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South Australian Arid Lands Natural Resources Management Board

Geomorphological assessment and analysis of the Cooper Creek Catchment, South Australia

Gresley A. Wakelin-King

GEOMORPHOLOGICAL ASSESSMENT AND ANALYSIS OF THE COOPER CREEK CATCHMENT (SA SECTION)

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October 2013

Report to the South Australian Arid Lands Natural Resources Management Board

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Cover images:

L) Panadinnie Waterhole forming around the nose of a longitudinal sand dune, amongst the swamps and anastomosing channels of the Cooper Creek Main Branch. Image prepared by Gresley Wakelin-King, Wakelin Associates, using part of the Strzelecki Rural 2001 orthophoto; red scale bar = 3 km. Orthophoto custodian: South Australian Department of Environment, Water and National Resources, Adelaide.

R) Cooper Creek's North West Branch is a complex of discontinuous distributary channels, set amongst dunefields, alluvial flats, lakes and swamps. Image prepared by Gresley Wakelin-King, Wakelin Associates, using part of the Strzelecki Rural 2001 orthophoto. Orthophoto custodian: South Australian Department of Environment, Water and National Resources, Adelaide.

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EXECUTIVE SUMMARY

This report summarises the current state of knowledge of the geomorphology of Cooper Creek in the Strzelecki Plain. This information is relevant to management because in an arid zone resource-limited system, the processes which control the distribution of water and nutrients underpin all ecosystems. Cooper Creek's key behaviour, upon which the ecosystems depend, is big floods that travel slowly.

Cooper Creek supports arid-zone wetlands because of its length: its upper catchment (in Queensland) receives monsoonal rainfall, which is transferred into the Strzelecki Desert by flooding. Its flow pattern is naturally extremely variable. The ecosystems and landforms are developed to work with alternating droughts and floods, and floods are required to preserve the waterholes and water the wetlands. The management goal must be to **preserve the natural variability of the flow** pattern. This precludes water-affecting activities in the upper (including Queensland) catchment: water extraction, attenuation of flood peaks, or continuous release of artificial waters.

Cooper Creek has a complex landform assemblage, including channels (simple, compound, ephemeral, and permanent), waterholes, floodplains, swamps, lakes, claypans, and palaeodrainages. The present-day drainage network, and the palaeodrainages which preceded it, have process relationships with equally complex dunefield assemblages. The Strzelecki Plain has many lakes and dry palaeolakes formed by combined fluvial, aeolian, and lacustrine processes.

The complex geomorphology contains landform elements that mediate (retard and retain) flows that pass through it. This permits rich and diverse ecologies to flourish. These elements include **sills, swamps, and small sinuous channels** in dense networks. It is critical that the **primary flow paths** should not be occluded (i.e. obstructed so flows may continue to water downstream ecosystems), while the landform elements that mediate flow routing should be preserved from erosion (so flows may continue to water the ecosystems through which they pass). To this end:

- planning for infrastructure placement should include process-based informed identification of diffuse or subtle flow paths;
- infrastructure should be designed to avoid, or minimise occlusion of, the important flow paths;
- where raised infrastructure must be installed across through-flow paths, culverts and bridges should be installed;
- culvert and bridge design and placement should be improved to ensure that all flow pathways and flood heights are catered for, and that flow concentration does not occur;

- existing installations should be reassessed in the light of the 2010-2012 flow events.

Riparian vegetation is an important part of the landform processes that maintain channel integrity and waterhole depth. Its density and diversity should be preserved.

Complex local mechanisms influence groundwater recharge from surface waters. Any required groundwater monitoring should be site-specific and start with a base-level study.

The well-watered and complex landforms provide pathways for **cane toad invasion**. Establishment of permanent populations is possible, particularly given the human-created permanent waters intersecting with the natural drainage network. Even if cold winter temperatures preclude establishment (which is not at all certain), opportunistic cane toad breeding on inundated floodplains will be detrimental to native fish populations during their flood-time recruitment phases. Opportunities to slow, control or monitor cane toad invasion exist along "weakest-link" reaches in the Queensland (Windorah to Nappa Merrie) section of Cooper Creek, and at the narrowest sections of the Innamincka Valley (the Cullyamurra Choke, and Nappa Merrie bridge).

The Strzelecki Plain falls into eight geomorphic zones (Geomorphic Zones Map), each characterised by a particular history of landscape evolution, suite of modern-day geomorphic processes, and characteristic **risk factors**. The geomorphic zones therefore also represent management zones. Although many risk factors may apply anywhere, the geomorphic management zone characteristics are:

- Innamincka valley: Cooper Creek is confined between rocky valley walls and high terraces; risk factors include erosion and gullying developing from human pathways between high and low surfaces.

- Cooper Creek Fan (including Inner Fan with Fan Apex, and Outer Fan): Cooper Creek is semi-confined by high terraces and other fluvial deposits, and is characterised by small distributary channels; risk factors include erosion and gullying at offtakes and sills, which may lead to diversion of water away from the primary flow path. The sills separating Strzelecki Creek from Cooper Creek are of particular concern. Five vulnerable zones are identified (one being the Innamincka Town Common).

- Outer Cooper Creek Fan: Cooper Creek is largely unconfined, and dominated by distributary drainage (including the division of the parent channel into the Main and North West Branches); risk factors include occlusion of or damage to the flow path by infrastructure.

- The Coongie Lakes: this area contains lakes, swamps, and linking channels, including Ramsar-listed wetlands; complex flow routing depends on the interaction between flood peaks and flow-mediating landforms; risk factors include loss of natural flow variability, flow occlusion, and damage which lowers the elevation of flow-mediating landforms.

- The northern overflows: poorly-defined flow pathways, comprising intermittent channels, and lakes from the North West Branch's overflow, rejoin the swamps and small channels of the Main Branch; risk factors include loss of natural flow variability.
- The southern Strzelecki Plain: including large lakes (Gregory, Blanche, and Callabonna), Strzelecki Creek, Cooper Creek's small intermittent channels and inundated areas, and lakes (including Lake Hope); risk factors include loss of natural flow variability in the upper (Queensland) catchment, and sill breaches diverting Cooper Creek flow down Strzelecki Creek.
- The Tirari reaches, including the Kopperamanna Floodout: a broad floodout with discontinuous flow path, then a sinuous single channel within an incised channel belt; risk factors include loss of natural flow variability.

Human activities (tourism, resources exploration and extraction, pastoralism, and civil development) can impact landforms. Existing legislation covers most aspects of human activity, however there is a lack of coordination and information-sharing between governing bodies, especially with respect to the special conditions of the arid zone. Information on designing and managing infrastructure in the Strzelecki Desert exists in an uncoordinated and uncatalogued way, and this is a real barrier to effective good practice. All human activities should be equally held to a standard of environmental care. To this end:

- A **coordinating mechanism** should exist to integrate the many legislations and jurisdictions of activities across the Strzelecki Plain, and to act as a clearing house of relevant information specific to the area.
- Regulation without enforcement is worthless; compliance oversight must be supported by a **public service which is properly resourced**.
- A mechanism should exist to provide **information** and environmental assessment services to poorly-resourced civil authorities.

Tourism in the Strzelecki Plain is valuable economically, and in its capacity to build positive relationships between desert communities and urban taxpayers. Tourist numbers are small but increasing, and negative impacts though currently few are likely to increase. Management strategies for 1) erosion along straight-down human and vehicle pathways, 2) erosion and devegetation around water access, 3) **rubbish and toilet paper**, and 4) the placement of tourist infrastructure with respect to landform age and renewability, are discussed.

Glossary

Avulsion: where a river channel relocates, often rapidly or catastrophically

Corrasion: to be eroded by abrasion

Depocentre: the location of the deepest deposit in a sedimentary basin, may be expressed at ground surface as a lake

Lacustrine: relating to lakes

Occluded: blocked or partially blocked

Palaeodrainages: river networks which were active in the past, but are not presently part of the primary flow path

Palaeolakes: places that were lakes in the geological past, but are not now lakes.

Seiche: a wave that oscillates in lakes or other waterbodies, over a few minutes to a few hours, as a result of seismic or atmospheric disturbance

PART 1: REPORT & RECOMMENDATIONS

1. INTRODUCTION

In the arid zone landscape, limitations on resources (water and nutrients) requires understanding of the geomorphological processes that govern resource distribution, in order to underpin assessments of ecosystem health. During 2011-2012, the South Australian Arid Lands Natural Resources Management Board (SAALNRM) undertook the (Caring for Country) Cooper Creek project “Managing the high ecological value aquatic ecosystems (HEVAE) of the Cooper Creek catchment (SA section)”. A sub-project examining the geomorphology of Cooper Creek is the subject of this report. This sub-project’s aim was to provide information to complement and support reports from the other disciplines (Costelloe 2012, Gillen & Reid 2012, Lee 2013, Reid & Gillen 2012, and Schmarr et al. 2012). The study area encompasses Cooper Creek's catchment within South Australia, including a 30-km section of the Innamincka valley extending into Queensland. In addition, an area extending northeast ~400 km upstream from the South Australia-Queensland border was assessed in remote study, as the geomorphology is of direct relevance to the aims of this project. The aims of this project were to:

- assess the geomorphological processes and landscape characteristics of the Cooper Creek catchment (SA section);
- assess the fluvial features contributing to the physical diversity of waterholes, and identify the spatial and temporal range of ecological refugia;
- assess landforms with respect to potential for harbouring feral cane toads (presented as a separate report, “Cane Toads and South Australian Arid Lands Geomorphology”);
- indicate the stability and sources of ecological functioning, across scales of time and space ranging from the human (years to decades, and meters to kilometres) to the geological (tens of thousands to millions of years, and kilometres to several hundreds of kilometres);
- identify potential on-ground management activities which will contribute to sustainable use and management of the catchment.

This report comprises two parts. “Part 1: Report and Recommendations” contains the results of this investigation, and the recommendations arising from it. The accompanying “Part 2: Technical Appendix” includes the information leading to the main report: the methodology, desktop study of the regional context, field observations, analysis and synthesis. Part 1 includes summarised results from published literature; the literature review where all information is attributed and cited is in Part 2. Place names within the study area are shown in the Locations map, Fig.

2, and Table 1. The inclusion of a place in this report does not indicate that public access is allowed, nor does it guarantee that access is physically possible

Table 1. Location of places mentioned in text.

*Merrimelia and Panadinnie Waterhole locations are ambiguous; location names here are as per the SANTOS map.

	Name	Type	Easting	Northing
	Windorah	Town	142.655	-25.422
	Innamincka	Town	140.737	-27.747
	Maapoo Waterhole	Waterhole	141.288	-27.592
In the Innamincka Dome	Nappa Merrie Waterhole	Waterhole	141.138	-27.591
	Nappaoonie Waterhole	Waterhole	141.049	-27.651
	Cullyamurra Choke	Reach	140.896	-27.712
	Cullyamurra Waterhole	Waterhole	140.840	-27.701
	Burke Waterhole	Waterhole	140.779	-27.720
	Mulkonbar Waterhole	waterhole	140.747	-27.728
Cooper Creek Fan	Sz1	offtake	140.734	-27.751
	Town Common	camping ground	140.73	-27.75
	Burlieburlie Waterhole	waterhole	140.727	-27.803
	Queerbiddie Waterhole	waterhole	140.731	-27.748
	Sz3	offtake	140.707	-27.759
	Sz4	offtake	140.711	-27.759
	Sz2	offtake	140.683	-27.770
	Minkie Waterhole	waterhole	140.635	-27.777
	Ooranie Creek	Offtake	140.626	-27.776
	Tilcha Waterhole	waterhole	140.607	-27.759
	Wills' Grave	Reach	140.600	-27.755
	Marpoo Waterhole	waterhole	140.587	-27.758
	Wilpinnie Creek	offtake	140.529	-27.777
	Munga Munga Waterhole	waterhole	140.517	-27.814
	F1	offtake	140.483	-27.766
	F2	offtake	140.455	-27.646
	Napiowie Waterhole	palaeodrainage waterhole	140.501	-27.726
	Montepirie Waterhole	palaeodrainage waterhole	140.572	-27.712
	Durantie Waterhole	palaeodrainage waterhole	140.608	-27.676
	Scrubby Camp Waterhole	waterhole	140.386	-27.662
	Mundrangie Waterhole	waterhole	140.249	-27.612
	Eulcaminga Waterhole	waterhole	140.301	-27.592
	Tirrawarra Waterhole	waterhole	140.153	-27.439

	Name	Type	Easting	Northing
	Merrimelia Waterhole *	waterhole	140.289	-27.765
	Panadinnie Waterhole*	waterhole	140.245	-27.732
	Embarka Waterhole	waterhole	140.194	-27.675
	Embarka Swamp	swamp	140.151	-27.658
	Narie Waterhole	channel	140.067	-27.449
	Toonman Waterhole	palaeodrainage waterhole	140.070	-27.424
	Chillimookoo Waterhole	palaeodrainage waterhole	139.971	-27.390
	southern end of Christmas Creek	palaeodrainage	139.905	-27.365
	Gidgealpa Waterhole	palaeodrainage waterhole	140.150	-27.818
Coongie Lakes area	Tirrawarra Swamp	swamp	140.142	-27.386
	Kudriemitchie Channel	channel	140.197	-27.348
	Lake Mundooroounie	Flats	140.212	-27.311
	Coongie Lake	Lake	140.165	-27.180
	Lake Apachirie	Lake	140.125	-27.182
	Swamp SSW of campground	swamp	140.081	-27.212
	Lake Marroocoolcannie	lake	140.211	-27.181
	Lake Marroocutchanie	lake	140.218	-27.144
	Browne Creek	channel	140.152	-27.137
	Lake Toontoowaranie	lake	140.178	-27.089
	Ellar Creek	channel	140.187	-27.061
	Lake Goyder	lake	140.174	-26.989
	Lake Marradibbadibba	lake	140.257	-26.981
	Sturt Ponds	channel	140.324	-26.976
	Lakes Lady Blanche and Sir Richard	lake	140.374	-27.022
	Mitkacaldratillie Lakes	lakes	140.413	-27.166
	Hamilton Creek	flats	140.102	-27.072
	Lake Apanburra	lake	140.077	-26.997
	Apanburra Channel	channel	140.134	-27.028
Overflows	Alfred Creek	channel	140.019	-27.034
	Strangeways/ Wattiecaroonie	Lake	139.991	-27.027
	Lake Androdumpa	lake	139.911	-27.128
	Lake Oolgoopiarie	lake	139.863	-27.126
	Lake Moolionburrina	lake	139.832	-27.319
	northern end of Christmas Creek	palaeodrainage	139.861	-27.199
	Cuttapirie Corner	waterhole	139.886	-27.596
	Boggy Lake	lake	139.824	-27.503
	Deparanie Waterhole	waterhole	139.635	-27.445

	Name	Type	Easting	Northing
	Walkers Crossing	channel with bridge	139.918	-27.529
SW Strzelecki Plain	Pilachilpna Waterhole	waterhole	139.439	-27.927
	Eaglehawk Waterhole	waterhole	139.429	-27.935
	Lake Warrakalanna	lake	139.320	-28.196
	Lake Appadare	lake	139.194	-28.216
	Lake Hope	lake	139.26	-28.37
	Red Lake (local name)	lake	139.182	-28.357
	low rise NE of Lake Gregory	low rise	139.23	-28.66
big southern playa lakes	Warrawoocara Channel	sill	138.88	-28.72
	Lake Gregory	lake	139.01	-28.85
	Lake Blanche	lake	139.66	-29.23
	Lake Callabonna	lake	140.09	-29.65
	Lake Frome	lake	139.83	-30.79
Lower Cooper	Kopperamanna Floodout	floodout	138.56	-28.68
	Lake Killamperpunna	lake	138.772	-28.590
	Lake Killalpaninna	lake	138.552	-28.579

1.1 Methods

The project comprised a remote-resources desktop study (geological maps, satellite images digital elevation models (DEMs), topographic datasets, literature review), followed by field investigation, then integration of remote and field data to produce this report. During the project, evidence for landscape processes was gathered from the spatial relationships between sediments, landforms, vegetation, and geomorphic context (for example, muddy sediments vegetated by lignum or Queensland bluebush, located in a wide flat depression along the primary flow path, identifies a dry swamp).

During the project, the Geoscience Australia smoothed dataset of 1-second Shuttle Radar Topography Mission (SRTM) digital elevation data was used. While these are excellent products, their limitations need to be understood:

- reflectance issues make some low-relief dry sandy areas look like lakes (Fig. 1 top right);
- because of inherent inaccuracies, the smoothed data (Fig. 1 bottom left) are good for regional studies, but are not suitable for local-scale studies, nor are they a substitute for actual surveying or high-resolution 3D data;
- the hydrologically-forced dataset departs from reality in places, placing entirely fictitious channels through inappropriate landforms (Fig. 1 bottom right).

Management implications:

In this flat landscape, the SRTM data has marked limitations. Management decisions based on incorrect information will be flawed.

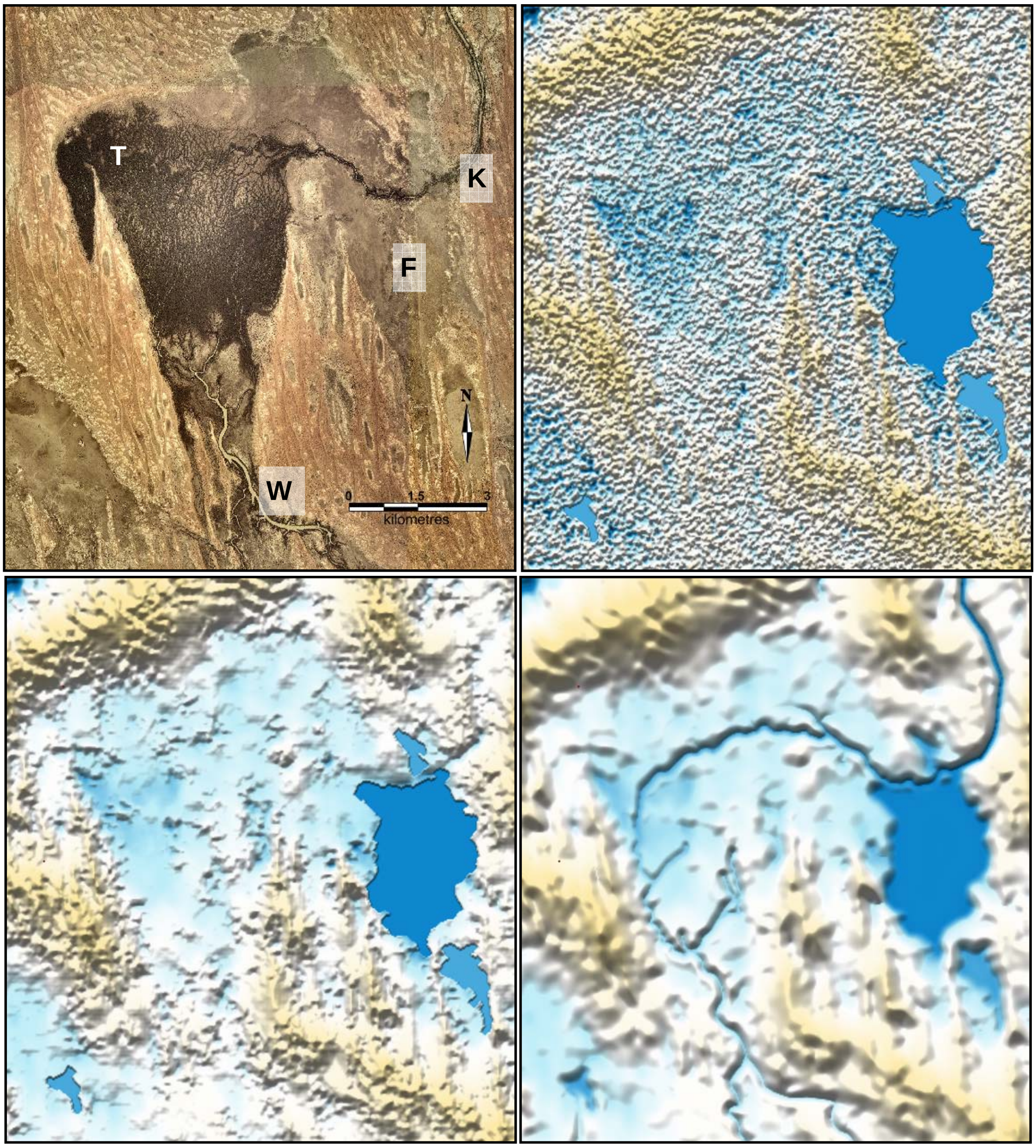


Fig. 1. Tirrawarra Swamp, orthophoto and DEMs.

All DEMs are processed with elevations dark blue low, grading up through light blue and white, to pale orange high, and daylight shading on, light source to the northwest. Top left: orthophoto, Tirrawarra Swamp (T), Tirrawarra Waterhole (W), Kudriemitchie channel (K), and an un-named flat area (F) to the east of the swamp. Flow is from south to center and center to northeast. Top right: processed raw DEM. Bottom left, smoothed DEM. Bottom right, use of a watercourse line from 1:250,000 topographic data to guide the hydrological forcing of this DEM has placed a fictitious channel through the swamp.

1.2 Physiography and Locations

The Lake Eyre Basin (LEB) is a very low-relief, wide and shallow basin with its terminal drainage sump (Lake Eyre) in the south-west. Low-gradient rivers of the Channel Country come from the semi-tropical north to enter Lake Eyre on its north and east sides (Fig. 2). LEB dunefields are the Simpson, the Tirari, and the Strzelecki Deserts. The stony uplands within the study area are Sturts Stony Desert (known geologically as the Gason Dome and Birdsville Track Ridge), and the Innamincka Dome, the Cordillo Dome, the Benangerie Ridge, and the Cooryanna Dome (Location Map, and Fig. 2).

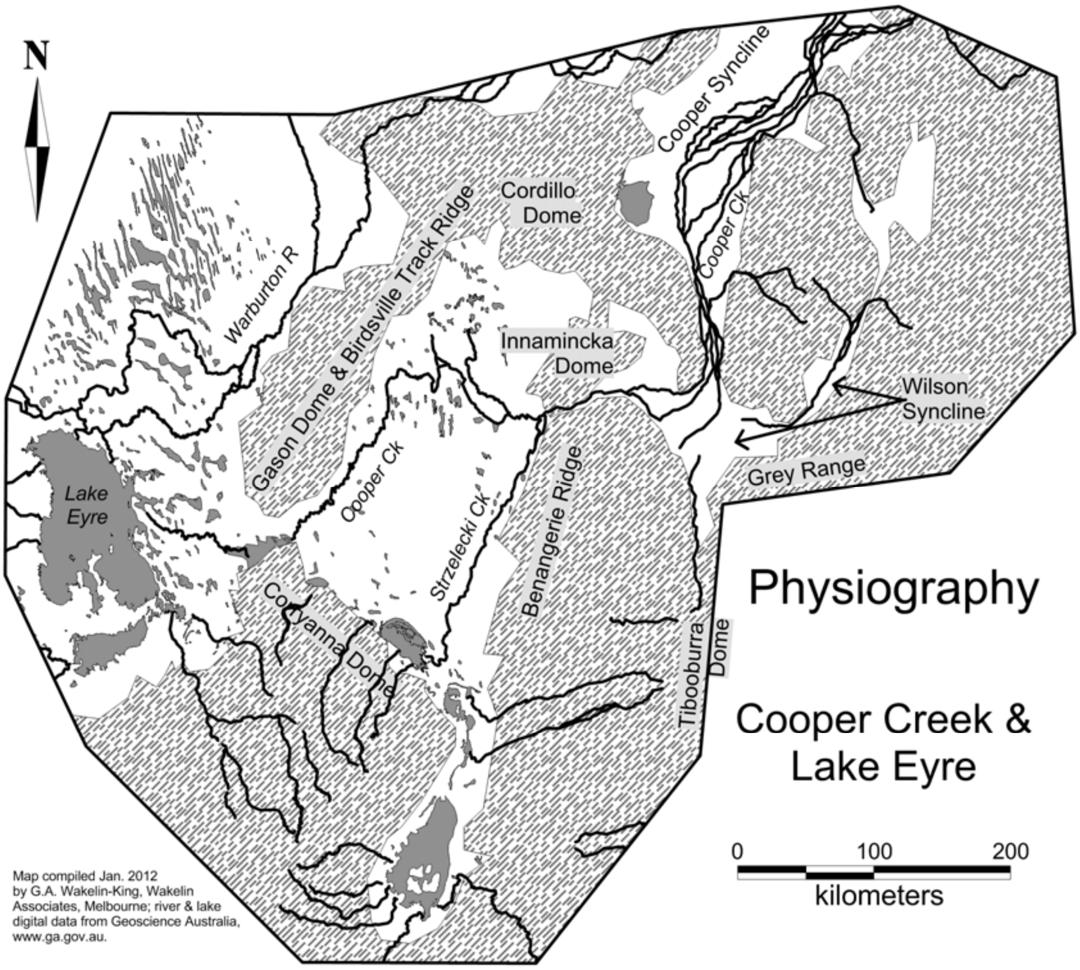


Fig. 2. Physiography of Cooper Creek from Windorah to Lake Eyre.

Dashed pattern indicates elevated areas.

In the northeast of South Australia and southwest Queensland, the topography is of broad shallow depressions separated by low-elevation stony rises. The Strzelecki Plain (the central and western portions of the Strzelecki Desert) and the Tirari Desert are topographic lows, within which sand dunes have accumulated amongst river and lake deposits. The eastern portion of the Strzelecki Desert (the Benangerie Ridge), although also cloaked by sandy sediments, is actually ~70 m above the Strzelecki plains. Between the Tirari and Strzelecki deserts lies the Sturts Stony Desert, a topographic high marked by gibber plain and without sand accumulation. The northeast-trending Birdsville Track Ridge links it to the Cordillo Dome in South Australia's northeast. Other stony rises of importance to this study include the Innamincka Dome, and the Cooryanna Dome near the Flinders Ranges (Location Map, and Fig. 2).

The Cooper Creek floodplain is extremely broad (at the widest, >60 km) from Windorah to its entrance into the east of the Innamincka Dome. From there until it exits the Dome near Burke Waterhole it becomes narrow (minimum 150 m). The Cooper Creek Fan (see Location Map) is a broad shallow low-angle distributary fan extending westwards from the edge of the Innamincka Dome. Rising 40-245 m above the Strzelecki Plain (fan edge to fan apex), its downvalley slope is approximately double that of the plains. As it flows across the Cooper Creek Fan, Cooper Creek's parent channel divides into three main distributary branches: the Strzelecki Creek, the Cooper (Main Branch), and the Cooper (North West Branch).

1.3 Geology

*Note: land managers use "Lake Eyre Basin" to refer to the present-day Lake Eyre catchment, whereas geologists use the same name to refer to the young rocks and sediments which lie beneath the earth's surface in approximately the same place. In this report, the latter will be referred to as the "Lake Eyre geological Basin".

The geology of the study area (Geology Map, and see Part 2: Technical Appendix) is dominated by overlapping sedimentary basins: the mostly Cretaceous Eromanga Basin (which is part of the Great Artesian Basin, GAB) and the Cainozoic Lake Eyre (geological) Basin. Over geological time, deposition of sediment by lakes and rivers has alternated with weathering events which have bleached some rocks, and also produced the hard silcretes and silicified rocks which now form the stony deserts. Subdued tectonic activity created the lake basin and uplifted the hills which now constrain the Cooper’s flow path (Figs. 2, 3). In the geological past, climates in the study area have been wet, and sediment deposits reflect large, high-energy river systems. The development of modern aridity in geologically recent times emplaced the dune fields, and stripped soil to reveal the stony gibber plains. One result of the tectonic activity has been north-to-south migration of the deepest part of the lake bed (the depocentre). Relics of ancient river and lake networks are preserved in the flat topography, the palaeodrainage lines, and the permeable sand layer beneath modern floodplain muds.

