Natural Resources
SA Arid Lands

Geomorphology of the Diamantina River Catchment (SA)

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Australian Government

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Cover image:

In Warburton Creek's active meander bends, outer-bank retreat is matched by inner-bank floodplain creation.

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1 Acknowledgements

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In 2014 I was given a priceless opportunity to traverse parts of the Simpson Desert dunefield by Andrew Harper of the Outback Camel Company. During that trip I learned how to spot Neogene fossil fragments, thanks to Aaron Camens and the late James Moore (Flinders University). James, a postgraduate student, was killed in a road accident later that year, and a palaeontology scholarship in his name is accepting donations at www.gofundme.com/lzmga8.

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2 Executive Summary

The Diamantina River brings monsoonal rainfall into the drylands of northern South Australia. It hosts the terrestrial and aquatic ecosystems which are fundamental to the region's amenity and economy. The geomorphology of the river – its landforms, and the processes that create and maintain them – underpins the ecological processes that sustain the area's biodiversity.

This report is the first whole-of-catchment description of the geomorphology in the South Australian section of the Diamantina River. It is based on a project combining field observations with regional-scale spatial investigations. It presents results indicating that the Diamantina River differs in significant ways from other Lake Eyre Basin rivers. On the basis of landform suites and the fluvial processes that they represent, the study area is divided into four management zones (Fig. 1).

The Diamantina Fan (Birdsville to Goyder Lagoon) is a low-angle alluvial fan. It has three principal flow paths: the Diamantina main channel, the Eleanor Creek flow path, and the Gumborie Creek flow path. The Diamantina main channel is a sinuous continuous channel flanked by alluvium; the channel is deep and essentially permanent, providing a stable base for aquatic ecosystems. Many reaches have wide and well-vegetated riparian zones in the scroll plains. At the downstream end of the Diamantina River, the alluvial fan is prograding into Goyder Lagoon. At this point the Diamantina River splits into the Andrewilla and Yammakira branches, separated by the Andrewilla Sand Plain. Eleanor Creek and Gumborie Creek flow paths are floodplain-level unconfined flow with a discontinuous string of widely-separated channel segments. Eleanor Creek is an important contributor of water to the Andrewilla branch of the Diamantina River. The drivers of the Diamantina River's fluvial style are the alluvial fan's relatively steep downvalley gradient, the almost unconstrained valleys with local topography constraining the main channel, and a relatively moderate sediment load of mixed composition (fine sand, mud aggregates). The Diamantina River's signature fluvial processes are meandering, distribution of channel water to the floodplain via bank-breach distributary channels, and unconfined floodplain flow.

Eyre Creek (South Australian border to Goyder Lagoon) is the downvalley termination of the Georgina River. It consists of multiple semi-parallel interlinked flow paths in which water flows down Simpson Desert interdunes. The flow is essentially unconfined (except in local topographic pinch points) and extremely low-energy, without sediment transport. Consequently, there are few channels and waterholes, and no aquatic refugia. However, Eyre Creek's wide slow flow supports broad densely-vegetated areas that are likely to be important terrestrial ecosystems. The driver of Eyre Creek's fluvial style is the distribution of flow down multiple interdunes, and its signature fluvial process is unconfined flow.

Goyder Lagoon is a broad shallow valley with no continuous channels. The few waterholes exist in local high-energy contexts around the valley margins (such as the topographic pinch points creating new Koonchera Waterhole or the Goyder Lagoon Waterhole). Its flow is almost entirely unconfined across the valley floor, with a variety of presently uninvestigated scour processes. There is no significant sediment transport. Goyder Lagoon has wide areas of dense vegetation. The drivers of Goyder Lagoon's fluvial style are its width and extremely low gradient, and the numerous dispersed water entry points. Its signature fluvial process is unconfined flow.

Warburton and Kallakoopah Creeks are incising into Pleistocene sediments, and/or flowing within palaeodrainage lines and playa lakes. Consequently the creeks exist in a valley context that is highly variable but generally more confined than the rest of the Diamantina system. The channels are similar width to those of the Diamantina River zone, but different in depth and profile, and have very restricted floodplains. Many reaches have multiple channels. The creeks carry high sediment loads, derived from remobilised Pleistocene sands. Riparian zones are sometimes narrow. The downvalley reaches of both creeks are quite saline, except where the local Pleistocene sediments are clay-rich. The Warburton and Kallakoopah Creeks' signature fluvial processes are in-channel flow, avulsive relocation, and rapid deposition of fluvial sediments across available floodplains. The drivers of this fluvial style are highly variable flow energy, moderate downvalley gradient, constrained valleys, and abundant sand in fluvial transport.

Three other factors are significant to the study area's water movements and ecosystems. **The unconfined aquifer** can provide deep-rooted vegetation with access to water that is largely independent of surface flows. The aquifer is recharged by Eyre Creek and the Diamantina River, and extends beneath the rivers and also the nearby dunefields. The aquifer is hosted in Pleistocene fluvial sediments; the lithological contrast between the permeable Pleistocene sands and the present-day floodplain vertic muds allows clear expression of the aquifer's influence on surface vegetation and landforms. The separation between ground surface and water table governs whether the aquifer will support vegetation through access to water, or suppress vegetation and promote playa lake formation through near-surface precipitation of evaporites. In Warburton and Kallakoopah Creeks, the unconfined aquifer contributes salinity into the channel, promoting halophyte in-channel vegetation. **Gibber hillslopes** are high-runoff surfaces, and can be an important source of water for local drainage lines (especially Derwent Creek). **Dunefields** are generally low-runoff surfaces, except where impermeable dune palaeosols are exposed.

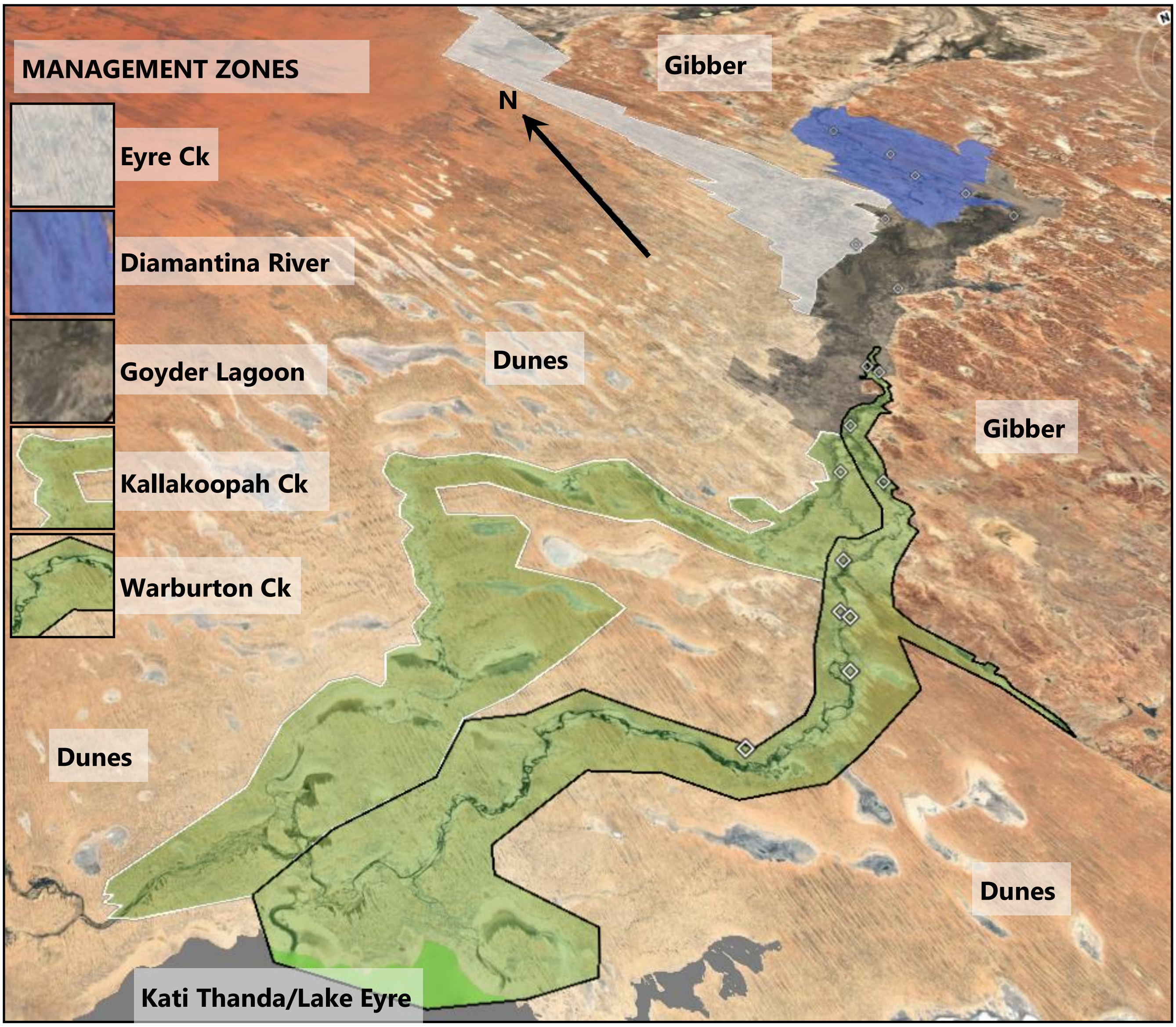

Fig. 1 The Diamantina catchment (SA) and its four management zones (Google Earth).

White diamonds are field locations, black north arrow and scale = 100 km, oblique Google Earth image, looking upstream.

The management implications of this study are:

- Riparian vegetation plays a key role in maintaining channel landforms, including maintaining waterhole depth and distributary offtake sill elevation.
- Recharge to the local unconfined aquifer is important to vegetation communities across the study area. It depends on flows from the upper catchment in Queensland.
- Unconfined flow is a key fluvial process in the study area, maintaining terrestrial ecosystems and routing floodwaters into downvalley fluvial networks (Eleanor Creek, Gumborie Creek, Andrewilla Waterhole, Goyder Lagoon, Warburton and Kallakoopah Creeks). Management practices must consider floodplain-level flow as well as in-channel flow.
- Many channels in the study area are quite dynamic, with active bank retreat as part of meandering, and terrace-edge gullying and bank incision (breaching) being part of highly variable flow regimes. Where a river assessment methodology uses bank stability as an indicator of condition, it is important to recognise when these features are part of the natural landscape behaviour. Furthermore, bank retreat and bank breaching are inherent parts of the processes that create biologically valuable landform suites (scroll plains and distributary channels respectively).
- Vegetation in the study area responds to geomorphology and hydrology, and its density or species richness is affected by e.g. spatial relationships between the ground surface and the underlying Pleistocene sediments, the various fluvial styles, and valley-scale controls on water retention. Where a rangeland assessment methodology uses vegetation as an indicator of condition, it is important to recognise the geomorphological and hydrological factors affecting the terrestrial ecosystems. These factors can vary markedly over quite small areas.
- Some parts of the Diamantina River and Eyre Creek are stable over time and change little, some are more active with visibly evolving landforms, and some areas are changing very rapidly. Within the study area and within the scope of this project, the active areas appear to be changing in response to natural conditions. Over the course of time, extremely large floods can be expected, and they will create change. Managing such changes as landscape renewal (rather than as a problem to be fixed) will be the most sustainable and effective strategy. Such management will include protecting vegetation stabilising new landforms.

The knowledge gaps identified by this study are:

- Goyder Lagoon's fluvial processes are unexpectedly complex. Landform-sediment-vegetation relationships were observed to be present, but are currently undocumented.
- The focus of other disciplines within the science team was on riparian and/or near-channel coolibah, however this geomorphology study identifies more isolated stands of coolibah associated with other landforms. If the coolibah are a keystone species in a near-channel context, what is their role in other settings?
- Lignum is likely to be a keystone species for terrestrial ecosystems in the study area, but its relationships to landforms (especially gilgai features) is not known.
- Floodplain-level discharge volumes are difficult to measure or model, owing to their difficulty of access and the variability of their boundary conditions (surface topography and vegetation roughness). Floodplain-level flow is not usually as significant to a river as in-channel flow, however unconfined flow is an important part of the Diamantina catchment in the study area.
- The identification of landforms that are not within 'normal' fluvial processes, and which host coolibah suggests the possibility of tree cohorts germinated during very large flood events. An interdisciplinary investigation of age-dating coolibah on targeted landforms in combination with hydrological modelling will provide a better deep-time flood history than currently exists. This will provide a better basis for land-use and infrastructure planning, and an improved understanding of mid-continent climate behaviour.
- This study identifies the possibility of Great Artesian Basin leakage to surface across the gibber plains of northern Sturts Stony Desert, suggesting that the plant communities may be groundwater-dependent ecosystems.

3 Introduction

This report documents the fluvial geomorphology of the South Australian sections of the Diamantina River catchment. It is the output of the investigation Geomorphological Assessment and Analysis of the Channel Country – Diamantina River catchment (SA), which was a sub-project of the Natural Resources SA Arid Lands project: Improving habitat condition and connectivity in SA's Channel Country (2013-17). The Channel Country project was an interdisciplinary study, in which geomorphological investigation was undertaken alongside parallel studies in aquatic ecology, plant and bird ecology and hydrology. As well as this present report, the Channel Country project reports are Costelloe (2017), Gillen (2017), Reid (2017), Mancini (2017), Schmarr et al. (2017) and Schmiechen (2017).

This was a baseline study: with the exception of a currently unpublished dissertation on channels, the fluvial geomorphology of Diamantina River has not previously been systematically documented (previous work has focused on geology, ecology, hydrology, palaeontology inter alia). The geographic scope of the project was the South Australian sections of the Diamantina River catchment (including its tributary the Georgina River catchment). The project focussed on factors affecting aquatic ecosystems, thus field investigations around primary flow paths and channels were given priority. The geomorphology project timeframe encompassed 2 field seasons (2014 in Kallakoopah Creek from Mona Downs to approximately Anarowdinna Waterhole, including the dunefields to the north; and 2015 waterholes as shown in Table 1). The objectives of this study were to

- develop an overview of the landscape processes characteristic of the Diamantina River in South Australia, especially those which differentiate it from other Lake Eyre Basin rivers;
- identify landscape processes which are most significant in the maintenance of healthy river ecology, and place them within their regional context with respect to fluvial connectivity and continental-scale climate;
- assess in general terms (as far as is possible within the scale of this project) those landscape processes which are compromised by present land use, and where relevant identify the risks and opportunities for pest control at the landscape level;
- communicate to other team members and to stakeholders the role that landforms play in contributing to the health of native biota.

This report is organised in two sections: the results of the study are the main body of the report, and supplementary details of methodology, terminology, data, citations and references are located in the Technical Appendix. Location coordinates are decimal degrees, datum WGS84. North is to the top of all images unless otherwise stated.

3.1 What Is Geomorphology?

Geomorphology is the geology and spatial science of landscape: how it originated, and how it operates in the present day. It is important because all habitats are hosted in some kind of landform. No ecosystem can be properly understood without knowledge of the processes that shape and maintain the ecosystem's physical environment. This goes beyond description of an organism's direct surroundings (its habitat): geomorphological processes are inter-related across all scales of space and time, from centimetres and moments to catchments and millennia. Events that take place far away or in the distant past have immediate relevance to ecosystem well-being. For example, an aquatic invertebrate's habitat – a small patch of mud in the depths of a waterhole – may be in good condition, but ultimately the invertebrate's well-being depends on the integrity of the waterhole, which could be threatened by an expanding gully network initiated decades ago and kilometres away.

Humans can affect landforms either directly (such as by bulldozing) or indirectly (such as by clear-felling vegetation and changing the geomorphic processes to such an extent that a landform is irrevocably changed). On the other hand, landforms themselves are often naturally in the process of changing. Sometimes the change is slow and incremental, sometimes (in threshold-driven systems) it is rapid and catastrophic. It is valuable to determine, as much as possible, which landscapes and geomorphic processes are in approximately natural* condition, and which are not. This is a first step in prioritising management actions.

*In this context, the integrity or 'natural' quality of landforms refers entirely to geomorphology, and has no implication for vegetation. A site may be in near-original condition with respect to landforms, at the same time as having vegetation communities which are compromised by grazing. Also, in this context, 'natural' is taken to mean post-Last Glacial Maximum (~12-18 thousand years ago (ka)), and immediately pre-European, while recognising that a landscape's processes change and develop over geological time, and that Aboriginal inhabitants also managed their lands.

Methodology

Geomorphology is investigated by a combination of remote and field techniques, in which the attributes of individual landforms are placed in their spatial context with respect to other nearby landforms, and with respect to broad-scale landscape features. Because fluvial features both form and are formed by flow events, the landforms (shape and size) and sediments (grain size, and depositional or erosional structures) also relate to flow conditions. Plant communities (species, abundance, size) are related to inundation frequency, flow energies, and underlying sediment; and they also influence scale and location of erosion and deposition. The types of and spatial relationships between these elements can therefore be used to reveal habitat- and reach-scale river behaviour. On a broad scale, the spatial and temporal relationships between site-specific sets of fluvial processes demonstrate process gradients across close and distant environments, and also demonstrates process relationships over timescales that that affect biota (e.g. occurrences such as flow events, weather cycles, or changes to land management practice).

In this study, broad-scale physical parameters were identified and preliminary interpretations of fluvial processes were made, using remote information sources (satellite imagery, aerial photography, digital elevation models) in combination with published literature. Specific flow paths or events were observed through remote imagery: the mid-1970s floods (~1% AEP) are bracketed by aerial photography (1969 and 1977), and the 2010-2012 period (~2.5-5% AEP) is covered by LANDSAT Water Observations from Space (WOfS), and MODIS. On WOfS, black indicates no observed water, and is taken in this report to define areas outside 'normal' flow. However, since LANDSAT coverage can be incomplete, and flow events in the study area may be brief, it is possible that such areas may in fact receive water more often than once every 20 years.

Sites for field investigations were chosen by the interdisciplinary team as a whole, prioritising waterholes and channels and their nearby floodplains and taking into account logistical considerations – dunes and floodways make some places inaccessible for long stretches of time. In the field, each location's characteristic suite of landforms was identified, and individual landforms were described with respect to their morphology, sediment (grain size and composition), sedimentary structures, and location and type of biota. Post-field analysis integrated the broad-scale (remote) and reach-scale (field) data, identifying landscape processes for the river as a whole. A critically important part of the integration phase is ground-truthing: matching remotely-identified characteristics with unambiguous field observations, in a way that allows extrapolation of process interpretations across wide areas. From this point, it is possible to determine the river's range of behaviours and understand what natural events and management practices support habitat and good landscape function.

The Channel Country project combines diverse research threads with collaborative dialogue, to investigate the relationships between organisms, ecosystems, and landscape. This occurs by independent discipline-based investigation taking place within joint field parties, so that the fish monitoring, bird surveys, plant community counts, cultural surveys, landform mapping, and hydrological investigations have overlapping spatial footprints. From communications amongst the research team, overarching themes were identified that articulate the interdependence between biota and physical processes.

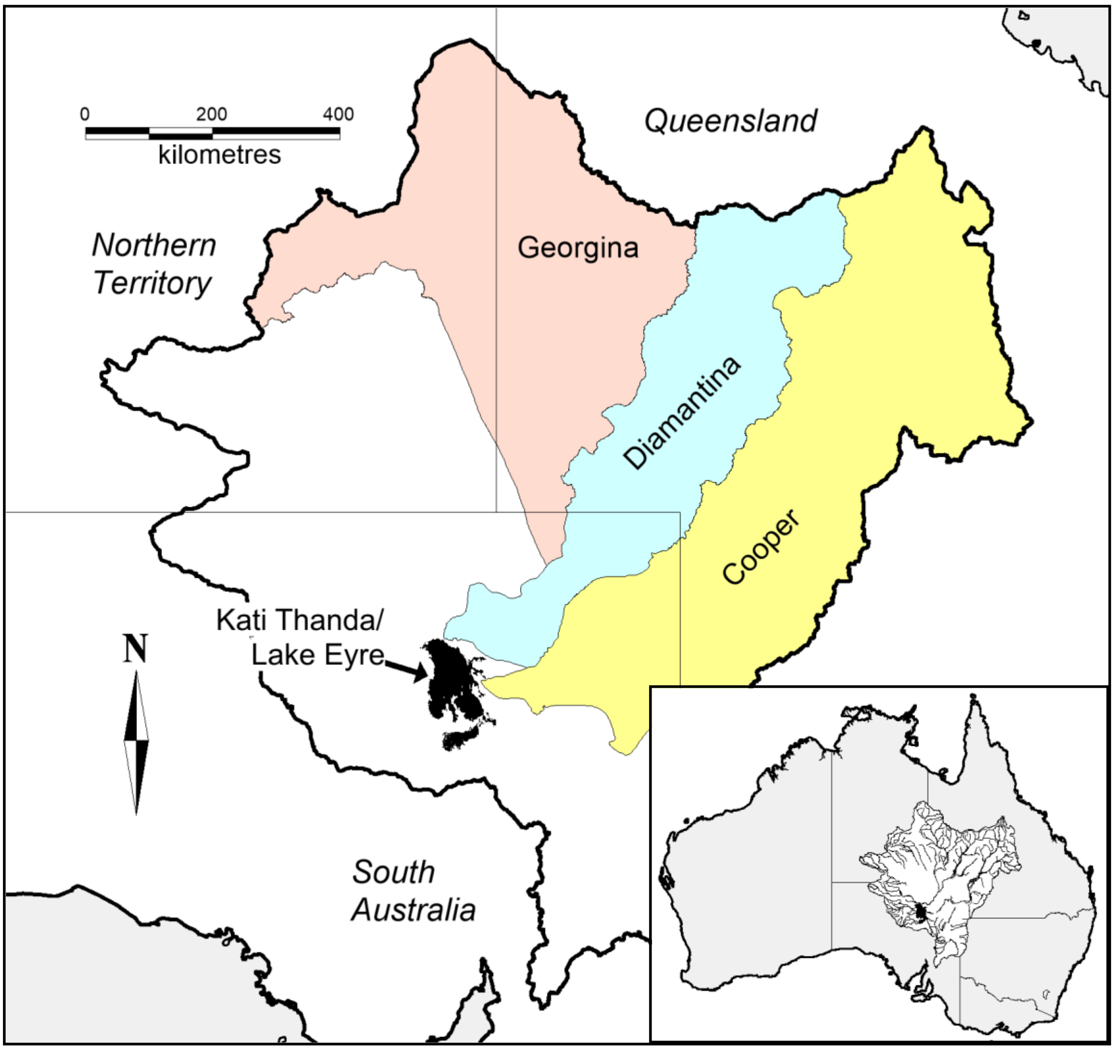

Fig. 2 The Lake Eyre Basin and the Channel Country catchments. Inset: the LEB and Australia.

3.2 Study Area

The Lake Eyre Basin (LEB) is a large endorheic (inwardly-draining) basin, in which rivers and waterways drain towards the depocentre Kati Thanda/Lake Eyre. This central playa lake system comprises Lake Eyre North and Lake Eyre South, and its lowest elevation point is ~15 m below sea level. The rivers entering Kati Thanda/Lake Eyre from the north and north-east are the Channel Country rivers: the Diamantina River catchment (including the Georgina River), and Cooper Creek (Fig. 2). The headwaters of the Diamantina and Georgina Rivers arise in Queensland and the Northern Territory, and most of the Diamantina River catchment is in western Queensland. Other broad-scale features relevant to this study are the Simpson and Tirari Desert dunefields and the gibber uplands of Sturts Stony Desert. Mungerannie Roadhouse, on the Birdsville Track, is the only public built-up area in the study area.

The study area is that part of the Diamantina River catchment which occurs in South Australia, comprising (Fig. 3):

- the Diamantina River between the Queensland border and Goyder Lagoon, including its channels, floodplains, and secondary flow paths (including Gumborie Creek and Eleanor Creek);
- Eyre Creek, which is the terminal section of the Georgina River catchment, is a broad flow path down the interdune corridors at the eastern edge of the Simpson Desert dunefield;
- Goyder Lagoon, a broad shallow basin which receives water from the Diamantina River and Eyre Creek;
- Warburton Creek, which arises at the downstream end of Goyder Lagoon and makes its way through the Tirari Desert dunefields to the Lake Eyre intake area;
- Kallakoopah Creek, which splits off from Warburton Creek and follows a different and more northerly path through the Simpson Desert dunefields to the Lake Eyre intake area.

The waterholes and other localities that formed the framework of the field investigations are listed in Table 1.

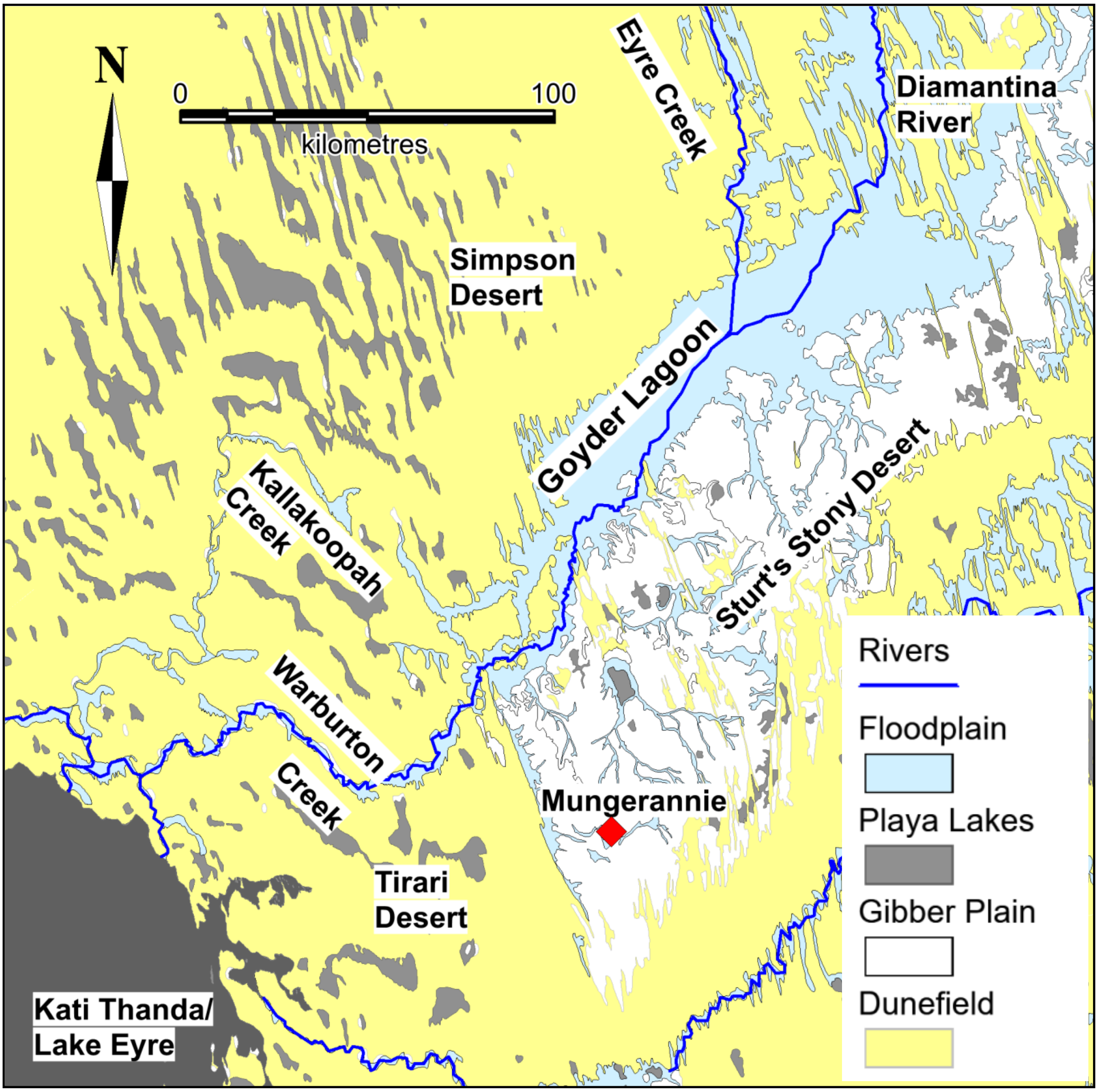

Fig. 3 Physiography of the South Australian parts of the Diamantina/Georgina catchment..

Name	Management Zone	Map #	Latitude	Longitude
Dickeree Waterhole	Diamantina River	1	26.066	139.325
Eleanor Creek	Diamantina River	2	26.359	139.347
Gumborie Creek	Diamantina River	3	26.062	139.499
Pandie Pandie homestead (windmill waterhole site)	Diamantina River	4	26.131	139.388
Double Bluff waterhole	Diamantina River	5	26.265	139.404
Lake Uloowaranie	Diamantina River	6	26.386	139.479
Diamantina-split waterhole	Diamantina River	7	26.412	139.423
Yammakira Waterhole	Diamantina River	8	26.532	139.460
Andrewilla Waterhole	Diamantina River	9	26.551	139.273
Tepamimi Waterhole	Eyre Creek	10	26.676	139.011
Burt Waterhole	Goyder Lagoon	11	26.594	139.164
Pelican Waterhole group	Goyder Lagoon	12	26.582	139.229
Peraka swamps	Goyder Lagoon	13	26.538	139.531
Koonchera Waterhole	Goyder Lagoon	14	26.690	139.514
Pandiburra Bore	Goyder Lagoon	15	26.754	139.429
Goyder Lagoon Waterhole	Goyder Lagoon	16	26.893	139.990
Warburton crossing	Warburton Creek	17	27.072	138.785
Yelpawaralinna Waterhole	Warburton Creek	18	27.136	138.728
Ultoomurra Waterhole	Warburton Creek	19	27.161	138.744
Kalamunkinna Waterhole	Warburton Creek	20	27.296	138.572
Stony Point	Warburton Creek	21	27.460	138.543
Kirrianthana Waterhole, Cowarie crossing, Derwent Ck confluence	Warburton Creek	22	27.633	138.386
Yellow Waterhole	Warburton Creek	23	27.736	138.307
stony crossing waterhole and Oolabarinna Crossing	Warburton Creek	24	27.783	138.259
Mia Mia Dam area	Warburton Creek	25	27.837	138.225
Wadlarkaninna Waterhole	Warburton Creek	26	27.855	138.158
Tinnie landing, near Murreebirrie Hill	Warburton Creek	27	27.882	138.028
Cliff Camp, near Poonarunna Bore	Warburton Creek	28	27.884	137.937
Kuncherinna Waterhole	Kallakoopah Creek	29	27.411	138.4602
Mona Downs	Kallakoopah Creek	30	27.410	138.445
Anarowdinna Waterhole	Kallakoopah Creek	31	27.496	138.305
Murdamarroo Waterhole	dunefield	34	26.98	138.42
Mirra Mitta Bore	gibber plain	35	27.71	138.75

Table 1 (Previous page) Waterholes and other key locations.

List is in upstream-downstream order (and see Fig. 8); only formal (gazetted) names are capitalised. Coordinates are approximate, WGS84 decimal degrees.

Climate and Palaeoclimate

The LEB's size and placement in the centre of the continent creates one of its unique characteristics: although the study area is one of the most arid places in Australia, the Channel Country headwaters are at the edge of the northern tropics, where they can receive monsoonal rain. Substantial floods can penetrate the long rivers that traverse the dunefields and stony deserts. This is one of the world's most variable flow regimes: river reaches routinely experience conditions encompassing complete dryness, ponded water, in-channel flowing water, and long-lasting floodplain inundation. The variable flow regime relates to variability in both runoff characteristics and rainfall: in Australia the combination of weather cycles (e.g. the El Niño-Southern Oscillation superimposed on the Interdecadal Pacific Oscillation) has produced some record-setting weather events, such as the Federation Drought and the mid-1970s flooding.

The variability is a driving factor in the rivers' geomorphic processes. Unlike the low-variability temperate zone rivers described in textbooks, and upon which our cultural expectations of river behaviour are based, in Channel Country rivers –

- as flood heights rise and fall, a single location can experience a range of flow energies and flow directions, leading to ambiguous or unusual landforms;
- many landforms deal with distributing water from the channel to floodplain during rising flood, and/or draining floodplain water back into the channel at the close of flow;
- vegetation communities can be located in places that are also the locus for strong geomorphic activity;
- there are many reaches, in which at certain flood heights the in-channel component of the flow will be less voluminous or less geomorphically important than the floodplain flow.

The hydrology of the study area and flow conditions during fieldwork is described in Costelloe 2017. Specific modern day flow events that are relevant to this geomorphology study are the mid-1970s floods (estimated as approximately 1% AEP or '1-in-100'), and the 2010-2012 wet period, with flows estimated as 20-40 year events (estimates J. Costelloe pers. comm. 2016).

During the past 60 million years the world has moved from a warm and wet climate towards the present strongly fluctuating shorter-term cycle of glaciations ('ice ages'). Broadly speaking, at the peak of glaciations the world is cool and dry, and at the interglacials the world is warmer. During the present day, we are experiencing interglacial conditions. The last glacial maximum (cold and dry) was ~12-24 thousand years before present (ka). Prior to that was a more complex period (~24-123 ka) of warmer and colder substages including a glacial at ~60-74 ka. The most recent interglacial with conditions similar to the present day was ~124-130 ka (late Pleistocene), and prior to that ~180-240 ka.

The LEB's climate history follows these trends but specifics are governed by factors such as climate zones and the degree of monsoonal presence. During the last ~30 million years the Lake Eyre Basin became increasingly arid, starting as woodland and rainforest with lakes and swamps and becoming dry open woodland and chenopod scrubland with shallow, hard-water lakes. During the last 6 Ma, warm wet episodes were superimposed on the overall drying trend. From ~2.6 Ma (the end of the Pliocene and the beginning of the Pleistocene) the LEB's climate was seasonally arid, although still wetter and with greater streamflow than today. The area supported a rich megafauna assemblage in a complex of streams and lakes. In the mid- to late Pleistocene, river systems in the study area carried considerably more water than they do in the present day, and the dominant fluvial style was actively meandering large rivers. The Mega-Frome lake system (a single semicircular lake: north and south Lake

Eyre and Lakes Gregory, Blanche, Callabonna, and Frome) was intermittently full between ~125 ka and 50-47 ka. After 45 ka, the LEB became markedly drier, but has experienced other short-term moderately wet periods and/or megafloods (e.g. in the Cooper Creek catchment, ~17 ka, ~13 ka, ~5 ka, and ~1 ka).

Geology and Hydrology

For the purposes of this study, the geological units in the study area fall into 5 groups: modern sediments, Pleistocene sandstones and mudstones, sediments and rocks from the Palaeogene and the Neogene (what used to be known as the Tertiary geological period), Mesozoic-age Great Artesian Basin rocks, and the overprint of the weathering profile (regolith).

The **modern sediments** occurring at surface are the dunefield sands, the floodplain muds, and the sands in fluvial transport. In many places the present-day sediments are thin, especially at the edges of the dunefields, where there is low sand supply and the interdunes are deflated, and parts of the river floodplain in which sediment is not deposited. The sediment types are:

- **Dune sands** have various grain colours, partially reflecting sand origin. Orange grains come from underlying weathering profiles (see below), and pale buff or clear grains once used to be transported fluvial sand. The colour of the dunefields therefore varies also, from dark orange deep in the dunefield where all the grains come from subcropping regolith, to the pale dunes on the floodplains and close to the mouth of Kati Thanda/Lake Eyre, which arise from local dune building from alluvial sediments.

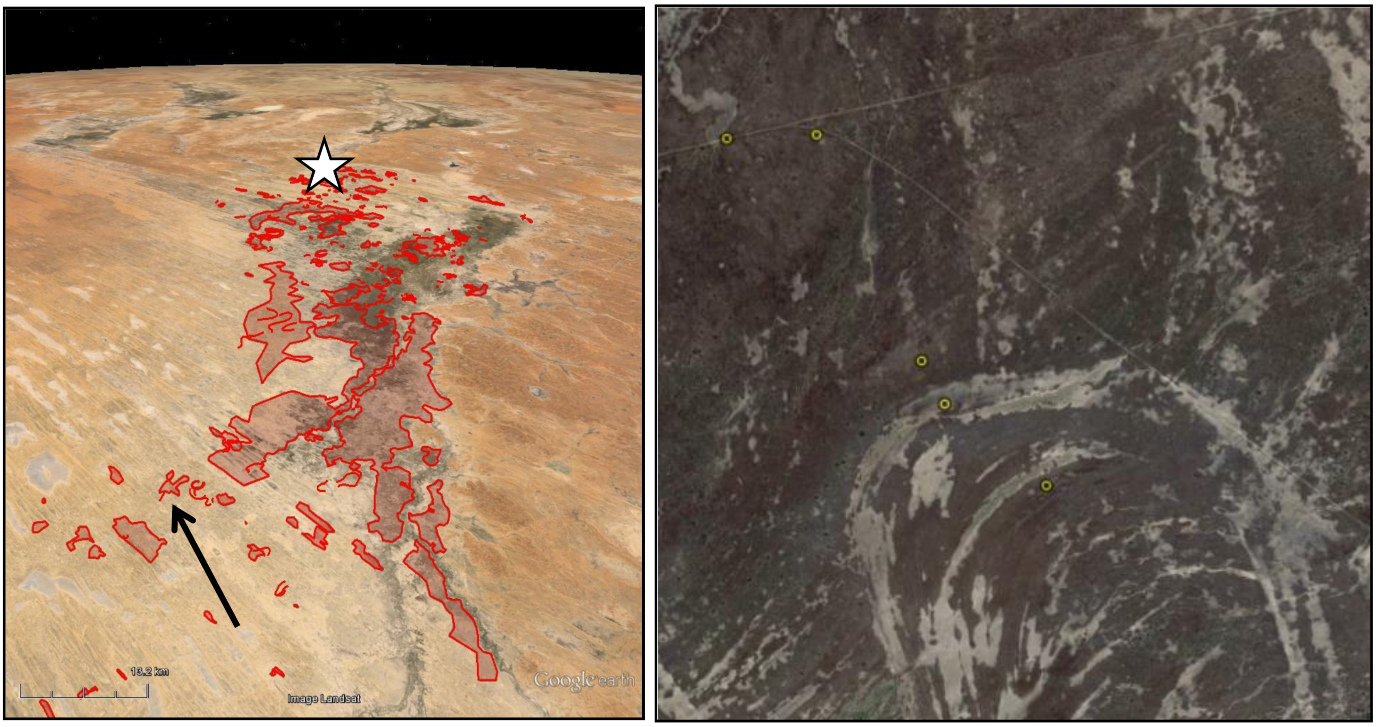

Fig. 4 Water-bearing Pleistocene sediments

Left, some of the shallow subcrop of the Pleistocene sediments originating from the Diamantina flow path. (Pleistocene sediments originating from the Georgina flow path are present but not shown.) Oblique Google Earth image looking upvalley along Goyder Lagoon. Black arrow points north and is scale = 20 km; star is Birdsville township. Right, surface expression of the subcropping Pleistocene is alternating vegetated and unvegetated bands. Goyder Lagoon near Warburton crossing; Google Earth image is ~1.3 km wide.

- The **floodplain muds** are dominantly vertisols (vertic soils), characterised by shrink-swell behaviour leading to gilgai features such as macropores ('crabholes'), crumbling and cracking surface texture, and rough surface heave. The vertisols are ecologically important: they can absorb and retain great quantities of water, so can support high degrees of biological productivity; however their shrink-swell behaviour is hostile to the roots of many plants (e.g. coolibah), so the terrestrial ecosystems they support are specialised (e.g. lignum).
- Most of the **sand in fluvial transport** is derived from remobilised Pleistocene sand from channels and banks locally and upstream. The Diamantina River's sand is deposited at the downstream terminations of the Diamantina Fan (see below): sand is not presently transported through Goyder Lagoon. The Warburton Creek's and Kallakoopah Creek's sand is derived from channel incision firstly into the downvalley sections of Goyder Lagoon, and subsequently from incision into the terraces flanking Kallakoopah Creek and Warburton Creek. The Warburton and Kallakoopah Creeks also contain abundant sand-sized gypsum crystals ("seed gypsum") in their bedload.

Shallowly underlying the rivers and dunefields, (Plio-) **Pleistocene sands** (and some muds) are almost ubiquitous across the study area (Fig. 4). They were deposited by large meandering rivers during times of wetter climates, and are visible in remote imagery by their effect on surface vegetation. They are identifiable by their characteristic scale, curved geometry (representing channels and scroll plains), and crosscut spatial relationships with dune crests and other present-day features. The Pleistocene sands are usually permeable and are an important host of the area's unconfined aquifer (see Costelloe 2017), in which capacity they are an important support to some non-fluvial terrestrial ecosystems. At the downvalley end of Goyder Lagoon, the river channels are incising into the Pleistocene sands, delivering significant amounts of sand into fluvial transport and thereby affecting the fluvial style.

The sedimentary rocks exposed at surface in the gibber plains of Sturt's Stony Desert (Fig. 5) and which underlie some of the dunefields were deposited during the Palaeogene and the Neogene. In the Simpson and Tirari deserts areas, some were a source of orange-coloured sand during the formation of the dunefields. Where these rocks are exposed at the edge of the gibber plain, they feed small amounts of sand into fluvial transport. The most easily recognisable of these rock units is the **Eyre Formation**, a Palaeogene quartz sandstone characterised by a conglomerate layer of strikingly smooth rounded stones. The Eyre Formation is widespread across the LEB and marks geologically significant events during the Palaeogene. In parts of the Lake Eyre Basin, the Eyre Formation is hydrologically connected with the underlying Winton Formation, by direct sand-to-sand contact and probably also through polygonal fault systems.

The top layer of the Great Artesian Basin (the **Winton Formation**) is exposed on the gibber plains of Sturt's Stony Desert (Fig. 5). Prior to deposition of the Eyre Formation, the Winton Formation was thinned by several hundred metres by erosion along dome crests.

Across most of Australia, repeated cycles of intense weathering have left an imprint (**regolith**). In the study area the regolith includes bleached or mottled weathering profiles, silcrete, and ferricrete, and they have been important in landscape evolution. The soft bleached rocks are susceptible to erosion, whereas the hard silcrete (and the gibber, which is silcrete rocks) protects from erosion, leading to the characteristic gibber plains and flat-topped tablelands. The weathering process involves chemical and volumetric changes from the original rock, leading to fracturing and therefore the potential for groundwater movement. Because the weathering happens after rocks have been deposited and folded, regolith profiles can extend across rocks of different ages (such as the Winton Formation and the Eyre Formation). Polygonal fault systems (such as permit GAB groundwater leakage in Queensland) can propagate through regolith profiles as pre-existing faults are reopened with renewed tectonic activity. The present geomorphological study suggests that some of the silcretes overprinting the Eyre Formation in the north-east exhibit polygonal fractures, and that GAB leakage to surface is taking place.

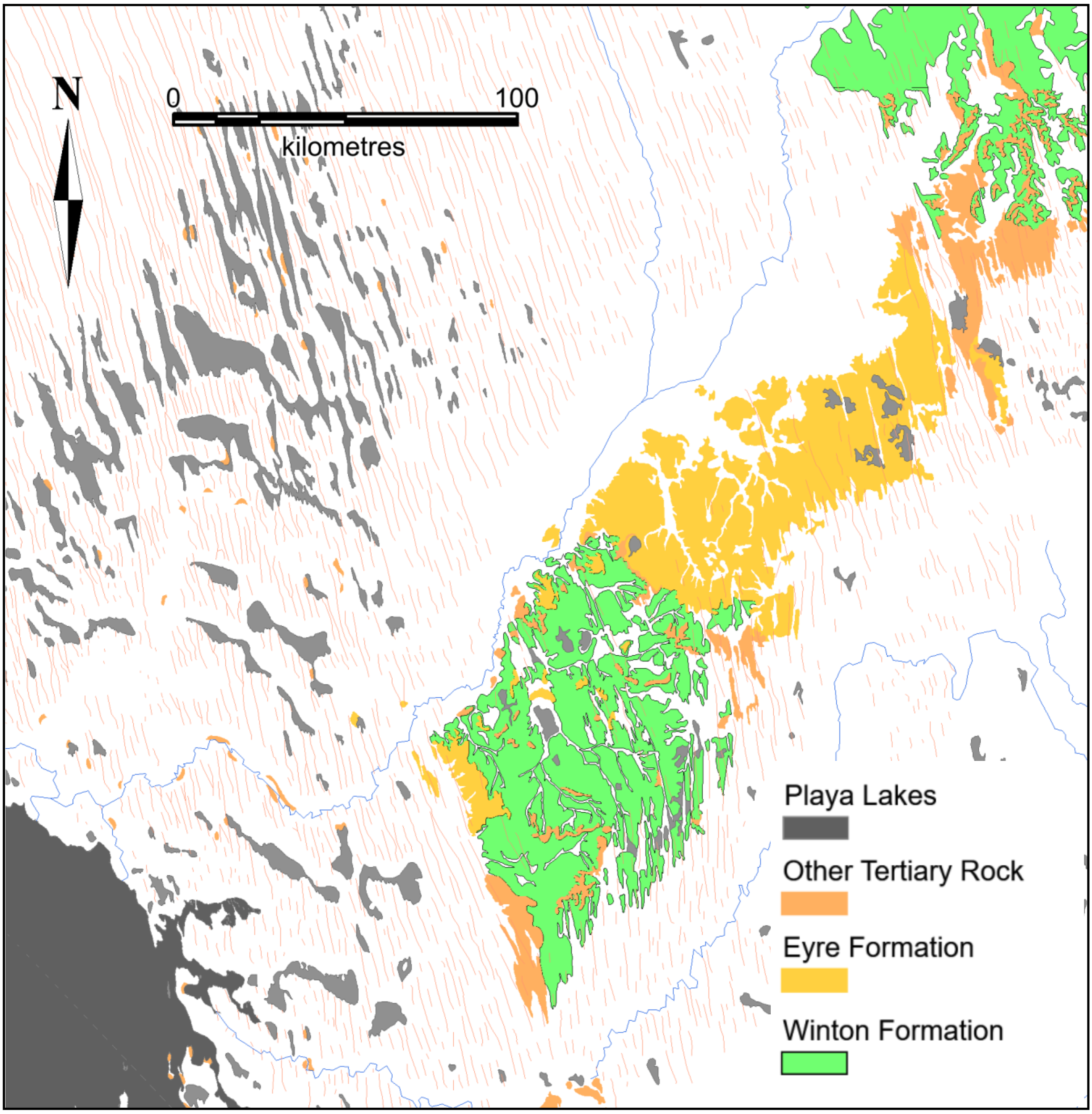

Fig. 5 Surface geology of the study area (see text).

The LEB is a continental-scale sag basin that has been developing since the early Palaeogene. Its overall structure has formed in response to deep mantle processes that have produced dynamic topography, in which overall subsidence (on a scale of hundreds to thousands of kilometres) has been modified by more local movements of uplift and subsidence (on a scale of tens of meters vertically and tens to hundreds of kilometres horizontally). Superimposed on this is crustal processes to do with movement within the Australian tectonic plate: the folding of the sedimentary basins beneath the LEB, creating the domes and river valleys of today's topography. Though subtle, these movements continue into the present day and have a direct effect on modern ecosystems. Features relevant to the present study are:

- The basin depocentre has shifted from north to south; in the late Neogene the lake was so far north as to be (approximately) to the west of Sturt's Stony Desert. It is likely that the flat topography of the mixed dunefield and playa lakes area, north of the present Kati Thanda/Lake Eyre, is at least partially related to the old lake surface.

- The domes (gibber uplands) have been areas of uplift, and at least some of them are currently uplifting. This promotes the present landform assemblage in which surface sediments have largely been stripped back to the resistant silcrete layer.
- The river basins (including Goyder Lagoon) are currently slowly subsiding. The rivers are not bringing in enough sediment to fill these subsiding basins, and this promotes the present landform assemblage of muddy swamps.
- At the interface between uplifting dome and subsiding swamp is a low-angled alluvial fan: the Diamantina Fan (described for the first time in this report). The gradient of the fan is a strong contributor to waterhole permanence in the Diamantina River management zone (see below).
- Numerous fault zones, concealed beneath the dunefields, have been mapped by previous workers. The variation within and complexity of fluvial styles in Warburton and Kallakoopah Creeks is likely to be partly related to currently undescribed neotectonism north and north-east of Kati Thanda/Lake Eyre.

