckina is likely to avulse in some future century. Avulsion may occur near the downstream splay, or possibly near the Peake-Allendale boundary. Preservation of the thick scrub in Algebuckina Pinch, (the reach between West Algebuckina and Algebuckina Waterhole), preservation of the non-channelised status of Algebuckina Pinch, and rehabilitation of erosion gullies

through the Algebuckina riparian zone, are management activities will likely to discourage avulsion

- Silt accumulation in waterholes can be a natural consequence of the river's sediment load. However, unusual events may deliver excessive silt to waterhole, making it shallow and destroying its refuge qualities. West Algebuckina has been shallowed by silt from the valley-floor incision near Ockenden Creek. Tardetakarinna Waterhole has been destroyed by the incision of the Wirriarrina Badlands. The relative roles of tectonism vs. land management in these incision events is not clear.
- Valley-floor incision in Algebuckina Pinch, leading to a channel connecting West Algebuckina to Algebuckina Waterhole, will deliver silt into Algebuckina Waterhole and destroy its refuge properties. Infrastructure development (for example, culverts) at the Oodnadatta Track crossing which created points of flow concentration would be highly likely to promote valley floor incision. The Oodnadatta Track crossing should remain a low-level causeway, and any further infrastructure development should be carefully designed.
- Vehicle access is implicated in the development of rilling in high silt plains flanking popular waterholes, and floodplain degradation in the area of thick scrub at Algebuckina Pinch.
- Human access to water is implicated in the development of gullying through waterhole banks.
- Human use of riparian vegetation is a concern, and will interfere with the self-maintenance of the waterholes.
- There was relatively little sign of stock in impacting on geomorphic processes over the wider river area (note this observation excludes affect on vegetation, and excludes hillslopes). In larger waterholes, it is likely that stock make less use of the steep banks to gain access to water, and more likely that they enter waterholes from their upstream and downstream ends. Stock pads linking upstream to downstream waterholes may have been a factor in the destruction of Tardetakarinna Waterhole.
- The presence of rabbits in the less-visited areas of Algebuckina and other big waterholes should be of concern, as their warrens substantially promote gullying and bank erosion, and as they are protected from drought at the refuge waterholes.
- At different flow stages, floodplains and waterhole/channel beds will have quite different physical characteristics (turbulence, noise, possible cavitation) and therefore habitat qualities.

Essential Monitoring and Further Earth-Science Research

- Ongoing monitoring of erosion gully response to forthcoming management actions is critical. Monitoring should include hydrographic surveys and high resolution photography or imagery (SPOT and LANDSAT are insufficient).
- Archived aerial photography will reveal timing and speed of erosion gully development.
- A doctoral-level investigation of the Peake-Neales confluence to investigate the origin of and management responses to the arroyos and badlands is highly recommended.
- An Honours-level project dating the last megaflood would be relevant to flood forecasting.
- A doctoral-level investigation of Neales Delta outflow palynology would aim to resolve whether the hummock fields are a degradation feature.

Technical Appendix 3: Methods, Imagery, Climate

The methods of this study were firstly a remote-resources desktop study, comprising analysis of geological maps, satellite images (Google Earth), SRTM digital elevation models (DEMs) (smoothed – "despeckled" – using the Sun algorithm, Stevenson et al. 2010), topographic dataset (Geoscience Australia), and the published literature on geology, drylands river processes, and other relevant topics. Note that

- there is almost nothing published on the Neales River specifically
- the Arid Lands of South Australia are under-researched
- the Arid Lands of South Australia have few available high-resolution, low-cost resources such as aerial photography, satellite images.