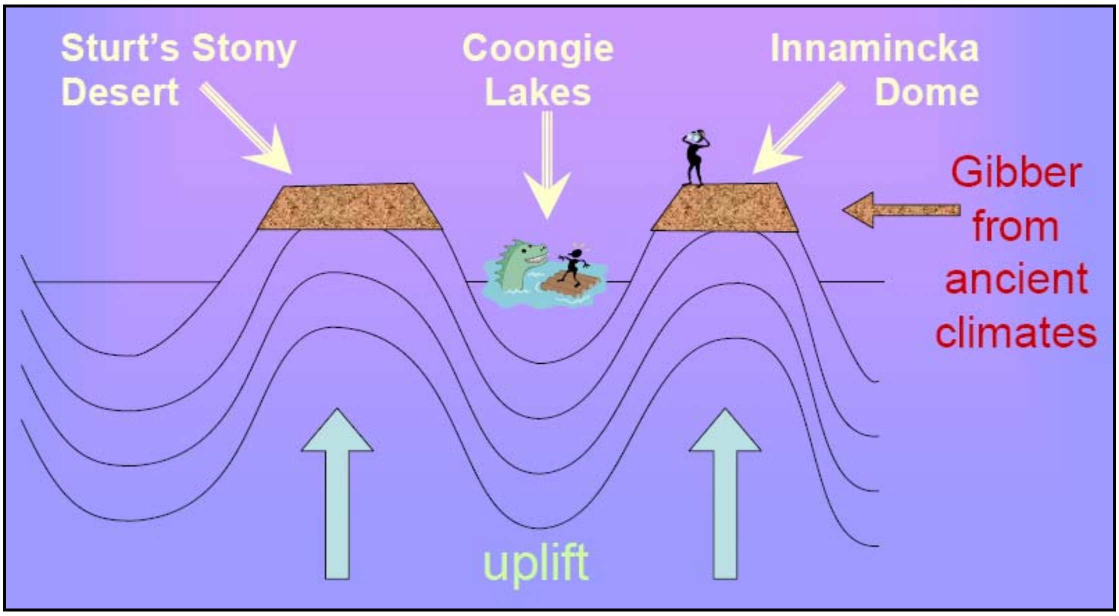


Fig. 3. Cross-section sketch of the geology of the northern Strzelecki Plain.

Dome-and-basin uplift defines the topography. Uplift and erosion exposed silcrete gibber to produce the stony uplands (see Fig. 4). River channels and sand dunes on low-gradient lowlands are underlain by thick accumulations of Cainozoic sediment in the subsiding basins.

In the modern landscape, the rocks and sediments are –

- older units (Eromanga Basin rocks, younger rocks and sediments, and silcretes) exposed by erosion along the uplands: in the Innamincka Dome (Fig. 3), along Sturts Stony Desert (the Gason Dome), and elsewhere (Fig. 2, Geological Map, Location Map);
- white quartzose sands of the geologically young Katipiri Formation, now mostly overlaid by the Cooper Creek's floodplain muds, from Queensland through to the lower Cooper; this sand is important as a source of transverse dune sand, a prominent landscape element, and a local aquifer;
- sand dunes and sand plains of the Simpson, Tirari, and Strzelecki Deserts;
- and greyish to dark grey floodplain muds, characterised by gilgai features (crabholes, self-mulching soils, deep cracking).

1.3.1 Landscape – Uplift and Subsidence

Tectonic activity, controlling the disposition and gradient of river valleys, directly controls water in the landscape and thus is the ultimate control of ecology. In the study area, slow uplift and subsidence was occurring ~300 million years ago, continued through more geologically recent times, and continues to the present day. In overview, there has been:

- uplift related to rocks beneath the Cooryanna Dome, the Benangerie Ridge and the Tibooburra Dome,
- continental-scale sagging to produce the Eromanga Basin, the Lake Eyre Basin (geological), and the Lake Eyre Basin (surface),
- east-west compression creating dome-and-trough structures:
    - the uplands of the Innamincka Dome and the Gason Dome (Sturts Stony Desert),
    - the troughs include the Strzelecki Plain, and floodplains of the Cooper Creek and the Wilson River respectively;
- buckling or tilting of the Lake Eyre Basin in geologically recent times, such that the depocentre has shifted from a more northerly position into its present location in the south of Lake Eyre;
- the floodplain of the Cooper (Windorah to Nappa Merrie reach) is now tilting to the west, such that the channel belt has shifted to the western margin, and floodplain sediments are invading the bordering interdunes.

1.4 Hydrology

1.4.1 Present Day: Large Playa Lakes, Cooper Creek, Coongie Lakes

Lake Eyre is usually dry, occasionally receives inflow waters, and on the rare occasion when it fills (usually during La Niña times) its waters may reach an elevation of -9.5 m AHD. Such fill events have been recorded for 1950, 1974, and recently. Three other large playa lakes (Gregory, Blanche, and Callabonna, see Location Map), occur around the base of the Cooryanna Dome. They receive runoff from nearby hills, and Lake Blanche receives water from Strzelecki Creek.

Cooper Creek runs from central-north Queensland down to Lake Eyre. The headwaters are fed by occasional monsoonal rainfall, of sufficient volume that flood pulses routinely travel as far as South Australia. The rainfall and river flows are extremely variable, and the nature of each flow event (single-peaked, multiple, or compound) depends on rainfall's volume and location within the tributary network.

Although downstream decreases in flow volume can be considerable, and despite its location in one of the driest parts of South Australia, the Innamincka Dome reaches of Cooper Creek have a more dependable water supply than might be expected. The area commonly experiences many flow days per year. In comparison with more upstream locations, flood peaks in the waterholes of the Innamincka Dome may be lower, yet flow events may be of longer duration.

As the Cooper Creek leaves the Innamincka Dome, the parent channel splits into three major branches: Strzelecki Creek (flowing south-southwest to Lake Blanche), the Cooper Main Branch (flowing northwest, west, then southwest into the Tirari Desert), and the Cooper North West Branch (flowing northwest to RAMSAR-listed wetlands in the Coongie Lakes). Under current conditions, the relative amount of water flowing through these three branches varies according to flood height (see Costelloe 2013 for a full description of Cooper Creek's hydrology).

1.4.2 Geological Past: Playa Lakes and Cooper Creek

Cooper Creek was previously a relatively high-energy and high-volume waterway, depositing white quartz sands which today underlie some floodplain muds, and elsewhere are exposed at or slightly above the level of the modern river. These sands are likely to have good aquifer properties, with potential to influence modern floodplain vegetation. The volume of sediment and water discharged by Cooper Creek has varied over recent geological time. Once 5-7 times larger than its present form, it has been reduced by increasing climatic aridity (though with intermittent strongly seasonal flows). Within the Innamincka Dome reaches, there may have been a very large but brief catastrophic event approximately 12-24,000 years ago.

During previous wetter climates, the dry lakes were full, and joined to form a single semicircular lake around the base of the Cooryanna Dome. The +10 m AHD shoreline around Lake Eyre and the +18 m shoreline around the Frome-Gregory system correspond to the wettest periods, during which Lake Gregory overflowed towards the Cooper through the Warrawoocara Channel. These lakes were linked by the overflow channel at ~125 ka (the last interglacial *Note: "ka" means "thousand years"*), and for the last time at 50-47 ka. Very large to extreme flow events on a multi-millennial timeframe have partially filled the lakes, most recently ~1,000 years ago.

2. LANDSCAPE ELEMENTS AND THEIR MANAGEMENT IMPLICATIONS

In this section the building-blocks of landscape are briefly described, and their management implications considered. Process analyses and greater detail are documented in Part 2 (Technical Appendix), section 6.

2.1 Stony and Sandy Uplands

The Strzelecki Plain is surrounded on all sides by stony and sandy uplands. Though their elevation is greater than the Strzelecki Plain, they are still typically of low relief, with flat-topped hills with steep sides (Fig. 4). The surface qualities of these uplands influences the amount of runoff delivered to the plain below.

Fig. 4. The crest of the Innamincka Dome.

Flat-topped hills mark outcrop. Foreground: the gibber plain is partially concealed by unusually good grass after a wet year. Mid-distance: a shallow valley holds a small creek with trees along its banks.

The Benangerie Ridge is largely covered by closely-spaced longitudinal sand dunes. Its elevation is not high and its surface is covered in permeable sand, so there is no run-off into the Strzelecki Plain during local rain. The other uplands are mostly stony (either rocky outcrop, gibber plain, or stony gilgai). Gibber-covered or rocky slopes shed water freely, and small drainages from the rocky uplands water the Strzelecki Plain fringes during local rainfall. Small upland creeks draining down to the plain are most prominent to the south and east-northeast (the Cooryanna and Innamincka Domes respectively), and least prominent to the west and north (the Gason and Cordillo Domes).

2.2 Topography of the Strzelecki Plain

The Strzelecki Plain encompasses the Coongie Lakes area, the Cooper Creek Fan, and the western section of the Strzelecki Desert (Fig. 2, Location Map, and Fig. 5). It is surrounded by sandy and stony uplands. Its topography is a strong determinant of river behavior and drainage network development. Overall, the Plain has extremely low relief, so the component of stream power derived from downvalley slope is very low. Geomorphic activity (erosion and sedimentation) during river flows is more strongly driven by flow volume, local topography (e.g. sand dunes and “flats”), and landform-scale flow effects (e.g. in waterholes).

There are two elements in the Strzelecki Plain with significant relief. The most important is the Cooper Creek Fan, a low-angle alluvial fan with its apex near the township of Innamincka (Fig. 5 and Location Map). It has a significantly greater gradient than elsewhere in the Strzelecki Plain. As a consequence, Cooper Creek's potential stream power is greater on the Cooper Creek Fan than it is elsewhere, and the possibility of landscape change is also therefore greater.

The second element of greater relief is a very low rise just to the northeast of Lake Gregory. Its relative elevation is only slight, but it is a significant influence on the existence and location of lakes of the southwest Strzelecki Plain (e.g. Lake Hope).

2.3 Cooper Creek Waterholes and Channels

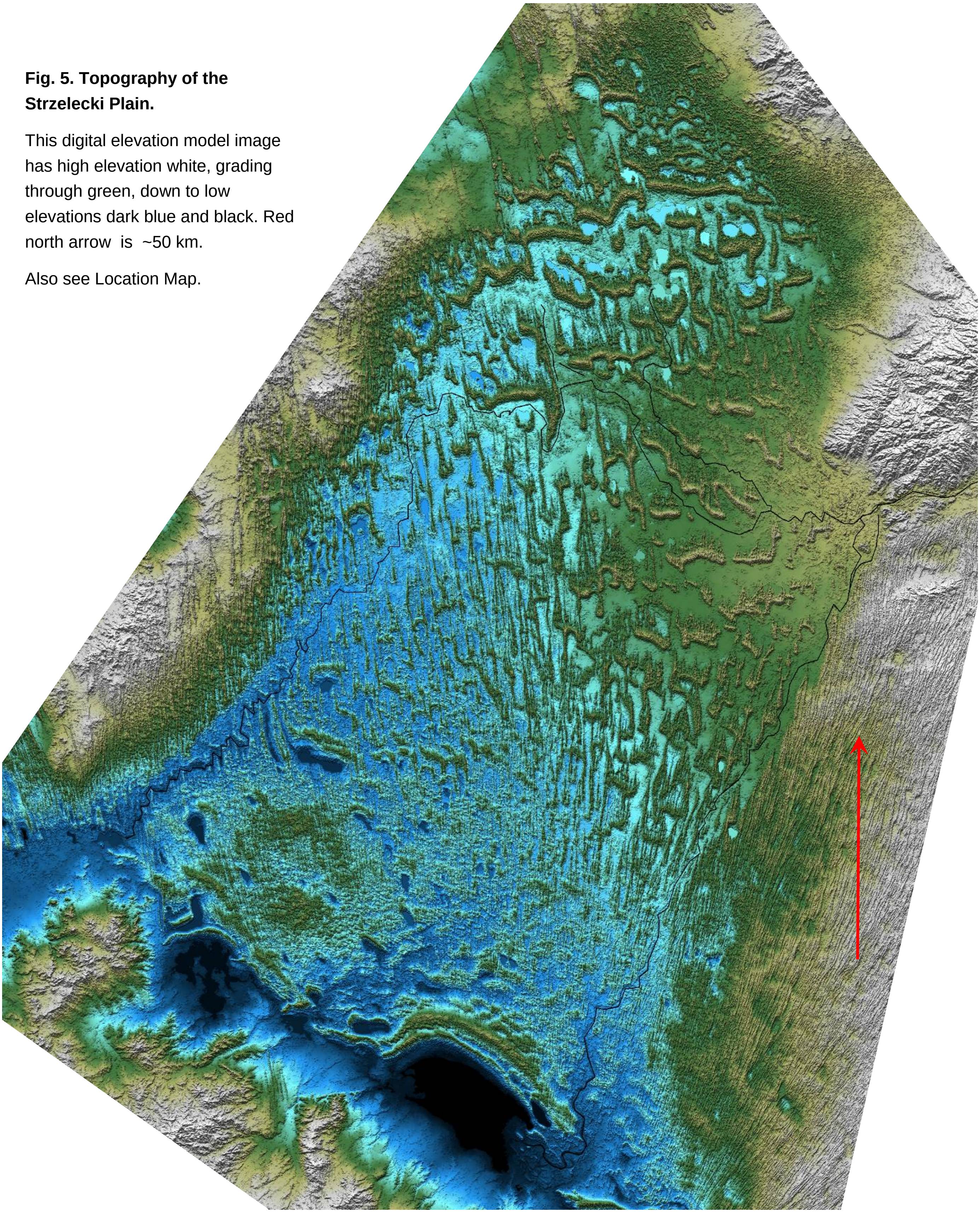
Reach-scale fluvial landforms are described here (Fig. 6); some descriptions are based on published literature (see Technical Appendix, Section 6.3):

- River channels occur at a range of scales. Primary channels have good longitudinal connectivity, and are inset up to 7 m deep into the muddy floodplain. They are highly sinuous to near-straight, and anastomosing, with 1-4 channels coexisting per reach. They are active at moderate flows, and their banks support riparian vegetation including Coolabah trees. Secondary and tertiary channels are smaller, and operate at different flood heights. Secondary channels tend to be continuous, and tertiary channels discontinuous but along a perceptible flow path.

Fig. 5. Topography of the Strzelecki Plain.

This digital elevation model image has high elevation white, grading through green, down to low elevations dark blue and black. Red north arrow is ~50 km.

Also see Location Map.



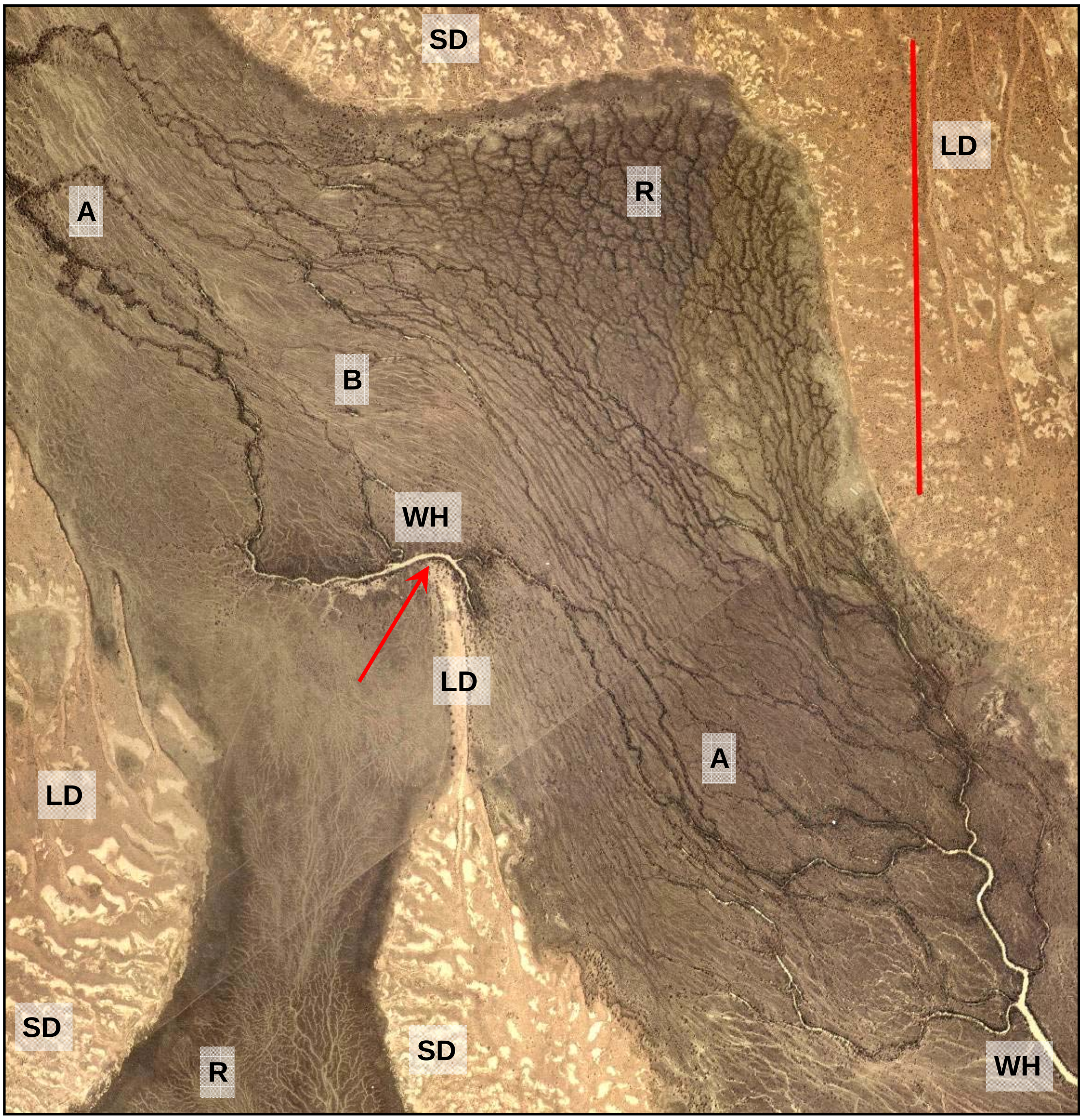


Fig. 6. Channels and dunes of the Cooper Creek Fan.

Aerial photograph, flow is from bottom right to top left, north to top, red scale line is 3 km long. Panadinnie Waterhole (arrowed; 8 km SW from Embarka Waterhole) is surrounded by dark grey floodplain, which is bounded by sand dunes (pale to dull orange). Landforms: LD longitudinal dunes (long narrow orange lines), SD scalded (wind-eroded) transverse dunes (irregular pale orange patches are unvegetated scalds, in darker orange vegetated sand), WH waterholes (the larger channel segments showing bright reflectance of open water), A anastomosing primary and secondary channels, R reticulate channels (swampy areas), B braid-like floodplain with shallow floodways.

A single longitudinal dune extends northwards from the small transverse dune at the photo's lower center. It concentrates floodplain flow, and the anastomosing channels from Merrimelia Waterhole (bottom right) coalesce to form Panadinnie Waterhole. High-level flow at the waterhole is likely to undercut the dune nose and northeast flank; note that pale overbank sediments are only evident downstream of the dune/channel interface, indicating dune sand entering fluvial transport there. White diagonal lines are old seismic lines.

- Waterholes are deep channel segments which are wider and deeper than ordinary channels. They retain water for longer than other channels, some of them being near-permanent, and a few being actually permanent. Waterholes are a self-maintaining landform created by present-day fluvial conditions, and the riparian vegetation plays a critical role in maintaining the steep banks and scoured bed that allows these waterholes to persist.
- Waterholes recharge groundwater during flood events, contributing to transmission loss and to the ecology of plants with deep roots. The groundwater does not supply the waterhole; the flow is in one direction only. The size of the fresh groundwater lens scales to waterhole size.
- The floodplain sediment is dominated by mud aggregates from vertic soils. Floodplain surfaces (braid-like with shallow floodways, reticulate, and unchannelled) reflect the balance between fluvial and gilgai-soil processes.
    - Braid-like floodplain experiences more frequent inundation and higher flow energy, is crossed by broad shallow (<1 m) floodways, dividing the floodplain into braid-like bars.
    - Reticulate floodplains experience some inundation, and gilgai processes operate. In the study area many of the shallow basins are reticulate-channelled swamps. Reticulate swamp areas are not necessarily low-elevation, they merely have to be wet but low-energy.
    - Unchannelled, featureless floodplains are not inundated. They occur in higher parts of the floodplain, and in palaeodrainages which are isolated from the modern flow path.

Both sand and mud are transported through Cooper Creek. White to buff medium to fine quartzose sand is the dominant sediment visible in the study area, along levees, banks, and downstream sediment splays from terminating channels.

Distributary channels are a particularly characteristic and important feature of the study area. Across the Cooper Creek Fan, many small creeks take water and sediment from the main channel and spread it across nearby flats. The largest are the size of small creeks and show on the maps: the channels feeding Strzelecki Creek, Ooranie and Wilpinnie Creeks, and the forks which divide the Cooper into Main and North West Branches. Distributary channels are created by floodwaters which breach the levee and splay out over the floodplain. Under the right topographic conditions, some of these splays will develop into distributary channels.

The junction where the small channel leaves the main channel is the offtake. Offtake areas experience two-way flow: outbound during the rising flood, and draining back into the channel during flood recession. This creates locally complex landforms. Even small distributary channels have offtakes which are sizeable gullies, and large distributary channels have offtakes which present as wide valleys with gentle gradients going down to the river.

Steep banks are characteristic of the waterholes and the main channels. Bank retreat, where present, is often slow. Tree-covered levees (<~1.5 m above the adjacent floodplain) are generally found flanking waterholes, whereas anastomosing channels rarely have levees. Shadow bars deposited downflow from in-channel vegetation are common.

Cooper Creek's low stream power predisposes the channel planform to be anabranching and anastomosing. Waterholes are formed at points of flow convergence, where constriction in flow width (e.g. between sand dunes, or where several anastomosing channels converge) increases stream power.

2.4 Strzelecki Plain: Sand Dunes

The Strzelecki Plain records a complex history of mutual action: wind and water, dune and river. The channels and the dunes co-developed over time, with fluvial and aeolian processes operating concurrently. Sand in river channels was blown to form the transverse dunes, channels relocated over time, they were deflected from one path to another by the transverse dunes or their daughter longitudinal dunes, new channels later created more transverse dunes, and so on.

On the scale most visible to human eyes, the dominant topographic features in the study area are the sand dunes, and the broad, mostly dune-free “flats” which are particularly a feature of the Cooper Creek Fan and Coongie Lake areas. Together, they are a very strong influence on river behaviour at the reach scale. The dunefields in the study area are dominated by either longitudinal or compound dunes. The dunes’ landscape functions are 1) as barriers to flow, 2) as creators of waterholes by flow concentration, and 3) as influences on the wind turbulence that excavated the shallow lakes.

Sand in fluvial sediments or rocks is released by corrasion and rearranged locally to form sand dunes as the climate dries. The underlying rocks or sediments which liberate sand to the dunefield are one of the reasons for the differences in dune colour. Most of the sands transported down the modern Cooper Creek are re-mobilised Katipiri Formation, characterised by buff to bright white colour.

Longitudinal dunes are characteristic of the Benangerie Ridge, some parts of the central Strzelecki Plain, and some of the upwind edges of the Gason and Cordillo Domes Longitudinal dunes are long but very narrow (one to scores of km long, but only 150-300 m wide). Their crests are parallel to the dominant wind direction at the time of their formation. Typically their flanks are well-vegetated (therefore anchored against migration or movement) while the narrow crests are often unvegetated and locally mobile. The interdune corridors frequently host claypans (Fig. 7). indicating locally strong deflationary processes (wind erosion). The longitudinal dune fields are of geologically recent origin and where their presence constraints the drainage network (such as Strzelecki Creek), the fluvial geography is also relatively young.

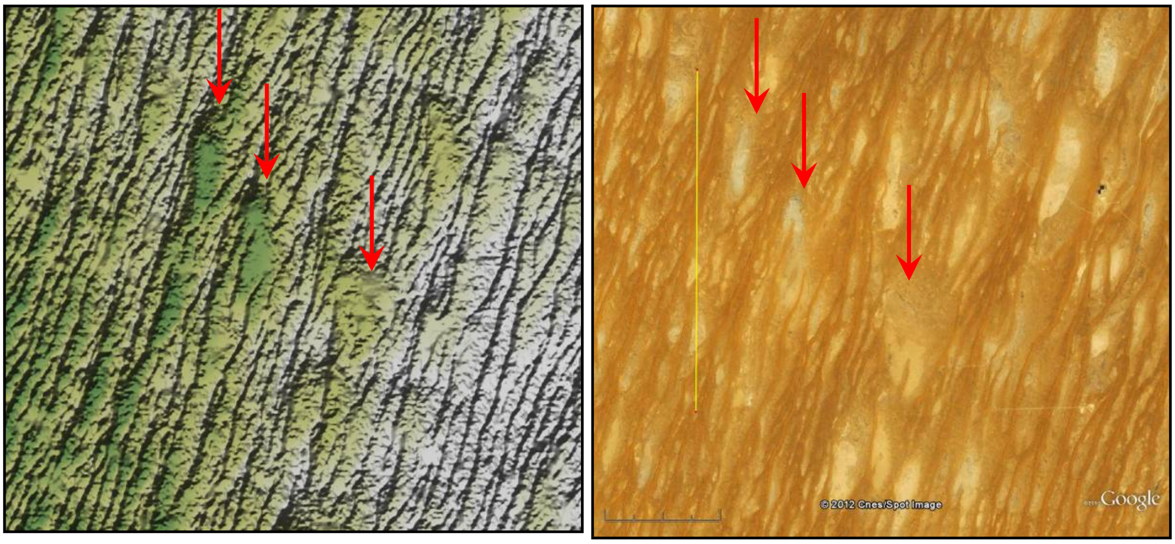


Fig. 7. Longitudinal dunes on the Benangerie Ridge.

Closely-spaced longitudinal dunes oriented N-NE are interspersed with small claypans (arrows show the same claypans in each image). Left, DEM ; right, Google Earth image; yellow scale line is 10 km long

The Cooper Creek Fan and the Coongie Lakes area are dominated by **compound dunes**, a mix of transverse and longitudinal dunes formed by the same prevailing winds. **Transverse dunes** (perpendicular to wind direction) are created by sediment blown northwards from rivers or lakes, and are deposited immediately adjacent to the sediment source (referred to as being “source-bordering”). Their length is scaled to the channel or lake from which they arose. The transverse dunes date back to at least 250 ka, with additional sand added during periods of fluvial activity, most recently during the Last Glacial Maximum (28-18 ka). The longitudinal dunes form from sand taken from the transverse dunes, and overprint their parent dunes (Fig. 8), leading to wind-eroded areas in the source dunes (Fig. 9). To the human eye, longitudinal dunes tend to mask the presence of older transverse dunes.

Northwards sand transport from previous geological ages is evident in the creation of longitudinal dunes from transverse dunes, but generally wind-driven sand transport has been limited to local areas (within a few km). Though in the past longitudinal dune extension has influenced the creation and location of waterholes, aeolian transport resulting in net downwind sand movement is unlikely to be a strong factor in modern landscape processes.

Sand movement from dune to floodplain is evident in the haloes of paler sediment at the dune/swamp edge (Fig. 6). From there, sand can be transported downstream as alluvial sediment. Where the dune is undercut by a nearby channel, substantial sediment can be delivered to fluvial transport (especially where gullies extend from dune to floodplain; see section 4.4.1, *Trampling, Erosion and Gullying*). Dune undercutting by rivers is likely to be common, since dunes act to narrow flow paths, focusing stream power. Dunes are also truncated by nearshore processes in lakes.

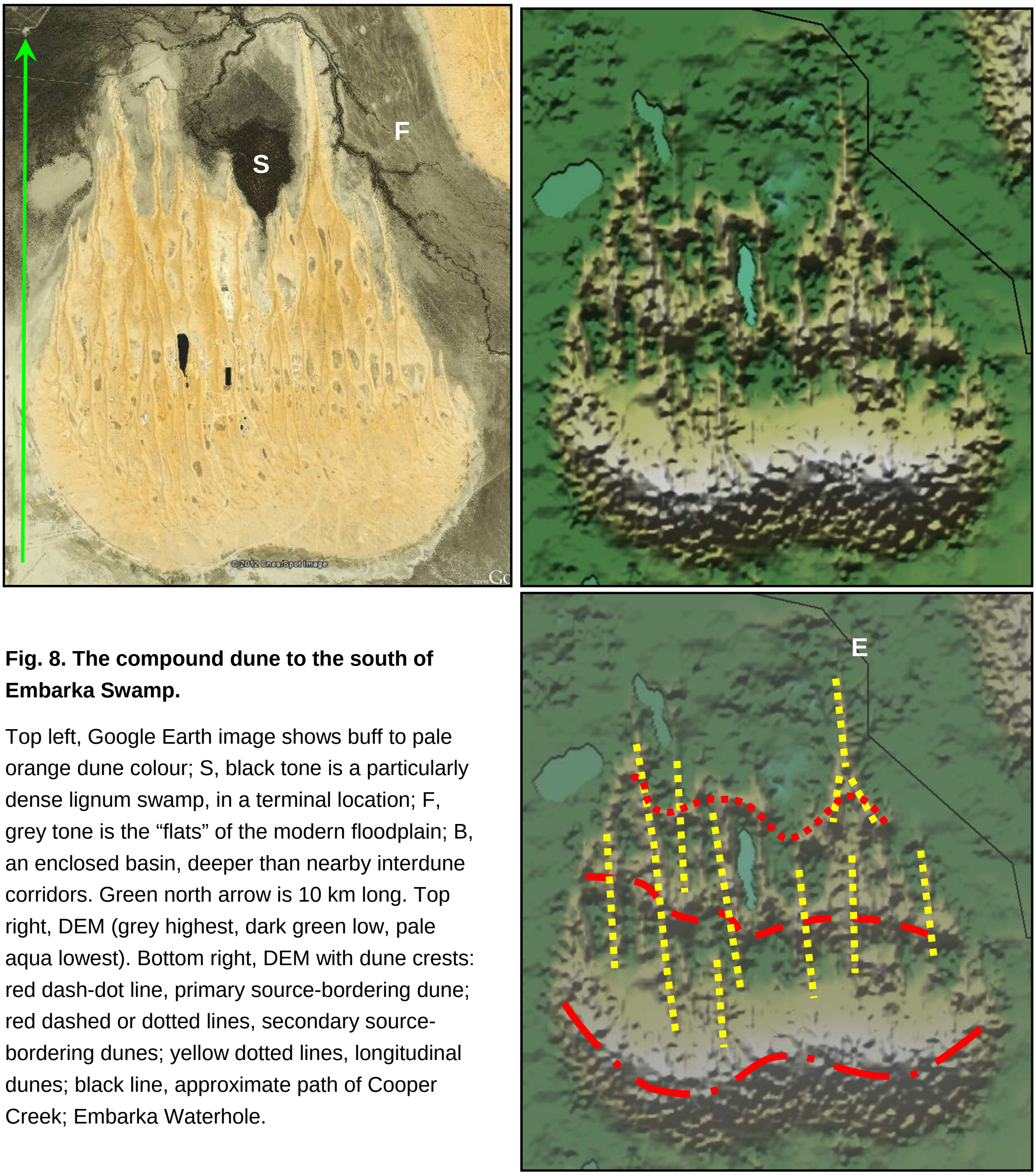


Fig. 8. The compound dune to the south of Embarka Swamp.