The hydrology of the study area is described in Costelloe (2017). Four aspects of the hydrology are relevant to describing the geomorphology.

- Surface water from upstream: tropical rainfall in northern Queensland can put sufficient water into the Georgina and Diamantina Rivers that floods extend into the study area.
- Local runoff: infrequent rainfall within the study area can support local ecosystems, especially if surrounding high-runoff surfaces (such as gibber plains and some exposed dune palaeosols) shed water onto the ecosystem.
- The unconfined aquifer is the near-surface groundwater hosted in (inter alia) the Pleistocene sediments. The aquifer's waters can be saline and contain dissolved iron. Where the water is concentrated by evaporation (such as in Kallakoopah Creek) it becomes visibly iron-stained and precipitates gypsum and halite (Fig. 6).

Fig. 6 Iron-stained saline waters in Kallakoopah Creek

The clumps of samphire (purple succulent) are characteristic of these highly saline reaches. Location 4.5 km east-north-east of Anarowdinna Waterhole.

- The top layer of the Great Artesian Basin (the Winton Formation) carries some small local supplies of poor quality groundwater, but is generally one of the aquiludes for the water-bearing strata below. The geological structure (the Gason Dome) that is the basis for the gibber uplands of Sturt's Stony Desert is underlain by a water table mound which is likely to be a groundwater discharge feature. Mira Mitta Bore (see Table 1) is artesian and flows to surface.

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Landscape Evolution 4Ma to Present

Before approximately 4 million years ago (the early Pliocene), the topography of the study area was similar to that of today, but the soil and vegetation was very different. Broad hills in the north-eastern corner, extending in a broad ridge towards where Mungerannie now is (see Fig. 3), were covered in soil and vegetated by open woodland and chenopod scrub. Vegetated wide plains carried rivers (e.g. the proto-Finke, Hale, etc.) from the central Australian ranges down the slopes towards a large shallow lake located west of the broad ridge. The proto-Georgina River connected into the large lake from the north, and the proto-Diamantina River travelled south-west and entered into the large lake from the lake's east.

From ~4 Ma, the global climate's trend towards aridity increased and the broad hills lost their soil cover and exposed the gibber plains. As well as changing ecosystems, this would have changed the behaviour of local watercourses: gibber plains shed rainfall rapidly, leading to flashy creek flow rather than sustained base level flow. As time progressed, the large shallow lake became smaller and also shifted southwards.

From the late Pliocene and early Pleistocene, the global climate became more arid but increasingly variable as the glacial cycles developed. The proto-Georgina and -Diamantina Rivers were large meandering rivers, depositing large quantities of sand in the river valleys and nearby plains (the Katipiri Formation and its correlatives). Around ~1 Ma, when the global glacial cycle intensified, the wide alluvial plains lost much of their vegetation, leaving their soils vulnerable to erosion. Under the steady wind from the south, the plains developed into longitudinal dunefields (the Simpson Desert). At the same time, rivers carried less water, and the rivers from central Australia became unable to cut through the dunefields. At this point the central Australian aquatic ecosystems became disconnected from the central lake. The development of longitudinal dunes and diminishment of river flows also diverted the proto-Georgina river from its previous ~south-westerly course, and constrained the Georgina River into its present south-south-east flow path. Similarly, the proto-Diamantina was deflected to a more southerly path.

During the Pleistocene, glacial/interglacial climate swings produced alternately arid and (slightly) wetter conditions. During wetter times, the rivers flowed abundantly and brought sediment into the alluvial valleys. During drier times, that alluvial sand was blown into source-bordering dunes that then developed longitudinal dunes, creating the compound dunes that are such a characteristic landform of the Diamantina River in the study area. During wetter times, it is likely that some of the playas north of Kati Thanda/Lake Eyre (Fig. 7) would have been permanently full, providing connectivity between the Channel Country rivers and the LEB western rivers (Macumba and Neales Rivers). However, it is unlikely that connectivity was ever re-established with the Finke River or other rivers from central Australia.

During the present interglacial, conditions have continued arid, however millennial-scale floods have occasionally left their mark upon the LEB landscape. The present project has not identified any particular megaflood landforms in the study area, however there will undoubtedly be some. It is likely that some of the waterholes, scour zones, dry flow paths and sheet sediments relate to rare very large floods.

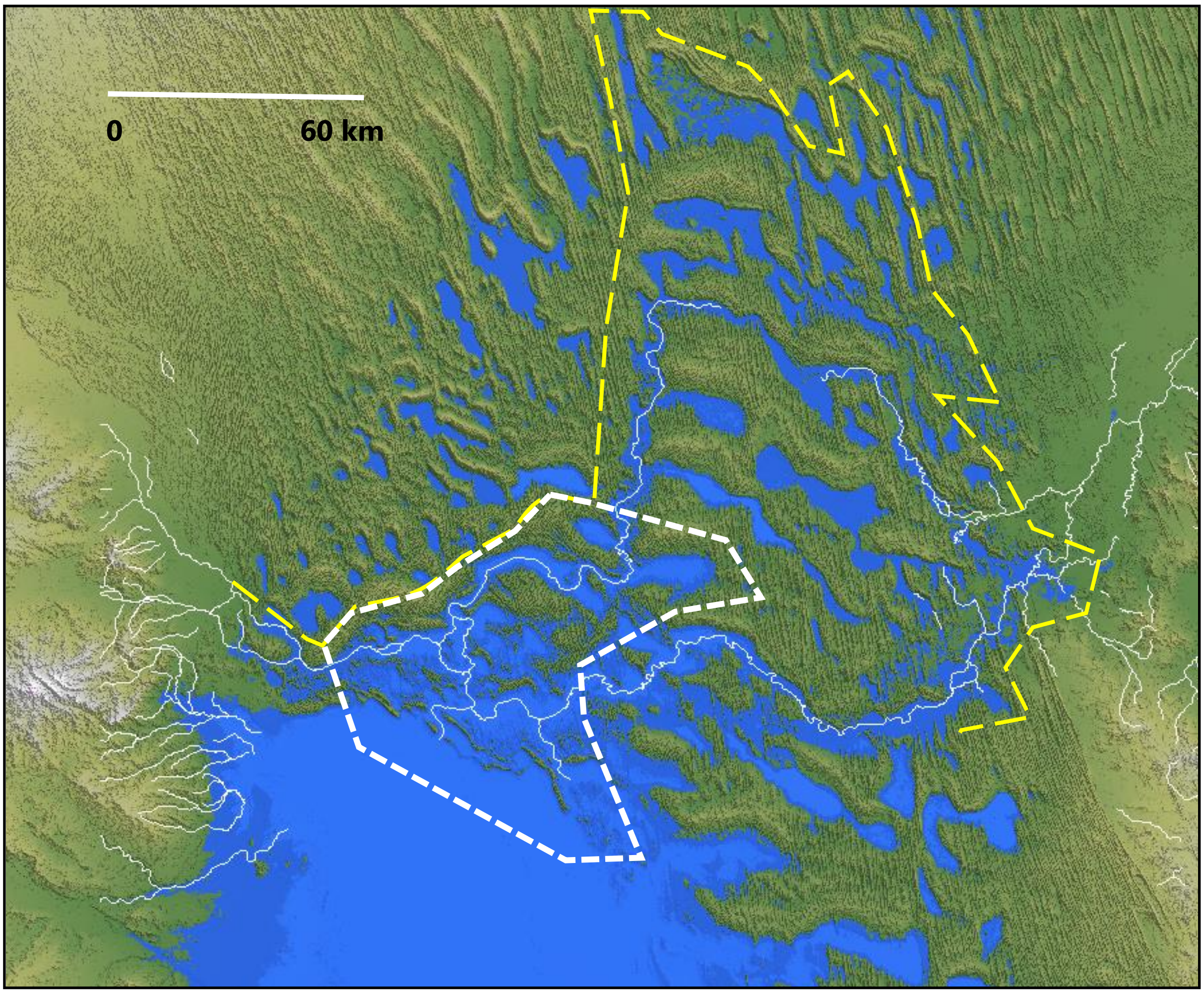


Fig. 7 Possible Pleistocene connectivity in interglacial wetlands.

The playas north of Kati Thanda/Lake Eyre are here shown inundated to +10m AHD, approximating the situation at ~125 ka. The Warburton, Kallakoopah and Macumba separately entered a marshy or lacustrine setting. Yellow long dashes indicate connectivity in this setting. Dashed white line encloses the present-day zone of disorganised drainage (also see Fig. 43).

3.3 Management Zones

The project area is here divided into four management zones, on the basis of the interdisciplinary team's post-field analyses. They are the Diamantina River, Eyre Creek, Goyder Lagoon, and Warburton and Kallakoopah Creeks (Figs. 1, 8). The gibber plains and the dunefields, while not a focus of this study, are relevant to the study's objectives, and are also considered in this geomorphology report.

The Diamantina River is characterised by its sinuous and often meandering continuous channel containing permanent or semipermanent water, wide floodplains with secondary flow paths (including Gumborie Creek and Eleanor Creek), deposits of fluvial sand, widely spaced compound dune sets, and the distributary channel network at its entrance into Goyder Lagoon. In this report, the whole is grouped as the Diamantina Fan.

Eyre Creek is characterised by its broad diffuse flow path down the interdunes of the Simpson Desert's eastern margin. There are no continuous channels and no permanent water, although there are numerous isolated channel segments, some of which are a few kilometres long. Its entrance into Goyder Lagoon is a ~60 km wide zone along the southern boundary of the dunefield.

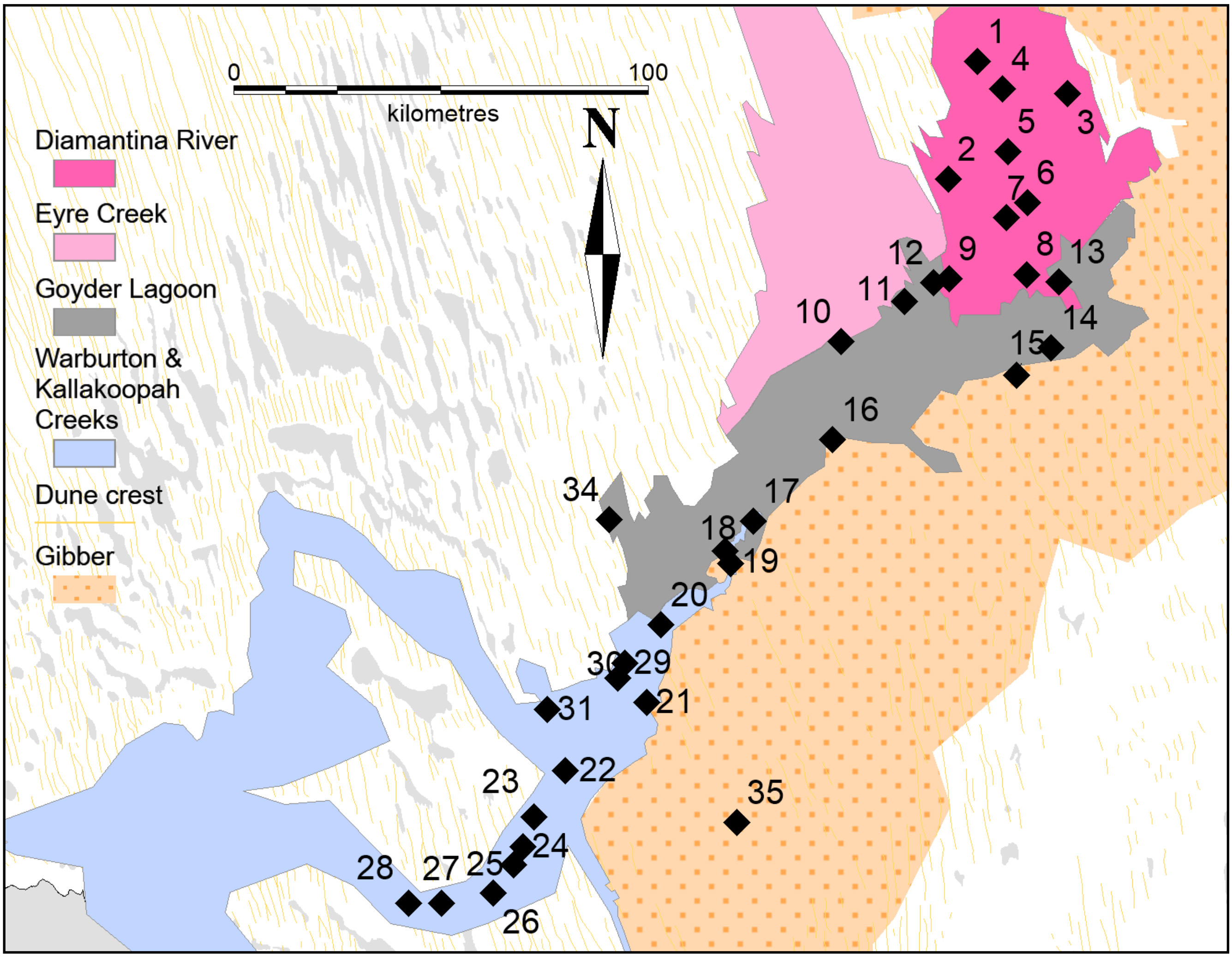


Fig. 8 Map of the Diamantina catchment (SA) management zones.

Black diamonds are field locations, see Table 1.

Goyder Lagoon is a wide, low-relief area of lignum swamps and vertic soil plains. Its diffuse flow path is marked by a great variety of small-scale flow landforms. It has wide areas of moderately long-term shallow inundation (in the sense of saturated boggy soils) but only a few permanent or semipermanent waterholes, mostly around the lagoon margins.

Warburton Creek extends from the downvalley end of Goyder Lagoon, and traverses the Tirari desert dunefields to the Kati Thanda/Lake Eyre entrance area. It has a largely continuous channel or set of channels and its floodplain width varies. Its waters can be very saline.

Kallakoopah Creek is a distributary from Warburton Creek which pursues an independent flow path deep into the Simpson Desert dunefields, before its confluence with the Kati Thanda/Lake Eyre entrance area. It has a largely continuous channel or set of channels and a narrow floodplain, set within terraces and cliffs. Its waters can be very saline and its channel sediments rich in small gypsum crystals.

The gibber plains are broad low-relief domes elevated ~15-40 m above the rivers and dunefields. The surface is usually covered by silcrete pebbles and cobbles in densities ranging from a loose scatter to a closely-packed pavement. In Queensland, the Diamantina and Georgina rivers emerge from relatively narrow valleys within the gibber plains, before traversing the dunefield margins. In South Australia, the gibber plains of Sturt's Stony Desert occur along the south-eastern margin of Goyder Lagoon.

The Simpson and Tirari Desert dunefields are characterised by north-north-west trending longitudinal dunes. In the study area the dunefields also contain compound dunes and playa lakes. Around the dunefield margins, the dunes can be relatively widely-spaced and their interdune sediments can be very thin. Deeper in the dunefields, the sand layer is thicker, the dune crests more closely spaced, and the interdune sediments can be a relatively thick layer of sand.

3.4 Landform Elements

This section describes the landform elements of the study area, and their attributes (Table 2).

Channels (Figs. 9, 10) are the most narrow and deep part of the river. In a temperate zone river the main channel could be expected to carry most of the river's water. In the Channel Country, during flood, there will be reaches where the floodplain carries more water than the channels.

- Channel planform (the shape of the channel from above) can be sinuous (strongly curved), braid-like, or low sinuosity (nearly straight). Channel sinuosity may be because the channel is actively meandering (channel migration), but it can also be because the channel is interacting with valley margins.
- Channels can be single-thread (one channel) or multi-thread (anabranching). (Another multi-thread style is braiding. Although Australian rivers have often been described as braided, there are no braided rivers in the study area.) Distributary channels can have a pattern of repeated splits or bifurcations, such that the channel size becomes progressively smaller.
- Channels can be continuous or discontinuous.
- Discontinuous channels are made up of channel segments (landforms with all the features of channels, but which are relatively short).
- Waterholes are markedly deeper and wider than other channels nearby. Some are part of continuous channels, and others are isolated channel segments.
- Channels can occur along the primary flow path (the most frequent, important, or largest flows), or along secondary or minor flow paths.

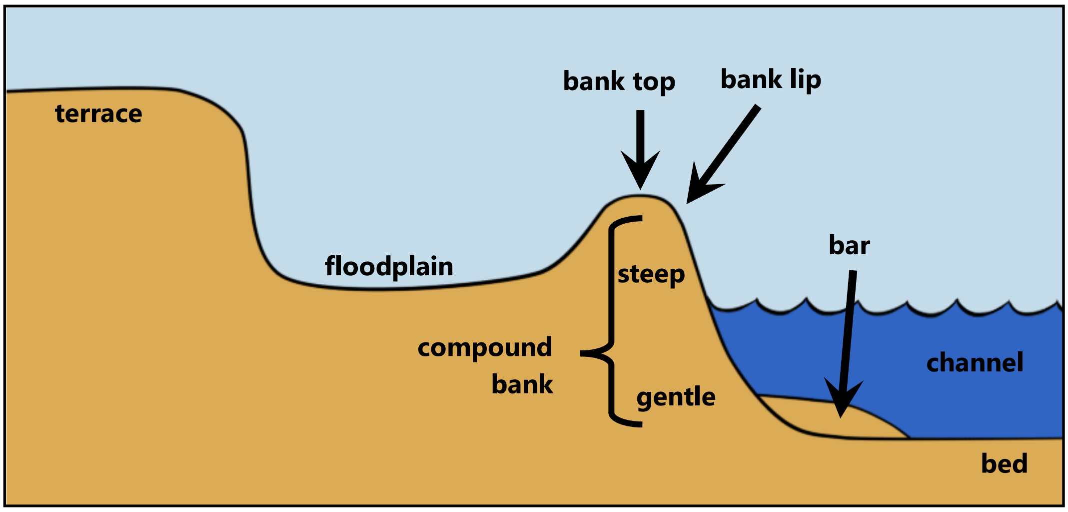


Fig. 9 Fluvial landform elements in the study area.

- Channels can be large or small in absolute terms (continuous channels are usually measured banktop to banktop width; for channel segments, length is also important).
- Channels can be shallow or deep (expressed as width:depth ratio).
- With respect to a particular main channel, minor channels can be distributary (act to remove water from the channel), tributary or intake (act to feed water into the channel), or in-out (distributary during the rising and peak flood, but draining water back into the channel during flood recession or after local rain). In-out channels are usually characterised by an inset gutter carrying the close of flow drainage back into the main channel, and a small delta of sediment in the main channel. In-out channels are the most likely minor channel type to be utilised by stock to access main channel water.
- Distributary channels can work by offtake (in which above a certain flood level a breach in the bank allows water out onto the floodplain) or by splitting/bifurcation (in which the channel divides into several smaller channels).

Flood Runners are channel-like forms which carry floodwaters at or above floodplain level. This general term covers a number of different landforms, including distributary channels, floodplain scours, and partially-infilled abandoned channels.

Banks are the sides of the channels.

- In the Channel Country, the main channels tend to have compound banks (Fig. 9) which are moderately to very steep from the bank top down to somewhere below cease-to-flow level. At that point there is a sharp break of slope and the angle becomes much more gentle (Fig. 9). During this study, usually only the upper part of the bank was available for examination.
- In reaches which are actively meandering, the inner bank will have a gentle slope of recently-deposited sediment.
- Main channel banks can be stable, retreating (eroding backwards), or in actively meandering reaches aggrading (lateral accretion on the point bar, see Meandering in Glossary).
- When banks are retreating, the roots of riparian trees are exposed. The shape and thickness of the tree 'knees' indicates the rate of bank retreat. If a bank is retreating slowly, tree roots have a chance to grow in a shape that fits the bank. Thick roots including downward bends indicate that the channel has been there for a long time, and the bank's retreat to its current location has been slow. Thick roots that stick straight out of the bank, or a thin roots that lie along the bank, indicate rapid bank retreat.
- Smaller channels tend to have gently sloping banks, which are usually stable (signs of aggradation or erosion are infrequent; however, small channels were not a focus of this study).

- Where a distributary channel leaves the main channel through a breach in the bank, the offtake area is usually complex, including a sill, evidence of rapid but localised bank retreat, and possibly several offtake entrances.

Bank tops are the crest or top of the area between channel and floodplain. Main-channel bank tops tend to be elevated above cease-to-flow and floodplain levels; these elevated bank tops are sometimes levees, but can also be other kinds of alluvium. This is relevant because it indicates different processes of sediment and seed deposition. Secondary channels and swamp channels tend to have low bank tops.

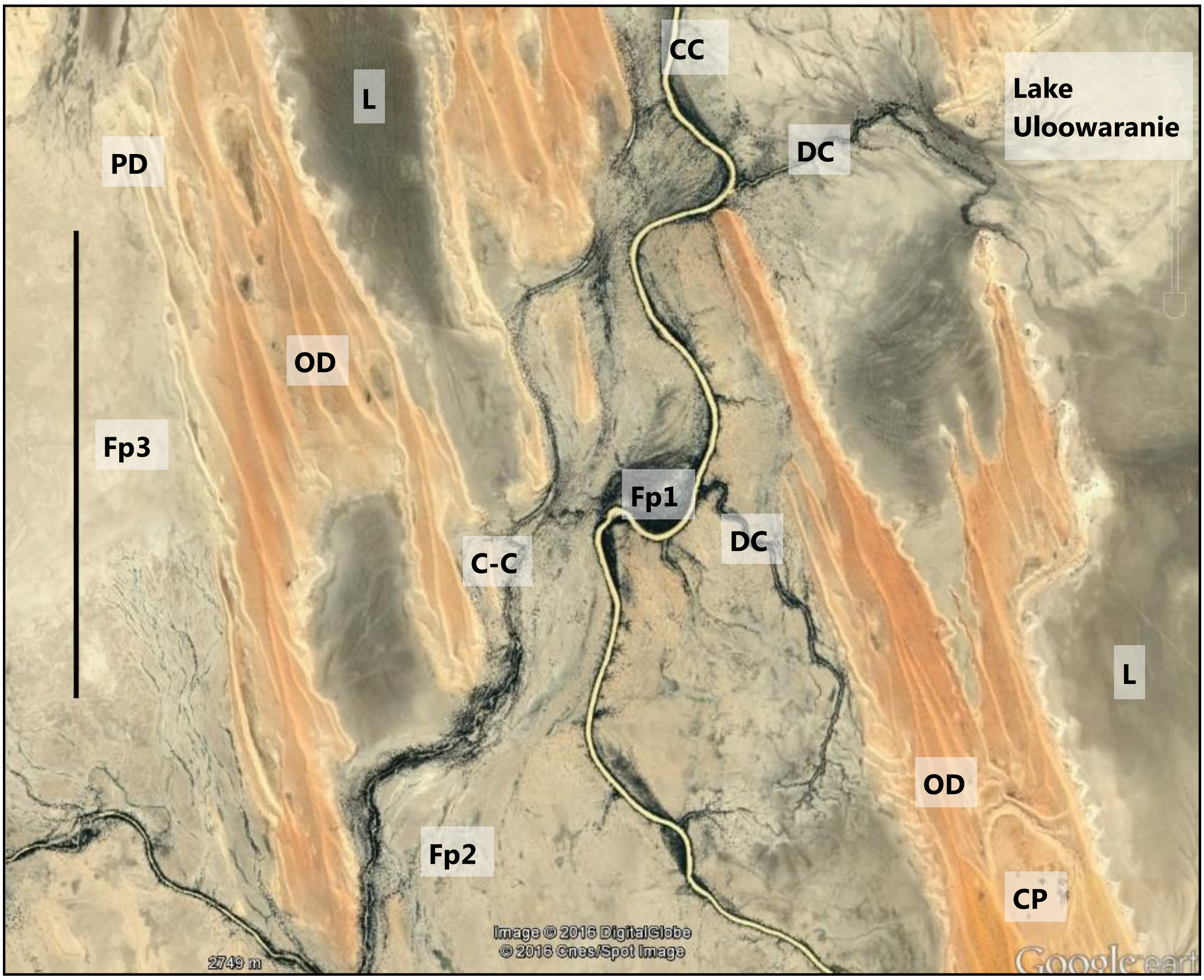


Fig. 10 Attributes of some landform elements in the Diamantina-split reach.

- **Diamantina River, Diamantina-split reach, Google Earth image, black scale bar = 5 km. Landform elements listed below; some landforms have several attributes.**
- **OD = Orange dunes; these are also compound dunes.**
- **PD = Pale dunes.**
- **L = Flood basins which are lakes (note the cuspate beach ridges); these are also interdunes.**
- **CP = Flood basins which is a claypan, this is also an interdune deflation pan.**
- **CC = Continuous channel (actively meandering).**
- **DC = Distributary channel; also, a flood runner.**
- **C-C = Discontinuous channel, in a secondary flow path**
- **Fp1 = Local floodplain, ridge-and-swale scroll plain, local to the channel at the Diamantina-split field site.**
- **Fp2 = Wider floodplain, irregular topography, in a secondary flow path (not local to a channel).**
- **Fp3 = Wider floodplain in a minor flow path, also a space between dune sets.**

Riparian zone is where vegetation benefits from proximity to regular surface water.

- Riparian zones can be densely vegetated or sparsely vegetated. The density of the vegetation is vulnerable to impact by stock (grazing and trampling) and human visitation (trampling, parking, firewood collection).
- Riparian zones can be narrow or wide, and this is usually a function of the geomorphology (that is, less likely to be a result of stock or humans). Riparian zones may be non-existent, if channel migration has cut the bank back so far as to remove the riparian zone.
- "Riparian" is most often used with reference to bank tops.
- Riparian zones also occur in scroll plains, partially infilled abandoned channels (especially those that maintain partial connectivity to a flow path), distributary channels and their outflow areas, and secondary and diffuse flow paths.

Bed of the channel includes the lowest-elevation areas, and carries first/last flow at the beginning/end of flow events, and the deepest flow during flood peaks.

- Bed topography could be simple, or more complex with benches and bars. Bed topography was not investigated during the geomorphology study, but might be an outcome of the bathymetric investigations.
- The bed surface could be scoured/erosional, or depositional. Sediments could be deposited during active flow (bedforms like dunes and ripples), or passively from still water. This distinction is likely to be important to a chronic invertebrate habitat, however was not within the scope of the present study.
- In meandering reaches, the bed may contain large woody debris (LWD) from trees that have fallen in during bank retreat.
- Channel sediments are described in terms of their grain size (e.g. muddy or sandy), degree of sorting (e.g. is it mostly mud or is it mixed sand and mud), and composition (is the mud component flocs or mud aggregates? Is the sand component quartz or seed gypsum?).

Floodplain is that part of the river that is only inundated above a certain flow height. Floodplain flow is by definition not contained within a channel.

- Floodplain topography may be flat or low-relief, gilgai, irregular (for example if the floodplain is a flow path, it will have small scours), or ridge-and-swale (if the floodplain is a scroll plain, or has partially-filled abandoned channels).
- Floodplains may be broad or narrow (width).
- Whether the floodplain flow is confined or unconfined depends not only on floodplain width, but also on the size of flows travelling down the floodplain. If the flows don't inundate the full width of the floodplain, or if they just lap against the edges, it is unconfined. If the flows are constrained by the valley edges to the extent that there is erosion at the toe of the hillslope or bed-scouring turbulence, than the flow is confined.
- In the study area the valley margins are usually either sand dunes or gibber hillslopes.
- Terraces are valley-edge landforms that can resemble floodplains, but which are above most present-day ordinary fluvial processes. Terraces can indicate either previous much larger rivers, or tectonic movement.
- In the study area (especially in the Diamantina River and Eyre Creek) many floodplains are also interdune corridors, or the spaces between dune sets.
- In parts of this report, a distinction has been made between local floodplain (directly associated with an immediately adjacent channel) and wider floodplain (distant from a channel) (Fig. 10). The process relationships are that a local floodplain has a causal relationship with its nearby channel, whereas wide floodplains are usually developed from a previously existing landform (including alluvial plains from a previous version of the river).

Landform	Attributes				
Flow Path1	primary	secondary	minor		
Flow Path 2	terminus (sink)	through-flow			
Channels	continuous	discontinuous	segment	waterhole	
Channel Size	absolute size	width:depth			
Channel Planform	active meandering	sinuous	low-sinuosity		
Channel Numbers	single thread	anabranching (multi-thread)	bifurcating or splitting		
Minor Channels	distributary (splitting)	distributary (offtake)	tributary or intake	in-out	
Flood Runners	distributary channels	floodplain swales and scours	abandoned channels		
Banks	steep/stable	steep/retreating	breached (offtake)	gentle/stable	gentle/ accreting
Bank Tops	elevated	low			
The landform hosting the riparian vegetation	bank top	distributary channel	scroll plain	other	
Riparian Vegetation Dimensions	width	density			
Sediments	composition	large woody debris	grain size	sorting	
Bed Topography	simple	complex			
Bed Surface 2	depositional (from bedload)	depositional (from suspended load)	scoured		
Floodplain Size	width	confined	unconfined		
Floodplain Topography	flat	gilgai	irregular	ridge-and-swale	
Dune Type	longitudinal	source -bordering			
Dune colour (Origin)	orange	pale			
Dune Dimensions	length	height			
Interdunes	thick sediments	thin or no sediments	deflation pans		
Interdunes	part of a flow path	no access to surface flow	terminus		
Flood Basins	swamp	lake	playa lake	claypan	
Flood Basins	confined	unconfined			
Silcrete	outcrop	gibber	desert pavement	gibber density	

Table 2 Attributes of landform elements. Coloured boxes are quantifiable, other attributes are categories.

Dunes in the study area are either longitudinal dunes, or compound dunes (source-bordering dunes overprinted with longitudinal dunes). The sand grains making up the dunes are either mid- to dark orange (regolith source), or pale orange / pale tan / white (alluvial source). Local community members have said that the vegetation is different between the orange and the pale dunes, but this comment was not followed up during this study. Dune length and dune height are likely to have some relationship to dune age (amongst other things).

Interdunes are the spaces between the longitudinal dune crests.

- In the study area, interdunes may be part of a flow path, or have no access to surface flow. Some interdunes that receive surface flow are terminal (have no outflow), and become flood basins.
- Some interdunes are floored with dune sands, especially in dune sets where the crests are closely-spaced such as deep in the Simpson Desert. Some sandy interdunes have deflation pans, where the interdune surface is eroded by wind (in some cases, as far down as the Pleistocene sediments). Some interdunes have little or no aeolian sediments, and they are either floored with alluvial sediments, or have Pleistocene sediments at or near the surface.

Flood basins (Fig. 10) are sites of water accumulation.

- Some are confined by landform boundaries (such as the dune-bounded lignum swamps of Peraka Lakes) and some are not (such as the lignum swamps in of Goyder Lagoon).
- Swamps are basins with a lot of freestanding vegetation.
- Lakes are basins, usually with some connection to the flow path, without much vegetation (except around the margins), and which display evidence of shoreline or lacustrine processes (such as wave action or seiches). Playa lakes are basins in which the lake floor processes are dominated by groundwater salinity. Claypans and interdune deflation pans are hard-floored basins which are only fed by local runoff.

Silcrete is the silica-rich rock created by weathering. It can occur as outcrop (big bouldery clumps) or as a gibber plain (a surface layer of rounded silcrete rocks). The gibbers are usually pebble to cobble sized and underlain by silt. They can be very densely packed or more widely scattered. Gibber may form a desert pavement, in which the layer is so densely packed that there is no space between gibbers, and the rocks are immediately underlain by a water-repellent vesicular layer.

4 Geomorphology

This section presents the geomorphology of each management zone in the study area. The information structure is based on the River Styles® framework (see Fryirs and Brierley, 2013) in which description of the river at broad to narrow scales develops the understanding of geomorphic processes:

- description:
  - valley setting
  - valley-scale landforms
  - reach-scale geomorphology
  - sediments and depositional bedforms

- processes:
  - valley-scale landforms and modern hydrology
  - river behaviour and habitat.

Information relevant to river processes is also presented in sections 5.1 Pleistocene Sediments and the Unconfined Aquifer and 5.2 Regional Flow Paths.

4.1 Eyre Creek

Description

Eyre Creek forms the downvalley terminus of the Georgina River catchment. Flow that reaches this part of Eyre Creek is relatively low energy, not only because of the Georgina River catchment's gradient and climate, but also because the area immediately upstream contains large water-retaining swamps and lakes, and is bordered by low-runoff hillslopes. From its entry into the basin of the Simpson Desert, ~100 km upstream from the Queensland border, Eyre Creek threads its way down Simpson Desert interdunes or spaces between one dune set and the next. The river's path, visible on Google Earth as the black colours of vegetation (Fig. 11), slopes 0.02% to the south-south-east and its orientation is governed by the longitudinal dunes. There are gibber uplands beyond the dune crests to the east and north-east, and the central plains of the Simpson Desert to the west. Within the study area, Eyre Creek extends 74 km from the Queensland border, and its flow path is 19-54 km wide. The flow path spreads out with increasing distance downslope, and is at its widest at its border with the Goyder Lagoon.

Although various digital datasets capture Eyre Creek as a continuous single line, apparently a single channel, this is a very poor representation of the river. Eyre Creek flows down all the interdunes that are available to it, in a broad and largely unchannelled flow path bounded on both sides by dune crests which are too elevated to be overtopped by floods. The character of the dunefield is therefore the most important valley-scale landform, as it governs the reach-scale features of the river. Flow is generally unconstrained, except where portions of flow are funnelled into narrow interdunes or spaces. Under those circumstances channel segments or short continuous channels may form. Even so, the channels are small and probably shallow, and constitute only a small part of total flow.

It was not possible in the present study to examine any of Eyre Creek's waterholes, with the exception of Tepamimi (below). The regional and remote survey indicates that reach-scale geomorphology is dominated by broad poorly defined flow paths down interdunes, with a variable distribution of vegetation influenced in part by local flow conditions, and in part by the underlying Pleistocene sediments. Channels and channel segments are a relatively minor component; the largest can be up to

30 m wide, and they appear to be shallow. Channel planform is generally low sinuosity (Fig. 11) and there are few distributary channels. In-channel bedload transport of sandy sediments is indicated by 100 m amplitude 2-D dunes, and sediment splays at the downflow side of waterholes.

As Eyre Creek approaches its boundary with Goyder Lagoon, the distances between some of the dune sets widens, and there are large lignum swamps with small channels in a reticulate network. The border between Eyre Creek and Goyder Lagoon is a line of small dune sets. Although these dunes do not look like a barrier to flow, since there are wide interdune spaces between the sets, they are a topographic barrier that the flood height has to overtop to go past. Floods reaching this height also seek to flow west and then north-north-west into the lower-elevation interdunes of the Simpson Desert.

There are five 'gateway' waterholes in the system, formed where water banked up behind topographic barriers forces its way through narrow spaces. At the north end of this stretch of Eyre Creek are Kudaree, Kalidawarry and Kuntianna Waterholes; in particular, Kudaree Waterhole is one of the few places in Eyre Creek that receives almost all the throughput from the Queensland parts of the catchment. At the south end, Tepamimi and Tepaminkanie Waterholes are located amongst wide

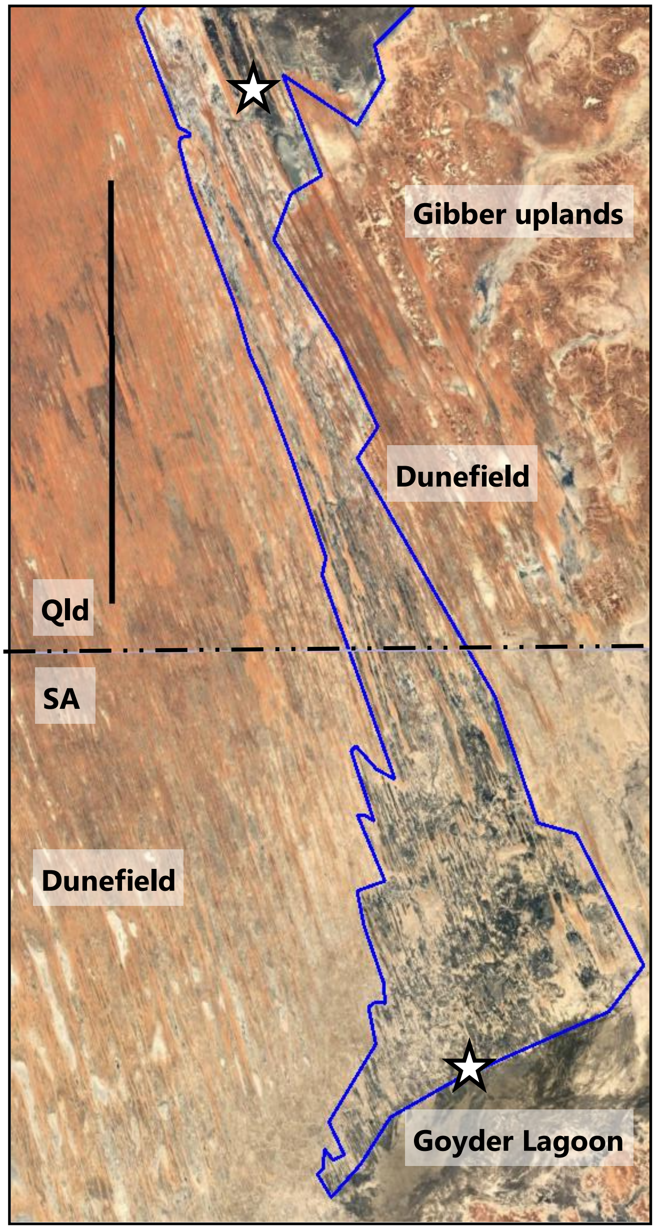
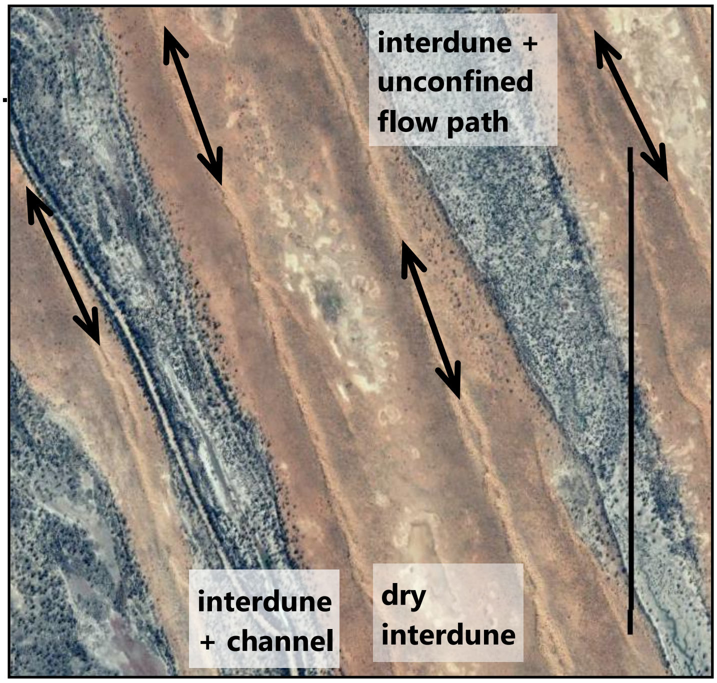


Fig. 11 Eyre Creek.

Left, overview: Eyre Creek flow path outlined in blue. White stars are the gateway waterholes: Kudarree, Kalidawarry, and Kuntianna in the north, and Tepamimi and Tepaminkanie in the south. Google Earth image, dashed line is the state border, black scale bar = 75 km. Right, typical Eyre Creek reach. Two of the interdunes carry unconfined flow, one interdune has a small channel, and one interdune is isolated from the flow path and carries no flow (although it does show groundwater influence in the deflation pans). Double-headed arrows are dune crests, black scale bar = 2 km. Location 45 km west south-west of Birdsville.



spaces between dune sets. Tepamimi Waterhole was visited during the field investigation, but as it is fed by an open artesian bore it cannot be considered representative of natural processes, and its landforms are not considered here. The rest of the boundary between Eyre Creek and Goyder Lagoon is alternating dunes and interdunes, in which the interdunes display few signs of scour or channelisation.

Processes

The flow that comes down Eyre Creek spreads out from Kudaree Waterhole and proceeds in parallel down the interdunes. Remotely-sensed datasets did not indicate a substantial component of in-channel flow preceding floodplain flow, and this is consistent with the low gradient and probable small volume of the channels. Downvalley travel of the flood front is slow, especially in the South Australian reaches where the flood front spreads out, and pauses for days to fill up 'sinks' in the flow path (the large lignum swamps). At the downslope and of Eyre Creek, the line of small dune sets does not appear to be a barrier to flow as the interdunes and spaces between sets are wide. However, rising flow is impounded behind the dune sets, flowing first through Tepamimi and Tepaminkanie Waterholes. As flood levels continue to rise, the flood front expands westward and flow enters Goyder Lagoon through a few wide shallow interdunes, widely separated along the border.

The low occurrence of scours, prevalence of unconfined flow, straight planform of such channels as are present, lack of distributary channels and close coincidence of channels with constrictions in the flow path all indicate exceptionally low-energy flow. It is possible that Eyre Creek has even lower flow energy than Goyder Lagoon (since Goyder Lagoon's floodplain has many scour features). This may have implications for surface and subsurface hydrology (e.g. is low energy linked to slow flow velocity, greater transmission loss and/or greater recharge to the unconfined aquifer), patterns of coolibah seed dispersal, or the suitability of Eyre Creek for some types of fish migration behaviour. The reaches of Eyre Creek shown in Fig. 11 contain no permanent or semipermanent waterholes (Silcock 2009), and this is another consequence of low-energy flow. Low-energy flow also indicates probable landform stability, and the dispersal of flow amongst the interdunes may buffer the system against the effects of high-magnitude flow events.

Eyre Creek does not contain aquatic refugia. Its connectivity during large flow events may provide fish migration pathways between the upper Georgina River and Goyder Lagoon. However, the open water visible on remotely imagery may be very shallow, and may act as multiple individual flow paths (as opposed to one large interconnected flow path). It is not clear if this is relevant to fish migration. The connectivity between Eyre Creek and Goyder Lagoon appears to be across a very broad area, however only the two gateway waterholes have demonstrated depth. It is not established in this study whether the other shallow entry points carry water deep enough or persistent enough to enable fish migration. Finally, it seems likely that connectivity between Eyre Creek and Goyder Lagoon will only be established if both are experiencing high flood levels.

Eyre Creek's widespread vegetation, close links with the unconfined aquifer, and large lignum swamps suggest that it will host important terrestrial ecosystems.

4.2 The Diamantina Fan

The Diamantina Fan is that part of the Diamantina River extending from around Birdsville (Queensland) down to and into Goyder Lagoon. This report is the first description of this part of the Diamantina River as a low-angle alluvial fan. The Diamantina Fan consists of the main channel and its nearby flow paths, and two secondary waterways: Eleanor Creek and Gumborie Creek (Fig. 12). The fan consists of 3 subsections:

- the northern flow paths (the main channel from Birdsville to Diamantina-split Waterhole, Eleanor Creek and Gumborie Creek),

- the distributary branches (from Diamantina-split Waterhole into Goyder Lagoon, the Andrewilla branch and the Yammakira branch; and including the Andrewilla Sand Plain between the branches),
- the downvalley edges (from approximately where the drainage network becomes densely bifurcated, and overbank sedimentation becomes minor).

Of these three subsections, the first two are included in this project's Diamantina River management zone. The fan's downvalley edges were not within the scope of this project and so were not examined in the field, and it is likely that it is more appropriate to manage the fan edge as part of Goyder Lagoon.

The fan is bounded on the north and east by gibber uplands, on the west by non-inundated dunefield and by Eyre Creek, and on the south by Goyder Lagoon. Its overall downvalley gradients are 0.01% (main channel, Queensland border to the Yammakira branch bifurcations) to 0.02% (secondary flow path along Eleanor Creek). Locally, slopes are more variable than this range, and can include reversed slopes where water from one flow path is delivered to (and must overtop) alluvial sediments deposited from a different flow path.

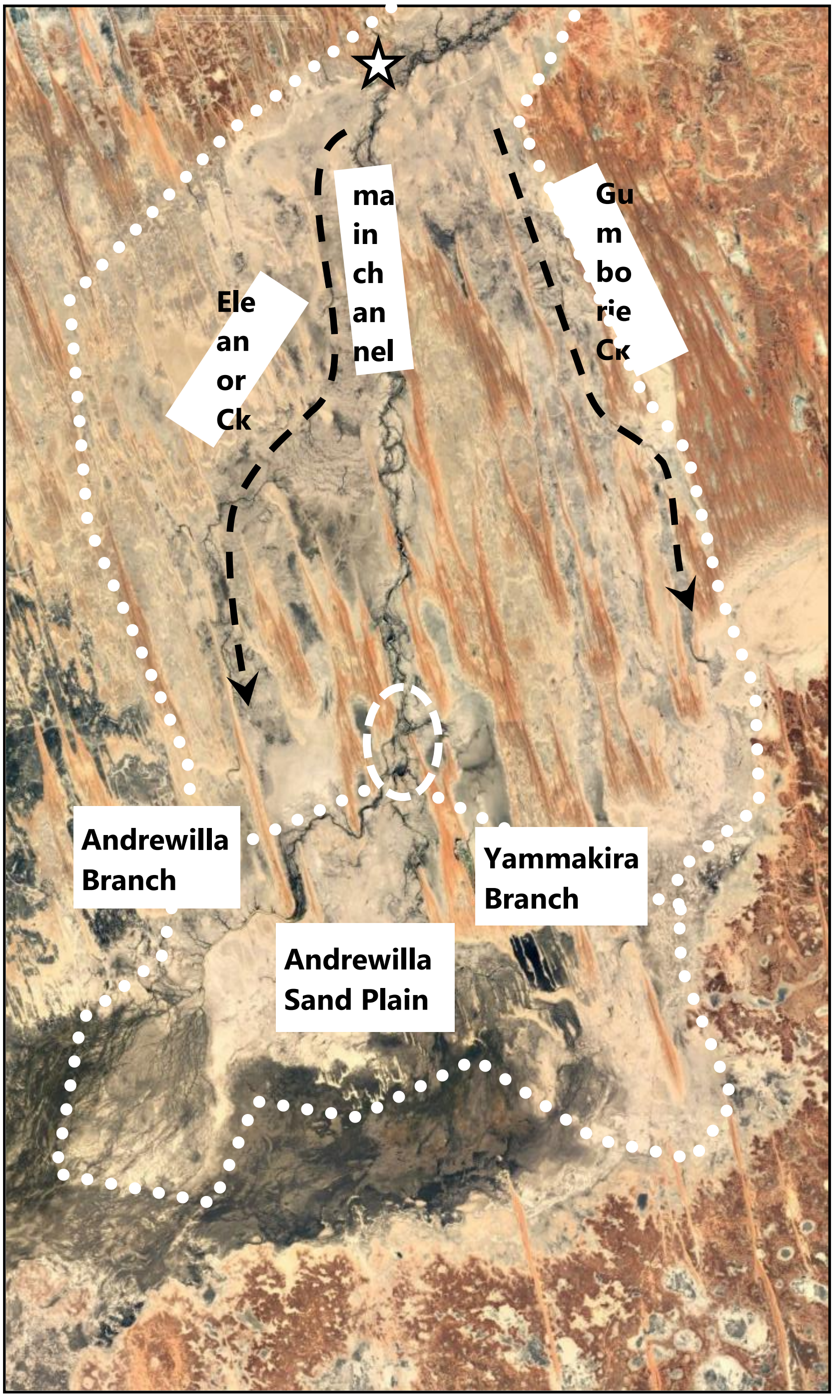


Fig. 12 Locations in the Diamantina Fan.

White dotted lines surround the Diamantina Fan, and separate the northern reaches from the distributary branches. Black dashed lines are the Gumborie Creek and Eleanor Creek flow paths (indicative only, as both creeks include broad areas of unchannelled floodplain flow). White star is Birdsville township, and white dashed circle is the Diamantina-split area. Google Earth image, white scale bar = 30 km.

The valley-scale landforms of the Diamantina Fan are the sets of orange and pale dunes, the relatively narrow interdune corridors, and the wide alluvial plains between dune sets. Where interdune and between- dune set spaces are open to the flow path but have no exit, lakes and lignum swamps develop. Where the spaces allow throughflow, the Diamantina River's flow paths are expressed as the main channel, and floodplain-level unchannelised flow. Only some of the floodplain-level flow paths are those associated with the main channel, (see section 5.2 Regional Flow Paths). In addition, there is the feature here named the Andrewilla Sand Plain (Fig. 12), a wedge of pale alluvial sands forming a topographic high between the Andrewilla and Yammakira branches.

