Lake Eyre Basin Rivers Monitoring Project

Geomorphology of Finke River and Arckaringa Creek: The bedload rivers

DEWNR Technical report 2015/51

Government of South Australia
Department of Environment, Water and Natural Resources

Funding for these projects has been provided by the Australian Government through the Bioregional Assessment Programme.

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ISBN 978-1-925369-22-9

Preferred way to cite this publication:

Wakelin-King, G.A., 2015. Geomorphology of Finke River and Arckaringa Creek: The Bedload Rivers. Report by Wakelin Associates to the South Australian Department of Environment, Water and Natural Resources.

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Foreword

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

Author’s Acknowledgements

The Lake Eyre Basin River Monitoring project was funded by the Australian Government through the Department of the Environment, and administered by the South Australian Department of Environment, Water, and Natural Resources. Tom Carrangis and Andy Harrison provided project management, and Dale McNeil shaped the study and its multidisciplinary team. Angus Duguid and Peter Jobson participated in joint fieldwork in the Finke River, and are thanked for sharing their botanical and ecological knowledge. Angus Duguid identified and provided access to the key mid-Finke waterholes, and defined particular lines of enquiry relevant to this study (the nature of banks, outcrop’s importance to waterholes, groundwater and salinity). Justin Costelloe is thanked for informative discussions on hydrologic and hydraulic modelling. I would like to thank the landholders at the following stations for permission to traverse their country: Henbury, New Crown, Wintinna, Welbourne Hill, and Arckaringa. I would like to thank Gordon Wakelin-King for assistance in the field. As always, the comments and discussions of the cross-discipline science teams are welcome and interesting, especially aquatic ecologists Dale McNeil and David Schmarr, and hydrologist Justin Costelloe. Martin Thoms is thanked for his review of the draft.

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Executive Summary

The Lake Eyre Basin River Monitoring (LEBRM) project was developed to document the physical and biological structures of Lake Eyre Basin's (LEB) aquatic ecosystems. This report presents baseline information on the fluvial geomorphology of Finke River and Arckaringa Creek. This study's aims were to document landforms and fluvial processes (especially those that support ecosystems), focusing on places and processes likely to be impacted by coal mining or coal-seam gas extraction. Geomorphology is relevant to ecology because in a resource-limited environment, landscape processes which distribute water and sediments fundamentally underpin all ecosystems. If a waterhole hosts a high-value aquatic community, what are the fluvial processes that created and now maintain the waterhole? Those processes will indicate the landform's strengths and vulnerabilities, and should inform management practice.

This project employed spatial science, sedimentology, and process geomorphology on a regional-scale investigation. Remote data and ground-truthed field data were integrated to link spatial processes and establish causal relationships. This report describes the study areas' previously unreported fluvial processes. It contains the maximum information that can be drawn from the available data, but the study area was large and remote: more and better detail will be achievable with long-term research.

Geomorphology: Landforms and River Behaviour

LEB rivers have these factors in common:

- they experience highly variable rainfall and flow conditions; though mostly dry, they are capable of sustained flow and/or very large floods, and
- floodplains are commonly active agents in the transmission of water and (where applicable) sediment.

However, LEB rivers are also diverse: risk factors and best-management practices are not identical across all. Rivers from central Australia (e.g. the Finke River) differ from those from the western uplands (e.g. the Neales River, or its tributary Arckaringa Creek), and both differ from Channel Country rivers (e.g. Cooper Creek). The present study finds that the Finke River and Arckaringa Creek transport large quantities of bedload downstream during routine (high recurrence-interval) flows, and this is a feature that differentiates them from other, better-known LEB rivers.

The bedload carried by the Finke River is quartzose sand, whereas Arckaringa Creek carries gravel and cobble conglomerates. This bedload transport has important consequences for aquatic habitats. In Arckaringa Creek, bedload fills spaces that would otherwise be waterholes and may also hinder waterhole creation. In the Finke River, bedload under transport contributes to some waterholes' impermanence, and in high-energy flow conditions may create a difficult environment for fish to exploit. Finke River waterholes may have constantly renewed boundaries, and may require specialised habitat adaptations for aquatic invertebrates.

The study area encompassed the mid- and lower **Finke River** (reaches between the central Australian uplands and the Finke Floodout Complex), set within the sinuous valley carved out by an older and larger "palaeo-Finke River". It is a largely single-thread channel, flanked by a discontinuous sandy modern floodplain, elevated sandy terraces, and valley-margin outcrop. Floodplain and terrace sediments probably constitute an important local aquifer (the "alluvial aquifer"), which is regularly recharged by infiltrating floodwaters. During routine flow events, water flows down both channel and floodplain, and the channel may migrate or avulse. The Finke River's channel mobility creates a topographically and ecologically diverse floodplain.

The Finke River contains **waterholes** created by locally high-energy or turbulent conditions. Some shift location or fill with sand, while those whose locations are forced by boundary conditions (e.g. channel constriction by outcrop) are more likely to be deep and permanent. Some are known to receive input from groundwater. The **Finke River's groundwater context** is complex, encompassing modern hyporheic water, old formation water from rock aquifers, and moderately old water from valley-fill sediments (the "alluvial aquifer").

The **Finke Floodout Complex** is at the distal end of the Finke River, near the Finke township. (A floodout is a fluvial landform characterised by low stream power, an absence of channel, and water transmission as unchannelised flow.) It is a heavily-vegetated low-elevation area containing the terminus of the Finke River's main channel (which is also the current locus of sediment deposition), a large area where unchanneled flow occurs, a single non-permanent waterhole, distributary channels, and a series of alternating channelised reaches and small floodouts extending into South Australia. The main fluvial processes are localised areas of erosion and sediment deposition, and widespread areas in which water is retained, or through which it very slowly percolates. The area is biologically very productive, in sharp contrast to the surrounding dunefields and gibber plains. Though it receives some local runoff, the Finke Floodout Complex cannot exist without large flows down the Finke

River. It is an aquatic ecosystem (because it relies on inundation), but one which supports terrestrial biota. It is likely to be a refuge ecosystem.

Arckaringa Creek is incising into the uplifted western edge of the LEB. Catchment-edge erosion has developed a landscape in which a narrow ribbon of combined channel and floodplain is flanked by high-runoff hillslope surfaces. It is likely to have a very flashy hydrograph (flows build rapidly to flood peak, and wane swiftly). Most reaches in the main drainage axis show coarse bedload transport in all channels, and both erosion and sedimentation across the narrow floodplains. That is, during routine flow events, high-energy flows will move water and sediment in short but rapid high-volume pulses, the scale of which may be unexpectedly large, in comparison to the relatively small size of the channels.

Implications for Land Management and Resource Industry Risk Management

LEB rivers

- The conceptual division between channel and floodplain which is applicable to temperate-zone rivers (in which channels carry the dominant flow and have the biota best used for river health assessment, while floodplains are less important) is not applicable to the LEB. Dryland river floodplains are important to river health, carry substantial active (sometimes high-energy) flow, and carry critical geomorphic and biotic river health indicators. This has applications in infrastructure planning, and in ecosystem management.
- LEB rivers are diverse, and should not be managed as if one-size-fits-all.
- Key concepts and classes of fluvial process that should be considered in the design phase of resource development are:
    - assessment should be specific to the site (not importing information or conclusions from other river systems);
    - flow paths should be identified, including floodplain-level flow and diffuse or unchannelled paths;
    - both the hydrology and the geomorphology affect reach-specific behaviours and both must be understood;
    - river behaviour (including sediment transport) specific to individual reaches should be identified.

Mid-Finke River

- It is possible that pipelines or other infrastructure extending from the Arckaringa Basin to the industry hub in Alice Springs may cross the middle reaches of the Finke river.
- Any proposed buried crossings of the mid-Finke River must be designed cognisant of possible high-energy bedload mobility down to at least 3 metres depth.
- Many Finke River floodplains are likely to be covered by floodwaters from time to time; some will carry strong or high-energy flows. Infrastructure developed on such

floodplains are at risk of damage or destruction. Additionally, any infrastructure in which contaminant risk must be managed should not be developed on such floodplains. Species and size of floodplain trees are a rough guide to the likelihood of inundation. Scour holes and floodplain topography are a rough guide to the force of recent flows.

- Cainozoic-age sedimentary rocks are poorly documented, yet in some places may be important in the transmission of local groundwater. Pumping from, or artificial discharge onto, rocks and sediments flanking the Finke River should not be undertaken without understanding the local geology.
- Because of the valley wall's complexity, the alluvial aquifer is likely to hold local areas of saline water; discharging water into the valley in such a way as to mobilise this groundwater or raise its level may create surface salinity problems. Identification of local hydrogeology must precede any such use.

Finke Floodout Complex

- The floodout complex requires large flows from the Finke River to survive. Flow regime changes that reduce flow volumes, attenuate flood peaks or change flood frequency are likely to be detrimental.
- The valley within which the main floodout occurs holds an accumulation of sandy sediment, which is likely to be a groundwater reservoir (similar to the "alluvial aquifer" of the mid-Finke River). Discharging water into floodout sediments will have unknown, but probably detrimental, effects.
- The valley of the main floodout has a complex pattern of sediment deposition, erosion, and inundation. Resource or infrastructure development should use landform mapping as part of its risk assessment.
- Infrastucture or other development should not occlude flow paths (even diffuse ones). Sill zones (at the “choke” and near distributary offtakes) should be treated carefully.
- Establishment of feral athol pine communities risks changing the distal Finke River's processes of channel mobility.

Arckaringa Creek

- The main axis of Arckaringa Creek overlies the largest of the coal deposits. Flanking hillslopes are likely to shed rainfall rapidly and prolifically; rainfall is infrequent but can be high-intensity. Arckaringa Creek is likely to experience flashy flow and high sediment loads, greater than might be expected from the small size of the channels. Any mine development should expect pulses of water and coarse sediments during mine life. Structures for dealing with sediments or water from upvalley need to be engineered to a large scale.
- Interruption to the sediment load (e.g. by infrastructure which diverts sediment load away from its channel without reintroducing it further downstream) could lead to downstream-propagating erosion, manifesting as bed degradation followed by gullying up the flanks of the valleys.
- Discharge of formation water down Arckaringa Creek is likely to be detrimental, rather than beneficial, to landforms and plant ecosystems.
- The flat, poorly-vegetated floodplains are an integral part of flow transmission and sediment deposition; they are not a good place for infrastructure, overburden, or ponds.

Key Knowledge Gaps

The qualitative river behaviour and identified vulnerablities described in this report are not yet integrated into Thresholds of Potential Concern identified in the overall LEBRM project.

Information on LEB river geomorphology should be collated into an LEB River Styles (R) report. This will 1) make existing geomorphological information available and visible, 2) create a locus for further concept development, and 3) address a current misconception that LEB rivers are not diverse.

The effect of artificial discharge of water into drylands river landforms is a question of wide geographic application, and is not (as far as this report understands) under investigation; it should be a high priority.

Management perceptions and methodologies of river assessment place low priority on fluvial landforms without free water, but in the drylands these river types can be ecologically important, and even refugia. Non-aquatic indicator species (e.g. reptiles, ants, termites) for non-lotic/lentic waterways should be identified and integrated into practice. The Finke Floodout Complex would be a good place to develop these concepts for drylands river monitoring.

Information on the role of dryland river floodplains and non-channelised landforms in active flow transmission needs to be expanded from geomorphology across discipline boundaries.

The hydrogeology of the Finke River's "alluvial aquifer" is not currently known.

Hillslope runoff qualities play an important role in parts of the Finke Floodout Complex, and in Arckaringa Creek. If detailed hydrological modelling for these places is desired, more information on these hillslopes may be beneficial.

Frontispiece: Eagles' nest in a River Red Gum, Finke Floodout.

Photo credit: Gresley Wakelin-King, 2013.

1 Introduction

The Lake Eyre Basin (LEB) is vast, and many of its rivers are poorly known in terms of their fluvial geomorphology (that is, the rivers' landforms, their behaviour as they transport water and sediment, the reasons why they behave as they do, and the relationships between fluvial processes and habitat creation and maintenance). In 2013, the South Australian Department of Environment, Water and Natural Resources commissioned the present study, which examines the fluvial geomorphology of two LEB rivers: the Finke River, and Arckaringa Creek.

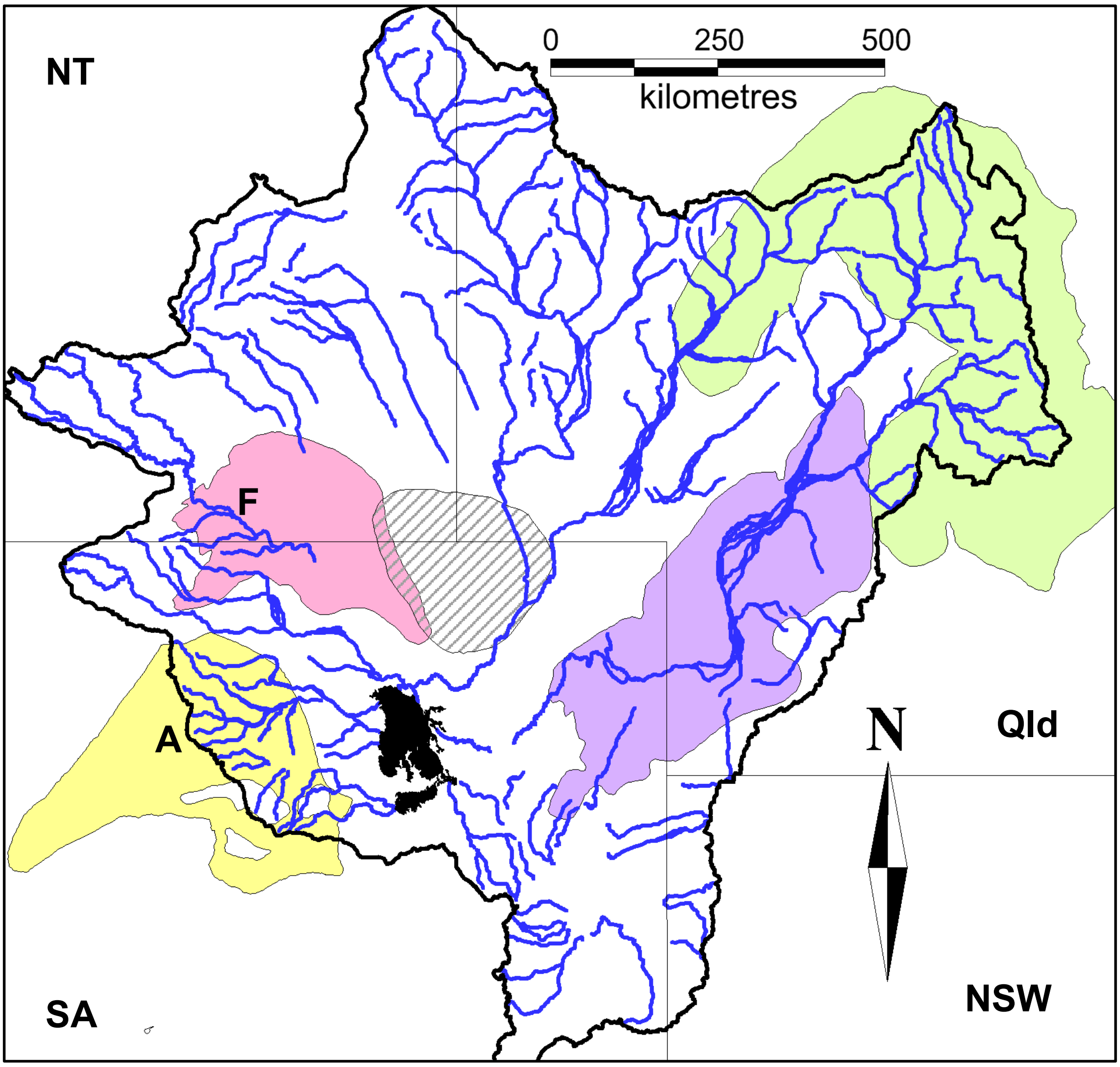


Fig. 1: Rivers of the Lake Eyre Basin, and underlying coal-bearing geological basins.

The Lake Eyre Basin (black outline) showing principal drainage lines (blue), Kati Thanda-Lake Eyre (black), and the Permo- Triassic coal basins: Pedirka, pink; Arckaringa, yellow; Cooper, purple; and Galilee, green. The Simpson Basin (diagonal stripes) is now considered part of the Pedirka (Munson and Ahmad 2013). This report considers the Finke River (F) and Arckaringa Creek (A); see Fig. 5 for detail of the study area.

Organisational Context

In 2012, South Australia signed the 'National Partnership Agreement on Coal Seam Gas and Large Coal Mining Development' (NPA) which strengthens the regulation of coal seam gas (CSG) and large coal mining by informing decisions with best-available science and advice from the Independent Expert Scientific Committee (IESC) (see Government of South Australia (2013) website for more information). As part of this agreement, a number of data collation and scientific investigative projects are being delivered by the South Australian Department of Environment, Water and Natural Resources (DEWNR) to the Commonwealth Department of the Environment's Office of Water Science (OWS). The projects align with the 'Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources' developed by OWS (Barrett et al. 2013). Funding for these projects has been provided by the Australian Government through the Department of the Environment.

The Bioregional Assessment Programme is a programme of baseline assessments that increase the available science for decision making associated on potential water-related impacts of coal seam gas and large coal mining developments. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale. The programme aims to be transparent and accessible: for more information, visit http://www.bioregionalassessments.gov.au.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the IESC) is a statutory body under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act). It provides scientific advice to Australian governments on the water-related impacts of coal seam gas and large coal mining development proposals. Under the EPBC Act, the IESC has several legislative functions:

- To provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed coal seam gas or large coal mining developments.
- To provide scientific advice to the Commonwealth Environment Minister on:
    - bioregional assessments being undertaken by the Australian Government, and

- research priorities and projects commissioned by the Commonwealth Environment Minister.
- To publish and disseminate scientific information about the impacts of coal seam gas and large coal mining activities on water resources.

This report is part of a series of studies forming part of the Lake Eyre Basin Rivers Monitoring project, one of three water knowledge projects undertaken by the South Australian Department of Water, Environment and Natural Resources (DEWNR) to inform the Bioregional Assessment Programme in the Lake Eyre Basin. The three projects are:

- Lake Eyre Basin Rivers Monitoring,
- Arckaringa and Pedirka Groundwater Assessment and
- Lake Eyre Basin Springs Assessment.

The Lake Eyre Basin Rivers Monitoring project's focus areas are those parts of the Lake Eyre Basin which are underlain by sedimentary basins containing coal: the Pedirka, Arckaringa, Cooper, and Galilee geological Basins (Fig. 1). The South Australian Government sub-contracted relevant agencies from other states to contribute to this project, where project activities extended into Queensland or the Northern Territory. This report examines the Finke River and Arckaringa Creek, which overlie possible economic coal deposits in the Pedirka and Arckaringa Basins.

1.1 About This Study

Aims and Scope

The aim of this investigation is improve the understanding of LEB surface water systems through presenting models of how the target rivers behave. This includes discussion on their geological context and such history of their landscape development as is relevant to their current state. It prioritises documentation of links between geomorphology and aquatic assets ("aquatic assets" including any ecosystem that relies on inundation; Aquatic Ecosystems Task Group, 2012). Specifically, the investigation aims to -

- characterise the landform-process relationships in the Finke River and Arckaringa Creek (by describing the landforms present, and relating them to their function in the landscape);
- identify knowledge gaps, or circumstances where inappropriate practices and methodologies might be applied (especially those relevant to managing or monitoring resource extraction);
- identify key classes of fluvial processes which should be part of development design considerations in order to effectively manage risk during resource development.

This report aims to present the investigation's results in a way that is accessible to the non-technical reader, as well as presenting some field data, citations, and lines of reasoning for readers with backgrounds in geomorphology, geology, or sedimentology.

The report's focus on landform-process relationships is presented spatially (see ***Methods***, below) in a way that permits the reader to extrapolate from the specific areas described in this report, out to other similar river reaches. In simplistic terms, if a river reach is similar in valley context, sedimentology, and reach-scale landforms to one of the reaches presented here, then it is likely to be operating in similar ways.

To achieve the objectives and overall project deadlines, this investigation was constrained to a total project length of 14 weeks, including 4 weeks of field time. This is a very short space of time for two rivers which have had little previous documentation of their fluvial processes. The small project scope is offset by the investigator's experience in i) regional-scale and process-based studies, and ii) different types of Australian drylands rivers.

Exclusions

Given its scope, this report does not claim to present the results of a fully fleshed-out research project. It cannot, for example, compare to the decades-long involvement of the Nanson research group with certain reaches of Cooper Creek (e.g. Nanson et al. 1986, Nanson et al. 2008). This report does not aim to present a full literature review for lines of reasoning which are supported by citations; generally, only one or two key references are given. In places, the report presents conclusions drawn from the investigator's field experience, or unpublished work-in-progress; these conclusions are presented in the spirit of providing maximum information, while recognising that such conclusions have the status of testable (but as yet untested) hypotheses.

This investigation does not aim to document or measure physical habitat. Geomorphology is the basis of habitat, insofar as ecosystems are hosted in/on landforms, but this study's focus is the fluvial processes that create and support the landforms.

The LEB's rivers are very different from each other in character; this report does not review the literature of other LEB rivers except where it specifically applies to the subjects of this study. Readers looking for literature on e.g. Cooper Creek or the northern plains rivers are referred to the literature review compiled for the Lake Eyre Basin Rivers Monitoring Project, Stage 1 (Miles and McNeil 2013).

Because the LEB's rivers differ from each other, it is important to note that this report may contain information that is not necessarily applicable to rivers outside the present study.

How to Use This Report

Because this report's readership will encompass a variety of technical backgrounds, the document is divided into the main report (sections 1-6), and the technical appendix (sections A1-A4), which contains information in support of the main report (e.g. field observations, discussion, citations), the bibliography, and a glossary. (A larger glossary with some explanations of geomorphological terms and ideas can be found in the Wakelin-King (2010) Neales River study.) The layout of the technical appendix approximately matches the layout of the main report, so readers seeking further information on a particular topic can cross between the two (e.g. section 1.1.1 ***Methods*** below pairs with section A1.1 ***Methods: Spatial and Sedimentological***).

In the main report, the introduction (section 1) contains context material on LEB geology, groundwater, hydrology, and palaeohydrology. Sections 2 and 3 describe Finke River’s and Arckaringa Creek’s sediments and landforms as encountered during the field study. These are descriptive sections, set out to approximately correspond to the River Styles (R) methodology (Brierley and Fryirs 2005, and see ***Methods*** below), which first considers a river's valley context, then its broad-scale landforms, its sediment load, and its smaller-scale landforms. From these, conclusions are drawn as to the river's behaviour at various flow levels, including implications for habitat. Sections 4, 5, and 6 summarise the project's results with respect to key fluvial processes, management and habitat implications (including information relevant to the resource industry), and knowledge gaps.

It is recommended that readers primarily consult the sections of this report which relate to their personal interests. If they wish to gain an overview of fluvial processes, management implications, or resource extraction implications they should read sections 4 or 5; if they wish to understand river behaviour they should read sections 2.1.6, 2.3.6, or 3.6; if their aim is familiarity with reach-specific landform-process relationships, they will find more detail in sections 2 and 3.

1.1.1 Methods

The project comprised a remote-resources desktop study (geological maps, satellite images, literature review, digital elevation models (DEMs), topographic datasets), followed by field investigation of the medial and distal reaches of the Finke River, the Finke Floodout (NT), and the proximal and medial parts of the Arckaringa catchment. Field investigation ground-truthed the conclusions of the remote study, examined the spatial relationships between sediments, landforms, vegetation, and lithotypes, and documented bedload grain size (class) and colour. Following fieldwork, analysis took place, interpreting the process implications of remote and field data in the light of published literature, and integrating those implications across a range of scales to form a picture of whole-river behaviour.

The methodology of this project is essentially spatial, because the relationships of landforms to each other result from (and give clues to) the fluvial processes which formed them. For example, in western New South Wales a double line of dead trees in a flat plain indicates the previous course of a river channel. Nearby, a double line of live trees flanking a channel indicates a modern-day channel. If the two channels are spatially linked upvalley (Fig. 2), this indicates a single river undergoing the geomorphic process of avulsion (channel relocation). The shape, number and age of channels indicates the river's mobility.

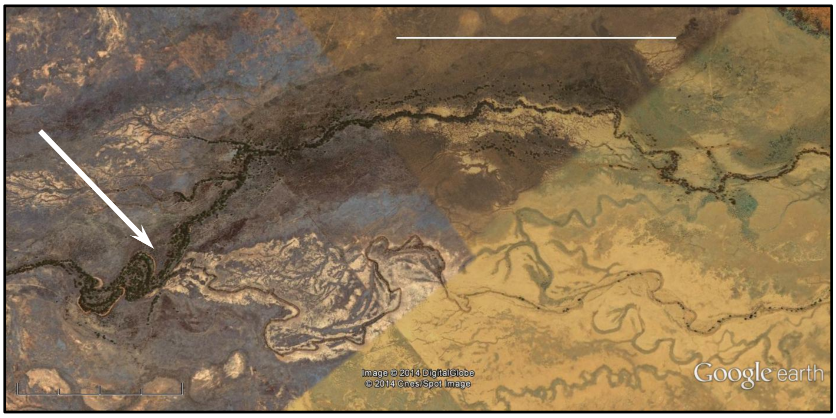


Fig. 2 Spatial relationships indicate geomorphic processes.

A modern channel (top) and an abandoned channel (bottom) are spatially linked at the avulsion node (arrow). After Wakelin-King (2007); Google Earth image, flow is left to right, white scale bar = 2 km.

In this report, many of these relationships are displayed pictorially (photographs of landforms and sediments, Google Earth images, or DEM images). This is a more reliable and succinct method of conveying the relevant information than a verbal description alone, and furthermore allows the reader to compare these spatial relationships with his/her own experience.

Spatial and qualitative data were more appropriate for the aims of this study than numerical data. Valid numerical measurements require an experimental design based on an existing understanding of the system being measured. The studied rivers did not have prior descriptions of their reach-scale fluvial processes. After the reach-scale fluvial processes were described, the scope of this study did not allow for any further investigation. The literature contains many investigations of fluvial geomorphology or sedimentology where numerical data are collected (e.g. Arthington et al. 2005, Zhang et al. 2010), and studies like these will be desirable here in the future.

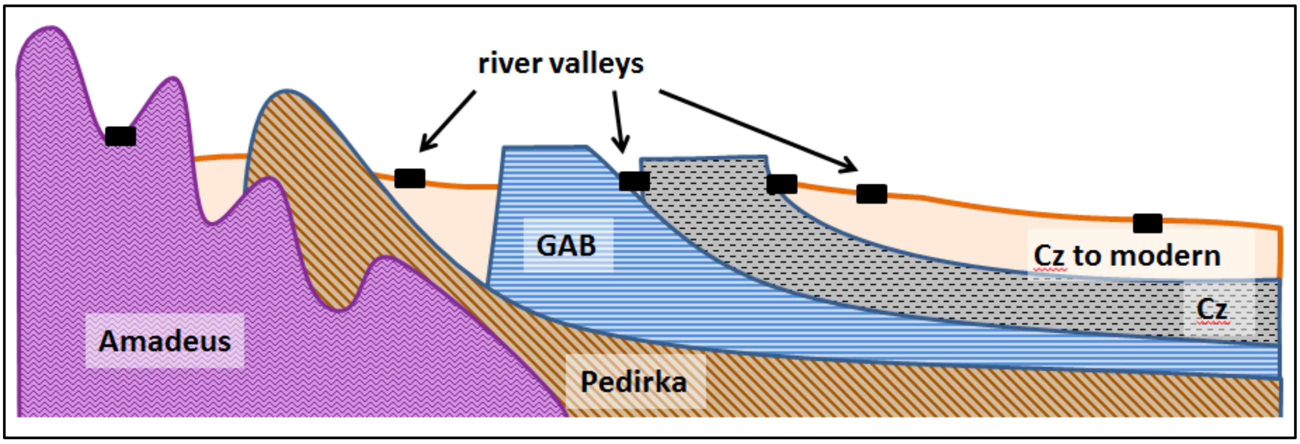


Fig. 3 Schematic diagram of sedimentary basin stratigraphy underlying the Finke River.

The Finke River's valley (black boxes) can interact with any of the sedimentary basins, including being set within several basins at the one location. Also see Fig. 17.

1.2 Lake Eyre Basin Context

1.2.1 Geology and Groundwater Hydrology

Kati Thanda-Lake Eyre sits within a vast topographic basin known as the Lake Eyre Basin (LEB). Beneath it are a number of geological basins, which (like the Lake Eyre Basin) were created by subsidence creating a space within which sediment could accumulate. These sedimentary basins contain economically and socially important resources including coal, petroleum, and water. They can be envisaged as a stack of differently-shaped bowls (Fig. 3). From youngest down to oldest, the major geological groups are:

- The Lake Eyre Basin (LEB) (the present-day catchment); for the purposes of the present report, this is defined as the topographic basin which contains modern sediments (deposited within the last ~10,000 years), and/or those responding to present-day geomorphic processes. Porous sediments (e.g. alluvial or dune sands) can act as unconfined aquifers, and as reservoirs for local run-off or fluvial overflow.
- Regolith: this is not a basin, but the product of a series of weathering events (late Mesozoic and throughout the Cainozoic) which overprinted the rocks and sediments. Rocks were bleached (Fig. 4A) and softened, making them prone to erosion; chemicals were leached and re-precipitated as erosion-resistant duricrusts (Figs. 4B,

C). Chemical deposits include widespread gypsum, silcretes (which play a critical role in LEB geomorphology and in pre-European material culture), ferricretes, and calcrete.

- Cainozoic (Cz) -age basins, which contain sediments and sedimentary rocks deposited during the last 60 million years (during the Palaeogene and Neogene periods, and the Pleistocene epoch). There are substantial Cainozoic deposits underlying the LEB over a very wide area, but they are often very poorly documented. Cainozoic stratigraphy documented for the Strzelecki Plain is complex and thick, with units including siltstones, limestones, sandstones, and sands, and some are locally important aquifers.
- The Great Artesian Basin (GAB), a Mesozoic-age (250-60 million years before present) series of rocks comprised of several geological basins, including the Eromanga Basin (Fig. 4B). The Eromanga Basin contains economically important hydrocarbon deposits, as well as artesian water which is important both economically and culturally. GAB water is also the basis of some ecosystems.
- Underlying the GAB, there are a number of Palaeozoic-age (540-250 million years before present) to Mesozoic sedimentary basins, including the Pedirka/Simpson, Galilee, Cooper, and Arckaringa Basins. In places these contain potentially economic coal deposits.
- Underlying the Palaeozoic basins are Neoproterozoic (≥1000 million years before present) to Palaeozoic sedimentary basins. The Amadeus Basin (Fig. 4A) contains several rock units important as both aquifers and hydrocarbon reservoirs. Uplifted Amadeus Basin rocks form the rocky uplands in central Australia.
- Metamorphic and igneous rocks (Fig. 4A) underlie all, exposed at surface in e.g. the Musgrave, Western MacDonnell, and Harts Ranges.

Each sedimentary basin contains a number of different rock types, with different capacities for transmitting water (aquifers) or excluding water. The rocks may be laid down in simple layers, or in more complex arrangements related to depositional environment. Further, each basin has a different geological history, which can include faulting, folding, or truncation of the aquifers. Water held in sedimentary basins can be discharged via fracture systems, voids, fault lines, or diffuse seeps. Thus, each sedimentary basin's water exists within its own potentially complex system, behaving differently to other groundwater systems which are geographically nearby but geologically dissimilar. A single river valley can experience many different groundwater contexts, for example the Finke valley cuts into all the sedimentary basins above which it passes (Fig. 3).

The term groundwater is sometimes used loosely, referring to any water that occurs below the ground surface. In this report, water transmitted through rock aquifers is referred to as formation water, distinguishing it from alluvial aquifer water (held in unconfined aquifers in geologically young alluvium confined within the river valley), and hyporheic water (modern water beneath a creek channel or flow path).

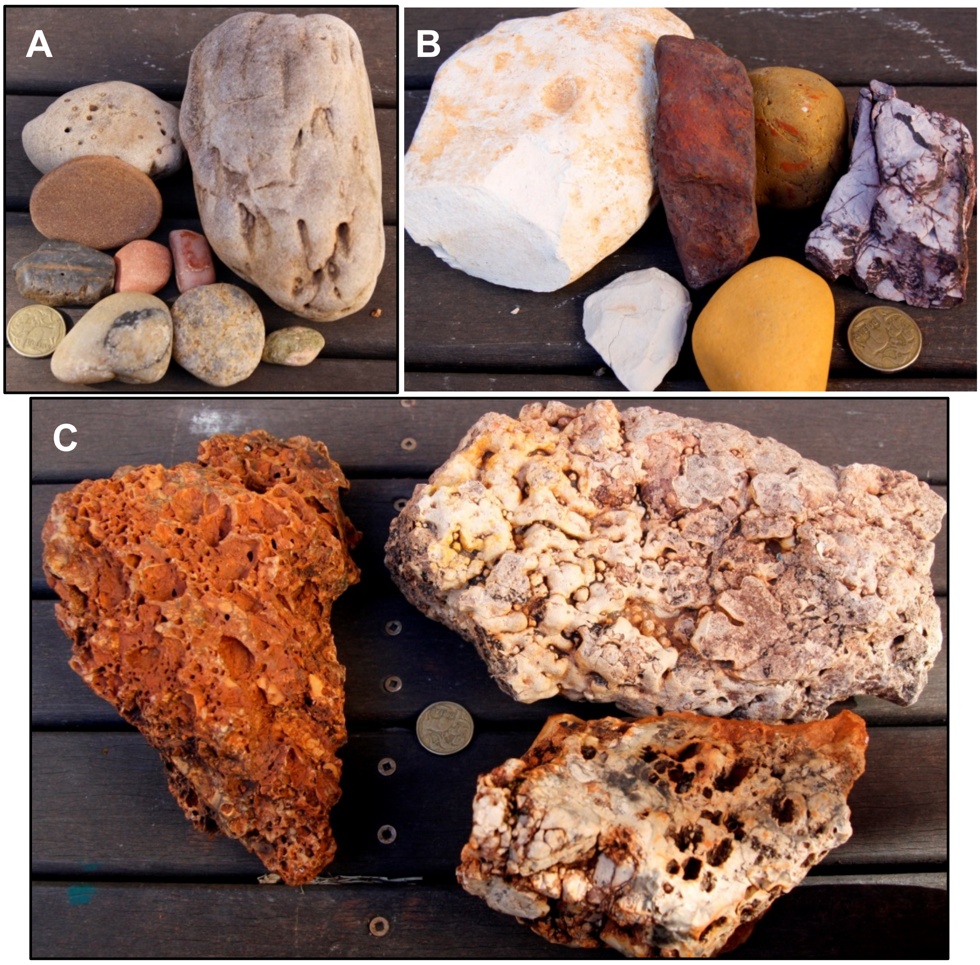


Fig. 4 Rocks from the Finke and Arckaringa catchments.

A, sedimentary rocks from the Amadeus Basin, and (bottom three pebbles) from metamorphic basement; B, Eromanga Basin rocks as regolith: weathered to soft bleached or coloured material, or hard ferricrete; C, regolith: different forms of silcrete.

1.2.2 Surface Hydrology and Palaeohydrology

The Lake Eyre Basin catchment is characterised by extremely low relief. Kati Thanda-Lake Eyre itself fills rarely, usually in association with La Niña climate events, and in the modern climatic regime its maximum fill elevation is approximately -9.5m AHD. A key factor in its fill pattern is that its vast catchment crosses continental-scale climate boundaries, allowing pulses of monsoonal rain to be delivered into Australia's most arid centre.