Top left, Google Earth image shows buff to pale orange dune colour; S, black tone is a particularly dense lignum swamp, in a terminal location; F, grey tone is the “flats” of the modern floodplain; B, an enclosed basin, deeper than nearby interdune corridors. Green north arrow is 10 km long. Top right, DEM (grey highest, dark green low, pale aqua lowest). Bottom right, DEM with dune crests: red dash-dot line, primary source-bordering dune; red dashed or dotted lines, secondary source-bordering dunes; yellow dotted lines, longitudinal dunes; black line, approximate path of Cooper Creek; Embarka Waterhole.

Fig. 9. Sand mobility in longitudinal dunes.

Top: Well- vegetated dune flanks stabilise longitudinal dune s against movement, but less-vegetated crests allow local sand mobility. Bushes (~1 m high) for scale. Bottom: Scalds (areas of bare sand) along the dune's lower flank show where wind erosion has lowered the ground surface. Note the pedestal of remnant sand (arrowed) near the two people.

Management implications:

- There is unlikely to be sufficient northward dune extension to affect present-day river flow. Dune crests are sometimes mobile; during drought local residents report devegetation, and good deal of sand mobility. However, it is likely that the bulk of sand transport will be back and forth within a local area.
- Dunes which are immediately adjacent to waterholes or primary channels are likely to be vulnerable to undercutting and slumping at the dune/waterhole edge. Large slumps dumping sand into smaller or less frequently inundated waterholes may change local ecology.
- Dune landforms which may be vulnerable to wind erosion are
    - interdune corridors and dune lower slopes (natural processes maintaining the longitudinal dunes will tend to move sediment from here to dune crests).

    - upwind (southern) faces of the transverse dunes (as the transverse dunes have no modern sediment supply to replace anything blown from base to crest).

- A consistent feature of the Strzelecki Desert dunes, especially the compound dunes of the Cooper Creek Fan, are the scalds (wind-eroded patches) along the lower flanks of the longitudinal dunes and southern margins of the transverse dunes. In some places fence effects demonstrate that a grazing history contributes to the number of scalds that are present. However the relative effects of grazing versus normal aeolian processes are not clear from this study, and further research is indicated.

2.5 Strzelecki Plain: "Flats"

Within the Strzelecki Plain, and especially Cooper Creek Fan, the Coongie Lakes area and the northern parts of Strzelecki Creek, the landscape is characterised by compound dunes set amongst kilometers-wide open flat areas ("flats"). The dunes-flats topographic relationships are amongst the strongest determinants of Cooper Creek's drainage network and therefore ecosystem distribution. Where flats are inundated by water they present as swamps or lakes. Where the flats do not commonly receive water, they present as broad claypans. Whether inundated or always dry, the scale, shape, and other features are similar (Fig 10). The flats have a microtopography including low rises and shallow basins, which influence reach-scale river function and local ecology. Most (perhaps all) of the flats are palaeodrainages – alluvial plains, flood basins, or lakes from previous versions of the Cooper Creek flow path.

The southern margin of some flats have shallow basins which are noticeably deeper than other nearby flats. In some places this expresses as particularly densely vegetated swamps, elsewhere as claypans or lakes. These basins are generally found immediately downwind of the trailing edge of the nearby compound dunes (e.g. Lakes Lady Blanche and Sir Richard), but there are also many in interdune areas, or forming the upwind source of transverse dunes. These basins and lakes are deflationary (created by wind erosion), relating to the vortices created downwind of an obstacle (the dune crest immediately upwind).

In the flats which are part of the present-day flow path it is clear that landform-scale sediment deposition is creating low sandy rises. Flood-driven sediment transport leads to sand deposition, for example from the downstream ends of waterhole splays, levee breaches and distributary channels. Since the sand currently transported down-system is white and the frequently-inundated areas are black with swamp vegetation, the microtopography is clearly visible on the GoogleEarth images and aerial photographs (Fig. 10).

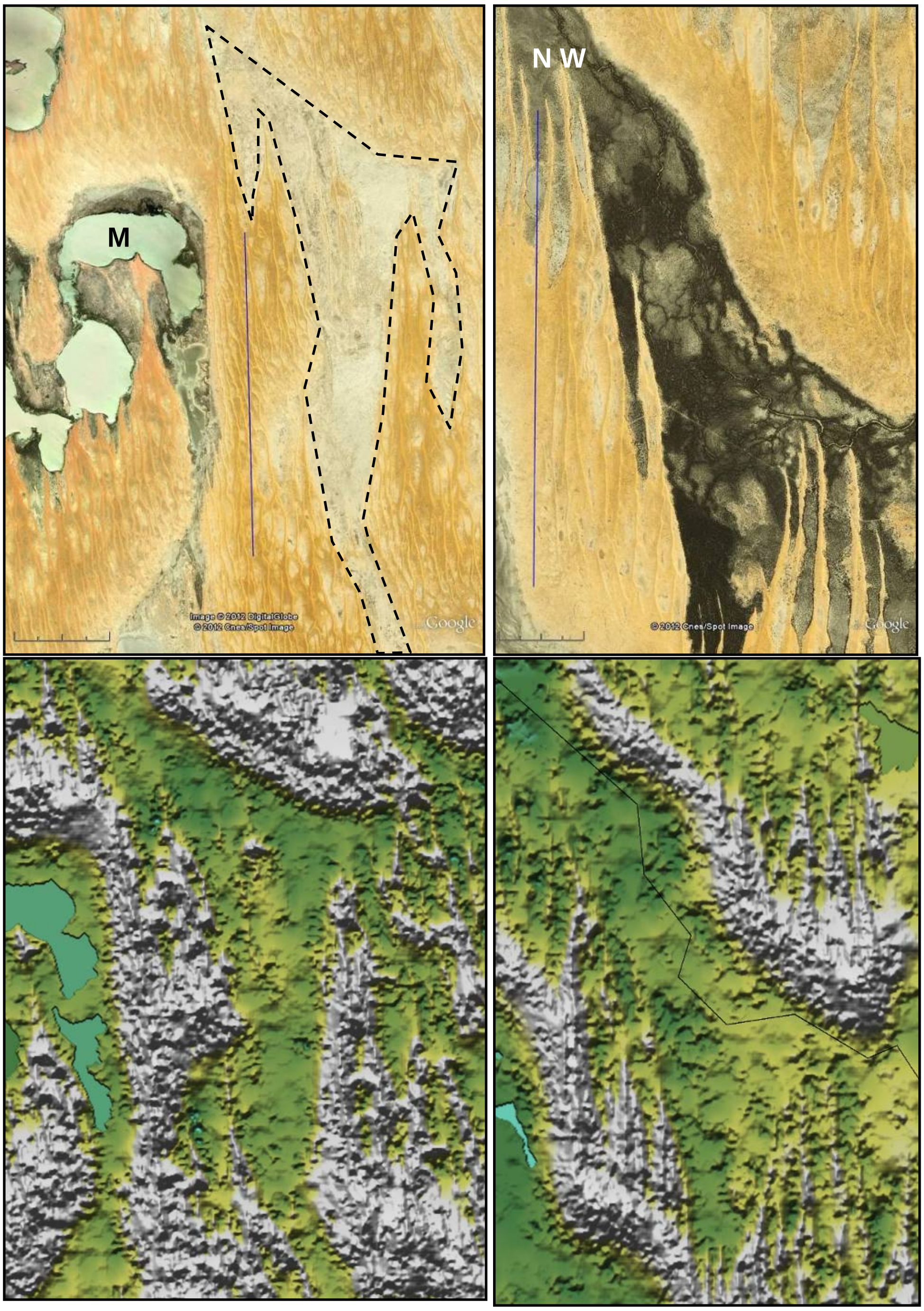


Fig. 10. “Flats” of Cooper Creek can be swamps or claypans.

The only difference between the swampy flats on the right and the dry claypan on the left is that the right is in the primary flow path, and the left is a palaeodrainage (no longer receives flow). Top, Google Earth images, north to top, grey scale line 10 km. The flats are grey (dry) or black (swampy), surrounded by the orange sand dunes. Bottom: DEMs; yellow/green colours show microtopography within the flats. Right, North West Branch in the reach containing Mundrangie Waterhole; flow center right to top left. Left, Lake Marracutchanie “M” is on the North West Branch, flow enters from bottom left of the lake and overflows out the bottom right. On the east of the compound dune the flats (dashed line) are a claypan.

3. AREA DESCRIPTIONS AND MANAGEMENT IMPLICATIONS

In this section the geomorphology of Cooper Creek is described, and management implications considered. The descriptions in this chapter are grouped according to the differing types of landscape. Cooper Creek in South Australia falls into eight geomorphic management zones, grouped by location (spatial proximity) and dominant landform types. The Queensland Windorah to Nappa Merrie reach is a ninth. Boundaries of these geomorphic zones are not intended to correspond to hydrological management reaches or ecological zones. Process analyses and greater detail are documented in Part 2 (Technical Appendix), section 7.

3.1 Windorah to Nappa Merrie: Super-Wide Cooper Floodplain

Cooper Creek between Windorah and Nappa Merrie waterhole (Queensland) is characterised by the number and complexity of anastomosing and reticulate channels, the number of waterholes, and the wide floodplain, which is dissected by many shallow floodways and presents a braid-like appearance. The belt of dominant fluvial activity is migrating westwards in response to subtle tectonic activity. The floodplain is up to 60 km wide (Fig. 11). It contains more than 300 recognisable waterholes, including many which are permanent (not known to dry out since European settlement) or semi-permanent (contains water >70% of the time), and is one of the "wettest" reaches in the Lake Eyre Basin. Waterhole distribution depends on local topography (e.g. sand dunes narrowing the floodplain, or two flow paths converging). Most occur along the major anastomosing channels.

The Cooper Creek in Queensland is outside the present study area, however its processes are critically important to the well-being of Cooper Creek in South Australia. This is the main source of water for the Coongie Lakes and the refuge waterholes, and is the pathway whereby monsoonal floods reach the arid inland. The extremely high degree of flow variability, including periodic large floods, is the only process that allows water to penetrate to the Coongie Lakes.

Management implications:

Cooper Creek depends on delivery of monsoonal floods from the north. Change to flow delivery from Queensland will undoubtedly have an extremely detrimental effect to the river in South Australia. Examples of change to flow delivery include attenuation of flood peaks (for example by dams) or reduction in flood volume (for example by extraction for irrigation or industrial processes). It is recommended that irrigated agriculture should not be developed using Cooper Creek waters, and that dam impoundment be limited to the small scale of pastoral dams such as currently exist.

The relatively well-watered nature of this reach suggests that it represents a very likely cane toad invasion pathway. It is recommended that the South Australian and Queensland governments coordinate an approach to reducing the opportunities for cane toad invasion in this reach.

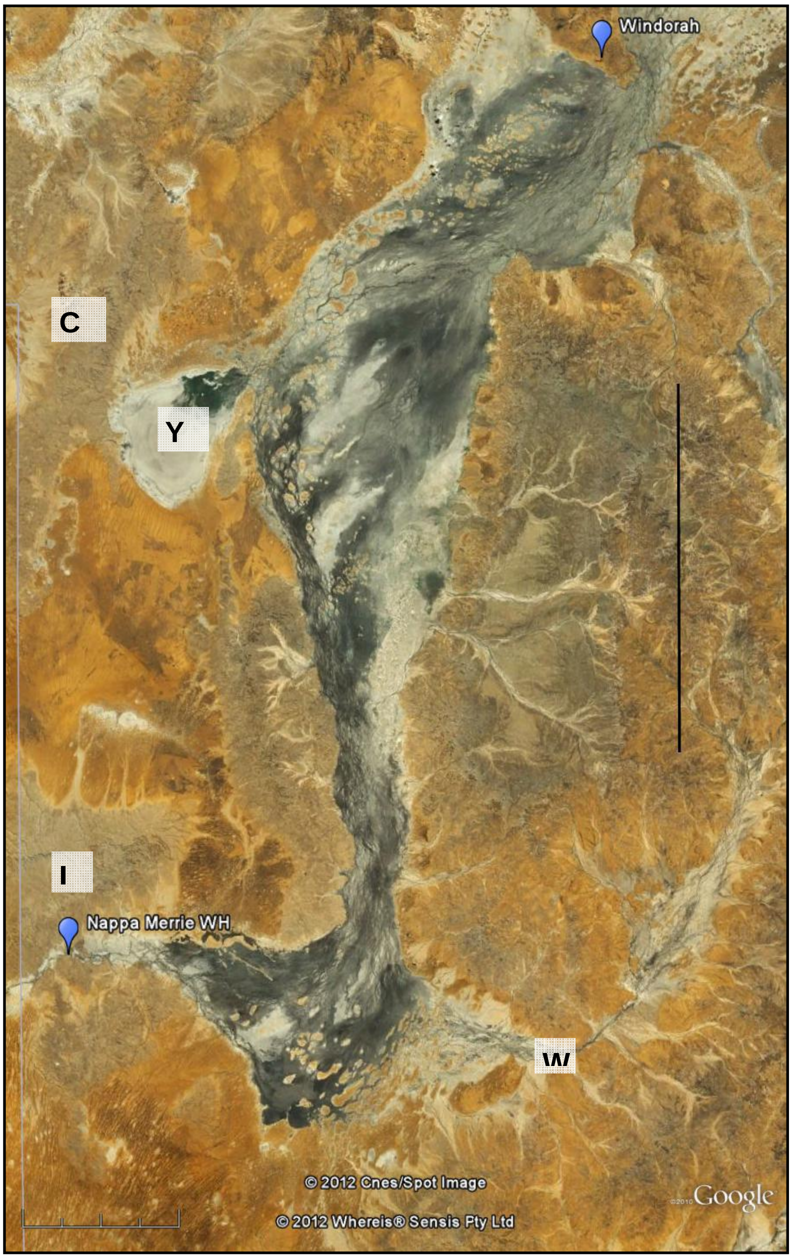


Fig. 11. The Cooper's wide floodplain between Windorah and Nappa Merrie.

The floodplain is pale grey (sand and mud), and dark grey to black (dense vegetation: frequent inundation), between the orange and grey-brown of the stony deserts and sandplains. W, Wilson River; YY, Lake Yamma Yamma; ID, the Innamincka Dome; CD, the Cordillo Dome; north to top, black scale bar is 100 km.

3.2 Cooper Creek in the Innamincka Valley

From just east of the South Australia-Queensland border to the township of Innamincka, Cooper Creek is confined within the rocky and stony walls and steep slopes of a valley through the Innamincka Dome. The width of the valley is very irregular (Fig. 12). The valley was created by Cooper Creek cutting its way down against the slow uplift of the Innamincka Dome. This part of the Cooper is extremely important:

- Ecologically, the main refuge waterholes are here. The higher stream power in this narrow valley carved deeper and longer waterholes than elsewhere in the study area.
- Geologically, the path of the river through the uplifting Innamincka Dome defines the base level of the Cooper Creek for hundreds of kilometres upstream, governing the fluvial geomorphology and therefore ecosystems.

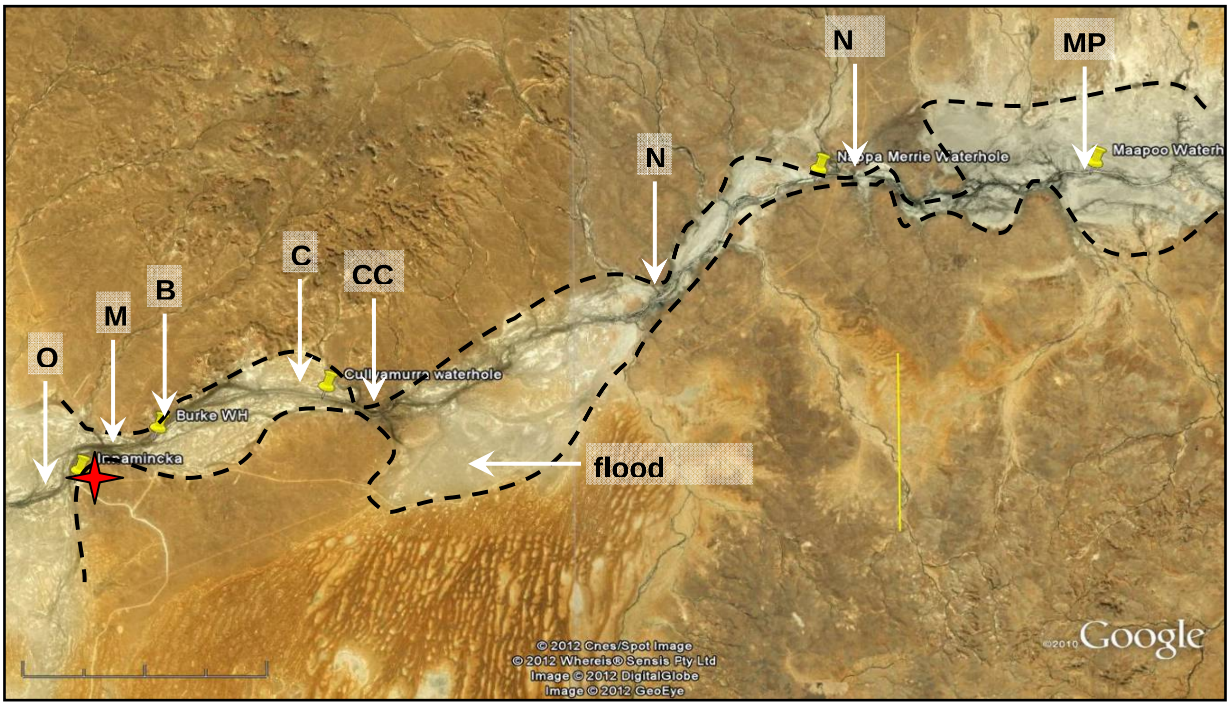


Fig. 12. Cooper Creek 's valley through the Innamincka Dome.

Irregular valley walls (dashed black line) enclose the pale fluvial sediments and the black line of the main creek channels; there are also some orange-brown patches within the valley which are isolated remnant rocky hills. The orange-brown and greyish-brown tones outside the valley walls are rocks and dunefields of the Innamincka Dome. Google Earth picture, flow right to left, north is to top, yellow scale line = 10 km, red star is Innamincka township. Waterholes: Q Queerbiddie, M Mulkonbar, B Burke, C Cullyamurra, CC the Cullyamurra Choke, N Nappaoonie, NM Nappa Merrie, MP Maapoo.

In this reach, the Cooper has carried much greater flows during times of previous wetter climates than it does today. The valley probably experienced short extreme flood events during the period 24-12 ka and ~5 ka. The traces left by these extreme floods still dominate the landscape, as the smaller modern-day flows do not have sufficient stream power to change them.

On a kilometer scale, and using the area around Cullyamurra Waterhole as an example, the landforms are (Figs. 12, 13, 14):

- Flat-topped plains, hills and mesas, made of rocks of the Innamincka Dome, are the highest landforms in the area. There is a mesa next to the road just near the Cullyamurra turnoff, and the 2010-2011 floods came up to the road sign at its base (see left-hand red arrow on Fig. 13).
- The next level down is a high terrace of white to pale buff sands. This is a palaeo-floodplain left behind from extreme floods (black arrow on Fig. 13). This level is above modern fluvial processes: the 2010-2011 floods did not come up to this level (see right-hand red arrow on Fig. 13).
- There are a few small orange dunes on the terrace.
- There are high-elevation shadow bars and slackwater deposits (white sand deposited in the lee of some floodplain obstacle during extreme floods).
- Several wide palaeochannels dissect the top of the terrace (Figs. 13, 14). They may be short-term bar top channels formed during extreme floods. Some of these wide palaeochannels carry within them smaller, inset modern channels or waterholes.
- The general level of the high terrace slopes down towards the river. Some small channels, above the level of the modern floodplain, evidently carry above-floodplain level flood-flow.
- The modern floodplain and waterhole are the lowest levels in this area.

The small-scale (tens of meters) landforms along the Cullyamurra reach include

- the subtle rise and fall in ground surface reflecting the various palaeochannels and flood channels
- the waterhole' s densely vegetated riparian zone
- the waterhole banks are generally very steep
- there is likely to be a levee along the main waterhole banks (an area defining the waterhole edge and including the riparian vegetation, which is a slightly greater elevation than the surrounding floodplain)
- in places, the levee is breached by overflow/drainage channels, which in times of rising flood will move water out onto the floodplain, and during

waning flood will be a pathway for water draining back into the central channel.

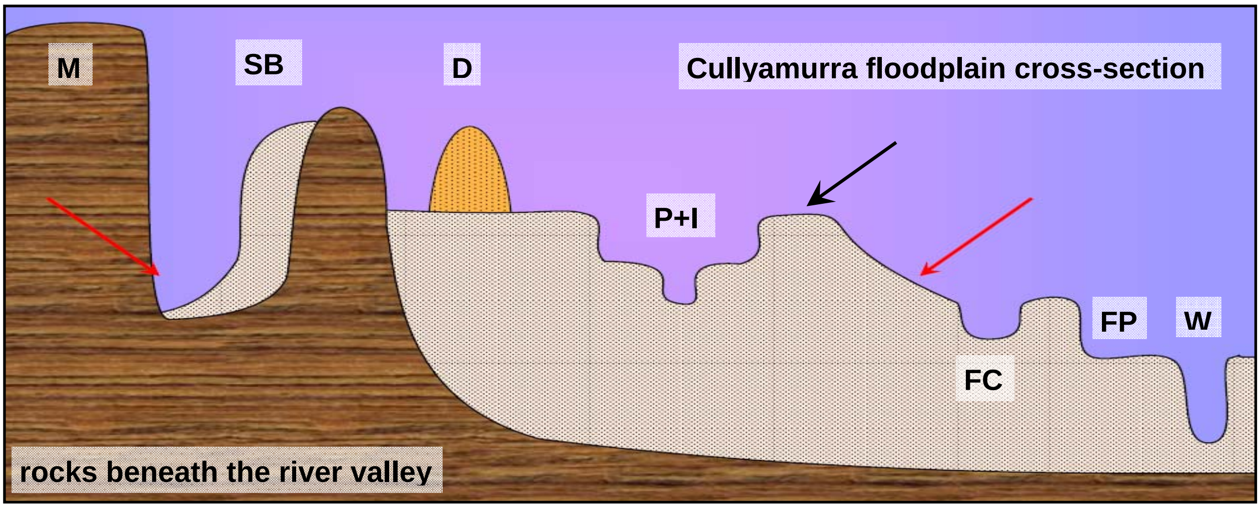


Fig. 13. Sketch cross-section across the Cooper valley near Cullyamurra Waterhole.

Brown stripes are rocks, grey and black stipple are the remobilised white quartzose sands, redeposited as fluvial landforms, orange and black stipple is the orange sand dunes. M, the mesa next to the road at the Cullyamurra turnoff; SB, a high-level shadow bar deposited downstream from outcrop during extreme flooding; D, an orange dune; P+I, a wide palaeochannel with an inset modern flood channel; FC, flood channel; FP, the modern floodplain; W, Cullyamurra Waterhole. Black arrow, high terrace formed from a palaeo-floodplain; red arrows, approximate flood levels during 2010-2012. Water level was high enough to inundate flood channels (including up to the road sign at the base of the mesa) but was not high enough to inundate the high terrace. Not to scale: vertical distance ~10 m, horizontal distance~3 km.

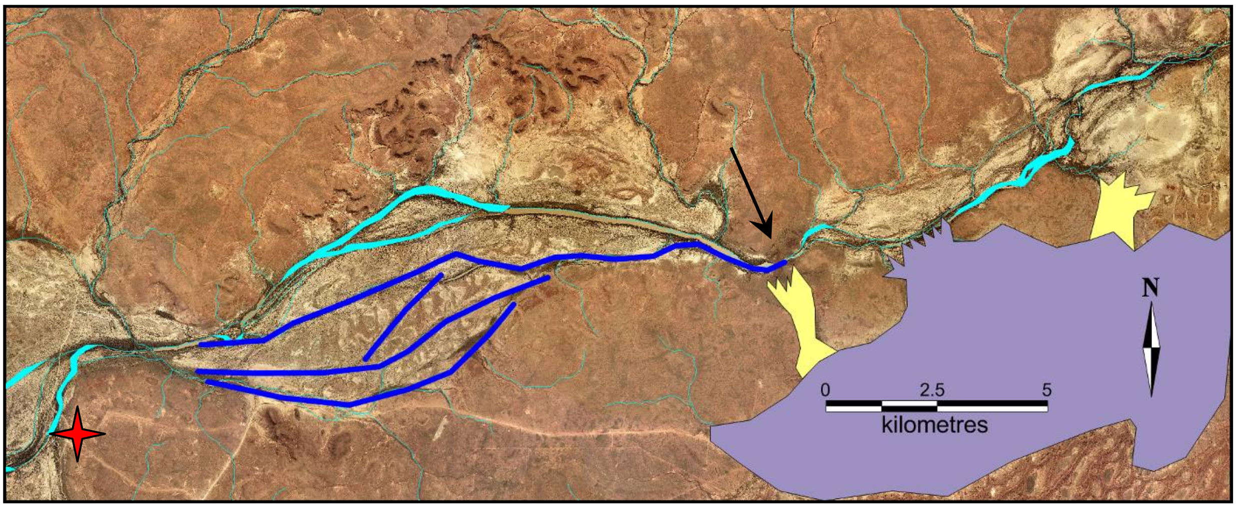


Fig. 14. The Cullyamurra reach and the upvalley flood basin.

The high palaeo-floodplain is cut by the present-day drainage (pale blue lines superimposed on the orthophoto), and by palaeochannels (dark blue lines). The floodplain is most constrained at Cullyamurra Choke (black arrow). A large flood basin (purple) filled during some extreme flood event, losing water back into the main valley through high-level outwash channels (yellow, jagged edge) before finally draining through a low-level outwash (purple, jagged edge). Red star is Innamincka township.

In the valley through the Innamincka Dome, there are two very narrow reaches: the Cullyamurra Choke, at the upstream end of Cullyamurra Waterhole, and a similar choke near the Nappa Merrie Waterhole. The valley becomes extremely narrow and there is almost no floodplain; these would be good cane toad monitoring locations. At the Cullyamurra Choke, a wider western section is flanked by strong rocky outcrop, which may be unfavourable habitat for cane toads. In the more narrow eastern section the channel is constrained by a low plain of large boulders (remnants of a catastrophic outwash event). The boulder plain is above present day fluvial processes, however it probably benefits from run-off from nearby rocky hills. There is certainly sufficient moisture to support stands of trees. After heavy rain, the boulder pools are capable of retaining free water for as much as a week (Fig. 15). These pools are a potential cane toad shelter; this rocky ground cannot be assumed to be a migration barrier.

Fig. 15. The boulders of the outwash field at Cullyamurra Choke.

The boulders show red where they are never submerged, and grey where ponded water is retained. White rings of evaporation show the water lasted for at least a week. Geological hammer for scale.

Management implications:

The high terrace surface is generally beyond the reach of modern fluvial processes, and would be a good location for any essential permanent infrastructure (for example, emergency water tank, or resident Ranger's house).

However, there is a high risk that erosion along tracks and footpaths from the high terrace surface down to lower levels would develop into extensive and irreversible gullying. As these high plains were created during extreme flood events, there is no present-day natural process for their maintenance. Any such infrastructure should therefore be not for public access.

The risk of erosion and gullying exists any place where the floodplain goes from a higher to a lower level. It is recommended that:

- Tourist camping areas should continue to be at the level of the modern floodplain, where occasional floods can refresh sediments.
- Tracks/roads going down from the gibber plain should be planned and managed carefully, to avoid the creation of gullies along the roadway.