After the desktop study, the field investigation took place, focusing on waterholes of specific relevance to the larger project, and on locations identified during the desktop study as likely to be 1) typical landforms, or 2) providing evidence of past geomorphic activity, or 3) expressing a range of post-European use intensities. During fieldwork, evidence for landscape processes was gathered from the relationships between sediments, landforms, vegetation, and geomorphic context (for example, an area of muddy sediments vegetated by nardoo which are located in a wide shallow depression along the primary above-floodplain flow path, is identified as a dry swamp formed by shallow scouring during flood). Evidence of these relationships is collected as photographs and maps (including GIS database). The point of mapping is that it examines the spatial relationships between landscape elements, allowing analysis of how they work. Post-field investigation revisits the desktop study in the light of collected field evidence, during which stage the majority of new information is uncovered.

A3.1 Imagery

Availability and Cost

The mapping process requires a base map, on which landscape features are plotted according to their location in coordinate space (the map is said to be georeferenced, or registered). Before computers, base maps were constructed by photogrammetric analysis of government-supplied aerial photographs. These days, orthophotos or satellite images are often used.

Landform analysis requires both true-colour and three-dimensional representation: the shape and colour of the landform are primary clues to its substance, cause, and effect on the landscape. High resolution is important, as some significant landscape elements are quite small. Before computers, aerial photography was routinely acquired by state government departments and available at reasonable cost, and it is an excellent tool for landscape analysis. Stereo pairs of airphotos allow 3-D visualisation in true colour, the resolution is excellent, and the view from above provides information that is not available to the researcher on the ground. These days, aerial photography is digital, and orthorectified using a DEM acquired at the same time.

Fig. A3.1 Comparison of SPOTMaps image, left with Digital Globe (Quickbird, from Google Earth) image, right. The SPOT image artificial colour is only a moderate representation of the true colour, and the resolution is not as good as Quickbird, but it is very good value for money.

The difficulty of acquiring usable imagery for this project relates to its size and remoteness. Remote areas are not a priority for the South Australian government to collect new data, or make easily available the existing aerial photographs. The Neales River catchment extends over a vast area (five 1:250,000 scale map sheets) and even if air photos were available they would be too expensive. A topographic base map is easily available but lacks two important characteristics: it does not show an actual picture of the land (so cannot be used to see landforms), and (in the project area) it is completely inaccurate in the most important characteristic, the representation of the drainage network. (This inaccuracy results from cartographer unfamiliarity with the nature of this fluvial system.) LANDSAT and MODIS, are free but their false-colour and their 12.5, 90, or 250m pixel size make them unsuitable for this kind of work. Other satellite imagery is close to true colour and can provide 3-D, but is expensive. Archived Quickbird for example for this area would be $432,500.

LIDAR, flown laser scanning which provides excellent DEMs of much greater elevation accuracy than SRTM, is highly desirable but also very expensive.

In this project Google Earth (Pro) was used during this technical analysis. Its images are either SPOT (2.5 m pixel, artificial colour) or Digital Globe QUICKBIRD (sub-metre pixel, true colour). It is suitable because it provides a picture of the land, and (with a Pro subscription) has some GIS capability. Its disadvantages are that it is not 3-D, it cannot be compiled into other GIS, and the licensing conditions are very stringent (images can't be used for public display). There are specialised Google Earth subscriptions and capabilities which will allow it to be used in the Neales project website, and this is recommended here.