The LEB's rivers differ in their gradients, profiles, sediment loads, flow regimes and runoff qualities. Consequently each river exhibits its own fluvial behaviours, which may differ in important respects from others. The present study considers Arckaringa Creek, one of the catchments from the western uplands, and the Finke River, one of the central Australian rivers which rises in the Amadeus Basin ranges.

All the LEB rivers have highly variable flow regimes. They are usually dry but many routinely experience inundation; inundation is highly to extremely variable in timing and amount. Depending on the river's catchment size and location with respect to climate zones, flow event frequency ranges from perhaps several times a year, to several times a decade; flow volumes range from not much to very large floods.

A consequence of this highly variable flow regime is that the channel-floodplain relationship is unlike that of the temperate zone's low-variability rivers; this is a significant feature of arid-zone fluvial process. This is important because industry standards (for example bridge engineering design) and cultural expectations (for example town planning practices) are designed for low-variability rivers. In temperate zone rivers the floodplain is often regarded as a passive receptacle for low-energy floodwaters. In LEB rivers (and Australian drylands rivers generally), the floodplain is an active part of peak-stage flow transmission. It may carry a substantial proportion of the floodwaters, sometimes under very high-energy conditions. In some drylands rivers, the channel is not continuous and there are reaches in which the floodplain carries the entire flow volume.

In general, the larger a flood is, the lower its recurrence interval. Australian design standards are based around a flood with a 1% chance of being exceeded in any given year (sometimes colloquially referred to as a 100-year-flood, although this term is not now used by hydrologists). Even larger floods (extreme floods, megafloods) take place on multi-century to millennial timescales. A megaflood record for LEB rivers has been documented (and in some cases dated) for Cooper Creek and the Finke, Todd and Neales Rivers. Megafloods leave behind them landscape elements which strongly influence the processes and landforms of later, smaller flow events; an understanding of megaflood landforms is relevant to assessing present-day fluvial processes.

Australia has experienced a trend of increasing aridity since the late Palaeogene (about 20 million years ago), and shorter-term wet-dry climatic fluctuations have been associated with the glacial cycles (on a scale of many tens of thousands of years). Throughout inland Australia, modern lake and river systems exist within the footprint of much larger, wetter systems (palaeodrainages), which have a very strong influence on landscape history and modern geomorphic processes.

The LEB's increasing aridity also altered land surfaces in such a way as to change surface hydrology (thus affecting runoff processes on the hillslopes that contribute water to modern rivers), and disconnect drainage lines. In geologically recent times (2-4 million years ago), intensified aridity promoted erosion of the old land surface's soils, which proceeded until it reached erosion-resistant layers of silcrete and gibber. This changed the surface from one which retains water and supports vegetation, to one which sheds water and supports little vegetation. Even more recently (only 1 million years ago), the dunefields were created by desiccation and localised sediment redistribution of alluvial plains, creating longitudinal dunes from sandy floodplains. The central Australian rivers, which used to flow into Kati Thanda-Lake Eyre from the north, became swallowed up in what is now the Simpson Desert.

2 Geomorphology: Finke River

The Finke River extends more than 550 km across central Australia, from the Amadeus Basin upland ranges, traversing the wide central plains, and terminating south of the Northern Territory-South Australian border. In this report, the Finke River is divided into the uplands (not considered in this project), the mid-Finke River, and the Finke Floodout Complex.

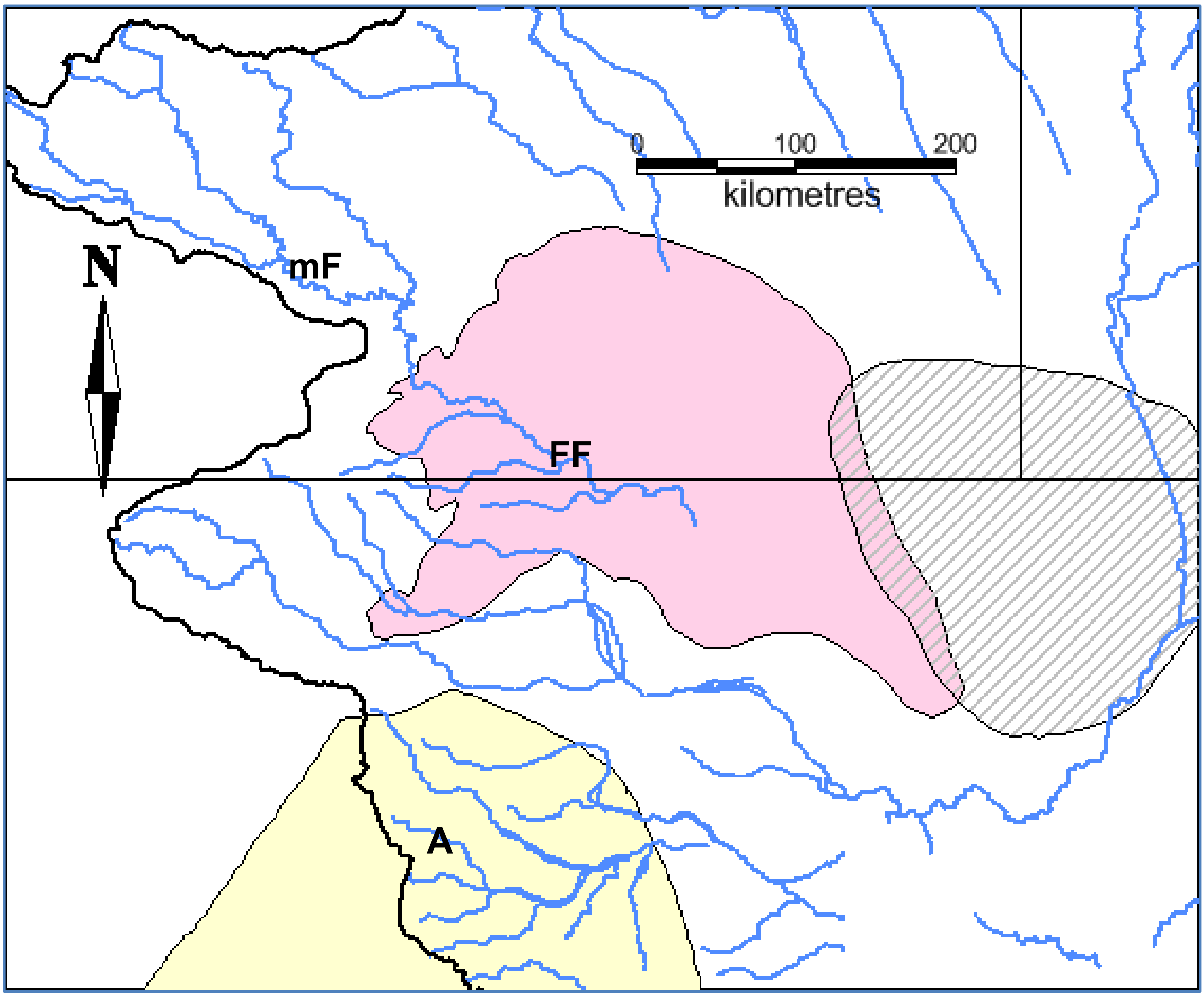


Fig. 5 Study area rivers and geological basins.

Map of the Arckaringa (yellow), Pedirka (pink), and Simpson (diagonal stripes) Basins, and their relationships to the Arckaringa (A) and Finke (mF mid-Finke, and FF Finke Floodout) drainage networks.

The uplands include the Western MacDonnell and James Ranges, and their downvalley extent is where the river exits the ranges near Running Waters (Duguid 2013). The mid-Finke River is defined in Duguid (2013, his section 1.3 and Fig. 3) as reaches containing permanent or near-permanent waterholes); it extends from Running Waters (approximately

132.90°E, -24.35°S), to approximately 133.84°E, -24.96°S. The waterholes are ecologically and culturally important, and are mapped and described in Duguid (2013). Duguid (2013, his section 1.3) empirically subdivides the mid-Finke River into the Henbury and Idracowra reaches (approximately correlating to the Henbury and Idracowra pastoral stations). Reaches further downvalley are the lower Finke River, extending to ~45 km east-southeast from Finke township, at which point the river changes character and becomes the Finke Floodout Complex. (Also see section A2.1.)

The Finke Floodout lies above the Pedirka Basin and is a focus area (Fig. 5). The mid-Finke River is included within this study because hydrocarbon pipelines extending from an hypothetical Pedirka Basin deposit must cross the Finke River before joining infrastructure near Alice Springs. Furthermore, the Finke Floodout is entirely dependent on water from the mid-Finke, so anything that affects the mid- and lower Finke River will affect the Finke Floodout.

2.1 Mid-Finke River

2.1.1 Description: Valley Setting

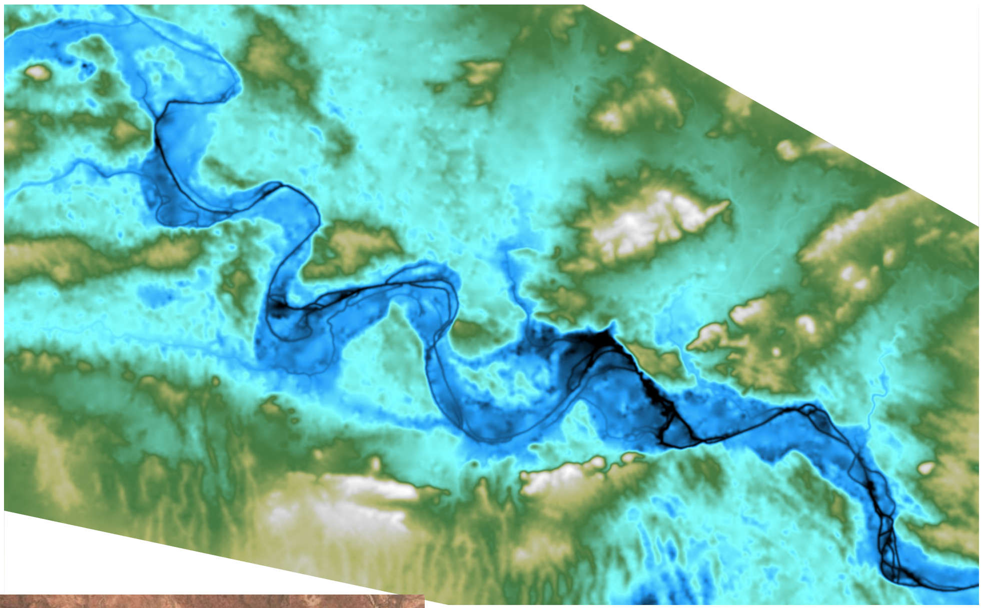
The mid-Finke river exists in a semi-confined setting, largely defined by the valley of the older, larger palaeo-Finke River. Flowing along the sinuous path of the ancient river's thalweg, the modern Finke River is under-fit (see Glossary). The valley's irregular width reflects past channel bend locations (Fig. 6). The valley is set into Cainozoic-age sediments, and sedimentary rocks of other ages (Fig. 3); they are commonly exposed at valley margins. The river channel also cuts into Cainozoic-age rocks or regolith, or Eromanga Basin rocks, or both (Fig. 7); the channel runs along or is crossed by Pedirka Basin and Amadeus Basin rocks in some reaches.

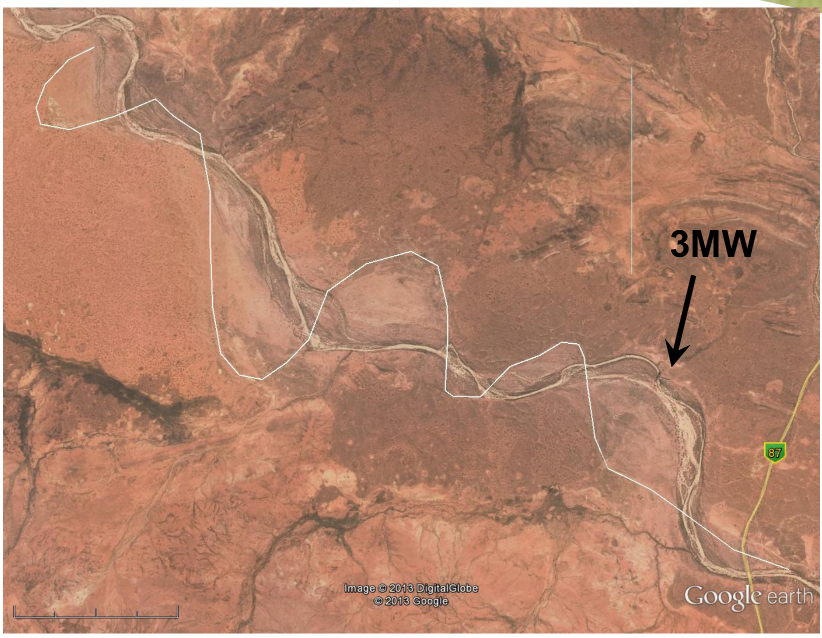
The country rock's control over valley width and channel planform decreases downstream. In the Henbury reaches, the valley is relatively narrow and constrained by outcrop and regolith. The orientation and bends of the modern channel are similar to those of the valley; the channel is semi-confined and bedrock-controlled (*sensu* Brierley and Fryirs 2005). Floodplain pockets are isolated and discontinuous and a greater proportion of the modern river width is taken up by the modern channel or its precursor old channels (see section 2.1.2). In the Idracowra reaches, the valley is wider and less constrained by outcrop and regolith. The channel has greater freedom to adjust laterally: it is semi-confined and planform-controlled (*sensu* Brierley and Fryirs 2005). The modern river width contains a greater proportion of floodplain (in comparison with the Henbury reaches), with continuous floodplain occurring along one side or the other of the valley.

As well as modern alluvium, the valley contains alluvial sediments from the palaeo-Finke River. These form high terraces, which further constrain the present-day river.

Fig. 6 Valley of the palaeo-Finke River.

Top, the valley of the palaeo-Finke (blue) contains the modern river (black), and is cut into the surrounding rocks and regolith (aqua, greens to white). Residual DEM after removal of downvalley gradient, Ampire Waterhole to beyond Main Camp Waterhole.





Bottom, Google Earth image of the present-day Finke River, superimposed with one of the channel paths of the palaeo-Finke River (thick white line). 3MW, 3-Mile Waterhole; thin white line, 5 km scale; Stuart Highway on the bottom right corner (yellow line).

Fig. 7 Finke River, Mesozoic rocks and duricrust.

Standing on a high duricrust surface (bottom left of photo) near Eromanga Basin outcrop, overlooking the Finke River channel at Fidlers Waterhole. Vehicles for scale.

2.1.2 Description: Valley-Scale Landforms

The valley-scale landforms of the mid-Finke River are (Fig. 8) (and see section A2.1.2):

- runoff slopes,
- old dunefields,
- terraces,
- modern channel,
- modern floodplain,
- old channels.

Runoff slopes is the term used in this report for hills, slopes, outcrop, shallow subcrop, regolith, or anything that is not dunefields or alluvial landforms.

Old dunefields are usually of higher elevation and darker colour than other dunefields. They show no sign of having ever been involved in fluvial processes. Neither dunes nor interdunes are likely to shed runoff into the fluvial system.

Terraces occur within the palaeodrainage valley. They are palaeo-Finke River alluvium with overlying dunes; they are not usually part of present-day fluvial processes. Their elevation is greater than present-day floodplains, but usually lesser than the old dunefield. Terrace sediments have a mixture of old dunefield sand with some paler grains, and their colour on Google Earth images is paler than that of the old dunefields. Terrace elevation and landforms vary according to how much they have been modified by past fluvial action. Many have low poorly defined sand dunes, or sand sheets or patches; interdunes may be floodplain surfaces or claypans.

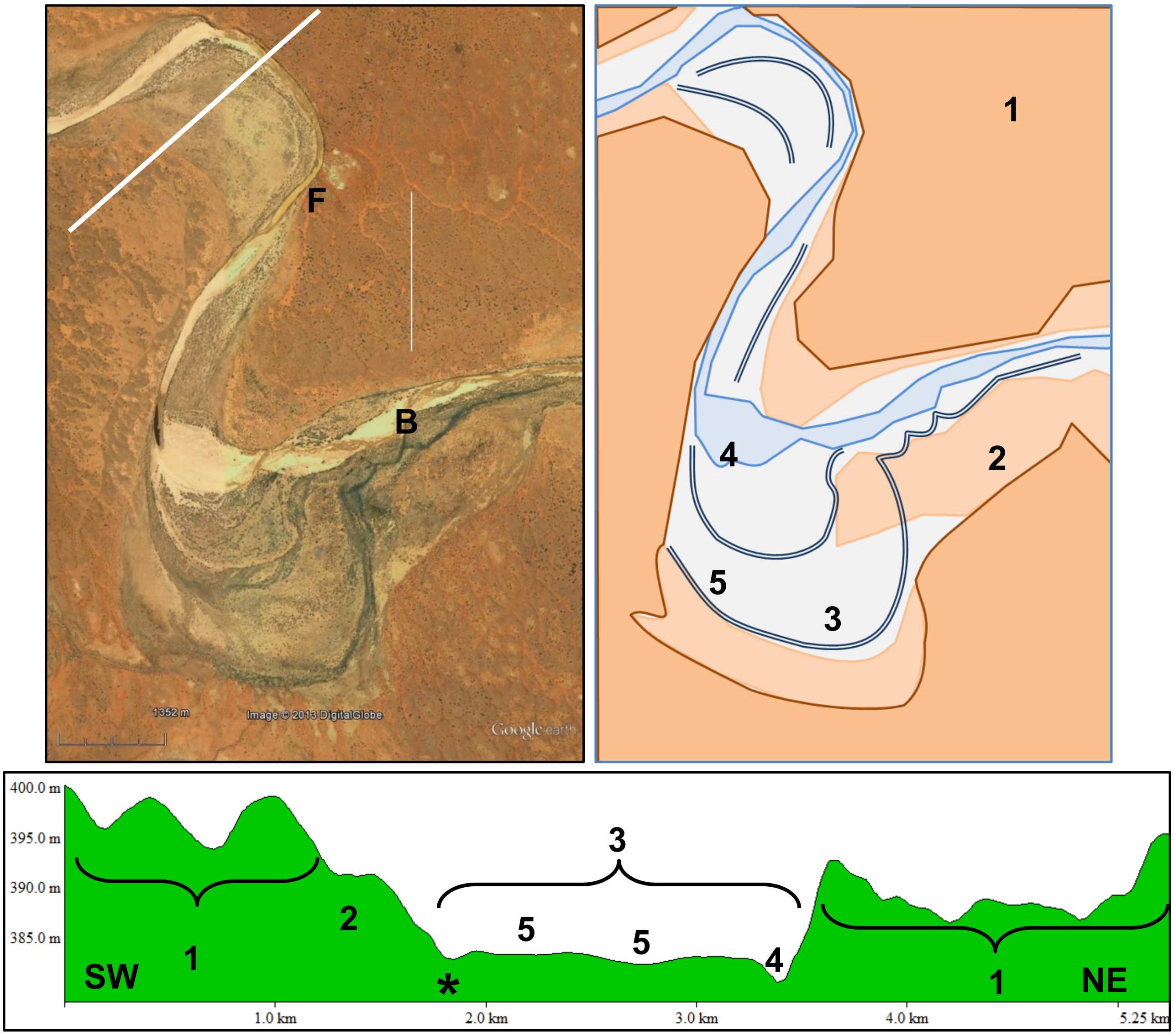


Fig. 8 Valley-scale landforms, Fidlers and Brumby Waterholes.

Fidlers Waterhole (F) and Brumby Waterhole (B) reaches of the Finke River. Left, Google Earth image, thin white scale bar = 2 km, thick white diagonal bar is location of topographic cross-section, north to top. Dashed box is location of Fig. 14. Right, sketch map: 1 (brown) old dunefield with minor runoff surfaces, 2 (orange) terraces, 3 (white) modern floodplain, 4 (blue) modern channel, and 5 (double blue lines) old channels. Bottom, southwest to northeast topographic cross-section, numbers as for map. Asterisk: a flood runner across the front of the dunefield has a greater topographic expression than either of the two old channels, but accumulates water so infrequently it carries little vegetation, and so is not easily discernible on the Google Earth image.

The **modern channel** is characterised by its white sand and relative lack of vegetation. The channel contains most of the water during rising and waning parts of the flood, but during flood peaks the channel and floodplain act together to transmit water downstream. An important consequence of this is that there are not always clear distinctions between the channels and some floodplain landforms. The most clear functional difference between channel and floodplain in the Finke River is that the channel transports most of the sediment. The sediment surface in the channel is therefore unstable on a timescale that discourages vegetation.

On Google Earth images, the **modern floodplain** is darker than the channel but less orange than the terraces and dunefields; its colour reflects more consistent vegetation cover than is present in channels. The modern floodplain is usually higher in elevation than the modern channel. It is very common to find several levels of floodplain surface, expressed on Google Earth images or airphotos as different types or densities of vegetation.

Old channels are previous versions of the modern channel, created by channel relocation (see Glossary). They are found within the modern floodplain, or alongside the present channel, or sometimes in a narrow belt of modern floodplain cutting through a terrace. Their expression depends on their location and age, and there is a gradation of features between these extremes (Fig. 9):

1. Recently abandoned channels are expressed on Google Earth images as linear or curvilinear belts of relatively dense to very dense vegetation, and on the ground they may retain a clear channel form including banks and riparian trees. They are usually located in association with the present-day channel, and consequently often act as flood runners (see Glossary) or swamps.
2. Old abandoned channels tend to be further away from the present-day channel, often at higher elevations. They are inundated less often, and are therefore poorly vegetated; they may be poorly or not at all expressed on Google Earth images. Old abandoned channels have had a longer time in which to fill with sediment, so on the ground all that may be visible is a poorly-defined swale, its origin only demonstrated by its scale, location and semi-linear nature.

Fig. 9 Old channels.

Top: Only recently abandoned, this old channel is almost unaltered in shape and still supports dense riparian vegetation, as well as trees down the bank slope. Camera at channel bed, banks rising to either side, looking upstream, person for scale. Bottom: This old channel is located on the upper floodplain, away from and above the present channel, and close to a terrace. It is a gentle swale with indistinct edges and very sparse vegetation: its origin is not apparent from the ground. Looking across the swale, vehicle for scale.

2.1.3 Description: Reach-Scale Geomorphology

Fluvial Margins

Old dunefields and runoff slopes occur around the edges of the river system (Fig. 10); they were not a focus of this study. Old dunefields' most characteristic vegetation community is desert oaks and spinifex, or Acacia and Eremophila scrub. Dune surfaces may be trampled by stock near pathways to water. Runoff slopes exposing regolith are generally poorly vegetated, especially the bleached weathering profiles and silcrete caps. The vegetation on runoff slopes exposing outcrop varies according to lithology and the elevation of the hills.

Fig. 10 Mid-Finke River runoff slopes.

Old dunefield sand (foreground) moving downslope over the lip of a high land surface (out of view to left). The old dunes overlie Amadeus Basin rock, such as the outlier hill (background), which is overprinted with a weathering profile (bleaching, and silcrete cap).

Terraces

The terraces were not a focus of this study, as they are outside ordinary fluvial processes. Where visited, along the margins of floodplains, there were low dunes with interdunes containing floodplains or claypans. Surfaces were heavily trampled by cattle. The border between (higher) terrace and (lower) floodplain was usually clear-cut, moderately sloped banks 1-3 m high. Remote study indicates three kinds of terrace-floodplain border: erosional, where high-level floods in the process of depositing floodplain have scoured away some of the terrace; interfingering, where dunes have advanced across floodplain, or floodplain sediments have been deposited in interdunes (Fig. 11), or fluvial, where a small channel from some external source cuts across the terrace, locally rearranging the dune sediment.

Fig. 11 Mid-Finke River terrace.

View from a low terrace dune, looking across an interdune which contains some pale floodplain sediments, towards the treeline of the Palmer River's southern distributary. Person for scale.

Modern channel - Banks

A river's banks are the interface between channel and floodplain. Understanding what is meant by a bank, and what a bank means to fluvial processes, is important in a number of ways. Banks can be habitat elements; they can define where water goes, or influence local stream power. Many standardised river description methodologies call for a description of banks; flow events are described in terms of “bankfull”, and the term is sometimes related to a ~1-2 year recurrence interval flow. These ideas are most relevant where banks are reasonably constant and identifiable, such as in temperate-zone rivers where flow variability is low and the channel is the landform that actively carries flow. In the Finke River, variable flow heights and the floodplain’s active role in flood transmission means that "banks" have more varied elevations and forms. This circumstance is exacerbated by the Finke’s channel mobility and the persistence of old fluvial landforms. Therefore, this section on the mid-Finke River’s banks discusses what a bank means in the context of this river’s behaviour, before describing what is present.

Examination of Google Earth images show that the mid-Finke River has a generally clear channel-floodplain interface, which most would refer to as a bank. Its general character is that it divides the (usually) unvegetated channel from the vegetated floodplain. However, flow variability is high: it is impossible to say that the banks correspond to a particular range of flow recurrence intervals, or even that banks in one reach correspond to the same magnitude of flow event as the banks in another reach. Furthermore, channel and floodplain are not distinguished on the basis of the channel being the most frequent carrier of water (as is the case in a temperate river); the Finke's channel is the sole carrier of water only in relatively unimportant small flows, while its floodplain carries large volumes of water at (in places) high energies, during flows with the greatest connectivity and geomorphic activity. The clearest distinction is in sediment transport: the channel transmits the greatest volume of sediment at the highest energies (see sections 2.1.4, 2.1.5).

Vegetation communities are a reasonable guide to the fluvial processes separating channel from floodplain, as they integrate flood height, inundation frequency, and substrate stability. Banks are the interface between the mobile channel sediments and the relatively stable (and therefore better-vegetated) floodplains. A rule-of-thumb guide to the location of the Finke River's channel bank is therefore an elevation change matched with a clear vegetation boundary. However, though some banks are unambiguous (pronounced elevation change, boundaries of stable vegetation communities), others are trivial and short-term (almost no elevation change and an obviously ephemeral vegetation boundary). Banks may be simple or complex depending on individual reach history. There is a range of bank morphologies which can be viewed as a sequence of bank development (Fig. 12):

1. A channel newly-incised into the floodplain has steep cut banks, from which may protrude older fluvial deposits that are coarser or more consolidated than the modern bedload (Fig. 12A). Observed erosional banks were ~0.1-2 m high.
2. Channel stability permits riparian vegetation, whose roots may further stabilise channel banks (Fig. 12B).
3. Bedload transport during subsequent flows fills the channel, possibly to a single flat level, or possibly in a multistage process where high flow bedforms (sandy bars attached to banks, Figs. 12C, 12D, or 2D dunes deposited at channel margins, Fig. 16), precede lower level sand deposition during waning flow. In this case, bank height is a transient feature, a function of bedform position at close of flow.
4. Where a channel re-occupies an old channel, or cross cuts a multi-level floodplain, the bank is likely to have a stepped profile. Where modern flow cuts new banks and deposits high-flow bars across a stepped profile, the bank zone will be complex (Fig. 12E).

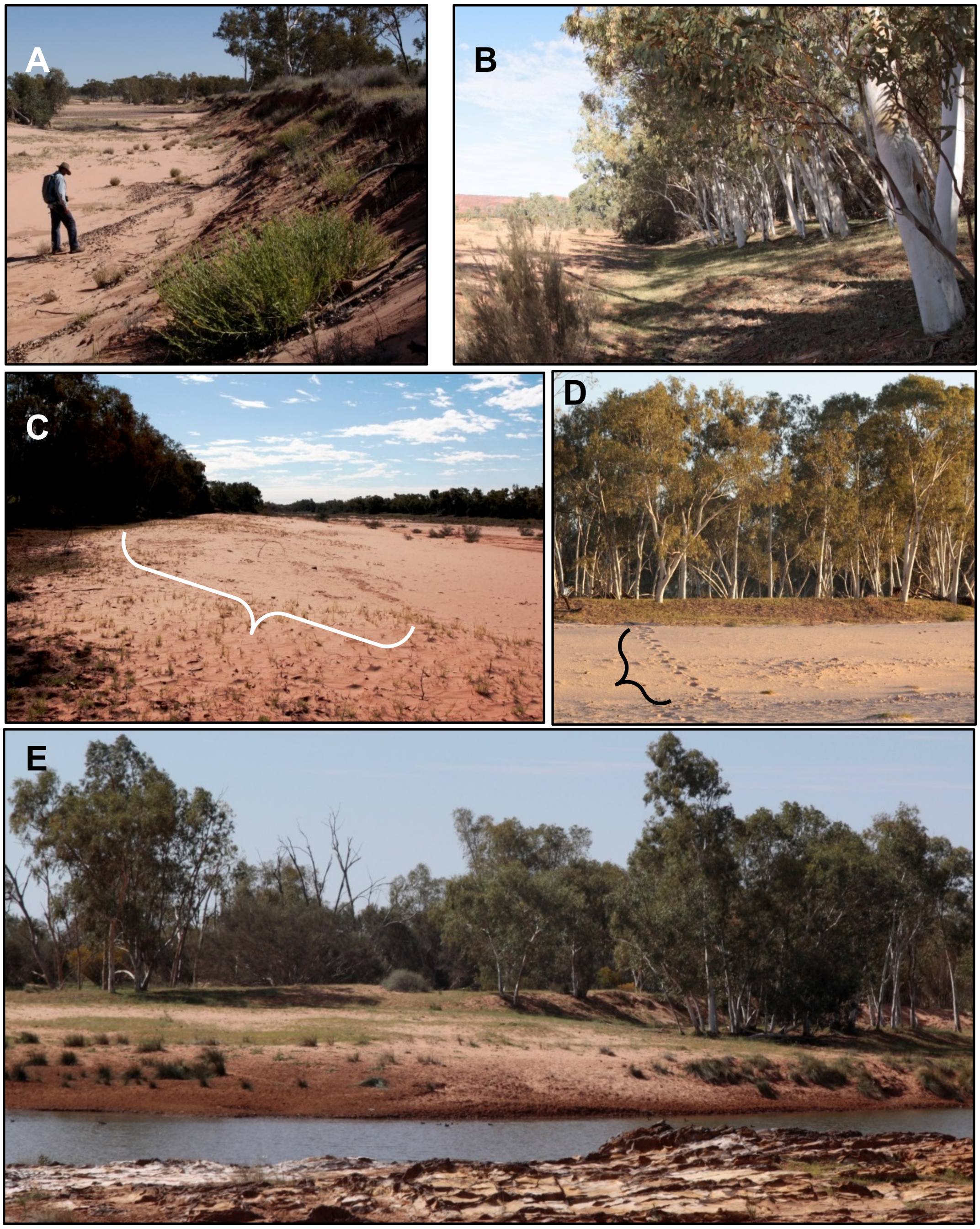


Fig. 12 Channel banks.

A) Cut bank 1 km south-southwest from 3 Mile Waterhole, person for scale, standing on exhumed gravel beds; B) looking downstream along the bank, 1.8 km west-northwest from Main Camp Waterhole; C) looking upstream along the same bank, riparian trees to left, high-level bank-attached bar (white bracket) sloping down to thalweg at right, riparian trees of opposite bank extending from right side of photo; D) a flat floodplain with a stand of eucalypts, a small grassy bank down to a sandy bank-attached bar (black bracket) which has a gentle slope down to the lower channel surface, human footprints for scale, 1.9 km north-west of Fidlers Waterhole; E) the northern bank of Main Camp Waterhole has multiple levels of both floodplain and channel.

Usually the bank surfaces are masked by grasses; some had diagonal cattle pads or were trampled. Very few erosion gullies were observed.

Modern Channel - Types

The Finke River's modern channel exhibits many forms, and the channel type can change from one reach to the next, or different channel types can coexist within a single reach (Fig. 13). This diversity results from flow variability, flow strength, and high levels of bedload transport. Flow variability enables landform creation and modification to take place at all elevations from thalweg to upper floodplain. The flow strength and sediment transport rates promote channel mobility, so at any reach the channel might have coexisting landforms,

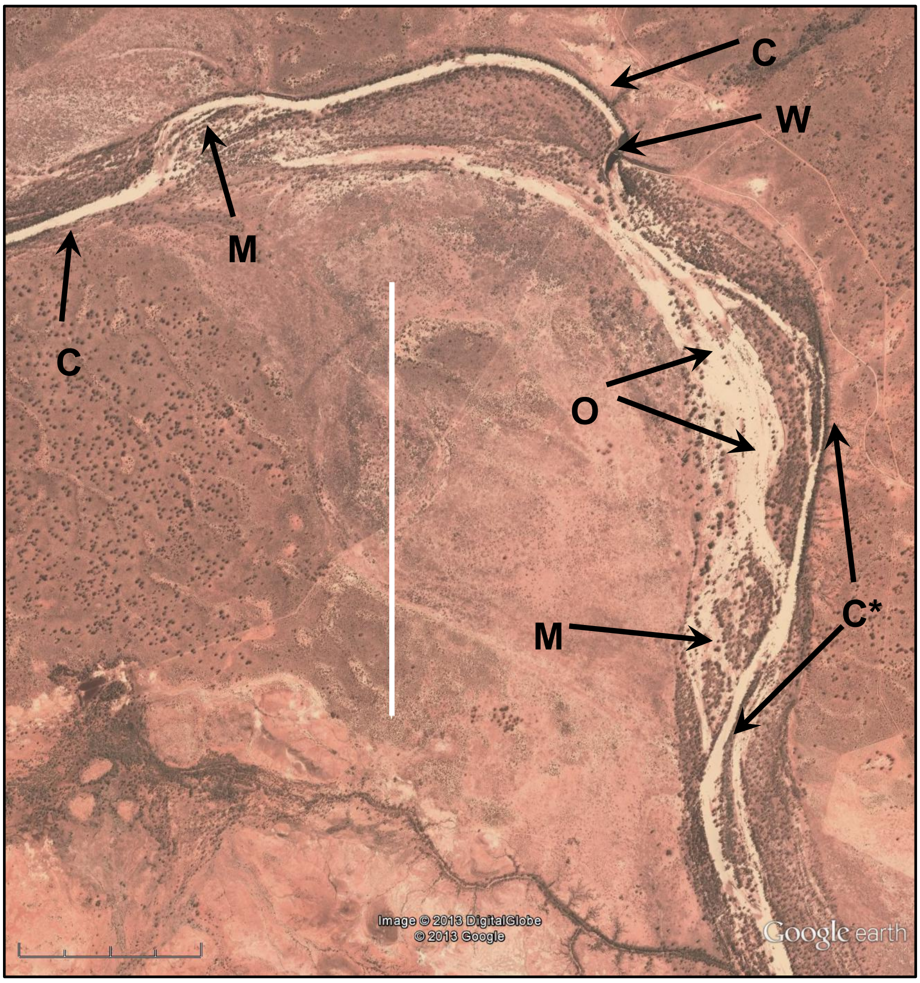


Fig. 13 Channel types at the 3 Mile Waterhole reach.

This range contains clearly-defined single channels (C), an open shallow channel (O), a waterhole (W), and some multithread channel segments (M). At C*, channels could equally be considered single channels with islands, or multithread channels. Google Earth image; white scale line = 2 km.

created at different times and under different flow conditions. Every reach will have its own developmental history.

For the purposes of this report (landform description and interpretation of fluvial process) channel types are broadly grouped into 1) clearly-defined single channels, 2) open shallow channels, 3) waterholes, and 4) multithread channel segments (Figs. 13, 14). Each group represents a particular river behaviour. These groups are a reasonable reflection of the field data, however a more detailed geomorphology study will certainly refine and expand on them. Note that these channel types are not intended to match any particular river classification scheme.