Riparian vegetation is critically important for trapping sediment, and for maintaining the waterhole's banks and depth. Tourist camping areas should be managed so as to preserve vegetation and rehabilitate degraded areas (e.g. by rotating camping spots, discouraging vehicles or tents under trees, active replanting in damaged areas).

The narrowest sections of the valley (the “Chokes”) may be good locations for cane toad monitoring, as they are constrained by rocky outcrop which is presumably unfavourable toad habitat. However part of the Cullyamurra Choke is a boulder field which has potential to be favourable for cane toads.

The overflow-and-drainage channels which cut through the waterhole levee are likely to be natural (it is in keeping with the rivers processes elsewhere). However, if these small vegetated gullies become widened or devegetated they may become an erosion problem, as they will focus flow (and increase the potential for erosion) during waning flood. People should be discouraged from using these gullies for access to water, as boat launching and vertical foot traffic are damaging activities, occurring in locations where the damage will trigger ongoing problems.

Since people’s desire for water is the heart of local amenity and the valuable tourist economy, it is strongly recommended that an investigation be made into alternate ways to provide access while 1) avoiding damage to banks and drainage channels, while 2) preserving the wild camping experience. Since this is not a simple question, and since this has application across the whole Lake Eyre Basin and many other parts of drylands Australia, it is recommended that such research be externally funded and include input from residents, design professionals, process geomorphologists, and landscape architects

3.3 The Cooper Creek Fan: Branches and Offtakes

The Cooper Creek Fan is a low-angle alluvial fan with its apex located where Cooper Creek exits the Innamincka valley (Location Map, Geomorphic Management Zones Map, and also see Figs 2 and 5, and section 2.2 *Topography of the Strzelecki Plain*). The Fan occupies nearly 25% of the Strzelecki Plain. The landscape appears flat to the eye, and the overall gradient is very low. Nonetheless the Fan's gradient is approximately twice what Cooper Creek experiences elsewhere on the Strzelecki Plain, and so the potential for geomorphic activity is higher here.

The topography of the Cooper Creek Fan is dominated by orange-brown compound sand dunes (Fig. 8), broad apparently featureless flat areas of greyish dusty muds (Fig. 16), and lakes and swamps (Fig. 10). The dunes were created during previous wetter climates. Fluvial sand transported through the Innamincka valley and across the Cooper Creek Fan was exposed in bars along the river's channels. Winds blew sand south-to-north, creating source-bordering transverse dunes along the river's northern banks. Later, the wind blew sand from the dune bases and towards the north, forming a series of longitudinal dunes from each transverse dune. The resulting compound dunes look like combs with the teeth pointing northwards.

Fig. 16. Flats in the Cooper Creek Fan.

These broad areas of extremely low relief are floored by clay with more or less silt, according to whether they receive water and sandy/silty sediments from a distributary channel. Where the sediments are clay-rich and there is regular inundation, strong gilgai features (heave and crabholes) are developed.

Cooper Creek extends across this landscape, deviating around the dunes, sometimes cutting through narrow valleys between the dunes or undercutting a dune edge, and wandering across the flats. In some cases, dunes influenced the location and directions of later channels. These processes have repeated over geological time, the aeolian and fluvial landforms developing together and in response to each other. Repeated avulsion and channel relocation has created a web of palaeochannels across the Fan. Some currently function as flood overflows, and have isolated waterholes in places of flow concentration.

The inner Cooper Creek Fan (Fig. 17) has Cooper Creek's parent channel as a sinuous, largely single-thread channel down to the forks (F1, F2, Fig.17). At the forks Cooper Creek splits into the Main Branch and the North West Branch. In this report, the forks mark the beginning of the outer Cooper Creek Fan. Throughout the Inner Fan, the channel alternates between deep simple reaches with steep tree-lined banks (waterholes) and more geomorphically complex reaches which are wider and shallower, with sandy bars extending across much of the channel.

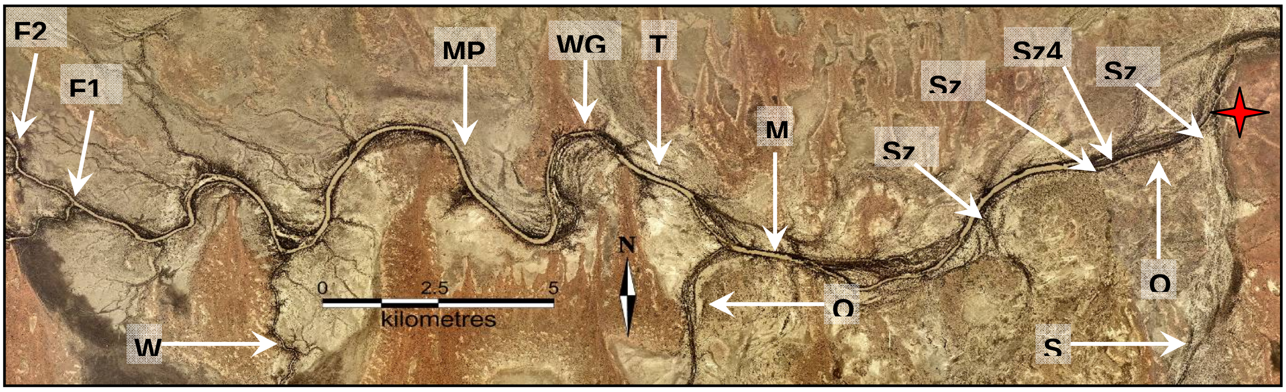


Fig. 17. The inner Cooper Creek Fan reaches of the Cooper Creek.

This orthophotograph shows main (parent) channel and the distributary channels. The main channel is pale grey (free water), lined by dark tones of riparian vegetation. Sediments: alluvial sands (white to pale grey), dune sands (shades of orange and brown), clay (mid to dark grey), vegetated areas (dark grey). Waterholes: Q Queerbiddie, M Minkie, T Tilcha, MP Marpoo. Locations: S Strzelecki Creek, O Ooranie Creek, WG Wills Grave, W Wilpinnie Creek, F1, F2 are the 1st and 2nd forks where the Main Branch and the North West Branch diverge. Sz1, Sz2, Sz3 and Sz4 are the offtakes delivering water to Strzelecki Ck.; Sz1 is located within the Town Common. Flow right to left, north is to top, red star is Innamincka township.

Distributary channels are a particularly characteristic and important feature of the Cooper, and are critically important to local ecosystems. At the offtake (where the small channel leaves the main channel) water and its accompanying sediment is diverted from the parent channel and spread it across nearby flats. This is an important process in creating the non-dune parts of the Cooper Creek Fan. The larger distributaries include Wilpinnie and Ooranie Creeks (Fig. 17). Offtakes are often located upstream from shallow complex reaches, probably indicating a formation process involving hydraulic damming and levee breaching.

The Cooper Creek Fan is complex, and this section's descriptions are subdivided into 1) Fan apex, 2) palaeodrainages and their waterholes, 3) parent and distributary channels & their waterholes (inner Fan), and 4) the Main and North West Branches (outer Fan). Further detail can be found in the Technical Appendix, section 7.3.

3.3.1 Fan Apex: Queerbiddie, Town Common, and Strzelecki Creek Offtakes

This eastern section of the Fan (the apex) hosts the Cooper Creek parent channel, and four offtakes which deliver water to Strzelecki Creek. The volume of water discharging down the creek channels is at its greatest at the Fan apex, and potential for geomorphic activity is high. Channel relocation has probably swept over and disrupted previous landforms, blurring the sand dunes and depositing sediments over palaeodrainages.

The main channel of the Cooper is strongly defined here, with very dense lignum and other riparian vegetation along Queerbiddie Waterhole and between the Town Common and the channel. Though airphotos (see Figs. 17, 18) and topographic maps show the present-day Cooper channel as being clearly the major channel, this is misleading. The DEM shows (see section 7.3.1) that the channel segment extending south towards Strzelecki Creek is just as big and deep as the main channel.

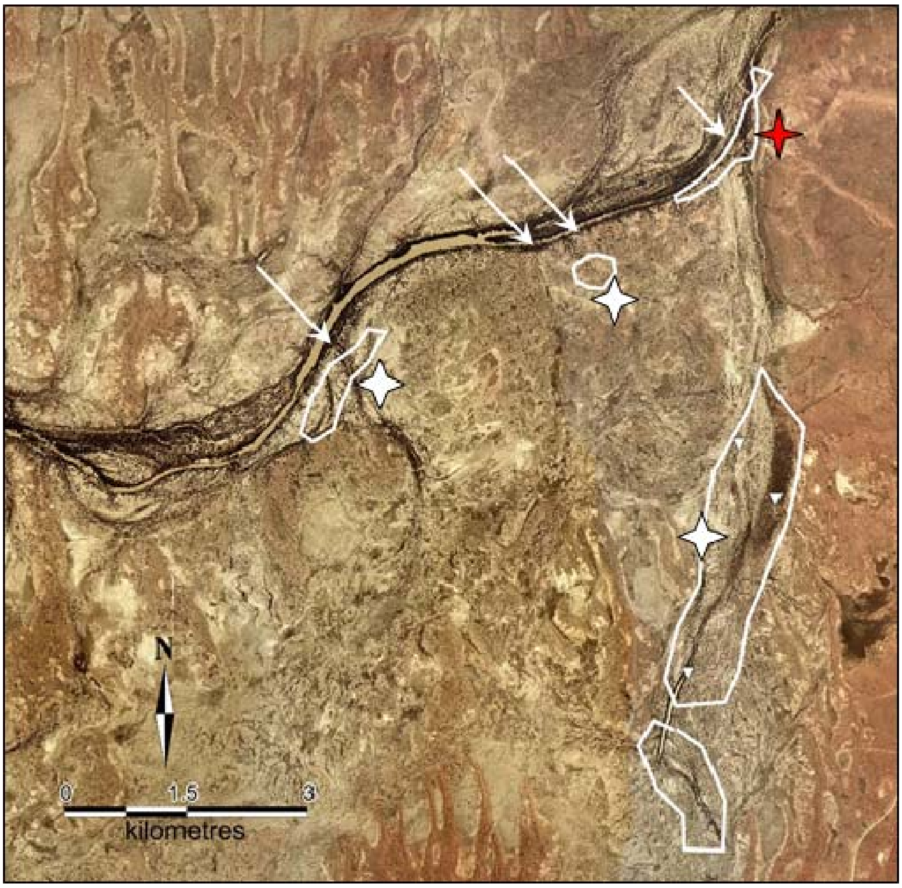


Fig. 18. Offtakes to Strzelecki Creek at the apex of the Cooper Creek Fan.

Five vulnerable areas (white outlines) at the apex of the Cooper Creek Fan: the three sills (near white stars), the Town Common, and the downstream end of Burlieburlie Waterhole. White arrows, offtakes; red star, Innamincka township; white triangles, highest elevations on the main offtake's sill

Only a small proportion of Cooper Creek’s flow goes down Strzelecki Creek, and two factors maintain this division of flow. Firstly, the riparian lignum and other vegetation keeps the Cooper Creek channel hydraulically efficient, encouraging flow to continue in the present path. Secondly, a wedge of sediment (see section 7.3.1) has created a sill, a barrier between the Cooper and Strzelecki Creeks. It was most likely deposited during an extreme flow event (possibly the same flood that deposited the high plains near Cullyamurra).

The sediment wedge’s white sands form a high terrace: a localised area of relatively elevated ground which discourages southwards flow except during high river levels (see section 7.3.1). The modern channel, including Queerbiddie Waterhole, cuts through it, and the 15 Mile Track travels across its high, dry plains as far as the Minkie Waterhole turnoff. Four offtakes leave the Cooper Main Channel along the left bank (Fig. 18), and there are three sills where the offtake water crosses the sill to deliver water from the Cooper into the Strzelecki Creek.

The ecologies of Cooper Creek, the Coongie Lakes and Strzelecki Creek are adjusted to the modern conditions of flood frequency and volume. Likewise, the human expectations of water availability (and its effect on quality of life and the pastoral and tourist industries) fit the present hydrological conditions. Presently, Strzelecki Creek only receives water infrequently and at relatively low volumes. Any changes which increase the proportion of flow going down Strzelecki Creek will decrease the availability of water to the swamps and lakes of downstream Cooper Creek. Any changes which decrease the proportion of flow going down Strzelecki Creek will be detrimental to the southern ecosystems and inhabitants. Therefore, the management goal must be to allow the status quo to maintain itself within its present degree of variability.

Five potentially vulnerable areas are identified (Fig. 18):

- the main channel's left bank riparian zones from 400 m upstream of the Innamincka Causeway all the way downstream through the Town Common
- the three sills, including the upstream part of Burlie Burlie Waterhole
- the downstream part of Burlie Burlie Waterhole.

In the main channel's left bank, either devegetation or levee breaching would simultaneously diminish the forces that keep the main channel scoured, and provide floodwaters with an easier flow path away from the main channel. In the sills and waterhole there is a risk that erosion could develop into self-extending arroyos and gully networks, providing flows with an easy, efficient flow path down Strzelecki Creek. Anything that promotes erosion should be avoided (such as devegetation, or flow concentration from roads, footpaths directly down steep slopes, or streamwise stock pads).

Management implications:

- The natural processes which promote flow down Cooper Creek and discourage water diversion down Strzelecki Creek should be maintained.
- The Cooper Creek Fan apex should be recognised as a separate management zone. Planning for Innamincka Township should prioritise preservation of the Town Common vegetation and landforms.
- The dense riparian vegetation along the main channel left-bank, for 2 km upstream and downstream from Sz2 (Fig. 17), should be protected from erosion, and managed to maintain riparian vegetation. Riparian vegetation should be rehabilitated where it can be demonstrated that it has degraded.
- When the Innamincka Causeway is open, campers should be encouraged to make use of the far side of the river, along the less-vulnerable right bank, while the Town Common within the defined vulnerable area is rested.
- The Strzelecki Track between the Town Common and the Burlie Burlie Waterhole should be carefully managed to prevent erosion. In particular, the upstream and downstream ends of waterhole should be protected from devegetation and streamwise stock pads, and the broad crest of the sill should be protected from infrastructure development or anything that might promote gullying and erosion.

3.3.2 Palaeodrainages and Isolated Waterholes

The Cooper Creek Fan has developed by channel relocation from one place to another. In repeated episodes over geological time, channels (in locations other than the present flow path) have created compound dunes, and dunes have influenced channel location and flow direction (most frequently towards the north, Fig. 19). Terminal lakes, like the present Coongie Lakes, would have been associated with some palaeodrainages. It is likely that most or all of the "flats" on the Cooper Creek Fan represent palaeodrainages (many have been later modified by deflationary basins, or cut by advancing longitudinal dunes). The most recently-abandoned palaeodrainage is Christmas Creek, which used to flow from south to north.

Palaeodrainages which are close to the main Cooper flow paths are more likely to receive floodwaters, and those close to stony uplands receive runoff from local rain. Where local topography focusses flow paths, isolated waterholes occur along these palaeodrainages (e.g. Montepirie, Durantie, Gidgealpa Waterholes). They are not relict in the true sense: it would be more accurate to consider them as waterholes along what are now flood pathways, and were once the main drainage line.

These isolated waterholes tend to be less deep than main-channel waterholes (Costelloe 2013, his Table 1), do not retain water for very long, and are less likely to act as refugia. However, they are likely to be important for local plant and terrestrial ecology. In addition, If they encounter sufficient flow volumes and have sufficient riparian vegetation that the self-scouring fluvial process happens during flood events, then it is likely that the waterholes are point sources of freshwater recharge for local groundwater, and so may be important for the ecology of deep-rooted plants.

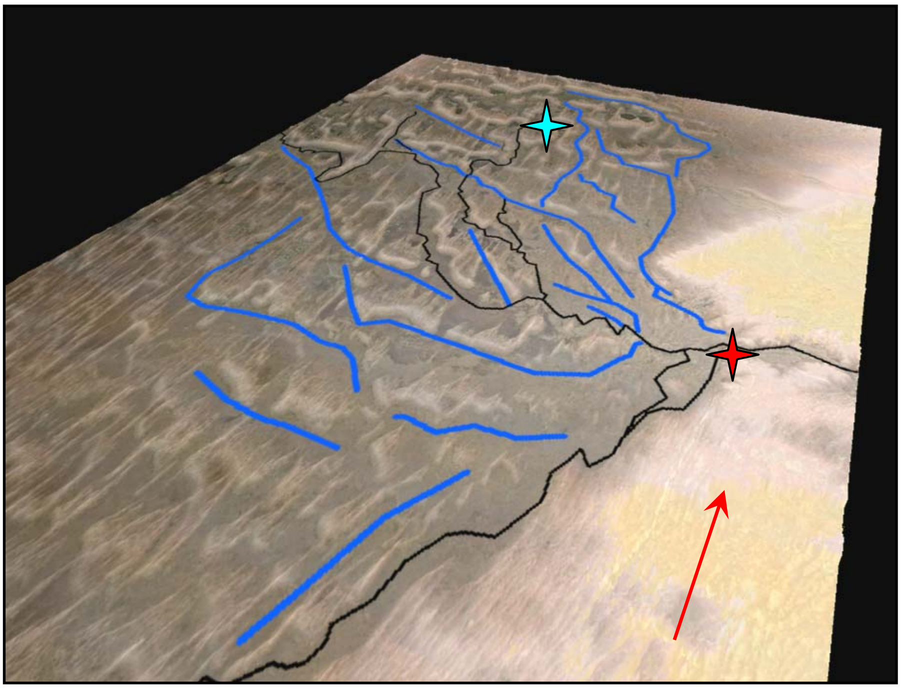


Fig. 19. Palaeodrainages of the Cooper Creek Fan.

Oblique 3D view looking northwest across the Cooper Creek Fan, showing the dominant northwesterly trend of the palaeodrainage network. Scale arrow is 30 km long and points north; red star is Innamincka township, blue star is the Coongie Lakes. Black lines are the present-day Cooper and Strzelecki Creeks (as expressed in the 1:5,000,000 topographic data), blue lines are some of the palaeodrainages. The image is a grey-to-white DEM overlain by a semi-transparent orthophoto.

On a geological timescale, the channels relocate, and wetlands come and go. Though unlikely, large-scale landscape change is possible. Channel relocation is likely to be sudden, and may happen in response to a large flow event (or some human-caused change to topography). Channel relocation will divert water away from some lakes or swamps, and (eventually) create new wetlands.

Management implications:

It should be a management goal to preserve the geomorphic processes that maintain the landforms, within the natural range of variability.

Though not part of the primary flow paths, and not deep enough to act as refugia, isolated waterholes are likely to recharge local near-surface aquifers and support local ecosystems.

3.3.3 Inner Fan: Channels, Distributaries, and Waterholes

Across the inner Cooper Creek Fan, Cooper Creek is a largely single-thread main channel, with secondary flood channels forming anabranches which only activate at higher flows. The channel is sinuous from the Town Common to Minkie Waterhole, and meandering from there down. The meandering is currently active but it is very slow. Riparian tree roots exposed as part of normal meander outer-bend processes indicate only minor bank retreat (Fig. 20). Elsewhere, riparian tree roots indicate general bank stability, except at the offtakes of the distributary channels, where there is often evidence of long-term bank stability followed by rapid bank retreat.

Fig. 20. Exposed tree roots indicate only slow bank retreat.

Left: The outer bend of the active meander ~3 km downstream from Wills Grave. Right: Outer bend of the less active meander at Marpoo Waterhole.

The Cooper Creek in the inner Fan can be considered to have two types of reach:

- Waterholes (Fig. 21) are relatively deep and have a single, simple, straight to gently sinuous channel. They are most likely to occur in high-energy contexts such as meander bands or downstream from the confluence of two anabranches. The banks are steep, and Coolibah and gum trees growing along the banks tend to lean over towards the water. The riparian zone at the bank top is vegetated with trees and shrubs, but only within a narrow zone parallel to the bank. If waterholes here are similar to those researched elsewhere in the Channel Country, the riparian zones will have levees, and the waterhole bed will be sealed by a layer of mud which prevents transmission of river water into the groundwater, except during flood scour.
- The shallow reaches between waterholes are more complex, often carrying a main channel and several anabranches or flood channels. The gently sloping banks are typically vegetated with often young-looking riparian trees growing

vertically, and dense lignum. Since these reaches are shallow they are more likely to carry in-channel large trees (Figs. 21, 22), and to dry out between floods. The combination of wide shallow channel cross-section and high boundary roughness indicates these reaches will be less efficient in passing water downstream during floods, predisposing the development of distributary channels in the reaches immediately upstream.

Fig. 21. Tilcha Waterhole and the shallow reach at its downstream end.

Looking downstream towards the end of Tilcha Waterhole (see Fig. 17), the clear deep channel (foreground) is succeeded by a shallow channel occluded by large trees (distant).

Fig. 22. The shallow complex reach upstream from Minkie Waterhole.

Looking upstream from the Minkie Waterhole tourist area into a shallow complex reach. A flood anabranch (left side of the photo) rejoins the main channel (right), with a heavily vegetated low sandy bar (white sand at left-center photo) between.

Many distributary channels come off the Cooper Creek main channel on the Cooper Creek Fan. Most are not named, but the largest are the size of small creeks and show on the maps: these are the channels feeding Strzelecki Creek, Ooranie and Wilpinnie Creeks, and the three distributaries which divide Cooper Creek into Cooper Main Branch and Cooper North West Branch. The offtakes of these distributaries are shown in Fig. 17 (Sz1, Sz2, Sz3, Sz4, W, O, F1, F2).

Distributary channels are created as floodwaters overtop and breach the riparian zone. There are some important distributaries at the Fan apex, but the greatest number are located from Marpoo Waterhole onwards (Fig. 17). In these reaches there is sufficient elevation difference (main channel to distributary termination) to develop and maintain the channel.

Distributary channels are critically important to local ecosystems, as they carry water and fine sediments out to the flats. They also are a key factor in the pattern of sediment deposition across the Cooper Creek Fan. Short distributaries deposit their sediment (pale river sand and silt) close to the main channel, where it builds up into sediment wedge flanking the channel (Fig. 23). Longer and larger distributary channels deliver water and sediment kilometers distant from the main channel (Fig. 23). Water carrying mud can travel well beyond distributary terminations, as unchannelled overland flow across the flats, or through the reticulate channels of the various swamps.

Management implications

- Riparian vegetation and in-channel vegetation are strong influences on sediment deposition and flow efficiency. Therefore, they are important contributors to fluvial function. Riparian vegetation should be managed to preserve its density and diversity, and in-channel trees should be respected.
- Distributary channels are a natural consequence of the Cooper’s flow pattern and sediment load. Most or all modern distributaries feed the primary flow paths or the flood overflows, and are an important component of local ecologies. The distributary channels should not be blocked by infrastructure (for example, road bunds).
- The high-volume flood peaks are an important factor in flows being able to access the distributaries. Infrastructure which crosses distributary channels should allow sufficient passage of water that high-volume flood peaks are not retarded or attenuated.
- Complex geomorphology exists at a local scale in many places (e.g. complex shallow reaches, offtakes, meander scroll plains). Landform mapping should be a preliminary step in tourist location design or feral animal management plans.
- Landform mapping at a detailed scale will require access to aerial photography; if scanned from existing photos, the scans should be at a very high resolution. For mapping purposes the existing photos are adequate, but for long-term erosion monitoring, future high-resolution data is necessary.

Fig. 23. The distributary channel Wilpinnie Creek.

Wilpinnie Creek extends south from Cooper Creek, depositing silty sand along its length. Middle arrows point to the creek's offtake, and bottom arrow to the Munga Munga Waterhole. Orange / brown colours are compound dunes, white to pale grey colours are alluvial sands deposited by distributaries, dark grey is vegetation and/or inundation areas, black is dense riparian vegetation. Flow is right to left in Cooper Creek and top to bottom in Wilpinnie Creek.

The longitudinal dune nose (top arrow) has not migrated north during the incremental shift of the meandering channel, a time period likely to be thousands of years.

3.3.4 Outer Fan (Main and North West Branches): Channels, Swamps and Waterholes

Cooper Creek in the outer Fan has a more diverse range of fluvial landforms than exists in the inner Fan. The channel types include (as they did in the Windorah to Nappa Merrie reaches) anabranching, anastomosing, and reticulate, while distributary flow, and lack of lateral confinement, allows swamps to develop in the flats. Swamps and lakes preferentially develop in deflationary basins within the flats. Where flow is gathered in one single-thread channel, the division between waterhole and not-waterhole is less clear: on air-photo it presents as a continuous channel, strongly marked by riparian vegetation, and only the naming of locations indicates some places hold water longer than others.

Cooper Creek divides between three distributary channels a few kilometers downstream from the Wilpinnie Creek offtake (Figs 17, 23). Two distributaries flow towards the southwest: they are the water source for the Cooper Creek Main Branch. The third distributary flows northwest, and is the source of the Cooper Creek North West Branch. Although the topographic maps and coarse-scale topographic digital data treat the North West Branch as if it is a single drainage line, in fact it splits in two a short distance north west of Scrubby Camp Waterhole.

The Main Branch distributaries are single-thread channels before entering the first of the wide “flats” where the channels divide repeatedly. The next ~40 km of flow path is a network of anastomosing channels, and swamps with reticulate channels, and waterholes in high-energy locations. The primary flow path is indicated by the largest or most dense cluster of anastomosing channels, or by swamps with visible upstream-downstream connectivity. However, it is more accurate to consider the entire "flat" as the flow path of a disconnected waterway. The only exceptions are the terminal swamps in deflation basins (see Fig. 8). The Main Branch flow path goes through Embarka Swamp, forms a single channel again through Narie Waterhole, and continues northwest (Fig. 24).

The North West Branch is a single-thread channel until downstream from Scrubby Camp Waterhole, where it splits into two flow paths (NW1, NW2, Fig. 24). For the next 10-12 km the flow path is a network of anastomosing channels and swamps, with small waterholes where the flow path is laterally constricted. A cluster of terminal swamps and lakes (hosted in deflation basins) are held within the interdune spaces to the south (Fig. 25). The flow path of both anabranches becomes constricted, and a narrow sinuous single channel reforms in each. The two flow paths rejoin at Tirrawarra Waterhole, then north into Tirrawarra Swamp. This "flat" is wholly occupied by swamp; its network of anastomosing and reticulate channels shows no clear primary flow path. Almost the entire swamp is flow path, making it a critical stage in water delivery to Coongie Lakes.

The offtakes from Embarka and Tirrawarra Swamps must cross over some barrier (a sill) that acts to retain water in the swamps until the flood has reached a certain height. It was not possible to examine these places during this project’s field work, however the remote investigation suggests these particular sills are a combination of poorly-defined local microtopography (possibly related to sediment deposition), and the increased elevation found at the downwind end of deflation basins. Sills are an important influence on flow routing. The other important mediators of flow in these reaches are roughness elements in the small anastomosing channels and the reticulate-channeled swamps. Flows passing through the dense vegetation, torturous channel pathways and very small channel sizes are slowed but not stopped. This allows biological productivity in swamp areas but still passes water downvalley to other wetlands. Anything that increases flow efficiency through these small channels, swamps, and sills will decrease the local productivity.

Fig. 24. The Main and North West Branches of Cooper Creek

Orthophotograph overlaid by drainage lines (blue) from 1:250,000 topographic data. White crosses mark road crossings. W, Wilpinnie Creek; G, Gidgealpa Waterhole; S, Scrubby Camp Waterhole; E, Embarka Swamp; T, Tirrawarra Swamp; N, Narie Waterhole; M, Main Branch; NW1 and NW2, North West Branch anabranches; pd, minor flood pathways along palaeodrainages; red stars mark the forks where Cooper Creek divides (see Fig. 17). Flow is from east to west and northwest, except the palaeodrainage along the bottom of the photo where water from Wilpinnie Creek flows southwest then northwest.