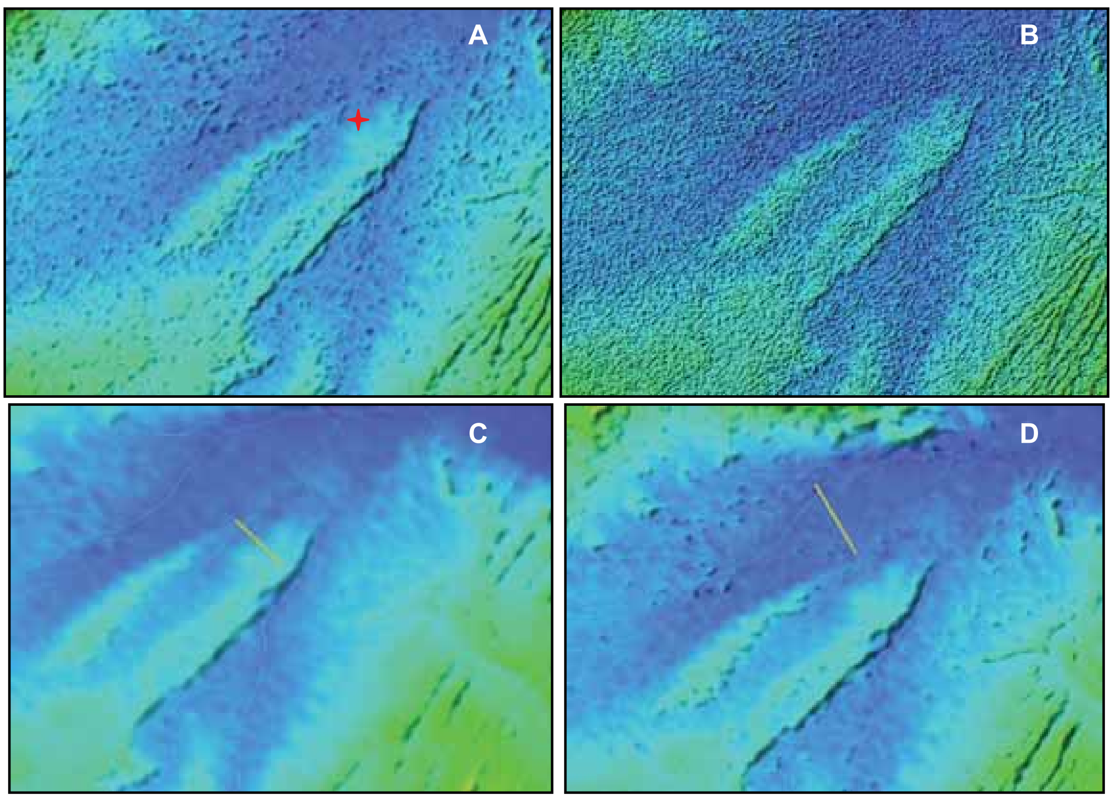
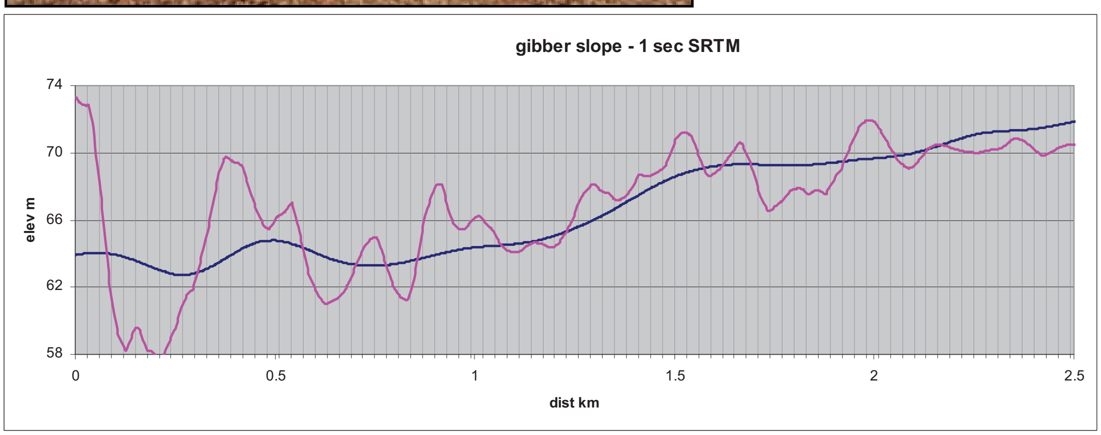