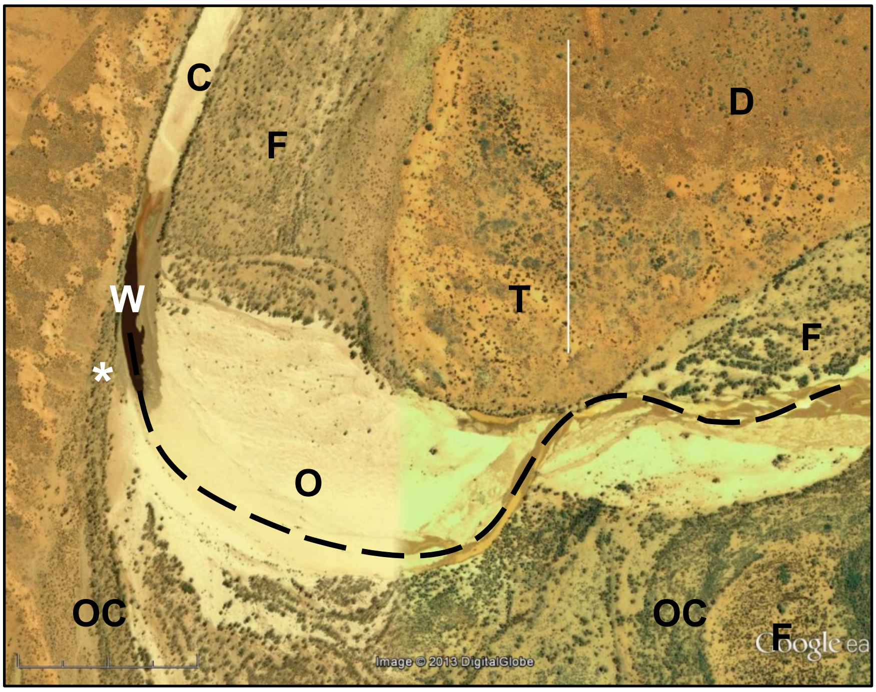


Fig. 14 Channel types in the Fidlers-Brumby reach.

The modern channel, containing thalweg (black dashed line), a clearly-defined single channel (C), an open shallow channel (O), and a waterhole (W), is flanked by the floodplain (F), old channels (OC), terrace (T), and old dunefields (D). White scale bar = 1 km; white asterisk is location for Fig. 14; see Fig. 8 for wider view. Google Earth image of the reach between Brumby and Fidlers waterholes, where a waterhole existed in 2005 but not in 2013 (133.46°E, -24.88°S).

Clearly-defined single channels are visible on Google Earth images as mostly vegetation-free sand with approximately parallel clearly-defined banks. Channels are ~50-150m wide, and have a lower width:depth ratio than the open shallow channels. Sediment in the single channels is more likely to be preserved as a single flat bed, or a gently undulating bed. Where the channels are stable, the banks are lined by dense riparian trees, on Google Earth image showing as a darker line flanking the white channel sands. Banks tend to be unambiguous, ~1-2.5 m high, moderately steep, and either erosional or clothed in long-lasting vegetation (trees). Vegetation may include coolabahs, red gums, melaleucas, and various grassy or shrubby understory.

Open shallow channels are 400-900 m wide, and have a very high width:depth ratio. They are more likely to have sediments deposited on multiple levels, including high-flow channel marginal bars and dunes. The thalweg may appear braided. Banks can be erosional, steep to vertical, and 0.5-2 m high, or they could be only a few centimetres high and depositional (formed by high-flow bar deposition at the channel margin). The banks tend to be unvegetated or colonised by short-term plants (grasses), although large eucalypts from previous channels may persist. The variation of form, ephemeral vegetation, and persistence of previous bank traces means these banks can be quite ambiguous in their character. Hardy, rapid-growing feral athol pine can also be found in these open channels. A number of the open shallow channels are immediately downstream of a waterhole or some other feature producing locally strong flow conditions. It is likely that the open shallow channels have formed as flow leaves a constrained reach; extra bedload and/or a reduction of stream power has moved the channel into a wide shallow geometry.

Waterholes are very short and very deep channel segments (very low width:depth ratio). They form under locally strong flow conditions which scour out a deep hole; at the close of flow, water remains in a deep pool. The waterholes visited during this study fall into three groups:

- where locally strong flows are externally forced by rocky outcrop in or flanking the channel (e.g. Main Camp Waterhole, Fig. 12E, Fidlers Waterhole),
- where the channel's geometry promotes turbulent conditions (typically where channels curve round a bend, or are hard up against the valley margin (Fig. 14),
- where strong flows are externally forced by multiple causes, for example at 3 Mile Waterhole and Snake Waterhole, channel relocation has placed channels where they are forced against rocky outcrop constraining them to change direction sharply and cut a narrow break through stable floodplain.

The Finke River is known to have many waterholes which appear and disappear over time (Angus Duguid, pers. comm. 2013), and the stability or otherwise of waterholes will be related to their conditions of formation. Waterholes created by channel geometry are not fixed in their location: they may be present in some years and not others (e.g. the waterhole in Fig. 14), or they may move upstream or downstream within the reach (as has likely happened with Dump Waterhole). Waterholes which are externally forced and which have little freedom to readjust their planform are likely to be stable in the long term (3 Mile Waterhole, Main Camp Waterhole). These include the deepest and most ecologically significant waterholes. Waterholes which are externally forced but where the channel may relocate (over a multi-century-scale timeframe) have an uncertain degree of stability. For all waterholes, small floods will tend to bring in sand, and large floods are needed to create the turbulence that scours them deep.

Waterhole locations, permanence qualities and salinities are described in Duguid (2013).

Multithread channel segments were identified in the remote study but not visited in the field. The remote study indicates that these areas will be a number of small channels delineated by lines of in-channel trees, or separated by stable islands excised from the floodplain. Multithread channel segments are likely to be similar to complex floodplains (see below), except that they are lower in elevation, and their swales carry active fluvial bedload rather than floodplain sediments. They are common in the Henbury reaches but less so in the Idracowra reaches.

In many reaches there is an upstream-downstream sequence of channel type, where a clearly-defined single channel displays an abrupt transition to either a waterhole, a multithread channel segment, or a wide shallow channel. Furthermore, where a clearly-defined single channel is immediately upstream of a waterhole, the wide shallow channel downstream frequently displays gravel and cobble beds. The Henbury reaches are more likely to have gravel and cobble beds, and more likely to have sequences including waterholes, multithread channels, and abrupt switches in channel flow direction (Fig. 13). The Idracowra reaches are more likely to have sequences which alternate between clearly-defined single channel and shallow wide channel.

Modern Floodplain

The modern floodplain surface is elevated above the channel bed, typically 0.5-2.5 m. The major geomorphic feature was the metre-scale topographic irregularity created by banks, beds, and tops of old channels in various degrees of preservation. The floodplain surfaces were heavily trampled by cattle and covered by grass and low vegetation: aside from a few low hummocks and swales, few small-scale structures were observed. In the Henbury reaches, there was a little flood debris and some bar-top swales where recent flows have overtopped the floodplain.

Floodplain surfaces commonly displayed large- to medium-scale topography where old channels occurred, and in a few instances ridge and swale topography indicated point bar deposition. Many floodplain surfaces were flat, indicating vertical accretion, or displayed extremely large swirl pits, indicating moderate-energy flood peak flow erosion (Fig. 15). The swirl pits were found in floodplains of moderately low elevation which were close to the present-day channel and supported well-spaced mature trees. Swirl pits had gentle to

Fig. 15 Mid-Finke River floodplains.

Top, a flat floodplain near Ampire Waterhole. Bottom, a large scour pit near Fidlers Waterhole; scales person (circled) midground right, one metre stick foreground left (circled), person in deepest scour visible from waist up, background left (half-circled).

vertical banks, and irregular sculpted undulating bottoms. They tended to be either circular or elongate; if elongate, the steepest banks and deepest section was at the upstream edge.

Old Channels

Like the floodplains, the old channels were heavily trampled by cattle or (where ungrazed) completely covered by couch and buffel grass. No small-scale geomorphic features were observed. However, though grass and trampling were universal, there were no indications that small-scale geomorphic features existed previously: the floodplains and old channels have apparently been dominantly influenced by reach-scale geomorphic processes.

2.1.4 Description: Sediments and Depositional Bedforms

The Finke River's sediment load is dominantly quartzose fine to medium sand, pale buff to white in colour. Channel bedforms observed during this project were almost universally lower flow regime flat bedding (Fig. 7), with occasional small stranded 2D dunes (~15 cm amplitude), all indicating very low flow energies. Redistribution of the sandy surface into small aeolian ripples was common.

The Finke River can also flow very strongly. Near the waterhole between Brumby and Fidlers (see open shallow channel, below), bars of mobile sand have been preserved which are ~1-2 m amplitude and at least 100 m wavelength (Fig. 16), and aerial reconnaissance and remote images also show large-scale 2D dunes. High-energy flow during flood peaks is indicated by landholder reports of large standing waves at a lower Finke homestead, floodplain-level scours (see below), and channel-floodplain boundaries which are commonly erosional. The sediment distribution is therefore consistent with waning flow modification of channel bedforms. Bedload transport during peak floods is likely to take place as higher-energy bedforms: migrating 2D and 3D dunes which may be several metres in amplitude. In very large floods there is the possibility of central wave-trains of supercritical flow.

In some places, bank-attached bars occur in which the sandy channel sediments are at a higher level along the bank edge than they are in the thalweg. Waning flow modification of the surface sediment, aeolian drift and trampling by cattle masks the shape of these bars and they are only evident in elevation changes across the channel width.

In places, the channel surface is covered in pebbles or cobbles deposited in flat sheets (Fig. 16) or low, poorly-defined 2D dunes. The clasts are commonly imbricated with cluster bedforms, and have been transported during the modern flow regime. They are most common in the Henbury area. In these areas they are associated with deep scour holes a short distance upstream: the gravels are the burst of sediment released by the construction of the scour hole. Gravelly reaches can also be found in the lower Finke, and are visible in Google Earth imagery as far downriver as Idracowra homestead. In these areas they appear to be associated with nearby riverbank outcrop.

Old dunefield sands are a very deep orange colour with few to no pale grains (Fig. 16). This deep colour is a useful marker when contrasted against the pale riverbed sand. The proportions of the two grain populations is a rule-of-thumb guide to the degrees of influence of dunefield versus fluvial processes, or to relative landform age. For example, both floodplains and terraces have a mixture of pale river sand and dark to pale orange dune sand, but terraces have less pale and more dark grains.

The river's finer suspended load sediments are deposited across the floodplain, so floodplain sediments are more silty, and liable to patches of bulldust in places where water accumulates. This greater percentage of fine sediments is likely to be more supportive of plant ecosystems than channel sands because of greater water retention properties. Sand is also deposited across the floodplain.

Fig. 16 Sediments and bedforms.

Top, large 2D dunes of pale river sands (arrows), viewed from > 400 m away. Bottom left, packed and imbricated cobbles and gravel deposited in-channel; 1 m scale. Bottom right, deep orange dune sediments; hammer for scale.

2.1.5 Processes: Valley-Scale Landforms and Modern Hydrology

The attributes of the mid-Finke waterholes (permanence, salinity, and ability to flow even in the absence of surface inflows) are spatially complex, and field investigation has demonstrated the influence of springs and groundwater (Duguid 2013). Some waterholes are observed to be fed by saline springs, and a degree of salinity contributes to the refuge qualities of some waterholes with respect to some species of fish (Duguid 2013). The present study concurs with the conclusion that there is likely to be an aquifer in the Finke valley (the alluvial aquifer, Duguid 2013), and identifies its two probable components: modern alluvium, and old alluvium of the paleo-Finke River (Fig. 17).

In any river, it is likely that the water that flows in the channel also infiltrates into permeable sediments of the channel boundaries, forming a lens within the modern alluvial sediments. In this report, this water is referred to as hyporheic water. When the channel dries, hyporheic water remains (at least for a while), and this is a key component of drylands riparian ecology. Conceptually, the hyporheic water is beneath the surface of the channel bed. In fact, a river with such a variable flow regime as the Finke is likely to have water infiltrating into the floodplain as well, so hyporheic water may occur beneath as much of the modern alluvium as experiences inundation. Though sub-surface, it is not groundwater in the ordinary understanding of the word: it is part of the present-day river. Water drawn from the floodplain would be modern.

The palaeo-Finke River not only carved out the sinuous valley within which the present river flows, it also deposited alluvium within that valley (Figs. 6, 17), forming the terraces that flank and constrain the modern Finke River (Figs. 8, 17). Since the palaeo-Finke River was transporting sandy and gravelly bedload, it is likely that this old alluvium is porous and permeable. It probably receives floodwaters, either directly through the terraces in extreme floods, or via the modern alluvium during ordinary flow events. Depending on the nature of the interface, water in the old alluvium could discharge back into present-day alluvium.

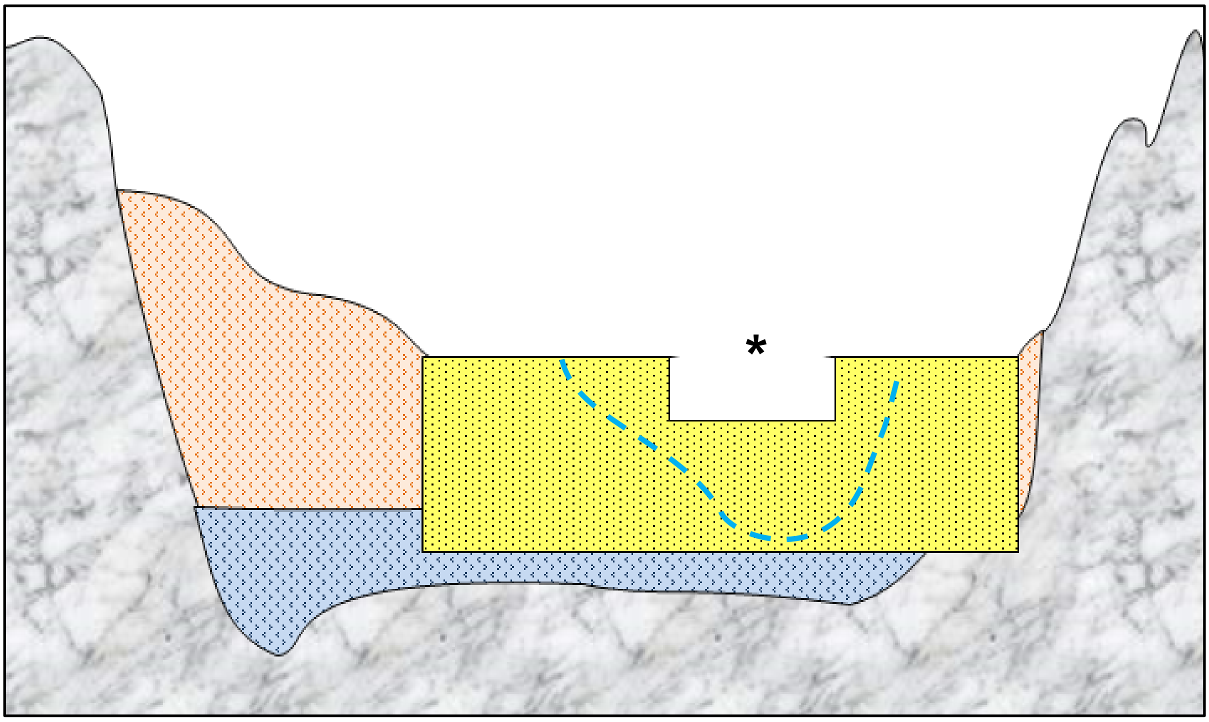


Fig. 17 Conceptual cross-section of the alluvial aquifer in the Finke valley.

Grey, rocks and regolith of the valley margin (see Fig. 3); orange, terraces of old alluvium; blue, old alluvium holding water; yellow, modern alluvium; asterisk, present-day Finke River channel; blue dashed line, lens of post-flood creek hyporheic water in modern alluvium.

It is proposed here that these palaeo-Finke sediments are an important component of the "alluvial aquifer" of Duguid (2013). Water hosted in the old sediments is conceptually in-between hyporheic water and formation water. Though not part of the surrounding rocks, the old alluvium is also not synonymous with the modern alluvium, and some of its waters are likely to be at least partially independent of the hyporheic water. Water drawn from the old alluvium might be hundreds to thousands of years old. Water held in the old alluvium is referred to in this report as alluvial aquifer water, with the understanding that there is also likely to be a component of hyporheic water. Further investigation is needed.

The old alluvium is held in a valley that has been carved out of the local rocks (Figs. 3, 6, 17). The rocky valley has irregular walls, and the floor has gradient and undoubtedly uneven topography. Alluvial aquifer water may flow towards the present river channel, but may also flow downvalley, or may stagnate in blind pockets, in which case it could become highly saline through evaporative concentration. Groundwater salinity patterns in the alluvial aquifer are therefore likely to be complex.

The alluvial aquifer may be bounded by rocks or sediments from any of five separate sedimentary basins (Fig. 3), which should be considered individually in any hydrological study. During the present study, Cainozoic regolith and rocks were observed to be common along the mid-Finke, and some were seen to be transmitting water (surface dampness, or efflorescent evaporites); they are definitely a potential source of water or solutes into the Finke or into the alluvial aquifer. Sedimentary basin rocks may also receive water from the Finke River and/or the alluvial aquifer: the lower Finke River valley crosses the GAB aquifer, and the Finke River is known to be one of the GAB's recharge sources.

2.1.6 Processes: River Behaviour and Habitat

This section describes the river behaviour at various flow heights. It should be noted that detailed work on the Finke River flow conditions and sediment transport remains to be done, and the descriptions below are not design parameters for engineering works.

No-Flow Stage

Hyporheic water supports in-channel trees (where present), and riparian and floodplain terrestrial habitat. This is a key process of the fluvial geomorphology: the vegetation thus supported has an important influence on fluvial behaviour during flow events. Water remains above-ground in waterholes along the channel, supporting aquatic animals. Waterholes shrink and become saline with evaporation; some waterholes receive formation water or alluvial aquifer water, which can affect salinity.

No substantial landform alteration or sediment transport takes place during dry, no-flow stages. A little localised aeolian sediment redistribution occurs, and local convective storms delivering high-intensity rainfall may further gully erosion, or locally alter topography by asynchronous tributary flow (Fig. 18).

Fig. 18 The Finke-Maloney confluence.

Strong flow from Maloney Creek (flow direction from top left to centre right) coming into the dry or nearly-dry Finke River has cut across a multithread channel segment (flow direction bottom left to centre right), forming a wide shallow channel. This was probably in October-November 2011 (see Duguid 2013, his p. 4). Google Earth image, 1 km white scale bar.

Low-Flow (in-Channel) Stage

Flows where the water is confined to the channel are likely to be the small flows, or the waxing or waning limbs of floods. Generally, the floodplain will not be inundated, and higher bars of the wide shallow channels may also stay dry.

Flow energy will be relatively low. Sediment transport in the channel centre may take place, so channel sands might be mobile to a depth of up to a metre. The channel's frequent sediment mobility discourages plant establishment. During waning flows, bedforms will gradually decrease in size until at cease-to-flow only a flat surface remains.

The volume of sediment under transport will be less than the amount moved in a big flow, but some sediment transport will occur. A series of small flows could bring sand into a waterhole and fill it up. This is likely to be one reason for the Finke's reputation of hosting transient waterholes.

Low flows may freshen up the water in waterholes, supporting aquatic ecology. However, they may be too low-energy to scour, so are unlikely to deliver the ecosystem service of maintaining waterhole depth. Low flows may also replenish hyporheic water; they may or may not establish sufficient connectivity to enable fish migration.

High-Flow (Channel + Floodplain) Stage

High flow energies and very large amounts of transported bedload make the Finke River different from most Channel Country rivers. At flood peaks of high flows, the entire channel will be actively transmitting water at moderate to moderately high energies. Flow energy will vary according to channel constraint or boundary conditions. Overall, channel sands will be mobile to ~1-2 m depth, with some reaches exhibiting greater or lesser degrees of bedload mobility.

During high flows, aquatic habitat will be experiencing moderate- to high-energy conditions. In the open channel, a blanket of saltating sand grains tens of centimetres deep will cover the bed of shifting sand. In waterholes, sand will be brought in forcefully and whirled round turbulently before being swept away downstream. At least some of these waterholes will virtually be recreated with every big flood. Of these, those which are permanent in their location (because of boundary forcing by rocky bars, etc.) might usefully be considered "recurrent" rather than permanent. This does not change their high value as fish refugia, but may have implications for invertebrate populations. For example, if benthic invertebrates have to re-establish after every large flood, monitoring which uses invertebrate populations as a metric for river health may produce an unrealistically low score.

The Finke's high-energy flow, abundant coarse sediment transport, and channel-floodplain coupling is unlike that of other LEB Rivers such as Neales River and Cooper Creek. In the Neales River, a topographically diverse floodplain has many pockets (slackwater refuges, e.g. Vietz et al. 2013) that might shelter small biota. In the ark/polo-club/disco model of fish migration (McNeil et al. 2011), floods are envisaged as an opportunity for fish to leave the refuge waterhole and find a favourable environment for feeding and mating in stepping-stone and disco habitats. In contrast, the Finke River is unlikely to be such a welcoming environment, with its high-energy sediment-rich flows. Stretching the ark/disco analogy, a fish's experience in a large Neales River flood would be like finding a café to shelter in during a rainstorm. In the Finke River, it would be like standing exposed on a beach during a cyclone.

Existing waterholes will be scoured and new waterholes might form. Though many mid-Finke waterhole locations have been stable for the length of living or traditional memory (Duguid 2013), it is likely that some at least will not have permanent boundaries. Waterhole sides and floors are likely to be either scoured surfaces, or the depositional surfaces of sand waves which have stopped moving at cease-to-flow. This is likely to be a different environment from that experienced by infauna in Channel Country waterholes.

At high flows, water will cover some or much of the floodplain. For any location, the degree of inundation and the local conditions of flow energy will depend on landform elevation, vegetation, and spatial relationships with the modern channel.

Energy may be up to moderately high: old channels may be converted to flood runners, and sand and silt may be deposited over the floodplain surface. Flow energies may be insufficient to scour floodplain surfaces except where local turbulence is created by well-spaced tree trunks. Depending on local circumstances of channel constrictions and pre-existing topography, flow energy may be high enough to trigger channel avulsion.

High-flow deposition of sediment across floodplains and filling in old channels and multithread channel segments is a key process of the floodplain construction. The waning stages of floodplain-level flood may redistribute sediment from higher floodplain to lower floodplain, or may fill in old channels.

High flows will refresh the hyporheic water beneath channel and floodplain, and may contribute water to the alluvial aquifer. They will contribute water to the Finke Floodout. A flow that is big enough to cover the floodplain is likely to have good upstream-downstream connectivity for fish passage, but it is not clear from this work whether the flow conditions would be too intense for some species.

Very High to Extreme Flows

At very high to extreme flows (century to multi-century recurrence interval), water will overtop all channels and cover most or all of the floodplain, activating the highest elevation flood runners and scouring the floodplain surface. In some locations, flow down the flood runners will trigger channel avulsion, which will release a burst of sediment downstream, to be deposited over floodplains or dumped in-channel. Flood waters may extend to terrace bases; in extreme floods waters remove parts of some terraces, including their underlying palaeo-Finke sediments. Flow strength will be variable across floodplain surfaces, depending on water depth and vegetation density, so some floodplain may receive sediment at the same time as other floodplain is being scoured. Sediment deposition will also occur as a flood peak begins to wane.

Flow energy down the channel will be higher than floodplain energy, because of water depth, lack of vegetation, and the clear down-gradient pathway. Channel sediments are likely to be mobile to depths of ≥3 m, and in mid-channel to experience very high-energy transport. It is likely that sand will be in suspension load, enabling it to be transported from the channel onto the highest floodplain.

The Finke River shows a high degree of channel mobility, and evolution of channel form is most likely to take place during very high to extreme flows. Alternate reaches have higher or lower energies, and are correspondingly scouring or depositional. This is similar to the processes maintaining pool-riffle sequences in temperate rivers, and to the processes of waterhole formation in Channel Country rivers. River behaviour is shown by the pattern of downvalley sequence of channel types. Briefly,

- flow is focused and strong within a clearly-defined single channel,
- scouring takes sediment from the channel bottom, typically with the deepest scour at the most downstream end of the single-channel reach,
- at the end of the clearly-defined single channel, channel bed elevation rises abruptly, flow becomes unconfined, stream power diminishes, and the scoured sediment is deposited in an expansion bar or splay. Splay sediments form landforms such as multithread channel segments (Fig. 13) or wide, shallow channels (Fig. 14).

This process is particularly relevant to the formation of the permanent waterholes. Where the scour-splay process has followed channel relocation and has created a new waterhole (e.g. 3 Mile Waterhole, Fig. 13), the reach immediately downvalley from the new waterhole commonly has gravel and cobble beds. These are the remnants of the sediments exhumed during waterhole formation.

In the Henbury reaches, the channel belt is constrained by outcrop and coarse alluvial fans: channel sequences commonly contain splays, exhumed gravel/cobble is common, and channel relocation tends to take place over a narrow geographic range. In the Idracowra reaches, the channel belt is wider, and flanking rock is softer. Relocated channels tend to be further apart, and the exhumed sediment has little gravel, so wide shallow channels are much more common than splays.

Landforms created during extreme flows persist in the landscape, altering the direction of subsequent smaller flows and thus governing fluvial function. For example, splays which block the pre-existing channel will divert subsequent flows and force the river onto a new path (Fig. 14). It is important to note that although channel relocation may occur somewhere along the Finke river during any high flood, it is a low recurrence interval event (pending more detailed investigation, probably on a multi-century scale). The timescale of waterhole creation and destruction is far greater than the timescale of human management practice. That is, the high ecological value of permanent waterholes is unaffected by whether the waterhole is boundary-forced (e.g. Main Camp Waterhole) or created by avulsion (e.g. 3 Mile Waterhole).

Very high to extreme flows will appear to have undesirable impact on landforms and ecologies, however these processes are natural, and an important part of landscape renewal. These flows will also provide high levels of recharge to the alluvial aquifer and the Finke Floodout. The effect of very high to extreme flows on populations of aquatic biota may be severe.

2.2 Lower Finke River

The lower Finke River is defined empirically as the reaches which do not host permanent waterholes and which are upvalley of the floodout complex. It was not a priority in this study, so few observations were made. However, the remote study shows it has many similarities to the mid-Finke River, so much of the information from that section of this report will also be relevant here.

The lower Finke River, extending southeast and south from the Idracowra area, displays a semi-confined valley setting similar to that described above for the mid-Finke River. The river changes character as it crosses over the GAB recharge zone (outcrop of the Jurassic age sandstone). From there to the Finke Floodout, the river is increasingly likely to have reaches where the channel is wide, probably shallow, and mobile on a sub-century to decadal scale.

At its most downvalley reaches (from the Goyder Creek confluence, near New Crown Station homestead), the river's characteristics are transitional to those of the proximal Finke Floodout Complex. The distal lower Finke River has a wide shallow very unstable modern channel which rapidly migrates across and reworks the floodplain (Fig. 19). Under ordinary flow conditions the river will only fill part of the floodplain (the modern channel and some nearby low-elevation floodplain), but in at least some reaches that will be sufficient to migrate the channel, scour the channel bed, and cut into floodplain. Larger flows will cover more of the floodplain or fill the floodplain. It is not clear from this investigation what recurrence interval will achieve what geomorphic activity.

Fig. 19 The lower Finke River.

Left: on the far side of person, a low transient bank marks where lowest flow has cut into modern channel sands. Centre: distant view of the 1.5-2.5m erosive bank where the modern channel has cut the floodplain. Right: shallow poorly-defined swale in the floodplain; evenly spaced relatively young coolabah; person for scale.

Reach-scale channel geomorphology indicates that the alternation of lower- and higher-energy reaches, with corresponding pulses of sediment transport, happens here as it does in the mid-Finke (although the sediment size and channel width:depth differences between reaches appear to be less pronounced than those of the mid-Finke).

Feral athol pine poses a possible risk to good fluvial processes, by its ability to establish in mobile channel sediments, and its ability to trap sediment.

2.3 Finke River Floodout Complex

A floodout is a landform in which downvalley decreases in stream power diminish and eventually remove a river's ability to transport sediment and maintain a channel. Floodouts are characterised by an absence of channel; floodwaters are carried by sheetflow. They are characteristic of the Australian arid zone, and are often biologically rich. The Finke Floodout Complex is a high-value aquatic ecosystem, as it is dependent on inundation by surface water from the upstream reaches of the Finke River (as per Aquatic Ecosystems Task Group 2012). It hosts rich ecosystems in an otherwise harsh environment, and it is likely to be a significant biological refuge.

It should be noted that although the Finke Floodout is exceptional, it is not the only runoff-dependant ecosystem overlying the Pedirka Basin. To the north, the Todd and Hale Rivers Floodout extends from the Rodinga Ranges down to the Allitra Tableland; to the south, the Dalhousie Springs outflow links the distal Finke River catchment with the Macumba River; and in the centre, high-runoff rocky surfaces support local creeks and swamps, including the Mac Clark (*Acacia peuce*) Conservation Reserve.

The Finke Floodout Complex begins at approximately 134.97°E, -25.77° (~45 km east-southeast from Aputula (Finke) township). The proximal floodout complex contains the channel tract (Fig. 20). The next reaches, through the main Finke Floodout, are mostly unchannelled, although isolated channel segments occur in places. The main flow path, visible on Google Earth as the dark tones of dense vegetation, goes east towards a narrow choke. There, the Snake Creek and McDills Bore distributaries divert some flow to the north-east and south-east, and the main Finke River (as defined on 1:250,000 maps) flows south into South Australia as a reformed channel. The main flow path then travels east along the base of the hills in Witjira National Park in reaches which mostly have some kind of channel, then south again in channelled and unchannelled reaches, extending to just north of the Dalhousie Springs outflow.

The scope of this project precluded investigation of the South Australian parts of the Finke Floodout Complex, however the comments presented here will be broadly relevant to that area as well as the NT parts of the complex.

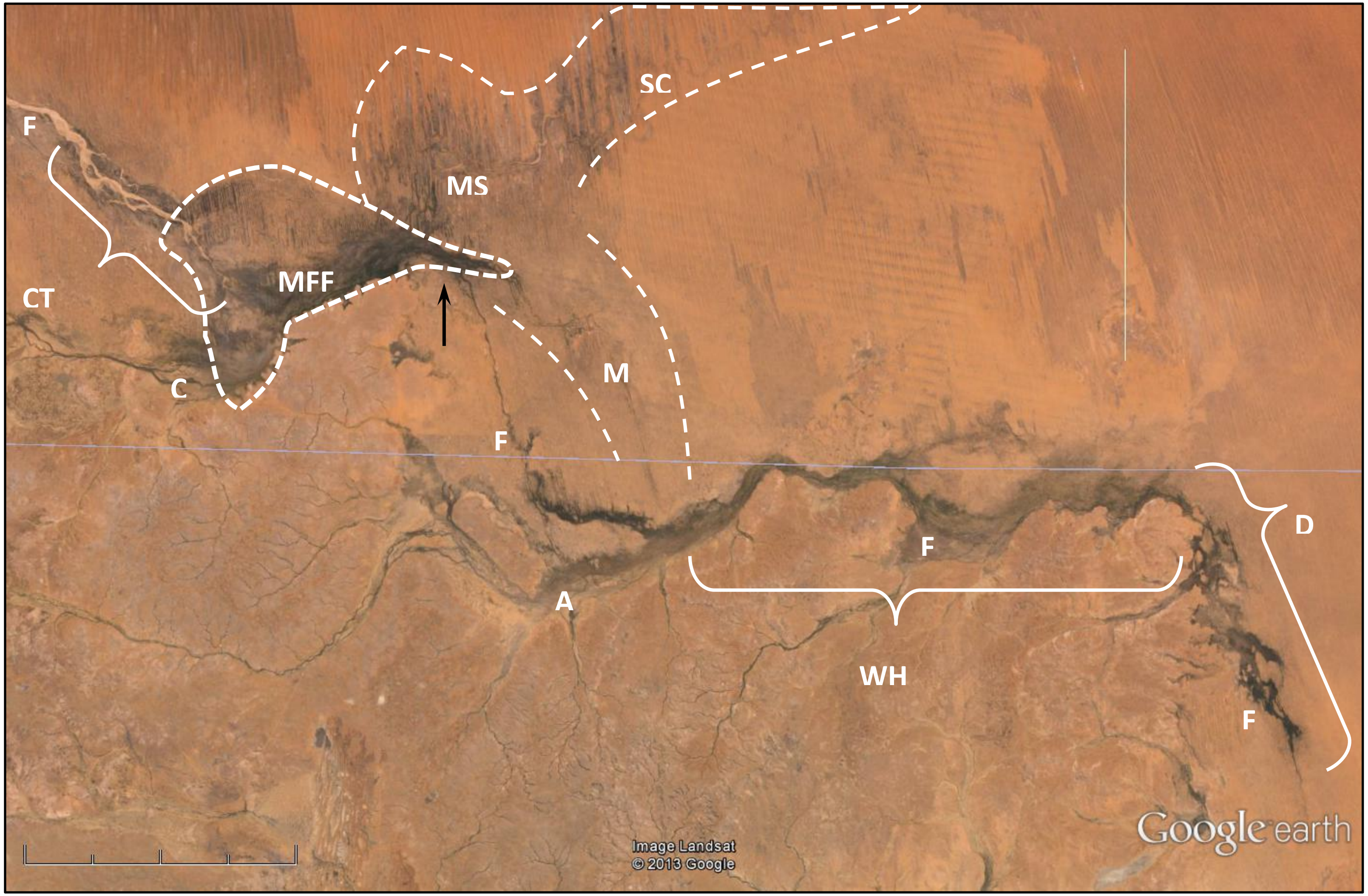


Fig. 20 The Finke Floodout Complex; black to dark grey colour is dense vegetation.

F, the lower Finke River 's main channel. CT, the channel tract in the proximal floodout. C, a tributary floodout from Coglin Ck. MFF, the main Finke Floodout. The choke is indicated by the black arrow. SC, the Snake Creek distributary. MS, Mayfield Swamp. M, the McDills Bore distributary. A, a tributary floodout from Abminga Ck. WH, the Witjira Hills part of the floodout complex. D, the distal part of the floodout complex. Narrow white bar is 25 km scale, grey horizontal line is the SA-NT border.

2.3.1 Description: Valley setting

The lower Finke River's valley setting is semi-confined, against compound dunes along the northern sides of the valley, and dunefield-covered GAB rocks on the south. From the Goyder Creek confluence, the influence of the southern rocks becomes less, and the valley widens. By the beginning of the Finke Floodout, the bedrock skeleton of the alluvial valley is very wide and extends from the location of the modern channel west into the valley of Coglin Creek and its tributaries. The present-day alluvial valley has been narrowed by dunefield development.

The Finke Floodout is defined here as beginning where the channel becomes unconfined, (continuous floodplain on both sides). The valley is bounded to the north by compound dunes, and to the south by low dunefield over old alluvial plain, or GAB and Cainozoic basin rocks which may be either masked by dunefield, or exposed as gibber plain (Fig. 21). In the main Finke Floodout, the valley is very wide, but elsewhere the Finke River's opportunities to spread out or migrate its channel are limited. There are "chokes" near McDills Bore and along the Witjira Hills area, and anywhere that the Finke River's flow direction and relatively low volume constrain it to travel down interdune corridors.