4.2.1 Northern Diamantina Fan

Description

The degree of valley confinement of the main channel varies, and is linked to channel and local floodplain type. The landform associations are (north to south):

From the Queensland border down to approximately Pandie Pandie Homestead reach, the main channel is partially confined between dunefield and alluvial sediments. The main channel bounds alternating pockets of local floodplain, channel and local floodplain together forming a clearly defined channel belt (Fig. 13). The main channel is sinuous in regular curves, and actively meandering along all parts; the local floodplain is scroll plain with ridge-and-swale topography. There are some distributary channels from the main channel, most associated with incipient or achieved chute cut-offs.

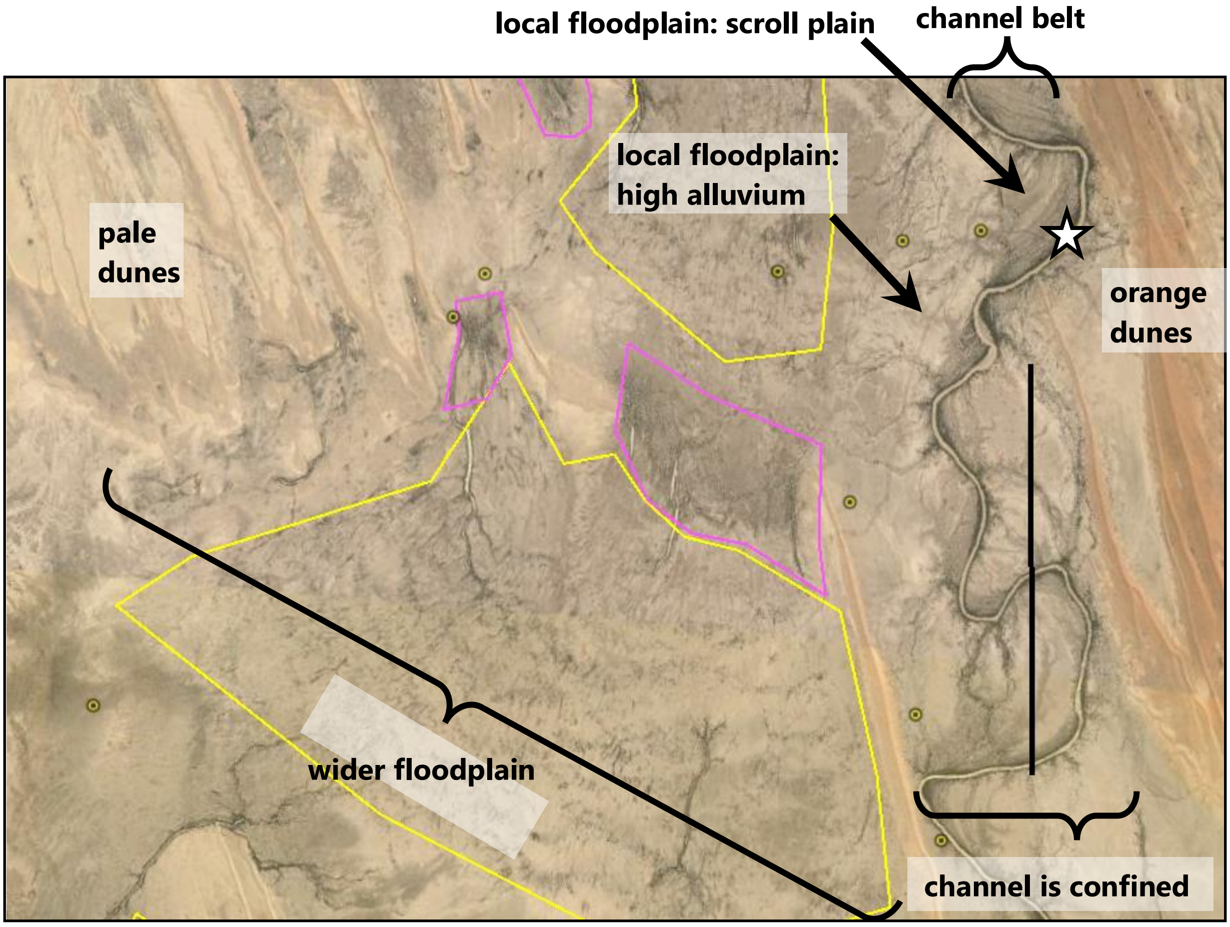


Fig. 13 Landform associations in the northern reaches of the Diamantina Fan.

Yellow outlines denote sheetflow deposits, pink outlines denote sets of parallel scours. White star is the Pandie Pandie Homestead reach.

From approximately Pandie Pandie Homestead down to approximately Double Bluff Waterhole, the main channel is almost entirely confined between high alluvium which is itself confined between dunes. The channel is irregularly sinuous with very small and isolated pockets of local floodplain: there is active meandering in very localised parts of the reach. The channel has many short and minor distributary channels.

From approximately Double Bluff Waterhole down to Diamantina-split Waterhole, the main channel has an irregular mixture of contexts ranging from confined between alluvial sediments, to almost unconfined. The main channel is irregularly sinuous. The isolated pockets of local floodplain are low elevation but their ridge-and-swale topography is somewhat less pronounced than the reaches further north. There are few distributary channels, but those that exist are long and significant (have riparian vegetation, and deliver water to significant floodplain-level flow paths or lakes) (Fig. 10).

The channel is continuous throughout the northern part of the Diamantina Fan. It is usually ~50-80 m wide, sometimes wider in areas of recent very active meandering. The channel banks are frequently associated with relatively elevated alluvial sediments, as a visible levee, or as a broad plain ("high alluvium", Fig. 13) which on remote imagery can be seen to be above the level of the wider floodplain. In unconfined wider floodplain settings, the high alluvium tends to be on the downflow side of channels; in more confined setting (e.g. between dune sets), the high alluvium tends to fill the available space.

In straight reaches, banks are usually compound, moderate to moderately steep in the upper bank and more gentle close to water level. In sinuous reaches, the outer bank usually has an elevated bank top (~2-4 m above water level), and steep sides showing evidence of bank retreat. Inside banks of sinuous reaches are usually low and gently sloping, in some cases heavily vegetated by lignum associated with bars of loose white sand. Bedload on the point bars is medium-fine to medium quartz sand, dominantly pale-coloured alluvial sand, minor to ~20% orange dune sand.

Distributary channels are most commonly found on the outside banks of sinuous channels. Distributary channels can be short, extending just the width of the alluvial ridge or levee flanking the bank, or long, with the bank breach leading to large gullies (~4-8 m wide, 3-4 meters deep) in networks extending out into the floodplain. Proximal to the main channel the gullies tend to be narrow and deep with steep banks and bank tops. With increasing distance from the main channel, the gully base usually rises up to floodplain level, and the distributary networks become more broad and shallow with gentle rounded banks.

Fig. 14 Vegetated swaley ground at the end of a Double Bluff reach distributary channel.

Distributary networks finish in vegetated swaley ground (Fig. 14). Many distributaries have a small inset channel associated with small tributary-mouth deltas leading back into the main channel. Distributaries which are not too narrow or steep are favoured ways for cattle to reach the main waterhole.

Distributary offtakes occur as breaches in the high banks. Where the offtakes feed substantial distributary channels, the offtakes are usually complex landforms (several openings, parallel flow areas behind the main channel banks, etc.) with evidence of rapid local erosion.

There are two sorts of floodplain local to the main channel in this part of the Diamantina Fan (Fig. 13). The high alluvium is about bank-height (higher than scroll plains or the wider floodplain), and so is not often inundated. It is usually low-relief with few and poorly-defined topographic features. The scroll plains have ridge-and-swale topography that undulates on a scale similar to the width and depth of the main channel, but with more gentle bank slopes and curved surfaces between bank top, slope, and the base of the swale. The ridges and swales closest to the current channel tend to be similar to it in elevation and relief, but those furthest from the current channel tend to have less relief and their elevation approaches that of the high alluvium.

The wider floodplain in the northern reaches of the Diamantina Fan is characterised by low elevation, low relief, and irregular topography. It was outside the scope of this study, but its landform suites include sets of parallel scours, sheets of alluvial sediment (Fig. 13), plains of cracking clays exhibiting a range of gilgai development from negligible, through light gilgai heave with small crabholes, to moderate degrees of gilgai heave and some medium-sized crabholes. Sediment deposition across the wider floodplain is variable: in most places modern sediment masks the underlying Pleistocene sediments, but in some places it does not. The modern sediments of the wider floodplain are mixture of mud aggregates, quartzose silt, and fine sand. The relative amounts of these components is likely to be variable across the floodplain, however quantified estimates could not be made without more detailed work (as the geomorphic expression of mud aggregates is dependent on inundation frequency, see Fagan and Nanson 2004, and a slaking test is required to estimate the proportion of mud aggregates, see section Technical Appendix A1, Methodology). Sediments deposited on the wider floodplain from recent flows included pale medium-fine to medium quartz sand, and mud aggregates, as mixed load and as separate layers.

The wider floodplain hosts the secondary flow paths of Gumborie and Eleanor Creeks. The Gumborie Creek flow path is largely unconfined flow spread between dune sets. There is a string of small channel segments and scour zones, mostly in slightly confined places. The Eleanor Creek flow path begins as unconfined floodplain-level flow with scour zones and isolated channel segments such as Dickeree Waterhole. The largest channelised section, Eleanor Creek itself, is actually two parallel channel segments and a parallel-scour zone, finishing with a broad distributary area upvalley from the Andrewilla inlet zone.

Channel segments and isolated waterholes typically have multi-channel inlet areas which are not flanked by high alluvium, and which coalesce into a single main waterhole area. After reaching a maximum size, the waterhole diminishes in width and depth with distance downstream, and these reaches are associated with high alluvium on the downflow sides. The channel segments usually terminate in downflow bifurcations and multiple splays, surrounded by a halo of deposited sediment (Fig. 15).

Coolibah and their associated understory tend to be large, healthy, and relatively closely spaced in low- to moderate-elevation areas with good connectivity to flow: scroll plains, low banks, gully and waterhole terminations, some bank tops. Smaller, less robust, and widely-scattered coolibah also occur on the wider floodplain, especially on secondary flow paths and in the swaley ground at the end of distributary channels. Some (presumably the more elevated) of the high alluvium is only thinly vegetated. The outer banks of some very active meanders have narrow or non-existent riparian zones.

Processes

At a valley scale, the most significant fluvial process of the northern Diamantina Fan is the separation of flow paths between floodplain-level flow and the main channel. During the rising flood, flow is contained within the main channel and the lower-elevation parts of its local floodplain (the scroll plains). As water levels rise distributary channels are activated, filling interdune lakes and swamps, and releasing water onto the unconfined spaces of the wider floodplain. There, flow is largely unchannelled and sediment deposition takes place according to very local conditions of transport energy. Significant offtake occurs from the northern reaches (north of the Queensland border down to about Pandie Pandie). Of this, the left-bank water enters Gumborie Creek and the right-bank water enters one of the flow paths leading to Dickeree Waterhole and Eleanor Creek.

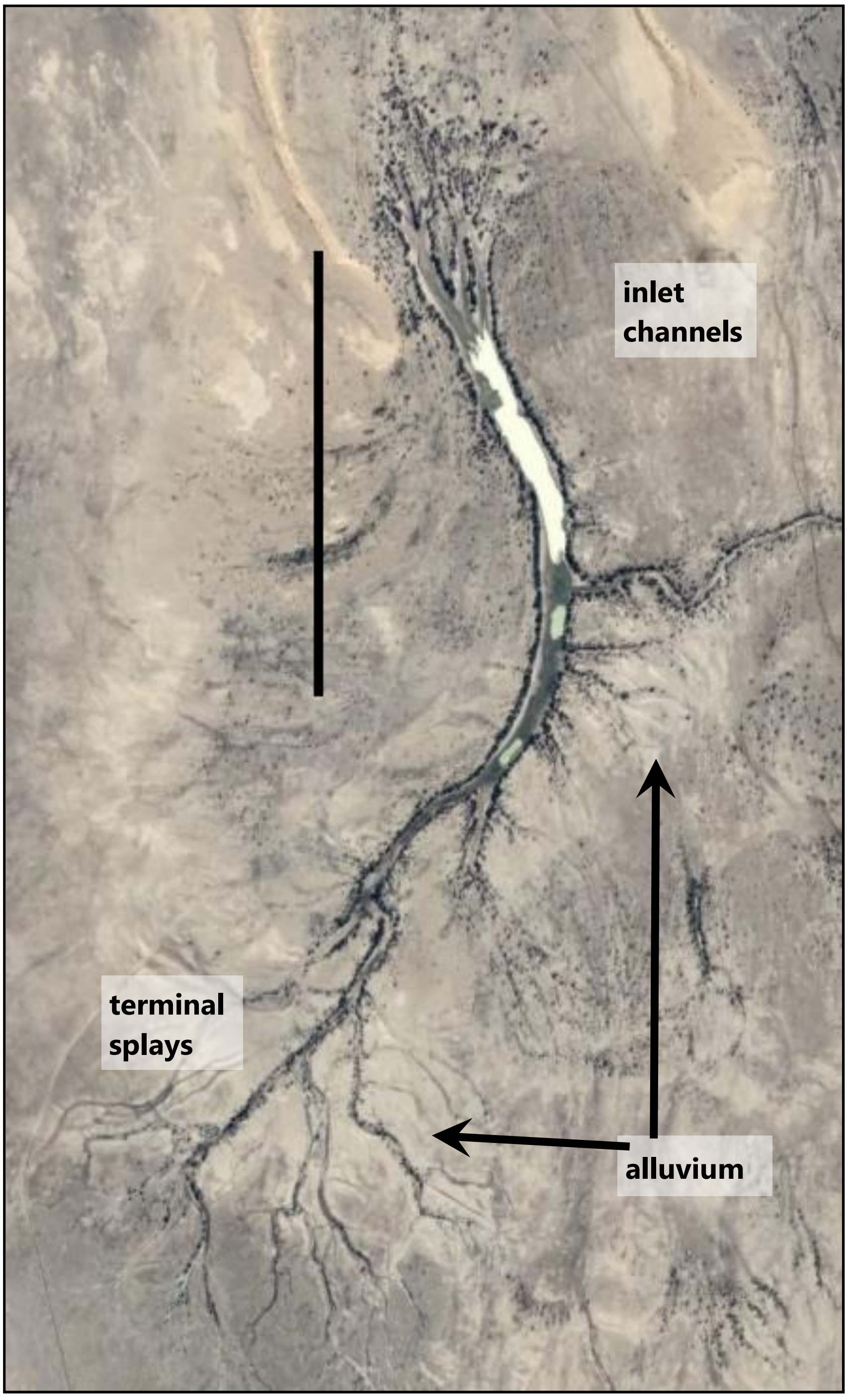


Fig. 15 Dickeree Waterhole, black scale bar = 1.5 km.

Near Double Bluff Waterhole the main channel flow path is forced into a narrow interdune space; at this point the main channel flow path is almost entirely in-channel water. Downvalley from Double Bluff, the main channel flow path picks up some of the wider floodplain flow from the north, and these combined waters move down towards Diamantina-split Waterhole. Independently, the rest of the wider floodplain flow from the north moves down the Eleanor Creek flow path, towards the Andrewilla Waterhole intake channels.

At a reach scale, the main channel's most significant fluvial processes are redistribution of water and mixed sediment from channel to floodplain by overbanking and distributary channels, meandering, and the bank breaching that creates distributary channels. The three different landform suites of the northern Diamantina Fan are related to bank conditions affecting the balance between the meandering and bank breaching.

In the most northerly reaches (Queensland border to Pandie Pandie Homestead), the main channel is free to meander within its channel belt. The channel migration is incremental, creating successive abandoned channels (the low-elevation and frequently inundated scroll plain) which are progressively filled by vertical floodplain aggradation (the higher-elevation parts of the scroll plain). Meander development is by downvalley translation, with occasional neck-cutoff and chute-cutoff.

From Pandie Pandie Homestead south to Double Bluff, the channel banks are strengthened by high alluvium; localised meandering still occurs (as increasing sinuosity) but most of the reaches are not migrating. Consequently, there are fewer areas with wide riparian zones. Flow banking up behind Double Bluff overtops the banks and deposits the high alluvium in the spaces between dune sets. Few distributary channels develop because these reaches have very little wider floodplain to distribute water to.

Downvalley from Double Bluff Waterhole the main channel has some reaches that are stable between high alluvium and some that are actively meandering. Distributary channels that develop here can deliver flow onto the wider floodplain, so there are important offtakes, including the feed channel into Lake Uloowaranie, and the right-bank distributaries that supply water to the Andrewilla branch flow path. (This includes the distributary at Diamantina-split Waterhole, however it is important to note that this distributary is not the main source of the Andrewilla branch water.)

At Diamantina-split Waterhole (Fig. 10) there are three main flow paths: the main channel is continuous down into the Yammakira branch, a left-bank distributary fills Lake Uloowaranie, and right-bank distributaries contribute water to the floodplain-level flow path that leads to the Andrewilla branch. The Andrewilla flow path, constrained between dune sets and alluvial sediments, forms upvalley as a discontinuous channel which coalesces downvalley into an increasingly well-defined continuous channel.

4.2.2 The Distributary Branches

Description

The distributary branches are located where the Diamantina River enters Goyder Lagoon. The relatively narrow flow paths near Diamantina-split Waterhole open up to an area >8 km east-west and >30 km north-south. Although this seems to be an unconfined setting, in fact the two branches of the Diamantina River are constrained between bordering dune sets to the east and northwest and the Andrewilla Sand Plain in the centre (Figs. 12, 16).

The Yammakira branch is a continuation of the main channel. Its valley is defined by the orange dunes to the east and Andrewilla Sand Plain to the west. Its channel is flanked by levees and high alluvium , forming an alluvial ridge along most of its length. It is sinuous but the curves are of small amplitude; there are small areas of densely vegetated scroll plain (Fig. 17). There are few distributary channels, and although one extends westwards the remote sensing images do not indicate that it delivers much water into the Andrewilla Sand Plain. Another poorly-developed distributary extends from the left-bank, just south of the orange dunes. There is a single abandoned channel, mostly infilled, ~1.5 km into Goyder Lagoon. At ~2.7 km downstream from its entry into Goyder Lagoon, the main channel bifurcates. From that point onwards, the Yammakira branch forms networks of radial distributaries, decreasing rapidly in size with distance downstream. The most dominant radial distributary was previously that leading to the Peraka swamps, but relatively recently the dominant channel has switched to one that flows southwards (Fig. 17). The chief distributaries are flanked by alluvium forming their own alluvial ridges (Fig. 16). At the downstream terminations of the distributaries there are splays of sandy alluvium, and the channels merge with the reticulate channels of Goyder Lagoon.

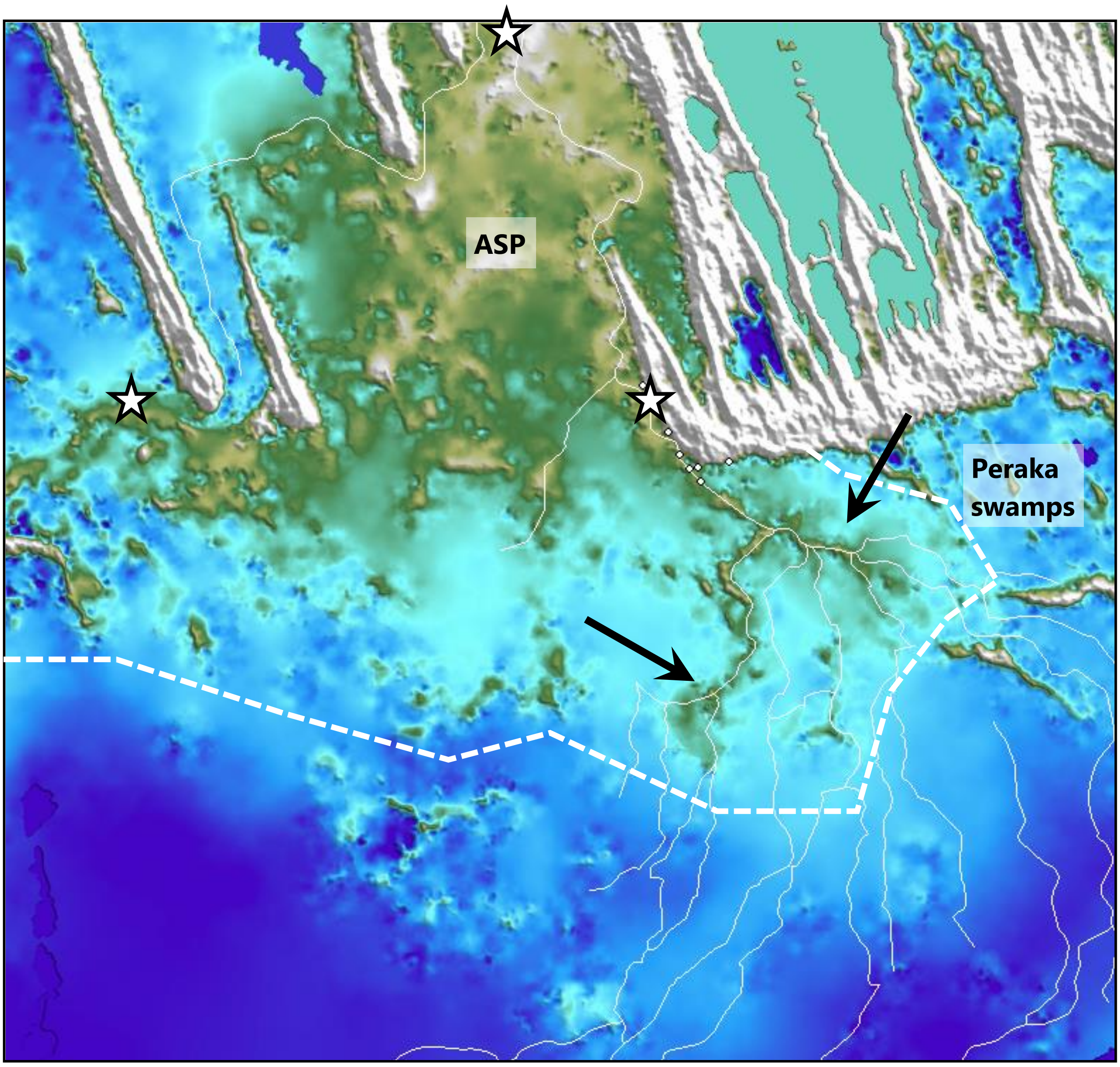


Fig. 16 Topography of the Diamantina River's entrance into Goyder Lagoon.

The Andrewilla Sand Plain (ASP) lies between the Andrewilla and Yammakira branches of the Diamantina River, and marks the progradation of alluvial sediment into Goyder Lagoon. Arrows indicate the alluvial ridges of the Yammakira branch. Digital elevation model, white and pale green are highest elevation, shading through dark green to dark blue at lowest elevation. White stars are the river reaches (north) Diamantina-split, (west) Andrewilla, (east) Yammakira; dashed white line is the approximate extent of overbank sediment deposition. Thin white lines are the Geoscience Australia 1:5 million drainage network; field of view is ~35 km in the east-west direction.

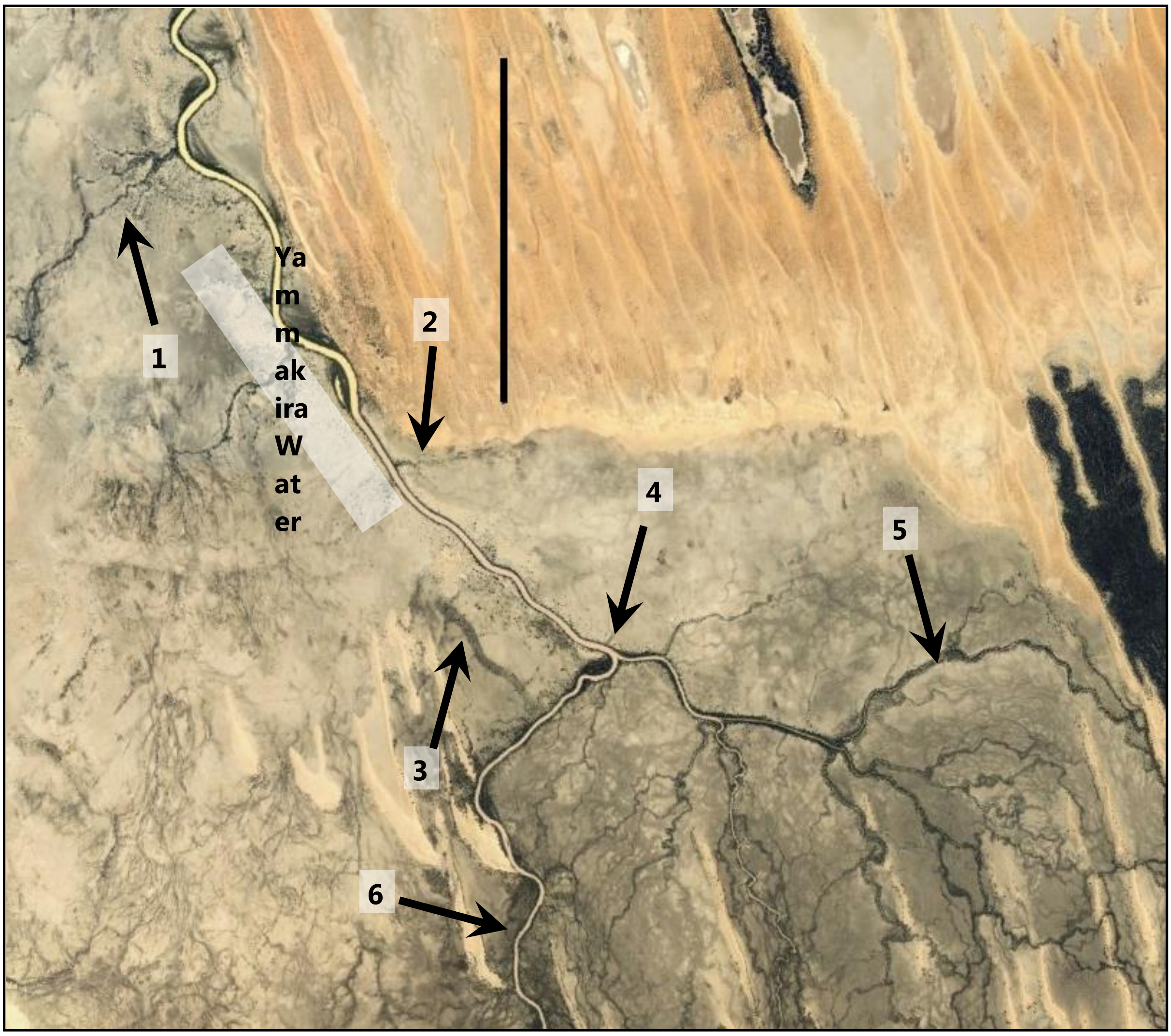


Fig. 17 Diamantina Fan, Yammakira distributary branch.

1 and 2, distributaries; 3, infilled abandoned channel; 4, bifurcation of the main channel; 5, a part of the radial distributary network that leads to the Peraka swamps; 6, the dominant channel of the radial distributary network. Google Earth image, black scale bar = 3 km.

The Andrewilla Sand Plain is a 12 km x 22 km expanse of hard sandy and muddy alluvium crowned by sparse pale dunes. Much of the plain is approximately the same elevation as the high alluvium, although some appears to be lower; the plain is topographically irregular (Fig. 16). A few poorly defined and shallow flow paths extend north-east to south-west across it (Fig. 18), however most of it is rarely if ever inundated under present flow conditions. It is very poorly vegetated. At the plain's north-western edge, short sets of narrow pale dunes extend up to the left-bank of Andrewilla Waterhole, where they form a ~4 m high bank. The sides and top of this channel-bordering sand ridge are vegetated by coolibah. In addition, large coolibah are found tens to >100 of meters away from the dune crest, on the sand plain side (Fig. 19). During field investigation, it was noted that in strong winds considerable northwards sand transport was taking place, with visible sand up to 15 m above the ground surface. The downwind side of the channel-bordering sand ridge is eroded by wind down to a faceted surface of consolidated fine-sandy mud or muddy fine sand.

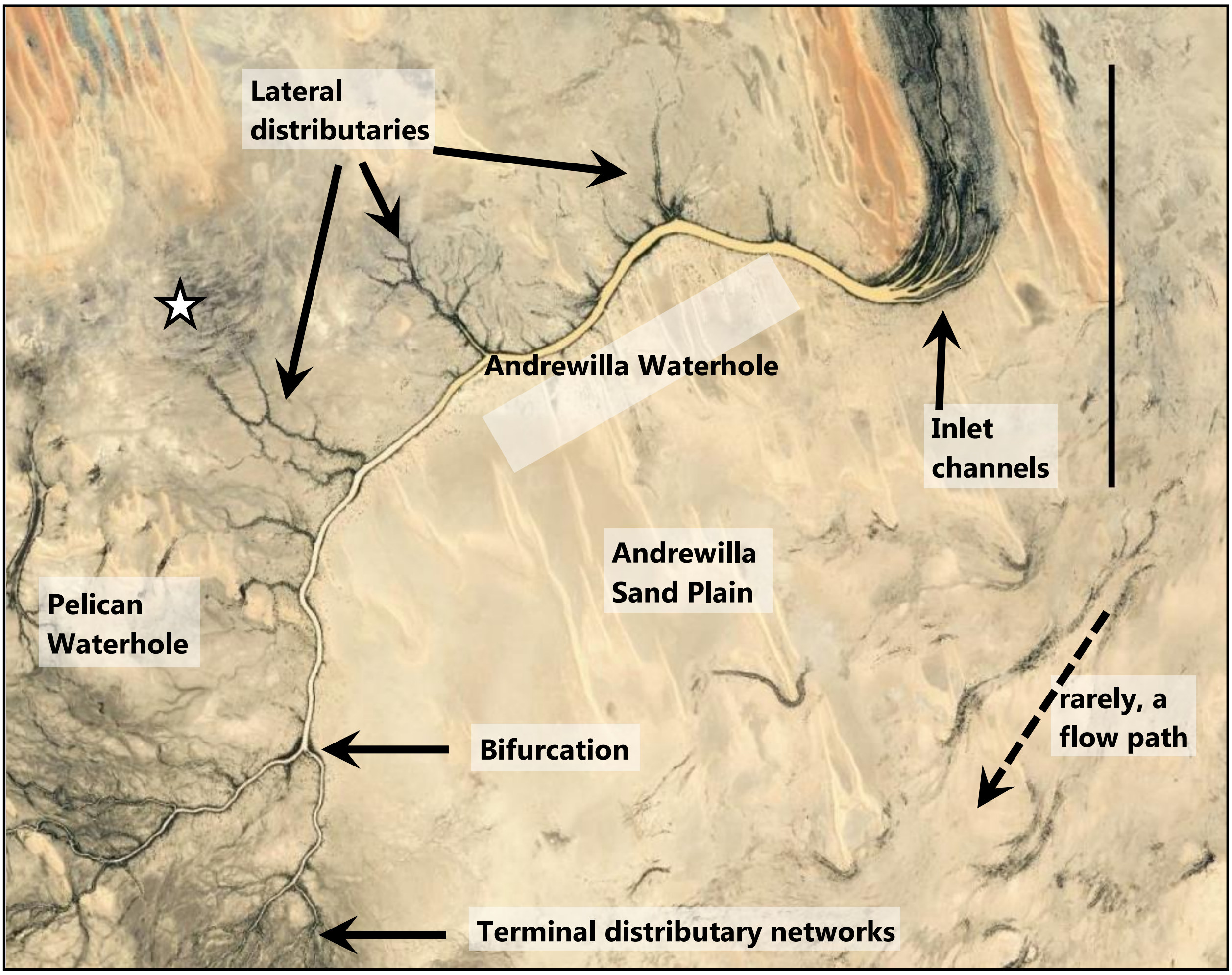


Fig. 18 Andrewilla Waterhole.

White star = low-elevation areas at the margin of Goyder Lagoon. Google Earth image, black scale bar = 5 km.

Andrewilla Waterhole is a continuous channel ~11 km long, 150 m wide at the upstream end, diminishing to 70 m wide at the downstream end. It is gently sinuous but not actively meandering. Channel banks are very steep. Its left-bank is constrained by the Andrewilla Sand Plain, and its right-bank by broad levees. The right-bank riparian zone is narrow, and shows vertical sediment aggradation. The left-bank has some short but deep gullies leading up to the sand plain, one of which is acting as a distributary. The gully visited during fieldwork did not show signs of cattle. The right-bank has a number of lateral distributaries, with offtakes mostly clustered around outside-bank bends. Right-bank distributaries are well-developed, up to 1.7 km long, >2 m deep with moderate banks and levees; bank-top and -slope vegetation indicates the banks are stable and not of recent origin. The distributaries cut through the levees and deliver water to a broad low-elevation area that is the Goyder Lagoon's northern margin (Fig. 18). The downslope end of the distributary channel is swaley and guttered landscape with patches of gilgai. Coolibah are closely spaced along the narrow riparian zone, and more widely scattered and smaller in the floodplain fed by the distributaries.

At the upstream end of Andrewilla Waterhole, all the flow from Eleanor Creek and the Diamantina split Waterhole reach is funnelled into an interdune space. A network of small channels coalesce and broaden into ~7 inlet channels, which themselves coalesce into the single channel of Andrewilla Waterhole. During the mid-1970s flood, one of the inlet channels expanded and cut back into the floodplain and the base of the orange dune, triggering an erosion gully network in the dune. At the downstream end of Andrewilla Waterhole the channel bifurcates and develops a radial pattern of terminal distributary channels (Fig. 20) that diminish in size as they descend into Goyder Lagoon.

For both the Andrewilla and Yammakira branches, the terminal distributary networks (and in the case of Andrewilla Waterhole, the lateral distributaries) are extending into spaces defined by Goyder Lagoon's pre-existing topography. As a result, the Diamantina Fan's downvalley-edge channel networks and flow paths either go around or cut through Goyder Lagoon landforms.

Fig. 19 A large coolibah growing from a fallen trunk, ~150 m from the channel-bordering dune; airborne sand.

Processes

The Yammakira branch has a relatively stable planform mostly constrained by high alluvium. Between the Andrewilla Sand Plain and the orange dunes it is not very geomorphically active, except for localised areas of active meandering, mostly by downvalley translation and some of it apparently rapid. There is evidence of one channel avulsion as the channel enters the unconfined space of Goyder Lagoon, however vertical aggradation of alluvium has partially filled that space and the channel's location appears fixed. (However, a low-elevation area with an incipient distributary exists on the left-bank side just south of the orange dune; this is a potential avulsion pathway.) At ~2.7 km downstream from the Yammakira branch's entry into Goyder Lagoon the channel becomes less constrained, and it bifurcates and becomes a radial distributary network. Repeated channel splitting and transmission loss means the channels decrease in size, however bedload transport and overbank deposition of alluvium takes place right to the end of the two current channels. The most east-directed of the radial distributary channels has recently been abandoned, and the Peraka swamps may not receive water until inundation has reached a level that activates the older channel.

The Andrewilla Sand Plain has been deposited from previous generations of the Diamantina Fan's channels. These old channels would have extended less far into Goyder Lagoon than the present channels do. Since deposition, the alluvium has been partially reworked into pale dunes. Trees and grasses currently trap aeolian sand. In the present day, the Andrewilla Sand Plain acts to divide the Diamantina Fan's flow into the two branches. By constraining the present river channels to narrow flow paths, the Andrewilla Sand Plain has extended the channelised reaches further into Goyder Lagoon. Extremely large flows might partially inundate the south-eastern part of the sand plain, however it appears that such a flow size would be >1% AEP.

Large coolibah are growing on the Andrewilla Sand Plain where they could not have germinated under ordinary flow conditions and where they have not had direct access to main-channel water. Although the Andrewilla Sand Plain's topography suggests low-elevation areas not far to the south-east that might have been inundated to allow strand-line germination of these coolibah (see Costelloe 2017), the digital elevation model and 1969/1977 aerial photography indicates that such a flood would have been greater than the ~1% AEP flood. It suggests therefore that these trees may be a record of a longer-term flood record than is currently available in the study area.

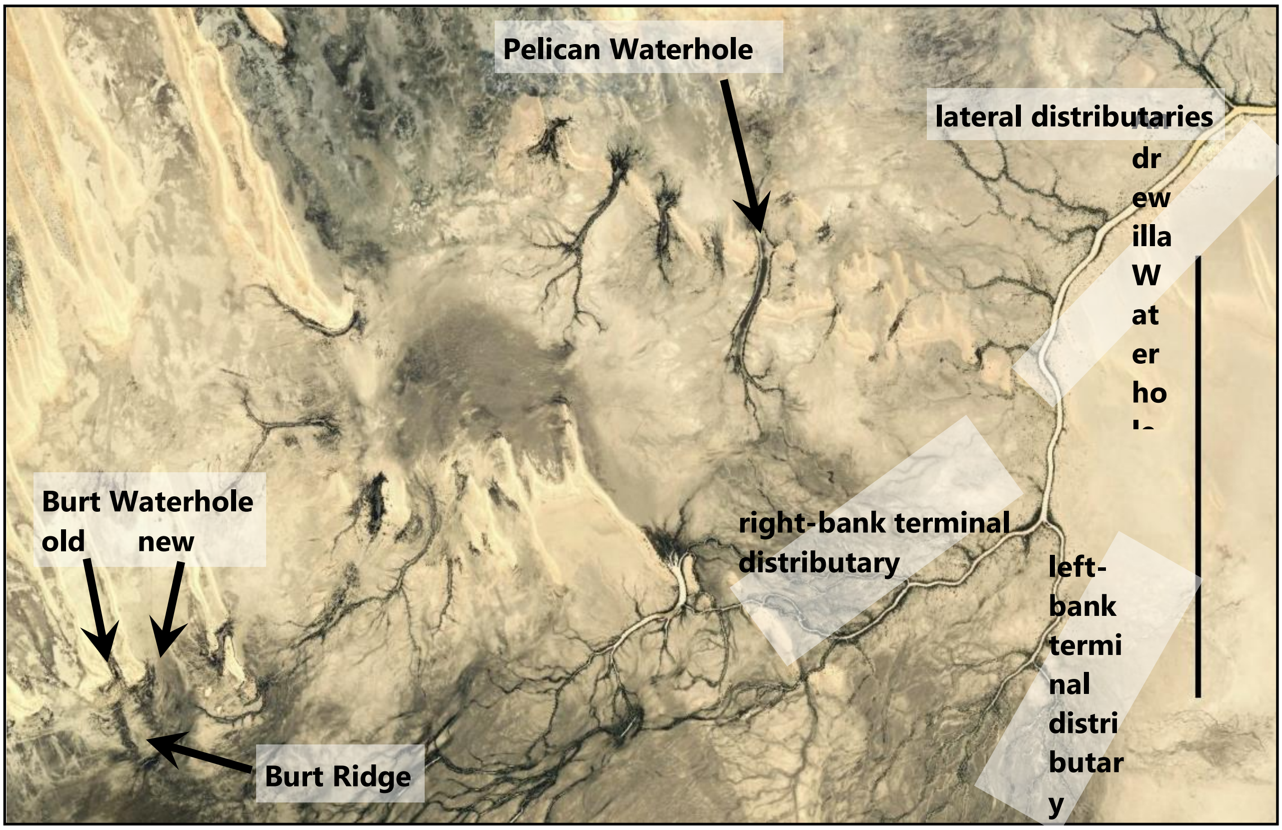


Fig. 20 Locations in the Andrewilla, Pelican, and Burt Waterhole areas. Scale bar = 5 km.

Andrewilla Waterhole's large size reflects that it gathers together in a confined space the water from several flow paths. The inlet channels are a high-energy zone that is likely to host strong turbulent conditions during large flows. During flow, sediment is carried high in the water column and deposited over right-bank levees during overbanks. In addition, above a certain flood height water flows down the distributary channels and accumulates in low-elevation areas to the north and north-west. It is likely that the downflow-decreasing channel size promotes backing-up of the in-channel water and triggering overbanking and offtake down the distributary channels. In turn, the transmission loss promotes the decrease of channel size; a positive feedback process.

The volumes of water coming down Andrewilla channel and the elevation difference between the bank top and the low-elevation areas to the north indicate that the channel may be naturally vulnerable to avulsion by the progressive incision of one of the distributaries. This would not necessarily be detrimental to the terrestrial ecosystems, it would just shift the entry point of Andrewilla branch water into Goyder Lagoon by a few kilometres. It would probably diminish Andrewilla Waterhole's value as an aquatic refuge, at least temporarily. However, it raises the question of what process allows transmission loss by both overbanking and distributary channel within the same reach. The distributary channel beds must be of lower elevation than the bank tops, so what prevents all the water from draining via the distributaries? A possible sequence of events is that 1) rapid rise to flood peak adds water into the channel more quickly than the distributaries can disperse it, 2) excess flows overtop the banks, 3) sediment deposition reinforces the levees and aggrades the distributary channels, maintaining the distributary channels' sills. If this is correct, it is likely that protecting the sediment-trapping riparian vegetation may be useful in promoting stability of the Andrewilla channel.

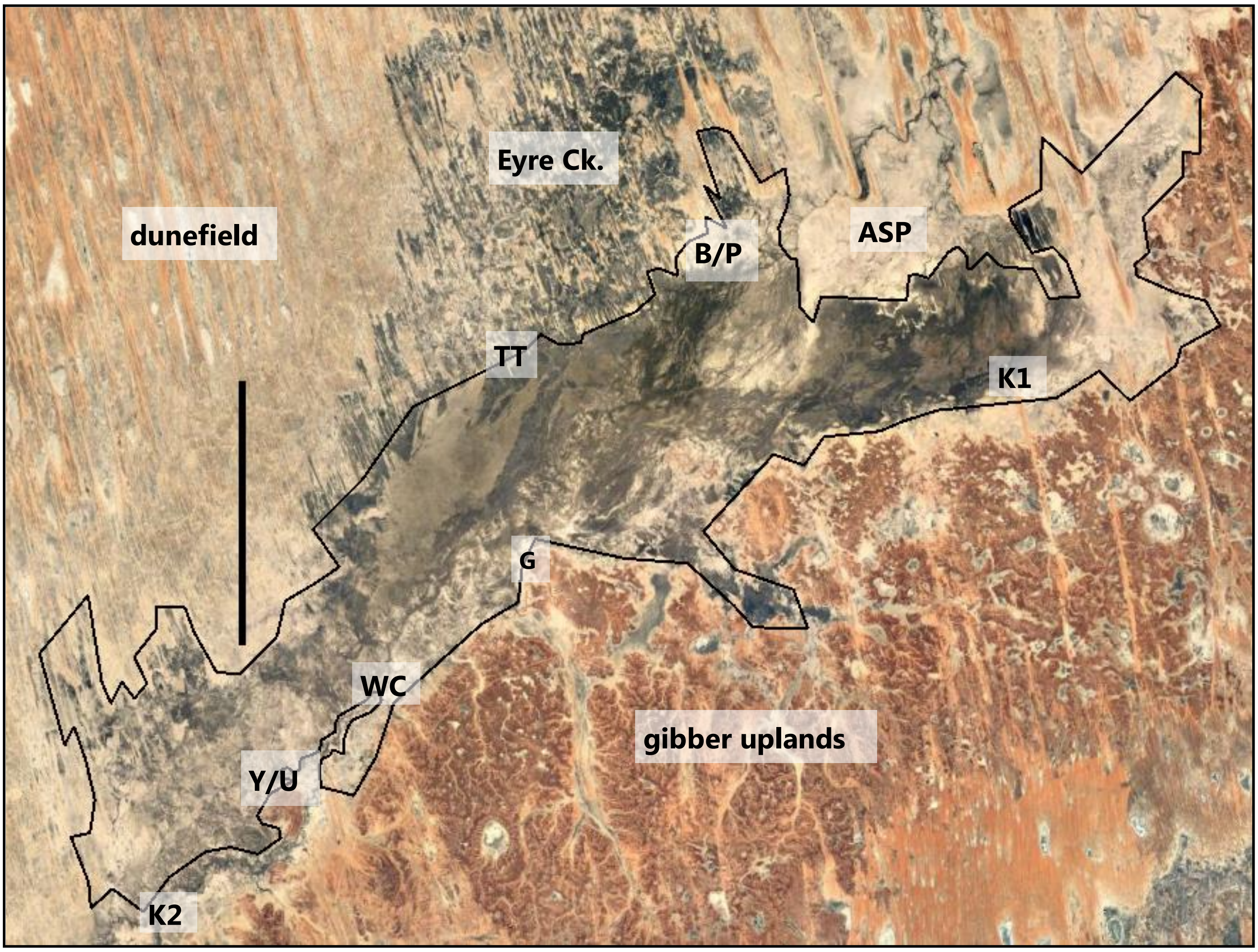


Fig. 21 Goyder Lagoon.

Goyder Lagoon management zone, black outline; ASP, Andrewilla Sand Plain; K1, Koonchera Waterhole; B/P, Burt and Pelican Waterholes, TT, Tepamimi and Tepaminkanie Waterholes; G, Goyder Lagoon Waterhole, WC, Warburton Crossing; Y/U Yelpawaralinna and Ultoomurra waterholes; K2, Kalamunkinna Waterhole. Google Earth image, black scale bar = 30 km.

4.3 Goyder Lagoon

Description

Goyder Lagoon is a broad shallow low-relief basin between Sturts Stony Desert and the Simpson Desert dunefield. Wide areas of lignum swamps (black on Google Earth images, Fig. 21) are the most easily recognisable parts of the lagoon; they extend 87 km in the downflow direction, from near the Peraka swamps to the dunefields north of Kalamunkinna Waterhole. As a landform, the lagoon is larger, extending 140 km ENE-WSW and 26 km across the valley. Goyder Lagoon is bordered by gibber hillslopes along the east and south and by the Simpson Desert dunefield to the north-west. The Diamantina Fan is prograding into the north-eastern section of Goyder Lagoon, and the flow path of Eyre Creek enters Goyder Lagoon from the north. The overall downvalley gradient is 0.001%.

Goyder Lagoon's most characteristic valley-scale landform element is its wide space and extremely low relief. Most of the landforms are not high – the trees and the larger lignum are bigger. The few exceptions are some short sets of pale dunes near the downvalley edges of the Diamantina Fan, and valley-margin landforms (dunes, and gibber hills). Within that overall character of wide space and low relief, there are some areas which are probably of slightly more elevated topography than the rest of Goyder Lagoon (Fig. 22). They are delineated by flow patterns, expression of the Pleistocene subcrop, and vegetation communities. The most important of these are the Diamantina Fan (the Andrewilla Sand Plain, and the sediments associated with the Andrewilla and Yammakira branches), and a broad flat area to the north-west and west of Goyder Lagoon. This broad area is associated with parts of the Eyre Creek confluence, and extends down to the beginning of the Warburton/Kallakoopah Creeks management zone (near Warburton Crossing).