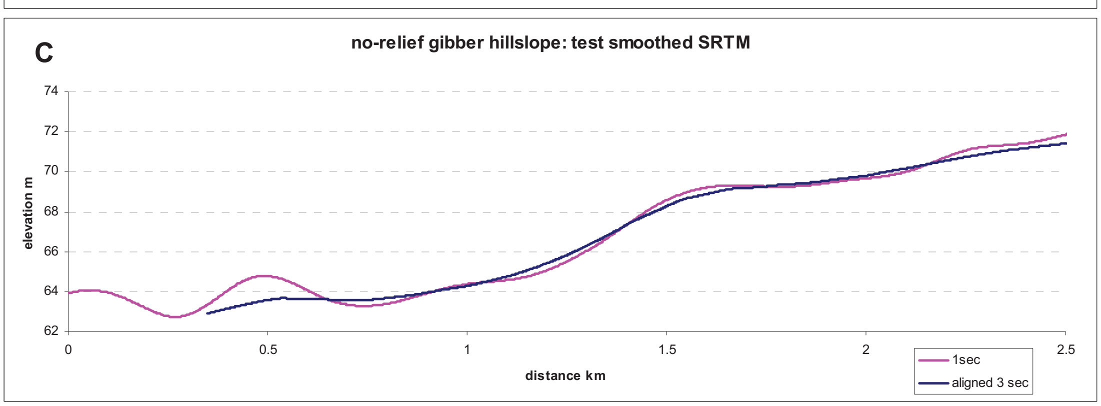
Fig. A3.2 SRTM DEMs of a floodplain and gibber hill near Nilpinna. A raw 3-sec, B raw 1-sec, C smoothed 3-sec, D smoothed 1-sec. Yellow lines are profile locations, red star is location of the photo

Quotes were sought for acquiring new imagery over the Neales catchment. New aerial photography over the whole catchment, including a new DEM, is equal to the cost of LIDAR and is ~$1.5 million. New aerial photography at 1:50,000 scale (pixel size 0.65 m) orthorectified using an existing DEM would cost ~$300,000, however the cost would be much less if only the main river corridors were flown. It is recommended here that if monitoring of vulnerable or significant areas is to take place, that new aerial photography, LIDAR, or Quickbird be considered for the target areas.

SPOTmaps is a new product from the commercial SPOT provider, in partnership with the Australian government. They can provide a Neales catchment image of moderately good quality (Fig. 1, 2.5 m pixel, artificial colour which is an approximation of true colour) to government agencies at a cost which is considerably below commercial: $53,544.85 for SAAL NRM use only (includes contractors), or $69,608.30 for general government use. Availability of a georeferenced image of this

Fig. A3.3 A, The low-relief gibber slope near Nilpinna, chosen to test DEM quality. B, This graph compares raw (pink) and smoothed (blue) 1-second SRTM data from the gibber hillslope; minor gridlines approximate data pixel size. C, This graph compares 1-second (pink) and 3-second (blue) smoothed SRTM data from the gibber hillslope; the agreement is good.





quality would have saved a lot of time during the geomorphology investigation (allowing more time for other outputs). It is recommended that SPOTMaps be acquired for future projects of this type.

Licence conditions currently allow the SPOTMaps image to be supplied to landholders by SAAL NRM. SAAL NRM could also use SPOTMaps to help in map- and overlay-making for landholders during management plan development. (SAAL NRM could also show them how to use Google Earth, or use Google Earth Pro to make .kmz files of their paddock plans, which landholders could load in Google Earth. That would be like having a permanent online picture.) It is recommended here that greater use be made of Google Earth in conveying information to stakeholders.

SPOT is not of sufficiently fine resolution to map erosion gullies or small landforms. LIDAR, aerial photography, or Quickbird would be best-practice imagery to use for these kinds of studies.