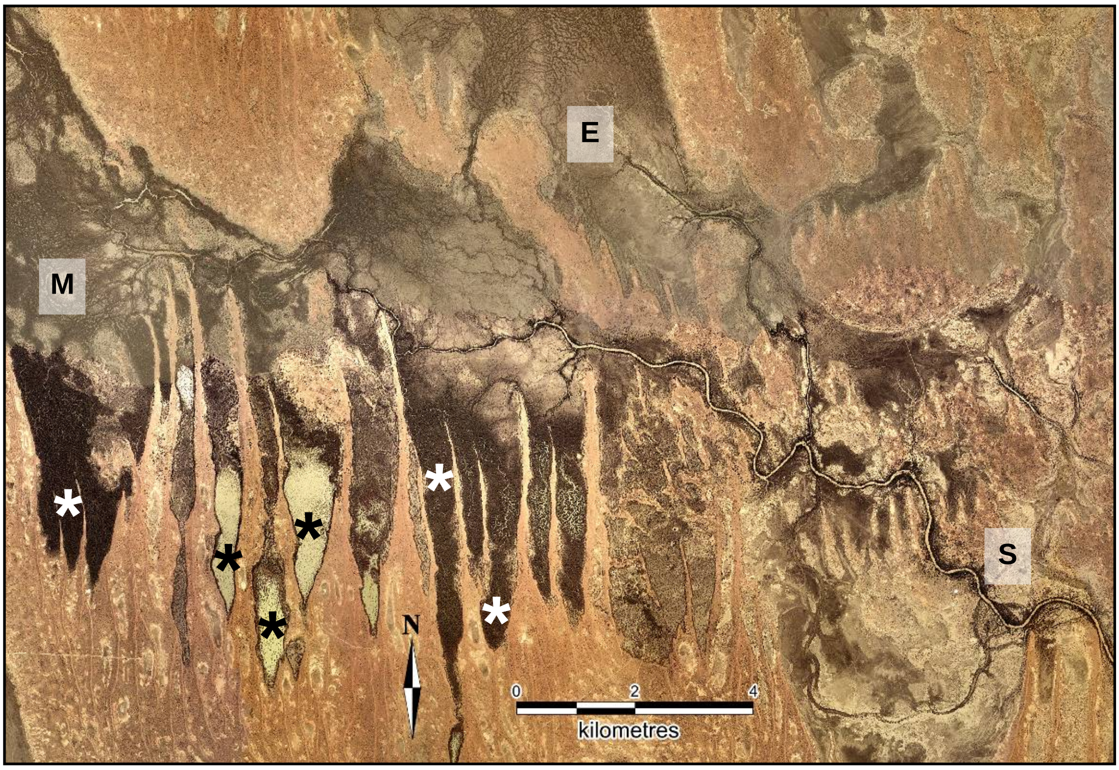


Fig. 25. The North West Branch anabranches and terminal swamps

The North West Branch divides into two a short distance downstream from Scrubby Camp Waterhole. Terminal lakes and swamps occupy deflation basins (white and black asterisks). S, Scrubby Camp Waterhole; E, Eulcaminga Waterhole; M, Mudrangie Waterhole. Flow from bottom right to top left.

Management implications:

Floods are never a “waste of water”. High-volume flood peaks are the only way that flows can penetrate from monsoonal Queensland to the Coongie Lakes. Natural flow variability should be preserved; upstream waters (for example, in Queensland) should not be diverted, extracted or impounded.

Riparian vegetation is an important contributor to channel integrity, and should be managed to preserve its density and diversity.

Distributary channels are important to ecosystem distribution. They should not be diverted, or blocked by infrastructure.

Flow paths through swamps are key components of the drainage network. They should not be occluded or obstructed.

Sills, and reaches with high resistance to flow (swamps and small channels) are important factors in flow routing, thus governing the distribution of productive ecosystems for the whole river. They should be managed so that the passage of flows is unimpeded across all flow stages (flow paths should not be blocked). Their roughness elements (vegetation, small channels) should also be maintained within their natural states (devegetation, gullying, and erosion should be avoided).

On the Strzelecki Plain, natural flow variability should be protected from alteration by infrastructure. Roads, bridges, industrial plant, and civic works should design to allow the river to operate normally under all flow situations. Human inhabitance requires infrastructure, so a range of design parameters should be applied, including:

- Where possible infrastructure should not cross main flow paths, e.g. roads could be placed along dune bases or non-inundating flats. (It should be noted that some deflationary basins can accumulate local runoff: being away from the flow paths is only one consideration for avoiding inundation.)
- Roads which must traverse the flow path should be at the same elevation as the ground surface, as far as possible (dry-weather roads).
- Elevated infrastructure (wet-weather roads, bridges) which must cross the main flow paths or the floodways should allow sufficient passage of water that high-volume flood peaks are not retarded or attenuated.
- Flow paths should be mapped as part of infrastructure design, using aerial photography (currently available). High-resolution elevation data (e.g. LIDAR) may be useful, but elevation data alone will not provide full information. It should be noted that SRTM elevation data are unsuitable for site-specific infrastructure design in sensitive areas of very low relief (too coarse, poor vertical resolution, and incorrect; see Figs. 1, 54, and section 5.1).

While all swamps are biologically rich, not all are along main flow paths: some are terminal. Occlusion of local drainage (reducing water to) such a swamp would be detrimental to local ecology but may not have consequences on a wider scale (subject to ecological investigation). Depending on other stakeholder interests, it may be possible to define sacrifice zones in which infrastructure design is not so critical.

3.4 Coongie and other Lakes

Grouped by location, the lakes of the Strzelecki Plain are:

- the Coongie Lakes, the main focus of this study
- the lakes of the northern Strzelecki Plain
- the overflow lakes
- Lake Hope, and other lakes of the southwestern Strzelecki Plain
- and the big lakes (Blanche, Callabonna, Gregory) which are dealt with separately in section 3.7.

The Coongie Lakes (Fig. 26) are the Ramsar-listed wetlands at the termination of Cooper Creek's North West Branch. When floodwaters of sufficient volume come down the river, they fill Coongie Lake. Coongie Lake dries out only rarely. Beyond Coongie Lakes, the sequential fill pattern of the various lakes depends on flood height, and is governed as much by micro-topography (lake margins, flats, dune corridors), as it is by the elevation differences between one lake and another. Each lake, channel, and inundated "flat" retains some of the water, and so flood frequency, and lake permanence decreases downstream, while salinity increases (Silcock 2009).

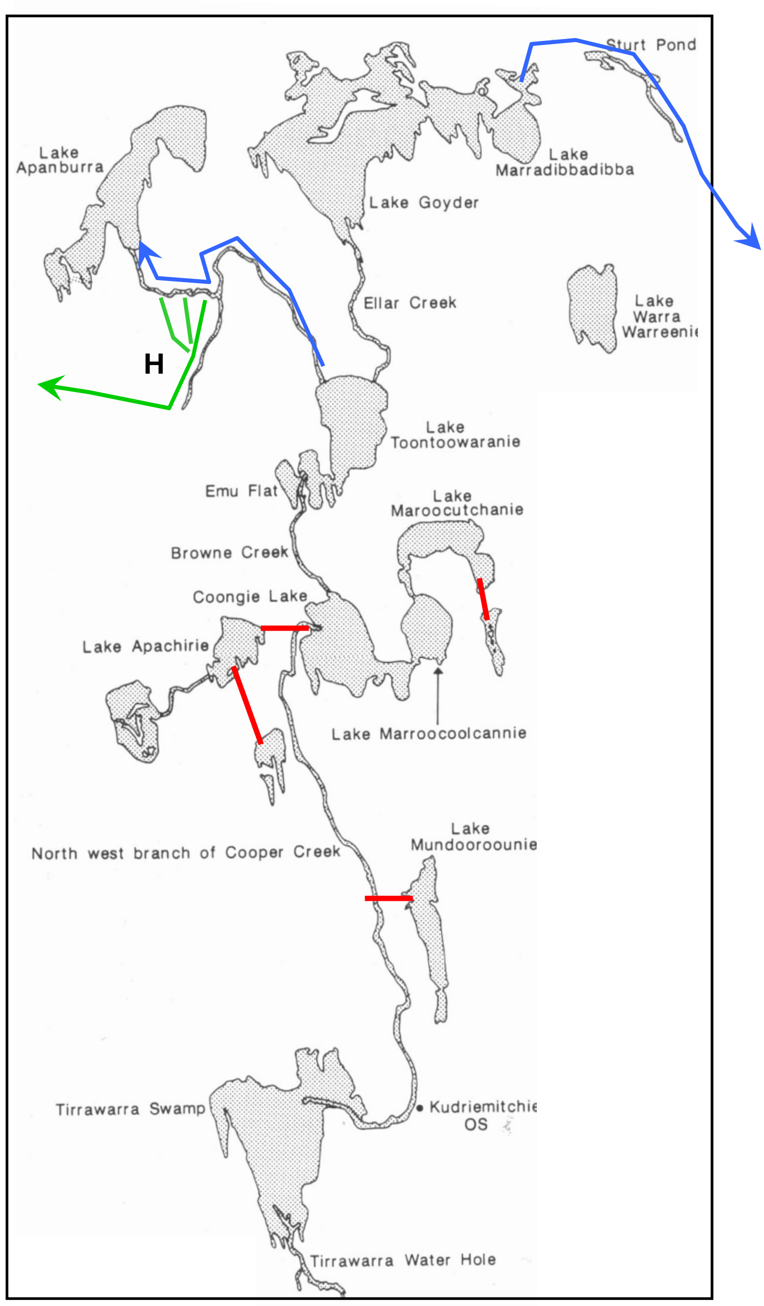


Fig. 26. Map of the Coongie Lakes (after Reid & Puckridge 1990).

The fill sequence is from south to north until Lake Maradibbadibba is full. Overflow into peripheral lakes then takes place, the first the red channels, then the blue channels. During very large flow events, water moves down the green path (H, Hamilton Creek) towards the overflow lakes.

The Coongie Lakes fill order and (where available) required lake/flow depth to extend beyond them are (Reid & Puckridge 1990, Silcock 2009):

- Tirrawarra Swamp, then Kudriemitchie channel
- Coongie Lake, and the nearby Lakes Marroocoolcannie and Marroocutchanie (to 1.5 m)
- Browne Creek, to Lake Toontoowaranie (to 1.5 m)
- Ellar Creek to Lake Goyder (to 1 m)
- Lake Marradibbadibba.

During very high flows, the peripheral lakes fill:

- Lake Mundooroounie, Lake Apachirie and its neighbour; the flats and palaeodrainages south of Apachirie and Marroocutchanie (red lines, Fig. 26)
- Lake Toontoowaranie (to 2.5 m) along Apanburra channel to Lake Apanburra; then Lake Marradibbadibba to Sturt Ponds, which is the inflow channel to the twin Lakes Lady Blanche and Sir Richard (blue arrows, Fig. 26).

During exceptional floods (such as occurred during 2011-12), distributaries from the Apanburra channel deliver flow to Hamilton Creek, which goes west to the overflow lakes (green arrow, Fig. 26).

In the northern Strzelecki Plain, medium-sized lakes are clustered in a dunefield between the Gason and Cordillo Domes. They receive water from the runoff of nearby stony uplands. Generally, uplands water has little opportunity to penetrate through the dunes into the Coongie Lakes area, but at least one drainage line contributes local runoff to Lake Goyder.

The overflow lakes (see section 3.5) are a small cluster of lakes and flats extending downvalley from the junction between Hamilton Creek and Alfred Creek, including Lakes Androdumpa and Oolgoopiarie at the northern end of Christmas Creek. The northern edge of the Strzelecki Plain – a narrow dunefield which slopes up to the stony uplands – is just to the north of the overflow lakes. The overflow lakes have not been the focus of study, probably because they only fill rarely, and so do not support rich ecologies.

In the dunefields of southwest Strzelecki Plain, there are a number of small to medium-sized lakes, some of which are connected to Cooper Creek by small channels. They are created by deflation, and some (including the largest, Lake Hope, Fig. 27) are related to the subtle area of elevated topography northeast of Lake Gregory.

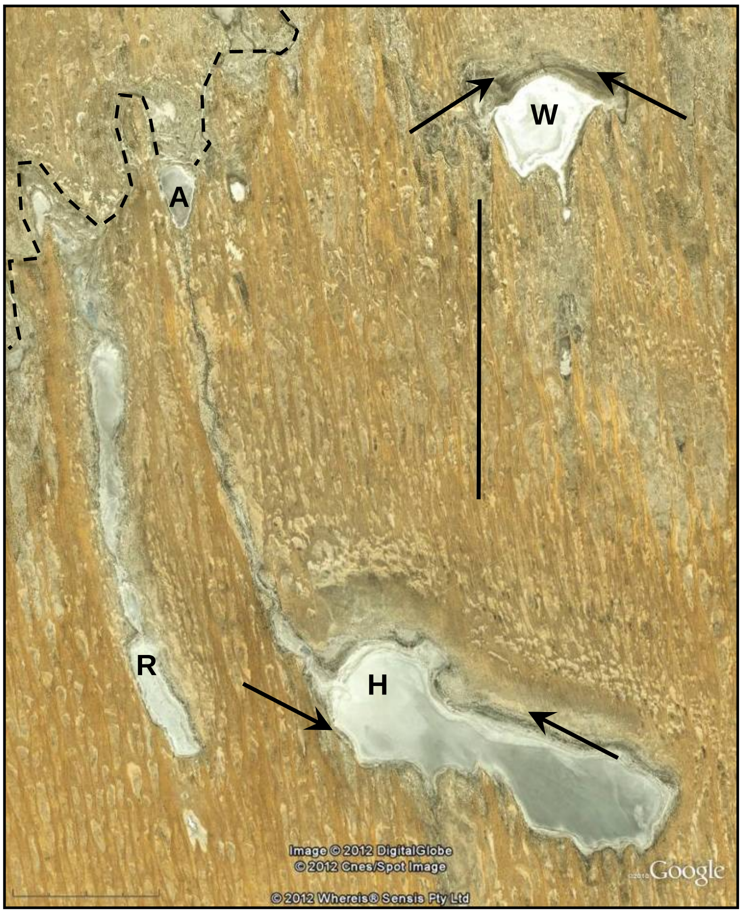


Fig. 27. Lakes of the southwest Strzelecki Plain.

H, Lake Hope; R, Red Lake; W, Lake Warrakalanna; A, Lake Appadare; arrows, beach ridges. Dashed black line is Cooper Creek, flow is top to left; north to top, black scale bar is 10 km.

3.4.1 Lakes: Created by Wind, Modified by Water

Most of the lakes were created in the “flats” by wind erosion, as vortexes are created behind obstacles (dune crests) in the wind’s path. In many lakes the wind-driven sediment makes a source-bordering dune downwind of the lake. A complex topography is created as lacustrine landforms overprint the fluvial. Lake bed elevation can be unrelated to the elevation of nearby lakes or drainage channels. In many lakes, several closely spaced deflationary basins will expand through shoreline processes, and merge (e.g. Lakes Marroocutchanie, Toontoowaranie and Apanburra; Fig. 28, and see section 7.4.1). The interaction between the Cooper Creek flow path and these non-fluvial lakes, in combination with the low overall gradient and the strong influence of local dune-and-flats topography, is the reason for the Coongie Lakes’ complex fill pattern.

The basins are altered by nearshore and lacustrine processes. Local report notes 0.5 m waves on Lake Hope, and waves fronts with a strong wind can be seen coming across the lake (Gary Overton, pers. comm., 2012). Wind-driven waves create beach ridges (Fig. 27), which are most strongly expressed along the northern (downwind) shores, but may be found elsewhere also. In some lakes beach ridges create the sills that are the barrier to the next stage of flow downvalley (e.g. Lakes Toontowarranie, Appadare).

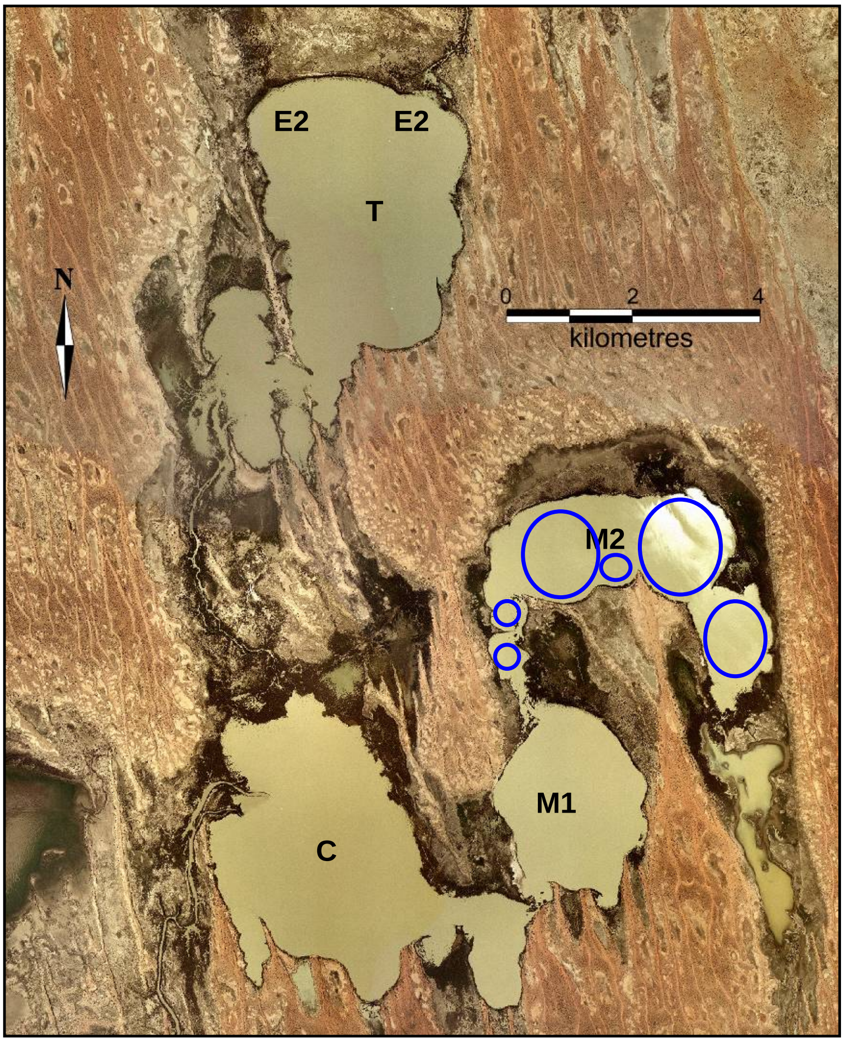


Fig. 28. Lakes created by the merging of several deflationary basins.

In this orthophoto, blue circles approximate the original deflationary basins in one of the lakes.

M1, Marroocoolcannie; M2, Marroocutchanie ; T, Toontoowaranie; E1, and E2, northeast and northwest exit channels; C, Coongie Lake.

Toontoowaranie's northeast exit channel main flow direction is south to north but deltaic deposits indicate it also flows north to south, from Lake Goyder back down into Toontoowaranie.

Seiches are also likely to be occurring (wind causes the water to slosh back and forth in an enclosed body of water). At Lake Hope, storm winds have been observed pushing the water level 2 m higher up the beach, and bottom currents strong enough to move anchors made from wheel rims (Gary Overton, pers. comm., 2012). These reports suggest seiches, which elsewhere in the world are known to create rapid rise and fall in water level and create strong bottom currents. Seiches can be a hazard along the shoreline from waves or sudden rises in water level, and on the open water the hazard is from choppy unpredictable waves. Seiches are also likely to be part of the process where water levels cross sills into the next lake or channel, suggesting that overtopping may sometimes be wind-dependent.

3.4.2 Lakes and Groundwater

In Queensland, waterholes contribute to groundwater only during high-flow periods, when the mud seal is temporarily scoured away. The freshwater lens around and down-valley from the waterhole supports the ecology of local deep-rooted plant species. The situation in the lakes is likely to be different. The relationships between lakes, local groundwater, and soil salinity is likely to be very site-specific. If so, this is likely to be strongly reflected in patterns of ecology, particularly the distribution of deep-rooted plants. If groundwater monitoring is ever to be of importance (e.g. after development of mining infrastructure) it would be important to establish site-specific baseline conditions first using the services of a groundwater hydrologist.

3.4.3 Lakes as Flow Buffers

The lakes and swamps are sumps, and act as local base levels and flow buffers: flow does not proceed downstream until the local topography has been filled to a certain level. For example in the southwestern Strzelecki Plain, the entire flow is abstracted by Lakes Appadare and Hope. Flow enters Lake Appadare through its northeastern channel and exits through the southern channel towards Lake Hope. When Lake Hope is sufficiently full, Lake Appadare returns water to Cooper Creek via a poorly-defined north-western exit and a clearly defined western exit (Fig. 29).

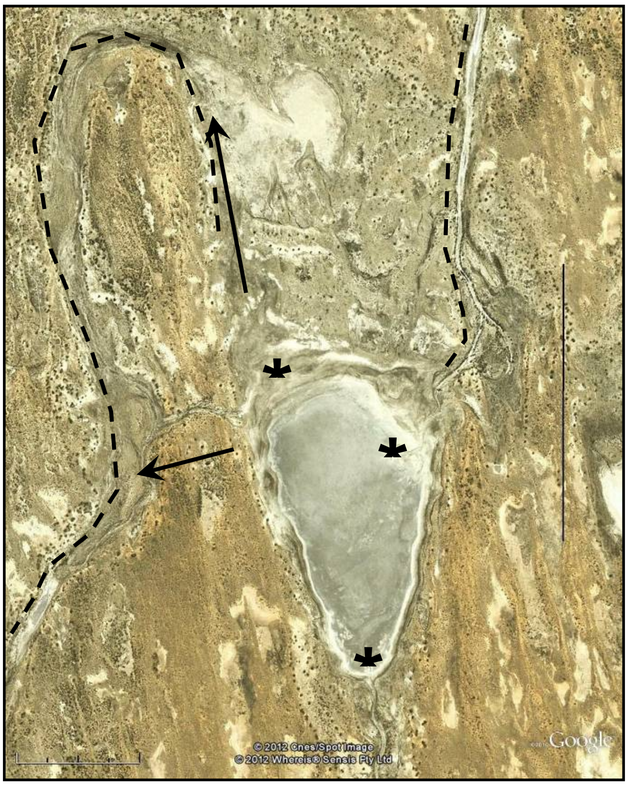


Fig. 29. Lake Appadare and its inlets and outlets.

Lake Appadare intercepts all of the Cooper Creek flow (right asterisk) and sends it to Lake Hope (bottom asterisk). When Lakes Hope and Appadare overflow the water leaves Lake Appadare (left asterisk, and arrows) and continues down Cooper Creek.

Management implications:

- In the North West Branch, Tirrawarra Swamp and the lakes and swamps downvalley from it act as flow buffers. Sills are the mechanism whereby this happens. A management goal should be that the sills be left unaltered, in order to preserve current hydrology.
- Sills should not be the sites of campgrounds, roads, or anything that risks triggering erosion.
- The complexity of the flow routing is an important driver of ecological richness, and relies on Cooper Creek's extreme degrees of flow variability. Upstream reaches of the Cooper should not engage in practices which attenuate flood peaks or decrease the volume or frequency of flooding (e.g. extraction or impoundment of waters in the Queensland catchment, or the construction of flow-altering infrastructure across the flow path.)
- Seiches are an important landform modifier. Seiches during large storms may be a hazard to people or equipment.
- Relationships between lakes, local groundwater, and soil salinity are likely to be complex and site-specific, and have direct relevance to local ecology. Groundwater monitoring, if ever undertaken, should begin with measurement of site-specific baseline conditions. The observations from one lake are extremely unlikely to be relevant to all.

3.5 The Northern Overflow and the Main Branch (Cuttapirie Corner)

During extremely wet years, the North West Branch’s flow path becomes diffuse and unchannelled as it moves beyond the overflow lakes and down the northern overflow to rejoin the Cooper near the Deparanie Waterhole. The northern overflow is flanked by a number of well-vegetated interdune corridors, some leading to deflationary lakes which have abstracted water from the overflow (Fig.30). Because of its difficulty of access, the Northern Overflow is apparently one of the few parts of drylands Australia not affected by grazing (J. Gillen pers. comm. 2012). Recently exploration roads have opened up that area, and it would be a pity not to document the existing conditions if they are still in this near-pristine state. It is recommended that funding be sought for this purpose.

The Cooper Main Branch travels northwest from Embarka Swamp (see Fig. 24) as a single channel until it enters a broad swampy flat where the flow path is blocked by longitudinal dunes. The channel becomes distributary. At Walkers Crossing the channel is re-formed but it is small, often multi-thread and anabranching, and mobile. From near Cuttapirie Corner the channel is more stable, single-thread where constrained by dunes, and follows a diffuse flow path through anastomosing channels and swamps when traversing flats.

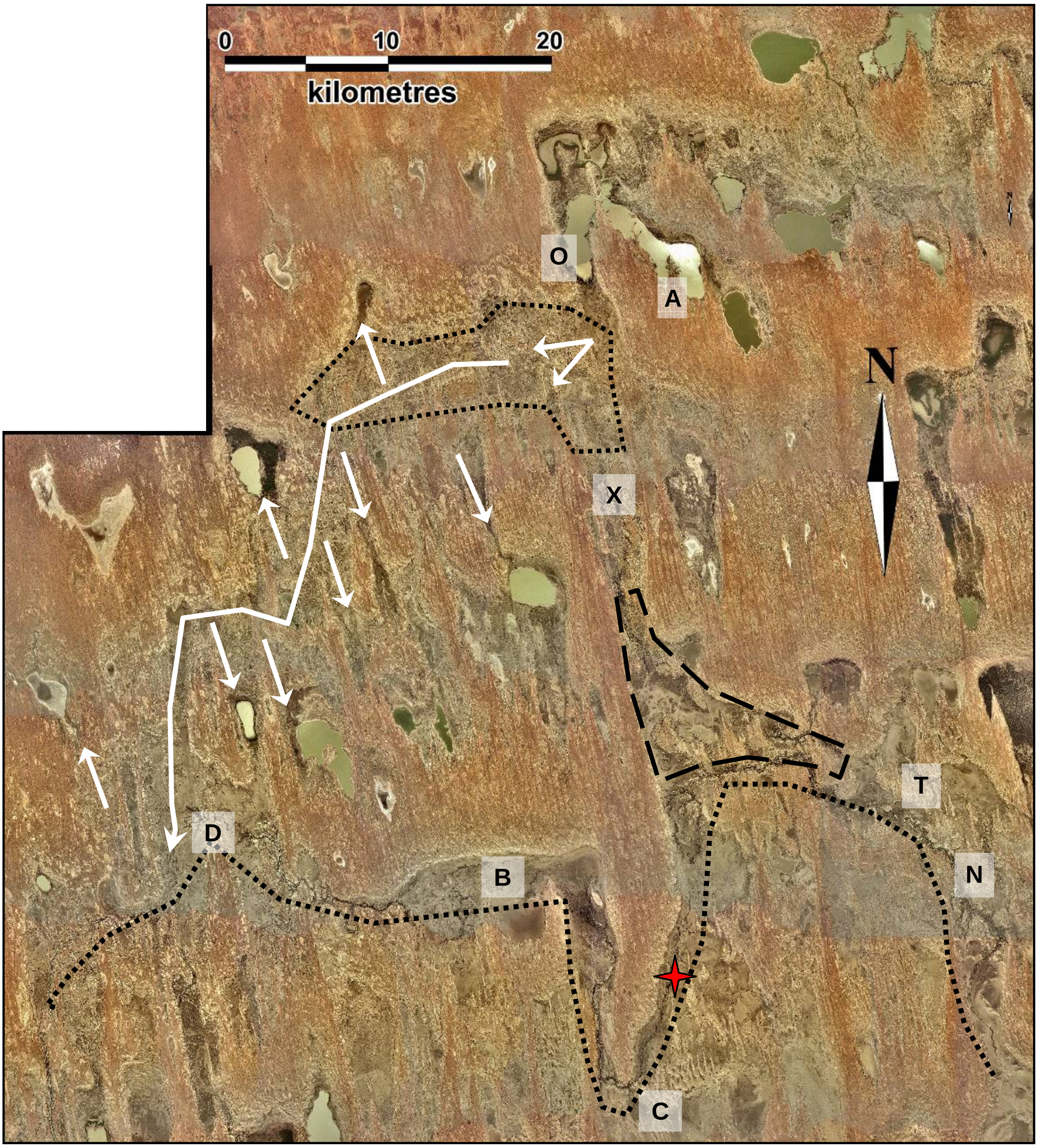


Fig.30. The overflow: where water from the North West Branch can rejoin the Main Branch.

The northern overflow (long arrow) begins as flow becomes diffuse (pair of short arrows) south of Lake Androdumpa (A) and Lake Oolgoopiarie (O). Flow is abstracted down interdune corridors into local deflationary basins (short arrows). Black dashed line encloses alluvial deposits of the palaeodrainage now known as Christmas Creek (X). The present-day main channel flows from right to left (parallel to and just above black dotted line), south of Toonman Waterhole (T), through Narie Waterhole (N) and Cuttapirie Corner (C). The Main Branch flow path is a diffuse network of minor channels and swamps at Walkers Crossing (red star), the Boggy Lake area (B), and Deparanie Waterhole (D) where the overflow rejoins the Main Branch.

The large longitudinal dune blocking the westward path of the present Cooper Main Branch also blocked the path of the Cooper's most recent palaeodrainage. What is now Christmas Creek was once the main flow path, flowing south to north towards Lake Oolgoopiarie (Fig. 30; and see section 7.3.2).

3.6 Cooper Creek’s Low-Discharge Reaches

This section describes Cooper Creek in those reaches where floodwaters only penetrate rarely, and the flow volumes are small. The fluvial landforms are therefore much smaller, and play a less dominant role in the landscape. With the exception of the Kopperamanna Floodout, the area was not accessible during the field work, and therefore there are few management implications derived from this part of the study.