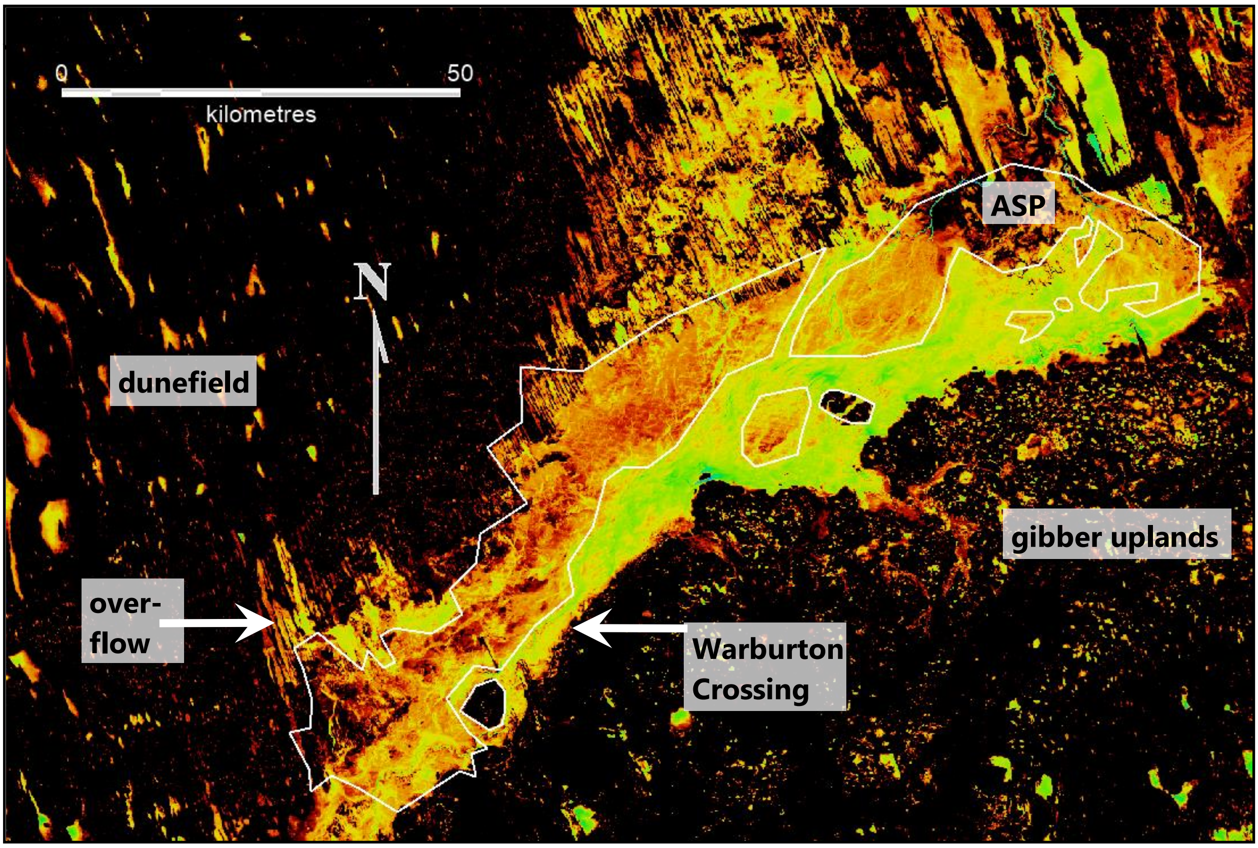


Fig. 22 Goyder Lagoon's areas of slightly higher elevation as defined by inundation frequency.

WOfS image. White outlines indicate areas of probable higher elevation; ASP = Andrewilla Sand Plain. Colours indicate inundation frequency, used here as a proxy for topography. Red and orange are inundated less frequently than yellow and green.

There are few waterholes, and they are mostly located around the lagoon's margins. Koonchera, Burt, Pelican (Fig. 5), Yelpawaralinna, Tepamimi and Tepaminkanie Waterholes are associated with sand dunes, and Ultoomurra and Goyder Lagoon Waterholes (Fig. 23) occur where some of the flow enters a narrow space between the gibber hills. The waterholes are isolated channel segments, similar to those of the Diamantina Fan: a group of inlet channels coalesces to a broad single channel, which decreases in size in the downflow direction. The waterhole's downflow end typically has multiple terminal distributary channels, usually associated with flanking and downvalley sediment deposition (Fig. 23). The waterholes usually have compound banks, with the upper section being moderately steep, and the bank top supporting riparian coolibah. Unlike the Diamantina Fan, Goyder Lagoon waterholes lack lateral distributary channels; there are some places where banks have been lowered to create a diffuse outflow area (Fig. 23).

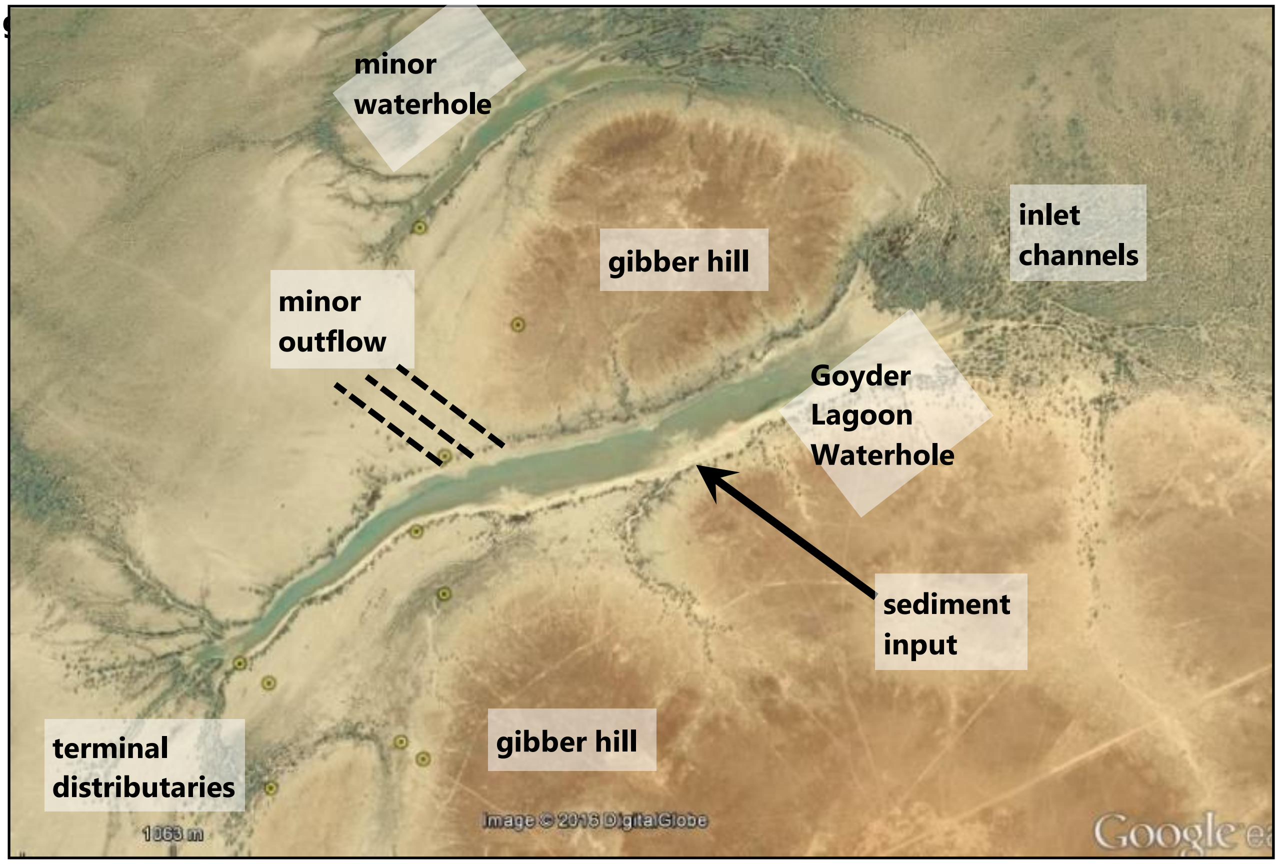


Fig. 23 Goyder Lagoon Waterhole; flow is from top right.

Google Earth image, field of view is 4.4 km wide.

The Burt Waterhole reach has a number of features of interest. In the present day there are three waterholes: two in a narrow interdune, and one around the nose of a dune (Fig. 24).

The two in the interdune (old Burt Waterhole) currently act as a single compound waterhole, however the channel on the west is narrow and long with old riparian trees, and the channel on the east is wide and short with young riparian trees. Both have clearly-defined planforms with inlet areas to the north and terminal splays to the south. The channels' banks are not very high, but are clearly defined by their bank slope and riparian (bank-top) trees. The western channel is visible in the 1969 aerial photography, but the eastern channel does not appear until after the mid-1970s flooding.

The waterhole around the nose of the dune (new Burt Waterhole, the fish monitoring site during this project) is very short, and has poorly-defined low swampy banks, very unlike most Channel Country waterholes. Its planform is also poorly-defined, with no clear inlet or outflow. This waterhole also appears after the mid-1970s flooding.

The Birdsville Inside Track comes down from the north and goes around the nose of the dune in the area of new Burt Waterhole. The track was well-established in the 1969 aerial photography, and looks like it was being maintained by a grader. Other landform features in this area are two sets of parallel scours where the main flow path sweeps around the corner formed by the dune (Fig. 24), and a ridge of pale sediment between them. This feature is named Burt Ridge on the old topographic maps. Flow is delivered into this area by the various Andrewilla Waterhole lateral and terminal distributaries via the local topography of small dunes and 'sinks' (Fig. 20).

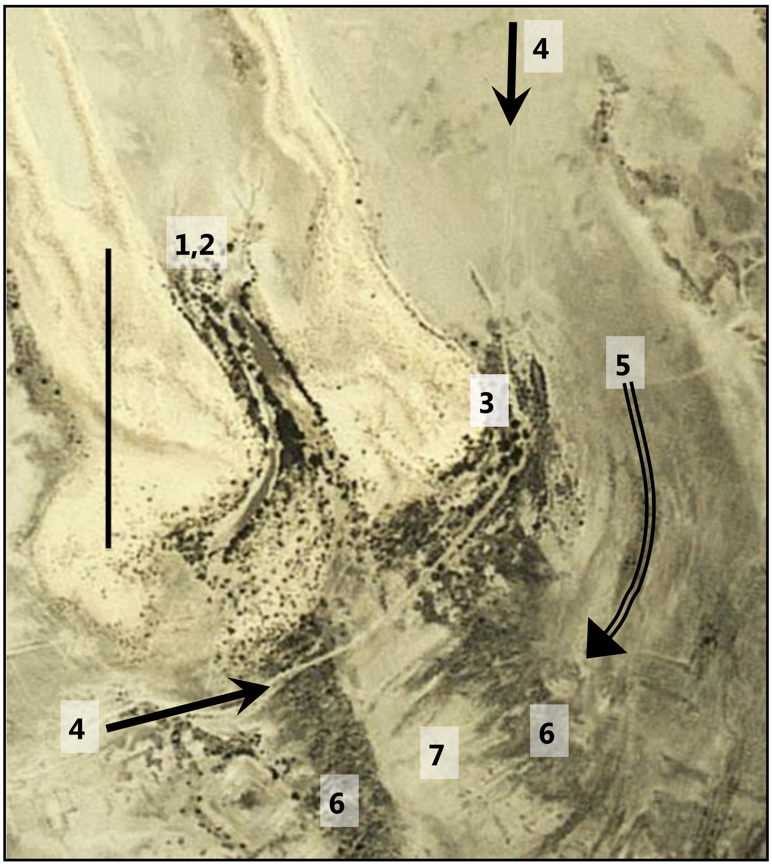


Fig. 24 old and new Burt Waterholes.

One, 2, 3, waterholes in the order of their formation; 4 and black arrow, the Birdsville Inside Track; 5 and black double arrow, the principal flow path; 6, parallel scour sets; 7 Burt Ridge. Google Earth image, black scale bar = 0.5 km.

Goyder Lagoon does not have a channel network that links the Diamantina Fan to the beginning of Warburton Creek: the few waterholes are the only channels of any size, and they are volumetrically insignificant in comparison to the scale of the lagoon. Flow follows diffuse pathways, and the lagoon surface carries numerous and varied reach-scale surface features, many with small-scale scours or other markers of flow behaviour. They were not within the scope of the present study. These features include zones of parallel scours and wide areas of sheetflow deposits (similar to those in the Diamantina Fan, Fig. 13), and scours with varying degrees of shallowness, edge and end definition, and landform associations (e.g. Fig. 25). With increasing distance downvalley, the diffuse flow paths become more well-defined and similarly oriented, and this corresponds to the narrowing of the low-elevation floodplain space (Fig. 22). Upstream from Warburton Crossing the flow path has coalesced into a broad belt of anastomosing floodway swales, with inset small you sites or channels. This is the beginning of the Warburton Creek management zone (described in section 4.4).

Fig. 25 Shallow scour set in Goyder Lagoon.

Top right, Google Earth image of cluster of narrow scours 5.4 km north of Yelpawaralinna Waterhole, white scale bar = 0.5 km. Top left and bottom, the scour comprises broad swales lined by lignum. Scattered medium-sized coolibah are also found here.

Goyder Lagoon's best-known landform-vegetation association is the densely vegetated lignum swamps that occur across wide areas. They tend to be 'sinks' (accumulate water rather than immediately transmitting it) and are characterised by reticulate channel networks, long-term inundation, and vertic soils with well-developed gilgai heave (Fig. 26). There are also lignum swamps in which the small channel networks are somewhat more oriented towards the overall flow path; there is a continuity of channel network geometry between reticulate, parallel-reticulate and anastomosing swales.

The sedimentary deposits in Goyder Lagoon were not a focus of this study, however it was noted that there was a surprising degree of variation. Some areas were vertic soil with little to no sand component. Of these, some had very well-developed gilgai features whereas others were flat with little gilgai. It is likely that this variation relates to frequency of inundation. There were also areas where the sediments were more sandy but which were unrelated to sand dunes, such as Burt Ridge (Fig. 24).

The vegetation communities away from the waterholes were also not a focus of this study, however there was a surprising degree of variation in this respect also. On the basis of the present study, there are strong indications of landform-sediment-vegetation assemblages, including lignum swamps with vertic soils, widespread but sparse coolibah distribution associated with small scours, and dense grass communities associated with patches of sandy sediments (in the Burt Waterhole area).

Processes

Goyder Lagoon is dominated by low-energy unconfined flow. This, combined with the low gradient and low relief, means that local conditions of microtopography will have more influence over immediate flow behaviour than would be the case in other rivers. This is reflected in the great variety and orientation of small-scale fluvial landforms across Goyder Lagoon. These features were not within the scope of the present investigation, however they indicate local differences in flow energy and sediment erosion/deposition, and they are associated with different vegetation communities (for example, the parallel scours, sandy ridge, and grass communities near Burt Waterhole). They indicate that Goyder Lagoon’s flow behaviour is complex, but is presently very poorly understood.

The underlying Pleistocene sediments are another influence on flow conditions or inundation length in Goyder Lagoon. They operate either directly, or indirectly via their influence on lignum distribution (Fig. 27). (Lignum bushes can be tall and dense; they have the potential to add roughness to the flow path, slowing flow speed or influencing flow direction.)

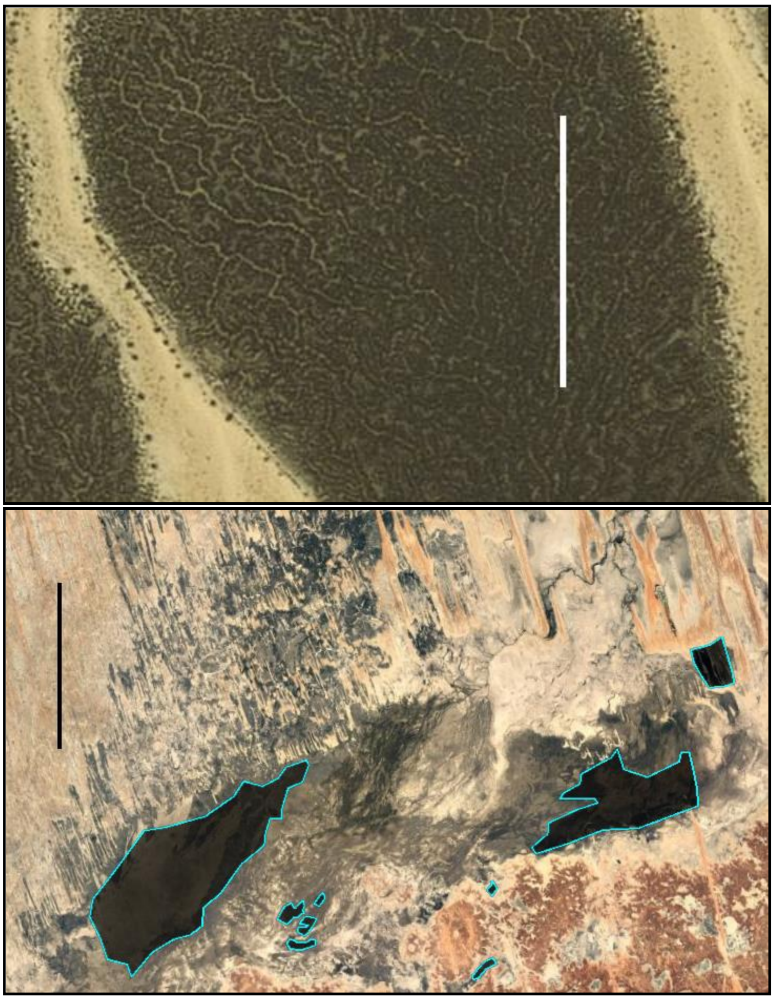


Fig. 26 Lignum swamps of Goyder Lagoon.

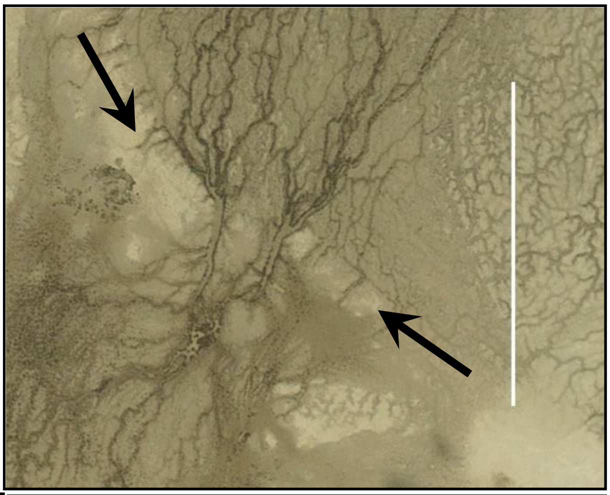
Top left, looking along a fence line across a small channel, edges heavily trampled by cattle; near Pandiburra bore. Top right, Google Earth image of the reticulate channel network in Peraka swamps, white scale bar = 0.5 km. Bottom, blue outline indicates distribution of reticulate-channelled lignum swamps; Google Earth image, black scale bar = 20 km.

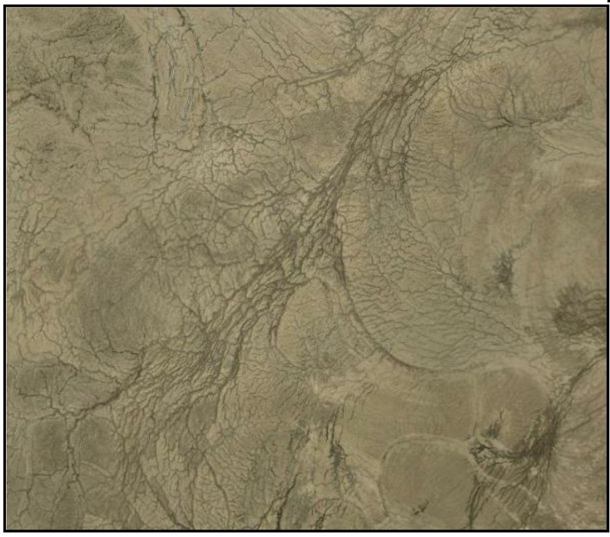
On a valley scale, Goyder Lagoon's water can be partitioned during at least some parts of the rising flood. When flow is active down the Diamantina Fan, the water from the Andrewilla and Yammakira branches may move for some distance down Goyder Lagoon side-by-side and with only a narrow mixed zone. When flow is active down the Diamantina Fan and Eyre Creek, there will be a component of Eyre Creek water that is not mixed with the Diamantina water. These conditions arise because of the different entry points of the water, and because of asynchronicity in flow (even if a widespread rain event occurs across both rivers' headwaters, flow from the Andrewilla branch, Yammakira branch, and Eyre Creek will reach Goyder Lagoon at different times). The actual geometry of which portions of water go where in the Lagoon depends on the relative timing and volume of flood peaks.

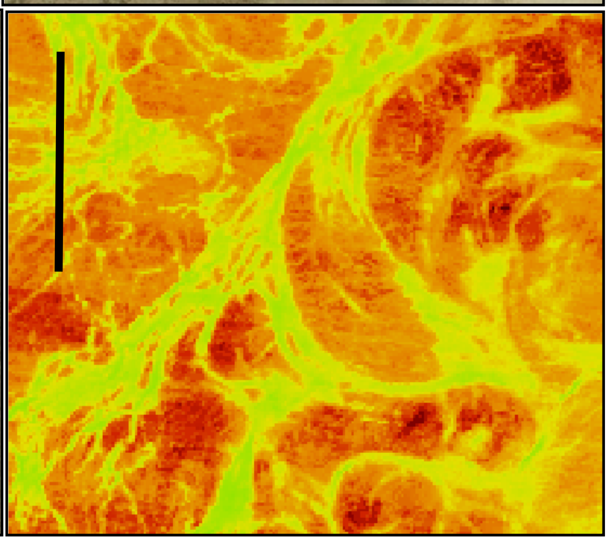
At a reach scale, Goyder Lagoon's flow routing can be complex, particularly around the downflow margins of the Diamantina Fan. This is because 1) water has multiple entry points into Goyder Lagoon, and 2) the water arrives in a topography created by non-fluvial processes. For example, in the Burt and Pelican Waterholes reaches (Fig. 20), water from Andrewilla Waterhole's lateral distributaries banks up behind the Pelican Waterhole area, while meanwhile water from Andrewilla's right-bank terminal distributary is entering Burt Waterhole from the south. After the low-elevation areas north-west of Andrewilla Waterhole have filled up, flow moves through the dunes at Pelican Waterhole, and enters Burt Waterhole from the north.

Fig. 27 The underlying Pleistocene sediments affect modern channels in Goyder Lagoon.

Top right, a bedding gap in the subcrop has constrained the flow enough to create two small waterholes. Google Earth image, white scale bar = 1 km; 6.8 km north-east of Koonchera Waterhole. Bottom left and right, underlying Pleistocene sediments influence the degree and direction of reticulate swamp channel distribution, probably by lithologies that influence gilgai development. Left, Google Earth image; right, Water Information from Space image; black scale bar = 2 km; location, 4 km south from Tepamimi Waterhole.







Waterholes are only formed in areas of locally high-energy flow: flow concentration between topographic highs (e.g. interdunes), or valley-margin turbulence as flow curves around some protruding landform (e.g. the minor waterhole near Goyder Lagoon Waterhole, Fig. 23). As the 1% AEP mid-1970s floods created only minor changes in Goyder Lagoon waterholes (e.g. adding additional channels to existing waterholes at Koonchera, old Burt, and Andrewilla Waterholes), it is likely that the Goyder Lagoon waterholes were created during unusually large flood events. The Goyder Lagoon waterholes have the same bank characteristics as other Channel Country channels (steep compound banks, bank-top riparian vegetation) and it is likely that bank steepness and channel depth are maintained by in-channel shear and turbulence related to flood interactions with (amongst other things) riparian vegetation. The absence of lateral distributary channels is likely to be due to the Goyder Lagoon waterholes filling up simultaneously with the lagoon itself. Goyder Lagoon waterhole features are influenced by waterhole context, for example Goyder Lagoon Waterhole's sediment load comes from nearby outcrop (Fig. 26), and Pelican Waterhole's short length and association with other short waterholes (Fig. 20) is because they were created by impounded water cutting through a dune set.

Flow concentration can also occur as a result of human-created features. In the area of Burt Waterhole, flow concentration along a graded track was almost certainly responsible for the formation of New Burt Waterhole. The Birdsville Inside Track is affected in this area because the flow energy is increased as the flow path narrows and sweeps around the dune nose.

At the north-western and the downvalley end of Goyder Lagoon, a slightly elevated surface acts to partially contain some of the inundated Goyder Lagoon's water (Fig. 22). Although the fully-inundated lagoon is still unconstrained (and indeed overflows into the Simpson Desert dunefield), the narrowed flow path of the first/last/deepest Goyder Lagoon water gives it the energy to re-establish a continuous channel (see section 4.4).

Although the Goyder Lagoon floodplain was not the focus of this project, it is clear that the area is biologically productive, and preliminary results from this project indicates it supports varied terrestrial ecosystems. There is an unexpectedly wide distribution of non-riparian coolibah across the lagoon; it is not established whether or not these relate to particular landforms. There are patches of thick grass, at least some of which appear to be linked to less muddy surface sediments, while lignum occurrence appears to be linked to both inundation and vertic soils. There is a variety of different small-scale fluvial processes taking place which govern the distribution of surface sediment, and therefore probably affecting plant distribution.

4.4 Warburton and Kallakoopah Creeks

Warburton and Kallakoopah Creeks are largely independent of each other, but are grouped within a single management zone (Fig. 1) because they occur within the same valley contexts, which governs their reach-scale geomorphology. The two creeks are located downvalley from Goyder Lagoon, and Kallakoopah Creek is a distributary from Warburton Creek. The upvalley beginning of Warburton Creek is where the continuous channel re-forms, in Goyder Lagoon not far upvalley from Warburton Crossing (Fig. 28). The first 40 km of Warburton Creek are the main channel re-establishing itself within a limited floodplain. From Kalamunkinna Waterhole, where Kallakoopah Creek diverges from Warburton Creek, both creeks enter a zone of valley-scale anabranching. Downvalley from Kallakinna and Derwent Creeks, the Warburton and Kallakoopah Creeks pursue independent paths through the Simpson Desert and Tirari Desert dunefields, before rejoining in the Kati Thanda/Lake Eyre inlet zones.

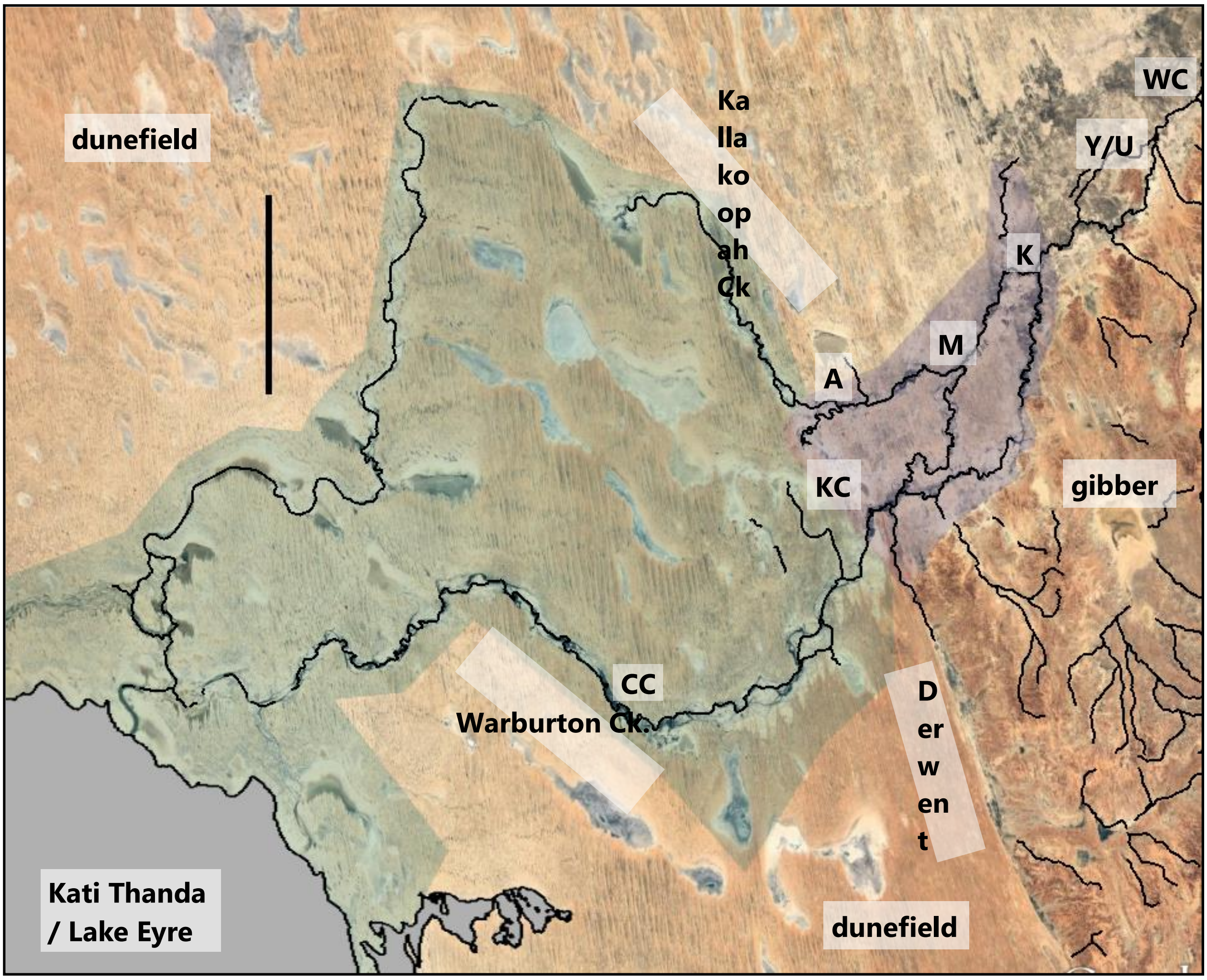


Fig. 28 Overview of Warburton and Kallakoopah creeks.

Purple overlay indicates the linked valleys zone, blue overlay indicates the dunefield zone. WC, Warburton Crossing; Y/U, Yelpawaralinna and Ultoomurra Waterholes; K, Kalamunkinna Waterhole; M, Mona Downs; A, Anarowdinna Waterhole; KC, Kallakinna Creek; CC, Cliff Camp. Google Earth image, overlain by Geoscience Australia drainage lines; black scale bar = 30 km.

4.4.1 Upvalley, Where The Channel Re-Forms

Description

The diffuse flow paths of Goyder Lagoon become more well-defined and similarly oriented below the Goyder Lagoon Waterhole reach. At that point the flow paths are located within the narrowing low-elevation floodplain space (Fig. 22). By Warburton Crossing (Fig. 29) the primary flow path has coalesced into a broad belt (~1 km wide) of anastomosing floodway swales, with an inset main channel (which is coalesced from upstream's small anabranching channels). This re-establishment of a continuous channel system marks the beginning of the Warburton Creek management zone. The main channel is small (~20 m wide, 1-3 m deep), with moderately sloping banks cut into a very cohesive sediment. The bank tops do not appear to be accumulating sediment. With increasing distance downstream, the channel becomes larger and better defined, before decreasing in size and reverting to anabranching as flow splits between Yelpawaralinna and Ultoomurra

Waterholes. In these reaches, the channels and floodways do not appear to be depositing alluvium; the channels lack distributaries.

At Ultoomurra Waterhole, the continuous channel has been re-established again, in a new fluvial style. From Ultoomurra Waterhole down to Kalamunkinna Waterhole the main channel is irregularly sinuous, within a narrow floodplain (constrained between gibber hills near Ultoomurra Waterhole, and between gibber and terraces of Pleistocene sediments closer to Kalamunkinna waterhole). The channel has small tight bends, and some scroll plain geometry indicates rapid and sometimes avulsive channel migration. Both short and long distributary channels are common, and several reaches have sinuous anabranches. Considerable alluvium flanks the channel in some reaches, especially where the floodplain is most constrained.

At Ultoomurra Waterhole, some sinuous reaches have steep to vertical outer-curve banks, riparian trees near the bank lip dying or dead and showing extreme degrees of root exposure (straight broken roots: no tree knees), abundant large woody debris in the channel. Inner-curve banks are low point bars of loose white sand colonised by large lignum bushes. Distributary channel offtakes are steep, eroded, and undercut, with piping and collapse in some areas (indicating buried swelling clays). The floodplain shows evidence of both gully incision (the distributary channels) and vertical accretion of sediments (tree burial, flat common surface), in some places in the same area. Floodplain sediments and cut bank exposures show both sand and mud aggregates in fluvial transport; the sand is medium to fine-grained, and pale buff to white in colour.

Processes

At Goyder Lagoon's downvalley end, a broad flat surface of thinly-covered Pleistocene sediments extends from the Simpson Desert dunefield to the base of the gibber hills (Figs. 22, 29). A relatively narrow pathway of slightly lower elevation allows rising floods to exit Goyder Lagoon. At the upstream end of that pathway – near Warburton Crossing – the narrowed flow has greater stream power, and a broad floodway begins to develop a channel system. The floodway and the channels are incising into consolidated Pleistocene sediment). In these reaches, eroded sediments are not being locally redeposited (therefore, no alluvium or distributary channels), they are transported downstream.

As the channel approaches the Ultoomurra reaches, it is now carrying considerable sediment; with the rise and fall of flow events, sediments are deposited along channel margins, creating banks and setting the context for distributary channels with bank-breach offtakes. At the same time, the increased stream power of the growing channel continues to erode Pleistocene sediments from the banks and bed. Ultoomurra waterhole therefore is an area of rapid geomorphic activity: both erosion and deposition across the floodplain, abundant bedload transport, and very rapid meandering with the development of anabranches. The reaches from Ultoomurra Waterhole to Kalamunkinna Waterhole continue in this style: sandy channel sediments deposited in 2-D dunes are visible even in satellite imagery, and meandering is so rapid that in some reaches it is avulsive rather than incremental.

There are two important consequences of this sequence of landscape evolution. Firstly, incision of the channel and the floodway belt into the Pleistocene sediments gives the channel greater exposure to the unconfined aquifer's salinity (see Costelloe 2017). Secondly, the reintroduction of sediment into fluvial transport contributes to Warburton and Kallakoopah Creeks' anabranching and avulsive fluvial style.

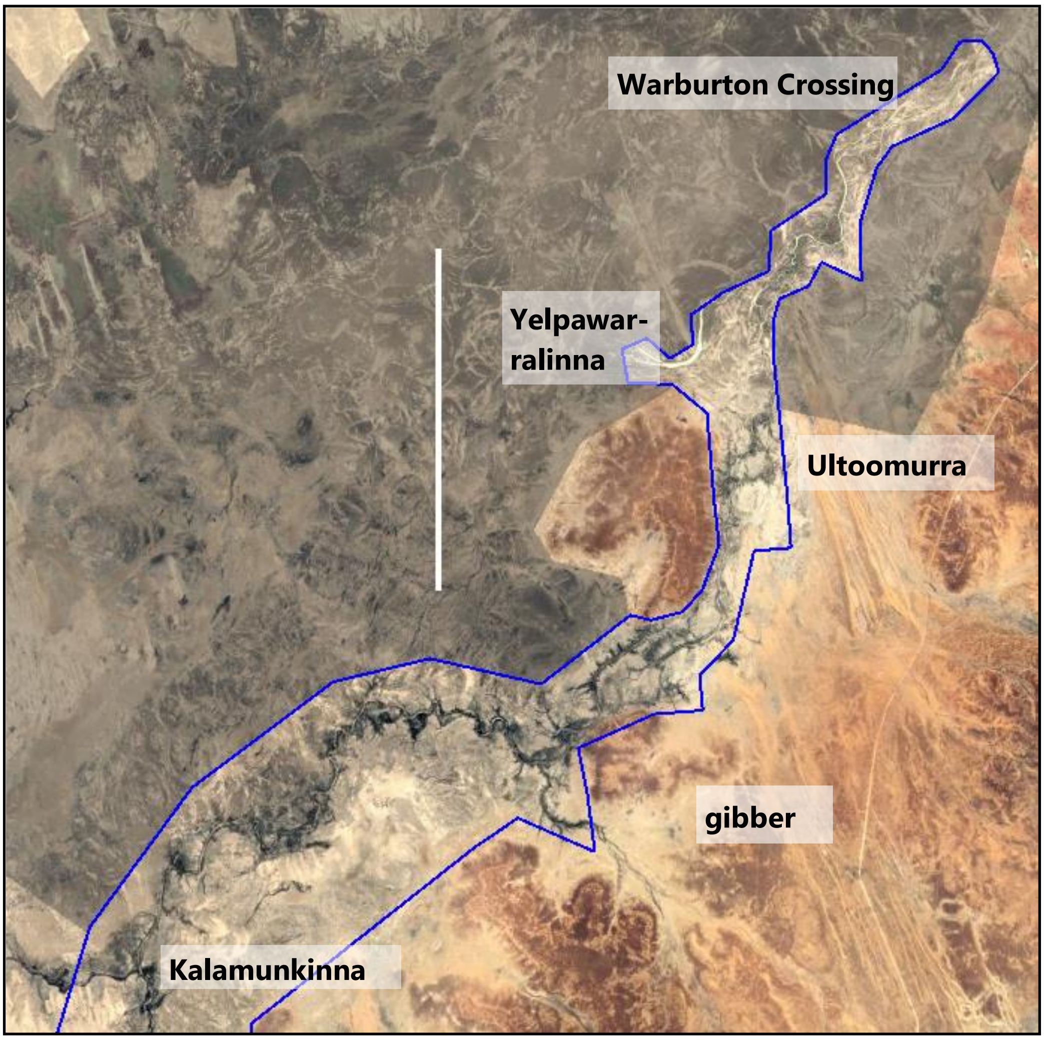


Fig. 29 Locations in the upvalley reaches of Warburton Creek.

Grey overlay is Goyder Lagoon, blue outline is the border of the Warburton Creek management zone. Google Earth image; white scale bar = 10 km.

4.4.2 Linked Valleys

Description

In the linked valley reaches of Warburton and Kallakoopah Creeks, the two creeks occupy semi-parallel flow paths, separated by small dune sets of mixed aeolian and regolith origin (pale to medium orange). The downvalley slope is 0.013-0.014%. Warburton Creek is constrained between the dunes and the gibber. Kallakoopah Creek is constrained between dunes on either side, or in some places (e.g. Mona Downs in the Kuncherinna Waterhole reach) between dunes to the south and terraces of Pleistocene consolidated muds to the north. The creeks are linked in three places (Fig. 28): at Kalamunkinna Waterhole, where a small distributary channel from Warburton Creek extends westward to the Kallakoopah Creek flow path; at Tumpawarrina Creek, where a flow path extends from Mona Downs to near Kirrianthana Waterhole, and Kallakinna Creek which extends from Kallakoopah Creek to Kirrianthana Waterhole reach.

Warburton Creek receives the flow down the Warburton main channel and some of the Warburton's floodplain-level flow, as well as local runoff from the gibber hills especially via Derwent Creek. Kallakoopah Creek receives water from the Warburton's right-bank floodplain-level flow, as well as floodplain flow from the western part of Goyder Lagoon (including small amounts flowing down the Yarraminghinna Waterhole drainage line). Kallakoopah Creek also receives local runoff from the terraces of Pleistocene consolidated muds to the north and north-west: the terraces have a hard bare surface that would provide rapid runoff after rainfall.

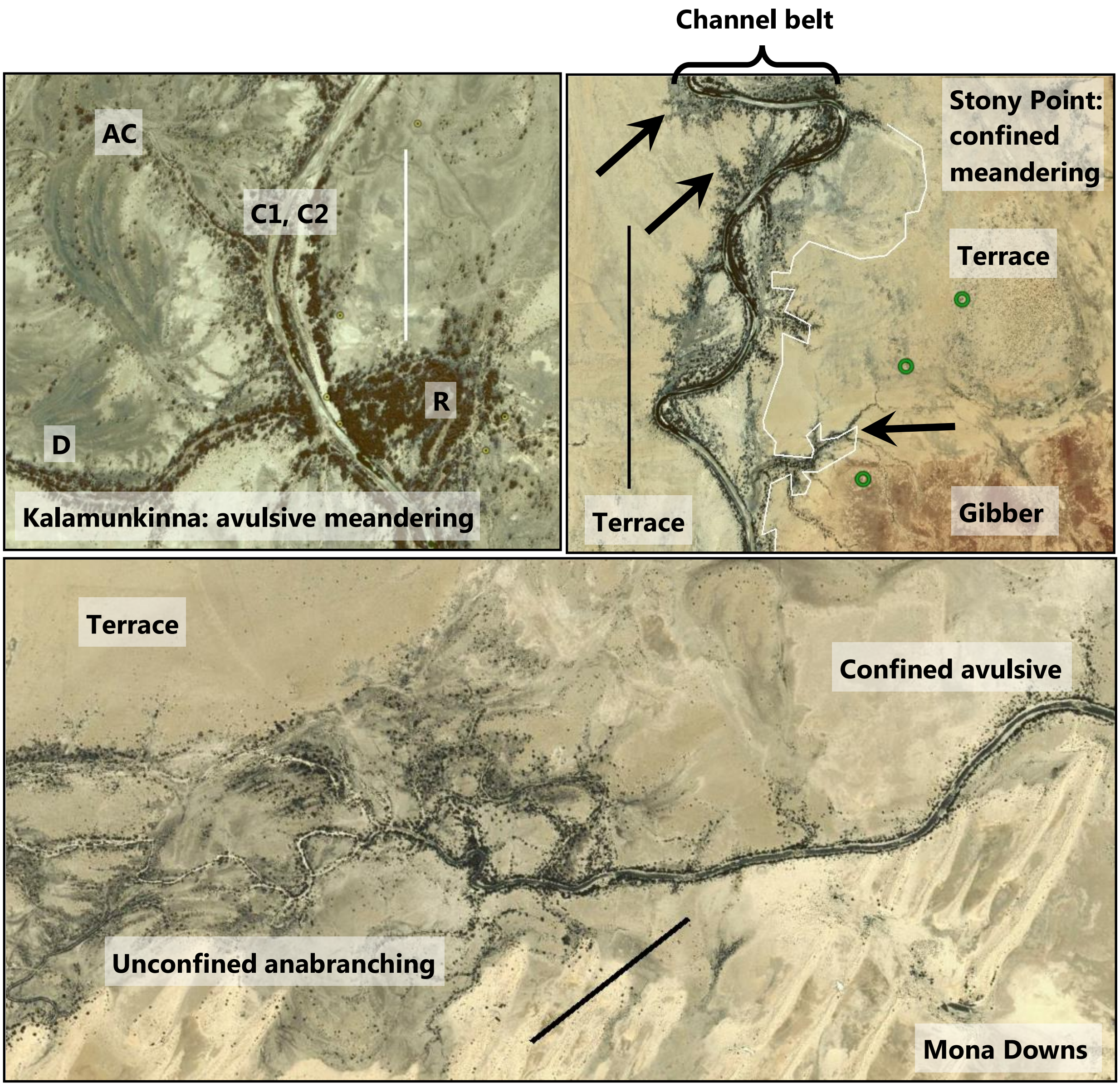


Fig. 30 Channel-floodplain associations in Warburton and Kallakoopah Creeks.

Top left, Kalamunkinna Waterhole. AC = abandoned channel,, with a short distributary channel feeding into it; D, the distributary channel contributing to Kallakoopah Creek; R, a complex riparian zone comprising multiple abandoned channel segments; C1 and C2, the present-day channel and its immediate precursor. Google Earth image, white scale bar = 0.5 km, flow is top to bottom. Top right, Stony Point. Green circles, probable coolibah; white line, boundary between local floodplain and terrace; arrows, gullies from local floodplain up to terrace level; black scale bar = 2 km, flow is top to bottom. Bottom, Kuncherinna Waterhole (Mona Downs). The upstream reach has a single static channel, the downstream reach has multiple anabranches. North is to top right of the image, black scale bar = 1 km, flow is right to left.

There are several fluvial styles in the linked valley reaches, combining elements that fall along the variable scales of valley confinement (completely confined/narrow channel belt with isolated local floodplain/connected local floodplain) and planform (sinuous/not sinuous, and single thread/anabranching). The degree of confinement and nature of the channel planform then controls reach-scale landforms such as the number and nature of distributary channels, and the local floodplain's vegetation, sediments and flood runners. It was not within the scope of this study to document these relationships in detail; some examples are (Figs. 30, 31):

Kalamunkinna Waterhole has a sinuous single channel paired with an abandoned channel on meandering bends; the abandoned channel still carries water at high-flow levels. The local floodplain does not have scroll plains, but is marked by other abandoned channels, some forming a thick riparian zone. The other abandoned channels are not seamlessly linked to present-day channel positions. Right-bank distributaries from the main channel deliver water to the Kallakoopah Creek flow path. The active channel and local floodplain are set within terraces of Pleistocene sediments, but the boundaries are not clear.

Stony Point (Warburton Creek) has a sinuous single channel, and a local floodplain consisting of alternate scroll plains isolated between the channel and the confining and clearly defined terraces of Pleistocene sediments. Short gullies lead from local floodplain up to terraces.

Mona Downs area, downstream (Kuncherinna Waterhole, Kallakoopah Creek) is a moderately wide local floodplain, moderately well vegetated, with multiple small anabranching channels, originating as distributary channels with offtakes at meander outer curves. The floodplain shows both erosion (anabranch and distributary channel incision) and vertical aggradation (tree burial). This local floodplain is constrained in the downvalley direction by an almost unvegetated high terrace of unusually mud-rich Pleistocene sediments. This relationship between mud-rich Pleistocene high terraces and relatively unconfined anabranching channels repeats down Kallakoopah Creek within the linked valley zone, and also occurs near Kirrianthana Waterhole (Warburton Creek) and in Kallakinna Creek.

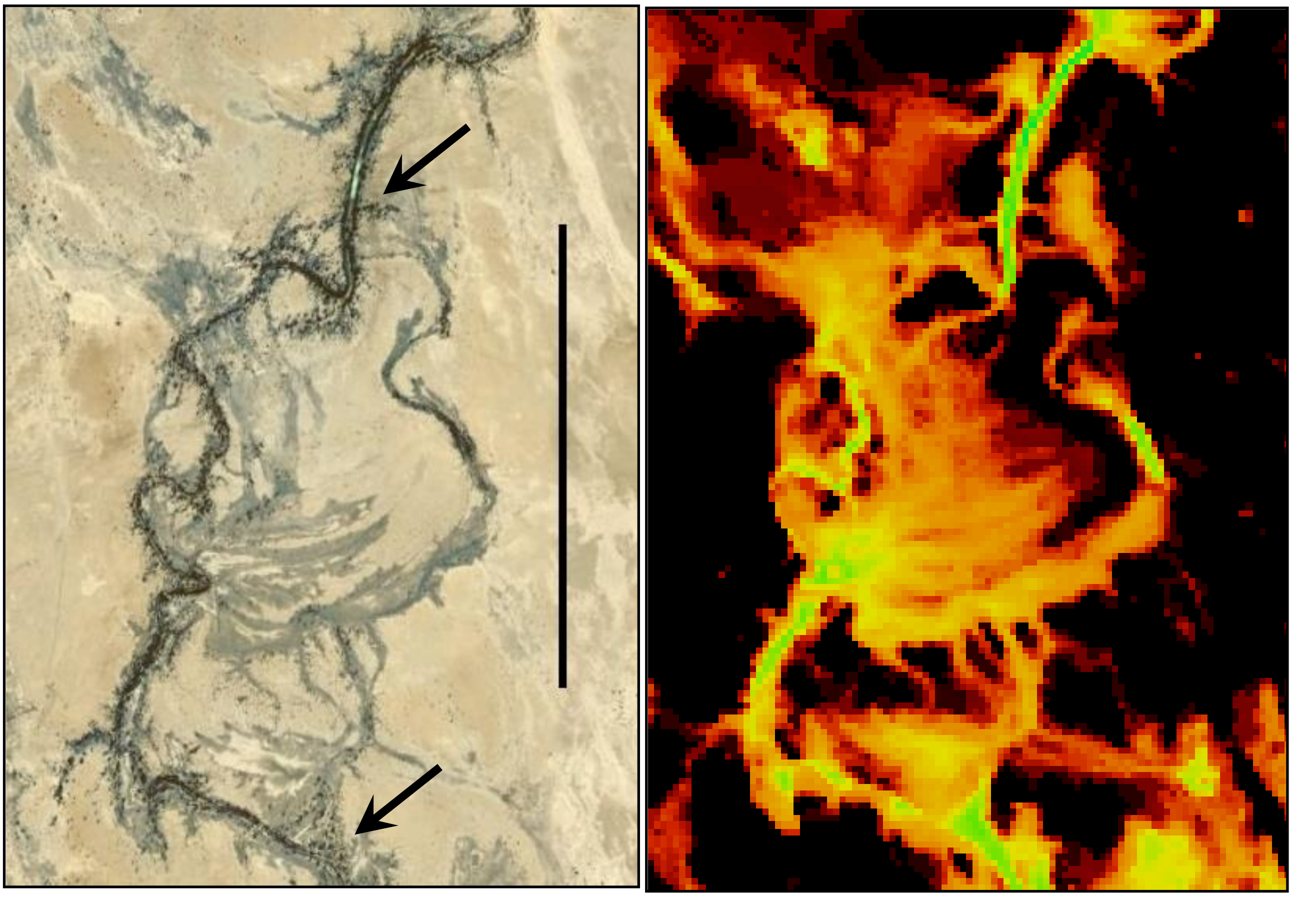


Fig. 31 Confined avulsive channels at Tumpawarrina Creek; arrows = avulsion nodes

Left, Google Earth image, black scale bar = 2 km, flow is from top to bottom. Right, Water Observations from Space image.