Assessment of Noise in the SRTM Data

The SRTM DEMs in their raw state had a lot of "speckle", resulting from signal noise which led to individual pixels having a greater range of elevation values than was justified by reality. The 3-second data, which is processed by NASA, has less noise than the 1-sec data which is unprocessed. The 1-sec data looks much worse because it has 9x the number of pixels and the same range of elevation noise. The data was greatly improved by despeckling (Fig. 2), but a good deal of elevation variation remained, making it impossible to use derivative functions in Global Mapper to measure such things as downvalley slope. The remaining "speckle" was a barrier to interpreting landform, since it made the floodplains look very bumpy and irregular. A test was done on a very smooth bit of hillslope (Fig. 3). The result of the test was that the smoothed data is actually of quite good quality (Fig. 3). The reason that the floodplains look irregular, is that they *are* irregular. This is an important result for understanding the imprint of previous fluvial stages on the landforms, the episodic nature of sediment transport, and the very high degree of stochastic forces affecting flow behaviour.

A3.2 Climatic Variability Leads to Flow Variability

Arid-zone rivers experience highly variable rainfall (Mabbutt 1977, Bullard 1997, Knighton & Nanson 1997, Nanson & Tooth 1999), ranging from long dry spells, to days or weeks of widespread gentle synoptic front rainfall, to brief but intense rainfall from localised convective thunderstorms, to extreme climatic events (Reid & Frostick 1997, Bourke & Pickup 1999, Tooth 2000a).

Arid zone rivers are therefore variable in the timing and quantity of their flow events. Though normally dry, many have large relative flood magnitudes (for a given recurrence interval, the discharge will be considerably greater than the annual mean; Graf 1988a, Nanson et al. 2002); large floods are experienced relatively frequently (Erskine & Livingstone 1999), and there is a large ratio of high- to low-magnitude flows (Tooth & Nanson 2000). Extreme behaviour is characteristic of some dryland rivers (Tooth 2000a), and of Australian rivers in general (Finlayson & McMahon 1988). As well as relative flood values, there is evidence for high absolute discharges for drylands flood peaks (Osterkamp & Freidman 2000, Tooth 2000a) and for Australian 100 year recurrence interval floods (Finlayson & McMahon 1988). Arid zone flow variability is also due to high runoff values (Osterkamp & Freidman 2000), and (in Australia) to greater variability in transferring rainfall to runoff, possibly related to higher evaporation values (Finlayson & McMahon 1988).

Arid zone river flow is also highly variable spatially. Thunderstorms may rain over a single tributary (Dunkerley & Brown 1999), or move over a sequence of tributaries (Frostick & Reid 1977), leading to asynchronous tributary activity (Reid & Frostick 1997, Bourke & Pickup 1999, Tooth 2000a). Across desert hillslopes, the distribution and amount of runoff varies according to interdependent hillslope characteristics (slope, fetch, vegetation, stone cover) (Brown & Dunkerley 1996). Transmission losses (downstream decreases in flow volume, by infiltration into channel bed and banks, overbank flooding, extraction into minor channels, or evaporation), occurring as the river becomes decoupled from runoff and tributary input (Dunkerley 1992, Reid & Frostick 1997, Tooth 2000a), are also variable with flood height and local fluvial landforms (Dunkerley & Brown 1999, Dunkerley 2008).

Thus, a flow event in a drylands river may occur at any scale, and may start and finish almost anywhere in the drainage network, depending upon the size and location of the rainfall event, and the nature of antecedent landscape conditions. Spatial and temporal flow variability is a defining characteristic of arid-zone rivers.