3.6.1 Southern Strzelecki Plain: Cooper Creek below Deparanie Waterhole, and Strzelecki Creek

Cooper Creek beyond Coongie Lakes is the driest reach in the Channel Country. Below Deparanie Waterhole, Cooper Creek is a discontinuous small channel. The river's flow path is influenced by interdune corridors, or cuts across the dune trend. For example, just downvalley of Deparanie Waterhole, the main flow goes west but some is abstracted down the Kanowana Channel. The Cooper's reaches alternates between small waterholes (which are really just slightly deeper channel segments), single-thread channels, and inundated areas (swamps, networks of anastomosing channels, small lakes) (Fig. 31).

The flanking dunefields contain deflation basins, some connecting to the Cooper via interdune corridors. The most significant of these is the Lake Appadare /Lake Hope complex (see sections 3.4 and 7.6), which captures the entire Cooper flow. No water can proceed down the Cooper until these and their neighboring Red Lake have filled. Below Lake Hope, the channel is more continuous but there are very few waterholes, and the lakes are smaller and fewer. The channel is sinuous around the ends of longitudinal dunes.

The Strzelecki Creek on the Cooper Creek Fan (north of the Della Road) is undefined inundated flats. South of that, the Strzelecki is largely discontinuous, with single-thread channel segments alternating with poorly-defined anabranches. As the creek approaches Lake Blanche, it displays channel mobility.

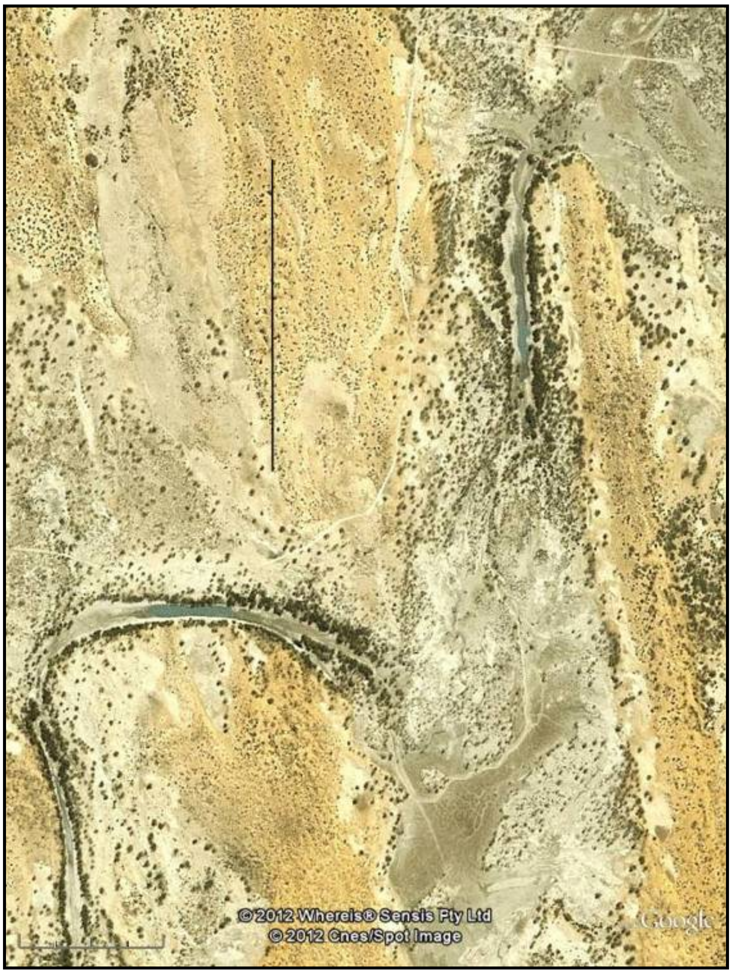


Fig. 31. Cooper Creek is very diminished in size below the Overflow reaches.

At Pilachilpna and Eaglehawk Waterholes, short channel segments are separated by inundated flats (white sand) within longitudinal dunes (orange sand). Flow top right to bottom left, scale bar 1 km.

3.6.2 The Tirari reaches: beyond the Strzelecki Plain

At the southwestern corner of the Strzelecki Plain, Cooper Creek enters the Kopperamanna Floodout, a wide, very low-gradient area of white sands with very irregular topography (Fig.32). The Floodout can be extensively inundated in very wet years, however was most likely created under previous wetter climate conditions. In pre-European times, Kopperamanna was a major trading location for the Aboriginal narcotic pituri. Lake Killalpaninna, just to Kopperamanna Floodout's north, is a lake extracting water from the Cooper flow path along interdune corridors.

The Cooper's flow path is very diffuse across the Floodout. At the western end, the channels re-form and leaves the Kopperamanna Floodout as a single sinuous channel, slightly inset and moderately mobile, which carves its way across the trend of longitudinal dunes towards its mouth into Kati Thanda-Lake Eyre (Fig. 33).

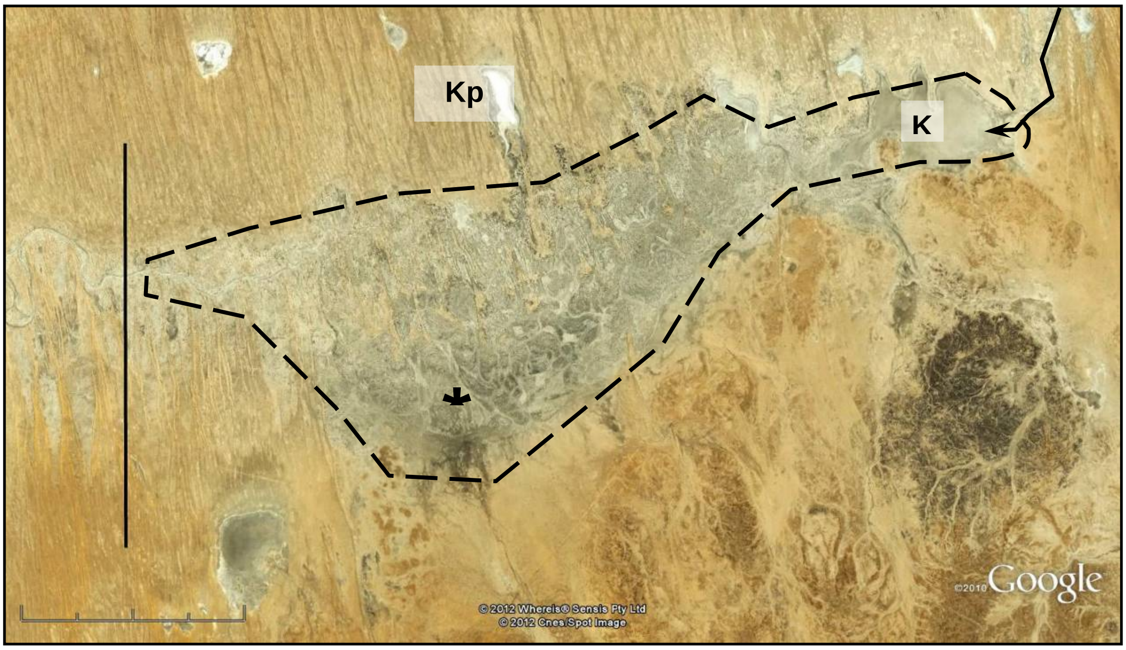


Fig. 32.. The Kopperamanna Floodout, where Cooper Creek leaves the Strzelecki Plain.

Cooper Creek (black arrow, top right) enters the Kopperamanna Floodout (enclosed by black dashed line) via Lake Killamperpunna (K). Lake Killalpaninna (Kp) draws water from the Floodout. Scrollbars of the previous river system are visible on satellite images (*). Flow top right to center left, 20 km scale bar

Fig. 33. The Lower Cooper Creek in the Tirari Desert.

Looking northwest towards Kati Thanda-Lake Eyre across the longitudinal dune fields containing the sinuous channels of Cooper Creek. Photographs Gini Lee.

Management implications:

The northern overflow and low-discharge reaches of Cooper Creek mostly rely on very large floods; water-affecting activities in the upper catchment would be detrimental. Runoff from local rain also contributes, especially areas like Kopperamanna Floodout which are downslope from rocky slopes (high-runoff surfaces).

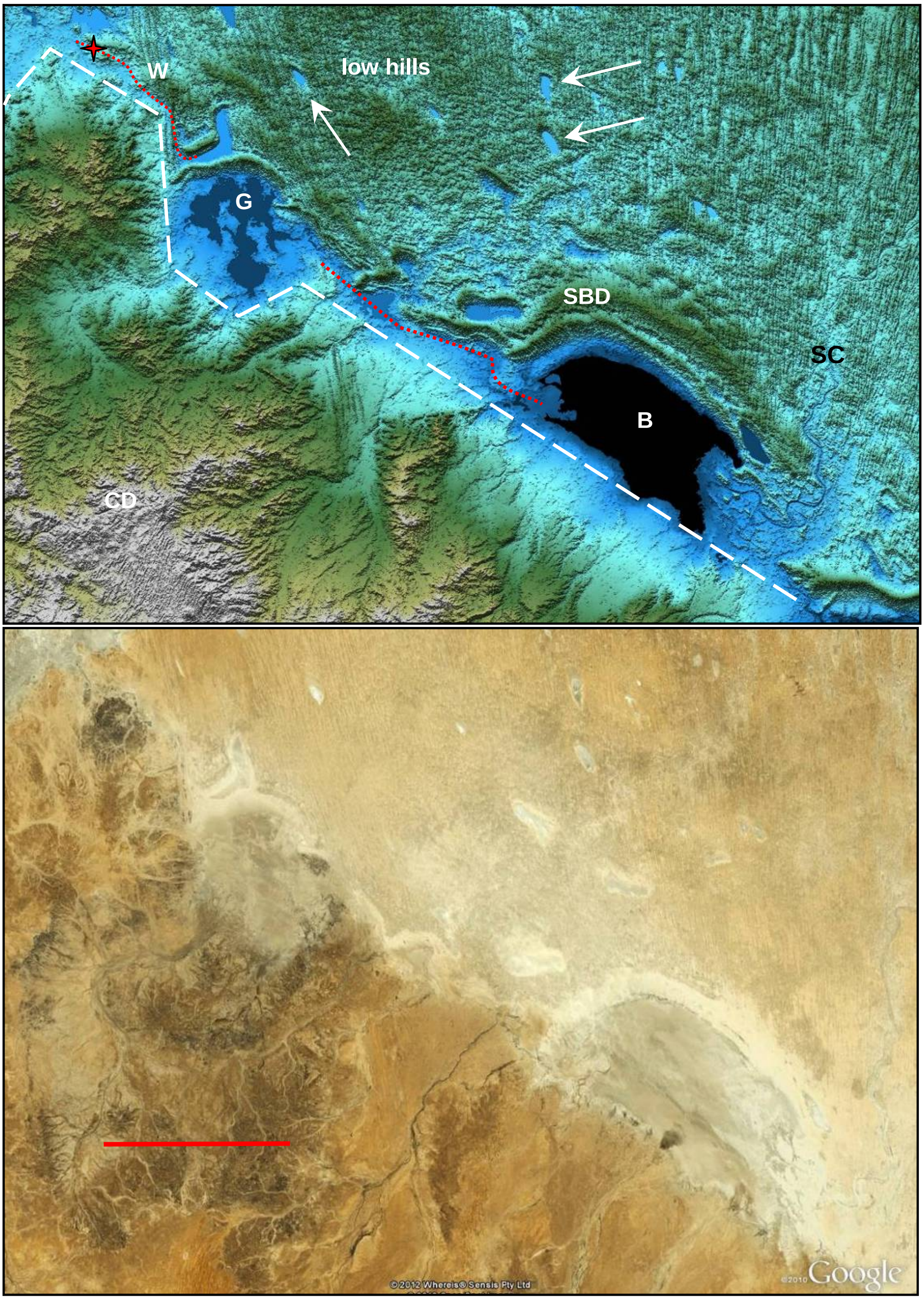


Fig. 34. Landforms of Lakes Blanche and Gregory.

Lakes Blanche and Gregory: top DEM, bottom, Google Earth image; north to top, red scale bar 28 km. Red star at top left of the DEM is the location of photo Fig. 59. On the DEM, the white dashed line is the edge of the Cooryanna Dome; red dotted lines, lake overflow channels; W Warrawoocara Channel, CD Cooryanna Dome, G Lake Gregory, B Lake Blanche, SC Strzelecki Creek, SBD source-bordering dunes outlining the palaeolake edge, arrows points to some of the claypans and lakes of the southern Strzelecki Plain.

3.7 Lakes Gregory, Blanche, Callabonna, and the Warrawoocara Channel

Lakes Gregory, Blanche, and Callabonna occur where the lowest-elevation parts of the Strzelecki Plain abut the footslopes of the Cooryanna Dome and the Benangerie Ridge (Fig. 2 and Location Map). The lakes have been full under previous wetter climates, and when at their most full, Lake Gregory overflowed down the Warrawoocara Channel (Fig. 34) towards the Kopperamanna Floodout. Within the last 18,000 years there have been some episodes of partial filling, but under the present climatic conditions these lakes are usually dry. For Lake Gregory to fill enough to overflow to the Cooper, all the other lakes would have to fill first, which would call for a completely different hydrological setting than occurs today.

Strzelecki Creek flows enters Lake Blanche on the lake's southeastern side (Fig. 34). There is a large flat delta extending from where the creek crosses the source-bordering dunes, and prograding across the lake bed. The tourist rest spot Montecollina Bore is in this area. The present channel flows across the delta in large open meanders. The landforms are complex assemblage of present-day flow paths, previous sinuous channels, small dunes, and relict landforms (including some now dissected by modern erosion). There are many large sediment accumulations, including some shadow bars deposited downflow from bushy vegetation, and some dunes. If some of the larger (>2 m high) landforms are shadow bars, they may relate to extra-large flows such as the ~1ka event.

4. HUMANS AND GEOMORPHOLOGY

4.1 Pre-European

The role of Cooper Creek and the Coongie Lakes in creating a rich ecosystem also extends to humans, who benefit from the availability of water and plant and animal food. Local and distant Aboriginal language groups derived benefit from this area: Cooper Creek was part of a major trading route extending from Cape York to Bass Strait. The Aboriginal drug pituri, made exclusively in the Mulligan River area, was traded widely, and the areas now known as Innamincka and Kopperamanna Floodout were markets. The first European reference to pituri comes from this area (in the diaries of Burke and Wills) (Watson 1983).

Throughout the fieldwork, it was clear that sheltered sandy areas close to free water (lakes or channels) were favoured pre-European occupation sites. (That is, the geomorphology of the area defines its desirability.) Occupation sites are characterised by scatters of flake tools and other artifacts (mostly grindstones). Occupation sites are most visible where there is little vegetation, and wind or other erosion has removed layers of covering sediment, revealing the artifacts (Fig. 35). One of the camping areas on Coongie Lakes is built over an extremely wide occupation site.

Fig. 35. Artifacts at Aboriginal occupation sites.

Left, flake tools scattered on pale alluvial sands near Cullyamurra, right, clay pipe (foreground) and tool flake (background) on orange dune sands in the Coongie Lakes area.

The Lake Eyre Basin is rich in the sort of rock that makes good stone tools: fine-grained silcrete, particularly phreatic (groundwater) silcrete, or highly silicified fine-grained rocks. Tool-working sites tend to be at or near outcrops of suitable rock. They are characterised by very many flakes and tool remnants, and often very little in the way of amenity (shade, water, or other comforts). In Australia it is illegal to collect artifacts. Though they appear randomly scattered on the ground, the spatial arrangement of artifacts yields information about Aboriginal life. At one site, amidst a large quantity of stone tools, there was a European clay pipe (Fig. 35); this was the only non-Aboriginal artifact present. Since Cooper Creek was an important trade pathway for pituri, and since patterns of pituri use started to be replaced by tobacco in early settlement (Watson 1983), it is possible that this occupation site might be datable within a few decades.

4.2 Introduced Animals

4.2.1 Cane Toads: Life, Habitat and Spread

Cane toads are an invasive species whose range in Australia is rapidly increasing, and whose effect on ecosystems derives from toad toxicity to predators (Shine 2010). In the high-value aquatic ecosystems of refuge waterholes, animals (including fish, Greenlees & Shine 2011) are at risk from eating the highly toxic eggs and less toxic tadpoles. Though in other locations larger fish and turtles are protected from the toxic eggs because of the eggs' emplacement in shallow water, the Cooper's succession of flood peaks risks washing eggs into deeper waters where larger animals can eat them. The rich riparian zones of refuge waterholes are equally important to land animals, who will be at risk from predation on the terrestrial adult toads. Established toad colonies along the Cooper are clearly undesirable.

It is less obvious (but equally true) that unsuccessful toad colonies may also be highly detrimental to Cooper Creek ecology. Toad colonies may not be able to establish if their breeding ponds – on the floodplain – are only temporary. The toads might lay eggs, but perhaps the shallow water will not persist long enough to grow adult toads able to migrate. However, that brief time of floodplain inundation is an important time in fish ecology (Schmarr et al.2012). Fish escaping from their refuge waterholes seek the floodplains as an opportunity to feed, grow, and find new breeding grounds. Thus, toad eggs may pose a new threat at a time which is critical for the genetic diversity of arid-zone fish.

The cane toad life cycle consists of breeding, eggs, tadpoles, metamorphs, and adults. Breeding must take place at the water's edge, and the eggs and tadpoles are aquatic. The metamorphs and adults are terrestrial, and risk drowning in deep water. The adults are extremely tough, can travel long distances (up to 1.3 km in a night), and can tolerate some desiccation, but they must rehydrate every couple of days. The metamorphs are highly vulnerable to desiccation, and must stay close to water.

For the cane toad invasion front to establish in a new location, the key habitat requirements are water for rehydration while travelling, daytime shelters, and suitable breeding habitat.

Across Australia, the cane toad invasion front has recently increased in rapidity, and by virtue of both behavioral change and genetic alteration the toads are increasingly able to occupy challenging habitat. Fortunately, cane toad dispersal takes place by movement of the terrestrial adults, not by swimming of the aquatic stages, so the recent wet years may not have promoted toad expansion beyond what has been observed in drier years. They have reached southwestern Queensland, and there is no reason why they can't penetrate further down Cooper Creek. Published models of cane toad expansion, which conclude that South Australia is too dry for cane toad populations to establish, are based on a poor understanding of Channel Country rivers and are certainly incorrect.

Whether water is available for rehydration of toads travelling down moisture corridors of the Cooper depends on 1) how far apart water bodies are, and 2) the hydrology at the time in question (how long since the last flood; the degree of floodplain inundation). In order to prioritise likely cane toad invasion pathways and identify “weakest link” reaches for targeted toad control, it is desirable to document for various flow conditions the locations of permanent, semi-permanent, and temporary waters, and what their upstream-downstream distance relationships are.

There is no shortage of landforms and landscape elements that could serve as toad shelters during the day (Fig. 36). This is not a limiting factor to cane toad invasion and establishment. As well as natural features, toads are good at exploiting human habitat, and community engagement will be an important factor of their control.

Fig. 36. Potential daytime shelter for toads.

Left, bank tree roots near Tilcha Waterhole; right, a distributary channel offtake with vegetation.

There are many potential breeding sites available to invading cane toads (Fig. 37, Table 2). Cooper Creek's hydrology is not dependent on locally-derived rainfall; much of its water comes from the semi-tropical north. Current hydrological investigation indicates that (Justin Costelloe, pers. comm. 2012):

- under the current evaporation rate and inflow frequency, many waterholes and lakes persist for years to decades (Table 2);
- the longest period of probable no flow in the Cooper since 1939 was 21 months, and waterbodies >4 m in depth should retain water for longer than that period;
- Coongie Lake has probably only dried twice, briefly, in the last 40 years
- upstream from Coongie Lake (Northwest Branch) and Embarka Waterhole (Main Branch) there are a string of essentially permanent waterholes all the way up to the upper catchment;
- downstream of these locations, the waterbodies would periodically dry out and could remain dry for several years.

Fig. 37. Potential toad breeding sites.

These places have access to shelter, water and clear, gently-sloping water edges. Top, a sandy bar at the offtake leading to Napeowie waterhole and the Coongie Lakes. Bottom, at Gidgealpa Waterhole a small fan of sediment extends into the waterhole from a stock pad and gully.

Locations	Maximum Cease-To-Flow Depth	Water persistence without inflow (y)	Inflow frequency /a
Murken waterhole (Qld) #	5.14	2.2	<1
Yalungah waterhole (Qld) #	4.31	1.9	<1
Meringhina waterhole (Qld) #	4.50	2.0	<1
Nappa Merrie waterhole	11.71	5.1	<1
Cullyamurra waterhole	25.0	10.9	<1
Minkie waterhole	6.35	2.8	<1
Coongie Lake	1.80	0.75	<1
Tirrawarra swamp*	<1.8?	0.75?	<1
Embarka waterhole	3.80	1.7	1
Gidgealpa waterhole	4.07	1.8	3.6-5.7
Lake Hope	6.80	3.0	3.6
Lake Killamperpunna	No information	<2?	5.7
Yaningurie waterhole	3.00	1.3	8.0-13.3

Table 2. Persistence of water in the Cooper Ck landscape.

Approximate values for selected water-retaining landforms in Cooper Creek, indicating (per annum) how long water persists after a fill event, and how frequently new flows may come in (Justin Costelloe, pers. comm. 2012). Note that these recurrence intervals are indicative only, and cannot fully express the variability of the flow patterns in this catchment; see Costelloe, 2012. # Data from: Hamilton et al. 2005. The mean annual open water evaporation loss at Moomba is 2.285 m y-1.

In fact, the Coongie Lakes area already supports Central Australia's richest frog community (Reid & Puckridge 1990). There are also many artificial water sources from human-built infrastructure: short-term but numerous over a wide area (e.g. borrow pits) and long-term to permanent (evaporation ponds, dams). Higher salinity or lower pH may be detrimental to toads, and a more detailed picture of the Cooper Creek's and the lakes' water chemistry would assist in prioritising control areas.

Some potential breeding sites are along the Cooper Creek Fan distributary channels, thus ideal sites for radial dispersal (Fig. 2). Others are landforms along the banks, or upstream-downstream margins, of high-value aquatic ecosystems such as the Coongie Lakes, Tirrawarra and other swamps, Lake Hope, and the Cooper Creek waterholes. In wet years, natural breeding sites may bring toad populations within reach of isolated artificial permanent waters, where (should they become established) they may survive through droughts to re-infect the catchment later.

It is highly desirable that the cane toad invasion front should be slowed and intensively managed while it is still in Queensland. Failing that, it is extremely desirable that the cane toads be intensively managed along the reaches of Cooper

Creek which flow through the Innamincka Dome (Nappa Merrie, Cullyamurra, down to Burkes waterhole). The narrowness of the floodplains, the flanking hills of gibber, and the good road access makes these appropriate control points. If the cane toads get as far as the Innamincka town common, they will have access to a radial, distributary river network, from which they will have access to the rest of Cooper Creek and the Strzelecki Creek.

Management implications and recommendations:

Cane toad invasion of the Strzelecki Plain is undesirable, but perfectly possible.

Development of a strategy for management of the cane toad invasion. Management of the cane toad invasion front may be more successful in the Queensland reach of Cooper Creek (Windorah to Nappa Merrie) than it has been in the Top End, since the invasion front would only be as wide as the inundated parts of the Cooper floodplain. In combination with maps of dispersion pathways, it may be possible to develop a strategy of slowing or holding the toad front in “weakest link” reaches, by dry-year toad busting and tadpole trapping along key landforms in the primary dispersion paths. If the toads reach the Innamincka Dome, the pinch points near Nappa Merrie and Cullyamurra waterholes are tightly constrained between waterless uplands, and may represent the best places for toad call monitoring, and the best opportunities for defensive toad busting and tadpole trapping.

Better understanding of the cane toads of southwestern Queensland. Working with the Queensland Desert Channels Group and toad ecologists, establish the location of the Jundah toad front since the 2010-2012 wet years, and verify the habitat preferences, dehydration and temperature tolerances, and capacity for overland travel of this population of toads. Particular attention should be given to investigating toad exploitation of landform elements that they have not previously encountered: gilgai macropores (“crabholes”), GAB springs, waterhole splay channels, etc.

Database and map of prioritised toad dispersion pathways in southwestern Queensland: finding the “weakest link”. To manage toad populations before they get to high-value waterholes in South Australia, it would be necessary to work with Queensland agencies to identify pathways along the river network where waterholes or other water sources are close enough together that cane toads may travel downriver. From this information, key locations (“weakest link” reaches) for monitoring, fencing, and toad busting may be selected, such that denying toads this water will break the upstream-downstream dispersion path. A database constructed from geomorphic, hydrologic, landholder and historical data would be used to map spatial relationships of accessible water locations at various flood heights. Water locations would be assessed with respect to toad-travel distances; ideally this work would be done in partnership with toad physiologists and modelers. A GIS dataset of waterhole locations and attributes is already available (Silcock 2009).

Stakeholder engagement with cane toad control in South Australia and Queensland. Cane toads are known to be particularly successful in exploiting human habitats. If cane toads successfully invade the Strzelecki plain, local control of artificial permanent water and shelter will be very important, especially during dry-year targeted toad control. Measures will include fencing evaporation ponds, monitoring and toad busting dams and borrow pits, and restricting access to daytime refuge sites. The cooperation of the hydrocarbon exploration and extraction industry is particularly important, because their infrastructure is widespread and closely-spaced, and also because their type of work makes toad stowaways a strong possibility.

Document water chemistry in the Cooper and its lakes. The present information merely covers total solutes expressed as conductivity. A survey of solute type and concentration, pH and other relevant information would assist in prioritising vulnerable areas, and would improve understanding of the nature and causes of down-gradient salinity change.

Landform/habitat mapping of key locations in South Australia and Queensland. Targeted pest control will be aided by detailed landform mapping to identify likely toad habitat. This will be of assistance in managing toad populations over large waterholes with limited budgets and staff. It is likely to be a very important precursor to toad busting and tadpole trapping in locations of complex geomorphology, such as distributary offtake valleys or complex shallow reaches.

4.2.2 Grazing Animals – Stock, Pigs and Rabbits

In the time available and with the poor access during the fieldwork, systematic field observations of grazing and landforms were not possible. However, opportunistic field observations and data from the remote study lead to the following conclusions. The destructive behaviour of pigs would be especially detrimental in landforms that are vulnerable to change, such as sills and some swamps. Rabbits were uncommon; however the two places where rabbits were observed had very intense warren development, to the extent that the sediment deposits were extremely disrupted and eroded. Both rabbit warrens were dug into dune tops, one in pale alluvial sand, one in orange dune sand. An expanded rabbit population is detrimental to landforms as well as vegetation.

General observations did not see noticeable effects of grazing on the landforms. (Note that this observation does not cover changes to vegetation communities.) However, the field trip did not examine places of intense grazing, and the unusual vegetation growth after very wet seasons concealed some landforms from rapid casual examination. The effect of stock pads is dealt with separately below.

The role of riparian vegetation in preserving bank integrity and maintaining channel and waterhole depth is critical: the vegetation traps sediment and focuses stream energy to the channel bottom.

Lignum from the densely-vegetated swamps are grazed by cattle. A relationship between grazing and plant density can be indicated by changes across a fenceline (e.g. Fig. 38, and also see Fig. 6). It is likely that grazing pressure affects lignum density, which might reduce the necessary resistance to flow offered by swamps in the primary flow path (see section 3.3.4). It is also likely that grazing along seismic lines plays a role in preventing old seismic lines in swamps from rehabilitating; this would be a question for further investigation. In addition, it is possible that plant roots are a necessary part of maintaining macropores in gilgai soils, so devegetation may affect the gilgai processes that make these areas so biologically rich, and also alter groundwater composition (as macropores are an important recharge element).