Channel width and depth varies according to whether the channel is in a single-thread reach (wider and deeper: 30-50 m wide, 3-5 m deep) or a multiple-thread anabranching reach (smaller: 10-30 m wide, 2-4 m deep). Banks are moderate to steep (Fig. 32), and tend to be most steep on meandering outer-curve banks and least steep on inner curve banks. Away from meander bends, bank slopes tend to be simple and ~planar (c.f. compound, the more common Channel Country condition). In-channel sediments are muddy fine sands, medium to fine sands and mud aggregates. Most reaches show signs of salinity: brine pools (some crystallising halite), iron-stained water, fluffy seed-gypsum sediments in the channel thalweg, in-channel samphire vegetation. The only exception is in the Mona Downs area which showed no salinity and no samphire. Bank top riparian zone tends to be narrow but moderately densely vegetated.

Local floodplains and low terraces are topographically irregular (reflecting partially-infilled channels). Vegetation is widespread but plant distribution is variable (sparse to relatively dense); the most biologically productive areas retain some connection to a flow path. The higher terraces of Pleistocene sediments tend to be very flat and almost unvegetated (Fig. 32), although some stands of large dead trees indicate past opportunities for tree growth.

Fig. 32 Kallakoopah Creek in the linked valley zone.

Top, the main channel in the Mona Downs anabranching reach, showing sloping banks, a narrow riparian zone fringing the bank lip, and channel bed of heavily cracked mud aggregates. Bottom, the high terrace surface north-east of Anarowdinna Waterhole.

Processes

An unexpected aspect of Warburton and Kallakoopah Creeks is the width of their main channels. Channel size is scaled to flow size. It would be expected that flow size would be much diminished in comparison to the Diamantina Fan, through transmission loss across Goyder Lagoon and the splitting of the flow between Warburton and Kallakoopah Creeks. However, the main channel in Diamantina Fan is ~50 m wide, whereas Warburton Creek's channel is ~50 m wide and Kallakoopah Creek's channel is 50-100 m wide. There are two likely reasons for this. Firstly, channel size is a function of width and depth, and in this study it was not possible to establish full details of channel geometry. Since the Warburton and Kallakoopah Creek's sediment load is more sandy than that of the Diamantina Fan, it is likely that their channels are more broad and shallow. Secondly, the Diamantina Fan has considerable floodplain-level flow, whereas Warburton and Kallakoopah Creeks are much more constrained. It is likely that Warburton and Kallakoopah Creeks carry a much greater proportion of their flow in-channel.

The linked valley creeks are incising into Pleistocene sediments and the dunefields that sit above them. The incision suggests either lowering of base level, or subtle uplift associated with the nearby gibber uplands. The incision confines Warburton and Kallakoopah Creeks into relatively narrow flow paths, which promotes sufficient stream power to create and maintain a continuous channel (despite the transmission losses which must have occurred in Goyder Lagoon). Moreover, most of the linked valley reaches have sufficient stream power to incise into or cut back against relatively consolidated Pleistocene sediments. The stream power is also sufficient to transport the significant quantities of sandy bedload which the incision has released into fluvial transport. Because the flow regime is variable, there are also opportunities for sediment deposition as stream energy decreases during waning flow. Thus, most of the reaches contain both erosion (bank retreat, bank breaching, channel incision) and vertical aggradation (infilling of abandoned channels, burial of bank trees). These reaches are actively evolving and dynamic.

The variable flow regime, occurring within a context of relatively narrow valleys and a relatively high sediment load, provides opportunities for flood-driven avulsion (channel relocation). In the meandering reaches, this takes the form of non-incremental channel migration, in which the new channel 'jumps' past the old channel, leaving intact both banks of the abandoned channel. In the anabranching reaches multiple channels may develop from distributary channels.

The bank profiles (simple planar slope, medium gradient) may be a result of the incising nature of these reaches. There may be a spatial relationship between the mud-rich Pleistocene sediments (more cohesive and resistant to erosion) and some anabranching reaches. Aside from these observations, the conditions shaping individual reach character are not clear from this study. In particular, for the different reach types, their channel and valley cross-section geometry (the relative sizes of channel and local floodplain; for a given size of flood, how much of the terrace is inundated?) should be examined.

During flow events, the Warburton and Kallakoopah Creeks have some degree of connectivity as far downvalley as Kirrianthana Waterhole. The conditions for aquatic animals during flow will probably be unlike those experienced in Goyder Lagoon: turbulence is likely to be stronger, overall patterns of flow energy probably more variable, and there will be sand in bedload transport.

In these reaches, there are fewer wide riparian zones and more narrow riparian zones than is the case in the channels of the Diamantina Fan. This probably reflects differing bank geometry, as well as the less common occurrence of low-elevation landforms with good connectivity to the main channel (e.g. scroll plains). In these avulsive reaches, the abandoned channels may suddenly be quite distant from the flow path (Fig. 31). Because of the amount of sediment deposition taking place here, the abandoned channels can be partially buried fairly quickly, limiting opportunities for the now-abandoned riparian trees to access stored water.

The nature of the non-channel space is a strong determinant of its likely support of terrestrial ecosystems. High terraces are least likely to support coolibah, and low terraces may support sparse coolibah and other plants especially in flood runners formed from abandoned channels. The local floodplains formed by scroll plains in meandering reaches and low-elevation areas in anabranching reaches are the most likely to be biologically productive.

4.4.3 The Dunefields Reaches

Description

Over geological time, the landscape evolution of the LEB's central plains has included shoreline retreat as the great megalakes dried up, the shift in the deepest part of the basin from north to its present location in the south (thus isolating the river valleys draining towards where the megalake used to be), surface expression of the increasingly saline groundwater promoting the development of playa lakes in the lowest-lying parts of the landscape (such as the old river valleys), and the development of the longitudinal dunes across the area. These factors have created the valley-scale landforms that dominate the dunefield reaches of Warburton and Kallakoopah Creeks: the palaeodrainages and the sand dunes.

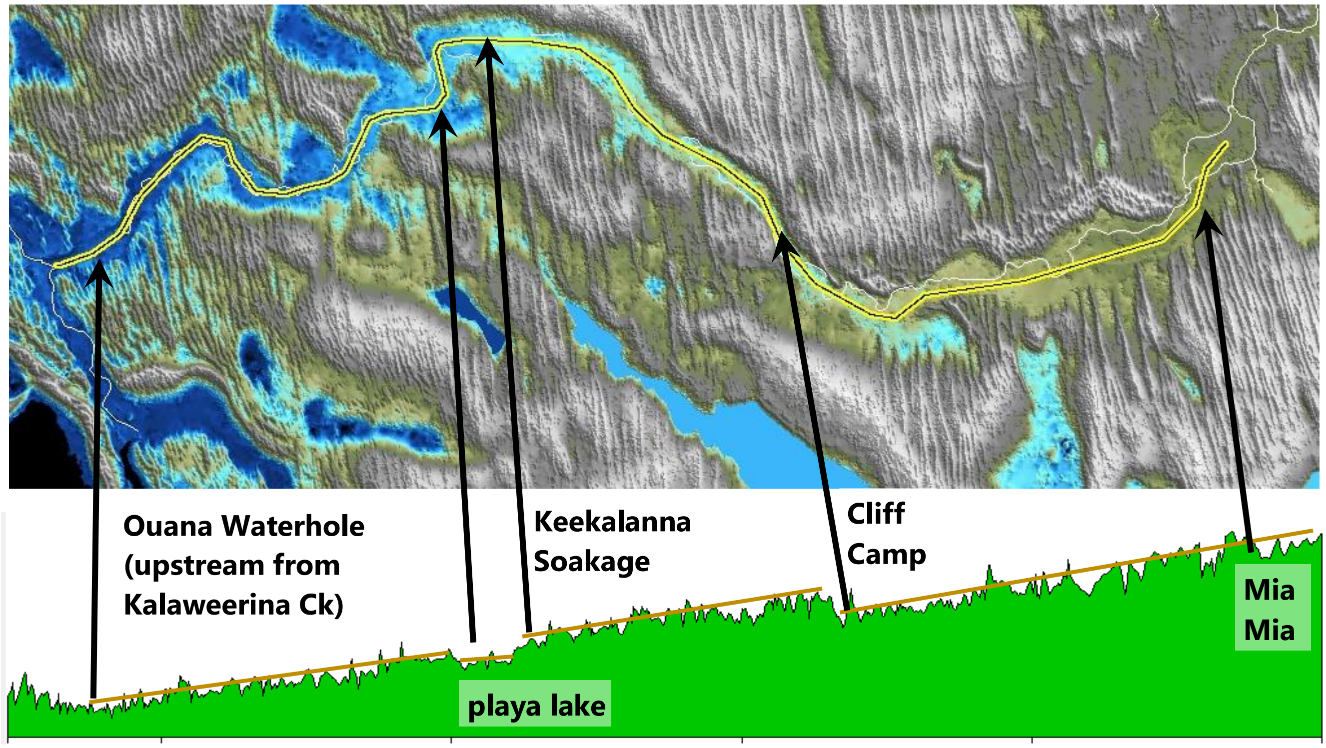


Fig. 33 Palaeovalley control on Warburton Creek's valley confinement and gradient.

Top, Digital Elevation Model; bottom, valley profile derived from the DEM, elevation range -10 to +5 m AHD, horizontal scale zero-113 km.

The creeks entering the dunefields are too small and the dunes are too big to allow the rivers to develop a straightforward path to base level. Instead, they utilise the existing palaeodrainage valleys, pursuing independent paths in a zigzag course towards the north of the Kati Thanda/Lake Eyre (Fig. 28). The creeks are generally confined or semi-confined between valley walls of source-bordering dunes and/or Pleistocene (or Neogene) sediments. The downvalley gradient, degree of confinement and even floodplain elevation experienced by the creek depends on that part of the valley's pre-existing conditions (Fig. 33).

An avulsive and slightly anabranching behaviour is the dominant style of creek in the dunefield reaches of Warburton and Kallakoopah Creeks. For example, from ~6 km below Kirrianthana Waterhole to nearly Tinnie Landing Waterhole (~86 km), Warburton Creek exists in an irregular wider floodplain space 1-8 km wide, bounded by closely spaced dunes sitting on a flat surface of Pleistocene sediments. To the south (the left-bank side of Warburton Creek) the dunes are the downwind tips of longitudinal dunes, and to the north the dunes are the upwind side of source-bordering dunes. The geometry of the wider floodplain and the source-bordering dunes indicates that Warburton Creek is flowing down a palaeodrainage. That is, the wider floodplain is not an alluvial plain created by the present-day Warburton Creek.

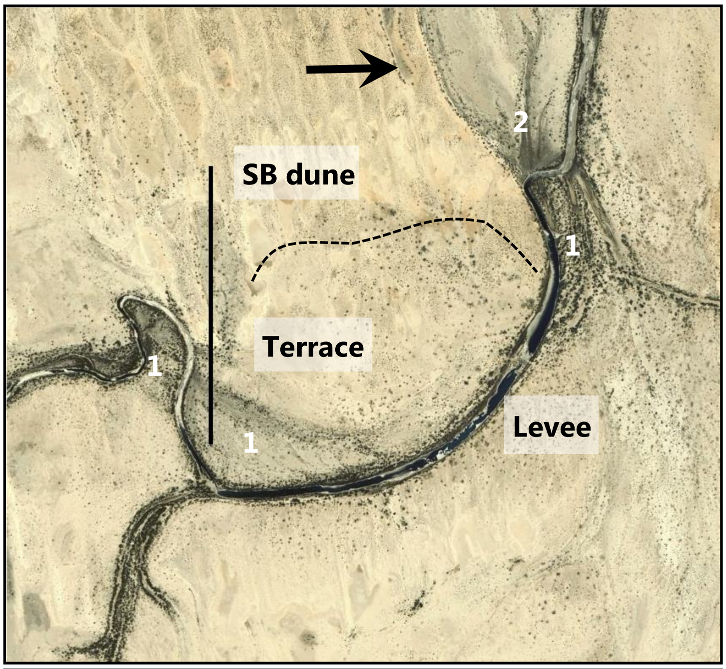
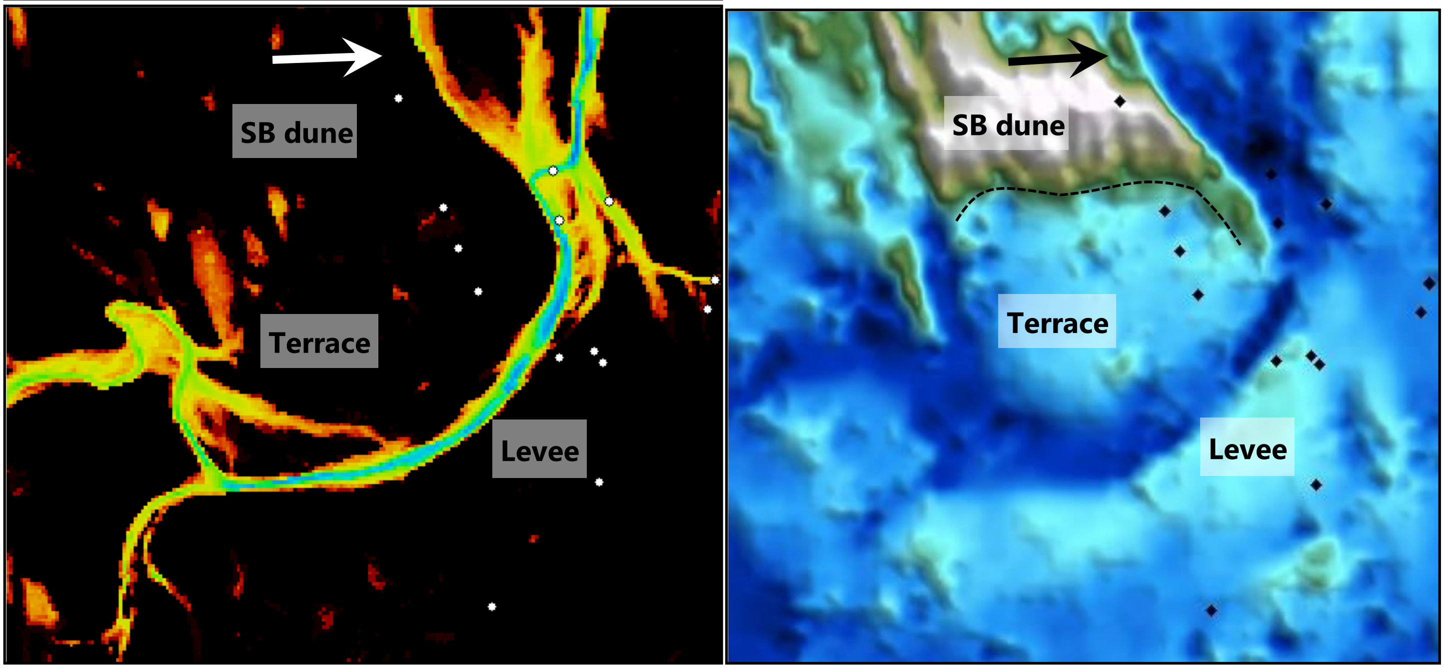


Fig. 34 The avulsive and anabranching Stony Crossing reach, Warburton Creek.

1, local floodplain; 2, abandoned channel; arrow indicates interdune isolated from present day flow path, black dashed line = southern border of source-bordering dune (SB dune). Top, Google Earth image, black scale bar = 2 km. Bottom left, Water Observations from Space; bottom right, digital elevation model.



The wider floodplain is composed of Pleistocene sediments thinly covered by alluvium. The Pleistocene sediments are exposed at surface in places, e.g. at Stony Crossing silcrete outcrop and underlying regolith is exposed in the channel bed, chips of regolith and silcrete were found in a deflation hollow in the left bank levee, and a fragment of fossil turtle was found on some slightly higher ground midway between the channel and the source-bordering dune. Although the wider floodplain gives the impression that the channel is largely unconstrained, in fact in many reaches the channel is bounded by slight terraces of Pleistocene sediments. The terraces are lightly vegetated, in places supporting well spaced medium to large sized coolibah trees, and on Google Earth image appear to be more or less continuous with lower-elevation local floodplain closer to the channel. However the digital elevation model shows a clear step in elevation, and the WOfS show that the terraces are not part of the normal present-day flow path (Fig. 34).

Warburton Creek in these reaches consists of a main channel (~50 m wide, 2-4 m deep) and in the wider reaches one or two subsidiary channels which at bankfull flow will be acting as anabranches. The channels have irregular planform, some with very low sinuosity, and some with sinuous reaches. The links between the main and the subsidiary channels are also irregular. Some channels are associated with narrow local floodplains, which either have the ridge-and-swale topography of channel migration, or the channel-scale topography of an infilled abandoned channel (Fig. 34). Local floodplains are well vegetated with trees and lignum where they are close to the main channel, and increasingly poorly vegetated the further they are from the channel. In the low-sinuosity reaches that were examined, the channel banks were moderately sloped and well-vegetated, and more complex and embayed at junction points with abandoned channels. Levees and other alluvium are patchily distributed across the wider floodplain, most often as a sediment wedge on the downflow side of channels oriented transverse to the downvalley direction. In these locations, the alluvium is often cut by short distributary channels. The floodplain alluvium has an irregular swaley surface with occasional scour holes, or occurs as flat-topped deposits cut by subsequent gullies. Much of the floodplain alluvium is not part of normal present-day flow (Fig. 34).

Some of the reaches in Warburton and Kallakoopah Creeks are responding to different conditions than those described above. The different conditions are usually encountered where the creek moves into a new palaeodrainage space. For example, in the Cliff Camp to Keekalanna Soakage reaches the floodplain is elevated with respect to the reaches upstream from it (Fig. 33). The Pleistocene sediments are exposed in cliffs (>10 m high), the channel becomes partially constrained by the valley sides, and the entire valley width is frequently-inundated local floodplain. Just upstream from this area (from Tinnie Landing down to Cliff Camp) the channel becomes increasingly sinuous up to a location 2.5 km downstream from Cliff Camp, where the channel abruptly becomes low-sinuosity. Near that location the floodplain abruptly ceases to be frequently inundated. A similar association of upstream-to-downstream increasing sinuosity and floodplain inundation with valley narrowing and cliff exposures is found in Kallakoopah Creek, in the reaches 30 km downriver from Anarowdinna Waterhole (Fig. 35).

Similarly, when the creek's flow path moves into a palaeodrainage playa lake (a wide space with low elevation compared to the floodplain immediately upstream), the channel becomes sinuous and the channel deposits a terminal sediment splay (Fig. 35). Along the dunefield reaches of Warburton and Kallakoopah creeks, some of these flow path playa lakes have been effectively filled with alluvium, and the main channel cuts through them and continues on.

North of Kati Thanda/Lake Eyre, Warburton and Kallakoopah Creeks enter the inlet area: an essentially flat area with the surface texture created by short closely set longitudinal dunes, and small palaeodrainage playa lakes. Warburton and Kallakoopah Creeks (and the Macumba Creek, which enters from the west) lose their channel definition in a series of sediment splays in successive playas. The sediment splay downvalley of Ouana Waterhole reverses the downvalley gradient (Fig. 33); Ouana waterhole is just downstream from the distributary Kalaweerina Creek, which leads to one of Lake Eyre North's significant inflow areas.

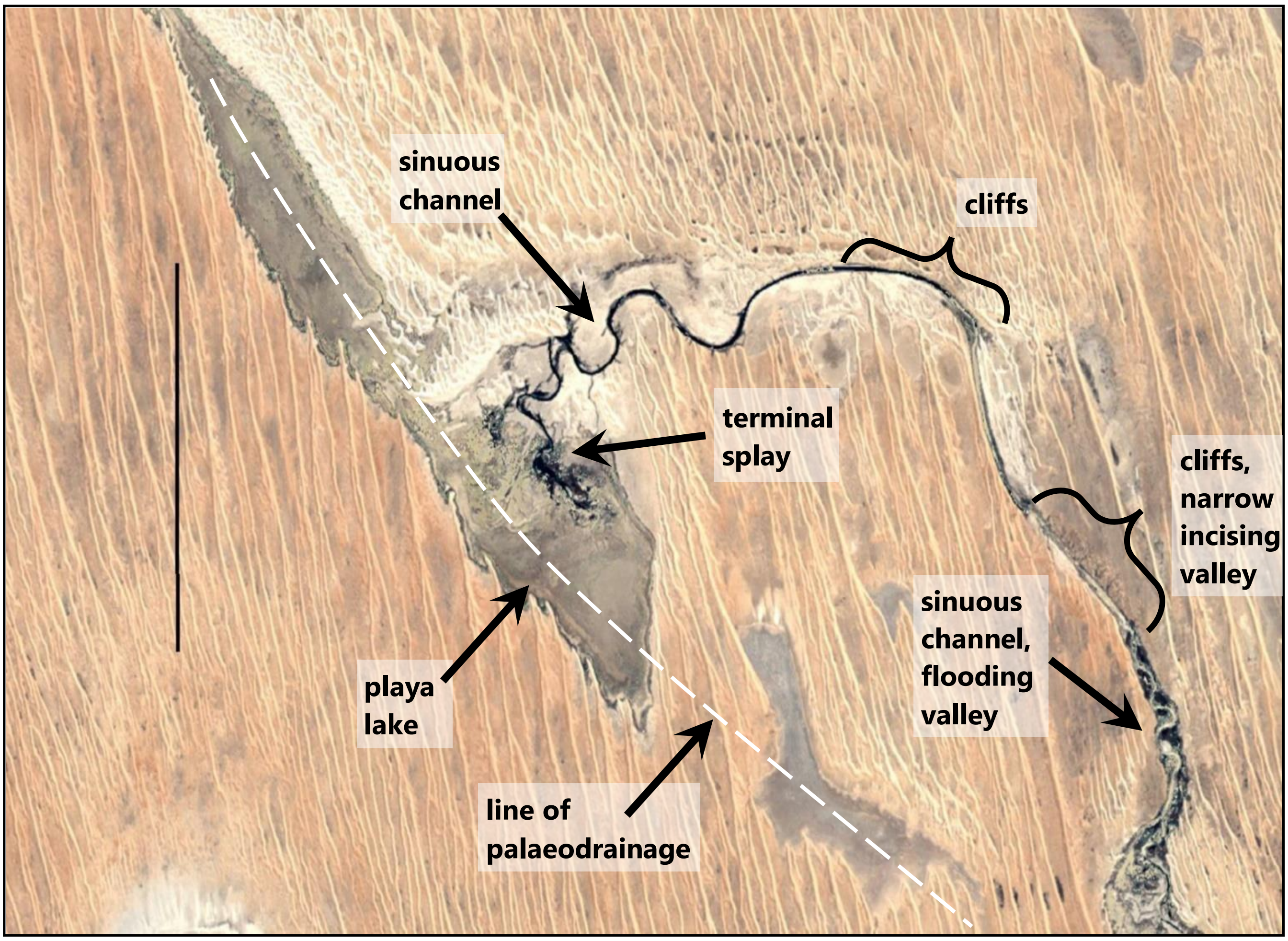


Fig. 35 The creek planform and degree of channel confinement varies with valley context (palaeodrainage playa lakes or probable uplift zone).

Processes

In the dunefield reaches, the main channel exists in a somewhat ambiguous condition. Under most flow conditions, the channels are confined or semi-confined, incising into or cutting back against Pleistocene sediments; they have limited opportunity for channel migration. However, under very high flow conditions, the terrace can be inundated and under those circumstances the river becomes almost unconfined. As the flows become high enough to overbank and deposit alluvium across the wider floodplain, the flows also have the opportunity to choose another path. A new channel is created, potentially abandoning the previously existing channel. Either both channels will continue to be active (making the reach anabranching), or one will be abandoned. Because of the high levels of sediment in transport, abandoned channels are rapidly filled (except at avulsion nodes which still receive some main channel flow). Avulsion taking place under these conditions can lead to channels relocating at some distance from their previous positions.

The local floodplains (scroll plains, and abandoned channels with some connectivity to the main channel) are reasonably biologically productive, with lowest-elevation areas being the most productive. However, the local floodplains are not present in all reaches: in confined or non-migrating channels the only riparian zone may be the narrow bank top. The wide patterns of avulsion and the rapid infilling of abandoned channels means that there are relatively few flood runners to support terrestrial ecosystems across the wider floodplain. In the avulsive and slightly anabranching reaches of Warburton and Kallakoopah Creeks, the degree to which the channel and floodplains are biologically productive depends on variations to local flow regime, degree of valley confinement and amount of sediment in fluvial transport.

The reaches in which increasing sinuosity and valley floor inundation is associated with cliffed valley walls and elevated floodplain profiles suggests recent uplift. The channel's response to erosion-resistant material uplifted in the flow path is increased sinuosity upstream from the uplift axis where the channel's ability to migrate downflow is blocked, and channel and valley-floor incision near the uplift axis. The bank's response is erosion, as it is lifted up above its previous base level, and as the meandering channels cut back the valley margins (e.g. at Cliff Camp). The floodplain's response is increased flooding upstream from the uplift axis, producing Cliff Camp's very unusual valley-wide riparian zone.

When the creek enters a palaeodrainage playa lake the flow path encounters locally steep gradient leading to a low-elevation space ready to be filled up with sediment. The channel becomes sinuous in response to the locally steep gradient, and if the channel is transporting sediments, it will deposit a terminal sediment splay (Fig. 35). Until the playa lake becomes filled with sediment, this effectively traps all the sediment in fluvial transport. A channel reforming downflow from such a terminal splay deposit will be a simple valley-floor incision until it collects a new sediment load with which to create fluvial landforms.

At the Kati Thanda/Lake Eyre inlet zone, Kallakoopah Creek and Warburton Creek have filled or partially filled a number of such small playa lakes. One such sedimentary deposit occurs just near the Lake Eyre North shoreline, and shows on the longitudinal profile as an area of reverse slope downflow from Ouana Waterhole (Fig. 33). It is likely that flow backs up in these reaches, and this is responsible for the diversion of flow to Kalaweerina Creek and Lake Eyre North's other inlet (see section 5.2 Regional Flow Paths).

4.5 Dunefields (Simpson and Tirari Deserts)

Although the dunefields were not a focus of this study, there are some dune characteristics which are relevant to this project's focus on the ways in which landform processes support ecosystems.

In the Simpson and Tirari Deserts, the dunes were created from the local sediments. Rather than the sand being blown in from somewhere else (as has sometimes been assumed), the sand was re-mobilised from regolith and alluvial plains and redistributed to form the present day dunefield. The colour of the sands reflects their origin: the deeper the dune's colour, the more it reflects the orange-brown-red colours of the underlying regolith. The more pale the dune, the more alluvial sediment it contains. Most of the dune sands have not travelled far in the last 10,000 years. Although there is a good deal of mobile sediment on dune crests, especially when vegetation is sparse, most of the sand movement is back and forth in a local area: there is little net sand transport in the present day. (Note that this is a very simplified version of a long and complex story, and that specific localities will have less straightforward relationships.)

There have been repeated episodes of dune building over the last 1 million years, punctuated by periods of stability during which soil horizons were developed. Internal dune architecture therefore contains sand-rich layers interspersed with more clay rich layers (the palaeosols). In some places the dunes are all longitudinal dunes. Along the river flow paths, there has been an interaction between the deposition of sandy fluvial sediments, and subsequent dune development. Source-bordering dunes developed along the downwind side of river flats. Later, longitudinal dunes were developed from the source-bordering dunes, by southerly winds that moved sand from the upwind bases of the source-bordering dunes and extended it northwards as 'fingers' of longitudinal dunes. Together, the source bordering and longitudinal dunes form a compound dune.

In this way, easily-eroded sand has been moved, exposing the more erosion-resistant palaeosol layers. The southern margin of many compound dunes has an eroded area near the base, with exposed palaeosol topped by remnant plinths of orange sand (Fig. 36). Exposed palaeosol is consolidated and firm underfoot. Rainfall will sculpt it into a faceted rill system (Fig. 36) which has a high capacity for shedding rainfall. In this way the dune palaeosols are quite different to the rest of the dune sediments: the loose sands have an extremely low capacity for shedding rainfall. In a traverse across the Simpson Desert dunefield north of Kallakoopah Creek, it was observed that exposed palaeosol played an important role in supplying water to the interdune surfaces. Those that had a catchment of exposed palaeosols on nearby slopes could accumulate greater depth of water, in some cases enough water to create local gullying between one interdune and the next. Low elevation areas flanked by mobile sand did not receive runoff. In this way, the distribution of exposed palaeosols may be a support to terrestrial ecosystems which are in interdunes isolated from creek flow.

Fig. 36 Dune palaeosols forming high-runoff faceted rill surfaces.

Top, the base of a compound dune near Stony Crossing, Warburton Creek (and see Fig. 34). A broad faceted surface has a few remnant sand plinths. Bottom, detail of rill system on a cliff-top dune near Tinnie Landing. The mobile crest of the dune is to the top right of the image.

The processes that maintain interdunes are also significant to interdune terrestrial ecosystems. During formation of longitudinal dunes, the wind eddies transfer sediment from the interdune surface to the dune crest. If the total sand cover is thin, the interdune space may be excavated down to a more erosion-resistant surface. In the study area, this is an important process for making the unconfined aquifer accessible to surface vegetation. In the lower-elevation areas, this process brings the aquifer's salinity sufficiently close to the ground surface that it influences the development of playa lakes.

4.6 Gibber Uplands

Although the gibber uplands were not a focus of this study, there are some gibber characteristics which are relevant to this project's focus on the ways in which landform processes support ecosystems.

Runoff

Gibber plains can be extremely high-runoff systems. The water-shedding properties of gibber hillslopes is an important support to valley-margin channels and ecosystems, and probably contributes to local recharge of the unconfined aquifer. A factor that contributes to the flow asynchronicity between the Diamantina River and Eyre Creek (see section 5.2 Regional Flow Paths) is that many of the hillslopes around the upper Eyre Creek are low-runoff sand dunes, whereas the hillslopes around Birdsville are high-runoff gibber. The high-runoff property is due to two factors. Firstly, gibber stones are extremely low-porosity, so each stone probably sheds all the water that falls on it. The nature of the silcrete that forms gibber means that many gibber plains have a dense cover of rocks, each shedding the water it receives. Furthermore, there are some soil processes which form a desert pavement: the ground surface evolves in such a way that each gibber is fitted like a jigsaw puzzle to its next neighbour, so the entire surface is impervious rock. Secondly, the processes that give rise to gibber plains can also result in a near-surface layer of small bubbles (a vesicular layer) in the quartzose silt between the gibbers (Fig. 37). This vesicular layer effectively seals the surface against the penetration of water, so that it becomes nearly as high-runoff as the gibber rocks.

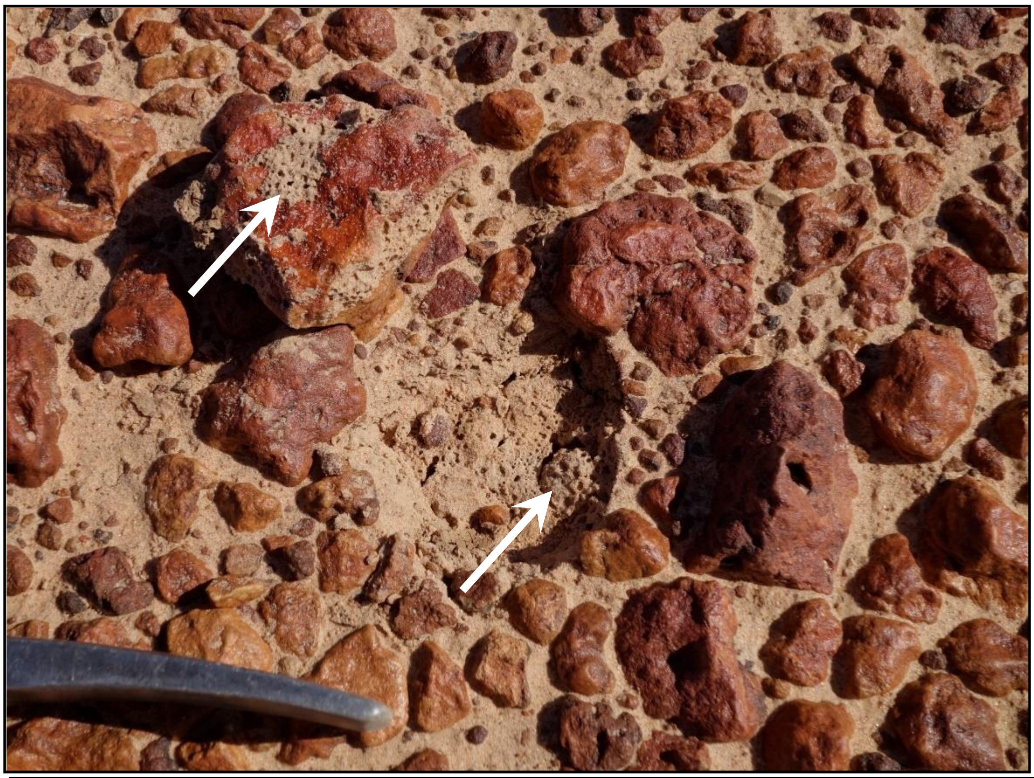


Fig. 37 Gibber surface with underlying vesicular silt (arrowed).

Possible GAB-Groundwater Dependence

The gibber plains are apparently reasonably productive grazing ground, which seems surprising in view of the water-shedding character of the gibber, and the generally barren appearance of many gibber plains. However, Google Earth images show dark patches of vegetation across the gibber uplands, and the WOfS suggest that they are wet or at least damp for unexpected lengths of time. In part, this may be because the high-runoff sections of gibber may be feeding rainfall runoff into local low-elevation zones, supporting patches of vegetation with the rainfall from the much wider area. However it is also possible that Sturts Stony Desert may be an area of diffuse Great Artesian Basin leakage to surface, and that there are groundwater-dependent ecosystems in the circular breaks in the gibber. It is a result of the present study that this is a likely process taking place in the uplands, which warrants further investigation. While it was not possible in the present study to investigate this in detail, the results of the regional investigation suggest this as a possibility, and this is supported by the results of other independent research (see section A2, Technical Appendix: Study Area).

Fragility

The process resulting in the gibber uplands has created a ground surface in which a very thin layer of rock overlays some thickness of quartzose silt, usually overlying a great thickness of weathered regolith. There isn't anything in this profile that is a soil in the sense that cropping farmers use the word. Removing the stony layer will not reveal soft sediment that will naturally grow vegetation; it is more likely that a downslope terrestrial ecosystem will decline because it has lost some of its upslope water supply. In addition, the stony surface layer protects the underlying soft silts from erosion, so disrupting the surface layer is likely to promote gullying. In many of the places where the gibber plains host towns or roads, near-infrastructure areas bear the scars of ripping or other ground works. These works never produce vegetation where only gibber existed before. Although there are places where ripping and contour furrowing are appropriate rehabilitation techniques (Wakelin-King 2011), such techniques are ineffective in the gibber plains, and are more likely to create ongoing erosion problems.

5 Key Fluvial Processes

5.1 Pleistocene Sediments and the Unconfined Aquifer

Pleistocene sediments occur as shallow subcrop beneath the river valleys and the dunefields in the study area. Most of these sediments are permeable sands, and they host the local unconfined aquifer. Some are muddy sediments, which have access to the aquifer's water but which are less permeable. (Other sediments or rocks may also host the unconfined aquifer; they are not considered in this discussion.) That is, most of the study area is underlain by an aquifer which can freely transmit groundwater and which has no barriers between it and the ground surface; small parts of the study area are underlain by sediments which hold groundwater but which do not freely transmit it.

The waters of the unconfined aquifer play a role in supporting ecosystems and creating landforms. The lithology and spatial relationships of the Pleistocene sediments determine the nature of the aquifer's surface expression. In the study area, the aquifer is recharged by the Georgina and Diamantina Rivers. Near the gibber uplands, the water table is relatively deep below the ground surface (see Costelloe 2017). Both the ground surface and the water table slope down towards Kati Thanda/Lake Eyre but at different rates, so the vertical distance between ground surface and water table decreases with increasing distance from the uplands. This means that across the study area there are differing degrees to which the groundwater affects the surface. Two additional factors are that above the water table there may be a zone of partial water availability (the capillary fringe, within the vadose zone), and that the groundwater is saline to some degree.

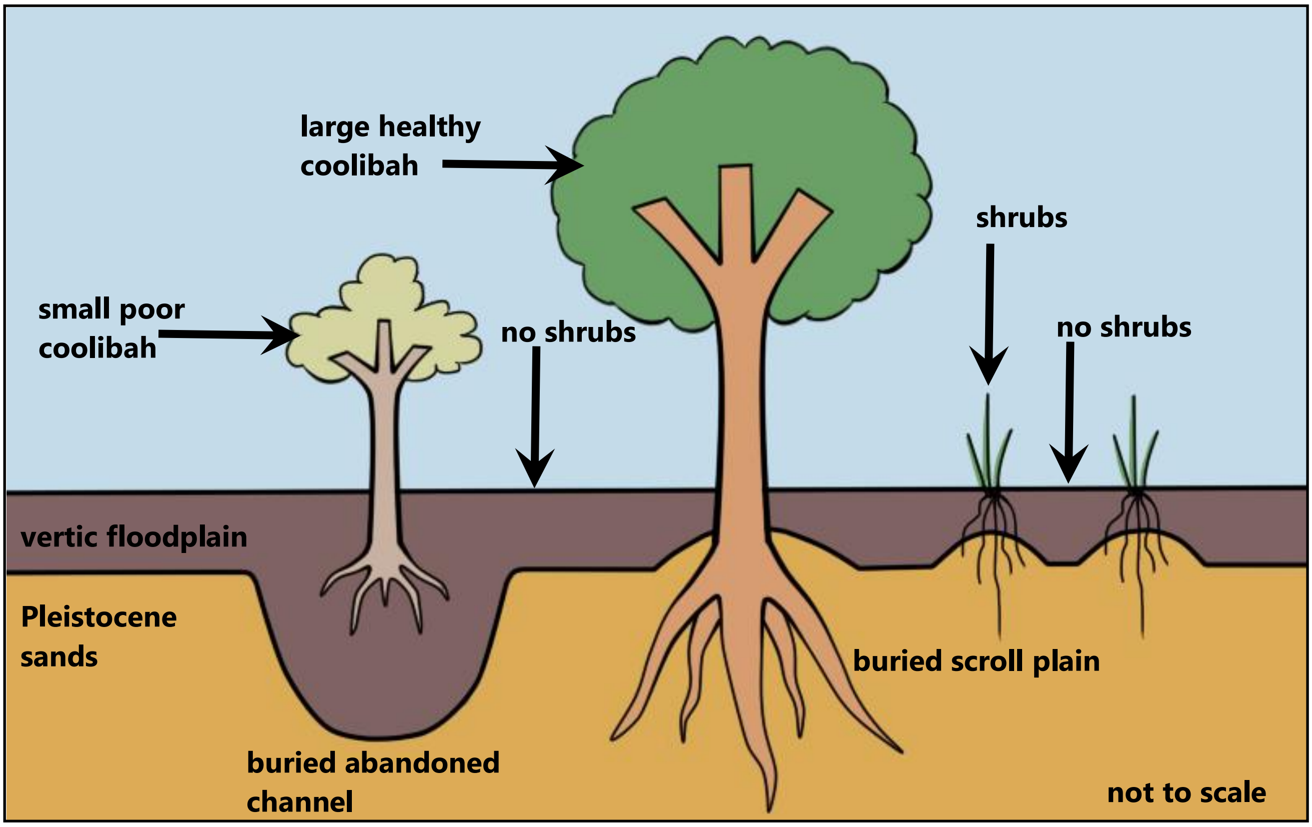


Fig. 38 The palaeo-topography of the Pleistocene sands influences surface ecosystems.

The groundwater's most visible expression is where the Pleistocene sediment's palaeo-topography governs surface vegetation (e.g. along the southern reaches of Eyre Creek). Before deposition of modern sediments, the Pleistocene alluvial plains included floodplain-level ridge-and-swale scroll plain topography, and empty abandoned channels. When the Pleistocene sediments were overlain by floodplain muds, the result was a mud layer of variable thickness above the aquifer. This affects surface vegetation in two ways. Firstly the depth to the aquifer varies, so that in a particular area, vegetation with better access to the groundwater will grow bigger, or survive longer droughts. Secondly, the vertic floodplain muds will be supportive of, or hostile to, the roots of certain sorts of plants.

The result is complexity in reach-scale plant communities. Plants with short root systems may only be able to reach the aquifer above buried palaeo-scroll plain ridges, so some places may have curved lines of understory (above palaeo-scroll plain ridges) close to bare areas (above abandoned channels) (Fig. 38). A coolibah tree needs a regular supply of water, and dislikes muddy soil around its roots. Coolibah germinating above a deep mud-filled abandoned channel will be unlikely to flourish, whereas the roots of coolibah germinating above an old scroll plain will have better access to wet sandy sediments, especially along the ridges of the palaeotopography (Fig. 38).

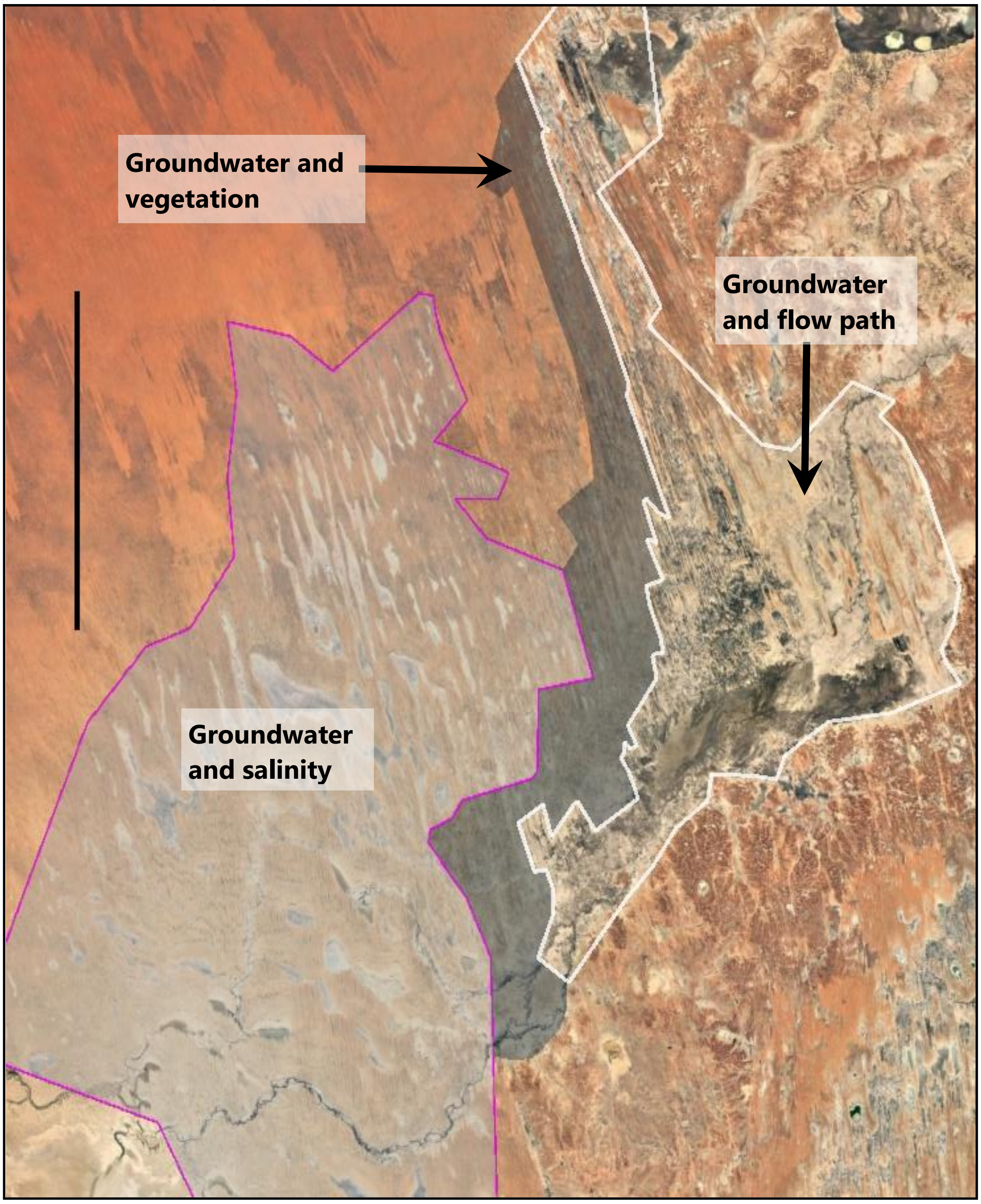


Fig. 39 The unconfined groundwater's spatial relationships with surface features.

Google Earth image, black scale bar = 100 km; also see Fig. 1.

Within the study area, variations of the aquifer expression include –

- floodplains with deposits of alluvial sand usually have little/no expression of the aquifer;
- if the water table is relatively deep, interdunes that do not receive surface water and grow little vegetation may have only subtle expression of the underlying Pleistocene sands, whereas interdunes that receive surface water and grow vegetation will have more clear expression;
- lignum (which prefers muddy soils) is not disadvantaged by growing in deeper mud layers, and in Goyder Lagoon the underlying palaeotopography instead influences the degree and direction of reticulate swamp channel development;
- if the water table is moderately shallow, very small plants may be supported by capillary water in the vadose zone, but possibly larger plants may be disadvantaged by their roots' exposure to salinity;
- if the water table is very shallow and the capillary water reaches the ground surface, vegetation is usually disadvantaged, and the Pleistocene sediments express at the surface by patterns in evaporite efflorescence. It is likely that this plays a role in lake basin creation (intra-sedimentary evaporite precipitation creating loose fragments which are easily blown away).

The net effect of these factors is that in the study area the surface expression of the unconfined aquifer has three zones (Fig. 39).

- Close to the uplands, the aquifer can assist in the support of surface vegetation, but the surface flow paths of Eyre Creek, the Diamantina River and Goyder Lagoon are usually more important to plant ecosystems.
- West of Eyre Creek and north-west of Goyder Lagoon, a strip of the eastern Simpson Desert dunefield (~250 km long , 12-35 km wide) is isolated from surface flow paths. The water table is shallow enough that at least the capillary zone is within reach of interdune vegetation, while not being so shallow as to promote salinity. In this project's field study the interdune vegetation included shrubs, small trees including probably Acacia and Hakea, grasses/forbs, and probably cryptogams. Along the margins of this zone, where the interdunes are accessible to very rare large floods and can receive flood-borne seeds, it possible to get cohorts of coolibah. At one such, a 10 km stand of mostly dead mature trees indicates a cohort of coolibah germinated from a ≥'100-year flood' and subsequently supported by the unconfined aquifer (assuming rainfall would be insufficient to grow very large trees). Relatively recently, something killed most of the trees, and this was probably a rise in groundwater level during the mid-1970s flooding. If the groundwater is too saline for the coolibah to extract water and it covers much of their active root zone, the trees can die from water stress (J. Costelloe pers. comm. 2016).
- In 100 km wide zone extending 300 km northwards from Kati Thanda/Lake Eyre, the groundwater is sufficiently close to the surface that low-elevation interdune soils are exposed to saline water, and in some places some or all vegetation is suppressed. In some interdunes evaporites precipitate at surface. This zone is rich in playa lakes, some formed along palaeodrainage lines and some formed in interdunes.

5.2 Regional Flow Paths

Diamantina Fan

In the Diamantina Fan the major flow paths are (Fig. 40):

- The main channel with its associated floodplain. Around Diamantina-split Waterhole, the main channel continues to flow south along the Yammakira branch, while right-bank distributary channels and floodplain-level flow coalesce and enter Andrewilla Waterhole. Where the Diamantina River enters Goyder Lagoon, the Yammakira and Andrewilla branches are separated by the broad Andrewilla Sand Plain which is rarely inundated.