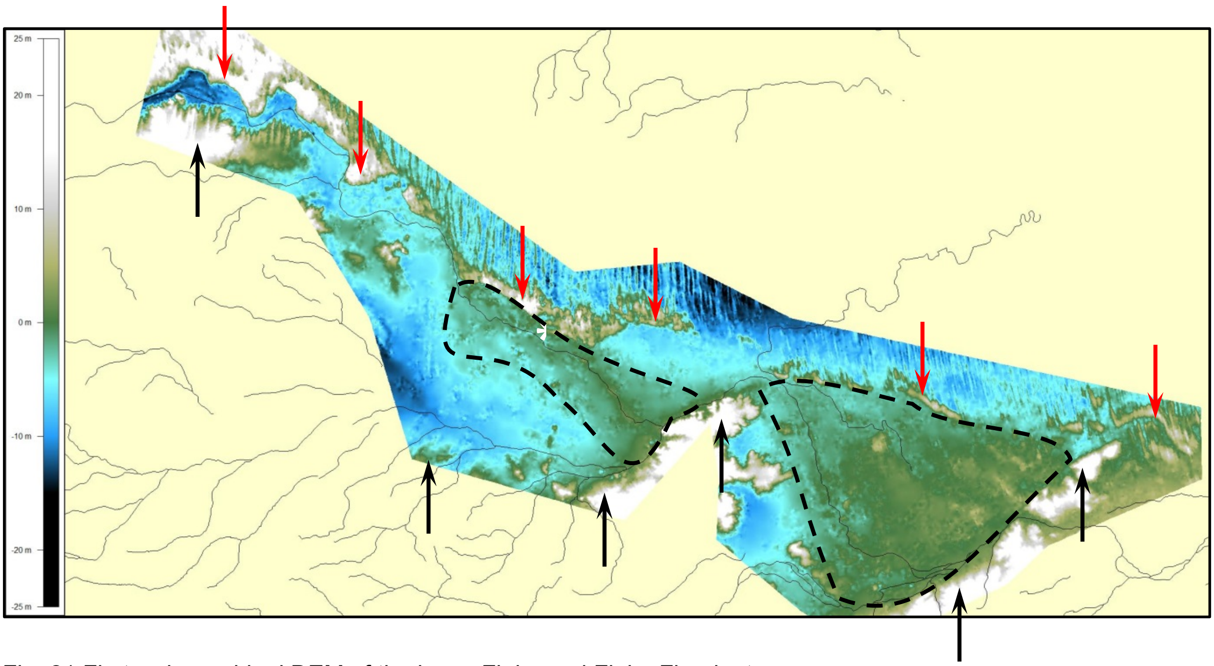


Fig. 21 First-order residual DEM of the lower Finke and Finke Floodout.

The elevation change of the downvalley gradient is removed, to better reveal local topography. The southern valley margin is GAB and Cz basin rocks (black arrows), the northern margin is compound dunes (red arrows). White asterisk: the beginning of the Finke Floodout. Black dashed lines surround approximate areas of sediment deposition (note this is a preliminary residual calculation and requires refinement). Elevation legend on left: blacks and blues are low, greens medium, grey to white high.

2.3.2 Description: Valley-Scale Landforms

The valley-scale landforms of the Finke Floodout Complex are (Fig. 22):

1. runoff slopes,
2. old dunefields and/or terraces,
3. floodouts,
4. modern channels,
5. floodplain (as a floodout component),
6. swamps (as a floodout component)
7. gilgai swamps (independent of the river network).

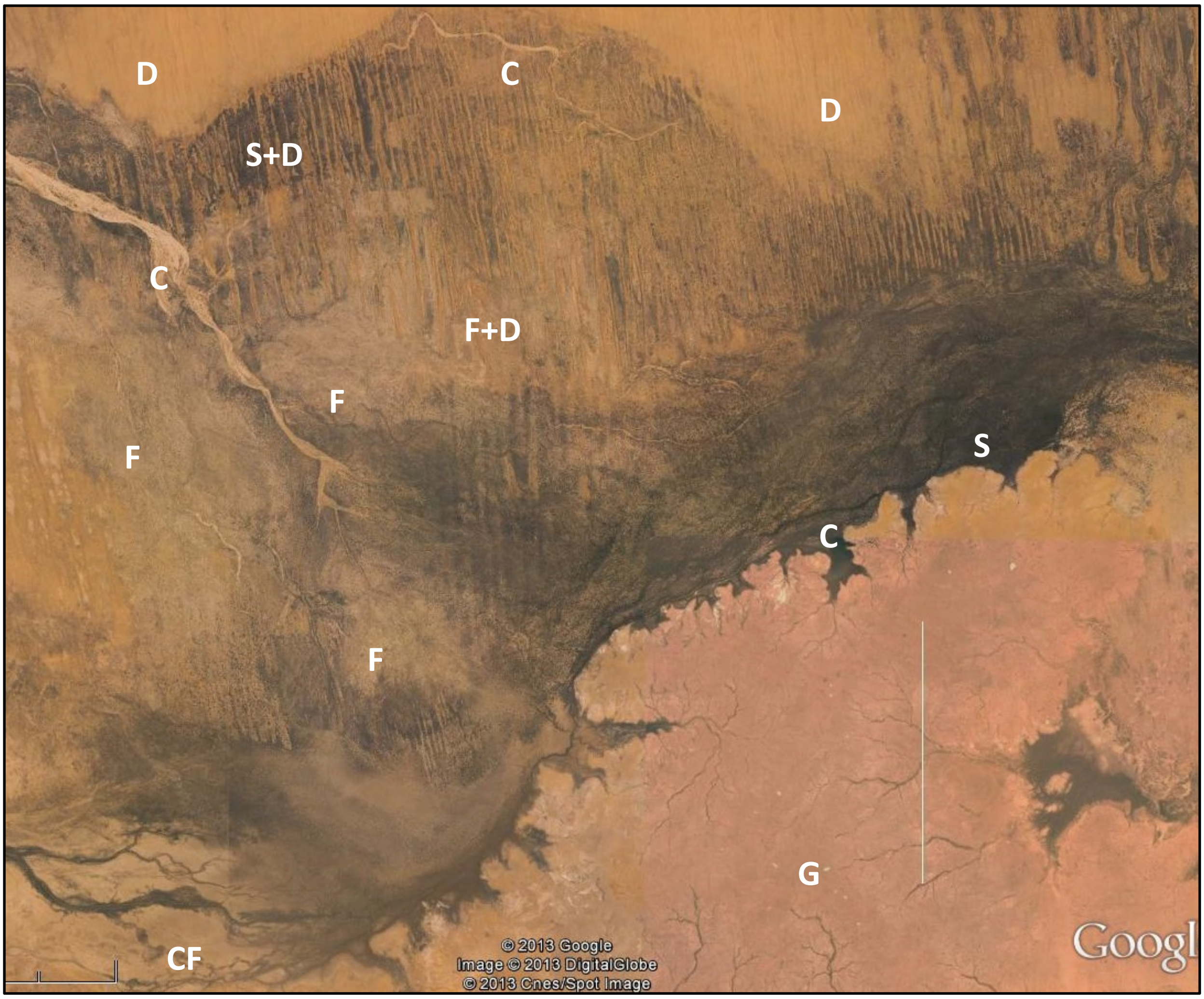


Fig. 22 Valley scale landforms of the main Finke Floodout.

Google Earth image, white scale bar is 5 km. G, gibber plain; CF, Coglin Creek floodout; D, dunes; F, floodplain; F + D floodplain with superimposed dunes; S, swamp; S + D, swamp with superimposed dunes; C, channels.

Runoff slopes is the term used in this report for hills, slopes, outcrop, shallow subcrop, regolith, or anything that is not dunefields or alluvial landforms. In the Finke Floodout Complex, gibber plains of the Dalhousie Anticline form significant runoff surfaces along the main floodout's southern margin. The gibber plain is often expressed as an elevated surface with 3-5 m scarps facing into the floodout. The sharp cliff edge is notched by small gullies which deliver runoff from small but locally significant upland catchments.

As in the mid-Finke River (section 2.1.2), the **old dunefield** is higher in elevation and has not been involved in fluvial processes. Most dunes are longitudinal dunes, and there are also some source-bordering dunes (Fig. 21), formed along the last palaeochannel's northern edge. Dunes play an important role in defining the present-day fluvial extent. In **mixed dune-alluvial areas**, dunes overlie alluvial sediments, or have been modified by fluvial action. In the Finke Floodout Complex the spatial distribution between old dunefield and the mixed dune-alluvial areas is complex, and no attempt has been made to map their spatial relationships in this study.

A **floodout** is a fluvial landform in which the channel diminishes and disappears with increasing distance downvalley, and floodwaters travel thereafter as unconfined sheetflow. Floodouts occur on all scales. The Main Finke Floodout (Fig. 20) will be described in terms of its floodplain and swamp elements (see below), but smaller floodouts (e.g. Coglin and Abminga Creeks) will not be so subdivided.

The **modern channel** is most marked in the proximal channel tract (sensu Tooth 1999) area (Fig. 20), where the channel is visible on Google Earth images as a wide expanse of pale sand, similar to the Finke River's channels upstream. There are also smaller and narrower isolated channel segments, which usually have irregular shapes, and may or may not be bordered by dense riparian vegetation. On Google Earth images, the channel beds may be pale if active sediment transport is taking place, or dark if the channel bed is heavily vegetated.

For the purposes of this report, parts of the Finke Floodout Complex are described in terms of **floodplain** (less densely vegetated areas, in which sediment deposition takes place or has previously taken place), and **swamps** (very densely vegetated areas, usually not showing evidence of sediment deposition). It should be noted that this is a pragmatic terminology division between two interdependent and spatially linked floodout components. A more detailed investigation of the Finke Floodout Complex is likely to refine this terminology.

The distribution of the valley-scale landforms indicates that in the past and presently most of the water and sediment in the main Finke Floodout has come from the Finke River. Coglin Creek occasionally produces volumes of water, but not often. Runoff from the gibber plain contributes to local ecosystems.

Independently of the fluvial system, **gilgai swamps** are found along the gibber surfaces of the Dalhousie Anticline. These shallow basins are characterised by gilgai soils exhibiting a rectangular reticulate drainage network, distinctively 'brain-like' in Google Earth images. Though not falling within the scope of the present study, they are likely to be locally important wetlands, and to provide information on landscape evolution in the Lake Eyre Basin. They are also found near Arckaringa Creek (see section 3.2). In the present study, they indicate provenance of the few gilgai (vertic) soils of the Finke Floodout Complex.

2.3.3 Description: Reach-Scale Geomorphology

Fluvial Margins: Gibber Plain and Compound Dunes

The fluvial margin is bordered by both longitudinal and compound dunes (similar to those in the Strzelecki Plain, see Wakelin-King 2013). They were not visited during the course of this work, but are visible on the DEM.

The gibber plain is extremely poorly vegetated. It has a very low-relief upper surface, completely covered in silcrete gibber, and steep sides exposing a weathering profile imprinted over Eromanga Basin mudstone (Fig. 23). Though individual gibber plain catchments are small, occasional runoff events are sufficiently strong to create the narrow

Fig. 23 The top surface (left) and scarps (right) of the gibber plain.

deep gullies which are carved into the colluvial apron and deliver water into the floodout (see Modern Channel: Waterhole and Swamp). The gibber plain is the source of locally important runoff, and the gullies and scarps contribute swelling clays into the swamps and floodouts.

Although runoff from the gibber hills is locally important to ecosystems, it is clear from the distribution of dense vegetation visible in Google Earth images that it is the flood pulses from the upstream Finke River that make the Finke Floodout Complex a biologically rich area.

Mixed Dune-Alluvial Areas

In the mixed dune-alluvial areas (Fig. 24) loose sandy sediment with an irregular surface is vegetated by coolabah woodland in swampy areas that are occasionally inundated, and by dense acacia scrub on the more elevated dune remnants. Dune topography is roughly preserved in the orientation of irregular swales (previously, interdune corridors) but the dune crests are low and flat, and the dune flanks are poorly-preserved.

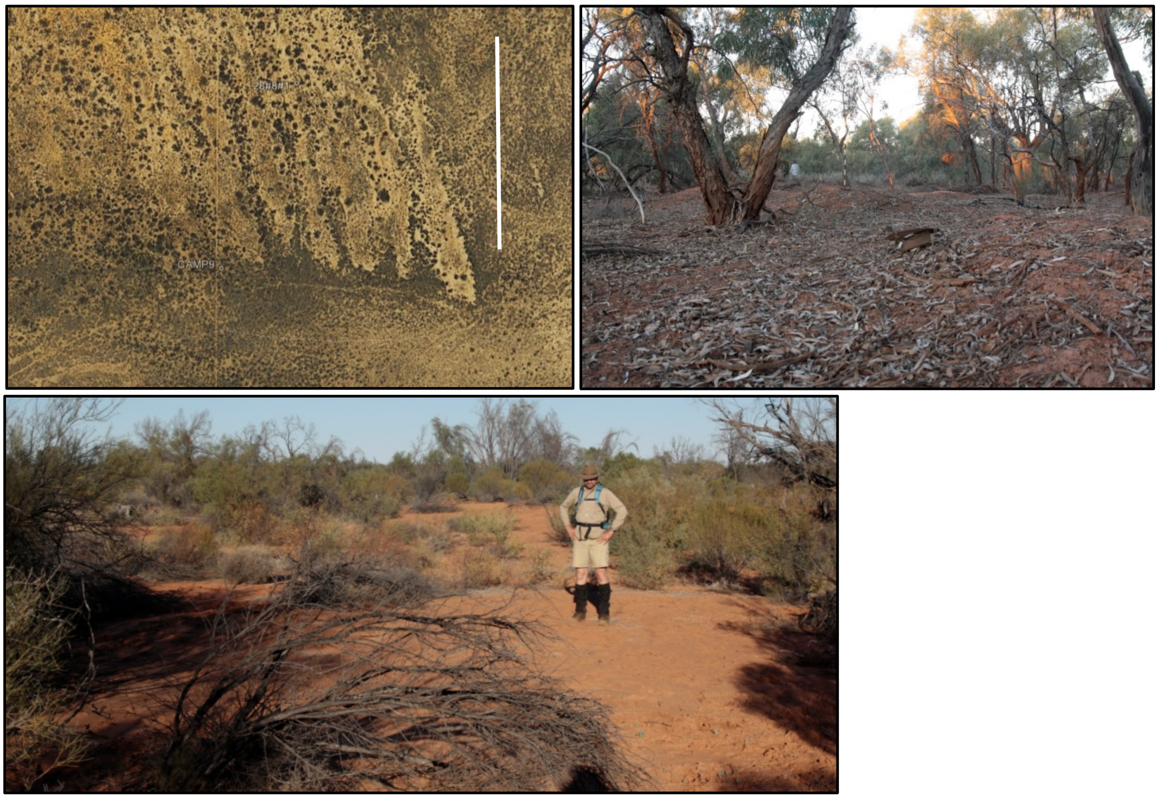
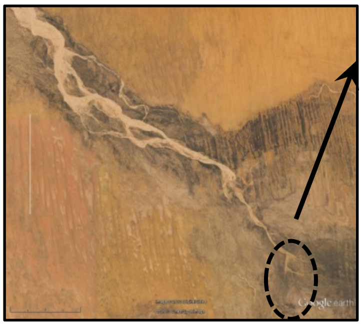


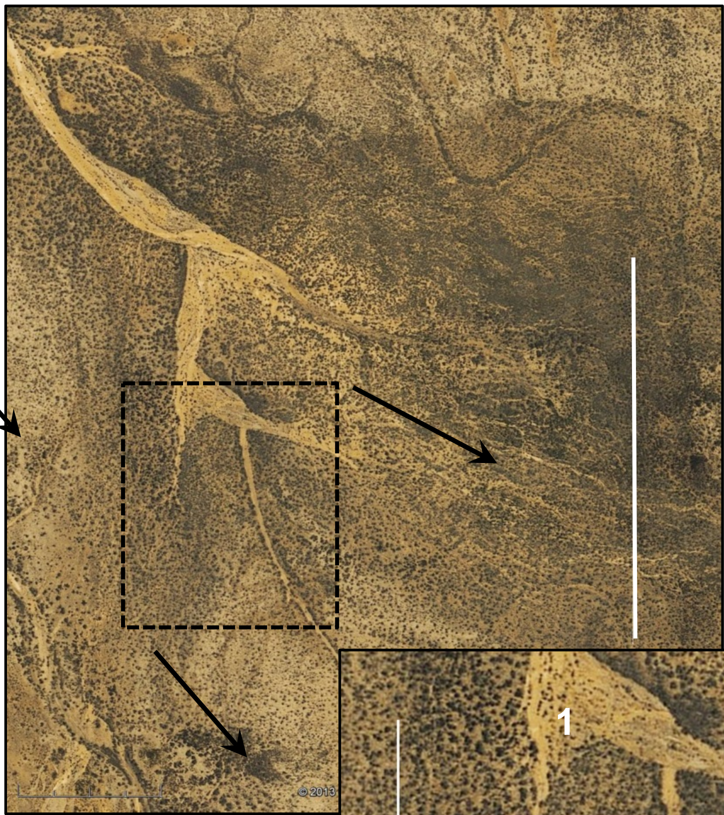
Fig. 24 Landforms of the mixed dune-alluvial area.

Top left, Google Earth image, 1 km white scale bar. Swampy area (patchy dark vegetation) and the remains of closely-spaced longitudinal dunes; Top right, coolabah woodland in the swamp. Bottom, acacia scrub in the dune remnants.

Modern Channel: Channel Tract, Splays and Floodplain

Finke River's channel width (~100-300 m) decreases abruptly as the channel divides between 3 splays. This wide sandy area (Figs. 25 # 1, 26) is a chaotic collection of 0.3-1 m deep scours, channels and swales, 3-10 m wide. Although the area is broadly characterised by erosive landforms, sandy bars occur in places (Fig. 26), and some tree trunks are partially buried.





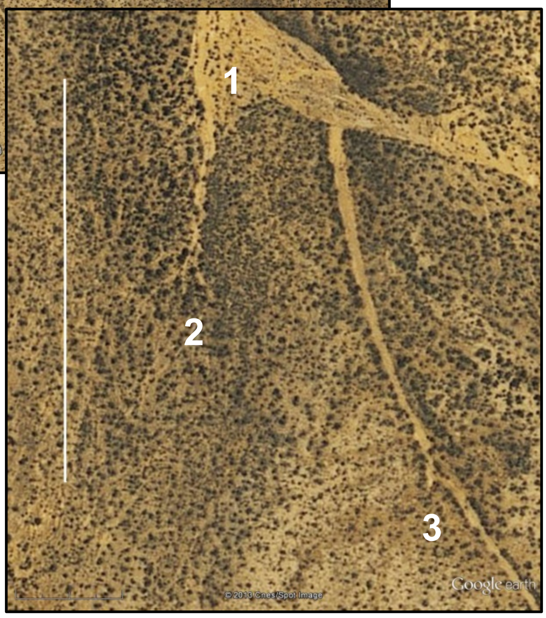


Fig. 25 Modern splays at the Finke River channel's end.

Top, the channel tract and the western part of the main Finke Floodout. Centre, the Finke River channel divides into 4 splays; 2 km white scale bar. Bottom, the short western splay delivers water into a swampy area, while the long curved channel delivers sediment onto a more elevated floodplain area to the southeast. Numbers refer to locations of Figs. 26, 27, 28; 1 km white scale bar.

The western splay is short, and apparently carries more water than sediment, as it discharges into a swampy area (Figs. 25 # 2, 27). However, it does transport modern bedload (clean, very well sorted medium-fine sand with orange and pale grains). Downvalley from the splay end, the ground surface is generally roughly flat and heavily grassed, but in places is cut by numerous small swales (~0.2-0.3 m deep, ~3 m wide, with erosive edges). Upstream from the splay end, the channel alternates between wide swaley reaches, and reaches in which the channel is narrow and scoured and finishes at the downstream edge with a jump-up (a short channel segment with a steep reverse slope, marking the location of a flow-event hydraulic jump).

Fig. 26 Splay landforms (location, # 1 Fig. 25).

Irregular edges and scoured base of the wide sandy area just upstream from the 3 splays. Pale sediment in the mid-ground is a bar which has less silt than the channel bed in the foreground. Person and person for scale.

The southernmost splay (Fig. 25 # 3) is long and straight, displaying the least evidence of channel mobility of all the splays. It is delivering the most sediment into the floodout: its distal ends are associated with a sandy floodplain 4.5 km long and 2 km wide (not shown in Fig. 25). This is likely to be the Finke Floodout's present-day dominant place of sediment accumulation, as Google Earth images of the floodplain here show no remnants of previous channels or overprinting by dunes. This splay channel carries silty fine sand to well sorted fine to medium sand, with coarser and cleaner pods and lenses as sills or bank-attached bars in places. The channel is wide and shallow (~0.5-0.7 m deep, ~20-30 m wide) (Fig. 28) and the banks are largely depositional (no erosional edges, and occasional partially-buried trees). The down-gradient floodplain is flat with occasional partly-buried trees, indicating vertical accretion, and much less densely vegetated than the swampy areas

Fig. 27 Splay landforms (location, # 2 Fig. 25).

Top, amidst plentiful vegetation, the blue backpack marks the tiny swale which is the end of this branch of the Finke River. Person for scale. Bottom, down-gradient of the swale, the swamp is grassy and cut by many small erosional swales.

Modern Channel: Waterhole and Swamp

The deepest part of the main Finke Floodout is hard up against the gibber plain (Figs. 22, 29). It hosts a long channel segment which begins near the Coglin Creek floodout and finishes 4.3 km southwest of (upvalley of) the choke. At the location visited, the channel is a waterhole: its dimensions are quite substantial (3- 4 m deep, 15-25 m wide), with indications of long-term water retention (puggy clay channel bed, heavily trampled by cattle). The bottom half of the steep banks have little to no vegetation; understory including clumps of lignum occur from ~halfway up the bank. The bank lip is a flat intersection between channel and floodplain: no levee was observed. The banks themselves can be steeply sloping, or have several levels. Bank-attached bars are present, usually as shadow bars behind large woody debris. The channel shows evidence of both erosion (multi-level banks, large woody debris which looks like undermined trees) and deposition (bars, partially-buried tree trunks).

Fig. 28 The most active present-day splay channel (location, # 3 Fig. 25).

Top, looking diagonally across the channel; white dotted line shows channel and banks surfaces. Bottom, the down-gradient floodplain is flat, with well-spaced tree cover.

The area is biologically very rich. Lignum grows along the banks and in the flanking swamps. Trees cluster thickly along the lip of the channel, forming a densely-vegetated riparian zone. The vegetation includes dense understory, abundant coolabah, and lines of very large gum trees (in which bird nests were seen, see front cover of this report). Google Earth images suggest a number of stock pads converge on this waterhole. Stock use the bank-attached bars as diagonal pathways, making a less steep approach to the channel bed than would be provided by the steep banks.

Fig. 29 The waterhole in the deepest part of the main Finke Floodout's swamp.

Top, Google Earth image shows dark colour of dense vegetation, and a dark double line which is the waterhole hard up against the orange gibber hills. Black scale line is ½ km. Bottom left, the bed and steep banks of the waterhole; 1 m scale. Bottom right, the densely vegetated swamp surrounding the waterhole; 1 m scale.

Other Channels

Viewed in a detailed image, the floodplains and swamps of the main Finke Floodout display a complexity that arises from a long history of episodic flows and sediment deposition. Present-day channel segments which are isolated from the main channels are most likely to be flood runners that are activated during large flow events. Palaeochannels are also visible, including the pale traces of sandy channels and the very dark shapes of partially-infilled swamp channels. The overprinting by longitudinal dunes provides a rule-of-thumb time line.

In the broader Finke Floodout Complex, there are other channels which are not described in this report. The distributary Snake Creek becomes channelised at Mayfield Swamp, and the channel extends into the Simpson Desert dunefield. The main flow path of the Finke River becomes re-channelised just down-gradient of the choke; the confinement of the channel by the longitudinal dunes is likely to be a factor in keeping flows sufficiently narrow and deep to maintain a channel. The channel carries remobilised bedload (Fig. 30) but the banks are composed of much more silty sediment, and are dominated by erosive landforms. Abminga Creek, the Witjira Hills and the distal parts of the floodout complex all have various channelled and unchannelled reaches.

Fig. 30 Channel beds of the Finke Floodout Complex.

Top left, flat silty sands of the channel tract splays. Top right, trampled mud of the bank and bed of the swamp’s biggest waterhole. Bottom, flat sands of the reformed channel are remobilised old alluvium.

2.3.4 Description: Sediments, Depositional Bedforms, Vegetation

In the Finke Floodout, the range and distribution of sediments reflects provenance from three sources: swelling clays from outcrop of Eromanga Basin rocks, pale sands and orange silt from the Finke River, and orange dunefield sands.

Where channels were visible on Google Earth as a pale broad ribbon, the channel sediment was the Finke River's typical sandy bedload, although in comparison to the mid-Finke the grain population contained a greater proportion of grains from the dunefields, and a greater proportion of fine sand and silt. In the channel tract and the isolated channel segments, no depositional bedforms were observed: the area was heavily trampled by stock (Fig. 30). In the reformed channel down-gradient of the choke, the channel sands were lower flow regime flat bedding. Where the channel (a waterhole) was set within a swamp, the channel sediment was heavily trampled slaking-clay mud, and elevated bank-attached bars of silty fine and medium sand.

The floodplain around the channel tract channels carries deposits of loose slightly silty sand. There is a fairly continuous cover of low grasses, with coolabah scrub in swampy areas, and living trees with trunks buried up to 1.3 m were observed. The floodplain around the reformed channel is red-brown silt and fine sand; a narrow riparian zone is heavily vegetated by trees and understory. Around the swamp waterhole, the floodplain sediment is crumbly slaking clay in crumb-sized mud aggregates. The riparian zone is heavily vegetated by large trees and understory, and the adjoining floodplain carries widely spaced, smaller coolabah with occasional bare patches.

In mixed dune-alluvial areas the grain population is mixed. Densely vegetated with acacia scrub, and usually heavily trampled, few depositional bedforms were visible. An exception is hummocks created by vegetation trapping aeolian sediment; the hummocks remain after vegetation dies, creating small-scale topographic irregularity. Hummocks were also present in some dunefield areas.

The Coglin Creek floodout and some Mayfield Swamp interdunes have silty clay gilgai soils, showing crabholes, cracks, slaking mud aggregates, and Queensland bluebush vegetation. The muds (and the absence of sand) indicate provenance from Eromanga Basin outcrop or subcrop. The Witjira Hills and distal parts of the Finke Floodout Complex will also have floodplains containing swelling clays. Gilgai soils retain water and are biologically productive, and it is probable that these areas will have slightly different ecosystems than the sandy parts of the floodout.

2.3.5 Processes: Valley-Scale Landforms and Modern Hydrology

The Finke River within the Finke Floodout Complex is an under-fit river: the present-day river is a smaller version of the palaeo-Finke River, which carved its valley during previous wetter climates. The edges and dimensions of the valley are less clear here than they are upstream in the lower Finke or mid-Finke. However, like those upstream areas, this valley will contain sediments from the palaeo-Finke as well as the modern Finke River.

As the palaeo-Finke came down from the central Australian uplands and entered the wide basin which is now the Simpson Desert, it deposited a broad low-angle fan (Fig. 31), similar to the Cooper Creek Fan (see Callan and Bradford 1992 and Wakelin-King 2013). This fan has not previously been described, and is here named the Finke Floodout Fan. From apex to base, the fan is ~56 km long and 36 m in elevation difference. The shallow valleys at the fan's distal edge (black arrows, Fig. 31) are on the order of 5 km wide and 7 m elevation difference between bottom and divide.

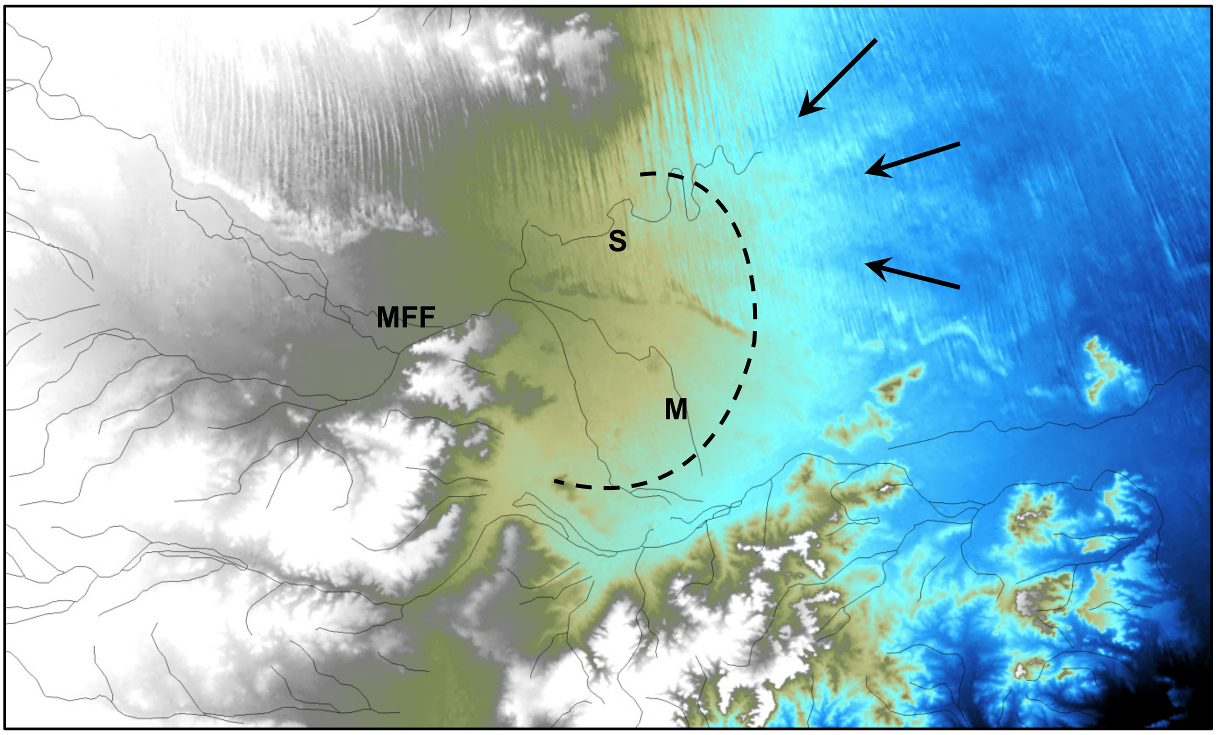


Fig. 31 DEM of the Finke Floodout Fan.

Black dashed line indicates the curved surface of the fan front, black arrows show shallow valleys of previous palaeodrainages. MFF, the main Finke Floodout; S, the Snake Creek distributary; M, the McDills Bore distributary. Geoscience Australia 1-second smoothed SRTM grid, image by Wakelin Associates.

Later development of source-bordering dunes on the fan surface created a "choke" at approximately the location of McDills Bore, near the T-junction where the station track goes west to Charlotte Waters, north to Mayfield Swamp, and south to Mount Dare. At this choke, the water accumulating in the deepest parts of the main Finke Floodout divides. Most goes down the main Finke channel, and some is diverted down distributary flow paths which originated as palaeodrainages on the Finke Floodout Fan. These distributaries are Snake Creek, and a previously un-named waterway which is here named the McDills Bore distributary. The nature of the sills (see Wakelin-King 2013) governing flow of water into these distributaries is not currently known.

2.3.6 Processes: River Behaviour and Habitat

No-Flow Stage

Surface and hyporheic water dries out after the last major flow event. Low-elevation areas will have captured more water, and will stay wetter for longer, so will support more vegetation. Some low-elevation areas have also accumulated clayey vertic soils, and on that account also will retain water for longer, and will support more vegetation. The slightly elevated and sandy remnants of longitudinal dunes will be earliest to dry out, and their ecosystems will not be so rich.

Low-Flow Stage: Local Convective Thunderstorms

Where high-intensity rainfall occurs over the gibber plain, local runoff may replenish surface water and groundwater supplies for the nearby ecosystems. The distribution of dense vegetation around the margins of the Dalhousie Anticline indicates that these flows can be important for local ecosystems, especially in the more distal reaches. High-intensity rainfall over a high-runoff surface (such as gibber, or weathered regolith) can produce local highly erosive flows, carving gullies into the floodout surface and locally redistributing sediment. Near gibber plain edges, local ecosystems will also be supported by water-retaining clayey soils eroded from the scarps. In contrast, high-intensity thunderstorms over the Coglin Creek catchment may deliver a relatively large volume of water with almost no sediment, playing a role in keeping the southern part of the main Finke Floodout deep (thus, supporting rich swamp ecologies) and maintaining the waterhole.

Low-Flow Stage: Gentle Rain in the Upper Catchment

Small flow events in the mid- and lower Finke River are unlikely to reach the Finke Floodout Complex.

High-Flow Stage

Large flows coming down the Finke River will promote channel mobility and anabranch development in the channel tract. In-channel sediment deposition of sandy bedload will take place as transmission loss occurs. Flows which are large enough to reach the splays at the distal end of the channel tract will deliver sands and silt on to some floodplains, and water into some swamps. Channel mobility and the development of new splays are also likely to occur. The distribution of water and sediment, and the development of new splay channels, is likely to be stochastic, responding in a chaotic fashion to local conditions.

In very high flows, the main Finke Floodout may fill to a sufficient depth that the Mayfield Swamp becomes activated, and flows go down the distributaries as well as the reformed Finke River channel. In the reformed Finke channel, the banks are likely to be regularly overtopped and subject to erosive flows. Banks may be sculpted and in-channel sand transport take place (probably as lower flow regime 2D dunes). The reformed Finke channel is constrained by the flanking longitudinal dunes: channel mobility is minimised, and the overbank waters are retained to create a narrow but productive riparian zone.

Very High to Extreme Flows

The higher the flow, the more likely it is that water will penetrate to the very end of the Finke Floodout Complex. Relatively large amounts of sandy bedload may be brought into the main floodout area and deposited there. There are indications that high flows may extend into the Simpson Desert dunefield in distributaries other than those described here. This remains to be investigated. It is theoretically possible that the Finke Floodout Complex could link with the Dalhousie Springs outflow, and from there to the Macumba River. However, present indications are that this has not happened since the development of the Simpson Desert dunefield.

3 Geomorphology: Arckaringa Creek

Arckaringa Creek is part of the Neales River catchment, which lies within the focus area underlain by the Arckaringa Basin (Fig. 5). Some of the potential coal deposits are directly beneath Arckaringa Creek or its catchment slopes. A popular tourist landmark, the *Painted Desert*, also occurs directly above one of the potential coal deposits, as does the Arckaringa homestead and a portion of the Oodnadatta Track (Fig. 32).

Arckaringa Creek has two main upstream tributaries: Henrietta and Oongudinna Creeks. Arckaringa Creek and Lora Creek are tributaries of Peake Creek which cuts through the Peake-Denison Ranges at Peake Gap and joins the Neales River (Fig. 33). From there, the Neales River empties into the northwestern side of Kati Thanda-Lake Eyre. In the present report, comparisons are drawn between Arckaringa Creek and that portion of the Neales River which is upstream from the Peake-Neales confluence. Where this report refers to the Neales catchment, it refers to the entire Peake + Neales catchment area.