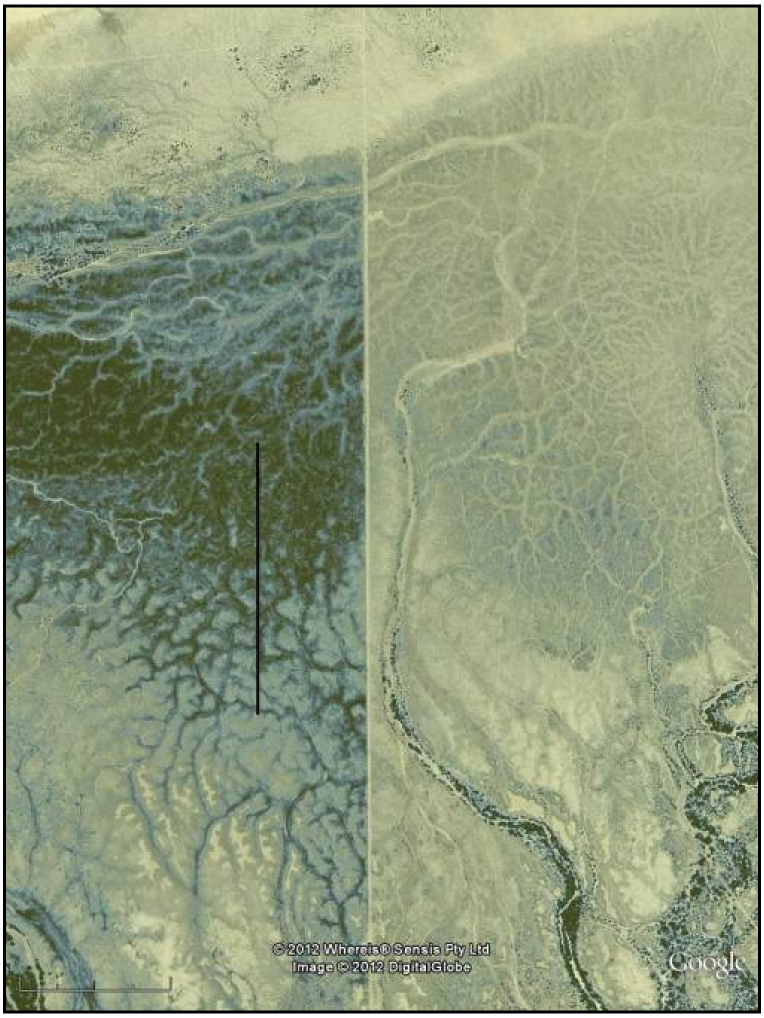


Fig. 38. The effect of grazing on swamp vegetation.

A fenceline (top to bottom, image center) separates a poorly vegetated area (right) from an area with denser vegetation. The difference is most likely to be related to grazing pressure (see Technical

Appendix, section 8.2, for analysis). Location near Boggy Lake, flow is from bottom right to top left, scale bar is 0.5 km.

Management implications:

- Continuous rabbit and pig control is very desirable.
- Grazing management should aim to preserve the integrity of swamp vegetation.
- Riparian zones should be carefully managed so as not to deplete the understory or the lignum, and so as to allow seedlings of new riparian trees to emerge and establish. Such management would include controlling both grazing and trampling. If waterholes are an important source of stock water, it would be desirable for the watering points to be established away from the waterhole itself.
- Where rehabilitation works take place, it is essential that total grazing pressure is managed. Where two land users coexist (e.g. hydrocarbon exploration and pastoral), cooperative plans should be developed so the rehabilitation efforts by one are not contrary to the expectations of the other, nor is the work of one undone by the other.

4.3 River and Lake Management

Four types of human activities impact on the land: pastoralism, resources exploration and extraction, tourism, and the development of civil infrastructure (e.g. township, roads, schools, shops). All infrastructure developments are governed by the SAAL-NRM’s Water Affecting Activities regulations, and the relevant legislation on Development, Aboriginal Heritage, Native Vegetation, and so on. The web of overlapping responsibilities is hard to navigate.

The resources industry is additionally regulated under the Department for Manufacturing, Innovation, Trade, Resources and Energy; resources bodies are required to post publically-available environmental planning documents, and to post an environmental bond (www.pir.sa.gov.au/petroleum/legislation/compliance; …/petroleum/legislation/regulation; …/petroleum/environment/register; and see the DMITRE flow chart, Technical Appendix, section 8.2). While the resources industry is required to develop, have assessed independently, and post publically the environmental plans which are specific to the development in question, it is less clear that civil and tourist developments have similar requirements. Furthermore, while the resources industry must have funds for environmental planning and rehabilitation (or their license applications should be denied), civil authorities may not.

The South Australian public service provides oversight on all activities. This is only possible if it is a community priority, that is if the public service has the staff and equipment to do so, and the independence to do so freely. A recent Australian Broadcasting Commission *4 Corners* report on coal seam gas in Queensland (April 2013; www.abc.net.au/4corners/stories /2013/04/01/3725150) described a situation in which the regulatory department had insufficient staff to assess the applicants' environmental documents, and alleges that hierarchical pressure was applied to pass the applications regardless. This is clearly an undesirable situation for all stakeholders.

There is apparently information aimed at making infrastructure development in the SA Arid Lands more environmentally sensitive, but it is hard to access. Documents include an "Outback Roads Manual" (an Austroads report, apparently not available to non-members), and the SANTOS "Arid Zone Field Environmental Handbook" (McLaren et al. 1997). There are also apparently fact sheets (issued by Natural Resources Management Boards and Catchment Management Authorities) on subjects like maintaining graded roads, rehabilitation techniques, and so on. However, most of this information is issued in an uncoordinated and uncatalogued way. Unless one knows where to look for it, it's invisible. This is a real barrier to effective good practice.

Management implications:

Rules without enforcement are worthless. Compliance oversight must be supported by an independent public service which is properly resourced.

Information on environmental and geomorphological information arising from the Cooper Creek project should be promoted to the resources industry, and to those sections of the South Australian public service who are responsible for regulation of human activities.

A coordinating body would facilitate equal standards of environmental care across all human activities and regulatory bodies. All stakeholders should have, or be assisted to have, the right kind of knowledge to apply to the local conditions, and the capacity to do the right kind of job. In the context of the present study, this is particularly the case for the sensitive areas of the Cooper Creek Fan, especially the Town Common (see sections 3.3.1, 3.3.2, and 7.3).

Existing information could be more widely available, and should be catalogued, curated, and indexed so it is available to all.

4.3.1 Maintenance of Flow Variability: Whole-River Management

The rich diversity of habitat and landforms which makes Cooper Creek and the Coongie Lakes so valuable arises from Cooper Creek's extreme flow variability, and the Strzelecki Plain's low-gradient and stochastic topography. The economies of the human inhabitants and the ecologies of Cooper Creek, the Coongie Lakes and Strzelecki Creek are adjusted to the present hydrological conditions of flood frequency and volume.

Attenuation of flood peaks or reduction in flood frequency (for example by dams) or reduction in flood volume (for example by extraction for irrigation, high-volume tourism or industrial processes) will undoubtedly have an extremely detrimental effect to the river in South Australia.

Management implications:

On a basin-wide scale, management goals must be to allow the Cooper's fluvial system to maintain itself within its present degree of variability. In the upstream catchment (South Australia and Queensland) Cooper Creek should be protected. Extraction and dam impoundment should be limited to the small scale of pastoral works such as currently exist.

4.3.2 Maintenance of Flow Qualities on a Reach Scale: Roads, Bunds and Bridges

With the development of the oil and gas exploration and extraction industry across the Strzelecki Plain, roads and other infrastructure has been developed. Structures include low roads, raised roads and bunds, bridges, and various plant and yards. All the important flow paths are crossed by some kind of structure (Fig. 39).

The entire Cooper Creek is crossed by the causeway at Innamincka and a bridge at Nappa Merrie. The North West Branch is crossed by Mitchie and Kudrieke Crossings, the Main Branch by Straw Bridge and Moorari Crossing (both at the outlet of Embarka Swamp), and also by Walkers Crossing and the Beach Bridge. Palaeodrainages acting as flood channels are crossed at the 15 Mile Swamp, Scorpion Flat, the un-named crossing downstream of Gidgealpa Waterhole along the main Moomba to Tirrawarra road, and various others (Fig. 39). Other bunds are built to service hydrocarbon production fields, such as the network at Tirrawarra Oil & Gas (Fig. 40).

All bridges and built-up roads have the potential to restrict or block flow, with detrimental effects on the river's flow patterns and biological productivity:

- Restricting water to any of the swamps or frequently-inundated floodplain will reduce or kill the vegetation. Even a small-scale of structure (e.g. graded windrow) is enough to block unchannelled flow and diminish downslope vegetation (Fig. 40).
- Restricting flows along the primary flow path will affect the timing and frequency of flood peaks, directly affecting the ability of flows to reach the more downstream parts of the system.

- Gilgai macropores are an important factor in groundwater recharge and salinity control (Costelloe et al. 2009); in gilgai areas, diminishing inundation and vegetation will eventually decrease those gilgai processes and hamper groundwater recharge.

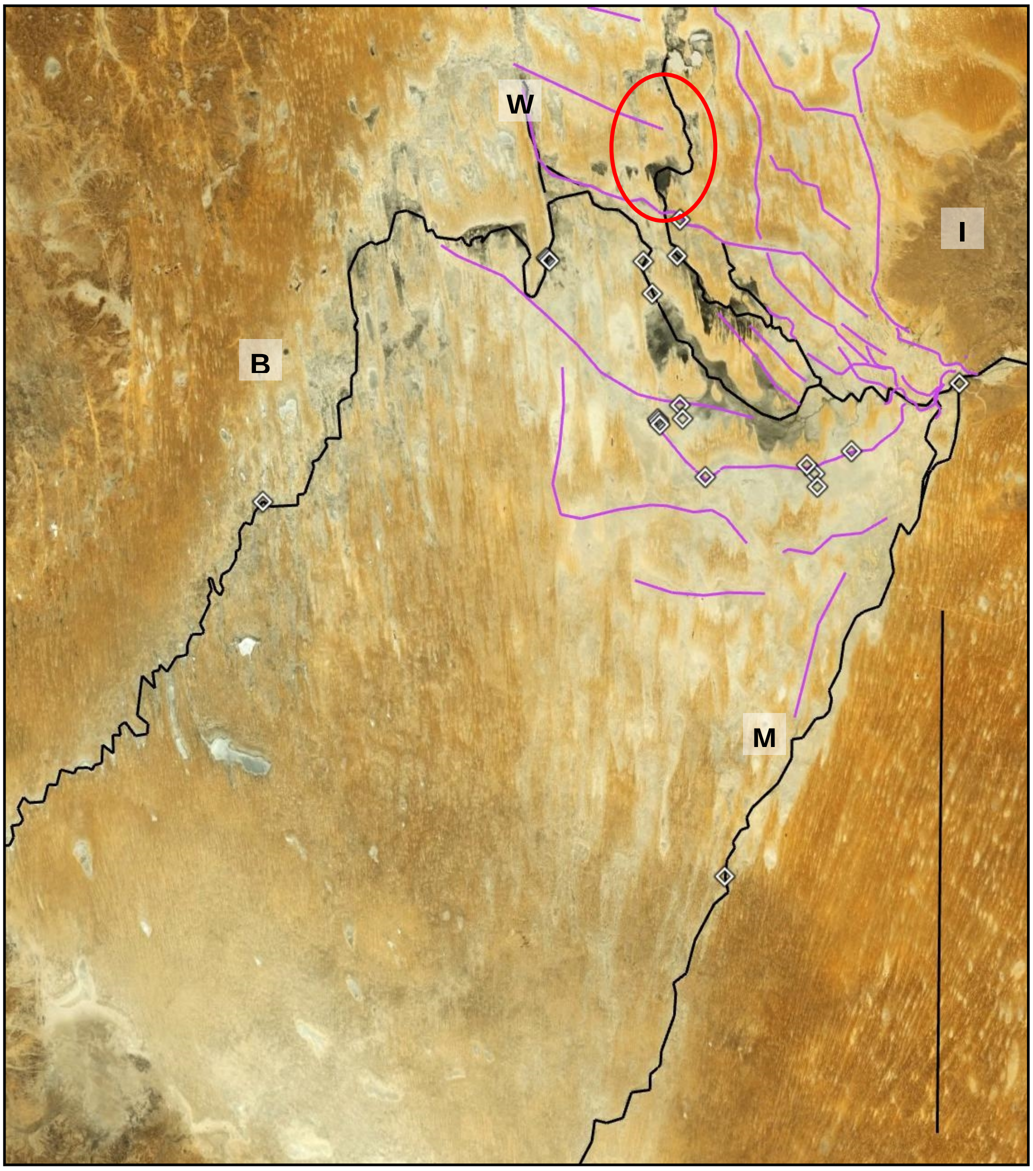


Fig. 39. Infrastructure on the Strzelecki Plain.

White diamonds are bridges and roads across Cooper Creek. I, Innamincka Causeway; M, Merty Merty Crossing; W, Walkers Crossing; B, Beach Energy's Kudnarri Bridge; red circle shows a cluster of crossings and bridges over the Cooper's main flow paths (Straw Bridge; Mitchie, Kudrieke and Moorari Crossings); purple lines are some of the palaeodrainage lines, some of which act as flood paths.

Bridges and bunds have been installed along the raised roads with the intention of not occluding flow: the bunds have large culverts, and the bridges stretch across the main channel. However, standard culvert and bridge design do not fully appreciate the importance of floodplain-level flow, the variability of possible flows, and the importance of flow along small anastomosing channels and swamps. In some places it appears that the culverts don't take peak flow and water is impounded upstream of the bunds (for example during fieldwork flow looked to be ponded on the east side of the Moomba to Tirrawarra Oil and Gas Field road).

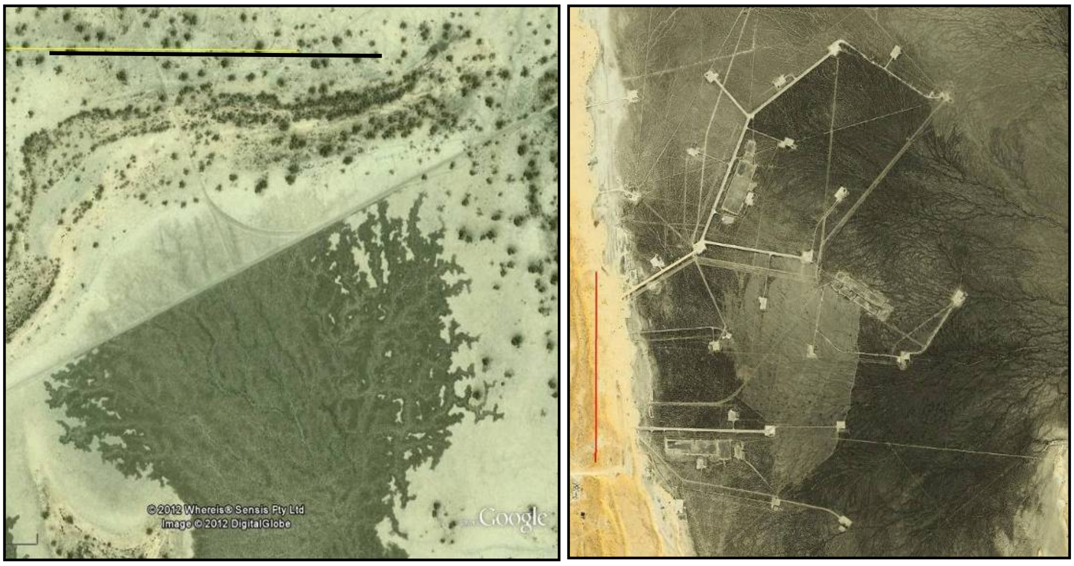


Fig. 40. Flow barriers which diminish vegetation.

Darker colour is dense vegetation, pale grey is less vegetation. Left, a road, or road plus fence, extends across a swamp 8 km SSW of Coongie campground. The graded line is enough to block flow and diminish vegetation. Flow is bottom to top, scale bar 0.5 km. Right, A network of elevated roads and bunds in the Tirrawarra Oil and Gas Field. This part of Embarka Swamp is terminal (does not transmit flow further downstream).

The other issue with too few or too small culverts is that during peak flooding, flow concentration will occur with consequent increases in stream power. This has the potential to create ongoing erosion issues. For example, during fieldwork it was noted near Walkers Crossing that some of the culverts were a point source of downstream erosion. During the 2010 floods, the Strzelecki Crossing impounded flow, causing increased stream power through a clearly insufficient number of culverts; the crossing washed out (Fig. 41a).

Similarly, bridge design in the study area seems to focus on accommodating main-channel flow, without accommodating the full width of the floodplain. Above-floodplain flow is an integral part of the fluvial process, and disregarding its potential volume will lead to erosion problems. A design where part of the river valley is occluded by bridge abutments (e.g. Walkers Crossing or Nappa Merrie, Fig. 41 b, c, d) will focus flow during peak flood times, increasing stream power and risking erosion around and through the structure. Nappa Merrie bridge's abutments were washed out during the 2010 flooding. Strong central flow can also result in channel degradation (channel deepening), which can propagate either up or down-valley, depending on the setting. Long-term consequences will include erosion networks, channel relocation or bank retreat. Although it was not possible to visit the abandoned Straw Bridge, the satellite image indicates downvalley widening and bank retreat, indicating such an erosion event.

Fig. 41. Increased stream power caused by poorly-designed road crossings.

A) The culverts at the Strzelecki Crossing impounding flow, increasing stream power, and washing out. (Compound image with captions on the wall of the Lyndhurst Pub, photographed April 2013; authors unknown.) B) At Walkers Crossing, the river valley has been narrowed (sandbags) and flow is concentrated in the channel center (arrow indicates turbulence of strengthened flow), increasing stream power. Flow is left to right. C) At Nappa Merrie Bridge, the valley is narrowed by an abutment (bracket). This section of road was washed out during recent flooding. D) The Nappa Merrie Bridge washing out in 2010. (Compound image with captions on the wall of the Lyndhurst Pub, photographed April 2013; authors unknown.)

Another type of flow impoundment can be created when clusters of buildings are installed. For example, Moomba township is built across a drainage line between two flats. A natural drainage line which may once have been a swamp or small waterhole is now occluded and impounded by a number of raised roads (e.g. Crocker Street) crossing from the main area to the Moomba Accommodation Camp on the east.

At the Tirrawarra Oil and Gas Field, a number of bunds have appreciable effects on the swamp vegetation (Fig. 40). In this location, regional through-flow is not occluded and although the local biological productivity is reduced, this development is not affecting downstream flow. In discussions between stakeholders in future hydrocarbon developments, the concept of "sacrifice zones" (similar to the sacrifice zone accepted by many pastoralists around watering points) may be useful. If a high-value development is proposed which isn’t located across flow paths, then the remaining question is what the development's effect will be on local biological productivity, and whether that sacrifice is acceptable or compensable in some way.

Management implications:

- Maintenance of the full range of flow variability should be a desired outcome for all land managers.
- Development of infrastructure which crosses flow paths is a Water Affecting Activity, and falls within the oversight of the SAALNRM’s Regional Plan.
- There needs to be enough culverts that flow can move through without experiencing increases in depth or velocity. Flow should never become banked up behind a bund. Bunds should be installed with more culverts than is presently the practice.
- Culverts need to be located along main flow paths even in areas of diffuse flow (swamps, or multiple anastomosing small channels).
- Swamps and anastomosing channels should be mapped prior to bund installation, so the culverts can be placed along the main flow paths.
- As part of environmental monitoring, exploration and production companies could use NDVI images of recent flood years to check whether their bunds are impounding flow.
- Bridges should not be built in such a way as to narrow the river valleys, or impede the above-floodplain level flow.
- In future exploration and production, techniques such as directional drilling should be considered to avoid siting infrastructure on through-flow drainage lines or biologically rich areas.

4.3.3 Maintenance of Flow Qualities on a Reach Scale: Mediation of Flow by Sills and Swamps

Sills (slightly elevated areas at the downstream end of a lake or swamp) are important mediators of flow routing. They allow water to be retained, halting the flow until it reaches a certain depth. As a result, soil moisture and groundwater is refreshed, and plants are watered. They are a critical element of ecosystem maintenance. Cutting through a sill (for example, by a gully network) would drain and reduce or kill the swamp or lake it supports.

Wherever the flow path is along small anastomosing channels and through reticulate-channeled swamps, the dense vegetation, torturous channel pathway and very small channel size are important mediators of flow. They allow passage of water, while slowing and retaining it. Reducing this flow resistance risks creating an easier downstream path, allowing water to bypass the swamp. The swamp will desiccate, and biological productivity will be severely reduced. Activities that could reduce flow resistance include devegetation (by grazing or fire), or creating a linear cleared path (e.g. firebreak, seismic line, road, track, fenceline, pipeline trench).

Whether a cleared line actually has this effect depends on the line’s position with respect to the flow path. A cleared line through a place where water is retained by a distant downstream sill is not likely to have a desiccating effect, because the water is held there regardless of the local conditions. For example, old seismic lines in Embarka Swamp’s terminal swamp (see Fig. 8) remain clear (possibly from grazing) but this has not detrimentally affected the swamp surrounding them. In this location, water is ponded by virtue of its being a natural basin. Similar cleared lines closer to the Embarka Swamp offtake could have a more severe effect if they were upstream from a sill which was compromised by a gully system. This scenario is similar to the valley-floor incision which has so severely affected western New South Wales.

Management implications:

Sills are important and should be managed carefully. Particularly sensitive areas include those in the Strzelecki Creek, the main flow path of the Coongie Lakes, and Lake Appadare.

Small channels and swamps are important and should be managed carefully. Line clearances in flow through-paths should be avoided or rehabilitated.

The potential combination of sill gullying downvalley from a devegetated swamp is a particular danger to the ecosystem. While not yet evident in the Strzelecki Plain, it is a circumstance that should be considered: it is not difficult to prevent but almost impossible to repair.

4.4 Erosion, Rubbish, and Other Issues

4.4.1 Trampling, Erosion and Gullying: Traffic by Stock and Humans

Aside from grazing, trampling is one of the strongest effects that stock animals have on landforms. Trampling can displace sediment, breaking up sediment surfaces so wind erosion has a greater effect, and stock pads can create linear disturbances in the ground which act as flow concentrators and trigger gullying. It is less often considered that human activity also triggers gullying and erosion. Across the study area, it was noted that the signs of cattle were more widespread, but had less intense effects, than human traffic. It should be noted however that in this very wet year, the stock (and therefore the intensity of their effects) could be expected to be more widely dispersed than normal.

In the sand dune country south of Cooper Creek on the Cooper Creek Fan (for example the areas between Moomba and the Merrimelia oil field) stock pads were relatively common. Most cattle tracks were parallel to dune trends, at crests or dune apron level, and cattle moving from high to low or vice versa made tracks that rose gradually in elevation, slanting diagonally up across the dune face. This type of stock pad leads to sediment being moved down to the base of the dune, where it might be blown back to the crest in the normal process of longitudinal dune maintenance. At the stocking level visible during fieldwork, and with the present level of good vegetation cover, these stock tracks did not appear to be a major issue for erosion.

It is possible that during earliest European settlement, when stocking rates were extremely high, that overgrazing and trampling along dune aprons contributed to the scalds (unvegetated, wind-eroded bare patches) that are so common throughout the study area. However, wind erosion has always been an important formative force for the landforms of the Strzelecki Plain (see sections 3.4 and 6.4). Compound dune formation requires that sand be moved from the southern margins of source-bordering dunes to create longitudinal dunes, so many of the scalded patches may be natural.

Although there is much less of it, a far more intense form of erosion is created by human traffic. Humans seem to like going straight down steep slopes, whether by vehicle or on foot, and the paths thus created are very susceptible to deep gullying. A camping spot on a dune top facing into Gidgealpa Waterhole had two extremely deep gullies leading from it, both straight down to the waterhole. It was clear from the tracks leading into the second gully that once the first gully (closest to the camp) became unusable, people walked a little further off and created a second path (Fig. 42). This also became a gully. Both gullies are actively eroding and expanding. They are oriented towards each other, and when the two gully systems meet it is likely that a very large block of sand (as big as two or three houses) will slump into Gidgealpa Waterhole, which is likely to be detrimental to the waterhole ecology.

Fig.42. Deep gullies in a sand dune.

A sand dune facing Gidgealpa Waterhole has two extremely deep gullies extending from crest to waterhole edge. The gully shown here was far too big to fit in a single photograph, and Hana is standing in the topmost section.

A similar comparison exists for tracks going down into waterholes. At Scrubby Camp Waterhole (a high-use location, with a stockyard and cattle loading ramp), there were a number of stock pads going down to the waterhole. They were triggers for erosion, but the gullies thus produced were not large. In comparison, the place where humans gained access to the waterhole showed signs of rapid bank retreat (Fig. 43). Elsewhere (e.g. Minkie Waterhole) places used for boat and canoe launching showed similar signs of rapid bank erosion.

In high-intensity usage areas, for example the camping grounds at Cullyamurra waterhole, widespread trampling leads to devegetation and risks the initiation of gullying. Gullies which extend from the floodplain to the waterhole will have relatively steep gradients, and be likely to propagate into the floodplain.

It is probable that vehicle tracks (especially graded or often-used tracks) cutting directly across the trend of sand dunes may be detrimental, however during fieldwork there was no opportunity to make observations on this topic. Vehicle tracks going straight up and down slopes between different levels on alluvial plains (for example at Cullyamurra) should be managed very carefully, as these are likely to develop erosion gullies.

It is difficult to think of a way in which bank erosion can be minimised in places where humans desire access to water, especially if the management goal is to try and preserve the wild bush camping experience. As more people visit the Channel Country, this will be an increasing problem.

Fig. 43. Tracks down to water at Scrubby Camp Waterhole

At Scrubby Camp Waterhole, the cattle track (right, hammer for scale) has created a small gully but has not led to wider effects, whereas the human access to the swimming area (left top and bottom) has led to devegetation, rapid erosion and bank retreat (arrow).

Management implications:

A valuable research project would be to assess the impact of grazing on landforms and vegetation in the Strzelecki Desert. The distribution of scalds on dune flanks should be mapped on a regional scale, and compared with grazing history (including watering point and fence layout), wind intensity and landform distribution.

In popular camping grounds, if camping is permitted alongside the river, camp spots should be managed to rotate use areas, and active revegetation be considered where vegetation is diminished.

Vehicle tracks going straight up and down slopes between different levels on alluvial plains (for example at Cullyamurra) should be managed very carefully, as these are likely to develop erosion gullies.

Tourism and park managers be aware of the potential for erosion by human foot traffic, especially that going straight downslope.

Management consideration should be given to new methods of minimising damage created by people and their boats going down steep slopes to gain access to water, while still preserving the wild camping experience (see *Management Implications*, section 3.2).

4.4.2 Artificial Waters: Dams, Pits, Ponds

Technological developments since the late 1800s have reduced the reliance of the pastoral and grazing industry on natural surface waters, by making it possible to construct earth dams along drainage lines and put down bores into groundwater and Great Artesian Basin water. As a result, most of Australia's potentially productive rangelands are within a few kilometers of some kind of permanent water (Silcock 2009). In the study area, the waterholes serve as the primary source of stock water, though there are some bores and dams. The importance of artificial waters is their ability to allow animals access into locations that were previously unavailable to them. With respect to grazing stock, the impact of artificial waters is part of the larger question of grazing management (see above). A separate question is the potential of artificial waters to be cane toad habitat.

As well as pastoral dams, bores, and watering points, artificial waters in the study area include infrastructure developed for the tourist and mining and exploration industries. Examples range from large ponds (interceptor, holding, pumpout, evaporation ponds, Fig. 44), borrow pits, and flare pits, to the random micro-habitats that occur around human settlements (leaky plumbing, dripping water-tank taps, toilet cisterns, roadside gutters and spoon drains). Another source of artificial water is where large building projects impound natural waters (for example just west of the Moomba Accommodation Camp), or where earthworks create microtopography that intercepts local waters (for example on the uphill side of workshop storage/parking areas).

The potential problem with these artificial waters is not only that they provide cane toad habitat. Some are extremely widespread (e.g. borrow pits, Fig.45) so they will aid in wide cane toad dispersal, and others are long-term, potentially allowing cane toads refuge during drought and allowing them to re-radiate during wet years.

Fig. 44. The evaporation pond at the Limestone Creek Oil Field

The pond is created from an existing deflation basin within a dune field.

Management implication:

It is recommended that all landholders and stakeholders be actively engaged with the process of cane toad control, should the toads reach the Strzelecki Plain.

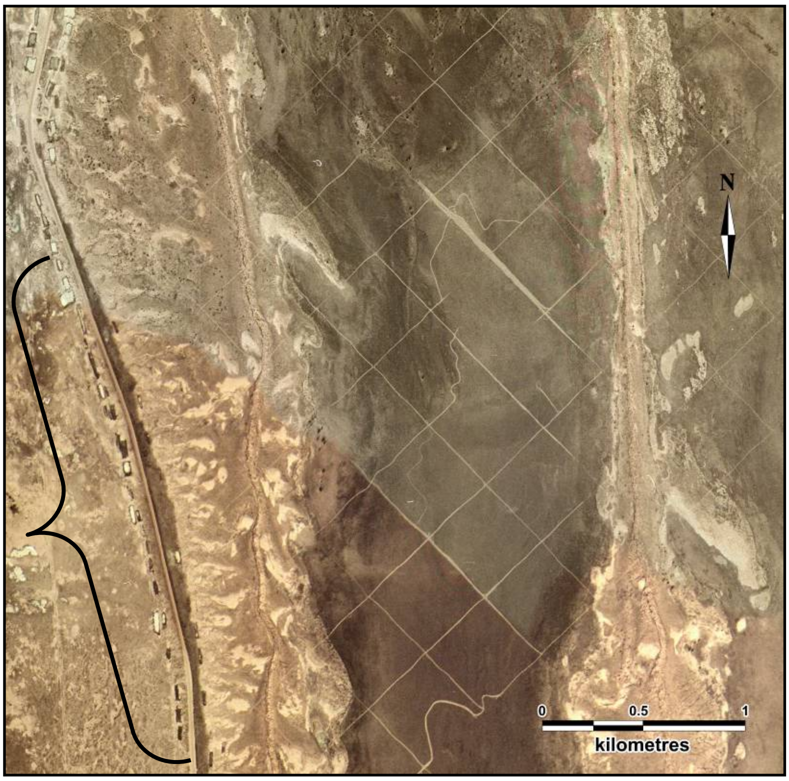


Fig. 45. Infrastructure south of Embarka Waterhole.