- The secondary flow paths from left-bank distributaries, including those terminating in interdune spaces such as Lake Uloowaranie. Gumborie Creek is the longest left-bank flow path; it mostly terminates in Lake Etamunbanie and nearby

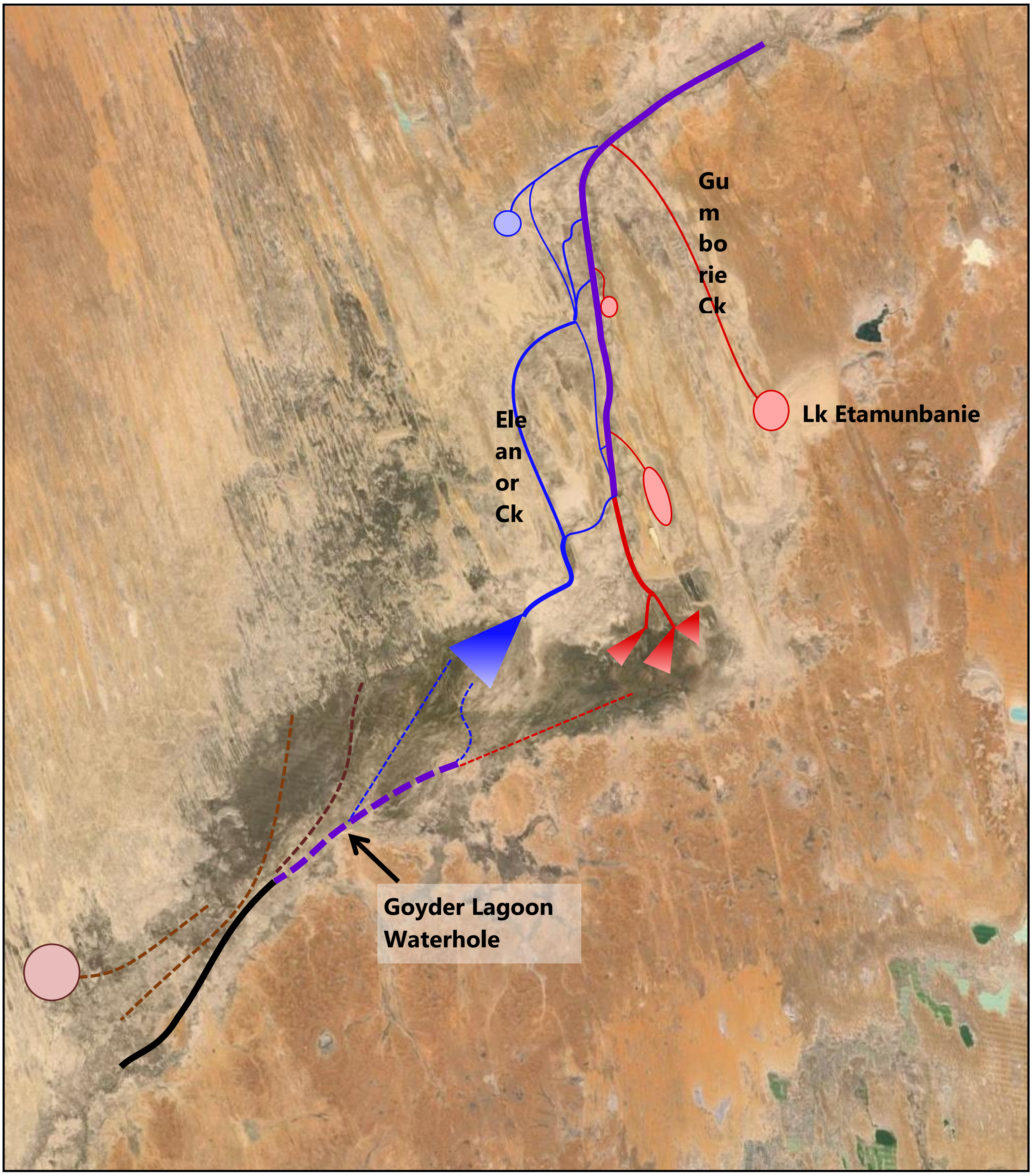


Fig. 40 Flow paths of the Diamantina Fan and Goyder Lagoon.

Thick lines: main flow; thin lines, smaller flow; dashed lines, diffuse flow; ovals, terminal flow; triangles, networks of small distributary channels. Diamantina River flow path is purple, left-bank distributaries are red, right-bank distributaries are blue, Eyre Creek flow is brown, integrated Diamantina River + Eyre Creek flow is black. Google Earth image, field of view ~170 km wide.

interdune flood basins. Some flow extends further south, but the WOfS indicates that little if any penetrates as far as Goyder Lagoon.

- The secondary flow paths from right-bank distributaries including Eleanor Creek (Fig. 40, and see Fig. 12). Most of the right-bank secondary flow paths have the potential to contribute water to the Andrewilla branch. All Andrewilla Waterhole's inlet channels are constrained within a single interdune (see Fig. 47). This undoubtedly forms a high-energy environment, and probably explains Andrewilla Waterhole's length and depth.

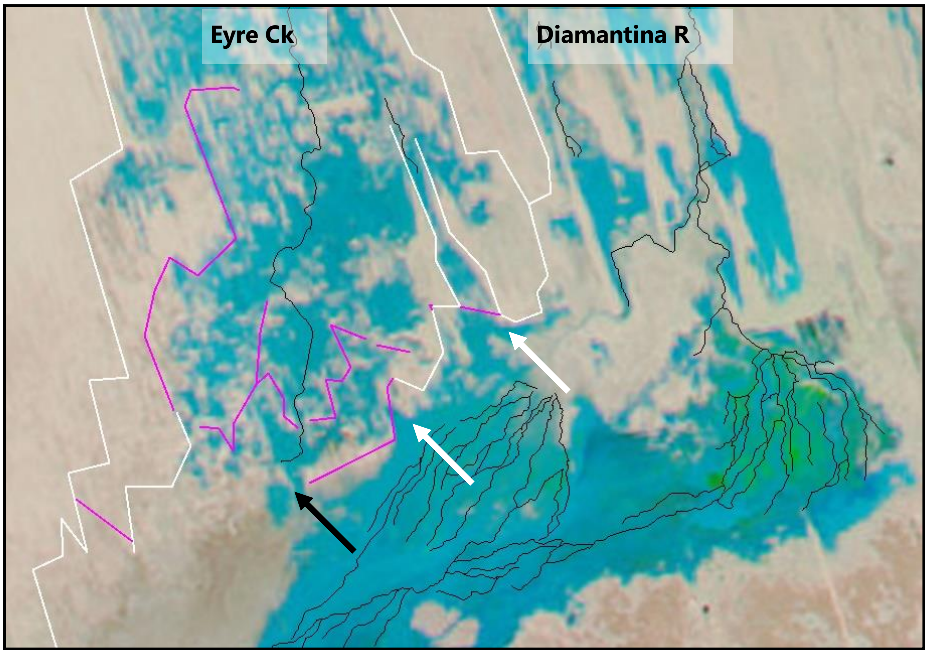


Fig. 41 Eyre Creek banked up behind dune sets along the northern Goyder Lagoon boundary.

White lines = permanent barriers to flow, pink lines = interdune sills, black arrow indicates Tepamimi and Tepaminkanie waterholes, white arrows indicate shallow flow zones where Eyre Creek water can enter the Andrewilla flow path. MODIS image February 13, 2009, overlain by author's linework (pink, white) and Geoscience Australia drainage network (black); field of view ~100 km wide.

Eyre Creek

As the Eyre Creek flood front approaches Goyder Lagoon, it spreads out and in banks up behind the small dune sets along the northern margin of Goyder Lagoon. Eyre Creek flow enters Goyder Lagoon firstly through Tepamimi and Tepaminkanie Waterholes. At the highest flood levels, Eyre Creek flow also overtops some interdunes and enters Goyder Lagoon through low-energy shallow broad unchannelled flow in the vicinity of Pelican and Burt reaches (Fig. 41), and probably also in areas west of Tepamimi Waterhole.

Whether Eyre Creek achieves connectivity with Diamantina River water depends on whether the Eyre Creek flood peak reaches Goyder Lagoon while Goyder Lagoon is inundated. Even if the Diamantina and Georgina headwaters receive rain at the same time, Eyre Creek water may arrive at Goyder Lagoon well after Diamantina River water (see Technical Appendix section A4 Specific Flow Events). If Eyre Creek and Goyder Lagoon eventually become simultaneously inundated (as happened during 2009) then the two bodies of water are juxtaposed. However, flow patterns in Goyder Lagoon suggest that the two bodies of water may not be strongly mixed for some distance. In addition the relative size of channels delivering water to Goyder Lagoon suggests that in e.g. the Pelican Waterhole reaches, although technically Eyre Creek water may be contributing to Diamantina River water, in fact the contribution may be small.

Goyder Lagoon

The flow paths in Goyder Lagoon are strongly dependent on which sources of water into the Lagoon are flowing (Yammakira branch, Andrewilla branch, or Eyre Creek). Because of Goyder Lagoon's low relief and low flow energies, flow from different sources can travel downvalley side-by-side for some tens of kilometres, with apparently little mixing.

During rising river levels, Diamantina River water enters Goyder Lagoon firstly through the Yammakira branch and later via the Andrewilla branch. The two bodies of water are initially separated by the Diamantina Fan sandplain (Figs. 12, 40). Yammakira water mixes with some Andrewilla water immediately south-west of the sand plain, while water from the northernmost Andrewilla terminal distributaries pursues an independent path until about Goyder Lagoon Waterhole (Fig. 40).

Eyre Creek enters Goyder Lagoon firstly via the gateway waterholes Tepamimi and Tepaminkanie, and then through a number of shallow floodways across the width of the boundary (Fig. 41). If Goyder Lagoon is not already inundated from the Diamantina River, Eyre Creek flow will travel south-west as well as west south-west, extending into the north-west parts of Goyder Lagoon and also to Goyder Lagoon Waterhole. On the other hand, if Diamantina River flow has already partially inundated Goyder Lagoon by this time (as it had during the 2009 flow event), the Eyre Creek flow travels south-west with possibly little mixing for some time. The flow along the southern and south-eastern margin of Goyder Lagoon is dominated by Diamantina River waters beyond Goyder Lagoon waterhole. Eyre Creek and Diamantina River waters are mixed by the time they have reached approximately Ultoomurra waterhole, however there continues to be relatively unmixed Eyre Creek water in the north-west, some of which is abstracted into the lower-elevation interdune corridors at the margin of the Simpson Desert.

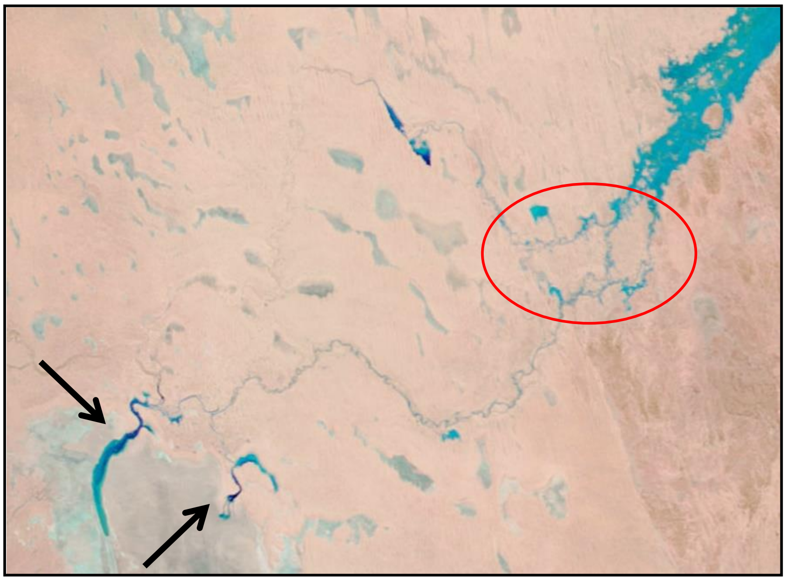


Fig. 42 Valley-scale anabranching between Warburton and Kallakoopah Creeks.

Area of valley-scale anabranching is circled in red; arrows indicate the outlets to Kati Thanda/Lake Eyre (Warburton Groove and the Kalaweerina Creek). MODIS March 5, 2009; field of view is ~250 km. in the east-west direction.

Warburton and Kallakoopah Creeks

For most of their lengths, the Warburton and Kallakoopah Creeks pursue independent flow paths through the Simpson Desert and Tirari desert dunefields. However, at the beginnings and ends their flow paths are linked, in a way that is not reflected in the boundaries of the management zones (see Fig. 1).

The clearest place at which Kallakoopah Creek begins is as a distributary channel from Warburton Creek near Kalamunkinna Waterhole. Actually, the division begins upstream from there. When the whole valley width is inundated downstream from Ultoomurra Waterhole, the north-western part of the floodplain flow path (including a substantial amount of Eyre Creek water) targets the Kallakoopah Creek valley. From Kalamunkinna Waterhole down to Kirrianthana Waterhole (on Warburton Creek) and beyond Anarowdinna camp waterhole (on Kallakoopah Creek) the creeks are anabranching on a valley scale (Fig. 42).

By the time the flood height has delivered flow down the Warburton Creek main channel as far as the Lake Eyre outlets, flow has entered the beginning of the Kallakoopah main channel. By the time the Kalamunkinna Waterhole valley is inundated, Kallakoopah Creek is carrying flow for ~95 km and all 3 anabranch valleys are potentially connected (Fig. 42), with offtake waters fed onto the floodplains, interdunes, and lakes.

Warburton and Kallakoopah Creeks rejoin in a low-elevation area of disorganised drainage that also receives the flow from Macumba Creek. The topography results from a combination of retreating shoreline, leaving behind a very flat surface, and subsequent dune-forming deflation. The drainage network here is almost entirely governed by pre-existing landforms. The Kallakoopah, Macumba and Warburton Creeks all join in this area, and enter Kati Thanda/Lake Eyre via the Warburton Groove (Figs. 7, 43). A distributary of Warburton Creek (Kalaweerina Creek) enters the other Kati Thanda/Lake Eyre inlet; it may carry Warburton Creek water only.

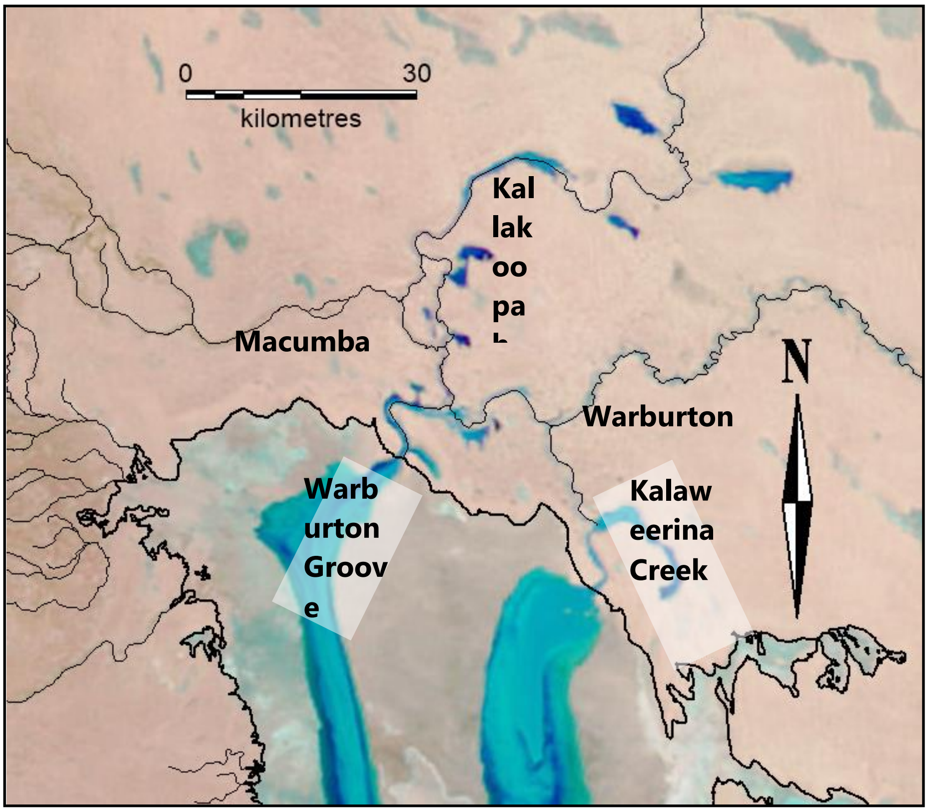


Fig. 43 Disorganised drainage at the Kati Thanda/Lake Eyre inlets.

5.3 Landscape Behaviour and Evolution

This section describes the way the study area's landforms behave and develop.

Sediments: Grain Size and Fluvial Transport

There are two kinds of sediment active in this river system: quartz grains (dominantly medium-fine sand size, ranging from coarse silt to medium sand), and mud aggregates (grain size approximately equivalent to medium sand). The mud aggregates are composed of a mixture of swelling clays and (probably) quartzose silt. The important characteristic of the mud aggregates is that they are robust under fluvial transport, and behave in most ways as if they were sand grains, including being deposited from active flow alongside quartz sand grains.

Active sediment transport takes place in the Diamantina Fan, and Warburton and Kallakoopah Creeks; under normal flow conditions, there is probably little sediment transport within Goyder Lagoon except on a very local scale.

Most sediment deposition is a mixture of quartz sand and mud aggregates (although it is difficult to tell the proportions without specific tests, because mud aggregate grains look and behave like sand). Because mud aggregates are less dense than quartz, they travel slightly higher in the water column, so there is some degree of segregation during transport. The more coarse quartz grains will be more likely to be in-channel and deposited on point bars and along thalwegs. The lighter mud aggregates may travel further across the floodplain, or be last to be deposited at the close of flow. The relative proportions of quartz vs. mud aggregates will affect the behaviour and type of landform the sediment creates.

Unconfined Flow

Shallow and low-energy flow where the flow path is unconstrained is the defining characteristic of large parts of the study area. In Eyre Creek, unconfined flow spreads across a downstream-increasing width of dunefield. In Goyder Lagoon, the termination of the Diamantina Fan's channels spreads unconfined waters across a very wide valley. In the Diamantina Fan, the unconfined flow released from overbanks and distributary channels forms an unknown (but probably significant) proportion of flood flow, including an important proportion of the floodwaters going to Andrewilla Waterhole. The low flow energy means that channels are not created, unless some pre-existing landform concentrates the flow to create locally high-energy conditions (for example, flow between gibber hills creating Goyder Lagoon Waterhole, Fig. 23). Since a focus of this project was refugia in channels and waterholes, there was little opportunity to examine the characteristics of the unconfined flow pathways. However, preliminary results from this project indicate that the unconfined flow conditions are more complex than had been supposed.

Meandering

Meanders occur where the river seeks to decrease stream power by increasing channel length, thus decreasing channel slope. Channel length is increased by making the channel sinuous. Erosion on the outer bank (the cut bank) and lateral accretion of a point-bar on the inner bank (Fig. 44) causes progressive channel migration. Either the amplitude of the meander curve increases, or there is downvalley translocation of a stable curve (as happens in the northern reaches of the Diamantina Fan). When the sinuosity becomes excessive, a new channel (a cutoff) makes a short-cut between two parts of the channel (e.g. the reach 3 km north of the Queensland border).

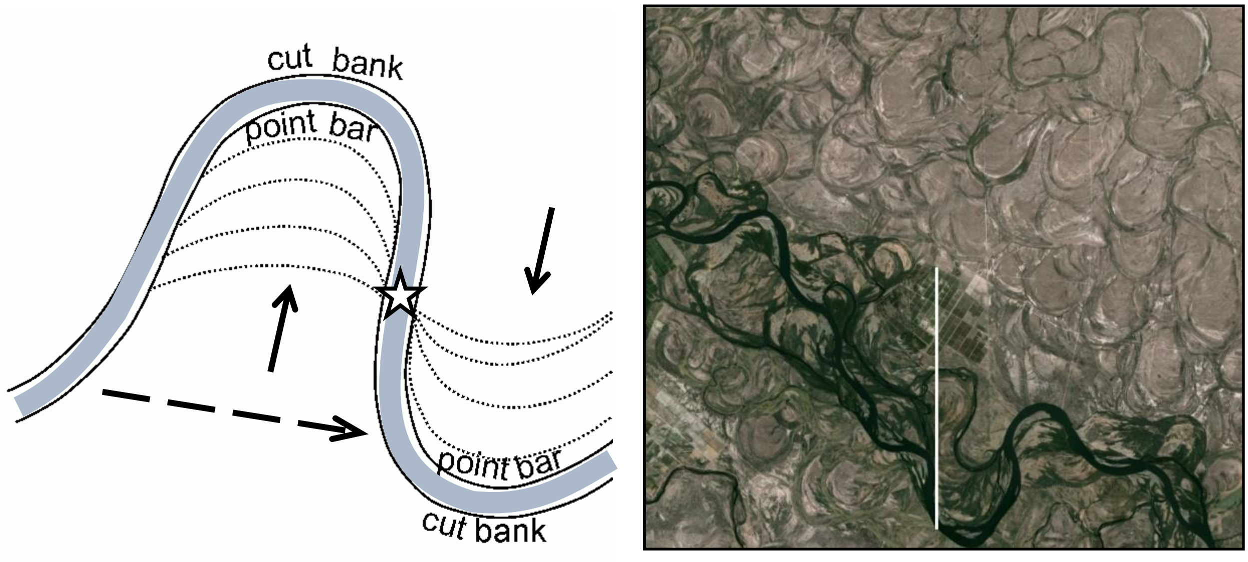


Fig. 44 Bird's-eye view of meandering river landforms.

Left: Diagram of an actively meandering channel; channel is blue, arrows indicate the direction of channel migration, dashed arrow indicates a potential future chute cutoff, star is inflection point. Right: The present-day channel belt of the meandering Rio Negro (Argentina) resembles what the study area would have looked like during the Pleistocene. Google Earth image, white scale bar = 5 km.

The mechanism for meandering is the distribution of in-channel turbulence and stream power. Meander outer bends are associated with (relatively) high-energy turbulence cells and lower-elevation channel bed (pools or deep spots). Relatively low-energy areas occur at the inner bends (allowing point-bar bedload deposition) and inflection points between curves (Fig. 44) (associated with higher-elevation channel bed).

Scroll plains are the ridge-and-swale floodplain created by accumulated point bars, or a combination of point bars and abandoned channels. Scroll plains develop first by lateral accretion of point bars, then vertical accretion as the old point bars are buried by successive flood deposits. In the modern river, the younger scroll-plain surfaces are therefore low-elevation landforms with good connectivity to the currently-active channel, and so they usually host biologically productive riparian plant communities. Older sections of the scroll plain are further from the active channel and more elevated: they are usually less productive.

The rapidity and geometry of channel migration during meander development will govern the width and productivity of the plant community. If channel migration is incremental, the outer bank is continuously being removed and the inner bank continuously created: the outer bank riparian trees will be (bigger) older than the trees on the point bank (e.g. Pandie Pandie Homestead reach). Slowly migrating channels will have riparian zones on both banks, with the point bar being the most productive. Rapidly migrating channels (e.g. upvalley from Double Bluff Waterhole) create especially wide and especially productive point bars. They also necessarily have rapid bank retreat on the outside curve, which means a narrow or absent band of riparian vegetation. On the other hand, channel migration could be avulsive, such that the channel relocates to a new place, leaving behind a portion of the old channel, with both banks intact (e.g. Kalamunkinna Waterhole). In this case, riparian trees on both banks of the new channel may be the same age, which would be younger than the trees on both banks of the abandoned channel. In a geomorphically active reach, this can lead to a staggered distribution of tree ages across the local floodplain.

Not all sinuous channels are actively meandering. Some channels are sinuous because of their interactions with nearby valley walls (e.g. reaches of Warburton and Kallakoopah Creeks), and some because their overbank deposits have hampered channel migration, thus discouraging meandering or confining it to very localised areas (e.g. the reaches 8 km upvalley from Double Bluff Waterhole).

Anabranching and Avulsing

Anabranching is the state of the river when several channels coexist within a single reach, the channels being hydraulically independent and separated by stable floodplain. It is a configuration the river adopts when the available stream power is insufficient to transmit the water and sediment load: several narrow deep channels have greater collective stream power than a single shallow channel. A river can move to an anabranching style when its sediment load has been increased, and this is likely to be one of the influences on the Warburton Creek's initial fluvial style as it begins to incise into the Pleistocene sediments.

Avulsion is the process of channel relocation, not as channel movement by incremental small steps but as wholesale creation of a new incised flow path. Avulsions are most likely to occur in variable flow regimes (where high levels of flooding occur, enabling overbank waters to cut a new flow path) and are promoted by low floodplain gradient and relief (the overbank waters' flow path can be more influenced by local topography than by regional gradient, allowing the new channel a wide range of possible orientations and locations). It is likely that there is another factor in promoting avulsion: some degree of floodplain confinement by the valley margin. In the Diamantina Fan, overbank and distributary waters become unconfined when they leave their channel: they do not retain enough energy to immediately carve a new channel. In Warburton and Kallakoopah creeks, overbank waters are in a much narrower valley, and they create a new channel from their offtake node.

One of the consequences of avulsion is that it releases a pulse of sediment into the flood stream. This contributes to the high sediment load transported by the river, promoting its deposition of sandy and muddy alluvium across the Warburton and Kallakoopah Creeks floodplains and filling up the abandoned channels. It is likely that the in-channel habitat for aquatic invertebrates will be different and/or more dynamic in the Warburton and Kallakoopah creeks than it is in Goyder Lagoon or the Diamantina Fan.

In avulsive reaches is possible that the riparian trees will have less time to grow to great size than in other parts of the river. If a channel moves it may move some distance, and the abandoned channel's riparian trees will decline or die (whereas in other parts of the Diamantina River, even when a channel moves it may not move far, and its riparian trees will still have access to water).

In avulsive reaches trees of different ages/sizes are likely to be distributed across the landscape in a way that does not relate to present-day channel geography. In particular, in the avulsive meandering reaches, where the new channel 'jumps' past the old channel, the process leaves both banks of the abandoned channel intact (e.g. Fig. 30). Estimating the rate of channel migration by tree girth (as a proxy for age) or tree age (e.g. by carbon-dating) will need to include understanding whether the channel being measured has produced an incremental scroll plain (where tree ages are likely to be successive along the radius of the curve) or an avulsive meander (where tree ages may repeat along the radius of the curve).

Bank Building and Bank Erosion

The study area's medium to large channels usually have clearly defined banks, many with tops elevated above the level of the wider floodplain. If the bank tops are levees, riparian ridges, or high alluvium, they have been created by deposition of flood-borne sediment. (Other bank tops may be created in other ways. Also, not all the study area's channels have clearly defined or elevated banks, particularly small channels and the reticulate channels of lignum swamps.)

Fast and turbulent floodwaters carry medium to fine sand and mud aggregates high in the water column. They will be deposited where the water loses energy: encountering dense vegetation, moving from deep channel to shallow overbank, or at the interface between water bodies moving at different speeds (see Glossary: levee). Riparian zones therefore are favourable locations for deposition of alluvium, as are the downflow terminations of waterholes and distributary channels. Under some conditions alluvium is deposited asymmetrically (more on one side of the channel or floodplain then the other; Fig. 13). In other circumstances, levees flank both sides of the channel. If levee aggradation is matched by deposition in the channel bed, the entire reach will become elevated, forming an alluvial ridge (Fig. 16). This predisposes the reach for avulsion.

Banks can be impacted by erosion: bank retreat (if the bank slope moves away from the channel), bank-top lowering or removal, or gullying (if the bank is breached). If bank erosion or instability occurs as a result of human activity, then it is a management problem. However, if it is part of normal river behaviour, then it is a process that needs to be given room to move, and it does not denote poor condition. Circumstances under which bank erosion can be expected are 1) active meandering and 2) bank incision or lowering during floods, especially in rivers with highly variable flow regimes (such as the Diamantina River).

Rules-of-thumb for estimating the rapidity of bank erosion are

- Exposed tree roots: riparian trees will grow corners into their roots to take into account a nearby bank slope. (In this report, the corners are referred to as 'knees'.) The longer the root exists, the thicker it will grow, indicating the length of time the bank has been in existence. Slow bank retreat is shown by thick tree knees that are exposed, but not far above the bank surface; moderate to rapid bank retreat is shown by thin tree knees some distance above the bank (Fig. 45); extremely rapid bank retreat is shown by broken straight roots (no tree knees) and a web of fine roots.

- Bank slope and condition: rapid bank retreat is indicated if the bank is steep to vertical, especially if it has a crumbling surface and a sharp lip. However, steep banks are also a common component of Channel Country compound banks. They indicate not erosion but in-channel shear during flows, which is an important process for maintaining channel depth. Stable steep banks have rounded bank lips and a cohesive surface.
- The age and condition of riparian trees: all other things being equal, large trees indicate an old landform and spindly small trees indicate a recent landform. Large trees in poor condition can indicate an old landform which has recently become eroded in the trees' root zone. Large woody debris in the channel adjacent to a very steep and poorly vegetated bank indicates that bank retreat has been so rapid that the riparian trees have fallen into the channel (Fig. 45).

Fig. 45 Tree 'knees' and in-channel large woody debris showing rapid bank retreat in a meander bend at Tinnie Landing.

Distributaries and Offtakes

Distributary channels are an important landscape element in the area. They transfer channel water out into the floodplain, supporting terrestrial ecosystems and secondary flow paths across a wide area. Some refresh main-channel waters by returning floodplain water into the channel during flood recession, or (J Reid pers. comm. 2017) after intense local rainfall. They occur in three contexts: splays at the downvalley terminations of channel-segment waterholes, radial distributaries at the downvalley terminations of the Andrewilla and Yammakira branches of the Diamantina Fan, and bank-breach distributaries which are found along channels and waterholes throughout the Diamantina River.

Distributary channels are most commonly found on the outside banks of sinuous channels (where the force of downflow current strikes most strongly). They form when flood waters overtop elevated banks and are concentrated by a gap in vegetation or a local low point, initiating erosion. The bank is breached, and floodwaters leave the channel. If the bank breach extends for any distance it will become a distributary. If the distributary can continuously deliver flow (e.g. to a lower-elevation or an unconfined floodplain), it can experience channel-forming processes and develop bed, banks, meanders, and other channel properties. Distributary channels are most likely to be well-developed where there is an elevation difference between bank top and nearby base level (that is, there is a slope to encourage channel development), and where there is accommodation space at the downflow end. The distributary channel that feeds water into Lake Uloowaranie is a particularly good example.

With rising flood heights, water is contained in the channel until it reaches the elevation of the offtake. Some of the channel's water flows into the offtake and through the distributary either up to floodplain level, or up to and over a sill and then down to the adjoining floodplain. How the distributary behaves during flood depends on the relative elevations of banks, floodplain, and sill. These relationships also influence how vulnerable the offtake/sill will be to erosion, for example if cattle use the distributary channel to access the main channel. The other influence on distributary behaviour and sensitivity to erosion is flood routing: if offtake flow is from full channel to inundated floodplain, hydraulic damming may restrict out-of-channel flow.

The distributary channel offtake is created by erosion and during each flow event it experiences locally high-energy and turbulent conditions. Offtakes can be unstable and complex areas with multiple entrances, back-bank flow and scour areas and evidence of rapid bank erosion. They may also present a wide variety of habitats in a small area (Fig. 46).

Fig. 46 A complex offtake at an Andrewilla distributary channel.

Google Earth image, black scale bar = 0.4 km.

Bioengineering by Large Plants

In the Channel Country, a well-vegetated riparian zone with large trees and bushy understory is likely to play a significant role in keeping channels steep and waterholes deep. Dense vegetation slows water flow, and when there is a slow-flowing body of water next to a fast-flowing body of water (such as a channel) a shear zone is created along the interface. This is likely to be a key process in maintaining the Channel Country's characteristic moderately steep upper banks. In Cooper Creek waterholes, a deep high-velocity band has been measured that penetrates towards the channel bed, a process that keeps the waterholes deep, and this is likely to be another consequence of the interface between slow riparian water and faster channel water. A further consequence of the riparian vegetation is that in slowing water flow, it will encourage the deposition of sediment. This process maintains the high banks and (if present) levees. In waterholes where the banks and levees are at some elevation above the wider floodplain, and therefore the distributary channels might incise and trigger an avulsion (e.g. Andrewilla Waterhole, Fig. 46), it is highly likely that the sediment deposition promoted by riparian vegetation plays an important role in maintaining a distributary channel sill.

If riparian vegetation plays such a key role in maintaining channel landforms, it is likely that it can help create channels as well. The 'strand line' process of coolibah seed placement (Costelloe 2017) puts tree seeds along the edges of newly created channels and gullies. If the trees establish and grow large enough to impact the hydrodynamics of floodwaters, they are likely to play a key role in creating new channels from short distributaries, and in stabilising newly-avulsed channels.

There is a possibility that a relationship exists between the degree of gilgai expression and the presence or absence of large plants such as lignum, but the possibility is currently unexplored. Surface flow in Goyder Lagoon is low-energy, so the channel network in the most dense lignum swamps is likely to result from processes involving the large lignum bushes. It has not been investigated in this study, but it is likely that at a local scale the landforms of the channel network will involve gilgai features such as deep and large macropores in the channels and heave between the channels. In Goyder Lagoon, the underlying Pleistocene sediments are influencing the locations of swamp channels (Fig. 27). If the link between surface and Pleistocene sediments is via plant roots (as it is elsewhere in the study area), then it is possible that the process whereby the unconfined aquifer influences the lignum swamp's channels is through the development of root macropores, promoting shrink-swell behaviour in heavily vegetated areas. If this relationship can be demonstrated, it will have implications for grazing management across large parts of Australia.

Flood Runners

As topographic lows which accumulate water and direct it across the wider floodplain, flood runners are important in ecosystem support and flow connectivity. Some also play a role in landscape evolution, for example a flood runner can mark the previous location of an avulsed channel, or it can be the future location of the next channel avulsion. Flood runner processes and trajectories of change depend on their origin e.g. distributary channel, partially infilled abandoned channel, non-channelised secondary flow path, shallow floodplain scour.

High-Runoff Slopes

Although the most important water comes to the Diamantina River and Eyre Creek as large surface flow from the Queensland catchment, runoff from rain on nearby hillslopes is also important to local ecosystems. Waterholes and vegetated areas that are downslope from a high-runoff surface benefit by having their water refreshed or their soil moisture renewed. High-runoff surfaces include dune palaeosols (important to interdune plant communities); clay-rich Pleistocene sediments (those near Kallakoopah Creek are in a position to refresh waterholes in the Mona Downs area); and gibber hillslopes, which are an important contributor to the proximal parts of the Diamantina Fan, and to Kalamunkinna Waterhole (via Derwent Creek).

Flow Asynchronicity

Tributary asynchronicity (where different sections of a drainage network are active at different times or levels) is a feature of drylands rivers, partly because drylands rainfall is so variable in space and time, and partly because the rapidity of river flow is strongly influenced by antecedent conditions. In the long and low-gradient rivers of the Lake Eyre Basin, the other factors are the geometry and landforms of the drainage networks. For a widespread rainfall event in the upper catchment, Eyre Creek takes much longer to deliver less water to Goyder Lagoon compared to the Diamantina River. Factors that slow Georgina River flow into Goyder Lagoon and/or reduce its quantity of water include (in Queensland) large swamps and lakes and low-runoff dunefield surfaces at the beginning of Eyre Creek, and (in South Australia) the diffuse flow path down Eyre Creek's interdune spaces. Factors that promote a more speedy and copious response from the Diamantina River include (in Queensland) fewer swamps, and more restricted valleys with widespread high-runoff gibber catchments in the Birdsville area, and (in South Australia) the Diamantina Fan's continuous channel which efficiently delivers flow into Goyder Lagoon. In the 2009-2010 rainfall event the Diamantina River received two flood peaks while Eyre Creek received one; Diamantina River water had inundated a large proportion of Goyder Lagoon before Eyre Creek's flood peak reached Goyder Lagoon; and Eyre Creek had inundated lignum swamps from Queensland down to the its border with Goyder Lagoon.

Differences in flow timing are likely to be beneficial to bird populations, because they can move from place to place as individual waters dry up (J. Reid pers. comm. 2016).

Mid-1970s Floods

The mid-1970s flooding was approximately a 1% AEP flood ("1-in-100" event). Effects of those floods were examined by comparing aerial photographs 1969 and 1977 with present-day Google Earth imagery, for those areas reputed to, or most likely to have experienced change:

- the Diamantina River
    - from the Queensland border to down to the beginning of the Eleanor Creek flow path at 8 Mile Waterhole,
    - from the Lake Uloowaranie entrance down to the old Yammakira Homestead,
    - the Andrewilla Waterhole intake channels,
    - the Andrewilla Waterhole terminal distributaries,
- Goyder Lagoon
    - Koonchera Waterhole, and the unconfined swamps to its north,
    - Burt Waterhole, and the unconfined swamps to its southwest.
- The Warburton and Kallakoopah Creeks were not investigated.

Despite a common perception that the 1970s floods wrought strong changes in the land, there was relatively little effect on the landforms in the areas examined. Reaches where the landforms indicate ongoing activity exhibited minor changes: in many of the Diamantina River's northern meandering reaches there was some incremental channel migration, and at Diamantina-Split and Andrewilla's terminus there were small new distributary channels.

Of the examined areas, there were three other places where minor and localised changes took place: a flood runner developed into a new intake channel at Andrewilla Waterhole (Fig. 47), floodwaters pushed through a dune and formed a second waterhole at Koonchera, and at Burt Waterhole, floodplain scour turned part of the Birdsville Inside Track into a waterhole, while the old waterhole (in a nearby interdune) developed a second channel segment. Although these changes were relatively small (on the scale of the river's landforms), they were transformative (crossed a geomorphic threshold such that the new landforms are either stable, or evolving in a new way; but in any case unlikely to return to the previous state). They also occurred where in places important to humans, so community perception assigns these changes greater significance in the landscape than they actually have.

Fig. 47 Post-1969 expansion of a single Andrewilla intake channel.

Arrows indicate bank retreat, floodplain removal, and dune-base gullying. Left, 1969 aerial photograph; right, Google Earth image; white scale bar = 2 km.

6 Management Implications

Riparian Vegetation and Landform Maintenance

The value of riparian vegetation to ecosystems is well-known. It is less well-known that the vegetation plays a role in building and maintaining landforms. When Channel Country rivers are completely inundated – when the line of trees poking out of the floodwaters is the only thing showing where the channel is – the flood waters move downvalley at two speeds. The water in the channel is faster, and the overbank water is slower. Riparian vegetation plays an important role in slowing the overbank water. This creates turbulent conditions at the interface between the two water bodies, which is likely to be a key process in maintaining the steepness of the upper banks, and scouring out the depth of the waterhole. Without regular scouring during large floods, the channels and waterholes would be vulnerable to silting up during smaller flows.

The slowing of overbank water is also encourages deposition of sediment and debris over the bank top. The debris will contain seeds and organic matter, renewing the bank top vegetation. The sediment deposition maintains the high banks and (if present) levees. In waterholes where the banks and levees are at some elevation above the wider floodplain, and therefore the distributary channels might incise and trigger an avulsion (e.g. Andrewilla Waterhole, Fig. 46), it is highly likely that the sediment deposition promoted by riparian vegetation plays an important role in maintaining a distributary channel sill. This could be particularly significant if stock travel along distributary channels to gain access to the waterhole (if the distributary's more gentle gradient is a preferable travel path than the steep banks). A stock pad along a distributary channel might promote above-normal degrees of channel incision.

As riparian vegetation plays such a key role in maintaining channel landforms, it is likely that it can help create channels as well. The 'strand line' process of coolibah seed placement (Costelloe 2017) puts tree seeds along the edges of newly created channels and gullies. If the trees establish and grow large enough to impact the hydrodynamics of floodwaters, new channels can be created from short distributaries, and newly-avulsed channels can be stabilised.

The management implication is that riparian vegetation preservation is important because of its services in landform processes which maintain the stability of aquatic habitats, especially the deeper channels and waterholes.

Flow Routing down Eleanor Creek

The relatively small size of the distributary channel at Diamantina-split Waterhole and the behaviour of the Diamantina Fan's flood fronts during the 2009-2010 flow event indicates that floodplain-level largely unconfined flow down the Eleanor Creek flow path is a significant contributor of water to Andrewilla Waterhole. A landholder's comment, that Andrewilla Waterhole seemed to be filling more often in comparison to Yammakira Waterhole than it used to, might reflect an increase in discharge down the Diamantina-split distributary channel (possibly from erosion widening the channel). On the other hand, if more of Andrewilla Waterhole's water comes from the floodplain, a change might reflect differences in the floodplain near the Queensland border, or a change to the flow regime with respect to the frequency of overbank flooding.

Groundwater Support for Terrestrial Ecosystems

By chance, the Pleistocene sediments that host the unconfined aquifer are sufficiently distinctive that their effects can be traced by satellite imagery through covering sediment. In conjunction with satellite imagery displaying individual flows (MODIS) or cumulative inundation (WOfS), this gives us the opportunity to determine the places where groundwater is likely to be what supports water-reliant vegetation in areas of insufficient surface water. In the study area, a number of places were identified where this was the case, for example the interdune discussed in section 5.1 Pleistocene Sediments and the Unconfined Aquifer, and Stony Crossing, where healthy coolibah are growing in locations isolated from normal surface water flow (Fig. 48).

There are several implications for this result.

- The unconfined aquifer will be important for interdune vegetation within the Simpson Desert dunefield in those areas where the depth to water table allows tree root access to water without stress of salinity (Fig. 39). This may have implications for bird fauna, and for pre-European Aboriginal land use.
- The unconfined aquifer probably explains the widespread but widely-separated coolibah occurrences in places that do not receive much flow or abundant flow e.g. Goyder Lagoon or rarely-inundated valley margins.
- Preliminary carbon-14 dating of coolibah ages indicates similar growth rates (Gillen 2017), even though the most upstream sample receives flow approximately annually and the most downstream sample receives flow slightly more than half as often (Costelloe 2017). If all the coolibah in the study area are receiving groundwater support then perhaps they are less dependent on surface flows to maintain their growth rate.
- The unconfined aquifer is recharged by flow from Queensland. Changes to the amount or frequency of flow coming from Queensland will affect groundwater-supported terrestrial ecosystems, as well as ecosystems along the creeks.

Fig. 48 Coolibah located outside the normal surface water flow path at the Stony Crossing reach.

Top, in an interdune; bottom, on a terrace (for locations, see Fig. 34).

Range and River Condition Assessment

Range assessments sometimes uses vegetation density or presence/absence as an indicator of condition. It is important to be aware of non-human factors that affect vegetation distribution. In the study area, several aspects of the geology and geomorphology influence terrestrial ecosystems, e.g. –

- Spatial relationships between the ground surface and the lithology of the underlying Pleistocene sediments can control plant distribution, through promoting or restricting access to groundwater. Quite marked differences in plant communities can develop, purely in response to the subcropping geology (Fig. 49, top) .
- A difference in fluvial style may make a sharp difference to the width of the riparian zone, and potentially to the age of its vegetation. A meandering channel in which channel migration is incremental and not too fast is likely to have a wide riparian zone that is densely vegetated, whereas a slow-moving or stable channel may have a narrow riparian zone (Fig. 49, middle).
- The valley-scale geomorphology may affect how often the floodplain is inundated, and how long the water stays on the floodplain (Fig. 49, bottom).

The management implications are firstly that some terrestrial ecosystems will be less robust than their immediate neighbours, so a particular grazing pressure may be sustainable in one area but less so elsewhere. Secondly, when assessing range condition, it is important to know the geomorphological context of the plant community, especially if comparing vegetation surveys from different locations. Finally, many systems of rangeland management have per-area stocking rates as a management tool. In an area where vegetation is very unevenly distributed due to non-human factors, paddock-scale stocking rates may be an oversimplification of landscape resources.

River assessments sometimes use bank stability as an indicator of condition, and some methodologies assign scored values according to the degree of bank erosion present on a reach. It is important to be aware that bank erosion can be (and in the study area, usually is) a natural process required by the river to be in good functional condition. Further, there are situations where bank erosion is necessary for there to be productive terrestrial ecosystems elsewhere. In meandering reaches, the wide and densely vegetated riparian zone found in the inner bank scroll plain is not possible without erosion on the outer bank.

Bank erosion can be expected in rivers where there is active meandering, and in highly variable flow regimes (such as the Diamantina River), flood-driven bank incision or breaching (creating a distributary channel) or bank lowering. In these circumstances, the condition assessment is not whether or not erosion should be present, it is whether or not erosion-prone landforms are operating outside their expected conditions in a way that is detrimental to the overall good function of the river. With the Diamantina River's current low level of documentation, this is a difficult call to make.

In the Australian rangelands, gully erosion and the development self-expanding gully networks is a common outcome of flow concentration through culverts and along tracks, cattle pads, and dam by-wash. There were some places in the study area where such erosion was noted, notably new Burt Waterhole, around a floodplain bund in Kalamurina Station, and some possible station tracks abandoned through gullying (in vulnerable areas where track gradient from interdune down to floodplain was steep). However, most of the large erosion gullies noted during fieldwork were triggered by natural causes: bank undercutting by channel development (Andrewilla intake, Tinnie Landing) or changes to base level (Cliff Camp). In the dunefields, interdune deflation leading to local gullying is a natural process (although it can be accelerated by grazing and trampling), as is deflation and rill development in palaeosol surfaces along the southern borders of source-bordering dunes (Fig. 36).

Fig. 49 Effects of geology and landforms on vegetation communities.

Top: A sharp boundary in plant communities reflects subcropping lithology. Left, view from dune top looking west south-west across the floodplain. There are no fences or other grazing-excluding structures between the two plant communities. Right, Google Earth image showing photo point location on a dune crest and orientation (white arrow). Location 1.2 km north-northwest of Yelpawaralinna Waterhole; white scale bar = 0.5 km. Middle left: wide riparian zones associated with a migrating sinuous channel; Diamantina Fan main channel, white scale bar = 0.5 km. Middle right: narrow riparian zone associated with a non-migrating sinuous channel; Diamantina Fan main channel, black scale bar = 0.5 km. Bottom: valley-bottom inundation downvalley from Cliff Camp. On the right side of the Google Earth image, the valley is inundated from margin to margin, and the water retention time is long. On the left side of the image, the valley is only inundated to that degree near the channel. Flow is from right to left, north is to the top left, orientation indicated by black scale bar which = 4 km.

Applicability of Other LEB Research

Some of the Lake Eyre Basin's fluvial processes have been studied in depth for over 30 years. This has revealed much about Channel Country fluvial processes, and has been the cornerstone of the world's understanding of anabranching and of mud aggregate floodplains. However, most of that research has taken place in Cooper Creek, and the Diamantina River has several points of difference from Cooper Creek.

In Cooper Creek (Queensland) the fluvial style is dominated by anabranching, and the anabranching channels coexist with anastomosing floodways in mud-aggregate floodplains (including lignum swamps on vertic soils). However, most of the present study area does not anabranch; only parts of Warburton and Kallakoopah Creeks include anabranching. The Warburton and Kallakoopah Creek anabranch channels are different in planform to those of Cooper Creek (Queensland), and the Warburton/Kallakoopah Creek channels are avulsive whereas those of Cooper Creek are stable. In addition, the Warburton/Kallakoopah Creeks floodplains are much less vertic than those of Cooper Creek, and the channels have a much greater sediment load which is occasionally deposited as alluvium across the floodplain. The study area does have widespread areas of vertic soils and lignum swamps in Goyder Lagoon, however the fluvial processes of Goyder Lagoon are not similar to those of Cooper Creek.

In summary, while the Cooper Creek research is relevant with respect to the geomorphic processes that drive waterholes, anabranching and mud aggregates, most of the work will not be directly relevant to Eyre Creek or the Diamantina River in South Australia. The best understanding of the study area's fluvial processes will be based on site-specific research.

Managing Dynamic Landscapes

Some parts of the Diamantina River and Eyre Creek are stable over time and change little, some are more active with visibly evolving landforms, and some areas are changing very rapidly. Within the study area and within the scope of this project, most of the areas that are active appear to be changing in response to natural conditions. For any river system, the most cost-effective and successful management strategy is usually to understand the way the river naturally behaves, and cooperate with it. Across the world it is becoming recognised that attempting to force a river into processes not natural to it at best leads to ongoing maintenance, and more usually leads to damage and expensive rehabilitation.