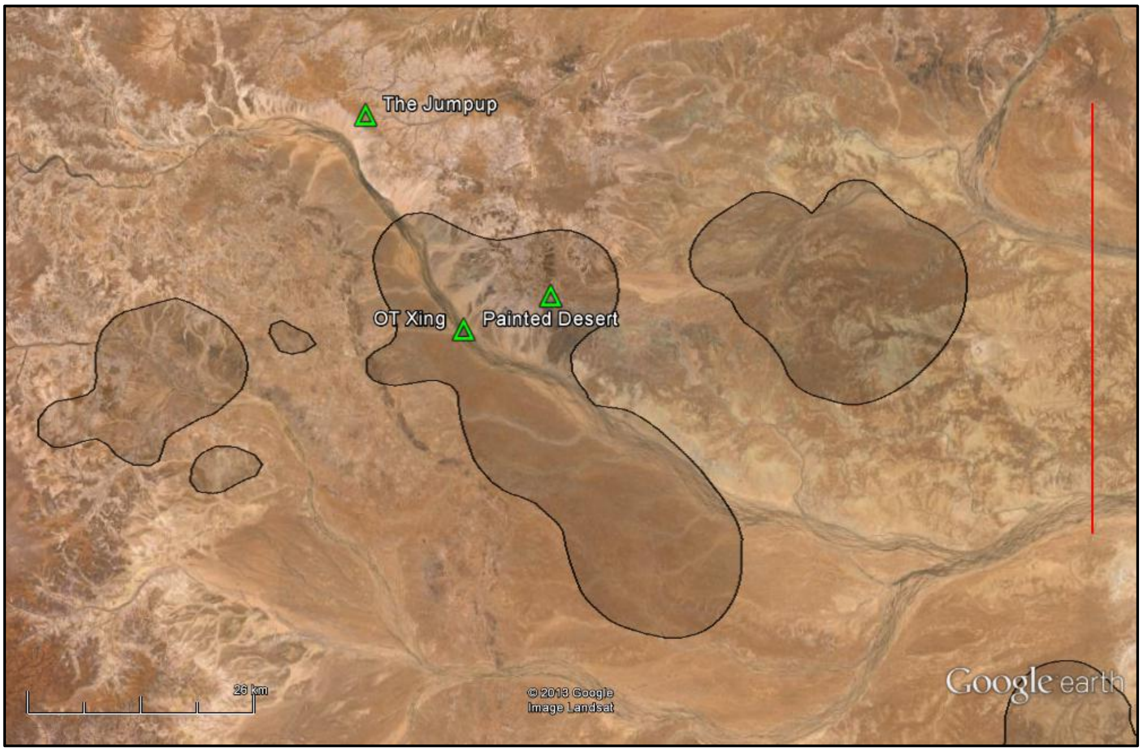


Fig. 32 Arckaringa Creek and its underlying coal occurrences.

Google Earth image of the medial reaches of Arckaringa Creek, and the footprint of known underlying coal occurrences (black outlines). Three landmarks are shown as green triangles: The Jump-Up, the Painted Desert, and where the Oodnadatta Track crosses Arckaringa Creek ("OT Xing"), close to Arckaringa homestead. Red scale bar = 50 km.

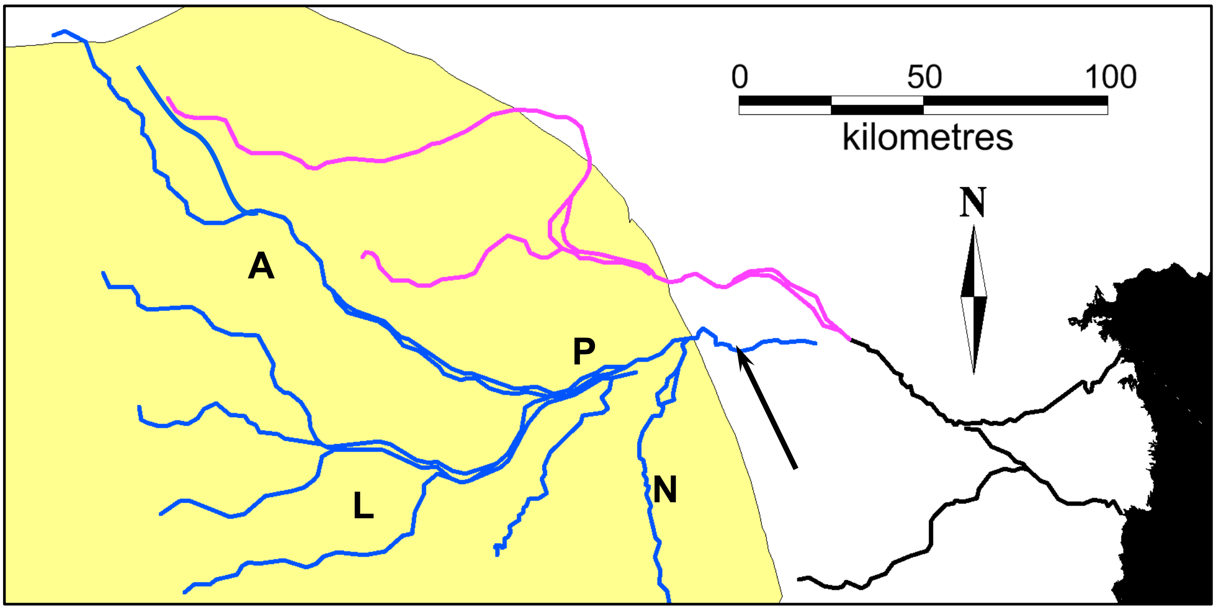


Fig. 33 The Neales catchment creeks and the Arckaringa geological Basin.

The major drainage lines of the Neales catchment: pink, the Neales River; blue, Arckaringa Creek (A), its tributary Lora Creek (L), and downvalley of the Arckaringa-Lora confluence, Peake Creek (P) and Nilpinna Creek (N); black lines, the Neales River downvalley from its confluence with Peake Creek. The underlying Arckaringa Basin is yellow. Arrow points to Peake Gap, where the Peake River flows through the Peake/Denison Ranges; Kati Thanda-Lake Eyre (black shape) is in the south-eastern corner.

Surprisingly, though part of the same catchment, Arckaringa Creek's fluvial style is significantly different from that of the Neales River. Arckaringa Creek has very few ecologically significant waterholes (only a few were sufficiently deep and permanent to be worth sampling for fish monitoring: David Schmarr, pers. comm. 2014). The geological and topographic differences which create this contrast dominate this report. From Peake Gap down to where it joins the Neales River, the fluvial style of Arckaringa Creek is similar to that of the Neales River, which is described in Wakelin-King (2010).

3.1 Description: Valley Setting

The Neales catchment is in a broadly erosional context. The upstream edges are in the western uplands, whereas the river's base level is the subsiding Kati Thanda-Lake Eyre depocentre in the south-east; rejuvenation is promoting headwards drainage extension and valley deepening, and there is concomitant valley widening. Beyond the western uplands, the red earth soils of the Great Victoria Desert support mulga grove communities in channel-less drainage networks. For the purposes of this report, it is useful to envisage the red earth soils and their underlying regolith as an old land surface. The Neales catchment proximal streams are eroding into the western uplands, and extending headwards into the basin of the Great

Victoria Desert (Fig. 34). As they do so, they thin and remove the old land surface: strip off the red earth soils, and then expose, erode, and transport away the underlying silcretes, duricrusts, and highly weathered rocks and sediments.

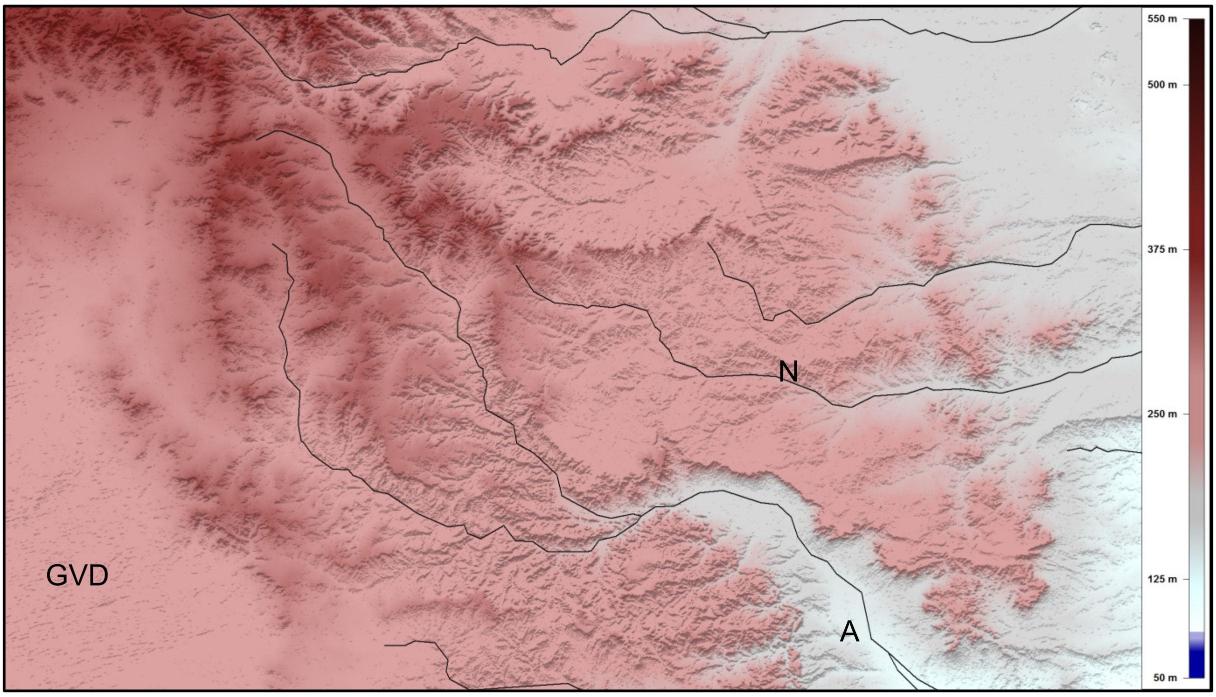


Fig. 34 At the Lake Eyre Basin's western edge, rivers are eroding into the uplands.

A, Arckaringa Creek; N, the north and south branches of the Neales River; GVD, the Great Victoria Desert (note the lack of mapped drainage). Colour-elevation legend on right: dark red (highest) to pale grey (lowest). The dark to pale red approximates the old surface's red soils and their underlying duricrusts.

Arckaringa Creek therefore is in a confined valley setting for almost its entire length. From its most proximal channels through to the confluence with Nilpinna Creek (Fig. 33), the creek is flanked by heavily-weathered bedrock, which is often accompanied by silcrete. Hillslope vegetation is scant to absent. In the lower-order creeks, such as in the Painted Desert, the landscape is actively eroding and there is direct hillslope-channel connectivity (Fig. 35). In the main branch of Arckaringa Creek, the north-eastern slope is a relatively steep scarp leading to elevated silcrete cliffs (most spectacularly at The Jump-Up, Fig. 36), and there is direct hillslope-channel connectivity. Here, the large deep valley of Arckaringa Creek is juxtaposed against the shallow, elevated valley of the south branch of the Neales River (Fig. 36). On the south-western side, the main branch of Arckaringa Creek is buffered from the hillslopes by a broad gibber plain bordered by a linear band of hills (the Mirackina Conglomerate). Small gullies arising from lower-order creeks west of the linear hills feed into the main Arckaringa Creek.

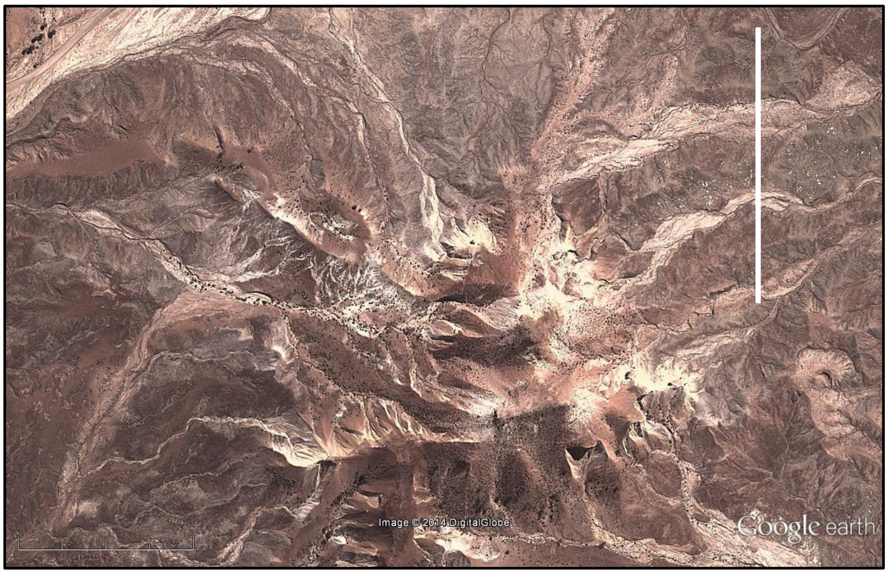
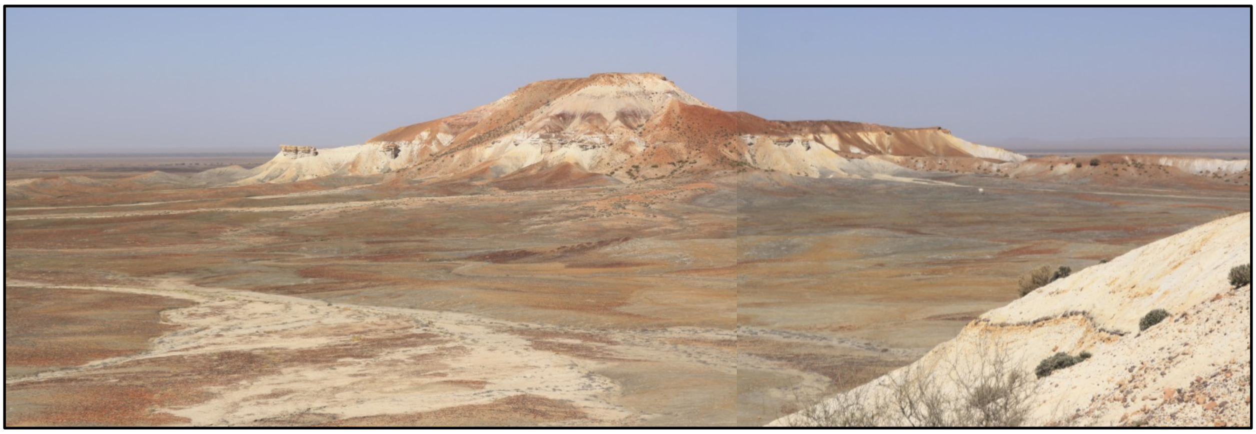


Fig. 35 Small creeks and gullies in the Painted Desert are cutting directly into weathered bedrock.

Top, Google Earth image, 3 km white scale bar; bottom, photo taken from a distance of 700 m; the hill is ~20 m high on the side facing the camera.



On a local scale, some reaches have channels which are semi-confined or unconfined (flanked on one or both sides by alluvium). These reaches do not reflect a continuous, well-developed alluvial system. Rather, the irregular valley topography and the transport-limited nature of the system means there are some places where a shallow layer of sediments accumulates as valley fill. In such places, the floodplain becomes locally wide. The most notable examples are near Francis Camp Waterhole, and at the confluence with Nilpinna Creek (see Fig. 33).

A significant factor for the geomorphology of the Neales catchment rivers, and for the distribution of refuge waterholes, is that the Neales River (upvalley of its confluence with Peake Creek) and Arckaringa Creek experience different facets of the local geology. The proximal Neales River has a shallow dendritic drainage network extending widely but for a relatively short distance over erosion-resistant silcrete and gibber plain. Arckaringa Creek has a much longer drainage network (Fig. 34) which is incised through the silcrete and deep into the soft weathering profile. (A more detailed discussion of the links between topography and drainage network development in the upper Neales River and Arckaringa Creek can be found in Wakelin-King (2010), Technical Appendix section A2.1.2, *Tectonic History Creates the River Network*.)

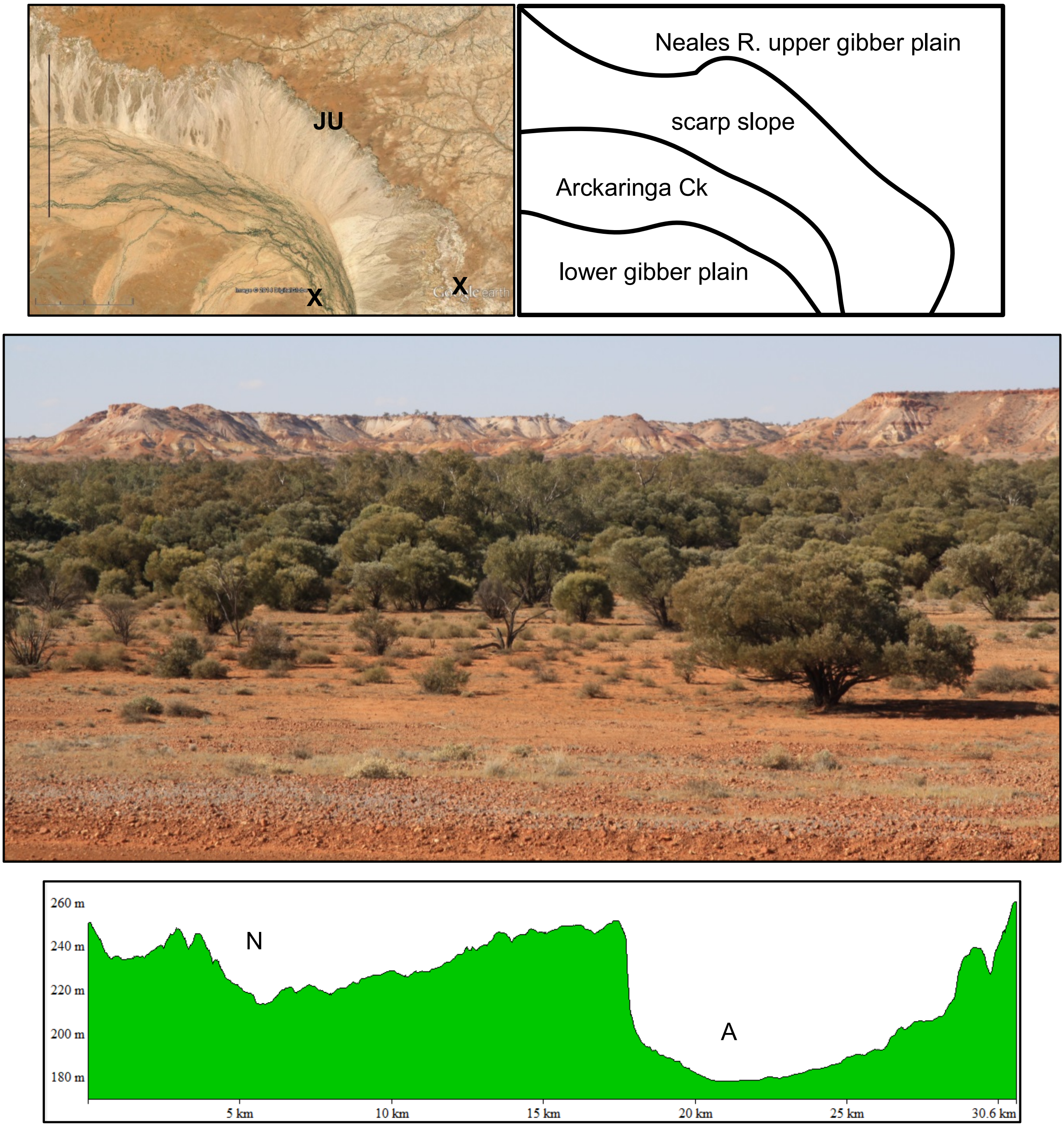


Fig. 36 The Jump-Up.

At The Jump-Up, the edge of the Neales River's sub-catchment is ~70 m above the floodplain of Arckaringa Creek. Top left, Google Earth image, 3 km black scale bar, north to top, JU is The Jump-Up's most prominent scarp. Dendritic drainage etched into the gibber plain shows in the northeast corner. Top right, sketch map of same image. Centre, looking across Arckaringa Creek to the scarp and edge of the upper gibber plain, taken from the lower gibber plain (at the edge of the Arckaringa Creek floodplain) at a distance of 4.5km. Xs on the Google Earth image indicate camera location (western X) and photo target (eastern X). Bottom, cross-valley profile at The Jump-Up of the Neales South Branch (N) and Arckaringa Creek (A).

3.2 Description: Valley-Scale Landforms

The valley-scale landforms of Arckaringa Creek are:

- fluvial-margin runoff slopes
- floodplain and channels,
- gilgai swamps.

Fluvial Margin: Runoff Slopes

Within the Neales catchment as a whole, one of the most common hillslope types is low-relief gibber plain etched by dendritic drainage (Wakelin-King 2010). The shallow dendritic drainage network extends widely but for a relatively short distance over erosion-resistant silcrete and gibber plain. This type of surface is likely to exhibit only moderate runoff quality, especially where underlying swelling clays interact with the gibber to form stony gilgai (likely to exhibit only moderate runoff qualities because of its rough heaved surface with water-retention depressions centred around macropores). The gibber hillslopes are associated with shallow valleys in which drainage line extension happens very slowly and in all directions. This hillslope is characteristic of the proximal Neales River. It occurs also around Arckaringa Creek's catchment margins, though the present study suggests that the Arckaringa Creek catchment has fewer and less well-developed gilgai (Fig. 37) than the proximal Neales catchment.

A less common hillslope type is more characteristic of Arckaringa Creek: scarp faces of strongly-weathered Eromanga Basin rocks are usually very poorly vegetated, are of relatively high gradient, display a high density of low-order channels, and often have a high degree of hillslope-channel connectivity (e.g. the Painted Desert, the main axis of Arckaringa Creek; Figs. 35, 37). These surfaces will have high to very high runoff coefficients. That is, they will generate more rapid runoff and transmit a greater proportion of rainfall than other types of hillslopes. They are associated with deeply incised valleys (Fig. 36) demonstrating relatively rapid headwards extension.

Other high-runoff surfaces in the Arckaringa catchment are duricrusts, and rocky outcrops of Tertiary-aged sedimentary rocks. Other hillslopes flanking Arckaringa Creek and Lora Creek are gibber plains, or eroded regolith hills with more or less gibber cover; their runoff qualities are not clear.

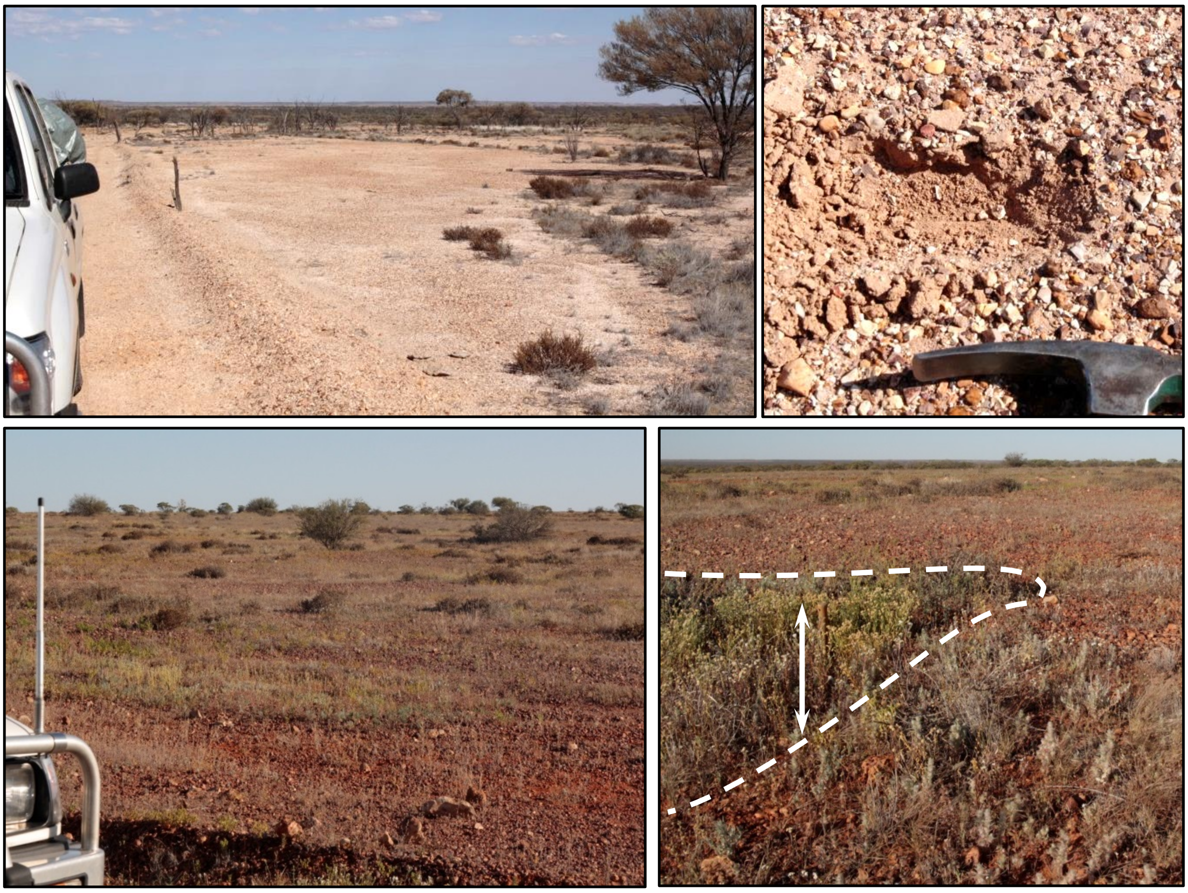


Fig. 37 Runoff surfaces in the Arckaringa Creek catchment.

Top left, a high-runoff surface near The Jump-Up is largely unvegetated, except in shallow drainage lines; vehicle for scale. Top right, the silty surface sediment is covered by a dense scatter of angular small fragments of weathered rock; geopick for scale. Bottom left, gibber-plain uplands with poorly-developed stony gilgai will have a lower runoff coefficient than the surface shown in the top left; vehicle for scale. Bottom right, a wide shallow gilgai depression (enclosed in white dashed line) hosts more vegetation than the surrounding gibber; upright hammer (white arrow) handle indicates depth of the depression.

Floodplain and Channels

The lower-order reaches of Arckaringa Creek are gullies and erosion channels incising directly into regolith; see *Runoff Slopes* above. In mid- and higher-order reaches, multithread channels are set within only small amounts of floodplain.

On Google Earth images, the channels and floodplains are a single entity visible as a continuous belt of vegetation and sediment, forming the main drainage axis of the creek. The gully networks which dissect the regolith plains are tributaries into the main drainage axis, often joining at a high angle (Fig. 38, and see Figs. 33, 36). Unlike the Finke River, there are no old channels.

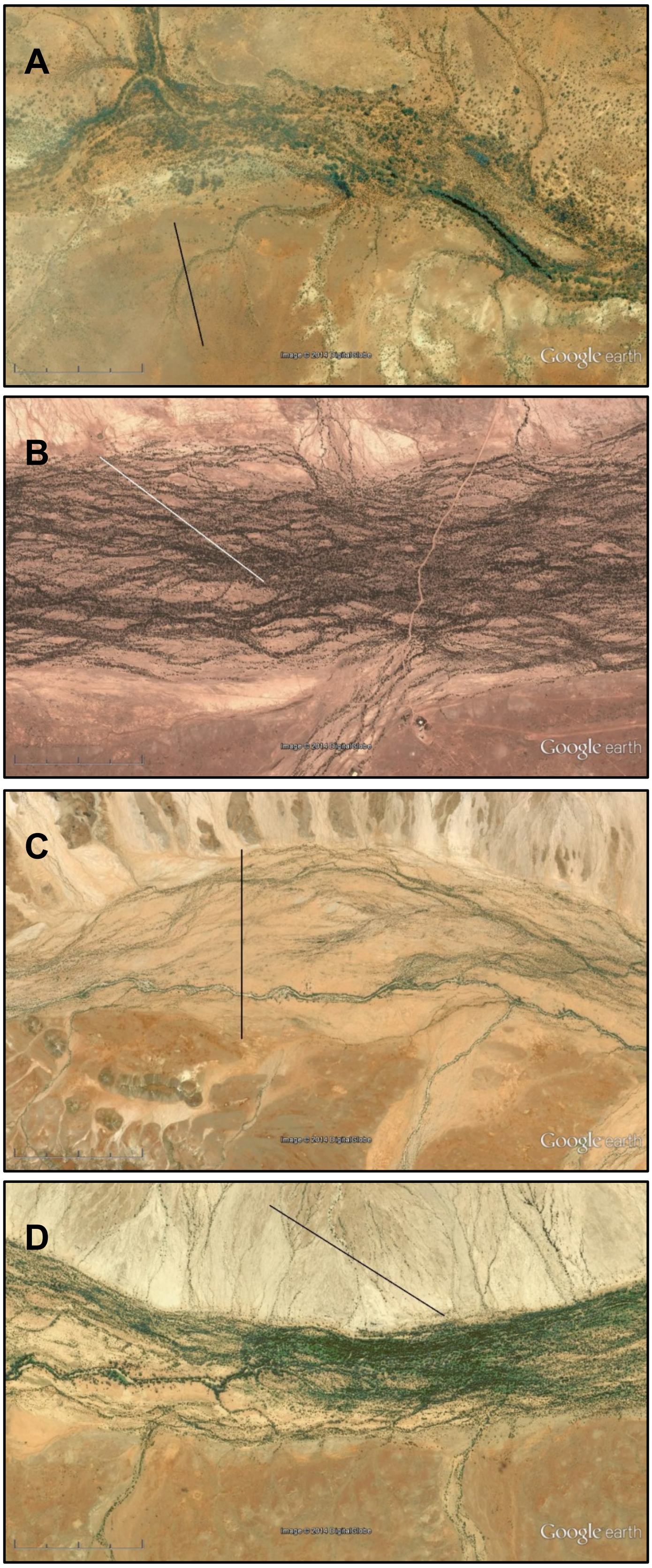


Fig. 38 Vegetation marks the channels of Arckaringa Creek.

A, channel segments and waterholes 4.5 km upstream from Wintinna homestead; black scale bar = 0.5 km. B, at the Oodnadatta Track crossing, near Arckaringa homestead, anastomosing channels fill the entire floodplain; white scale bar = 1.5 km. C, near Francis Camp Waterhole the floodplain is wide and largely unvegetated; two larger channels anabranch; black scale bar = 3 km. D, in a narrow floodplain neck 20 km north-west of the Arckaringa homestead, channels cluster and form a densely vegetated combined flow path; black scale bar = 1.5 km. In all these Google Earth images, the scale bar is oriented north-south.

Gilgai Swamps

Arckaringa Creek, like the Finke River, is associated with gilgai swamps, which are wide shallow depressions in hillslopes marginal to the fluvial system. They are often more densely vegetated than nearby landforms, usually with water-loving vegetation (e.g. Queensland bluebush). They contain crumbly grey soils in a reticulate drainage pattern which is often somewhat rectangular (Fig. 39). In Google Earth images, the pattern is distinctive. In the field the drainage network is found to be an expression of deep gilgai cracking. These gilgai swamps are associated with local geology in which the duricrusts overlying Eromanga Basin rocks are thinned or removed. Though not falling within the scope of the present study, they are mentioned here because they are likely to be locally important wetlands, and to provide information on landscape evolution in the Lake Eyre Basin.

Fig. 39 Wintinna Swamp.

Shallow basins set within the red earths along the western catchment boundary, these gilgai swamps show pale grey sediments with an internally-draining reticulate channel pattern. The small lake on the north-western swamp is an artificial dam. North is to top left; white scale bar = 3 km.

3.3 Description: Reach-Scale Geomorphology

Anastomosing Channels

In some reaches, multiple channels of approximately equal scale form an anastomosing network (Figs. 38B, 41). The closeness of the channels and the degree to which floodplain is visible beneath them is variable, approximately according to the width of the available floodplain (Fig. 38).

In anastomosing reaches, the floodplain is heavily vegetated with Acacia scrub (probably gidgea), with coolabah where channel segments are particularly large or stable. The coolabah are visible from a distance because their canopies are several metres higher than the gidgea (Fig. 40). The floodplain surface is swaley, with hummocks of fine sediments accumulating as shadow bars (Fig. 41). Trains of Acacia grow in long linear hummocks and these streamwise features are visible in Google Earth images.

Fig. 40 A locally wide floodplain near Francis Camp Waterhole.

The floodplain is flat hard silt, with thin scatters of fine gravel. In the distance, coolabahs or gumtrees rise above the more common Acacia scrub. Vehicle for scale.

The channels are cut into the floodplain; they are fairly simple and boxy in cross-section, and on a scale of 0.5-2 m deep and 1-5 m wide. Banks are irregular and sculpted, and tree roots and trunks show both erosion and burial. There were no observed abandoned channels – all presently existing channels appear to be active transmitters of flow at some height. In a number of places lines of coolabah trees exist independently of the present-day major channels. The relatively small scale of the channels and floodplains (c.f. the amount of sediment under transport), in combination with the other signs of active erosion and sediment deposition indicate that channels relocate frequently, and that abandoned channels are rapidly buried.

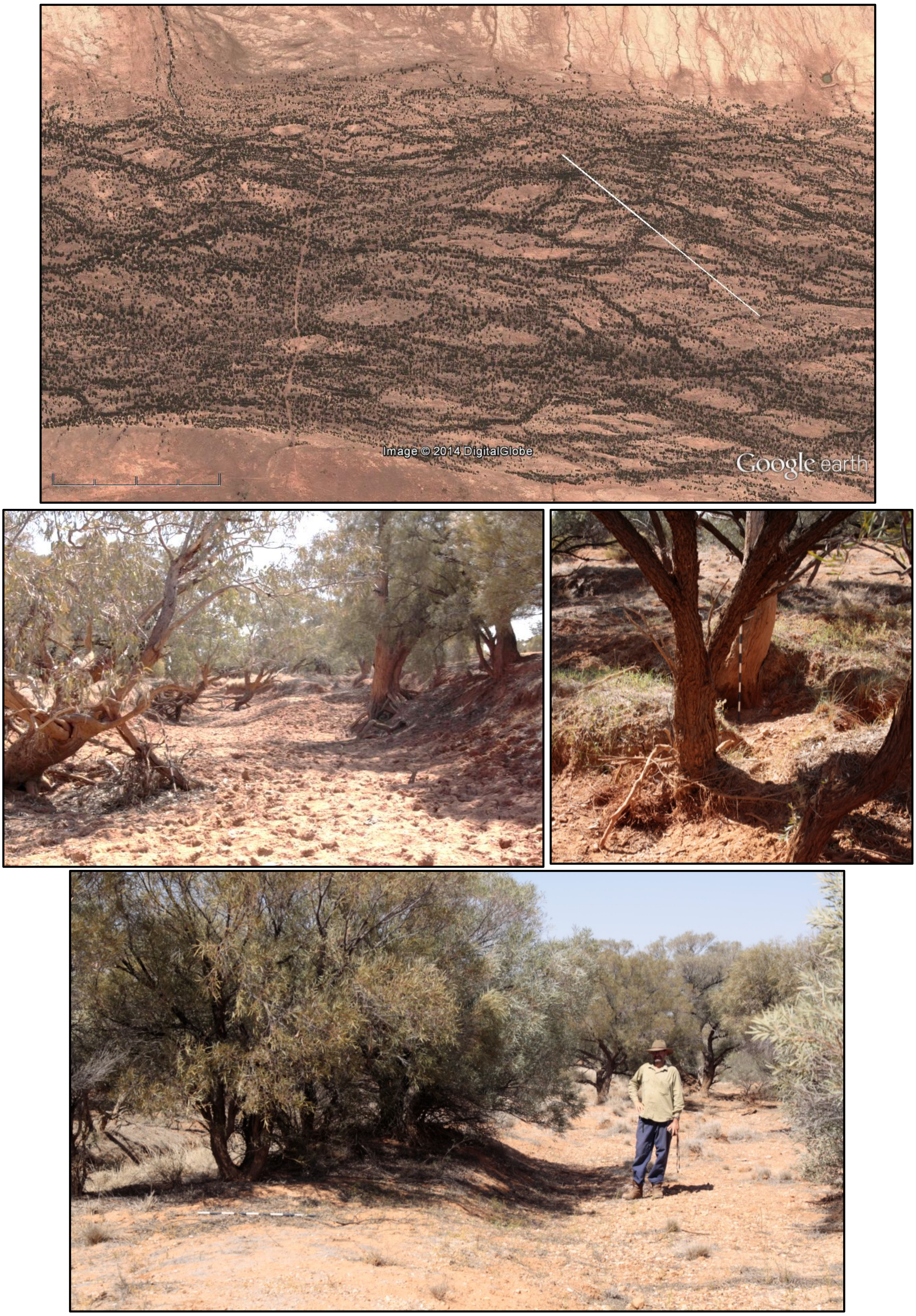


Fig. 41 Anastomosing channels in the main axis of Arckaringa Creek.