A4 Technical Appendix 4: Bibliography

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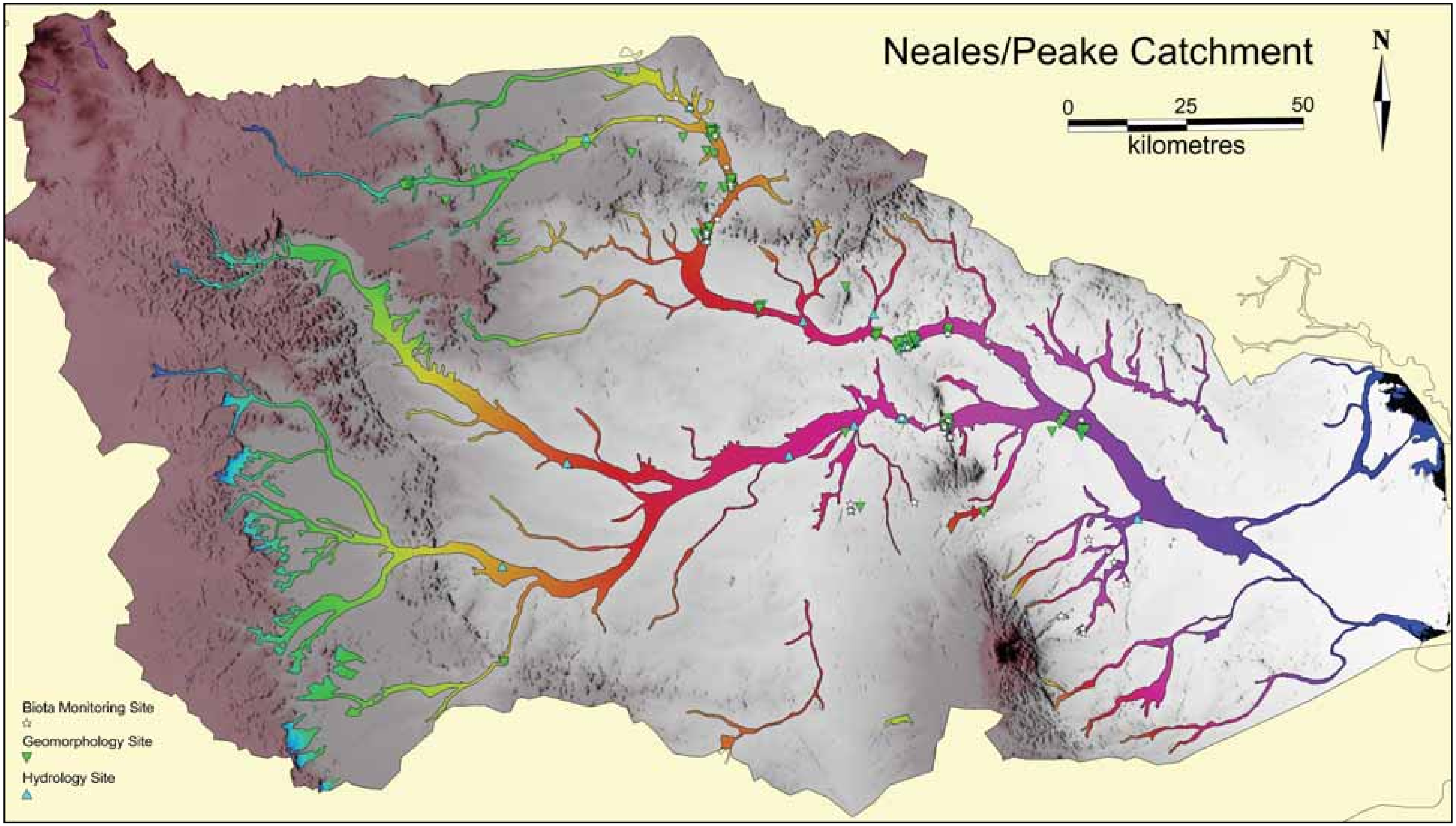
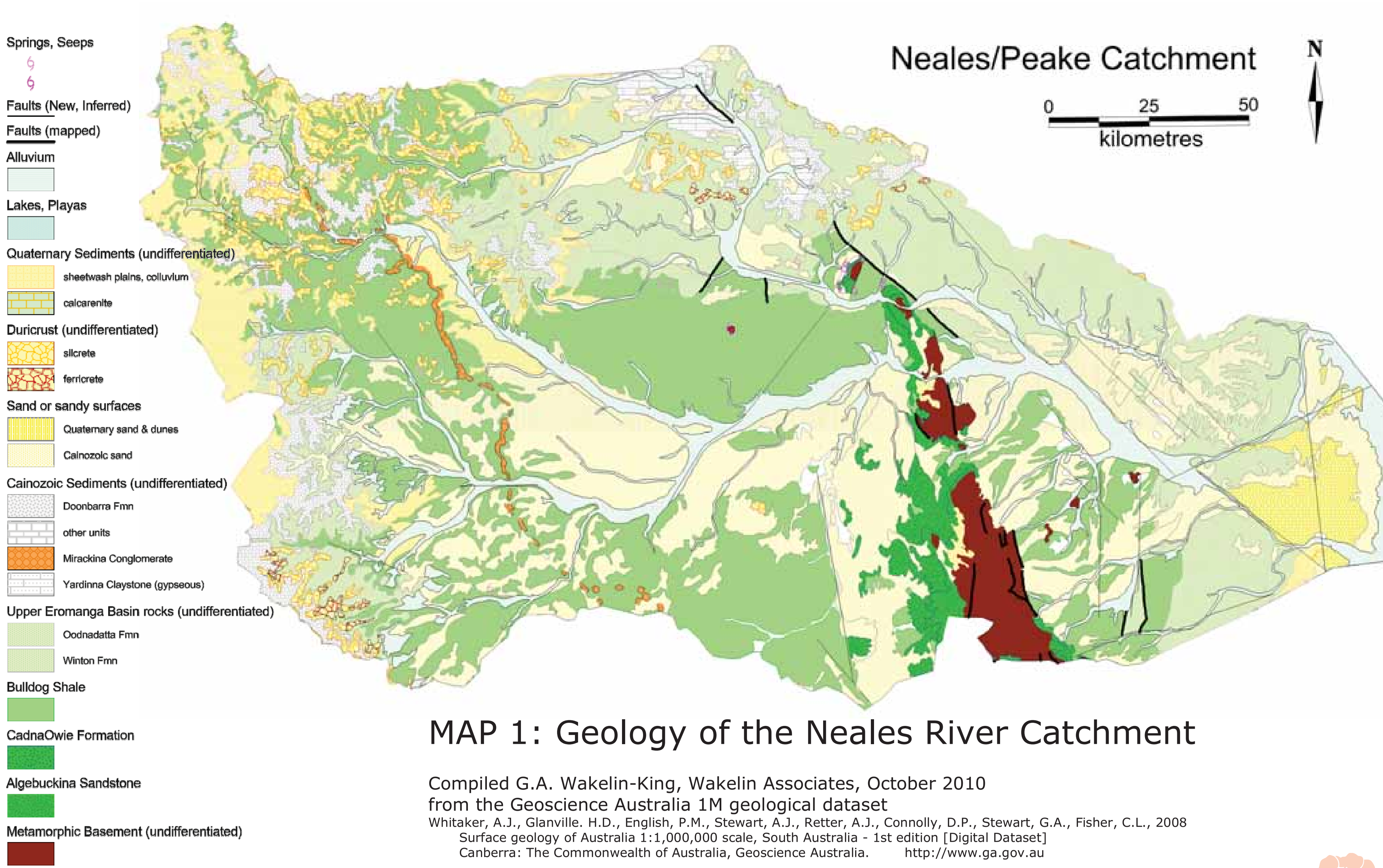


MAP 2: Digital Elevation Map of the Neales River Catchment

Compiled G.A. Wakelin-King, Wakelin Associates, October 2010
from SRTM 3-second data

Hillslopes: black > 390m, dark red 390-250 m, dark grey 250-125 m, white 50- minus 11 m AHD. Maximum elevation in western catchment, and in the central ranges.
Alluvial Valleys: descending from west to east, dark blue 280 m, red 90 m, magenta 57 m, violet 25 m, dark blue 0 m, black -12 m AHD (Lake Eyre).



MAP 1: Geology of the Neales River Catchment

Compiled G.A. Wakelin-King, Wakelin Associates, October 2010
from the Geoscience Australia 1M geological dataset

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