The Channel Country rivers have highly variable flow regimes, so large floods with accompanying changes to landforms will inevitably happen. There are some processes of landscape evolution that happen most readily during floods, such as bank-breach erosion or overbank sediment deposition. The bigger the flood, the bigger the effect it may have on landforms, such as the really big floods required to create waterholes. There are some landforms which are threshold-driven: they evolve by sudden changes as a result of some triggering event, e.g. a meander cutoff or a channel avulsion. Threshold-driven events involve considerable change over a short period of time (even over a single flow event), and this may appear to be a negative or detrimental outcome. Infrastructure or ecosystems may be buried by new sediment, or a new cut made into the valley floor. However, if it is part of the river's natural style, this is not a problem to be fixed, it is a river process to be worked around. Further, the new landform is likely to have elements that will develop into new productive systems: a new channel for fish, new banks for riparian vegetation. In this case, the most useful management action is to protect those areas that will develop into functioning landform systems, for example protect the new bank top vegetation so that riparian systems can develop that maintain both landforms and ecosystems.

GAB Leakage to Surface

Although it was not a focus of this project, one of this study's results is that the gibber uplands of Sturts Stony Desert may be have groundwater-dependent plant ecosystems linked to Great Artesian Basin leakage to surface (see section 3.2 Study Area: Geology and technical appendix section A2 Study Area: Polygonal Faulting in the GAB).

Soil Analysis

Mud aggregates only lose their cohesive shape after long inundation. Dried and on the floodplain, mud aggregates are difficult to tell from sand without a slaking test (see Technical Appendix section A1 Methodology). In measuring grain sizes (for example, for soil characterisation to examine plant germination conditions) it is important to be clear whether the testing result measures as-transported grain size or primary grain size, and equally important to be clear which is the desired metric.

7 Knowledge Gaps

Goyder Lagoon

Preliminary results of the present project indicate that Goyder Lagoon's fluvial processes are complex and unusual, however they are currently undocumented. There are indications that the fluvial landforms are tied to sediment and vegetation associations. An integrated field-based botany and geomorphology survey is recommended, especially for the difficult-to-access areas away from the Birdsville Inside Track.

Lignum

Part of the Goyder Lagoon work would be the role of lignum as a keystone species, including its possible positive feedback relationships with the degree of gilgai expression from vertic soils. If this relationship can be demonstrated, it will have important implications for grazing management and rehabilitation design across large parts of the Australian rangelands.

Floodplain-level discharge volumes

Although in non-flood flows the Diamantina Fan's main channel carries most of the water volume, during floods the river also carries substantial non-channel water. Eyre Creek and Goyder Lagoon are dominated by unconfined flow, and the Diamantina Fan carries floodplain-level flow down flow paths that are independent of the main channel. An important but currently unknown proportion of Andrewilla Waterhole's and Kallakoopah Creek's waters are derived from floodplain-level flow. At present, flow monitoring takes place at river channels. Understanding the relative volumes of channel vs. floodplain water will provide a more true picture of the system's water requirements.

Non-riparian coolibah

The vegetation-landform associations between coolibah and riparian zones are well-documented, and Costelloe (2017) proposes an association between coolibah's floating seed and strand-line germination. During this project, the distribution of coolibah in other places was noted but not examined. If coolibah are a keystone species (Gillen 2017) it would be valuable to understand the non-riparian coolibah occurrences. Looking at the landforms on which they occur will clarify their germination and growth histories.

Deep-time flood history

Understanding flood sizes and recurrence intervals is important for land-use planning and infrastructure design. It is also important for understanding the history of climate change in the centre of the continent, which will be a key to understanding future climates across Australia. Because the Diamantina has such a high-variability flow regime and we have such a short time span of written records, we are unlikely to have a good understanding of the Channel Country's deep-time flood record. Very large coolibah in unusual locations may mark strand-line germination points for extremely large floods (e.g. the Andrewilla Sand Plain trees, or the interdune 27 km north-northwest of Kalamunkinna Waterhole). Carbon dating to give the germination age of these trees may considerably extend the flood record for the Channel Country rivers. This will benefit design flood estimations and improve our understanding of Holocene climate fluctuations pre- and post-industrialisation.

GAB leakage to surface

If the Great Artesian Basin is supporting plant communities in Sturts Stony Desert, this will be significant to grazing management across the gibber plains, and also will be important for correct calculations of GAB discharge through upwards leakage.

8 Conclusions: Models and Themes

This project has been the first whole-of-catchment geomorphological examination of the Diamantina River within South Australia. The outcome has been baseline documentation of the area's landforms and fluvial processes.

Discussions amongst the interdisciplinary research team identified common themes of variability, gradients, connectivity, and coolibah. This section considers the themes as they are expressed in the study area's landforms and landscape processes.

Dynamics and Variability

The Channel Country rivers are amongst the world's most variable rivers, encompassing droughts to megafloods. They are 'unusual' – that is, unlike the northern-hemisphere temperate rivers upon which most of the general and non-drylands river paradigms are based. (For example, 'normal' rivers might be expected to have low flow variability, stable or slowly-evolving landforms, flow paths dominated by channels, and plant communities which are only moderately dependent on fluvial water for survival). The present project (and its precursors in the Neales River and the Cooper Creek (SA), Wakelin-King 2010, Wakelin-King 2013) describe the geomorphology of variable and dynamic systems.

In Channel Country rivers a substantial part of flood-level flow volume is unconfined floodplain flow. It can take a separate flow path to the main channel, and create a system of secondary disconnected channel segments and waterholes. This challenges our expectations of how rivers behave; our expectations create the details of 1) the regulatory environment (for example management codes or river condition assessments that focus on channels and banks), or 2) engineering standards (for example, road-crossing culverts that don't encompass channel + floodplain volume will be insufficient during floods, and will create self-propagating gully networks).

Because of droughts, water-loving vegetation needs to live near water-retaining landforms. During floods, this places vegetation within the locus of strong geomorphic activity, not only responding to landforms but engineering them.

The rapid rise and fall of flood peaks creates landforms that distribute water from the channel to the floodplain, and drain waning-flow water back into the channel. Bank breaching and erosion at distributary offtakes, and the development of distributary channels are a part of the fluvial process.

Very large to extreme floods have an important role in creating waterholes. Even moderate floods can create sudden change to landforms, especially if the landform is part of a threshold-driven system. Although catastrophic change will appear as destruction and loss to the landholder, it is landscape renewal. If the change was in an area unaffected by human activity – that is, if the change was a natural part of the fluvial process – then attempting to re-create a previous state is likely to be expensive and futile. Working with the new landform as it stabilises its channel and establishes is riparian zone is likely to be more productive. Since bioengineering by trees is a key process in bank stability, protecting vegetation on new landforms is likely to be important.

Gradients

The downvalley slope (elevation gradient) is a key factor in the fluvial style, steeper gradients promoting meandering in the Diamantina Fan, the extremely low gradients promoting unconfined flow in Goyder Lagoon, and the disorganised drainage in the inlet areas of Kati Thanda/Lake Eyre.

Reach-scale topographic gradients govern landform formation and therefore water distribution, flow connectivity, and plant ecosystem location and productivity. The most common of these are

- channel:interdune elevation differences control water sequestration into lakes;
- in distributary channels, channel:floodplain elevation differences and the elevation of the offtake sill determines at what flood height water is distributed to the floodplain, therefore determining inundation frequencies for floodplain ecosystems. Since offtake is a significant contributor to channel transmission loss, this is also an influence on downstream channel size;
- microtopography within the Goyder Lagoon influences plant communities.

The sand transport gradient is another important factor in fluvial style. The medium to fine sand transported through the Diamantina Fan is deposited in levees and other kinds of overbank alluvium. Alluvium deposited on the floodplain is one of the things that confines the Diamantina Fan's main channel, permitting it to develop its meandering fluvial style, and shaping its distributary channels. The sand transported down the Diamantina Fan is the reason for the progradation of the fan into Goyder Lagoon, and the reason for the multiple entry points of Diamantina River water into Goyder Lagoon. There is no sand transport through Goyder Lagoon. Medium fine to fine sand re-enters fluvial transport from the beginning of Warburton Creek, and the amount of sand in transport increases with distance downstream. This sand creates the Warburton and Kallakoopah Creek's rapidly changing and essentially non-vertic floodplain.

There is a decreasing vertical separation between the top of the unconfined aquifer and the ground surface over a space of ~300 km. The top of the water table decreases in elevation from the gibber uplands down to Kati Thanda/Lake Eyre. In the same space, the ground surface elevation decreases also, but not at the same rate. Near the gibber uplands, the water table and the ground surface are further apart, whilst to the north of Kati Thanda/Lake Eyre the groundwater is roughly at the same level as deflation pans and interdune surfaces. The distance between the two governs whether the water table supports vegetation by supply of moisture, or suppresses vegetation and promotes playa lake formation by near-surface salinity.

Connectivity

Fluvial landforms direct the hydrological connectivity that is important to aquatic ecosystems, because they control the direction and depth of flow. Reach-scale topography controls the flood heights at which different landscape elements become connected (therefore controlling opportunities for fish migration and seed distribution).

There is connectivity between plants growing on the surface and the unconfined aquifer which is largely hosted by the subcropping Pleistocene sediments. Plants in the main flow paths are most influenced by surface waters, but in less frequently inundated areas access to groundwater can be an important resource for terrestrial communities. Plant access to groundwater is strongly influenced by the pre-burial geomorphology of the Pleistocene proto-Georgina and proto-Diamantina Rivers.

During the past 3 million years the world's climate cooled, became more arid, and developed glacial/interglacial climate fluctuations. In the past Lake Eyre Basin was a wetter place, with a large central lake system fed by rivers from the west, from the Channel Country, and from central Australia, flowing across broad hillslopes and alluvial plains. Over time flow sizes decreased, and the alluvial plains became dunefield. Fish populations became disconnected between central Australia and the Channel Country. During wetter parts of the glacial cycle, there is likely to have been intermittent intervals of long-term connectivity between the western creeks (Neales and Macumba) and the Channel Country via marshlands in what is now the playa lake area north of Kati Thanda/Lake Eyre. The last such interval would have been ~125 ka and lasted ~10,000 years (very approximately).

Coolibah

Coolibah's water requirements make it a useful marker for water-retaining landforms, locations that experience regular flow, or are supported by the unconfined aquifer. (Other water-requiring plants are also useful, e.g. lignum, Queensland bluebush, nardoo.)

Coolibah and their attendant sub-story plants are important bioengineers of channel margins and channel extensions.

Coolibah can be carbon-dated. Knowing their growth rate permits a rule-of-thumb estimation of the age of the landforms they grow on. Dating specific trees on specific landforms has the potential to produce a long-term flood record for the Diamantina catchment, especially coolibah on the Andrewilla Sand Plain and in rarely-inundated parts of the dunefield margin. Such a flood record would be valuable in palaeoclimate reconstructions for the inland, and in calibrating the design criterion 'hundred year flood'.

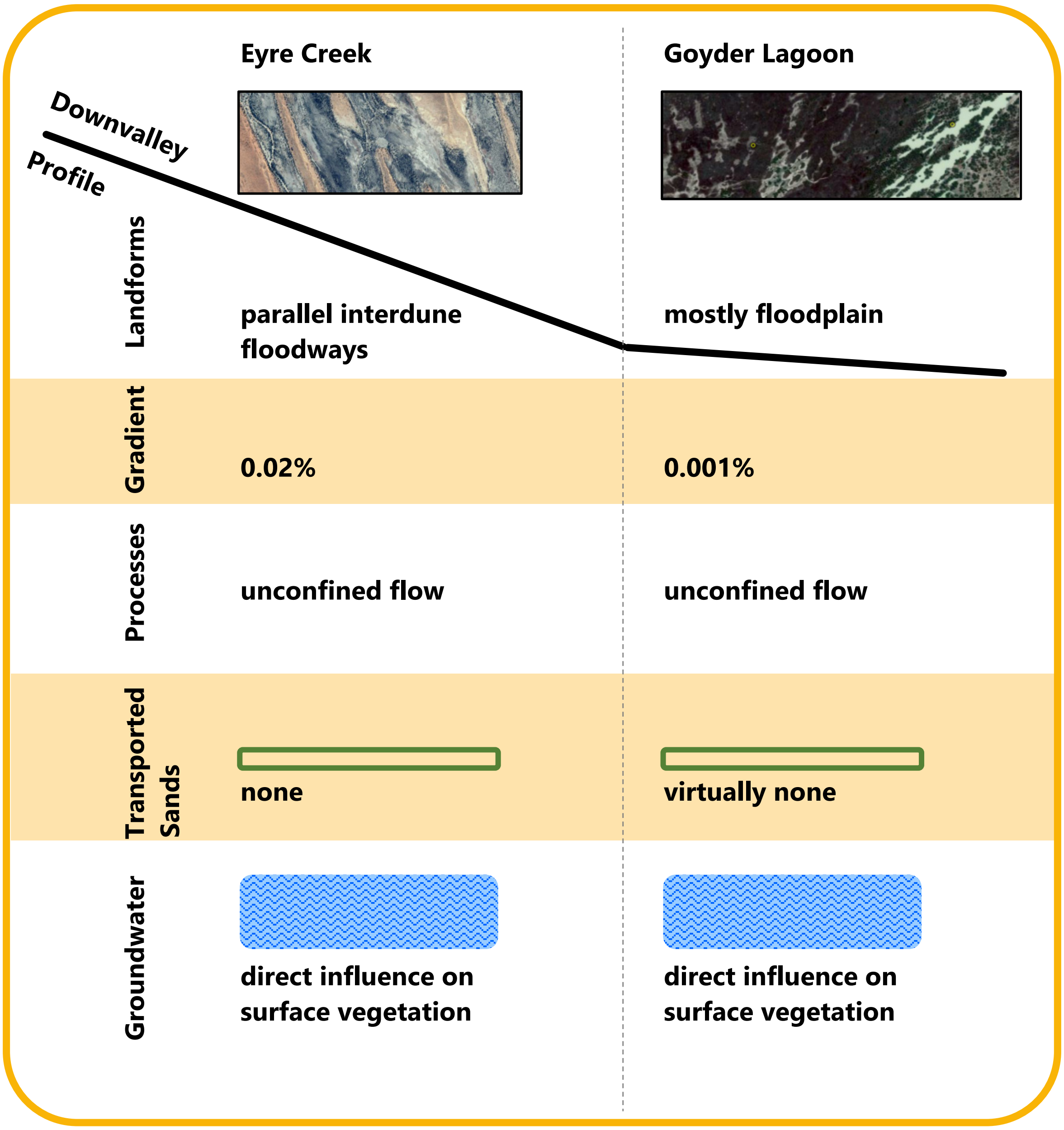
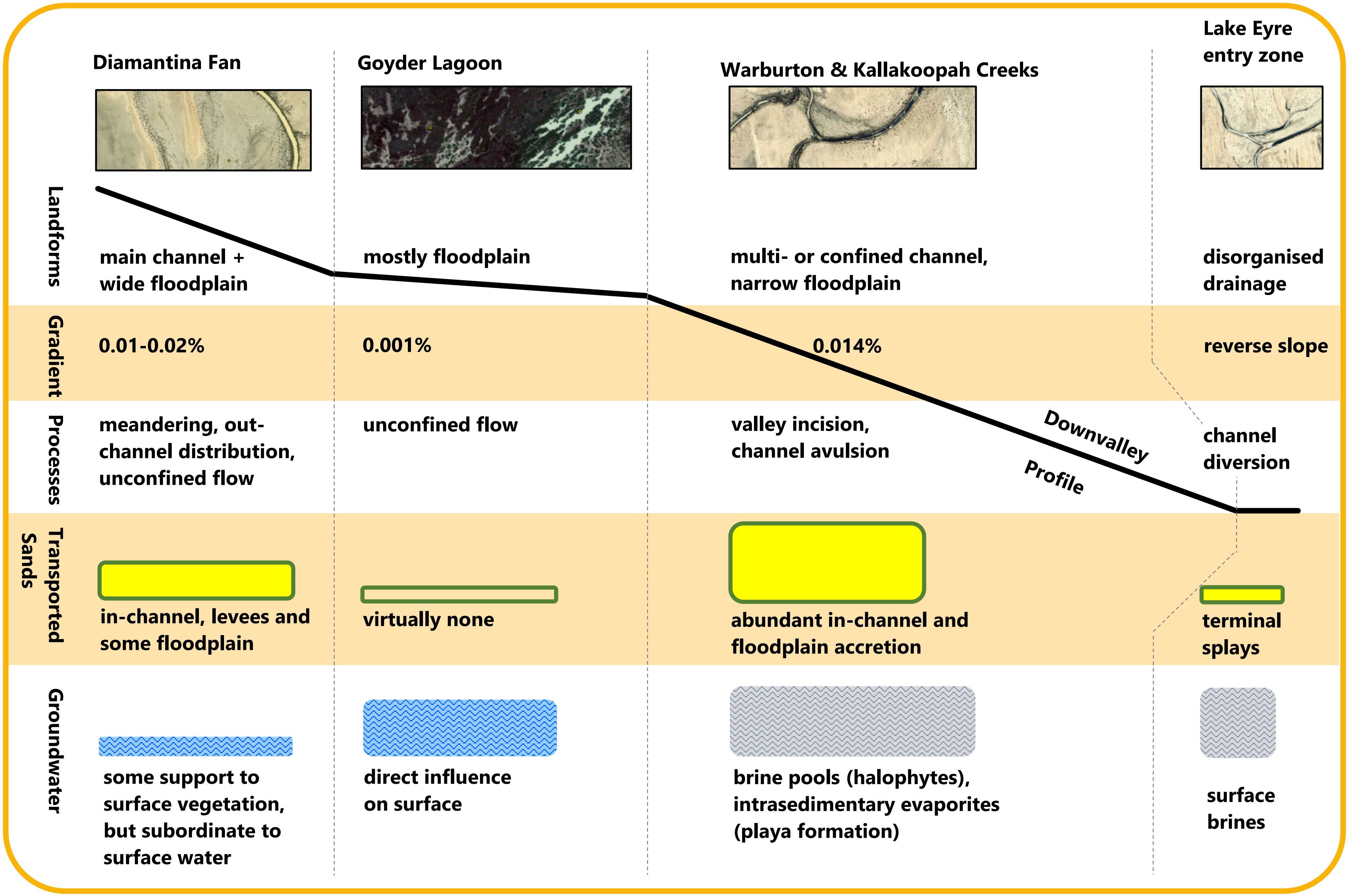


Fig. 50 Conceptual model: management zones, downvalley gradient, landforms and processes.

Fig. 50A (this page), Eyre Creek and its transition to Goyder Lagoon. Fig. 50B (next page) the Diamantina River's main flow path from the Diamantina Fan (upvalley) through to its entry into Lake Eyre North. In both diagrams, gradient and length of the downvalley profile is proportionate between management zones, however the gradient is extremely exaggerated for clarity.



Diamantina Fan
Goyder Lagoon
Warburton & Kallakoopah Creeks
Lake Eyre entry zone
Landforms
main channel + wide floodplain
mostly floodplain
multi- or confined channel, narrow floodplain
disorganised drainage
Gradient
0.01-0.02%
0.001%
0.014%
reverse slope
Processes
meandering, out-channel distribution, unconfined flow
unconfined flow
valley incision, channel avulsion
channel diversion
Downvalley Profile
Transported Sands
in-channel, levees and some floodplain
virtually none
abundant in-channel and floodplain accretion
terminal splays
Groundwater
some support to surface vegetation, but subordinate to surface water
direct influence on surface
brine pools (halophytes), intrasedimentary evaporites (playa formation)
surface brines

The Conceptual Model

The productivity, viability, and composition of the boom-and-bust ecosystems in the study area depends on the interaction between hydrology (the amount and timing of water that enters the system) and geomorphology (the structures that hold or distribute water and make it available or unavailable to biota) (Fig. 50). In the Diamantina River management zone, the hydrology delivers approximately annual floods (Costelloe 2017) and the landforms of the Diamantina Fan distribute flow down the main channel, and across the wide floodplains. In the Eyre Creek management zone, flows extend the length of the creek approximately every 5 years (Costelloe 2017) and the landforms spread low-energy flow across multiple parallel paths. In the Goyder Lagoon management zone, inundation every one to two years (Costelloe 2017) (varies for different parts of the Lagoon) is spread by the landforms spread across a wide area with variable conditions of local turbulence. In the Warburton and Kallakoopah Creeks management zone, flows every one to two years (Costelloe 2017) drive valley incision, floodplain aggradation, and frequent channel relocations. In the dunefields, the hydrology relies on local rainfall, and the landforms either absorb the rainfall, or shed it as local runoff. The gibber plains receive local rainfall and shed it as runoff, benefiting downslope communities.

Technical Appendix

The technical appendix contains background material relevant to the report, and expanded details that may be relevant to a technical audience.

9 Technical Appendix: Methodology

The methodology of using sediment and landform attributes to discern habitat- and reach-scale fluvial processes is a standard procedure in sedimentology. Picard and High (1973) is an example where detailed observations of sediment attributes and their spatial/temporal relationships are used to understand flow conditions. Knighton and Nanson (2000) demonstrate the use of broad-scale spatial relationships to deduce flow conditions that cannot be observed directly: the distribution of dunes and various types of channel in a wide floodplain reveals the role of locally high-energy flow in the formation and maintenance of waterholes. Integrated studies, using Geographic Information Systems software to manipulate multiple datasets, is now a standard procedure in geology and geography, and has produced better understandings of landscape process and history (e.g. Lawrie et al. 2016). Digital elevation models (DEM) are a valuable tool: manipulation of colour ranges assigned to elevations can produce informative landform maps (e.g. Hayakawa et al. 2010) which can be integrated with information from other imagery and geo-referenced field observations.

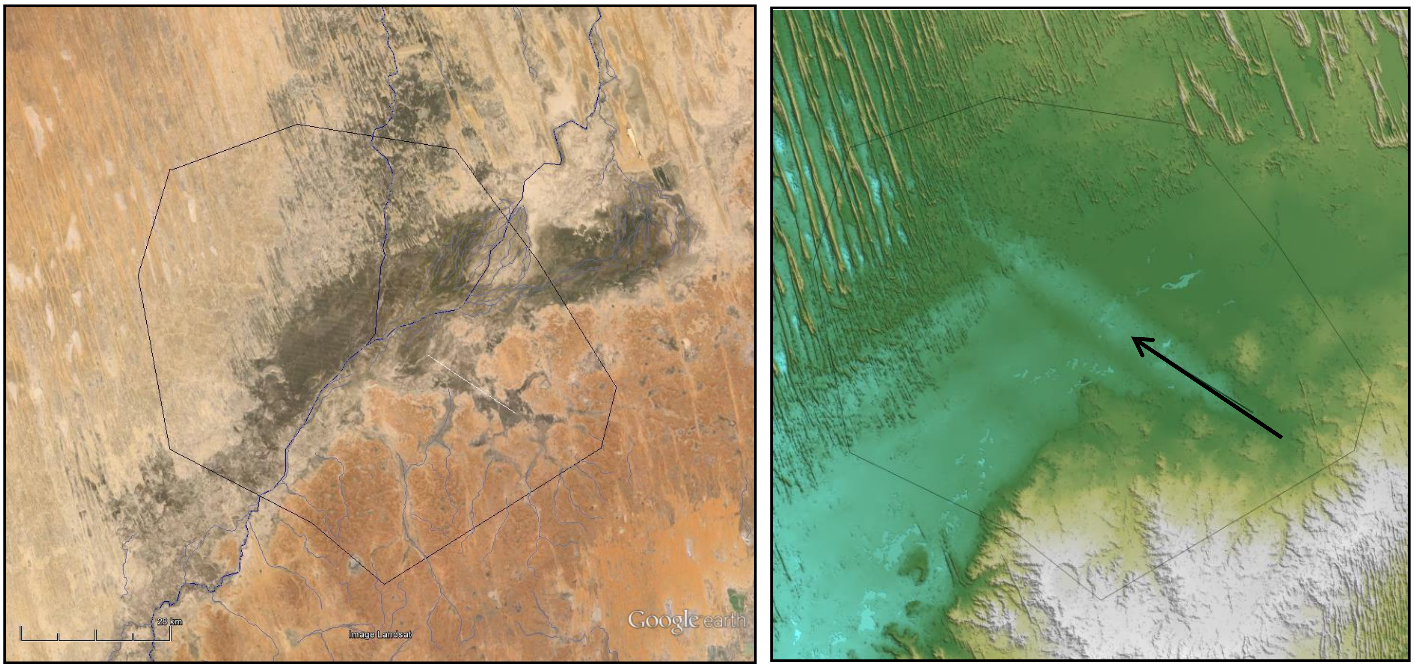


Fig. 51 Anomaly in the SRTM elevation data of Goyder Lagoon.

Left, Google Earth image; black outline surrounds the area with the most pronounced error (although the effect is likely to extend across the entire lagoon). Field of view is ~150 km in the east-west direction; north to top. Right, DEM, with the same black outline. The anomaly's strongest expression (arrow) is in the trough (pale green) outlined by ridges (dark green).

The remote sources of information in this study were true-colour satellite imagery (Google Earth), Commonwealth government aerial photographs (1969, film #1152; 1977, film #2122-2123), the Geoscience Australia ASTER dataset, the USGS 3-second SRTM data digital elevation grid, the Geoscience Australia smoothed 1-second SRTM digital elevation grid. Note that the Geoscience Australia hydrologically forced digital elevation grid was not used, because the conditions imposed by the hydrological forcing are sometimes incorrect for these kinds of rivers (see Wakelin-King 2013, section 5.1.1: Caveats on Using the 1-2nd SRTM Digital Elevation Grid in the LEB). The 1-second SRTM is generally very good for valley- and reach-scale features, although its resolution and vertical accuracy is insufficient for individual landforms. Unfortunately the SRTM data has a substantial anomaly across Goyder Lagoon, in the form of a series of undulations imposed on the real data. The undulations are ~1-5 m amplitude, ~10 km wavelength, with crests oriented west-northwest. The largest undulation is upslope from Goyder Lagoon Waterhole (Fig. 51), but it is likely that the DEM is suspect for the whole Goyder Lagoon.

MODIS (Moderate Resolution Imaging Spectroradiometer) was used to determine the pathways of individual flood events, and WOfS(WOfS) was used to determine the 1987-present occurrence of water on the ground. When the WOfS observation is of the flow path, a bright colour can indicate frequent flows, but when the observation is of some water-retaining landform (swamp, waterhole, flat ground) bright colour can indicate long-term surface water even if flows are infrequent. In the latter case it is possible to use the WOfS as a proxy for approximate elevation data. In Goyder Lagoon the WOfS was used in this way.

Because of the scope of this project and its baseline nature, the geomorphology investigation focused on collecting qualitative data rather than metrics. Landform sizes and downvalley gradients are visual estimates, or based on remotely-sourced data. Sediment grain sizes were estimated visually and sediment types named according to standard geological practice. The proportion of mud aggregates in floodplain sediments was estimated using a slaking test (e.g. Fig. 52, an example from the Thomson River, Queensland). Because of the robust nature of mud aggregates, different grain size analysis techniques will give quite different results, according to whether the measurement captures aggregate size or primary particle size (e.g. Wakelin-King and Webb 2007).

Fig. 52 Wetted vertic soils slake to aggregates.

Two clods of Thompson River mud aggregate sediment on a white rock. The left one has been wetted with fresh water, and has collapsed into its constituent sand-sized aggregates. Wet aggregates can be mashed into mud by fingertip pressure. A few sand- and grit-sized lithic clasts are also present. Using standard sedimentological nomenclature, this is a slightly coarse-sandy mud. Hammer tip for scale.

ASTER Satellite Imagery

The Geoscience Australia ASTER Maps is a series of geo-referenced satellite images in which various band combinations highlight certain mineral groups. In this project, the most useful maps were the regolith, ferric oxide content, AlOH (clays), silica, and opaques (Fig. 53). In combination with Google Earth true-colour imagery, the ASTER dataset was used to define the characteristics of the Pleistocene subcrop, identify where the unconfined aquifer (largely hosted in the Pleistocene sediments) was expressed at the surface, and investigate the possibility of Great Artesian Basin leakage to surface.

A limitation of the ASTER Maps set is that ASTER data is strongly influenced by striping and fire scars. This means that the colour values shown on the images are not absolute over the study area; features are not consistently represented over great distances. The best use of the ASTER Maps is by comparing different maps over a local area, rather than trying to use a single map over a wide area.

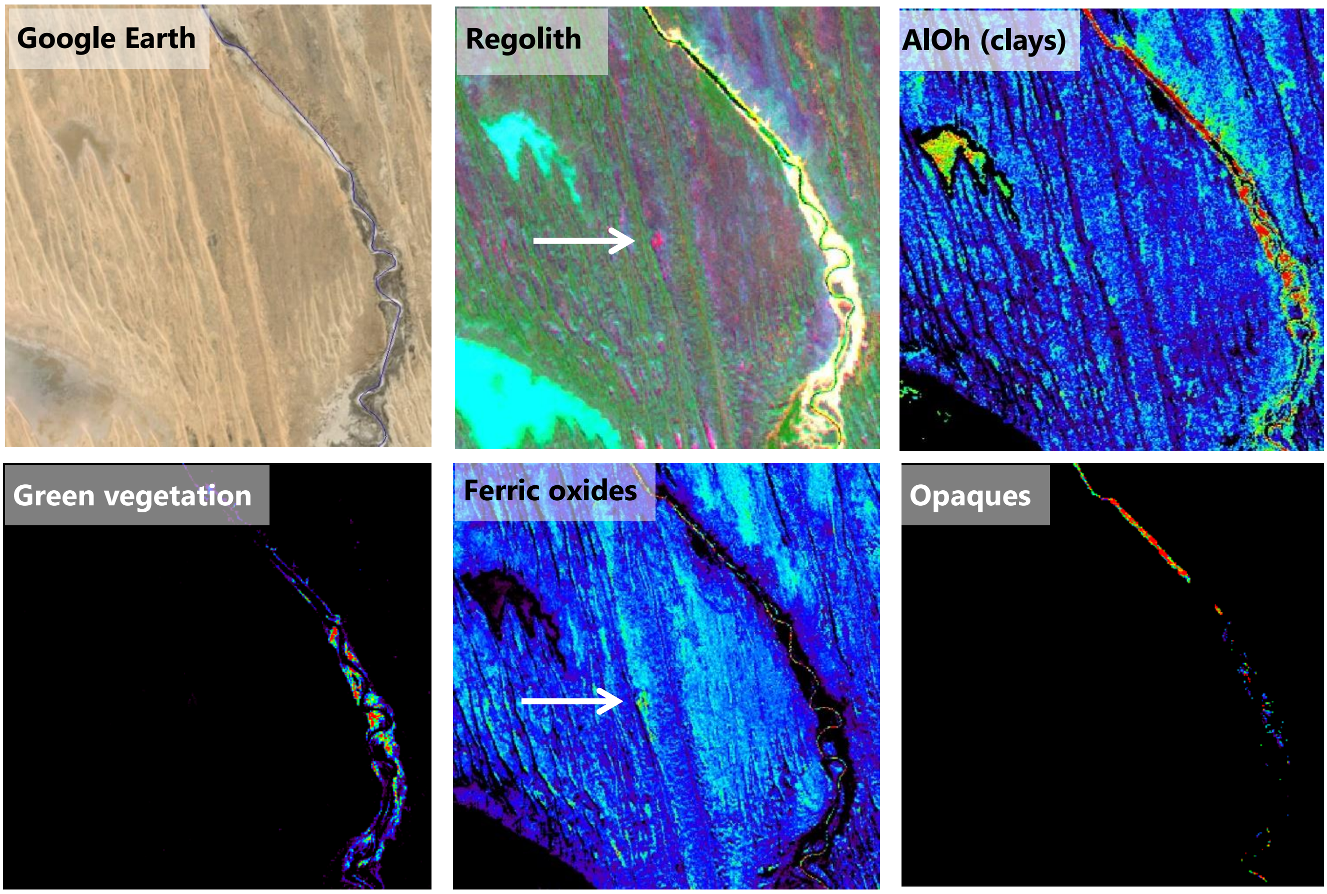


Fig. 53 Iron content in Kallakoopah Creek water and groundwater is visible on satellite imagery.

The main channel carries iron-rich water, showing in the ferric oxides and opaques maps. The channel has no signal in the green vegetation bands, and the creek's riparian vegetation has no signal in the ferric oxide bands, so the response of the ferric oxides and opaques bands is not a vegetation effect. Fe in groundwater shows up in the ferric oxide map of the dunefields also – as generalised bright blue surface in some interdunes, and as yellow/red in some interdune groundwater windows (arrow). Vegetation associated with the shallow groundwater is magenta / hot pink in the Regolith bands. Kallakoopah Ck, near Lake Pirriepatchillie, east-west field of view ~11 km.

10 Technical Appendix: Study Area

In non-geological circles (e.g. land or catchment management), the word ‘basin’ can be used to mean a topographic basin, such as the Lake Eyre Basin (LEB). In geology, 'basin' is used to mean an accumulation of sedimentary rock, for example the Great Artesian Basin (GAB). Many of the references cited in this study use the phrase Lake Eyre Basin to refer to the sedimentary basin accumulating rocks during the Palaeogene and Neogene. The Lake Eyre geological Basin is not the same as the Lake Eyre topographic Basin, although the two entities lie one above the other.

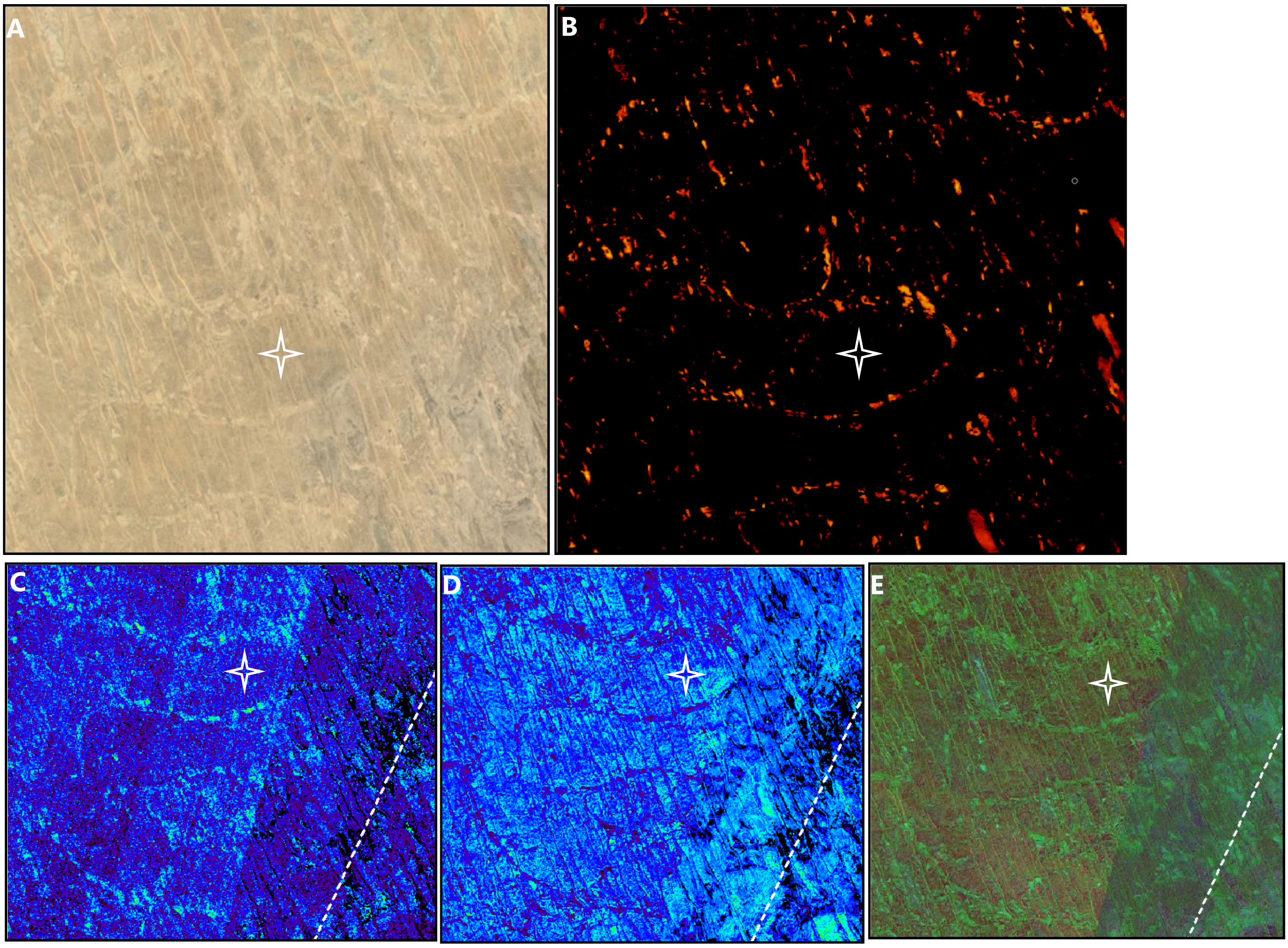


Fig. 54 The surface expression of the subcropping Pleistocene sands in the marginal dunefield.

A, Google Earth image shows poorly-vegetated (pale) large curved elements amongst thinly-vegetated (dark grey tone over orange) interdunes. B, Water Information from Space, the large curved elements stay wetter for longer. C, the ASTER AlOH bands show the large curved elements are richer in clay. D, the large curved elements are lower in ferric oxide content, indicating low permeability to groundwater. E, the ASTER regolith band shows the characteristic palaeoriver geometry in maroon and pale green, reflecting vegetated and wet elements respectively. All images show the same site, a dunefield not connected to the flow path, 35 km N of Yelpawaralinna Waterhole. The white star is the same location in each image; parallel dune crests trend north-north-east; image extends ~15 km in the east-west direction.

Pleistocene Sediments and the Unconfined Aquifer

The Pleistocene sands referred to in this report are the Katipiri Formation and its correlatives, and other Pleistocene or partly Pleistocene units (e.g. the Millyera or Eurinilla Formations, or the Plio-Pleistocene Tirari Formation). While most of the sediment is permeable quartz sand from the channel belt of a large meandering river, there are also mud and clay deposits from lake-edge depositional settings.

The most common expression of the Pleistocene sediment is as large open curves, sometimes tens of kilometres long and hundreds of meters wide, and narrower semi-parallel bands. In many places the semi-parallel bands are within the large open curves and similar to them in orientation and scale. Remotely sensed characteristics (Fig. 54) indicate that the large curved elements are mostly mud, and the smaller elements have greater access to aquifer water. This study proposes that the large open curves are abandoned channels, and the smaller elements are scroll plains, in a palaeo-topography that was blanketed by modern floodplain muds. The abandoned channels have a greater depth of floodplain mud, which is relatively impermeable to the underlying aquifer. The scroll plains are buried less deeply, and have a preserved ridge and swale topography (Fig. 38). In Cooper Creek (Queensland) this kind of relationship between Pleistocene Katipiri Formation's depositional topography and the overlying floodplain mud was revealed by a detailed study of augering and sediment age-dating (Maroulis et al. 2007).

Polygonal Fault Structures in the GAB

Where Great Artesian Basin water is sufficiently pressured, it is able to flow to surface wherever the overlying aquitards are breached. This can happen naturally, such as the faults and other structures that allow the mound springs to develop, and by human action, as when an uncontrolled bore is drilled down into the aquifer and the water flows to surface and into a bore drain. It is proposed in this report that parts of Sturt's Stony Desert (especially east and south-east of Koonchera Waterhole)

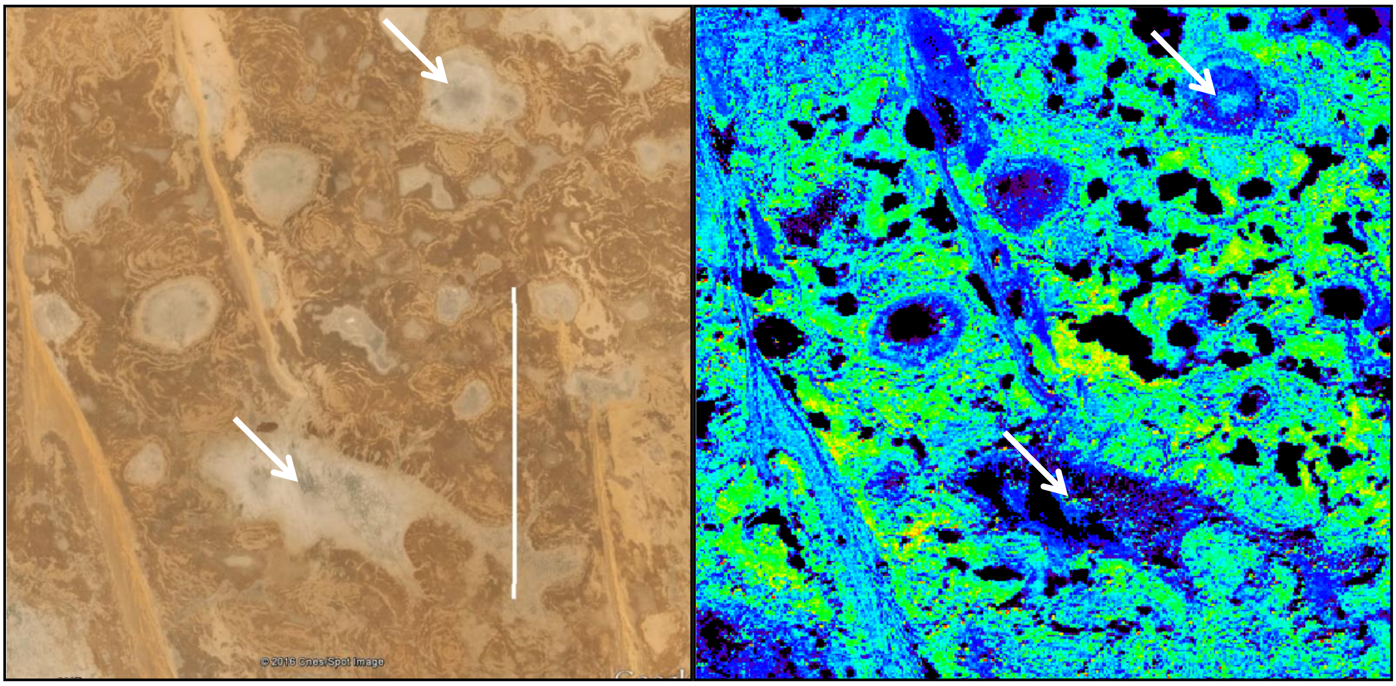


Fig. 55 Slight discharge of ferric -containing water (arrows) in the gibber plain east of Koonchera Waterhole.

Left, Google Earth image; right, ASTER ferric iron content; white scale bar = 5 km; location 25 km east south-east from Koonchera waterhole.

are experiencing diffuse GAB leakage to surface, supporting local plant ecosystems in circular breaks in the silcrete cover (Fig. 55) and in drainage lines incised into the gibber surface. In addition, Ransley and Smerdon (2012) suggest that the upvalley components of Warburton Creek are also supported by GAB leakage. That is, this report suggests GAB leakage in the area of silicified Eyre Formation outcrop, and other work indicates GAB leakage in the areas of Winton Formation outcrop (see Fig. 5). Reports from landholders during the Neales River and present study indicate that the gibber plains are surprisingly productive – "what do they eat? The stock just lick the sunshine off the rocks" – and it is important to discern if the gibber plains are also groundwater -dependent ecosystems which contribute to local economies.

Polygonal Fault Structures (PFS) are fracture systems within a rock in which the faults are oriented such that the fault planes multiply intersect one another. In plan view, the PFS looks like irregular, roughly circular or polygonal structures. PFS develop during deposition and early diagenesis, especially along pre-existing fault zones, and propagate upwards into overlying units (Radke pers. comm. 2016).

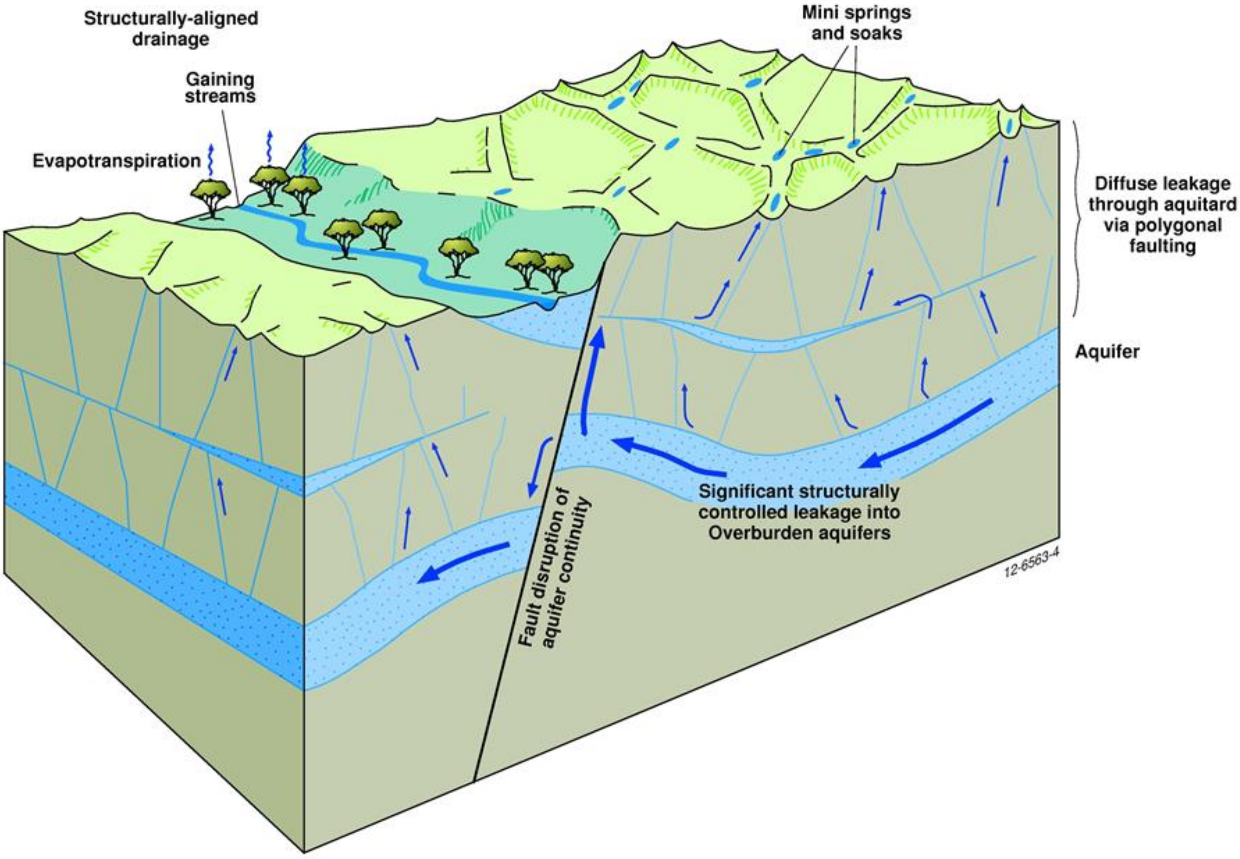


Fig. 56 GAB upward leakage mechanisms (from Ransley and Smerdon 2012).

PFS are widespread throughout the Rolling Downs Group of the Eromanga Basin (which includes the Winton Formation), and it has been suggested that upward leakage along PFS to Cainozoic sediments and/or to surface explains certain groundwater characteristics, and supports riparian trees in some areas (Fig. 56) (Ransley and Smerdon 2012, Ransley et al. 2015). Regional geological studies indicate that structures similar in appearance and scale to PFS are evident in silcretes and other Cainozoic weathering profiles (for example near Tibooburra), and Radke (pers. comm. 2016) suggests that they have been active as conduits for leakage for over 125 Ma. His proposed mechanism for upwards fault propagation and/or fluid leakage includes fault plane dilation during uplift and doming.

The places where the Winton Formation's weathering profile has been thinned by erosion are broadly associated with many of the mapped PFS in Winton Formation outcrop, and with some of the proposed groundwater-supported riparian trees (Ransley et al. 2015, their maps 16-18). Although they have not mapped definite occurrence of PFS penetrating Cainozoic units (Ransley et al. 2015), Ransley and Smerdon (2012) indicate the Eyre Formation has hydraulic connectivity with Winton Formation aquifers in places. In the study area's geological evolution, long-term domal uplift during periods of erosion and deposition have thinned the Winton Formation and the Eyre Formation (independently) by several tens of metres (Alley et al. 2011). It is proposed here that:

- previous geological research and mapping indicates that the north-east section of Sturt's Stony Desert has silicified Eyre Formation cropping out at the surface, but that it is likely to overlie a truncated section of Winton Formation;
- that there is likely to be hydraulic connectivity between Winton Formation and Eyre Formation via PFS;
- that the present study has observed unexpected levels of biological productivity in circular windows in the gibber and in some creek lines incised in the gibber;
- that the evidence best supports terrestrial ecosystems supported by GAB upwards leakage, especially in light of the groundwater mound observed by Ransley and Smerdon (2012).