Top, Google Earth image, the channel belt occupies the entire floodplain. A small track crosses at mid-left. North to top left, white scale bar = 1 km. Middle, the irregular banks show both erosion (left, tree roots) and burial (right). Bottom, a swaley heavily vegetated floodplain; the Acacias grow in lines or trains, rooted in long hummocks of fine sediments, person for scale.

Channels and Anabranching Channels in Wider Floodplains

In reaches with wider floodplain (such as near Francis Camp Waterhole), in lower-order reaches (such as the Arckaringa's two main tributaries), and in many reaches of Lora Creek, there is a dominant channel, visible on Google Earth images as a double line of riparian trees (Fig. 42). In some reaches the floodplain also supports a few subsidiary anabranching

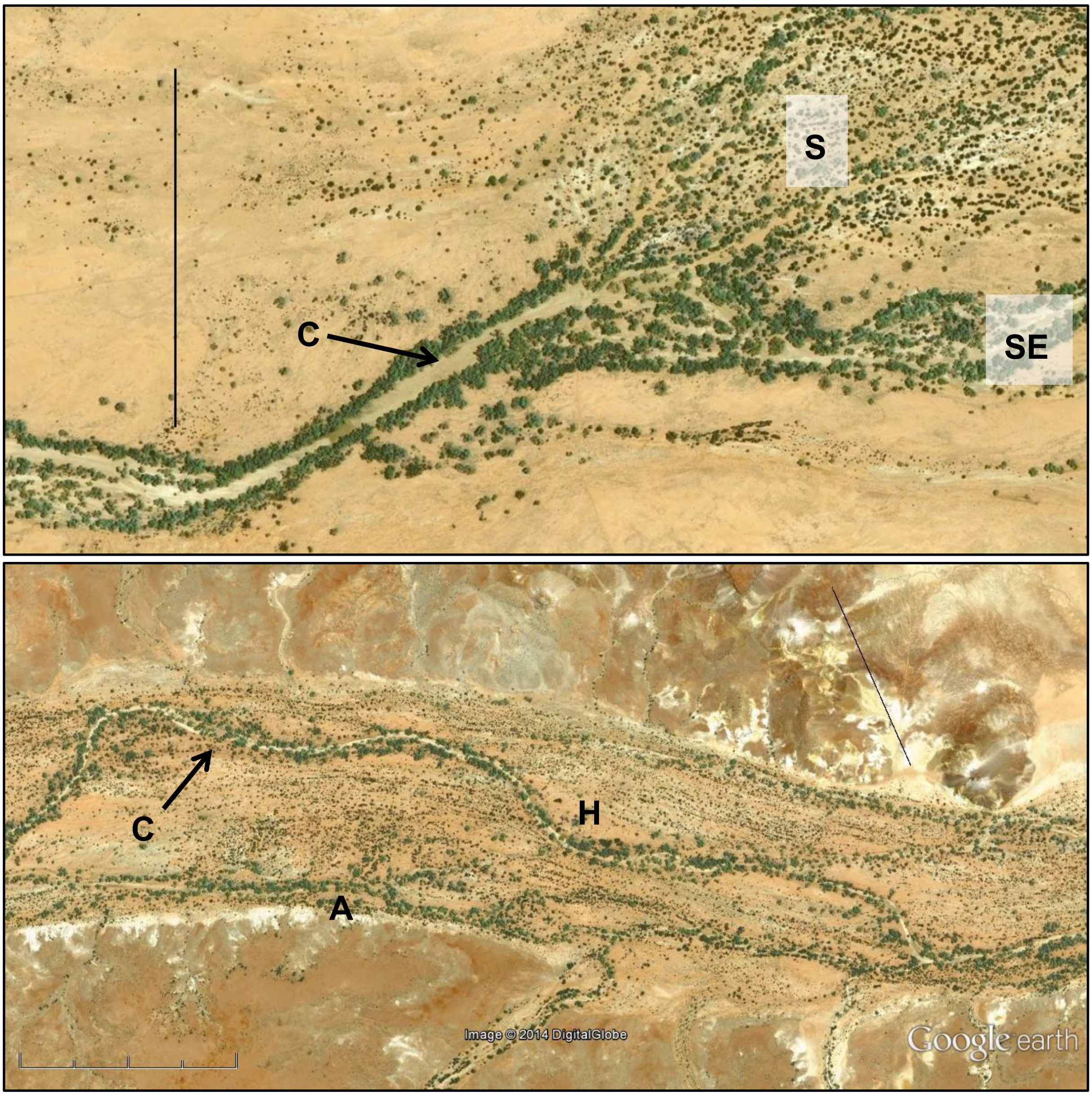


Fig. 42 Anabranching channels in Arckaringa and Lora Creeks.

Top, at Francis Camp Waterhole on Arckaringa Creek's main axis, the channel displays typical waterhole form. C, main channel; S, splay; SE, a splay extended into a channel in its own right; black scale bar = 0.5 km. Bottom, in Lora Creek (30 km west-southwest from Arckaringa homestead) there is a continuous main channel (C), a more or less discontinuous anabranching channel (A), and the floodplain displays streamwise vegetated hummock trains (H). North-south black scale bar = 0.5 km, asterisk is location for photos in Fig. 45.

channels (Fig. 38C). Frequent above-floodplain flow occupying most or all of the floodplain is indicated in most reaches by floodplain landforms e.g. flood runners (Fig. 38C), or floodplain shrubs and small trees which are oriented in streamwise lines (Fig. 42). Although it was beyond the scope of the present study to ground-truth the nature of this floodplain vegetation, Google Earth images correspond exactly to similar reaches on the south branch of the Neales River (Wakelin-King 2010, Fig. 7). In these areas, above-floodplain flows deposit silt behind floodplain vegetation in hummocky shadow bars which coalesce into shrub-crowned small ridges (Wakelin-King 2010, pp12-16 and 74-76). It is most likely therefore that the anabranching reaches of Arckaringa and Lora Creeks also display these hummock trains, and this is consistent with sediments deposited across the anastomosing reaches (Fig. 41).

Remote study of reaches with anabranching channels and continuous main channels suggests that many of their features correspond to similar channels on the Neales River (see Wakelin-King 2010). These include the sometimes discontinuous nature of the channel, the scales of channel and floodplain, and the way some channel segments are wider and apparently deeper than others nearby. It is likely therefore that some on-ground features will also be similar, such as riparian ridges, or the wide, shallow primary flow paths that link channelised segments. It was not within the scope of this project to ground-truth these features. The Arckaringa/Lora and the Neales anabranching reaches also differ in some aspects, notably the variability of floodplain and channel sediment colour in Arckaringa and Lora Creeks, which suggests variations in grainsize or mineralogy arising from differences in provenance.

Wider reaches of the Peake River (downvalley of the Arckaringa/Lora confluence) show the floodplain consisting of lobes of sediment (Wakelin-King 2010, Fig. A1.12), indicating single-flood pulses of sediments, deposited in accumulation zones where valley widening decreases stream power.

Waterholes

The most significant way in which the Arckaringa Creek anabranching channels are similar to, and different from, the Neales River is in the waterholes. Some Arckaringa and Lora Creek reaches host waterhole-like channel segments: channel segments which are wider than the same channel's dimensions immediately upstream (Figs. 38A, 42), with prominent but narrow belts of riparian vegetation, and a downvalley termination splay or expansion bar, in which the main waterhole-like channel becomes distributary. The splay channels either lose definition and segue into an unchannelled above-floodplain flow path, or coalesce into another channel. These features are all characteristic of waterholes, and are similar to those that can be found in the Neales River (Figs. 6, 12, 13, 14, 16 of Wakelin-King 2010). Some on-ground features are also similar, such as the steep banks crowned by large trees, the reverse slope of the channel bed in the hydraulic jump leading up to the splay, and the splay’s complex of erosional and depositional features which indicate the landform's evolution (Fig. 45). As a local landholder remarked, "looks like it ought to be a . . . good waterhole, but it isn't".

The key difference is that Arckaringa Creek's waterhole-like channel segments are full of coarse bedload. Though the channels probably retain water after flows, most of the available space between banks and the scoured channel base is occupied by sandy conglomerates. These sediments are highly porous, and with post-flow evaporation and evapotranspiration the water level would rapidly sink below the sediment surface.

Arckaringa and Lora Creeks have "waterholes" which retain water long enough to merit being named on topographic maps. However, they are much smaller and less deep than those of the Neales River. There is nothing upstream of the Lora-Arckaringa confluence zone which is sufficiently large to host important fish populations (David Schmarr, pers. comm. 2014). In addition, visual assessment suggests that there are far fewer waterhole-shaped channel segments in Arckaringa and Lora Creeks, in comparison to the Neales River.

Floodouts

The floodplains of Lora Creek host some floodouts, which will be locally important to the terrestrial ecosystems, and/or to productivity of the local grazing industry. It was not within the scope of this study to investigate them.

3.4 Description: Sediments and Depositional Bedforms

With its upper reaches incising into abundant sources of coarse sediment (Figs. 4, 43), Arckaringa Creek channels carry large amounts of very coarse bedload. Most channels are floored by sandy cobble or gravel conglomerate; few were observed to carry anything finer than a pebbly coarse sand. All within-channel gravel and cobbles were observed to be subjected to modern transport: there was no evidence of any exhumed or lag conglomerates. Further, some channels showed evidence of vigorous transport (Fig. 44): high-level valley-margin gravel bars, gravel and cobbles in 2D dunes, hydraulic jumps, and places where sheets of coarse bedload were swept out of the channel and up over the floodplain. Additionally, there were no observations of cluster bedforms (created under low-energy conditions in which flow is strong enough to move cobbles, but not transport it).

Fig. 43 Silcrete.

In-situ silcrete breaks into pebbles and cobbles; lens cap for scale.

The coarse bedload is almost entirely quartzose (silcrete, or quartz-rich lithics), so it will resist breaking down into smaller particles. Bedload of this sort is a very powerful agent of erosion, and has probably contributed to Arckaringa Creek's greater degree of incision (in comparison to the Neales River).

Finer grain sizes and lower-energy bedforms are also present in some channels. In some lower-order channels sand was the dominant grainsize, although it more commonly occurred as shadow bars behind in-channel trees, or stringers on floodplain-level minor channels. Other bedforms included bank-attached bars, and waning-flow poorly-defined 2D dunes or semi-planar beds. Channel sediments were frequently trampled by stock, obscuring the less prominent bedforms.

Finer sediments are also transported through and deposited within the system. Silts and fine sands are deposited across riparian zones and floodplains, especially in the main axis of Arckaringa Creek where there is some width in the valley to accommodate shallow floodplain deposits. Fine sediments tend to be red-brown if downvalley from dissected red earth plains (e.g. Fig. 44), and buff to pale orange if downslope from scarp faces (e.g. near The Jump-Up, Fig. 37). In anastomosing reaches, where the floodplain is narrow and channels are close together, the fine sediments tend to be loose, consistent with deposition from suspension as overbank flows encounter dense vegetation. In those reaches where the floodplain is broader and the channels more widely separated (e.g. near Francis Camp Waterhole, see below), floodplain sediments are characterised by a hard very flat surface and a thin scattering of coarser clasts (Fig. 40), consistent with deposition from shallow sheetflow.

Arckaringa Creek's coarse and abundant sediment load is substantially different from that of the Neales River (upstream from the Neales-Peake confluence), which transports only a little fine sediment (no bedload).

Fig. 44 A channel 4.5 km west of Wintinna homestead.

The photo is taken standing on the elevated bed immediately downstream of a hydraulic jump, looking upstream. The channel is floored by sandy and gravelly cobble conglomerate. The bottom section of the 1 m scale (white dashed arc) is concealed in the deepest part of the hydraulic jump's scour. Banks indicate erosion and channel widening (exposed riparian tree roots) but also deposition of overbank silts.

3.5 Processes: Valley-Scale Landforms and Modern Hydrology

The Neales catchment’s range of fluvial styles and bedload grain sizes suggests that the runoff coefficients of the various surfaces are sufficiently different to affect fluvial processes and therefore ecology. High-runoff surfaces promote a flashy flow regime with greater transport of coarser bedload, whereas lower-runoff stony gilgai surfaces promote a lower-intensity, more sustained flow regime which transports less and smaller sediments (Wakelin-King 2010).

Fig. 45 Reach-scale geomorphology at Francis Camp Waterhole.

Top, looking upstream, coarse bedload, steep well-treed banks, and a gravelly shadow bar behind large woody debris; 1 m scale.

Middle, looking downstream into the splay, the channel has widened and shallowed, and divided into several channels. A line of large gum trees (centre-left to centre) marks the previous location of the waterhole bank. Vehicle and person for scale.

Bottom, at the upstream end of the splay, 90° bends in large riparian tree roots indicate that previously the tree stood adjacent to a long-term incised channel on a stable floodplain or bank which is now eroded away. Person for scale.

Arckaringa Creek's high-runoff surfaces are likely to be a key determinant in its fluvial style, and one of the reasons it differs from the proximal and mid-reaches of the Neales River. The main axis of Arckaringa Creek has a very high degree of connectivity between hillslope and channel (since it occurs in a confined valley setting, with little to no floodplain). During intense rainfall (e.g. summer convective thunderstorms), streams downslope from and downvalley from high-runoff surfaces will exhibit flashy creek flow (water levels rise very rapidly to flood peak, and then decline rapidly). Under these conditions, stream competency and capacity can be high but only for brief periods of time (very coarse sediments can be transported for short distances). Rapid erosion at gully heads delivers very coarse sediment to the river, high-energy flow carries the coarse sediment into the channels and downstream through the drainage network, but the short-lived nature of the peak flow strands the coarse sediments in-channel. Pulses of finer sediments can be carried further, but are deposited in lobes or layers where the valley widens. The river is highly transport-limited.

3.6 Processes: River Behaviour and Habitat

This section describes the river behaviour at various flow heights. It should be noted that detailed work on flow conditions and sediment transport of rivers in the Neales catchment remains to be done. The descriptions below are not design parameters for engineering works. Some hypotheses on habitats and ecosystems are proposed, but there has not been scope within this project to engage in cross-discipline discussion with ecologists.

No-Flow Stage

Free surface water will be retained in some channel segments which are relatively large and deep. However, there are few waterholes deep enough to retain water for long, and significant fish populations are unlikely to establish.

The river valleys are the most important terrestrial habitat in the Arckaringa catchment; hillslopes are sparsely vegetated to almost bare. The only non-fluvial habitats with the possibility of productivity are the gilgai swamps, which are mostly small and located along the catchment edges.

Hyporheic water supports riparian and floodplain trees and terrestrial habitat; however, the alluvium, where present, is usually thin. It is likely that subsurface reserves of soil moisture are only available for a short time, in comparison to the Finke River which will have deep groundwater reserves for trees to draw upon. This suggests that in Arckaringa and Lora Creeks, deep-rooted vegetation may not have much of an advantage over shallow rooted vegetation.

Localised high-intensity rainfall from a single convective thunderstorms is likely to play an important role in delivering sediment from the hillslopes into fluvial transport, and promoting scarp retreat and headwards drainage extension. It may deliver flashy floods into the main Arckaringa drainage axis, but is unlikely to generate flow in the main creek channels downvalley of the Arckaringa/Lora confluence.

Low-Flow Stage

Small flows are unlikely to achieve much direct geomorphic activity. In the anabranching reaches, low water levels (where water is confined to channels) will not have enough stream power to entrain and transport the coarse sediments. In the anastomosing reaches, some bank erosion and transport of silty sediments may occur. However, consolidated fine sediments are difficult to entrain, and at low flows some degree of antecedent moisture may be required for bank erosion to occur. In the absence of sediment transport, flowing water is likely to be clear.

Low flows will refresh moisture levels in channels and their adjacent floodplains, supporting terrestrial habitats. This is not only important ecologically, it is an important geomorphological process since floodplain vegetation is a key element in fluvial processes.

Across the Neales catchment, hillslopes of different runoff coefficients will deliver rainfall into the fluvial system with different degrees of speed and intensity. Where high-intensity local rainfall coincides with a flow event, the runoff coefficient of the hillslope that delivers the water to the creek will determine whether the pulse of water is flashy or sustained.

High-Flow Stage

At high flows, channels and floodplains will be inundated, and will be actively transmitting water at fairly high to very high energies. Many parts of Arckaringa and Lora Creeks will experience flashy flow: brief but intense flood peaks, with very rapid build-up towards the peak and very rapid waning flow thereafter. Water will infiltrate into floodplain sediments, benefiting the terrestrial ecosystems.

Sediment transport is episodic, and is likely to occur in two phases: silty sediments transported during most of the flow event, and in-channel bedload transport during the flood peak. It is not clear from this investigation what size of flow event is required to mobilise most of the river's bedload, or the depth to which the bedload will be mobile.

Bedload sediments will mostly travel within channels, but may be swept up onto bars and floodplains in high-energy locations or during local turbulence. Scouring of the channel base by moving bedload is likely to occur in high-energy locations. During waning flow, pulses of bedload are stranded at various points down the drainage axis. Pulses of bedload moving down-channel may alter stream configuration, clearing a channel in one section while filling a valley downstream with gravel (forming a riffle reach).

Fine sand and silt will be transported as suspended load, to be deposited over the floodplain. The two most common mechanisms for fine sediment deposition will be

- in the anastomosing reaches and in riparian zones, deposition as flow is slowed through dense vegetation;
- in reaches with wider floodplains, especially those downslope from valley constrictions, deposition as flow spreads out and becomes shallow. Pulses of stronger flow will transport small pebbles across the floodplain.

The small size and scarcity of "waterholes" in Arckaringa and Lora Creeks is due to the constant bedload transport down the channels. It is hypothesised here that the presence of bedload during flow events dampens turbulence, reducing the likelihood of the macroturbulent scour which is responsible for waterhole formation. Few wide, deep channel segments will be created; where they do occur they will not be as big as those of the Neales River. Most importantly, bedload fills up the channels, so any waterhole-shaped channel segment is unable to maintain space for free water.

In the anastomosing reaches, incision and erosion may create small channels, and a combination of sediment deposition and locally erosive flows is likely to promote channel relocation. Abandoned channels will almost immediately be filled with transported sediments. Sediment levels under transport in the water will probably be variable spatially and temporally on a small scale, as small pulses of sediment released by erosion or avulsion are likely to be trapped by vegetation and redeposited nearby.

Very High to Extreme Flows

At very high to extreme flows (century to multi-century recurrence interval), bedload transport volumes will be very high, and the bedload will be mobilised to a greater depth than in less extreme flows. The channel base is likely to be scoured along a great percentage of its length. Flow strength may be sufficient to generate macroturbulent scour despite the sediment load, initiating new waterhole segments. Channel avulsion may take place in the anabranching reaches. Large-scale changes may occur in the anastomosing reaches, with many channels relocating or being created, and possibly including widespread destruction of the vegetation. Scarp retreat in the higher-order valleys, headwards drainage line extension, and gullying and widening of the lower-ordered valleys are likely to occur.

4 Key Fluvial Processes

This section summarises key fluvial processes. Information presented here is based on the work described in sections 1-3 and in the Technical Appendix.

4.1 Lake Eyre Basin Rivers

Lake Eyre Basin Rivers fall into groups that differ substantially in their gradient, sediment load, landforms, fluvial processes, and therefore habitat. The major groups are the Central Australian rivers (including the Finke River), the western uplands rivers (including the Neales catchment rivers), the Channel Country (e.g. Cooper Creek), and the southern uplands rivers.

Broadscale Landform Elements

Palaeodrainages and past megafloods create a landform context that modern Lake Eyre Basin rivers operate within; their influence needs to be recognised to fully understand modern fluvial processes.

Floodplains of Lake Eyre Basin rivers play an active role in flow transmission. Floodplains and channels are interdependent in the creation and maintenance of landforms and habitat.

Groundwater

Groundwater, as a broad term, encompasses waters of different origins and behaviours, including hyporheic water, water from shallow aquifers (such as those in valley-fill sediments), and formation water from rocks of various ages and geological basins.

4.2 Mid- and Lower Finke River

Groundwater and Salinity

In the Finke River, different river reaches may receive groundwater from different sources: 1) hyporheic water; 2) alluvial aquifer water from valley-fill alluvial sediments from the palaeo-

Finke River (the “alluvial aquifer” of Duguid (2013); 3) formation water from Cainozoic rocks or regolith, as well as Amadeus Basin rocks. Any of these groundwater inputs may also be a source of solutes (salinity).

Unlike temperate-zone rivers, hyporheic water may also be found beneath floodplains in the Finke River.

Cainozoic rocks/regolith are probably a source of water or solutes to the Finke River. There are likely to be substantial thicknesses of Cainozoic sediments in places; many will be poorly- or un-documented.

The “alluvial aquifer” (Duguid 2013) is a probable source of water or solutes for at least some waterholes, and almost certainly forms part of the GAB recharge. It is here identified as comprising sediments from the present-day river, and from the palaeo-Finke River. Because of the valley margin’s irregularity, the alluvial aquifer is likely to hold waters which have complex localised patterns of salinity and flow.

River Character and Behaviour

The Finke River exists within a context of highly variable rainfall, including common drought, sustained rain, intense convective thunderstorms, and occasional high-volume rainfall events. Flow is therefore variable, ranging from its normal dry condition to localised flows to sustained events over the whole drainage network. The Finke River has a large catchment allowing it to take advantage of more widespread rain events. Large flow events are critical for water delivery to the lower Finke River and the Finke Floodout Complex.

The Finke River is a "sand-bed river", with sandy bed and banks, and a wide shallow cross-section. It owes its sinuous planform to its confining valley (which was created by the palaeo-Finke River). It is characterised by channel mobility, occasional very high-energy conditions in some places or during some events, and a very high degree of bedload transport.

The valley setting of the Finke River changes from semi-constrained to almost unconstrained as it moves from the central ranges towards the Finke Floodout Complex. As the valley setting changes, there are changes to the degree of channel mobility and the relative proportions of channel to floodplain.

Floodplains are regularly part of active flow transmission; they carry a substantial portion of the flood peak, and are integral to the fluvial processes. The element that defines channel versus floodplain in the Finke River is not water transmission, it is the channel’s role in bedload transport. (During small flows the channel may move some sediment, and during large flows, the channel carries the most vigorous sediment movement whereas sediment movement is less likely across the floodplains.) This expresses itself as presence (on the floodplain) or absence (in the channel) of stable vegetation in areas that are routinely inundated.

The dominant sediment is quartzose sand transported as bedload, which mostly travels down the channels. During large flood peaks, the channel sands may be mobile to a depth of 3 m or greater. Sand also moves on and off the floodplains. Floodplain storage is an important part of the sand's journey from MacDonnell Ranges to Finke Floodout. Pebble and cobble conglomerate is a minor component, usually released into transport by local high-energy scouring; it does not travel far.

Within the mid-Finke River's channel, waterholes occur: deeper sections of channel in which water is retained after the close of flow. They may occupy the full channel width, or only a part of the channel. The location of some waterholes is forced by boundary conditions (e.g. rocky outcrop), and these tend to be the most permanent (deepest, and/or most likely to exist year after year). Mid-Finke River waterhole locations can be permanent on a scale of many centuries. The location of others may be related to local flow conditions (valley-margin, or outside-bend) and these may be more liable to impermanence (shallowing, moving, or disappearing).

Occasional large floods maintain waterhole depth by turbulent scour. Small flows will tend to deposit sand in waterholes, shallowing them and diminishing their permanence.

Riparian and floodplain trees play a role in sediment deposition and landform stability. However, the scale of large flood events and the volume of sediment under transport can overwhelm established trees, particularly in reaches undergoing rapid channel migration and floodplain renewal.

Athol pine were introduced to Central Australia in the 1950s and have spread rapidly. There has been concern that, amongst their other undesirable effects, they could trap sediment and alter river processes. Although the present project did not allow much examination of the lower Finke River, it was clear that athol pine can rapidly colonise the shifting channel in a way that native vegetation cannot, and that it is currently trapping sediments.

4.3 Finke Floodout Complex

River Character and Behaviour

A floodout occurs where a river's stream power has declined to the point where it can no longer maintain a channel. The Finke Floodout Complex is the terminus of the Finke River: flow declines, the channel diminishes and disappears in a zone of sediment deposition. The present-day depositional locus is on the west section of the main floodout.

During a very large flow event in the Finke River, waters will extend into the floodout. The flow will be slowing and depositing sediment; the channel will be wide, shallow, and shifting. With increasing distance downstream, the channel becomes more wide and shallow, and a greater proportion of the waters flows across the floodplain. Waters infiltrate the sandy sediments. At some point along the flow path the channel disappears; water continues to travel as unchannelised flow in the lower-elevation areas of the main floodout. If flood levels are high enough, flow will enter distributary channels and disperse into the Simpson Desert at Snake Creek and McDills Bore. Flow travelling southwards down interdune corridors regathers into new floodouts and distributary points along the base of the gibber hills in Witjira National Park. The present-day flow path extends to within 10 km of the Dalhousie Springs outflow. Dense vegetation is supported along the entire flow path.

The Finke Floodout Complex is contained within, and shaped by, large-scale landforms created by the palaeo-Finke River.

The single large waterhole, and the narrow reaches where channels re-form, indicate there are circumstances during which turbulent scour can occur. However this will be rare; during most flows, dense vegetation and the shallow unchannelled flow will ensure low stream power.

Hydrology and Groundwater

Most of the Finke Floodout Complex's surroundings are dunefield, and are unlikely to generate runoff or flow to feed into the complex. Consequently, the Finke Floodout Complex’s ecosystems rely on the Finke River for almost all of their water. Finke River flow events must be large and sustained to water this area. Local input to some vegetated areas is sometimes received from Coglin and Abminga Creeks, and from the high-runoff surfaces of the gibber plain hills.

Most of the sediment in the floodout complex is clean porous quartzose sand from the Finke River. Accumulated sediments are likely to form a good local aquifer (similar to the mid-Finke River alluvial aquifer), probably retaining post-flood groundwater.

In contrast, Coglin Creek's catchment is dominated by stony gilgai. Coglin Creek floodout sediments indicate that the creek transports little bedload. At least some flows exiting this creek are unlikely to be carrying a sediment load to capacity, that is the flows may have some remaining erosive potential. As such this creek is likely to play a role in maintaining the main floodout's waterhole.

4.4 Arckaringa Creek

Hillslopes and Runoff Hydrology

Arckaringa Creek is part of the Neales catchment. It experiences a very high degree of rainfall variability, including occasional sustained periods of gentle rainfall, and intense cloudbursts from convective thunderstorms. In comparison to other LEB rivers (e.g. the Finke River or Cooper Creek), it has a relatively small catchment and has less opportunity to generate sustained flow. However, many of its reaches are flanked by hillslopes which will have high to very high runoff coefficients (will shed water readily). Arckaringa Creek is likely to exhibit a flashy hydrograph; despite its relatively small catchment, under intense local rainfall it may rapidly generate high-energy and temporarily high-volume floods. Although intense local rainfall can create flash-flood conditions anywhere, it is most likely below high-runoff surfaces.

The channels and floodplains of Arckaringa Creek are flanked by hillslopes which will have moderately high to very high runoff coefficients. Unlike dunefields, or the red-earth plains of the Great Victoria Desert (see section 3.1), the hillslopes around Arckaringa Creek will shed water readily. However, the geomorphology indicates that some hillslopes will have much greater water-shedding character than others.

This hydrological character underlies Arckaringa Creek's unusual (for the LEB) sediment load, and thus its relative lack of refuge waterholes.

River Character and Behaviour

Arckaringa Creek is most strongly influenced by its geological situation, in which the uplifted proximal edges are incising through solid duricrust and into deep regolith profiles. The creek is characterised by a very high degree of bedload transport. The bedload is extremely coarse: gravel or cobble conglomerate, sandy gravels, or cobbley gravelly sands. Some fine sands and silt are transported as suspended load.

Fine sands and silt can be moved during low energy flow, and are transported during most of a flow event, whereas coarse bedload most likely experiences brief transport during high-energy flood peaks. At this time, the erosive power of the bedload may be great. As soon as the flood peak is past, the bedload is deposited in-channel at whatever point it has reached in its transport path. Sediment transport is therefore episodic.

Arckaringa Creek has reaches hosting a network of relatively small anastomosing channels in amongst a narrow floodplain, and reaches hosting larger channels (either a single or a few anabranching channels) amongst wider floodplains showing evidence of above-floodplain unchannelised flow. Both channels and floodplain are equally important in the transmission of water and sediment.

Pulses of water and coarse sediments will occur during flow events; their size will be much greater than might be expected from the small size of individual channels.

In the reaches hosting single channels or anabranching channels, landforms are similar to those found in the Neales River. This includes channel segments which display most of the characteristics of waterholes. However, because of Arckaringa Creek's abundance of coarse bedload, waterhole-like channel segments are always filled with coarse sediment: Arckaringa Creek therefore lacks the type of refuge waterholes found in the Neales River.

Arckaringa Creek has fewer waterhole-like channel segments along its length (in comparison to the Neales River). It is hypothesised here that during high-energy flow events, Arckaringa Creek's volume of bedload also suppresses the macroturbulent scour which is needed to form waterholes.

5 Management and Habitat Implications

This section discusses the management implications and some of the likely habitat linkages for the study area. Information presented here is based on the information described in sections 1-3 and in the Technical Appendix. As much inference as is justifiable is made from the data generated from this necessarily limited investigation. For many of the points made here, more detailed investigation would be beneficial.

The project's aims included description of river processes, especially those

1. which create and maintain the landforms which host ecosystems, and/or
2. which may be at risk from coal industry resource exploration and extraction, or which should be design considerations during asset development.

The management issues (relevant to fluvial geomorphology) arising from coal resource development may include open-cut pit design, landform stability with reference to infrastructure development (including pipeline location), alterations to flow regimes that reduce water availability to the fluvial system (groundwater extraction, surface water extraction, flood peak attenuation) or that artificially increase water availability to the fluvial system (discharge of formation water), or surface subsidence related to groundwater extraction. Note that the same or similar management issues also arise from other industries: examples include tourist infrastructure, which is vulnerable to limitations in landform stability, or irrigation requirements causing subsidence by groundwater extraction or changes to flow regimes by damming surface flows.

General management issues (relevant to fluvial geomorphology) include the lack of baseline information on catchment-specific fluvial processes, and overuse of information derived from geomorphically dissimilar rivers or from remote studies lacking a field-check component.

5.1 Lake Eyre Basin Rivers

Though linked by their common terminus in Kati Thanda-Lake Eyre, the different Lake Eyre Basin river groups have a variety of processes: their risk factors and best management practices are not interchangeable, and are also unlikely to correspond to factors and practices which are standard elsewhere in Australia. This is a crucial concept for risk management in LEB resource development.

The well-being of the channel cannot be regarded as independent of the well-being of the floodplain. The role of the floodplain should be included in all conceptual models and Thresholds of Potential Concern.

River Monitoring, Physical Habitat, and Geomorphology

Where standardised habitat description and assessment methodologies are to be employed (e.g. Thoms et al. 2009), it is important that any pro forma data collection sheets (e.g. Parsons et al. 2002) are applicable to the landforms of the river in question. Methodologies that require slotting observations into pre-set "pigeonhole" categories are likely to be ineffective if the river under observation is outside the range of characteristics on the pro forma. A successful approach is likely to be one that

- allows either flexible terminology, descriptive terminology, or use of a blank field for non-standard landforms;
- focuses on element description, rather than standardised landform names;
- considers landform context (assuming there is some available description of landscape processes);
- records photographs and is spatially located (GPS waypoints, including knowing what datum the points are recorded under), so relational information is available for future work.

Given the great variety of LEB fluvial landforms and processes, it would be ideal if pro forma data collection sheets for habitat description were reviewed for landform relevance at the beginning of each catchment's data acquisition program.

It is important to separate the concept of physical habitat description from the concept of interpretation of fluvial processes. While there is descriptive overlap at channel scale (metres to hundreds of metres), landform description at this scale is not an investigation of fluvial process. Documentation of a niche habitat may require e.g. reach-scale examination for signs of bank stability, but an investigation of fluvial process will also require valley-scale channel and floodplain history, bedform-scale hydrodynamic history, upstream and downstream fluvial process linkages, and geological context. Where a river's fluvial processes are poorly known (as is the case in many LEB rivers), attempting to determine reach-specific fluvial behaviour as an adjunct to aquatic habitat description is unlikely to produce good results. Furthermore, good physical habitat is not necessarily the same as good (intact, functioning) fluvial processes. For example, the Finke River's mobile sand bed will be a very poor aquatic invertebrate habitat for most of its length, but its fluvial processes are in good condition.

Groundwater

Where aquatic ecosystems have a groundwater-fed component, it is incorrect to envisage that all groundwater inputs are alike. Formation water, alluvial aquifer water, and hyporheic water are different components which may be available to a fluvial ecosystem. If groundwater behaviour is an important part of an ecological conceptual model, location-specific or type-specific groundwater behaviours should be acknowledged and described.

Despite a generally poor degree of formal documentation, Cainozoic rock formations are important in local groundwater hydrology. In considerations of water extraction or discharge, it is important to have a sound understanding of the local conditions: 1) Cainozoic geology; 2) the sedimentary composition of nearby landforms. Some information may be available in state Geological Survey maps and publications, and hydrocarbon or water drilling records.

Landforms and Habitat

Where hillslopes are biologically poorly- or non-productive, floodplains are almost the only terrestrial habitat. To focus on aquatic animals without acknowledging terrestrial biota is to ignore half the ecosystem. Floodplain landforms include floodouts, which are known to act as refugia for terrestrial ecosystems.

Presently, the conceptual models and stressor-response models do not consider the risks posed by artificial discharge of water into river systems whose landforms are in equilibrium with long periods of no-flow. The risk areas are likely to be 1) direct effects of erosion and gullying, and 2) indirect effects related to vegetation community changes.

Because riparian and floodplain vegetation is an agent in geomorphic processes, changes to vegetation communities are likely to change landforms, which would result in permanent habitat change. The two areas of concern are:

- if constant discharge of water permanently raises groundwater levels and kills susceptible trees;
- if constant discharge of water removes the contrast between water-adjacent and usually-dry landforms, there will be fundamental changes to vegetation communities and therefore landforms.

Management and Resource Industry Considerations

A temperate-zone view of drylands rivers might imagine that they are only working when they flow; that between flows, they are inactive. From this, a corollary might be drawn that discharging large volumes of extra water into drylands rivers might be beneficial, or at least neutral in its effect. However, this is unlikely to be so. Drylands river landforms and their ecosystems are presently in equilibrium with long periods of no-flow, and change in that flow regime will certainly change both ecosystems and landforms. In the absence of research on this topic, examples of factors that may change with increased discharge are given here. Note that these examples are based on location-specific conditions.

1. *Salinity* The balance between rain- or flow-driven flushing of salts from surface to depth, and the presence of deep saline groundwater, is currently set to the present flow regime (e.g. Costelloe et al. 2009). Discharge of water here may flush salts to the surface, to the direct detriment of ecosystems, and (through vegetation death) eventual detriment of landforms.
2. *Vegetation and Flow Dynamics* Vegetation plays a key role in flow dynamics, governing qualities such as scour and sedimentation on spatial scales ranging from bedform to reach (e.g. Graeme and Dunkerley 1993; there is a rich literature on this topic). Riparian vegetation plays a role in maintaining waterhole depth (e.g. Knighton and Nanson 2000, Wakelin-King 2010), and floodplain vegetation is an important roughness element that maintains valley-floor integrity (e.g. Bull 1997). Drylands rivers trees (e.g. black box, coolabah, red gum) have different requirements with respect to period of inundation, groundwater salinity, or duration of waterlogging. Changes to flow regimes that increase salinity or length of waterlogging may diminish or kill communities of susceptible trees, to the direct detriment of ecosystems, and (through vegetation death) eventual detriment of landforms. In a river flat with a small channel, artificial discharge of water may initially produce lush vegetation and so would appear to be beneficial. However, if long term inundation produces vegetation death, the follow-on effect is likely to be valley-floor incision leading to floodplain desiccation and habitat destruction, and erosion releasing sediment which will silt up downvalley waterholes (Wakelin-King and Webb 2007b, and see Wakelin-King 2010 Fig. 5 and section 3.1).