Within the scope of the present study, it was not possible to assess this proposition, especially as the high-runoff qualities of the gibber would naturally feed local rainfall into nearby lower-elevation areas. However it was noted that some productive areas were fed by very small local catchments, making it unlikely that local rainfall could be the only ecosystem support. It is recommended in this report that further studies be undertaken.

11 Technical Appendix: Geomorphology

The Diamantina Fan

In this report the Diamantina Fan is divided into 3 subsections:

- the northern flow paths (the main channel from Birdsville to Diamantina-split Waterhole, Eleanor Creek and Gumborie Creek),
- the distributary branches (from Diamantina-split Waterhole into Goyder Lagoon, the Andrewilla branch and the Yammakira branch; and including the Andrewilla Sand Plain between the branches),
- the downvalley edges (from approximately where the drainage network becomes densely bifurcated, and overbank sedimentation becomes minor).

In terms of the fan's geomorphology, these subsections correspond to:

- proximal fan (river processes are dominant over basinal processes; the main channel's constraint by flanking alluvial sediments isolates it somewhat from the basinal condition of unconfined flow);
- mid-fan (river processes become modified by basinal processes; the main channel's process dominance is decreased by (probably) transmission loss, and it begins to respond to unconfined valley context and low gradient by becoming distributary;
- the distal fan, where the landforms and processes transition from alluvial to dry swamp.

The Diamantina Fan is in some ways similar to the Cooper Creek Fan, which was first described by Callen and Bradford (1992). Both have developed where Channel Country rivers leave the gibber uplands and descend into the plain, and both are a mixture of alluvial and aeolian landforms. The Diamantina Fan has a more strongly elongate pattern of sediment deposition (c.f. the Cooper Creek Fan's generally radial structure), suggesting a greater degree of influence by the longitudinal dune fields. Both have similar downvalley slopes, and this is reflected in similarities in their fluvial styles of sinuous and sometimes actively meandering main channels and numerous bank-breach distributary channels. The meandering indicates that the fans are moderately high-energy (relative to the overall low energy of these low-gradient systems).

It is interesting that the Eyre Creek downvalley slope (0.02%) is equal to or greater than the Diamantina Fan's downvalley slopes (0.01-0.02%), yet Eyre Creek's channelled reaches are more often straight than meandering planforms. Eyre Creek's flow is extremely low-energy, being dissipated across multiple interdune pathways, whereas the Diamantina River's main flow is contained between and focused by its high banks. Thus, Eyre Creek is either unchannelled or has the straight channel of rivers whose sediment and fluid loads are ~equal to its available energy, whereas the Diamantina River adopts the meandering strategy which acts to lower stream power by decreasing effective gradient.

Distributary Channels or Crevasse Splays?

The suite of landforms referred to in this report as a bank-breach offtake and its distributary channel is similar to an assemblage referred to in the geological literature as a crevasse splay. The geological terminology is not used here because it is not appropriate to the present discussions of ecology and land management, and because its usage usually refers to specific landforms and sediments which are not represented here. Specifically, the gap through which water leaves the channel in the study area is not a crevasse, it is a gully or a fluvial structure; and in most cases the landform downflow of the gap is not a splay, it's a channel.

12 Technical Appendix: Specific Flow Events

This section describes specific flow events examined in this study. Each has contributed information towards understanding the study area's fluvial processes.

12.1 Mid-1970s Floods

This section describes in more detail the changes in the examined reached between 1969, 1977, and today. The 1977 photos were evidently after a large flow, as they show widespread standing water. The 1969 airphotos film #1152 photos 0046, 0150, displayed the areas from the Queensland border down to the beginning of the Eleanor Creek flow path at 8 Mile Waterhole (north part of Diamantina Fan), and from the Lake Uloowaranie entrance down to the old Yammakira Homestead (south part of Diamantina Fan).

Diamantina Fan (North)

The northern reaches show incremental channel migration as either increased meander sinuosity or translated meander curves downvalley. Over the last ~50 years, the change has been ~10-30 m bank displacement in the most active parts of each meander (though the flanks of the meanders have generally not moved at all during this period). In one location chute neck cut-off has taken place. The cut-off was initiated prior to 1969 (as high-flow flood runners across the meander neck), connectivity was established during mid 1970s flooding (as a narrow channel across the meander neck), and the new planform established post-1977. This location, ~4 km east north-east from Dickeree Waterhole, is evidently a particularly active area as the landforms indicate 3 previous cut-offs. However, this is not unusual: at least 4 other reaches have evidence of past cut-offs or indications of a future cut-off. The proximal fan also has some areas where floodplain scours appear to have been deepened into more substantial channel segments, although it is difficult to be definitive about this.

There are no indications of post-1969 change to the landforms of the proximal fan floodplain. This includes Dickeree waterhole, and the minor channels and scour zones that constitute the beginning of the Eleanor Creek flow path.

Fig. 57 Negligible change at Diamantina-Split Waterhole between 1969 and 2006.

Arrows indicate bank retreat with developing sinuosity, and a new offtake and distributary channel. Left, 1969 aerial photograph; right, Google Earth image; black scale bar = 1 km.

Diamantina Fan (South)

In the southern reaches, although the channel planform is sinuous, meandering does not seem to be as active as it is in the north. The only place showing appreciable rapid channel migration is the Diamantina-split Waterhole reach. Since 1969 a short reach of the channel has increased its sinuosity by ~50 m and translated the maximum curve of the meander downvalley by ~70 m (Fig. 57). This is the most channel movement of any of the places examined on the Diamantina Fan.

At the Andrewilla Waterhole intake area, valley-margin scour around the dune nose transformed a minor flood runner into a wider new channel (Fig. 47). The scour has cut back the base of the dune, triggering or expanding steep gully networks into the Pleistocene sediments underlying the dune. The scour has also removed a wedge of floodplain, including what may have been the old homestead.

Diamantina Fan (Distributary Branches), and Goyder Lagoon

The Andrewilla Sand Plain experienced no post-1969 changes: the rarely inundated high-flow path (Fig. 18) has the same scours and small waterholes in 1969 as it does in 2006. There were no changes to the Yammakira terminal distributaries, and (as far as could be determined) no changes to those parts of Goyder Lagoon's dense lignum swamps that were available for examination.

In the Andrewilla Waterhole terminal distributaries, the only change is a slight widening and bank development in the most left-bank of the distal distributaries (Fig. 58).

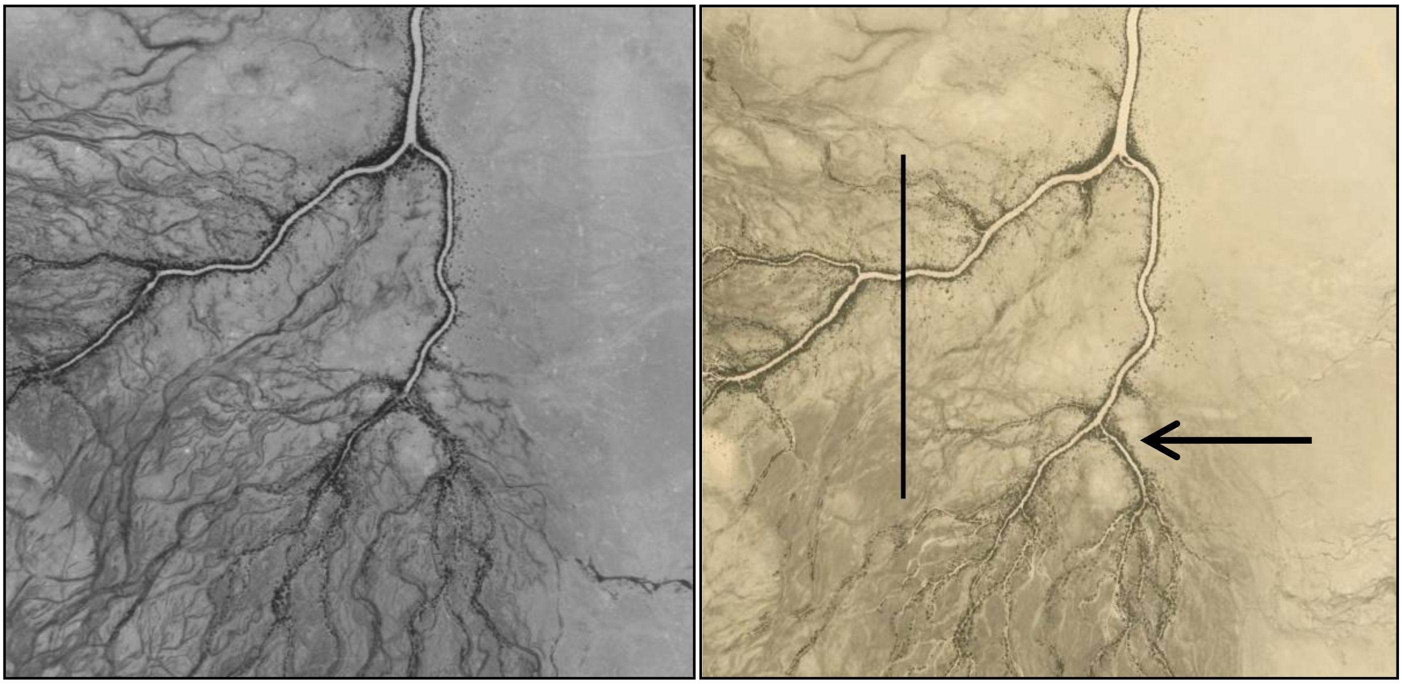


Fig. 58 Negligible change at the distal Diamantina Fan between 1969 and 2006.

Slight development of an existing distributary channel (arrow). Left, 1969 aerial photograph; right, Google Earth image; black scale bar = 2 km.

Koonchera Waterhole

in 1969, old Koonchera Waterhole consisted of the main waterhole ~1 km long, curved around the nose of a longitudinal dune, with a bifurcating extension channel extending through the waterhole's downvalley sediment splay. There was also a smaller channel on the inside of the curve. In 1977, the smaller channel had been widened (and probably deepened), and a new waterhole was created by floodwaters eroding the eastern side of the longitudinal dune then cutting through it (Fig. 59).

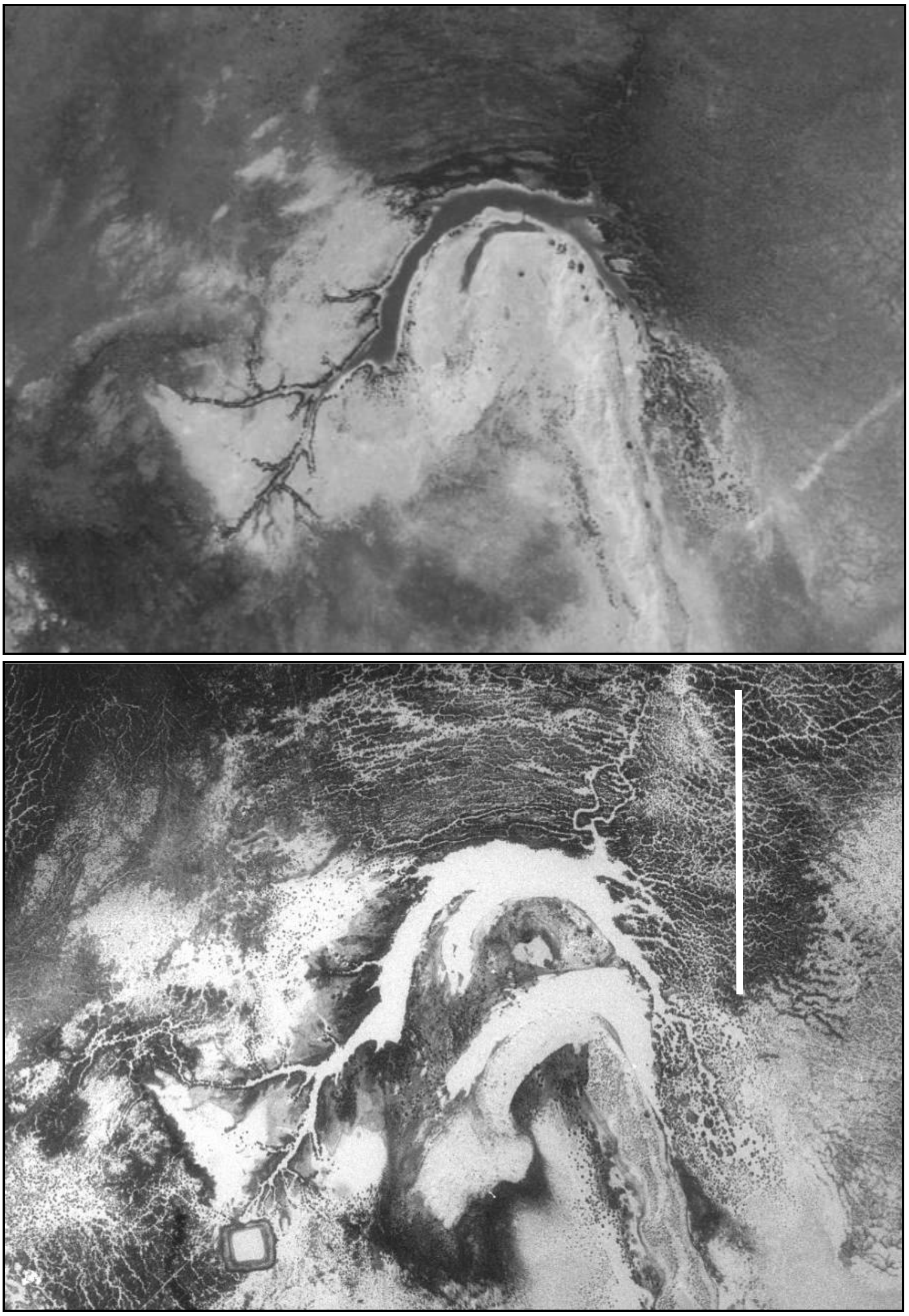


Fig. 59 The new Koonchera Waterhole, created during mid-1970s flooding.

Aerial photography, top: 1969, bottom: 1977; white scale bar = 750 m.

Burt Waterhole (Old and New)

There are two Burt Waterholes: the historic old waterhole, and the present-day road waterhole.

The old waterhole is located between two dunes. In 1969 it was a single ~300 m long channel with a simple double row of trees along the banks. It did not occupy the full width of the interdune. During the mid-1970s floods the historic waterhole extended to ~500 m long, and a second wider waterhole was scoured next to it, filling the interdune space (Fig. 60). In the present day, the old waterhole is wide but shallow, and compound. Its banks are as for a normal waterhole: clearly defined by slope and vegetation distribution, with bank top riparian trees.

The new waterhole, a site in the 2015 field season, did not exist in 1969 (Fig. 60). At that location, several tracks of the Birdsville Inside Track curved around the nose of the dune, converging with other tracks from the east. At some time in the 1970s the main track had begun to be maintained by a grader. During the mid-1970s flooding, a deep scour was created around the nose of the dune, along the track. Since that time, the scour has developed further into the present waterhole, although it is shallow and lacks definite banks. Other scours have developed along other track alignments.

Fig. 60 Evolution of the two Burt Waterholes.

Top left: 1969. Old Burt Waterhole is west of the dune (D): sparse riparian vegetation flanking a single channel segment. Five trees (arrow) exist in all photos. The Birdsville Inside Track curves around the dune nose near the trees.

Top right: 1977. Floodwaters occupy old Burt Waterhole, now a compound structure with a new, wider and deeper waterhole scoured alongside the previously existing waterhole. A shallow scour has also formed between the five trees and the dune nose.

Bottom: Google Earth image. The old Burt Waterhole is west of the dune, the new waterhole is between the dune nose and the five trees. The present-day Birdsville Inside Track is to the east of the trees.

12.2 Diamantina and Georgina Rivers, 2009

The development of a large flow event was examined using MODIS satellite imagery. Over the time for which MODIS is available, the 2010-2012 wet years produced the largest flows (approximately 1-in-20 or-40 year events, see section A6 Citations). The Australian Bureau of Meteorology rainfall records were examined to find the largest widespread rain event in that approximate timeframe. In 5-8 and 13-25 January 2009, the upper catchments of the Georgina and the Diamantina Rivers received >90 percentile rains (respectively: Boulia, 188.2 mm; Brighton Downs, 284.8 mm), and during 7-8 January heavy local rain also fell at the upland edge areas of both rivers (Glengyle Station on the Georgina River received 144 mm, and Birdsville on the Diamantina River received 50.6 mm). Because of differences in the fluvial and catchment geomorphology, the two rivers responded to the rain events with different numbers of flood peaks, and a different speed at which the flood peaks travelled.

On 11 January 2009, after the local rain event at the uplands edge, the Diamantina River valley was inundated by runoff from the gibber hillslopes in the Birdsville area. The flow which was generated was concentrated within the continuous channel of the Diamantina Fan, and thus reached Goyder Lagoon. On the other hand, the surrounding dunefields at Glengyle Station generated only just enough runoff to accumulate water at the edge of the Georgina River valley (Fig. 61), despite receiving twice the rainfall.

On 11 January the upper catchment had responded to the widespread rain event by generating flows in both rivers. The flood fronts progressed at approximately the same rate down the river valleys , but by 23 January the Georgina River flood front paused to backfill the Mulligan River before proceeding to Eyre Creek, whereas the Diamantina River flood front had passed Birdsville and merged with the existing in-channel water from the first locally-generated first pulse. By 27 January (Fig. 62), the

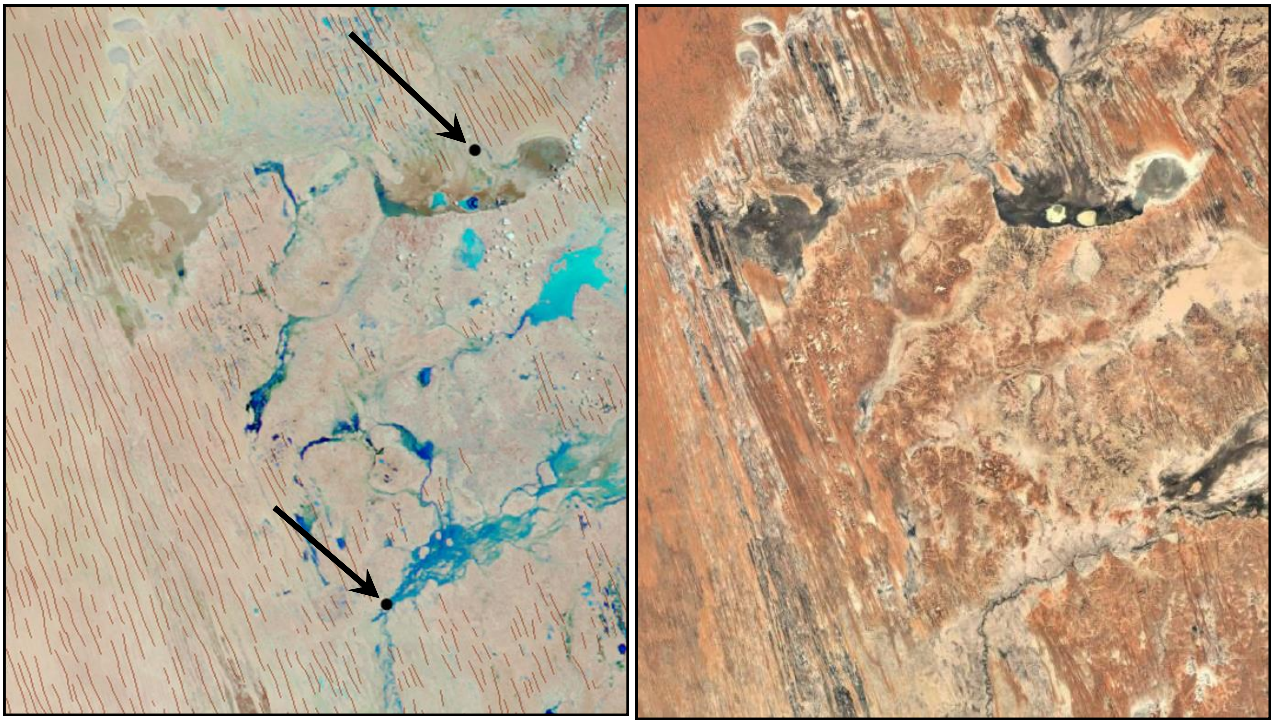


Fig. 61 High-runoff gibber slopes route rainfall into downslope drainage lines, but sand dunes are low-runoff slopes.

Left, MODIS image 11 January 2009, blue colours = surface water, top arrow points to Glengyle Station (Georgina River), bottom arrow points to Birdsville (Diamantina River). Right, Google Earth image of the same area, image width is ~185 km.

Diamantina River flood front was filling the eastern section of Goyder Lagoon (discharging a lot of water from the Yammakira branch distributaries and less water from the Andrewilla branch distributaries). In contrast, the Georgina River flood front was only just moving through the gateway waterholes to enter the upstream reaches of Eyre Creek.

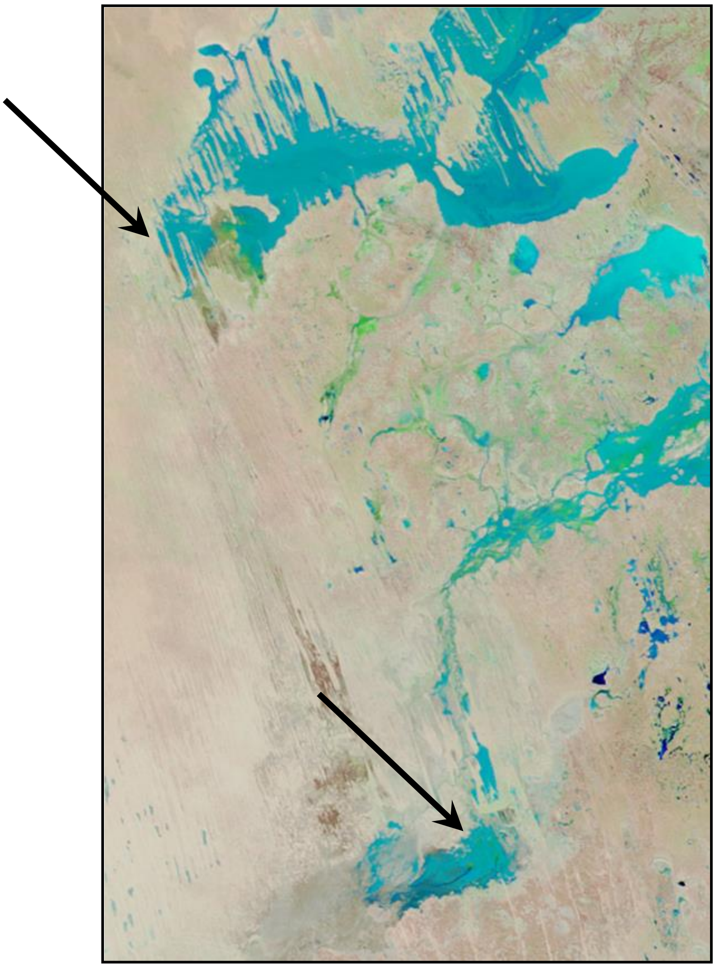


Fig. 62 Different flood fronts from the same rain event.

The Georgina River's flood front is only just entering Eyre Creek (top arrow), while the Diamantina River's flood front has already inundated the eastern part of Goyder Lagoon (bottom arrow). MODIS image, 27 January 2009, field of view ~185 km wide.

The timing of activation of the Diamantina River's Yammakira and Andrewilla distributary branches indicates that the Yammakira branch receives most contributions from main-channel water of the primary flow path, whereas the Andrewilla branch receives most contributions from floodplain-level flow along the Eleanor Creek secondary flow path. On 17 January 2009, flood levels in the Diamantina River main channel was sufficiently high that the distributary channel feeding Lake Uloowaranie (Fig. 10) was activated. The Andrewilla branch was receiving some water (probably from right-bank distributary channels such as the one at Diamantina-split Waterhole), as shown by the fringe of water around its terminal distributaries (Fig. 63). However, the Yammakira distributary was discharging much more water into Goyder Lagoon at that date. This distribution of water delivery into Goyder Lagoon continued until Eleanor Creek's floodplain-level flow path was inundated all the way down to the Andrewilla Waterhole intake channels (February 11 2009). At that point, the Andrewilla branch distributaries started delivering greater quantities of water into Goyder Lagoon (Fig. 63).

By 11 February 2009, the floodplain-level flow paths of Gumborie Creek and Eleanor Creek were activated. Flow in Eleanor Creek entered the Goyder Lagoon via Andrewilla Waterhole. Eyre Creek's diffuse interdune flow path was filling from north to south, with the flood front pausing as the flow filled unconfined lignum swamps along the way. Flow in Gumborie Creek terminated 18 February with a small discharge into a claypan. By 18 February, Eyre Creek was full and impounded behind dune sets along its southern edge; water was entering Goyder Lagoon via the gateway waterholes Tepamimi and Tepaminkanie. The eastern and central sections of Goyder Lagoon were inundated by flow from the Yammakira and Andrewilla branch distributaries, but the north western section of Goyder Lagoon had not yet received water from Eyre Creek. By February 26, the boundary between Eyre Creek and Goyder Lagoon was fully inundated, and Georgina River water was filling the north-western parts of Goyder Lagoon. Diamantina River water extended as far down as Kirrianthana Waterhole, beginning to fill both Warburton and Kallakoopah Creeks. By March 14, 2009, Goyder Lagoon was at its maximum inundation. Water (dominantly Georgina River water) was extracted from the main downvalley flow path, into the lower-elevation interdunes at the fringes of the Simpson Desert dunefield

A landholder reports two different-coloured bodies of water travelling side-by-side down the lagoon during a big flood. During the 2009 flow, Goyder Lagoon exhibited partitioning of its bodies of water. While Goyder Lagoon was being inundated from the east, the Andrewilla and Yammakira branch flows are separated by a zone of mixing, and at higher flood levels the Eyre Creek water was separated from the Diamantina River water by a mixed zone which was predominantly water from the Andrewilla branch, but which also contained at least some Eyre Creek water (Fig. 64).

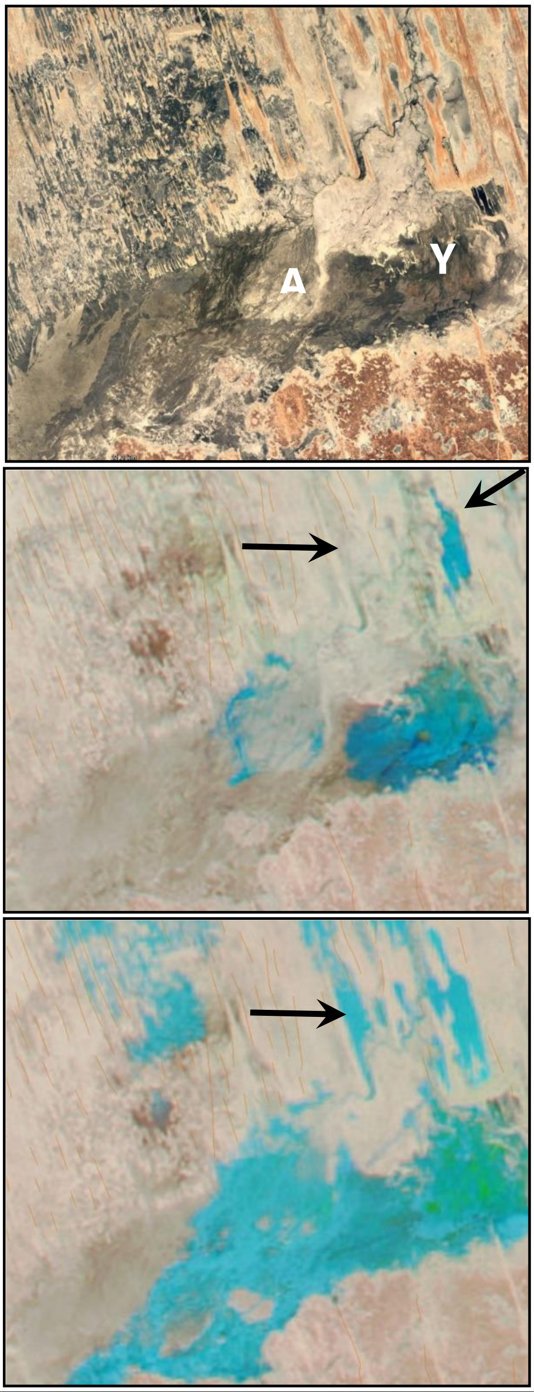


Fig. 63 Channel vs. floodplain flow into Goyder Lagoon 17 Jan.–11 Feb. 2009.

Top, Google Earth image, field of view ~85 km wide. A = the Andrewilla branch terminal distributaries, Y = the Andrewilla branch terminal distributaries.

Middle, MODIS image, 17 January; blue colour indicates surface water. In the Yammakira branch, in-channel flow has filled Lake Uloowaranie (top arrow) and has begun to inundate the eastern part of Goyder Lagoon. In the Andrewilla branch, there is no floodplain level flow along the Eleanor Creek flow path (bottom arrow), and only a little flow is entering the central part of Goyder Lagoon.

Bottom, MODIS image, 11 February 2009. The Eleanor Creek floodplain is fully inundated (arrow), and more flow is leaving the Andrewilla branch terminal distributaries.

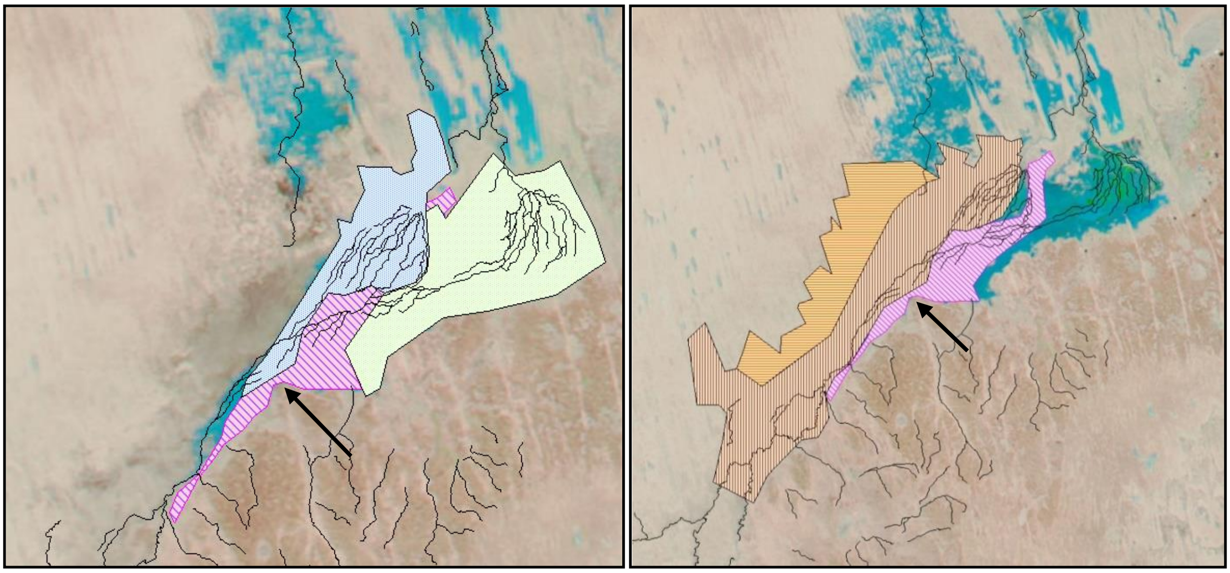


Fig. 64 Bands of water in Goyder Lagoon at moderate and high flood levels.

Left, Partial inundation in Goyder Lagoon: Andrewilla branch water (blue), Yammakira branch water (green), mixed waters (pink). Right, the fully-inundated lagoon carries unmixed Eyre Creek water (orange) in the north-west, unmixed Diamantina water (pink) in the south-east to beyond Goyder Lagoon Waterhole (arrow), and mixed Eyre/Diamantina water in the centre (brown). Both images based on MODIS January 2009; field of view ~170 km east to west.

12.3 Burt and Pelican Reaches, 2009

The Burt and Pelican groups of waterholes are formed by floodplain-level flow interacting with sets of small compound dunes at the northern margin of Goyder Lagoon. Flood routing is complex, as a result of multiple flow paths in a very low-relief landscape (Fig. 65). The events described below are based on flows January to February 2009.

During rising flow, waters leaving the terminal Andrewilla distributary (see Fig. 20) enter Burt Waterhole from the south . During peak flow of large floods, waters leaving Andrewilla Waterhole from its right-bank distributaries enters Burt Waterholes (old and new) from the north; peak flow from the north is the most influential in landform development. Burt Waterhole is predominantly filled by Diamantina River water. It is only likely to achieve connectivity with Georgina River water if high flood levels in the Burt Waterhole area coincide with the Georgina flood peak reaching the northern boundary of the Goyder Lagoon.

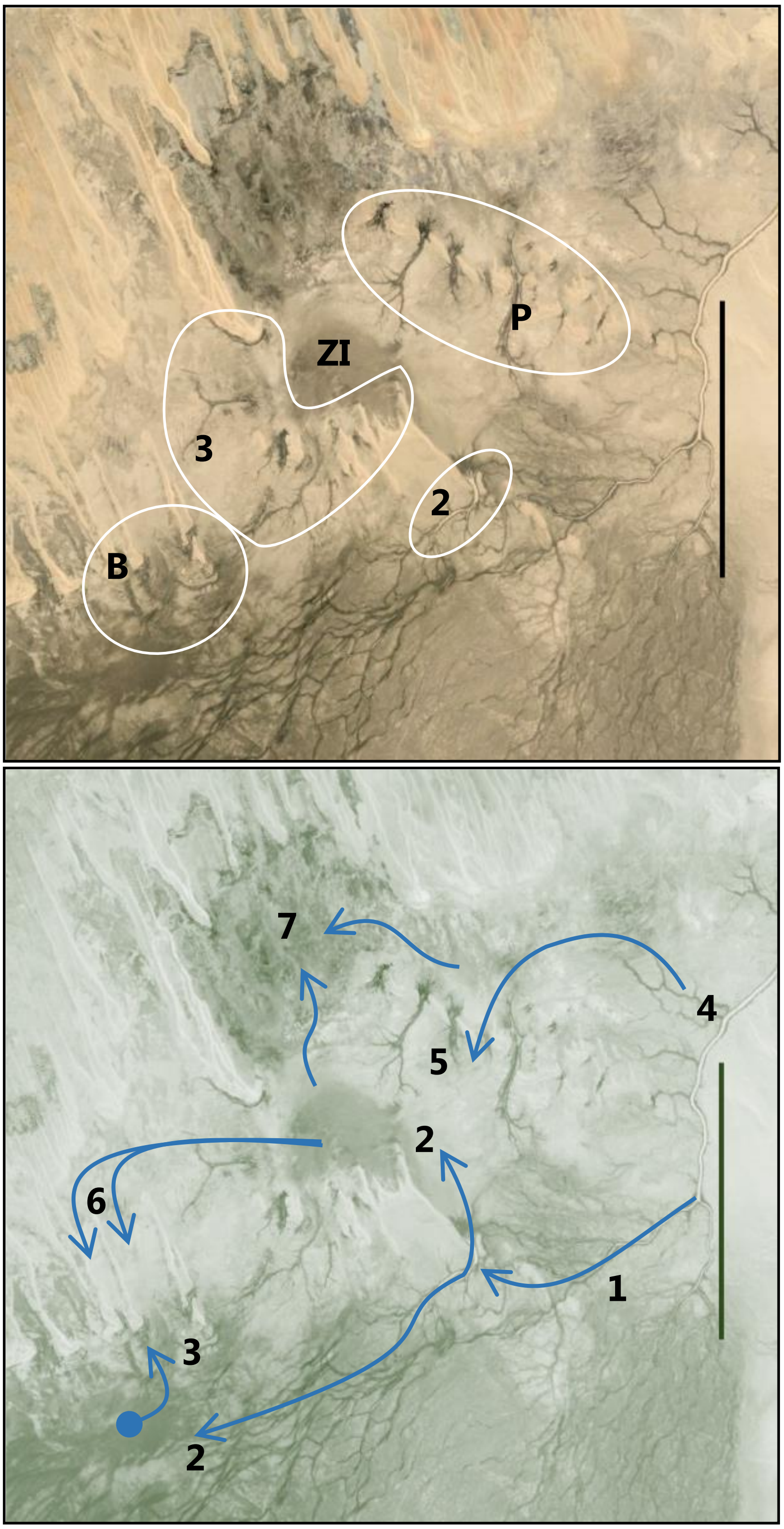


Fig. 65 Flood routing in the Burt/Pelican Waterhole reaches.

Top: Groups of waterholes located along the northern section of Goyder Lagoon. Floodplain flow from Andrewilla distributaries is locally confined by small compound dunes, forming scour zones and waterholes. P, Pelican Waterhole area; B, Burt Waterhole area; ZI, a zone of inundation. Black scale bar = 5 km.

Bottom: Flow routing with rising Diamantina flood levels. Initial flow (1) comes down from Andrewilla Waterhole's terminal right-bank distributary (see Fig. 20). It fills a waterhole which distributes water at two outlets simultaneously (2). One of these outlets fills a floodplain sink which then transfers water into both old and new Burt Waterholes from the south (3). Approaching flood peak, flood height overtops the rest of the Andrewilla right-bank distributaries (4), water accumulates in low-elevation floodplains, eventually moving through Pelican and other waterholes (5) to add to the water already accumulating in the zone of inundation. Water then moves into the Burt waterholes area from the north (6). As the flood reaches its peak, water moves into a swamp (7). At this point there is a chance of connectivity with the Georgina, but only if the Georgina flood peak reaches this point at the same time.

13 Technical Appendix: Glossary

Also see Section 3.4, Landform Elements

'100-year' flood – Rivers carry small flows more often and bigger flows less often. As a general rule of thumb, the bigger the flood, the less often it is likely to occur. In the popular media, this is sometimes expressed in terms of the recurrence interval, for example a '100-year' flood. In fact this is misleading: weather events are not regularly spaced, and it is quite possible to get clusters of wet years and flood events. The preferred metric is annual exceedance probability (AEP), e.g. in any one year there is a 1% chance of a flood that size or bigger. The significance of the 1% AEP flood (or the old '100-year' flood) is that this is usually the design criterion for flood risk management in e.g. bridge design or town planning. The key issue for the Lake Eyre Basin is that we do not have enough years of records to accurately understand the 1% AEP, especially in the Channel Country which has some of the world's most variable flow regimes.

Alluvial ridge – a compound landform in which vertical aggradation of a channel's levees, banks and bed leads to a ridge of alluvial sediments. In this circumstance, the channel will not be in the lowest-elevation part of the valley, the stream bed may be higher than the surrounding floodplain, and the channel will be prone to avulsion.

Anabranching – a type of river behaviour in which the river's discharge is split between multiple channels, rather than being gathered into a single channel. Anabranches occur where the river seeks to increase its stream power (to cope with e.g. increased amount of sediment under fluvial transport) by developing more narrow and deep channels.

Annual Exceedance Probability (AEP) – see '100-year' flood.

Aquifer – sediments or rocks which carry water. An aquifer can be confined (capped by impervious rocks which prevent upwards water movement, such as the aquifers of the Great Artesian Basin) or unconfined (such as the aquifer in the study area). An unconfined aquifer has a deeper saturated layer (the phreatic zone), the top of which is the water table. Above this is the vadose zone, an unsaturated zone in which sediment pore spaces can contain water wicked up from the phreatic zone.

Avulsion – channel relocation, usually in a rapid or catastrophic fashion.

Cease-to-flow – the water level above which flow occurs in a channel, and below which flow stops. Cease-to-flow level is often related to the elevation of landforms that mediate water distribution: sills in distributary channel offtakes, or the floodplain elevation of terminal bifurcating distributaries.

Deflation, deflated – where the ground surface has been lowered by wind erosion. This is a natural process in e.g. interdune corridors and playa lakes.

DEM – digital elevation model.

Design flood – see '100-year' flood.

Gilgai – the landforms created by soils with strong shrink-swell behaviour; includes heave (a topography of swells and depressions), crabholes / macropores (cracks or holes that are deep and wide), self-mulching (developing a crumbly loose surface), and heavy cracking or multiply cracked (the mud cracks and cracks again in a way that is more intense than normal muds).

ka – thousand years before present.

Kati Thanda/Lake Eyre – the playa lake system that is the depocentre of the Lake Eyre Basin, comprising Lake Eyre North and Lake Eyre South. All the river catchments in the LEB drain towards Kati Thanda/Lake Eyre.

High alluvium – see levee.

LEB – Lake Eyre Basin.

Left-bank, right-bank – orientation with respect to the river flow direction; if facing downstream, the left-bank side is at your left hand.

Levee, riparian ridge, high alluvium – A levee is a ridge or other bank-high landform made of alluvial sediments deposited alongside a river channel. It forms as sediment under transport moves from channel to banks. Levees form by advection (sediment settles out as in-channel water overtops un-inundated banks) or where channel and floodplain are equally inundated by turbulent diffusion (deposition occurs as a result of free shear eddies created along the boundary between bodies of water moving at different velocities). Advected levees tend to be broad and gently sloped, levees from turbulence tend to be narrow with steep slopes (Adams et al. 2004). In the study area, some channel-flanking landforms are clearly levees, some levees form a narrow riparian ridges, and some channel-marginal broad areas of bank-high alluvium may or may not be levees.

Ma – million years before present.

Meandering – a type of river behaviour in which channel sinuosity is developed by erosion on one bank and deposition on the opposite bank (cut bank and point bar respectively, Fig. 44). The scale of the meanders is an indication of the size of the river which formed them: the meanders in the present day Diamantina River are much smaller than those from the river that deposited the Pleistocene sands.

Mud – as a technical sedimentological term, refers to a mixture of clay and silt.

'Normal' flow conditions – for the purposes of this report, flow with a recurrence interval of at least 20-40 years; flows captured by the Water Observations from Space imagery.

Palaeosol – an ancient soil horizon. In the context of this study, landscape evolution of alternating dune-building and dune-stable episodes means that most of the sand dunes have palaeosol layers within them. The palaeosols are more clay-rich (Fitzsimmons et al. 2007b) and less permeable than the rest of the dune sands, and they may present a barrier to water movement (as they do in Cooper Creek: Maroulis et al. 2007, Cendón et al. 2010).

Reach – a section of river. The size of a "reach" depends on the size of the river. It is smaller than the whole valley and bigger than the bit of bank you're standing on. A reach is big enough to encompass the suite of landforms characteristic of that part of the river.

Recurrence interval – see '100-year' flood.

Regolith – rocks that have been affected by weathering; sediments that have not yet been lithified; "everything between fresh rock and fresh air".

Right-bank – see left-bank.

Riparian Ridge – see levee.

Scroll plain – the ridge-and-swale landform created by accumulated point bars, see 'meandering'.

Subcrop, outcrop – a geological unit that is exposed at surface is an outcrop, if it is present beneath the ground surface it is subcrop.

Unconfined aquifer – see Aquifer.

Unconfined flow – surface water that is not flowing within a channel.

Vadose zone – see Aquifer.

Vertisol, vertic muds – cracking-clay soils displaying strong shrink-swell behaviour upon drying or wetting. They are associated with gilgai features: macropores (large cracks, crabholes: centimetres-wide voids extending metres into the soil profile), self-mulching behaviour presenting a loose crumbly surface, and gilgai heave (ground surface microtopography ~1-50 cm vertically across 1-20 m horizontally). The degree of expression of gilgai features depends on frequency of inundation (Fagan and Nanson 2004).

Water table – see Aquifer.

WOfS – Water Observations from Space: historical surface water observations derived from Landsat satellite imagery for all of Australia from 1987 to present day.

14 Technical Appendix: Citations

In this section, citations are given for such information referred to in the main body of the report which does not arise from the present research project.

There is little pre-existing research into the geomorphology and sedimentology of the Diamantina River. Silcock (2009) undertook a regional study on Channel Country waterholes, during which she amassed a large body of information on waterhole form and behaviour. A dissertation on the Diamantina River channels (Brunner 2013) exists but as of this study date there have not been peer-reviewed publications arising from it. The Diamantina River's mud aggregate sedimentology is briefly described in Wakelin-King and Amos (2016). Other previous research into the Diamantina River (section 3 Introduction) is dominated by hydrological (e.g. Costelloe et al 2003, Bullard et al. 2007), ecological, and historical/cultural studies.

Most of the existing knowledge on Channel Country fluvial geomorphology and sedimentology is derived from Cooper Creek, a system which is similar but not identical to the Diamantina. The University of Wollongong's Nanson research group and its academic successors has pursued intensive research (inter alia: Nanson et al. 1988, Knighton and Nanson 1994a and 1994b, Maroulis and Nanson 1996, Nanson and Knighton 1996, Gibling et al. 1998, Nanson and Huang 1999, Knighton and Nanson 2000, Tooth and Nanson 2000, Knighton and Nanson 2001, Fagan and Nanson 2004, Nanson et al. 2008, Cendón et al. 2010). The work presented for the first time the role of mud aggregates in active fluvial transport and the dual nature of Channel Country channel structures, recognised the importance of the LEB's footprint across different climate zones, uncovered the relationship between present-day floodplain muds and the underlying Katipiri Formation, described anabranching channel systems and the reason why they exist. Their most recent review paper is Habeck-Fardy and Nanson 2014.

Information on the present-day climate is derived from records available on the Australian Bureau of Meteorology website (Bureau of Meteorology, accessed 2016), and Knighton and Nanson 1994a, Knighton and Nanson 2001, Habeck-Fardy and Nanson 2014. Rainfall and fluvial variability in the drylands is discussed in Finlayson and McMahon 1988 and Tooth 2000, and the role of ENSO and IPO in the drought/flood cycle of inland Australia is mapped in McKeon et al 2004 and regularly updated on the website The Long Paddock (accessed January 2017). Estimation of the mid-1970s flow events as being ~1% AEP ('1 –in-100') and the 2010-2012 flow events as being approximately 20-40 years flow events is based on The Long Paddock and discussions pers. comm. Justin Costelloe 2016 (and see Costelloe 2017). The summary of the Lake Eyre Basin's history of climate change is based on Benbow et al. 1998, Callen and Benbow 1998, De Vogel et al. 2004, Cohen et al. 2011, Cohen et al. 2012.

The geology of north-eastern South Australia has been documented by the South Australian Geological Survey, and the sedimentary basins underlying the Lake Eyre Basin have been researched because of their hydrocarbon and groundwater prospectivity. Stratigraphy, lithology and mapping of or relevant to the study area's geology is discussed in Wells and Callen 1986, Alley 1998, Benbow et al. 1998, Callen and Benbow 1998, Callen et al. 1998, Habermehl no date, Kirkby et al 2009, Cendón et al. 2010, Cohen et al. 2010, Alley et al. 2011, Habeck-Fardy and Nanson 2014. Regolith and structural geology relevant to the study area is discussed in Simon-Coincon et al. 1996, Moussavi-Harami and Alexander 1998, Anand 2005, Quigley et al. 2006, Thiry et al. 2006, Sandiford 2007, Sandiford et al. 2009, Quigley et al. 2010, Ransley and Smerdon 2012, Ransley et al. 2015, Schellart and Spakman 2015. As well is the above, landscape evolution is discussed in Pell et al. 2000, Fujioka et al. 2005, Fitzsimmons 2007, Fitzsimmons et al. 2007a, Fitzsimmons et al. 2007b, Fujioka et al. 2009, Craddock et al. 2010, Hesse 2010, Jansen et al. 2013, Fitzsimmons et al. 2013.

The composition and properties of sand dunes are described in Fitzsimmons et al. 2009, levee formation is analysed in Abbado et al. (2009), and desert soils in Dunkerley (2011). Aspects of fluvial processes are considered in Picard and High (1973), Amos et al. (2008), Tooth and Nanson (2009). Vegetation-landform feedback loops are considered in Wakelin-King 1999, and with respect to gilgai in Wakelin-King 2009.

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