Hydrological Modelling

Where hydrological modelling of flow behaviour is a desirable management tool, it is important to understand the underlying assumptions of the model. Use of numerical values for flow properties to determine management actions must include a clear understanding of that value's uncertainty, both numerically and in terms of whether or not the number corresponds to real-world behaviour of the river.

Broadly speaking, there are two ways to numerically model a river's behaviour (Justin Costelloe, pers. comm. 2014). If a large infrastructure development was planned, at the first stage a hydrologic model could provide river-scale flood frequency analysis. Detailed mine planning might later require the development of a hydraulic model to better understand likely reach-scale spatial distribution of flooding over a range of flood sizes.

A **hydrologic model** (a rainfall-runoff routing model) is conceptually based. It uses simplified algorithms to route the flow through a simplified model of the flow path, such as a link-node network. This kind of model outputs discharge values on a multi-reach or whole-river scale, and is calibrated to real flow occurrences. This is the approach taken in Ryu et al. (2014) and DEWNR in hydrological modelling of the Neales River catchment (Justin Costelloe, pers. comm. 2014). This approach has the practical benefits of being achievable and able to clarify the output uncertainty limits. In theoretical terms, use of real flow events to calibrate the model incorporates the integration of complex reach-scale hydraulic behaviour. In hydrological modelling, good models are usually parsimonious (incorporate the fewest possible number of variables), and the experience is often that adding new factors increases the complexity without improving the accuracy of the result (Justin Costelloe, pers. comm. 2014).

Geomorphology can add value to hydrologic modelling by bringing a process-based understanding to model use and interpretation. If the model diverges from the real-world flow in a particular reach, it may be effective to consider if the reach's geomorphology (boundary conditions and flow behaviours) are a good match to the assumptions underlying the model's input values. If a particular subcatchment is the target of a modelling run, its geomorphology may guide the selection of model parameters.

For example, if hydrologic modelling was part of risk assessment for a resource development, geomorphology would suggest different scenarios to be run according to the nature of the project. If the study was for a pipeline to be run across the Finke River, the flow to model would be one that inundates the entire floodplain (because that will mobilise the greatest depth of channel sediment), which would likely call for input conditions of high antecedent moisture and widespread rainfall. If the study was for an open-cut mine along the axis of Arckaringa Creek, the model to run would be for a flash flood (because that will generate sufficiently great water and sediment discharge at the flood peak to risk overwhelming site retention structures). This would probably call for input conditions of high-intensity local rainfall, and high hillslope runoff values.

A **hydraulic** (hydrodynamic) **model** is specific to a reach area. It might have flood height and water velocity for the modelled reach as outputs; measurable components would frame the model as inputs (e.g. rainfall, evapotranspiration) or parameters (e.g. roughness, infiltration) (Justin Costelloe, pers. comm. 2014). Some other factors which affect a river's behaviour are water slope, water density (which varies with sediment load), hillslope runoff coefficient, distribution and intensity of rainfall, floodplain roughness (and how it varies with increasing flood height), in-channel roughness (including boundary shape, bedforms, and vegetation), and valley cross-section. Hydraulic models can be challenging in the Australian drylands, where it is difficult to obtain some of these data. For example, the empirically-derived roughness value which is most used in such calculations (Mannings *n*) has not been estimated for some very common occurrences in Australian drylands rivers, such as in-channel large trees (see Graeme and Dunkerley 1993). Some inputs are based on relatively few data points, for example daily rainfall patterns are interpolated from information collected from meteorological stations, and these are sparse in drylands Australia.

If the numerical values for the relevant components can be obtained, then it would be possible to model the flow in the reach for which the measurements had been taken. (It would be a complex task: for example, the roughness values and therefore flow velocity would vary across different landforms, according to the distribution of trees.) The model outputs would yield valuable information for that reach, but would not necessarily be applicable to adjoining reaches, as they would be different. The distribution of different channel types down the Finke River, or anastomosing versus anabranching reaches in Arckaringa Creek, are a reflection of different flow behaviours in different reaches. Other factors change between reaches, for example transmission loss reduces discharge.

5.2 Mid- and lower Finke River

The mid-Finke River's relevance to this study is that 1) it contains permanent and semipermanent waterholes with fish populations, 2) hydrocarbon pipelines from the Arckaringa Basin to industry hubs in central Australia would need to cross the mid-Finke River, and 3) the mid-Finke River is the major source of water for the Finke Floodout.

Groundwater and Salinity

The Finke River's groundwater context is complex. Some parts of the river receive groundwater inputs, some of which are more prolific or more saline than others. The Finke River recharges GAB aquifers along the edge of the Pedirka basin. The palaeo-Finke River's sediments are likely to play a role in that recharge.

Artificial addition of water into the alluvial aquifer (for example, from mine waste) has the potential to create a salinity problem if alluvial aquifer waters are flushed to the surface.

Habitats: Rivers

The Finke River's main aquatic habitats are likely to be the permanent and semipermanent waterholes; the small waterholes, channels, and floodplains are unlikely to support the life cycles of aquatic invertebrates or fish (c.f. Cooper Creek and the Neales River). The Finke River's main terrestrial habitats are the more regularly inundated parts of the floodplains, which host water-retaining landforms and are supported by hyporheic water.

During high-flow and very large flood conditions, the Finke River's channel will host a dense cloud of rapidly-moving sand at depth, and the water column over channel and floodplain will hold moving fine sand and silt. This is likely to be a hostile environment for migrating fish, and is very different to the situation in the Neales River or the Channel Country rivers.

Habitats: Waterholes

Mid-Finke River waterhole locations can be permanent on a scale of many centuries (Duguid 2013), especially if their location is forced by boundary conditions. This is a similar degree of permanence to other important LEB refuge waterholes. It is a slightly lesser degree of permanence than upper-Finke River waterholes in the rocky ranges, but the difference is irrelevant on a human management timescale.

Occasional large floods are necessary to maintain waterhole depth. A long-term run of small flows would promote waterhole shallowing, which would be detrimental to refuge values.

Scouring and bedload transport during flood conditions may mean that waterhole substrate is frequently renewed: waterholes in permanent locations may be recurrent rather than permanent, in the sense that the substrate could be renewed with every large flow event. This is likely to have implications for invertebrate habitat.

Some waterholes benefit from groundwater input. If proximity to certain aquifers affects waterhole habitat qualities (e.g. salinity), and if some aquifers have tight constraints on their locations, then even small shifts in waterhole location may affect habitat persistence.

Banks and Habitat Description

The Finke River's channel mobility and diversity results in diverse bank types, from unambiguous long-term banks to obviously transient forms. This can be a challenge in description of physical habitat or vegetation communities, as the standard terminology may be a poor fit.

Management and Resource Industry Considerations

When making impact assessments on the effects of water extraction or discharge, it is important to have a sound understanding of the local geology, including the (sometimes poorly documented) Cainozoic geology, and the sedimentary composition of nearby landforms.

Artificial addition of water into the Finke River’s channel, floodplains, or terraces has the potential to create a salinity problem if alluvial aquifer waters are flushed to the surface.

Infrastructure such as pipeline crossings, compressor stations, pipeline access points etc. should be designed and sited to minimise risk of damage and unplanned gas releases. In particular, gas pipelines across the Finke channel should be buried deep enough to avoid being vulnerable during bedload movement or channel relocation, and other infrastructure should not be placed on floodplains or lower terraces.

Overseas experience and theoretical modelling has indicated that feral trees can contribute to a complete change in river processes by immobilising bedload, with concomitant destruction of habitat. Thickets of athol pine in areas of greatest channel mobility (such as the lower Finke River) are likely to be detrimental; they should be controlled.

Changes to the Finke River's flow regime, especially flood peak attenuation or flood volume reduction, would be detrimental to the Finke Floodout.

5.3 Finke Floodout Complex

Habitats

Field investigation confirmed that the Finke Floodout Complex is biologically very productive. It has one waterhole, which does not appear to be permanent or semipermanent, but its terrestrial ecosystem includes dense vegetation, old trees, and bird nests (frontispiece). An environment such as this is likely to contain abundant reptiles, birds, and insects (M. Gillam, pers. comm. 2014), and to be a refuge habitat for terrestrial biota. Since it relies on inundation, it is a high-value aquatic ecosystem.

Distributary drainage lines from the main Finke Floodout extend for up to 50 km along three separate pathways into the Simpson Desert. They feed interdune corridor lakes, which may support bird populations during times of flood.

Management and Resource Industry Considerations

Large floods in the Finke River are almost the entire source of water for the Finke Floodout. Management actions which reduce mid-Finke River flood frequency or size, or increase water salinity, will be detrimental to the Finke Floodout.

The more distal floodout elements also rely on runoff from the gibber plains. Infrastructure development on the gibber plains should avoid occluding gully surfaces.

Transport of water and sediment takes place actively across the main Finke Floodout. It should not be regarded as a stable place to develop intensive or high-value infrastructure. Any infrastructure that is developed should take care not to occlude present-day or potential flow paths.

Artificially discharged waters at the eastern end of the main Finke Floodout, where offtake areas for distributary channels exist, could affect habitat corridors (including potential bird areas) extending ≤50 km along three separate pathways into the Simpson Desert.

5.4 Arckaringa Creek

Habitats

The high volume of coarse bedload may restrict invertebrate habitat. The possibility of a different aquatic community between Arckaringa Creek and the Neales River, attributable to the bedload character, might be worth investigation.

Rates of bedload transport in Arckaringa and Lora Creeks mean that these rivers hold no refuge waterholes upriver of the confluence area. It is possible that infrastructure development across these creeks is unlikely to be detrimental to wider fish populations, however this hypothesis should be tested by an aquatic ecologist.

There are some floodouts in Lora Creek which are likely to be productive terrestrial habitats, and may be terrestrial refugia.

Management and Resource Industry Considerations

Certain kinds of mining infrastructure must be designed to retain integrity during weather events. These include

- tailings dams and stormwater ponds, which need to have sufficient capacity that they are not overwhelmed by rainfall or flow events;
- overburden piles, which need to be located such that their bases are not undercut by floodwaters, and designed such that they will not slump during rainfall;
- open cut mine pits, which need to be protected from flooding (especially in the case of sulphur-bearing coal deposits, where flooded pits can develop extremely low pH waters).

Consequences of incorrect design can be damaging and costly. For example, floodwaters overwhelmed infrastructure at the Lady Annie copper mine (Queensland) in 2009 (Latimer 2012). The spill of mine water contaminated 52 km of creek and cost the company $8.5 million in cleanup and fines. The mine ponds were not large enough for flows of that size. However similar rainfalls had been recorded in the area in 1893 and 1974 (Thorne and Personnaz 2012), which were years in which the IPO (Interdecadal Pacific Oscillation) and the ENSO (El Niño-Southern Oscillation) weather cycles coincided (McKeon et al. 2004, their Plate 1.1). That is, rainfall on that scale can be expected every 20-40 years – well within the lifespan of a mine or its post-mining rehabilitation works.

Flow variability in Australian rivers is so great that our few years of records are insufficient to tell us what to expect (Finlayson and McMahon 1988). However, the fluvial geomorphology of any river system should be able to provide indications of high-flow conditions. In Arckaringa Creek, the following characteristics should be considered during mine design:

- Intense local rainfall during convective thunderstorms can create flash-flood conditions anywhere, but it is most likely below high-runoff surfaces. Runoff coefficients should be established for surfaces upslope or upvalley from mine infrastructure, as part of risk assessment modelling.
- Pulses of water and coarse sediments will occur in the creek during mine life; their size will be much greater than might be expected from the small size of the channels.
- Down-drainage bedload transport is an important part of the creek's present-day fluvial processes. Interruption to the sediment load (for example, by mining structures which divert some sediment load away from its channel without reintroducing it further downstream) may lead to strong downstream-propagating erosion in downstream reaches. Bed degradation and gullying up the flanks of the valleys is the most likely result.
- Floodplains are an integral part of flow transmission. The flat, poorly-vegetated areas down the Arckaringa Creek valley axis are not a good place for infrastructure, overburden, or ponds.

Constant discharge of water down a drylands river is likely to be detrimental, rather than being a positive community benefit. In Arckaringa Creek, the risk would be death (through waterlogging) of floodplain vegetation. This in turn can lead to valley-floor incision; the released sediment would be transported downvalley. Sediment pulses might be stranded at the Peake-Nilpinna confluence, or they might be transported through Peake Gap in which case there is a risk of shallowing up the Baltucoodna and Warrarawoona Waterholes.

Lora Creek was not a particular focus of this study. It is quite possible that its runoff slopes and sediment character may be different from that of Arckaringa Creek. If mining infrastructure is developed across Lora Creek, investigation of the creek's attributes should precede infrastructure design.

6 Knowledge Gaps

This section outlines knowledge gaps relevant to the study area's fluvial geomorphology. Information presented here is based on the information described in sections 1-3 and in the Technical Appendix. The scope of this project was necessarily limited; this section may identify, as knowledge gaps, life-science topics which were merely outside the reach of the study.

Lake Eyre Basin

This report qualitatively describes river behaviour in the study area, and identifies potentially vulnerable places or processes. The information should be integrated into the development of Thresholds of Potential Concern.

In the author's experience, the idea that Australian drylands rivers are alike is widespread amongst many stakeholders; this is detrimental to effective river management. There is unrecognised diversity in drylands rivers worldwide (Tooth 2000, Nanson et al. 2002), and within Australia. LEB river geomorphology is (with a few notable exceptions) poorly known. Where it is well-documented (e.g. Nanson et al. 2008), the information is not very accessible to the non-geomorphologists who are responsible for management. Ideally, the landforms and behaviours of LEB rivers would be described in a single stakeholder-friendly resource, according to a consistent methodology. However, LEB rivers will be difficult to fit within river classification schemes that have fixed taxa, or are based on a single landform group (e.g. planform, floodplain). It is recommended here that a River Styles (R) report (Brierley and Fryirs 2005) on LEB rivers may best serve the Lake Eyre Basin community, as it will be process-based, able to encompass river types not previously described in the literature, and can be constructed in an open-ended style that will permit ongoing integration of new information.

The effect on fluvial geomorphology of artificial discharge of water onto arid-zone floodplains (whose modern landforms are in equilibrium with long periods of no-flow) is yet to be investigated. Preliminary indications (Wakelin-King, work in progress, and see Wakelin-King 2010 section A2.2.6, discussion of the scour near Big Blythe Bore) are that vegetation suppression prevents waterhole formation, however an investigation of this question was outside the scope of this study. Investigation of landforms and plant ecology near artificial discharge points in comparison to nearby control areas should be a high priority.

Most Australian drylands river landforms rarely if ever retain free water, but are nevertheless ecologically vital. River assessment protocols which focus on lotic/lentic biota implicitly exclude these places from being valued as aquatic ecosystems, despite their importance to local ecosystems. In most cases, these undervalued landforms are floodplains, yet floodplain function is a critical determinant of channel and waterhole health (e.g. see Wakelin-King 2010, section A2.2.9). In some cases, they can be ecological sweet spots, and/or refugia for terrestrial species (e.g. floodouts: Bull 1997, Tooth 1999, Wakelin-King and Webb 2007b). River monitoring projects within the Lake Eyre Basin have not conducted surveys in terrestrial species in the same way as they have collected information on fish. Reptiles, ants and termites, are likely to be valuable indicators of drylands ecosystem health, and it would be desirable to know more about them, and integrate them into ecosystem assessment methodologies.

The role of dryland river floodplains in active flow transmission is known in the geomorphology literature, but is yet to be integrated into conceptual models used in ecosystem management (e.g. Imgraben and McNeil 2013; and see Pringle et al. 2006). Drylands floodplain flow and unchannelised flow is also poorly recognised in engineering practices (e.g. Wakelin-King 2013). This information needs to be expanded across discipline boundaries.

Mid- and Lower Finke River

The mid-Finke River's alluvial aquifer is likely to hold waters which have complex localised patterns of salinity and flow; this is currently unresearched.

This link between waterhole permanence and boundary conditions could be better-documented. The Finke River is well-known for its sometimes transient waterholes, but hard data for individual waterholes is not available. A history of individual waterholes is sometimes complicated by their mis-identification on maps (see Duguid 2013). It is recommended that a comprehensive study of waterhole location and stability be undertaken, using aerial photography dating back to the 1940s, early pastoral records, satellite imagery, and oral histories from the traditional owners. Rates of lower Finke River channel mobility could be similarly studied.

Finke Floodout Complex

This is the first description of the Finke Floodout Complex's geomorphology, and the project scope only allowed for a preliminary study. The area's landforms are complex, and appear to be unaltered by human activity. It is recommended that the geomorphology and ecology of this area should be studied in more detail. The study would be suitable for a doctoral project.

The terrestrial ecology of the floodout complex may not yet have been investigated. The area is likely to be particularly diverse in ant, termite, and reptile fauna, and may host rare or relict species. This would be a good place to develop concepts of non-lotic and non-lentic biological indicators of river health.

Modelling a long-term water budget for the main Finke Floodout will require consideration of local rainfall in the Coglin and Abminga Creek catchments, and on the Dalhousie Anticline.

Nothing is known about the groundwater hydrology of this area, but (by analogy with the mid-Finke) it may be complex and there may be saline components.

The nature of the landforms governing distribution of water from the main Finke Floodout into the Simpson Desert distributaries is not currently known.

Arckaringa Creek

Delivery of water from hillslope into the drainage network is mediated by a hillslope's runoff coefficient. The absolute and relative values of runoff coefficients in the Neales catchment is a knowledge gap which should be addressed, particularly if there needs to be risk management around mining projects in the Arckaringa Creek catchment. Runoff coefficient measurement should be conducted in conjunction with spatial assessment (that is, the types and locations of different ground surfaces should be mapped, firstly to understand how many different runoff coefficient measurements should be taken, and secondly to be able to apply the measured runoff coefficients to specific sites). This would be a doctoral-scale project.

Arckaringa Creek's fluvial processes and characteristic landforms are surprisingly different from those of the Neales River. While the present study has identified Arckaringa Creek's fundamental fluvial character, its scope was not large enough to properly investigate reach-scale landforms and processes. Additionally, differences between Arckaringa and Lora Creeks have been identified but not documented.

River monitoring projects have not surveyed terrestrial animal ecology in the Arckaringa and Lora Creeks. It cannot be said whether this area is important to vertebrate populations (birds, reptiles, small mammals), or whether it hosts endangered or unusual species.

Technical appendix

This Technical Appendix is the material supporting the information presented in Part 1 of this report. It includes literature attributions, and (where relevant) greater detail on the regional context, field observations, analysis and synthesis.

A1 Introduction

A1.1 Methods: Spatial and Sedimentological

Spatial Science, Geomorphology, and Geological Mapping

The methodology employed in this project is that of standard geological mapping, such as has been employed in the production of all Australia's 1:250,000 scale geological maps, and in countless other geological studies in Australia and throughout the world. In brief, a broad-scale remote study of the field area sets context, identifies units* whose attributes* are similar enough that they may be grouped, and permits preliminary interpretations of causation*. In pre-digital times, remote studies used topographic maps and stereo sets of aerial photographs. More recently, remote studies can also employ satellite imagery, DEMs, GIS, and geophysical images; but the principle remains the same.

*In geological mapping, the units are rock or regolith outcrops, the attributes are lithology and structure (visible on remote images as colour and shape), and the causation is the geological history. In a fluvial geomorphology study, the units are landforms or river reaches, the attributes are surface material, vegetation and structure (visible on remote images as colour and shape), and the causation is the sequence of fluvial processes.

Following the remote study, field study ground-truths the remote study, establishing what real-world attributes correspond to a unit's remote-study characteristics. This is an absolutely crucial step unless the study area's geomorphology is already well-known (a condition which is not the case in most of the Lake Eyre Basin's rivers). Ground-truthing tests the causation hypotheses that were formed during the remote study. It also permits regional-scale interpretation to be derived from relatively few field sites, as long as good-quality geolocation links the remote study units to the field site observations. In pre-digital times, this was known as mapping.

During the field study, information is collected on unit attributes: observations of a kind that are not possible in the remote study (the surface materials' grain size and lithology, vegetation-sediment relationships, the ground surface's status with respect to erosion or deposition, etc.). This study employs *process geomorphology*: that is, the goal is not description or classification of the landform's shape, it is understanding what the landforms reveal about the landscape processes they experience. Each piece of data holds an implication of process or causality. The total project data collectively present a picture of (in this case) fluvial process. The integrated project data not only presents a picture of the whole field area, it also represents multiple testing of the process hypotheses (since the interpretation of each piece of data has to make sense with respect to other linked datapoints, and to the system as a whole).

This partly geological methodology is appropriate, because the scale of the study is regional, and the forces governing river behaviour involve geological disciplines (sedimentology, tectonic history, petrology, stratigraphy, regolith science) or physical disciplines invoked to explain geological phenomena (fluid dynamics). Other geomorphology studies employ different methodologies, some at much narrower scales, or using controlled experiments to produce numerical data (e.g. Dunkerley 2004). Though different, all are valid; future LEB investigations may require these techniques..

River Classification Schemes, and the River Styles ® Framework

Rivers are complex systems, responding adaptively to interlinked variables such as slope, bank sediment, water and sediment load, etc. Various classification schemes have been proposed in an attempt to clarify and standardise river description. Most are based on channel planform, some on floodplain type, some on other factors. In the author's experience there are two reasons for being cautious in the application of such schemes to Australian drylands rivers.

1. Some (particularly older schemes) are based on morphology, without reference to fluvial process. Such schemes ignore equifinality (where different processes can create similar landforms), and thus may conflate two dissimilar river types. For example, a lack of distinction between braiding and anabranching led many Australian drylands rivers to be incorrectly described. Though both planforms are multithread, the process differences are strong: braiding is a response to high stream power, whereas anabranching is a response to low stream power. In another example, some classification schemes define

river sinuosity numerically (channel length/valley length). However, while sinuosity in unconfined (fully alluvial) rivers is generally due to meandering processes, rivers in semi-confined valleys maybe sinuous in response to channel-valley wall interaction. Similar degrees of sinuosity in different rivers may thus result from different processes.

2. Many schemes attempt to achieve standardisation by delineating a limited selection of channel or floodplain types, within which natural rivers are supposed to fit. Such schemes may be very useful when applied to the rivers for which they were designed, but fail when confronted with a river that does not fit within pre-set categories. The Australian continent's special conditions of aridity, low relief, palimpsest landforms, and deeply weathered clay-rich regolith produce a number of drainage types that do not fit within standardised schemes.

Like the present investigation, the author’s previous studies on fluvial geomorphology in western New South Wales and the Lake Eyre Basin have been process-based, and have not used standardised schemes of river classification (Wakelin-King 1999, 2007, 2010, 2013; Wakelin-King and Webb 2007a, 2000 7b). In the present investigation, the format has been based on Brierley and Fryirs (2005) in the River Styles (R) framework. River Styles (R) is an open-ended and process-based methodology for investigating, understanding, and reporting on rivers of all types. It is very suitable for dealing with non-standard rivers, especially those whose fluvial processes are poorly documented.

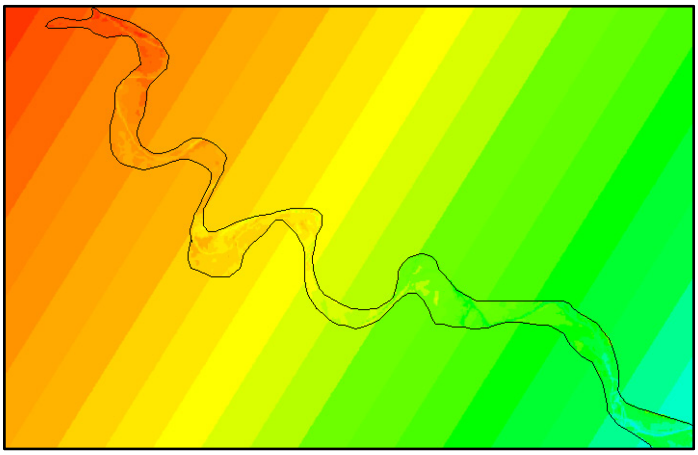


Fig. 46 The mid-Finke regional gradient surface.

This first order surface is matched to south west drainage direction of the mid-Finke River. Image by Gordon Wakelin-King.

Residual DEM image creation (Gordon. J. Wakelin-King)

In a low-relief area, geomorphic features defined by elevation changes can be masked by the dominant downvalley gradient. Further image enhancement to visualise subtle landforms requires removal of this regional gradient to create a residual image.

The Geoscience Australia smoothed 1 second SRTM was windowed to the area of interest. A first-order (planar) regional gradient surface was fitted to the surface and adjusted to fit the down-slope gradient valley (Fig. 46). The match of the calculated regional gradient surface to the valley was checked by overlaying the river valley elevation data over the regional gradient using the same colour bar (Fig.47).

In the mid-Finke River residual, a down-river profile shows departures from the regional gradient of the same wavelength as the valley sinuosity, as the azimuth of the valley changes with respect to the gradient direction. The scale of the departures is low (<5m) and does not impact on interpretation of the features of interest in the image.

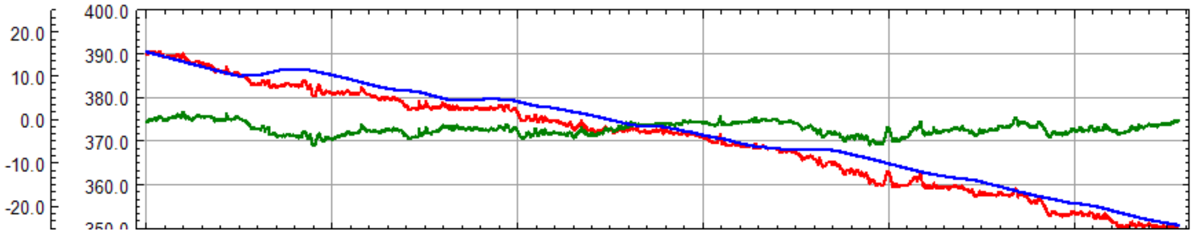


Fig. 47 Assessment of the residual image.

The down-river profile of original SRTM (red) calculated gradient (blue) and first order residual (green) shows the calculated gradient conforms to raw data within +/- 5 metres. . Image by Gordon Wakelin-King.

Sediments and Bedforms

In this study, sediment grain size and depositional bedforms are used as indicators of stream behaviour, particularly stream power during flow events. The relationships between grain size, bedform, and flow conditions are well-documented from both field and laboratory studies. In this study, grain size assessments were grouped into the standard classes, (cobble, gravel, sands, muds) and sedimentary structures identified according to standard geological nomenclature. Had the scope of this study permitted measurement, numerical estimates may have been obtainable for some river qualities (for example, measurement of cobble β-axes could produce an estimate of stream power occurring during excavation of the mid-Finke River 3 Mile Waterhole).

The following paragraphs briefly describe the information provided by grain size and bedform. Key references for bedforms in general, drylands rivers bedforms, and high-energy flow include Picard and High 1973, Barlow 1988, Ashley 1990, Tinkler and Wohl 1998, Bridge 2003, Wakelin-King and Webb 2007a.

A river's stream power governs the grain size of bedload that can be transported, and the total amount of sediment that can be transported (competence and capacity respectively). Coarse sediments which have been moved typically display armouring, imbrication, or cluster bedforms, allowing them to be distinguished from layers of coarse sediments exhumed by erosion. Where a river carries a variety of grain sizes, coarse grain sizes may be transported for smaller distances in comparison to smaller grain sizes. If an erosion event releases a pulse of sediment, it is likely that the coarse cobbles and gravels will be redeposited not too far downstream, whereas the sand may travel much further.

Bedform shape is related to grain size, flow depth and flow velocity. Dunes are divided into 2D and 3D forms. The 2D forms (previously known as sand waves) are common in central Australian rivers and are deposited in lower–energy conditions than the 3D forms (sinuous-crested dunes). Dune amplitude is related to flow depth, and flow depth is proportional to stream power: the larger the dune, the deeper and stronger the flow that created it. Sedimentologists generally refer to a standard diagram of bedform stability fields (Fig. 48), but these fields are not the same for all grain sizes and flow depth.

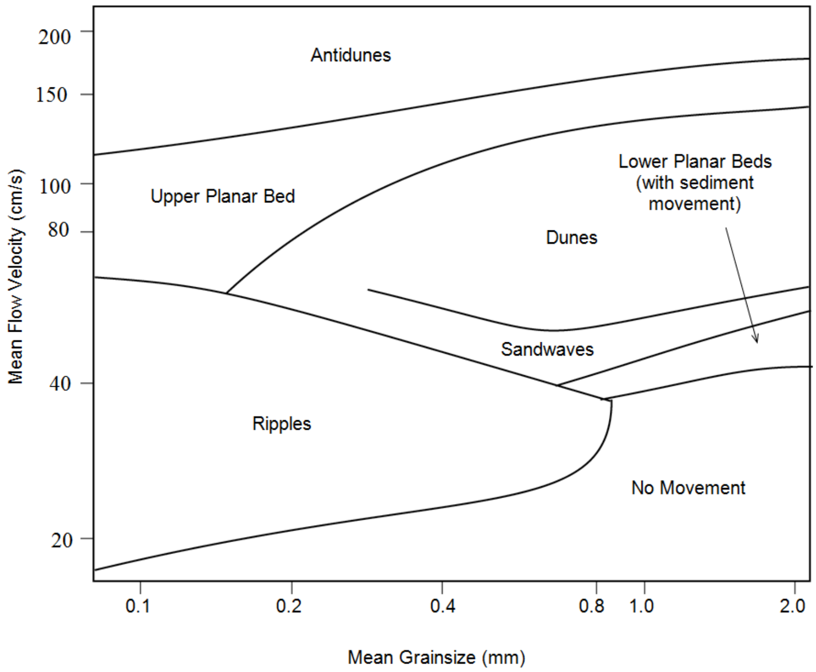


Fig. 48 Bedform stability fields.

Derived for fine to very coarse sand at a flow depth of ~40 cm (after Reineck and Singh 1980).

In dryland rivers, flood hydrographs typically show narrow peaks and a rapid drop from strong peak flow to a longer period of much less powerful waning-flow conditions. In such conditions, unusual bedform relationships are sometimes observed. Most importantly, the high-energy bedforms developed during peak flood flow are often not preserved, they are replaced by lower-energy bedforms deposited near the close of flow. The bedload of sandy drylands rivers is commonly observed to be either low amplitude flat-topped 2D dunes, or planar surfaces. These low energy bedforms do not represent the high-energy conditions of peak flood transport.

A1.2 Context: The Lake Eyre Basin

LEB Geology

In this report, all basins of Cainozoic (Cz) age are referred to as Cz basins, however the largest basin of this age has been referred to in geological literature as the Lake Eyre Basin. Because ambiguity would result from using a geological name that is the same as a topographic name, that usage is not followed in this report.

The geology of the Amadeus and Pedirka Basins are summarised in Ahmad and Munson (2013), and that of the Eromanga Basin in Krieg et al. (1990), Whitaker et al. (2008), Alley et al. (2011), Ahmad and Munson (2013), and geology of Queensland. Rocks of the Cainozoic basins, now preserved beneath the LEB's surface, have spatially complex lithologies reflecting both long-term climate change, and the basin hydrology at the time of deposition (Wopfner et al. 1974, Ambrose and Flint 1981, Wells and Callen 1986, Krieg et al. 1990, Alley 1998, Callen and Cowley 1998, Magee 2009, Geoscience Australia 2012, Cohen et al. 2010). Tectonic influences on modern geomorphology include Amadeus Basin salt-cored folding (Warren and Shaw 1995), the Eromanga Basin's syndepositional folding (Moussavi-Harami and Alexander 1998, Nanson et al. 2008, Alley et al. 2011), and low-key but hydrologically significant flexure of the land surface (Sandiford et al. 2009).

Weathering – the chemical alteration of rocks and sediments by the action of soil moisture or groundwater – has been widespread across Australia for a timespan that is long even in geological terms (Anand 2005, Pillans 2005). In the LEB, results include bleaching rock to bright white colours or mottling rocks with ochres and reds; softening rock and making it liable to erosion; widespread gypsum mobilisation and emplacement; and the emplacement of duricrusts. Of these, silcrete is the most important, for its strong influence on topography (this report), and its pre-European cultural importance as a prime stone tool component (e.g. Holdaway et al. 2008, Webb and Domanski 2008). Silcretes occur across a very wide area, and their formation, distribution and influence on landscape development is described in Wopfner et al. (1974), Moussavi-Harami (1996), Moussavi-Harami and Alexander (1998), Alley (1998), Thiry et al. (2006), Alley et al. (2011).

LEB Surface Hydrology and Palaeohydrology

The Lake Eyre Basin occupies nearly 1/6th of the Australian mainland, and its elevation range is +1354 m to -15 m AHD. It is very low relief; by far the greatest area lies below 300 m AHD (Fig. 49). Its highest elevations, 750-1354 m AHD, occur only in the northwest (the Amadeus Basin ranges of Central Australia) and the south (the Flinders Ranges).
Kati Thanda-Lake Eyre itself is divided into Kati Thanda-Lake Eyre North and Kati Thanda-Lake Eyre South; its lowest points (-15 m AHD) are in the southern bays of Kati Thanda-Lake Eyre North.
Kati Thanda-Lake Eyre fills rarely, usually in association with La Niña climate events. In the modern climatic regime, fill elevation for a 5% Annual Exceedance Probability (colloquially, a 1:20 year flood) is approximately -11m AHD (Fig. 49) (Kotwicki and Allen 1998). The Lake's fill pattern reflects the extent of the catchment; the northern and north-western rivers are placed where they may intercept monsoonal rain (Knighton and Nanson, 2001).

The LEB's rivers can be grouped according to catchment characteristics such as gradient, length, climate zone, and sedimentology (Wakelin-King, work in progress):

- the Channel Country rivers, including Cooper Creek and the Diamantina River;
- the catchments from the western uplands, including the Neales River and its tributary Arckaringa Creek;
- the creeks which flow from the Flinders Ranges;
- small creeks flowing through the Strzelecki Desert dunefield; and
- the central Australian rivers, arising in Amadeus Basin ranges and flooding out in the Simpson Desert (including the Finke River).

The hydrology of some LEB rivers has recently been monitored and modelled under the ARIDFLO program, and/or under work carried out for the South Australian Arid Lands Natural Resource Management Board (Costelloe 2011, 2013; Costelloe at al. 2003, 2004).

Megaflood or extreme flood landforms have been documented for LEB rivers by Pickup (1991), Patton et al. (1993), Bourke (1994), Bourke and Pickup (1999), Nanson et al. (2008), and Wakelin-King (2010). Palaeodrainages and their influence on modern landforms have been documented for (inter alia) Lake Lewis (English 2001), the Lachlan River (Kemp and Rhodes 2010), Lake Amadeus (Chen and Barton 1991), arid Western Australia (Clarke 1994). Australia's climate history is reviewed in Pillans (2005), and the timing of dunefield and gibber development with aridity is discussed in Fujioka et al. (2005) and Fujioka et al. (2009).

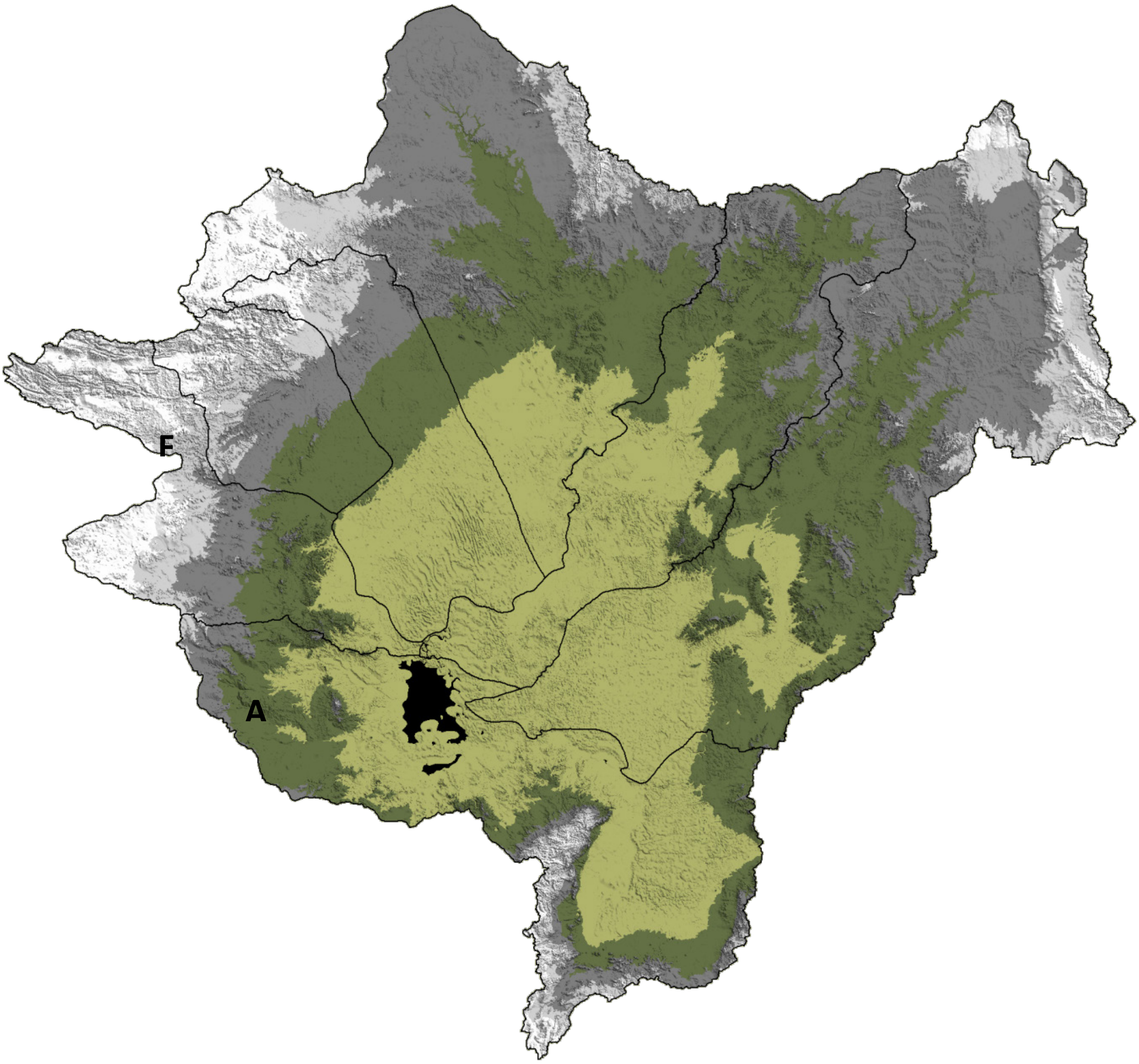


Fig. 49 Digital elevation model of the Lake Eyre physiographic Basin.

The basin is very low-relief: the great majority of the basin lies below 300m AMSL. Elevations -15 m to -9.5m (modern lake-full level) black, -9.5m to 400m, in 100 m increments, pale green, dark green, dark grey, pale grey and 400-1354 m white. Catchments boundaries (as defined by Geoscience Australia) are black lines. F, Finke catchment; A, Arckaringa Creek.

A2 Geomorphology

A2.1 Mid-Finke River

Valley Setting

The Finke River leaves uplands and extends south-easterly across the Henbury and Rodinga 1:250,000 map sheets. From its junction with the Hugh River it flows south then east across the Finke 1:250,000 map sheet. Duguid (2013, his Fig. 2) defines the mid-Finke River as starting where the river exits the ranges near Running Waters and finishing near Pascoe Springs; the coordinates for these points are 132.90°E, -24.35°S, and approximately 133.84°E, -24.96°S. The lower Finke River extends to ~45 km east-southeast from Aputula (Finke) township (134.97°E, -25.77°). Duguid (2013) subdivides the mid-Finke River into the Henbury reaches (from the uplands to approximately the Palmer River junction) and the Idracowra reaches (from the Palmer River junction to the lower Finke).

The channel belt (see Glossary) of the palaeo-Finke River has carved a valley, defined in this report as being where floodplains or terraces meet dunefield or rock, and where there is a clear change in level. Valley edges often have exposures of regolith or sedimentary rocks, and many have a distinctive bordering sand dune, in which the dune crest follows the valley edge even though the nearby dunefield's crests trend in some other direction.

In the Henbury reaches the palaeodrainage valley is relatively narrow. Abundant nearby Amadeus Basin rocks, though not forming uplands as they do in the central Australian ranges, are still a constraint on the valley width. Surrounding land surfaces are a mixture of patches of low sand dunes or sand sheets, and wide areas of flat rubbly outcrop, shallow subcrop, and coarse alluvial fans (Fig. 50). The modern channel abuts the valley margin or the palaeoriver's terraces to a greater extent, and the orientation and bends of the modern channel do not differ greatly from those of the valley. In the Idracowra reaches the land surfaces around the palaeo-Finke valley are dominated by deep red, highly organised sand dunes. Belts of outcrop and shallow subcrop occur but are widely separated; Cainozoic-age sediments are more dominant (Fig. 50). The modern channel abuts the valley margin or the terraces to a lesser extent.

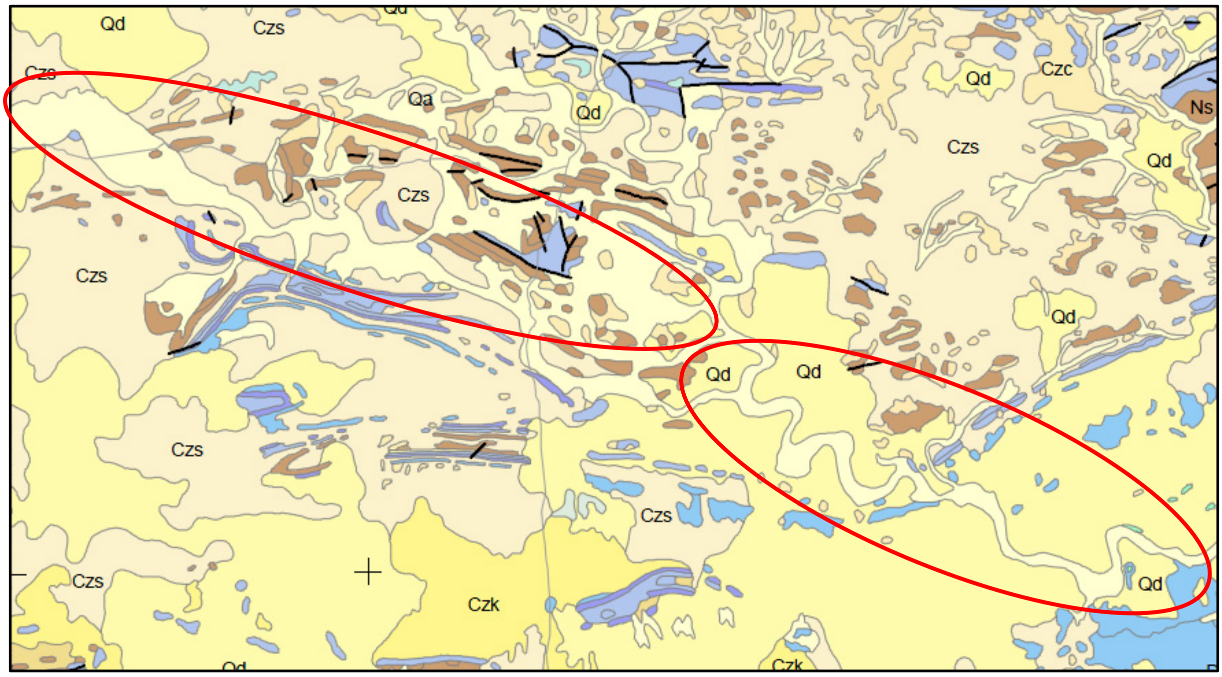


Fig. 50 Geology map of the mid-Finke River (very pale yellow sinuous shape).

Henbury reaches, upper left red outline, are surrounded by outcrop of rocks (coloured shapes) and regolith (light tan, unit Czs). Idracowra reaches, lower right red outline, are mostly surrounded by dunefield (yellow, unit Qd). 1:1 Million geological data, from MapConnect, Geoscience Australia.

Landforms and Sediments: Further Comments

Runoff slopes will shed rainwater, forming important erosion and catchment areas and influencing the direction of drainage network development.

“Old dunefield” is an informal designation, indicating a working hypothesis that these dunefields have had their present character for a very long time; that they are older than the terraces. Their landforms indicates that they have not been involved in fluvial processes: dune organisation is coherent over a wide area, and crests are very well-defined. They may represent a relict land surface. Dune sand is well-sorted, demonstrating aeolian transport, and the grains’ deep red colour is distinctive. The lack of pale grains demonstrates no admixture of alluvial sediments. In some cases old dunefield sands may find their way into the fluvial system, but this is not common. As they are not actively part of the fluvial system, they are low priority in this study.

Terraces are fluvial deposits of the palaeo-Finke River. Though not usually part of present-day fluvial processes, they may be affected by externally-driven erosion paths. Some reaches have several levels of terraces. Upper terraces are older and have been less modified by past fluvial action: their sand dunes tend to be more coherent with moderately-well defined crests. Lower terraces have been more modified by past fluvial action, their sand dunes tend to be lower and poorly defined, or sand may be present as sheets or patches; interdunes may be floodplain surfaces or claypans. More detailed geomorphological study will certainly find greater complexity, including instances where the distinction between terraces or between old dunefield and terrace is gradational.

Terrace sediments are dominantly sand. Two grain populations are indicated by grain sizes (less well-sorted than dunefields) and grain colours (red, orange, or pale): terraces are a mixture of alluvial and dunefield sands. Since dunefield development occurred at certain times in the recent geological past, and since it has not been an ongoing process up to the present day (Maroulis et al. 2007, Fujioka et al. 2009, Cohen et al. 2010), it is possible to use dune coherence and crest definition as a rule-of-thumb time marker. The terraces were interacting with the river at a time when dune formation had already occurred, and was to some minor extent still occurring. Upper terraces were formed earlier, when dune creation was more active, and lower terraces were later, when dune creation was lesser.

The Finke River modern channel includes the thalweg, and generally (not necessarily always) has the lowest-elevation surfaces in the river. The modern channel is notable for the very pale to white colour of the Finke's clean quartzose sand bedload. As this colour is consistent from the uplands down to the lower Finke River, and is also consistent with other central Australian rivers (e.g. Todd River), it is probable that the Finke River's bedload derives almost entirely from its central Australian uplands.

The modern floodplain is darker than the channel on Google Earth images; its grey to grey-orange tone reflects the more silty sediments and more consistent vegetation cover. Sand is the dominant sediment: grain colour is a mixture of buff to white alluvial sands and pale orange sands that are probably dune sands that have undergone a significant degree of fluvial transport. Sandy patches or low dunes on the floodplain, or grain populations containing darker orange grains or a greater proportion of orange grains can occur where there is local input of dunefield material. The silty and bulldusty patches are from the suspended sediment load which is deposited over the floodplain, however it is evidently a minor component of the sediment load. Unlike the terraces, modern floodplain has no dune development. Different floodplain levels can reflect different ages of the floodplain construction, or floodplain construction during different flood heights, or both. Regardless of the age and origin of individual floodplain elements, the location and elevation of each landform defines its present-day inundation frequency, and thus the density and type of vegetation it supports.

Although the mid-Finke River (and other central Australian rivers) has a (generally) unvegetated channel and a (generally) vegetated floodplain, this is unusual in comparison to other Australian drylands rivers. Many have at least some components in which vigorous in-channel vegetation occurs, including very large trees.

Valley-Scale Landforms and Modern Hydrology

GAB recharge zones in the Finke area are discussed in Matthews (1997), and Herczeg and Love (2007).

Assuming the alluvial aquifer corresponds to the contents of the incised palaeodrainage valley, its extent could be mapped using DEMs and geomorphology to define the lateral valley edges, and geophysical methods to determine depth and bottom topography (e.g. Wilford (2009).

River Behaviour and Habitat

No-Flow Stage: Creek water infiltrated into channel sediments is available to sustain plant growth. Though plant establishment is discouraged by channel sediment mobility, trees that already exist in-channel (in multithread channel segments, or floodplain remnants that have been reoccupied by the modern channel) will be supported. In the drylands, preferential tree growth along watercourses places substantial roughness elements along the drainage pathway, substantially contributing to fluvial behaviour. This is a defining character of Australian drylands rivers.

Low-Flow (in-Channel) Stage: Flow energy will be within the lower flow regime. Bedload transport is likely to take place at least at the channel centre (the grain size and amount of sediment moved will vary from flow to flow and place to place). There is no information on the depth of sediment that may be moved, however it is would be on the order of 0.2-1 m amplitude 2D sand dunes. During waning flow after a large flood, sediment-laden water may fill any abandoned channels which are still connected to the main channel. Channel sand mobility discourages plant establishment, although small or rapidly-growing species may take root in places.

High-Flow (Channel + Floodplain) Stage: At high flows (flood peaks), the entire channel will be actively transmitting water at moderate to moderately high energies. Flow energy will be:

- highest where channel boundary conditions promote turbulence (channels along valley margins, rocky outcrop) or the channel is constrained (narrow channels cut through floodplains),
- high in the clearly-defined single channels,
- lowest in the wide shallow channels.

In the clearly-defined single channels, sand transport will take place as 2D dunes, with amplitude on the order of 1-2 m. Depending on flow volume, some reaches may exhibit high-energy flow down the channel centre, with bedload transport as gravelly 2D dunes of moderately low amplitude, or high-amplitude 3-D dunes. Sediment transport in the wide shallow channels will depend on bed topography: deeper sections may exhibit 2D or 3D dunes, whereas the highest sections may experience little sediment movement. Existing waterholes will be scoured and new waterholes might form.

At any reach, the degree of floodplain inundation depends on the height of the flow and the elevation of the floodplain element. For any flow, energy will be highest where the water is deepest (low elevation landforms), where there is a possibility of flow (old channels), and where there is little vegetation (belts of trees and bushes are roughness elements which substantially retard flow).

Floodplain storage is likely to be an important part of the Finke River's sediment transport processes: a grain's path from uplands to floodout will involve slow episodic travel down the channel, punctuated by long periods of time resident on the floodplain.

Very High to Extreme Flows: Low recurrence interval, high magnitude floods create the landscape in which smaller flows move and deposit sediments (Gupta 1983): their effects persist in the landscape. Highly variable flow regimes (such as the LEB) are especially liable to the effects of extreme flow events, (e.g. the Todd Rivers, Bourke 1994).

In centennial to millennial floods, channel sands are likely to move in 3-D dunes, and the channel centre is likely to display high-energy wave trains exhibiting supercritical flow (see Tinkler and Wohl 1998). During the flood peak, sediment transport down-channel will be rapid, and channel sediments may be mobile to a depth of >3 metres. During the 1988 Todd River flood, the bed centre was mobile to a depth of 3 m (Barlow 1988), and that was higher up in the catchment (so probably less contributing area than the mid-Finke) and only a 2% annual exceedance probability (in the old terminology, a 50-year flood). Bedload is likely to include active transport of gravel and cobbles, while sand will be in suspension load.

Splay sediments deposited downstream from a high-energy reach may:

- be dissected into elongate bars during waning flow or subsequent flows, in which case they form multithread channel segments (Fig. 14),
- or block the pre-existing channel, in which case subsequent flows will divert around the splay and force the river onto a new path (Fig. 14),
- or, if deposited in-channel where the channel has the freedom to adjust its planform, create a wide, shallow channel (Fig. 13).

A2.2 Lower Finke River

In the distal lower Finke River, the bedload is well-sorted medium fine sand. Colour is pale orange overall, and on a grain scale the orange grains are outnumbered by the pale grains. The sediment in transport here is a mixed-population sediment, containing a proportion of old floodplain, terrace and dune sands from upstream. It is different in this respect to the mid-Finke sediments which have few orange grains. This is an indication that any pulse of post-European sediments, released from the Amadeus Basin ranges, has not yet reached the Finke Floodout. However, a definitive answer to this question would require more research.

Near New Crown Station homestead, the river's characteristics are transitional to those of the proximal floodout. The modern channel is very wide and shallow with a multi-level bed, and highly variable width. Small anabranches occasionally depart and rejoin the modern channel, but it is generally single-thread. There is an alternation between relatively narrow (100-200 m) reaches with reasonably well-defined boundaries, and wide (700-1700 m) reaches which are chaotic. The narrow reaches are only 10-30% the length of the wide reaches.

The channel has scattered populations of feral athol pine, but no gum trees (indicating that it is quite recent: Angus Duguid pers. comm. 2013). On more elevated portions of the channel, sandy shadow bars and hummocks (0.2-0.8 m) are deposited behind slightly older trees. Waning-flow channels are cut into the broader channel: they have small (30 cm) transient banks. The broader channel has erosive banks (~1.5-2.5 m) against the floodplain. The floodplain vegetation is patchy but generally without definite boundaries; it is dominated by coolabah, indicating inundation on a decadal scale (Angus Duguid pers. comm. 2013). The floodplain surface is swaley with hummocks, hollows, and flood trash. In some places elongate streamwise swales 2-10 m broad indicate former flow paths, but clearly-defined old channels characteristic of the mid-Finke are rarely present. The area is heavily trampled by cattle. The river valley is bordered by old dunefield to the north, and to the south by a low hill consisting of weathered Cainozoic sediments which include rounded clasts of Mesozoic shale, and which are overprinted by calcrete. The valley margin has a very silty bench indicating deposition of suspended load during high flows.

Flow strength and sediment transport conditions are not clear from this brief investigation, so there is no information to offer for conditions during fish migration. However, as there are no waterholes or aquatic habitat the question is probably irrelevant to this study.

The floodplain supports a healthy but not especially rich vegetation community. In-channel, it is clear that athol pine can survive in the mobile channel sediments in a way that gum trees cannot, and also that in-channel vegetation is trapping channel sediments. Athol pine in the Finke River is documented by Fuller (1993). The role of post-European management actions (changes to flow regime and sedimentation, infrastructure development, and vegetation establishment along the river banks) in changing the River Platte (USA) from braided to anabranching planforms is described in Murphy et al. (2004). Tal and Paola (2007) describe modelling of vegetation-induced changes to river planform. It is possible that in the lower Finke River, athol pine may be a risk factor for changing fluvial processes in a similar way.

A2.3 Finke Floodout Complex

The term ‘floodout’ is in widespread use by landholders across Australia, and probably has been since early (European) settlement. It was common enough to be used in Australian geomorphological literature in the 1970s (Mabbutt 1977, his p. 171 and Fig. 41). Floodout geomorphology and processes were first defined in Australia by Tooth (1999) and are also discussed in Bull (1999) and Wakelin-King and Webb (2007b).

In the Finke Floodout there are wide areas in which late-stage dune development has taken place over alluvial sediments, and/or which have been modified by fluvial action during or after dune formation (the *mixed dune-alluvial areas*). If terminology was to be consistent with respect to landform morphology, these fluvial-aeolian areas would have been termed terraces (as in section 2.1, for the mid-Finke River). However, this study’s geomorphology is process-based (see section A1.1), and the areas in question are probably not old floodplain in the same sense as the mid-Finke terraces are. For the purposes of this study and pending further research, the descriptive name will be used.

Sediments and Depositional Bedforms

Along some channel margins, and at the distal end of one of the channel tract's splays (Fig. 20), where bedload is deposited on the floodout, the channel sediment is clean, very well sorted medium-fine sand with a mixture of pale and orange grains. Surrounding floodplain is also sandy, but carries a higher proportion of silt. No depositional bedforms were observed. Trees with partly-buried trunks, and the generally loose (non-indurated) nature of the sediments indicated modern deposition.

The main Finke Floodout's deepest swamp contains a long deep waterhole. The channel sediment is mud with a high proportion of slaking clays. The area is heavily trampled by stock, and no depositional landforms remain, but the channel appears to host bank-attached bars consisting of mixed silty fine and medium sand. The nearby floodplain sediment is crumbly slaking clay, and untrampled ground showed crumb-sized mud aggregates. The riparian zone is heavily vegetated by large trees (coolabah and red gum) and understory. The nearby swamp is vegetated by more widely spaced, smaller coolabah and less understory.

The reformed Finke River channel (south of the choke) carries fine to medium fine, occasionally medium coarse quartzose sand; there is no silt. The grain population is a mixture of pale and orange grains. The bedform is waning-flow flat beds. Because this channel is not continuous with the channels of the channel tract, the sand transported down this channel is remobilised alluvial sands from the choke area and from the banks and bed of the channel itself. The floodplain is red-brown silt and fine sand. The narrow riparian zone is heavily vegetated by trees and understory; there is no in-channel vegetation.

Hummocks created by vegetation trapping aeolian sediment can persist after the plant has died. Along some dune flanks and crests, the vegetation was cane grass and the hummocks (1-1.5 m scale) were very pronounced; although elongate, they did not align to any particular direction. Along mixed dune-alluvial surfaces the vegetation was old man saltbush and the hummocks were poorly defined and low (0.2-0.4 m scale). (Plant identification and role in trapping aeolian sediment, Angus Duguid, Peter Jobson pers. comm. 2013.)

The Coglin Creek floodout's sediments are not sandy: they are silty clay with gilgai features (crabholes, and a reticulate network of small channels within a downvalley swamp), and it is vegetated by Queensland bluebush (vegetation identification Angus Duguid pers. comm. 2013). Gilgai is also apparent in the interdune corridors of the Mayfield Swamp dunes. The muds are brown to pale grey, and crumble into small pellets which slake quickly in water. These characteristics are unlike most of the Finke River catchment, instead resembling the small circular to ellipsoid gilgai swamps that occur at outcrop or subcrop of silcrete-capped Eromanga Basin mudstones (e.g. 7 km west of New Crown Homestead, or Wantirna Swamp, on the Stuart Highway, or the Dalhousie Springs outflow area). The Coglin Creek muds are derived from Eromanga Basin outcrop of the Beddome Range to the west. The

Mayfield Swamp muds may possibly derive from shallow Eromanga Basin subcrop, although it is more likely to be at least partly alluvium of palaeodrainages from the rocky area around Andado homestead to the north.

A2.4 Arckaringa Creek

Physiography

The western boundary of the Lake Eyre Basin marks a very significant physiographic divide between the Western Plateau and the Interior Lowlands Divisions (as defined in Pain et al. 2011). The Neales Catchment is at the western boundary of the Interior Lowlands Division, falling within the Oodnadatta Tablelands physiographic region (“silcrete-capped low tablelands”). The easternmost part of the Western Plateau Division is the Great Victoria Desert Dunes region ("west-east longitudinal dunes"). In this region, red earths (red-brown to red earthy soils; Belperio 1995) support mulga grove communities. The vegetation patterns reflect the primary flow paths and relative abundance of the unconfined sheetflow which is the drainage network in these areas (see Wakelin-King 1999).

It is clear from the DEMs that the Neales Catchment rivers are extending into the Great Victoria Desert Dunes region by headwards erosion and channel extension. Conceptually one could imagine the Great Victoria Desert Dunes region as a shallow topographic basin, cloaked in old red soils, which is being nibbled into along its eastern edge by the encroaching Lake Eyre Basin western rivers. (This is a highly simplified version of an undoubtedly complex story. It is given here for the purposes of understanding processes in the upper reaches of the Neales Catchment.)

Traversing from beyond the catchment boundary down-section towards the main axis of Arckaringa Creek, the following sequence emerges:

- dense mulga grove communities growing on a substantial thickness of red earth soils, no gibber or pebbles, drainage lines are unchannelled;
- less dense mulga communities, small gibber or heavy scatters of ironstone pebbles (known as "buckshot gravel" in South Australia), a few gullies;
- increasingly sparse vegetation, increasingly heavy gibber groundcover, more and larger incised gullies, silcrete and ferricrete exposed in gully walls;
- dense gibber groundcover supporting sparse small scrubby vegetation, silcrete outcrops and scarps, incised gully and creek networks supporting trees, gully walls show silcretes (both vadose and phreatic) and highly weathered rock outcrop, in some places showing the boundary between silicified and non-silicified regolith. Laminar calcrete overlies some highest-elevation silcrete.

Silcrete scarps and outcrops occurred at various elevations: there are undoubtedly several layers of silcrete, and (as a duricrust) no likelihood that silcrete layers will follow laws of superposition.

Geology

One of the many Tertiary-aged rocks in the Neales/Arckaringa catchment is the Mirackina Conglomerate (Barnes and Pitt 1976), which occur as a long thin line of flat-topped hills to the west of Arckaringa Creek and crossing Lora Creek. This unit originated as a valley-bottom fluvial conglomerate; the sinuous line of its outcrop is a reflection of the original river's location. Differential erosion has now led to a topographic inversion. The Mirackina Conglomerate's significance with respect to palaeodrainage is discussed in Wakelin-King (2010). The conglomerate is also significant as being a substantial source of very coarse sediment into Arckaringa Creek's main axis.

Mudrocks of the Great Artesian Basin often contain a percentage of swelling clays. Where these are exposed near the ground surface, they are often expressed as gilgai or stony gilgai. In gilgai soils, repeated shrink-swell episodes drive slow soil circulation, heaving the ground surface into uneven swellings and depressions. Gilgai soils are characterised by very deep cracking, and deep macropores which may extend metres down into the subsoil. Discussion of those aspects of gilgai which relate to runoff retention can be found in Wakelin-King (2011).

Sediments and Bedforms

The wider valley downvalley of the Lora/Arckaringa confluence shows sediment lobes that will be related to pulses of sediment coming down the drainage axis in single flow events; see Wakelin-King 2010.

The Wintinna landholder reports that during the 1980s, big floods in Oongudinna Creek bought down huge amounts of gravel and deposited them in the reach near the homestead, increasing the amount of gravel beyond what was normally present in the creek, and bringing gravel up onto the floodplain near the house. The reach near the homestead is just downvalley of a reach which is constrained on either side by outcrops of silcrete (that is, flow entering the homestead reach will experience a loss in stream energy and would deposit bedload). The homestead reach is 4.5 km downvalley from the channel segment exhibiting high-energy flow structures (Fig. 44). The homestead reach displayed high bank-attached bars, silty banks with scoured edges, very large mid-channel trees with scours between the tree and the bank, in-channel lines and double lines of large gum trees set on bank-attached bars which are higher than the nearby main channel. The landforms and the landholder's report are consistent with a pulse of gravel being transported from upstream and being deposited in this reach.

Arckaringa Creek's channels are overwhelmed by coarse sediments transported from areas of very active erosion around the zero-order and 1st-order channels. As a whole, Arckaringa Creek is transport-limited. The only channels observed to be not storing bedload are the lowest-order gullies incising into duricrusts around the fringes of the uplands. At a site near the Stuart Highway 51 km south-east from Marla, the hillslopes leading into the gullies were observed to carry abundant loose cobbles and pebbles of regolith. In contrast, the gullies were scoured clear of loose material. Downslope, in widened gullies, gully-margin bars of coarse material was accumulating. This suggests that while gibber plain hillslopes are transport-limited (local rainfall runoff is only occasionally strong enough to wash clasts into the gullies), once water has accumulated in the gullies it is frequently strong enough to transport coarse sediment. This indicates that rainfall on the gibber plain is a locally important geomorphic agent. Furthermore, it suggests that hillslope erosion may be marginal – that only some flows are strong enough to transport and erode. If there is a threshold, it may be exceeded more often in convergent zero-order channels, and less often in divergent hillslopes. This implies gully-head extension will be more rapid than gully-wall or gully-nose erosion, which will affect the relative speed and direction of drainage network expansion. This may explain the dendritic nature of the drainage network as the river expands into the uplands, and the elongate shape of many remnant tabletop hills (Fig. 51).

The hypothesis that the high degree of coarse bedload discourages waterhole formation is based on the relative numbers of waterhole-sized channel in the Neales River and Arckaringa Creek, in conjunction with their strongest point of difference (amount and size of bedload); and flume studies demonstrating that increased sediment load leads to a decrease in turbulence, flow velocity, and unit stream power (Zhang et al. 2010).

Fig. 51 Linear extension of drainage networks, Lora Creek.

Drainage 100 km north-northwest from Coober Pedy, black scale bar = 2 km.

A3 Glossary

Alluvial aquifer water: see Groundwater.

Annual Exceedance Probability: the probability that a given flow size will be exceeded in any one year. This term is sometimes preferred over the Recurrence Interval (e.g. 1:100 year flood), since it is quite possible to get e.g. several "100-year floods" within a 100 year period.

Aquitards, aquicludes: retard or prevent throughflow of groundwater.

Avulsion: see *Channel relocation*.

Basin

- (topographic): A depression in the ground surface: e.g. the Lake Eyre Basin (LEB), the continent-scale basin with rivers that flow towards the lowest point at Kati Thanda-Lake Eyre.
- (geological): An accumulation of sedimentary rocks, usually below the ground surface: e.g. the Great Artesian Basin, the Cooper Basin. Some Cainozoic-age (Cz) sedimentary basins have been referred to in the geological literature as the Lake Eyre Basin, referring in this case to a geological basin, not the LEB. They have been given this name because their distribution underlies the present-day LEB. In this report, to avoid ambiguity, such sedimentary basins are referred to as Cz basins.

Bedload: sediment that is bounced, dragged, or rolled along the river's floor during sediment transport. Typically bedload is the heavier grains. Cobbles, gravel, and coarse sand are almost always bedload. Sand is usually bedload, but rivers that have strong, high-volume flood peaks (like the Finke River) can transport sand as suspended load. During waning flow, as the stream power decreases, bedload transport ceases. First the gravels cease to move, then the sand is deposited in shapes that reflect the river's energy levels (see bedforms), and finally at the close of flow the sand is deposited in flat sheets.

Bedforms: the shapes in which sediment is deposited from flowing water. Bedforms reflect the river's energy at the time of sediment deposition. "Sand waves" (2D dunes) indicate moderately low energy, and flat sediments usually indicate either extremely low energy or (rarely) extremely high energy. The grain size of the sediment under transport also reflects the river's energy: a gravelly 2D dune indicates higher flow energy than a sandy 2D dune.

Channel belt: during normal processes of channel evolution, a channel will occupy different parts of the floodplain over geological time. In Fig. 52, the channel belt (orange dashed lines) contains the places where the channel is or has been (blue lines).

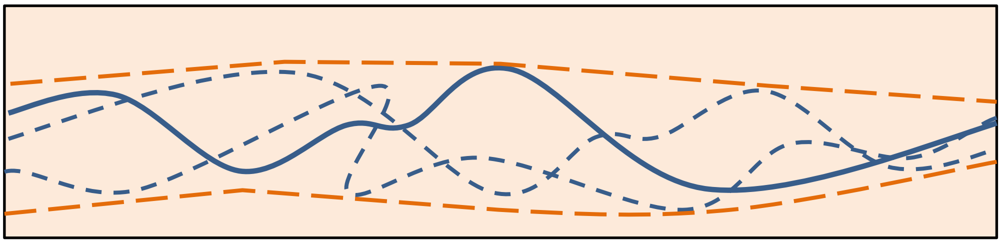


Fig. 52 The channel belt.

Channel order: a standardised way of describing where a reach is in the hierarchy of the drainage network. A first-order channel is the very smallest, where two first-order channels join the next reach downstream is a second-order channel, and so on. A zero-order channel is an unchannelled swale or drainage line upslope from the first-order channel.

Channel relocation, also known as **avulsion**: where a channel moves non-incrementally from one place to another, often in an episodic or catastrophic fashion. Channel relocation is promoted by variable flow regimes and episodic styles of sediment transport.

Crabhole: see *Macropore*.

Distal: see *Proximal*.

Duricrust: a regolith rock formed by the precipitation of a mineral from groundwater or soil water. They are named according to their dominant chemistry (silcrete, calcrete, ferricrete, gypcrete). Duricrusts can cement or even replace the sediments they form within. Duricrusts are important landform elements. Silcrete in particular is the dominant landscape element across wide areas in drylands Australia.

Floodout (noun): a fluvial landform in which the channel disappears, the reach becomes 100% floodplain, and down-gradient flow takes place as unconfined sheetflow. Floodouts can be terminal (at the end of the drainage network) or intermediate/mid-creek (the channel re-forms down-gradient of the floodout) (Tooth 1999). The verb is "**floods out**". Example: 'The Todd River has many mid-creek floodouts, such as on Emily Plain where it floods out just east of the airport.'

Flood runner: a swale or depression, usually across the floodplain, which carries water during high flows. Flood runners may be created from old abandoned channels, or floodplain scour landforms.

Formation water: see *Groundwater*.

Gilgai: a soil landform in which the soil surface is very irregular, with highs and lows resulting from soil heave and circulation during wet-dry cycles. Gilgai is usually characterised by patterned ground, crabholes (deep, usually steep-sided small holes created by shrinkage as the soil dries), very intense mud cracking, and small soil aggregates which may either slake in water, or resist slaking until the wet aggregate smeared. Gilgai soils are usually strongly associated with swelling-clay mineralogy. Eromanga Basin mudstones are known for their swelling clays.

Groundwater: water which is beneath the ground's surface, in this report divided into:

- **hyporheic water**: for the purposes of this report, water from recent flows which has sunk beneath the surface of the channel and inundated floodplain;
- **alluvial aquifer water**: for the purposes of this report, modern to nearly-modern water held within the alluvial sediments of the Finke River valley (alluvial sediments deposited by both the modern Finke River and the palaeo-Finke River);
- **formation water**: water that is held within rocks or sediments, and which is not modern.

Hyporheic water: see *Groundwater*.

Jump-up: a colloquial Australian expression for a landform that rises abruptly and steeply, in a somewhat unusual or unexpected way. The term is used at all scales, from major landmarks to small features a few metres high.

Macropore: a void through the soil which is large enough to see (as opposed to the small pores between soil grains which is the more usual expression of soil permeability). Macropores are characteristic features of gilgai soils; they can form large branch networks of spaces, several metres in depth. At the ground surface they are usually expressed as steep-sided irregular holes, known as "crabholes" in parts of inland Australia.

Medial: see *Proximal*.

Order: see *Channel order*.

Proximal, medial, distal: describing relative distance along a drainage network, respectively closer to the beginning, middle sections, closer to the end.

Recurrence interval: see *Annual Exceedance Probability*.

Regolith: weathered rocks, bleached profiles, ochre, duricrusts, soils, loose sediment: “everything between fresh rock and fresh air”. Regolith is formed by the action of weathering over geological timespans.

Runoff slopes: used in this report for hills, slopes, outcrop, shallow subcrop, regolith, or anything that isn't dunefields or alluvial landforms.

Source-bordering dune: a dune in which the long axis lies along the place from which its sand came; typically, a lake or river channel. In the Strzelecki Plain, source-bordering dunes formed on the downwind side of Cooper Creek palaeochannels as increasing aridity exposed channel sediments to wind erosion (Cohen et al. 2010, Wakelin-King 2013).

Splay: an expansion bar; the sediment deposited as flow becomes unconfined and loses stream power; in Lake Eyre Basin rivers, waterholes are commonly associated with a downvalley splay at their termination. Splays are often elongate or fan-shaped, and may be rich in coarse sediments which have been excavated during waterhole creation.

Streamwise: something that is oriented in the same direction as dominant stream flow.

Thalweg: the linear flow path of the lowest points in the channel, the last places where water flows at the close of a flow event.

Underfit river: a river which flows within a fluvial setting that was created by a much larger version of the same river, which existed in the geological past.

Waning-flow deposit: see *Bedload*.

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