Seismic lines through lignum swamp (grid of straight lines) and many borrow pits along the western side of a road (bracket).

4.4.3 Mining Infrastructure: Contamination and Pest Control

Temporary infrastructure used by the mining and exploration industry includes exploration wells (containing mud pits, sewerage treatment systems, and various necessary supply areas: fuel, mud supplies, mechanic supplies, etc.). Correct procedure at the close of the exploration well is for the removal of all chemicals, trash, sewerage etc. from the site, and appropriate site rehabilitation. Assuming correct procedure is followed, there are still a few areas of potential concern:

- potential chemical contamination if a wellsite is caught in floodwaters
- risk of erosion if inappropriate rehabilitation techniques are applied
- potential to carry pest animals (especially cane toads) or seeds of pest plants from place to place during rig moves.

Permanent infrastructure used by the mining and exploration industry includes industrial complexes (e.g. Moomba, Tirrawarra), accommodation and office camps, roads, production wellheads (Fig. 46), pipelines, flow management areas, and hydrocarbon storage facilities. (Artificial waters, roads, and bunds are dealt with separately. Assuming correct procedure is followed regarding environmental management of industrial areas, the areas of remaining potential concern are:

- potential chemical contamination if a production well, evaporation pond or oil storage tank is caught in floodwaters
- risk of erosion if new pipelines are sited in vulnerable areas, or if inappropriate rehabilitation techniques are applied
- potential to harbour cane toads in the human environment.

Fig. 46. A production well: the “nodding donkey” pump, and hydrocarbon storage tank.

Management implications:

Exploration and production wells should avoid flood risk areas, including swamps, primary flow paths, and any palaeodrainages which act as flood channels. Risk mapping can be done on a regional scale with a combination of DEM and NDVI. A provisional palaeodrainage GIS layer is available from the author of this report.

Some relatively deep deflation basins along the north side of compound dunes are also a flood risk. Even if not connected to the Cooper Creek flow path, they can accumulate water from intense local rain falling on nearby “flats”. While they may be an acceptable risk for short-term infrastructure (exploration wells), they are unlikely to be a good proposition for long-term infrastructure (e.g. Moomba North #154, Fig.47; or any evaporation pond). Inundation of infrastructure in these areas is a contamination risk and also risks damaging the equipment.

Risk assessments for flooding should be applied to existing and proposed new permanent infrastructure, especially concerning procedures for cleaning up chemical contamination, and consideration of the integrity of foundations of large structures if inundated.

Mining and exploration industry employees and subcontractors should be aware of the risk of cane toad transport during rig moves or other transportation. If the cane toad invasion front penetrates beyond Windorah, hydrocarbon company management should be encouraged to put in place practices to discourage cane toad occupation of oilfield places and equipment.

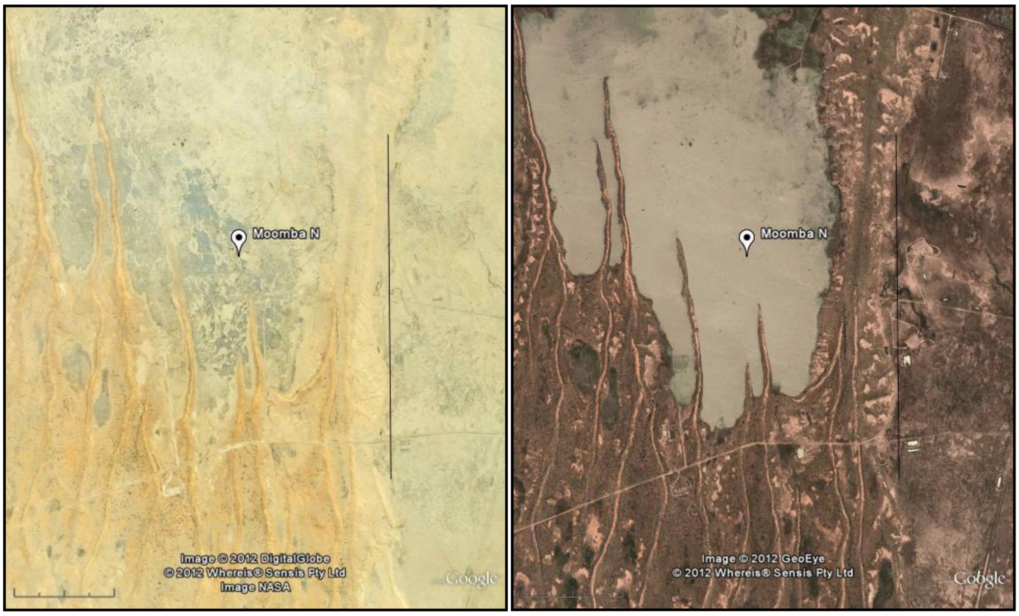


Fig. 47. Infrastructure in deflationary basins.

Moomba North production wells in deflationary basins, unconnected to the main Cooper flow path but capable of accumulating water. Left, 2006 (dry flats); right, 2010 (underwater).

4.4.4 Seismic Lines and Firebreaks

In the previous century, seismic lines were created by bulldozing away the vegetation and top few centimeters of soil along grid networks of many kilometers. Modern practices aim to minimise disturbance, and do not do this kind of extensive bulldozing; and they rehabilitate afterwards (see McLaren 1997). It was not within the scope of this project to compare old and recent seismic project areas. During this project it was observed that old seismic lines in sand dune country were more likely to be clearly visible and prominent if their post-seismic use involved something that kept the vegetation clear, such as pastoral roads or fences. Old seismic lines in lignum swamps seem to remain clear for decades (Fig. 45). Due to lack of access, it was not possible to investigate this. The regional study indicates that the cleared lines in the lignum swamps do not seem to be suffering erosion or gullying, which is positive. On the other hand they do not seem to be rehabilitating, which is a negative outcome. Something is preventing the germination and establishment of new lignum. It is likely that introduced animals are taking the opportunity of the cleared lines to graze new lignum shoots. This remains to be investigated.

From an aeroplane, it is possible to see newly-created bulldozed lines which appear to be firebreaks (they occur singly, not in grids as seismic). It was not possible to investigate these, however if firebreaks are installed by creating a devegetated linear ground disturbance, they are likely to present a risk of subsequent gullying and erosion.

Management implications:

Research could be undertaken to establish why the lignum swamps aren't regenerating, and to investigate the possibility of human-directed revegetation.

If not already existing, an independent study be conducted, comparing the environmental effects of the old and the new seismic methods.

The potential erosion risks created by bulldozed firebreaks should be considered by whatever land managers, Park managers or SAAL NRM officers who currently work on erosion problems created by roads.

4.4.5 Local Erosion: Roads and Borrow Pits

In drylands Australia, a common problem is the creation of large erosion gullies by water flowing down vehicle tracks or poorly-designed graded roads. The dominant process is flow concentration leading to increased stream power, triggering erosion which then becomes self-propagating. Prevention measures include not grading a road down below the ground surface, not leaving road-edge windrows, and properly directed spoon drains.

The roads in the study area did not appear to be associated with gullying, however much of the fieldwork took place on hydrocarbon industry (maintained) roads. Some pastoral tracks across sand dune country were associated with some gullying. The largest gullies and erosion networks associated with road development were associated with a now-abandoned hydrocarbon road northwest of Tirrawarra Oil and Gas field. The gullies were initiated where the elevated road-bed crossed over dune crests, and propagated into the road surface, delivering sediment into the flanking interdune corridors.

Small to medium-scale erosion gullies were commonly observed around the edges of borrow pits. In such a flat landscape, a borrow pit creates a new base level, from which erosion gullies may develop. Erosion gullies did not appear to be propagating rapidly, however borrow pits are extremely numerous and it is undesirable that they should develop into gully networks. It is likely that the risk of erosion can be minimised if the borrow pits are not located where they will experience runoff water, and if they are rehabilitated to be not too deep, with sides not too steeply sloped.

Management implications:

Borrow pits should be designed and rehabilitated with respect to local conditions of gradient and sediment type.

Consideration should be given to the feasibility of rehabilitating abandoned oilfield roads, and whether it is possible to re-use the road base in other new roads.

4.4.6 Tourism: Wood, Garbage, Toileting, Driving

The impacts of human visitation include trampling and path creation (see section 4.4.1), collection of wood, rubbish, and toileting.

Throughout the study area, vegetation along the riparian zone plays an extremely important role in maintaining landform integrity, and thus preserving the ecosystems. Human visitation should be managed in such a way as to preserve riparian vegetation. Vegetation is also negatively impacted by vehicles parking beneath trees or frequently driving close to them (e.g. in the Town Common).

The old practice of burying rubbish in a pit is insufficient, as rubbish can be re-exposed especially where gullying occurs at a high-usage site (Fig. 48). Tourists and local inhabitants should be encouraged to carry away whatever rubbish can't be completely burnt. (It should be made clear that putting e.g. bottles into a fire doesn't burn them.) Organic material (food scraps) should also be burned, as the decay processes that turned buried food into soil do not operate well or rapidly in the arid zone. Best practice should include raking through the ashes of a campfire and removing partially-burnt debris.

In camping areas without toilet facilities, travelers commonly dig single-use toilet pits, and the used toilet paper buried. Two issues are created:

- riparian landforms are degraded by being dug into, and there is the potential for triggering erosion
- in a dry climate, toilet paper is not biodegradable and organic solids do not rapidly turn into soil. Toilet pits are easily eroded, the toilet paper is exposed and blows around: the result is very unappealing.

Fig. 48. Rubbish dating back to the 1980s exposed in an expanding gully, Scrubby Camp Waterhole.

Both issues are most severe where the landforms are high-elevation relics of previous climate phases: the terraces flanking Cullyamurra waterhole, or the Strzelecki Creek delta into Lake Blanche (e.g. Montecollina Bore) (sections 3.2, 3.3.1, 3.7). In these areas, the existing landscape processes no longer support landform construction, so erosion is likely to be uncontrolled. In addition, because these areas are away from current fluvial processes, there may not be water available to aid in the process of biodegrading toilet paper and organic materials. Popular camping areas in relict landform zones should have infrastructure support (composting toilets) and education about rubbish removal.

Landform renewal and biodegradation of organic material is more possible in areas that occasionally experience inundation, as moisture promotes breakdown of biodegradable materials and flowing water renews landforms (as long as the vegetation is in good condition). Areas that experience inundation (for example the shallow, usually dry parts of the channels) are more suitable for a wild camping experience. Removal of non-organic rubbish continues to be important in these areas. Wild camping in areas of occasional inundation is subject to some risk to the camper, and from a park management point of view permission should not be accompanied by promotion.

Management implications:

Visitation should be managed in such a way as to preserve riparian vegetation.

In popular camping spots, parking beneath trees should be discouraged, or camping areas should be managed so as to periodically rest and revegetate high-use areas under trees.

In popular camping spots

- organic rubbish (paper, food scraps) should be burned, and non-organic rubbish carried away;
- best camping practice should include raking through the ashes of a campfire and removing partially-burnt debris before leaving the site.

Local towns should be prepared to accept and manage tourist rubbish, so the areas around them continue to be clean and attractive to tourists.

Public education on best-practice remote camping should include mention of circumstances in which toilet paper is not biodegradable.

Park planning should distinguish between

- high-elevation and/or relict and/or rarely inundated landforms (such as terraces), where natural processes of landscape renewal are unlikely to occur. In these areas, camping with facilities (managed and rotated sites, compost toilets) is more appropriate.
- and low-elevation landforms which are likely to experience periodic inundation and natural processes of landscape renewal are more likely (as long as gullying is prevented and vegetation is preserved). These areas may be more appropriate for wild camping;

Risk management should be considered if low-elevation wild camping is permitted.

PART 2: TECHNICAL APPENDIX

5. INTRODUCTION TO PART 2

This Technical Appendix is the material supporting the information presented in Part 1 of this report. It includes greater detail on the methodology, literature review, desktop study of the regional context, field observations, analysis and synthesis. Part 2's section heading names match those in Part 1, to facilitate cross-referencing of information.

5.1 Methods

The project's first stage was a remote-resources desktop study, comprising analysis of geological maps, satellite images (Google Earth, MODIS), 1-, 3-, and 9-second SRTM digital elevation models (DEMs), and topographic datasets (Geoscience Australia), and the published literature on geology, geomorphology, and other relevant topics.

Although the Arid Lands of South Australia are generally under-researched, in the study area concentrations of knowledge exist around

- the geology of the Eromanga Basin (after more than a century of drilling for artesian water, and more recently exploration for oil and gas),
- surface expression of the geology (the Lake Eyre Basin sedimentary rocks and duricrusts preserve an important record of Australia's fossil history and palaeoclimates)
- the sedimentology and fluvial geomorphology of the Cooper Creek in Queensland and around Innamincka (especially by the Nanson research group at Wollongong University)
- and the history and processes of the Simpson, Strzelecki and Tirari sand deserts.

The Arid Lands of South Australia have little high-resolution spatial data (aerial photography or true-colour hi-res satellite images) available at low cost. Some low-cost to free alternative are available but their quality is only moderate; they are adequate for regional scale studies but sub-optimal and inefficient for detailed studies of high-value or at-risk areas.

After the desktop study, the field investigation took place, focusing on locations of specific relevance to the larger project, and/or identified during the desktop study as likely to be 1) typical landforms, or 2) providing evidence of geomorphic activity, or 3) likely to be particularly relevant to pest species dispersal. During fieldwork, evidence for landscape processes was gathered from the relationships between sediments, landforms, vegetation, and geomorphic context (for example, muddy sediments vegetated by lignum or Queensland bluebush, located in a wide flat depression along the primary flow path, identifies a dry swamp). Evidence of these relationships was collected as photographs and maps (including GIS database). Mapping examines the spatial relationships between landscape elements, allowing analysis of how they work. Post-field investigation revisited the desktop study in the light of collected field evidence, during which stage the majority of new information was uncovered.

5.1.1 Caveats on Using the One-Second SRTM Digital Elevation Grid in the LEB

The 1-second Shuttle Radar Topography Mission (SRTM) digital elevation data, and especially the Geoscience Australia dataset (described in Gallant et al. 2011), is a far superior product than what has been available previously for the same price bracket. However, it has some issues that users in the Lake Eyre Basin and other low-relief arid zone areas should be aware of.

The raw data is processed before it becomes available for public use, in a way designed to make the information more reliable and usable. Initial processing includes void filling, where null-value areas (where no signal was returned to the satellite) are given a value consistent with their edge values. One cause of no signal is poor reflectance from dry sandy areas, and “salt lake areas in central Australia” is specifically mentioned in the Geoscience Australia user guide (Gallant et al. 2011). Post-processing, these filled voids look the same as lakes: flat-bottomed areas with a clear edge.

The Cooper Creek landscape has many very flat dry sandy areas. East of Tirrawarra Swamp, a flat area which may experience occasional inundation but which is definitely not a lake (Fig.1, top left) is given a flat profile at an interpolated elevation during initial processing (Fig.1, top right). The DEM preserves the information of the area’s outline but creates an impression that the landform might be a lake, and offers information on bed elevation which should be understood to be indicative only.

The 1-second SRTM data is available from Geoscience Australia in three forms: original processed data, smoothed data (improving the signal-to-noise ratio so that the landforms can more easily be seen), and hydrologically-forced data. In the hydrologically-forced set, ANUDEM software uses drainage line vectors from topographic datasets on the gridded elevation data, enforcing continuous descent along the drainage lines (Gallant et al. 2011) and assigning an arbitrary channel depth to the creek line (1-2 m in Fig. 33 of Gallant et al. 2011) .

The raw SRTM data have “noise” (pixel-to-pixel elevation differences 2-3 m, sometimes up to 10 m; Gallant et al. 2011). The smoothed DEM (Fig. 1 bottom left) improves the relative pixel-to-pixel elevations, and provides a useful image without sacrificing too much information. The smoothed DEM was used throughout this project. It should be noted however that these data have a 30 m pixel and ~9 m vertical uncertainty (in terms of absolute elevation values, and relative to other forms of measurement; Gallant et al. 2011). These are not suitable for detailed site analysis. For example at one part of Tilcha Waterhole, the DEM indicates relatively deep water whereas both the geomorphology and the hydrologist's measured depth profile indicate shallowness.

The hydrological forcing of the DEM is a valid undertaking in many parts of Australia, but the results depart from reality when 1) the input data are wrong, or 2) the landscapes in question behave differently to those upon which the processing algorithms have been based. This is the case in the study area, and incorrect information in the hydrologically-forced DEM is of particular concern here. The drainage lines used in this processing are derived from 1:250,000 topographic data created by cartographers whose expertise in air-photo interpretation was not matched by their experience in arid-zone fluvial landforms. During the creation of topographic maps across drylands Australia, disconnected drainage lines have been drawn as if separate channel segments were linked in continuous channels. Using these misinterpreted drainage lines to create hydrologically-forced DEMs places entirely fictitious channels through inappropriate landforms (Fig. 1 bottom right). Continual descent is an invalid assumption in the Strzelecki Plain’s fairly stochastic microtopography. Enforced continual descent along a misinterpreted drainage line can lead to drainage anomalies, such as Christmas Creek, which in the DEM-h slopes in the opposite direction to its actual slope (see section 7.3.2, and Fig. 54). Management decisions based on this apparently scientific dataset will be incorrect.

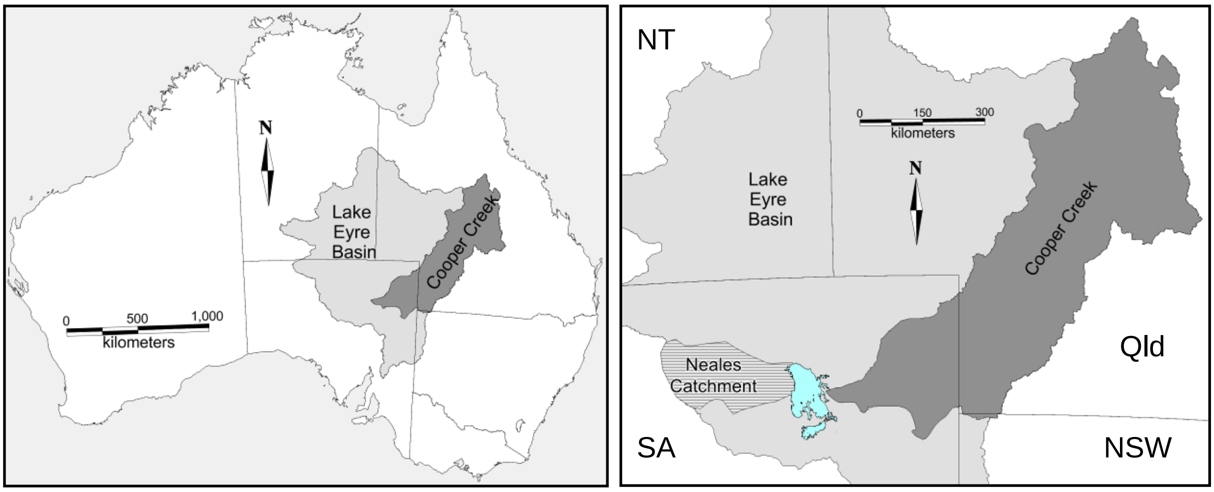


Fig. 49. The Cooper Creek catchment in the Lake Eyre Basin.

The Cooper Creek catchment (dark grey) is part of the Lake Eyre Basin (pale grey). Left: The Lake Eyre Basin is the largest catchment in Australia. Right: The Lake Eyre Basin, showing Lake Eyre (pale blue), the Neales River catchment (mid-grey stripes) and the state boundaries of South Australia (SA), New South Wales (NSW), Queensland (Qld), and the Northern Territory (NT).

5.2 Physiography and Locations

The Lake Eyre Basin covers almost one sixth of the Australian continent. At 1.2 million square kilometers, it is more than twice the size of the Amazon River's catchment. It is a very low-relief, wide and shallow basin with its terminal drainage sump (Lake Eyre, the world's fourth-largest terminal lake) near its south west section. Low-gradient rivers supply Lake Eyre, particularly Channel Country from the north and north east, and the Neales River catchment to the west (Fig. 49).

The Lake Eyre Basin is bounded by the Central Australian uplands (north and northwest), the Billa Kalina Basin (south west), the Flinders and Willouran Ranges (south), and the Tibooburra Dome (east). Within the Lake Eyre Basin, the dunefield deserts are the Simpson Desert (north of Lake Eyre), the Tirari Desert (immediately east of Lake Eyre), and the Strzelecki Desert (further east, on the east side of the Gason Dome). The stony uplands within the study area are Sturts Stony Desert, known geologically as the Gason Dome and Birdsville Track Ridge; and the Innamincka Dome, the Cordillo Dome, the Benangerie Ridge, and the Cooryanna Dome (Location Map, and Fig. 2).

In the northeast corner of South Australia and extending into Queensland, the topography comprises broad shallow depressions separated by low-elevation stony rises. The Tirari Desert and the central and western portions of the Strzelecki Desert are topographic lows, within which sand dunes have accumulated amongst river and lake deposits. The eastern portion of the Strzelecki Desert, although also cloaked by sandy sediments, is actually ~70 m above the Strzelecki plains, and rises towards topographic highs at the Tibooburra Dome and Benangerie Ridge (NSW) and the Grey Ranges (Qld) (Fig. 2). Between the Tirari and Strzelecki deserts lies the Sturts Stony Desert (known geologically as the Gason Dome), a topographic high marked by gibber plain and without sand accumulation. The northeast-trending Birdsville Track Ridge links it to the Cordillo Dome in South Australia's northeast. Other stony rises of importance to this study include the Innamincka Dome, and the Cooryanna Dome near the Flinders Ranges (Location Map, Fig. 2).

The river systems known collectively as the Channel Country flow from the semi-tropical north in Queensland and the Northern Territory, and enter Lake Eyre on the lake's north and east sides (Fig. 2). Of these, the geomorphology and sedimentology of Cooper Creek is by far the most comprehensively studied (e.g. Rust & Nanson 1989, Knighton & Nanson 1994, Nanson et al. 2008, Cohen et al 2010). Cooper Creek's total catchment is 298,200 square km (20% bigger than the United Kingdom); within South Australia the Cooper's catchment is 53,270 square km (bigger than Denmark). The Cooper Creek floodplain is extremely broad (at the widest, >60 km) from Windorah to its entrance into the east of the Innamincka Dome; there, upstream from Nappa Merrie Waterhole it becomes narrow (minimum 150 m) until it exits the Dome near Burke’s waterhole.

The Cooper Creek catchment within South Australia is 53,270 square km (bigger than Denmark). Where the Cooper Creek exits from the Innamincka Dome, a broad shallow low-angle distributary fan exists: the Cooper Creek Fan (Location Map). Its elevation ranges from 40 to 245 m above the Strzelecki Plain (fan edge to fan apex), and its downvalley slope is approximately double that of the plains (Callan & Bradford 1992). As it flows across the Cooper Creek Fan, Cooper Creek's flow path divides into three main distributary branches: the Strzelecki Creek, the Cooper (Main Branch), and the Cooper (North West Branch).

5.3 Geology

5.3.1 Rocks, Sediments, and Geological History

The oldest rocks in the area, Precambrian igneous and metamorphic basement, are only exposed in the Flinders and Willouran Ranges to the south.

The Cretaceous-age Eromanga Basin rocks are part of the Great Artesian Basin (GAB). In the study area they are dominated by the Winton Formation (Table 2, Geology Map). In the subsurface this is a dark carbonaceous and pyritic claystone and siltstone, and at surface they crop out as bleached and weathered pale kaolinitic sandstone, siltstone and claystone (Williams 1975, Krieg et al. 1990). In the Cordillo Dome, the Winton Formation also includes medium to coarse-grained quartzose sandstone with large-scale crossbeds, which resembles (but is substantially older than) the widespread Palaeogene-age Eyre Formation (Alley et al. 2011). At the Cooryanna Dome, other GAB rocks are exposed: the Bulldog Shale (dark grey shale, sometimes fossiliferous), the Oodnadatta Formation (grey siltstone-claystone, with laminae and interbeds of fine to very fine sand), and the Mackunda Formation (thinly bedded and crossbedded fine sandstone) (Krieg et al. 1990, Whitaker et al. 2008). After deposition, uplift exposed Eromanga Basin rocks to erosion. Folding developed the dome-and-basin structure which is visible today, and some silcretes were emplaced (Moussavi-Harami & Alexander 1998, Alley et al. 2011).

The Cainozoic geological era is subdivided into Paleogene (65-23 million years ago), the Neogene (23-2.6 million years ago), and the Quaternary (from 2.6 million years ago up to the present day). The Paleogene and Neogene were previously known jointly as the Tertiary geological period. The Quaternary geological period includes the Pleistocene (from 2.6 million to 11 thousand years ago, during which the many Ice Ages took place), and the Holocene (from 11,000 years ago to the present, covering the present interglacial and the span of recorded human history).

During the Cainozoic, the Lake Eyre geological Basin accumulated layers of sediments (mostly now lithified into sedimentary rocks). The rock record reflects the changing climates experienced by the Australian continent, and the geological units can be grouped into three phases (Krieg et al. 1990).

First phase (early Paleogene) The Lake Eyre Basin at this time may have been even larger than it is today. Under a wet climate, forest, woodland, swamps, and vigorously-flowing waterways deposited clean quartz sands. The sand source was erosion of the Eromanga Basin rocks, especially from the Flinders/Willouran Ranges, the Peake/Denison ranges, and areas of uplift such as the Cordillo Dome (Wells & Callen 1986, Krieg et al. 1990). The Eyre and Glendower Formations (Table 2) are extremely widespread. The Eyre Formation consists of fine to medium grained sands, usually crossbedded, lignite, carbonaceous clays, and a characteristic basal conglomerate of polished pebbles. In outcrop it is usually <10m to ~40m thick, but in subsurface it can be >100m (Wopfner et al. 1974, Callen et al. 1986, Krieg et al. 1990, Alley 1998). The Glendower Formation in Queensland is a lateritised and silicified pebbly clayey quartzose sandstone, with some siltstone, conglomerate and mudstone (Geoscience Australia 2011). Folding and uplift developed the Gason Dome and Birdsville Track Ridge (subdividing subsequent phases of the Lake Eyre geological Basin into the Tirari and Callabonna sub-basins), and led to erosion of the Eyre Formation from dome crests (50-60 m may have been lost from the top of the Innamincka Dome, Moussavi-Harami 1996). A weathering event, including ferricrete and silcrete emplacement, is correlated to this widespread planation surface (Wopfner et al. 1974), and Eyre Formation rocks are often capped by silcretes. Continued tectonic activity folded these silcretes prior to the next phase of sedimentation (Table 2, and Geology Map).

Second phase (late Paleogene to Neogene) Lake Eyre Basin's climate became drier (though still wetter than it is now). Under a warm climate, shallow brackish to saline lakes deposited the Etadunna and Namba Formations (Table 2, Geology Map) (Krieg et al. 1990, Alley 1998). A rich fauna included tree-browsing marsupials, the flesh-eating hunter *Thylacoleo carnifex*, flamingos, crocodiles, turtles, and dolphins (Wells & Callen 1986, Alley 1998). Towards the end of this phase, the lakes progressively dried, leaving behind relict landforms. The most geologically significant deposits of this type are from the palaeolake Billa Kalina (Callen & Cowley 1998). Silicification of inter-ridge sediments followed by uplift and erosion has resulted in an interesting topographic inversion: ancient beach ridges grade downslope to box-canyons, whereas silicified interdunes are preserved as flat-top hills; present-day longitudinal dunes cut across the trend of these fossil beach ridges (Ambrose & Flint 1981, Wells & Callen 1986). The area demonstrates that in only a few million years the local depocentre has been uplifted to form the drainage divide between Lakes Eyre and Torrens: low-key but hydrologically significant tectonism and flexure (Sandiford et al. 2009). At the close of this phase, another episode of widespread silcrete and ferricrete formation took place, and tectonic activity created the new Lake Eyre depocentre, well to the north of its present-day location (Wells & Callen 1986).

Table 3. Summary of geological history and stratigraphy.

Basin	Age	Unit Names	Lithology at Surface	Comments
Lake Eyre	Late Pleistocene to present day	alluvium, lake sediments	Floodplain and lake muds.	Includes Tingana Clay associated with Strzelecki Creek
		lunettes	Clay and gypsum dunes, downwind from lake margins.	
		sand dunes: Simpson, Tirari, Strzelecki Deserts	Quartzose sand, some clays; Longitudinal and compound dunes	Near Cooper Creek, compound dunes link to palaeochannels (transverse source-bordering dunes blown from Katapiri Formation in repeated episodes, then extending northwards in linear dunes).
	late Pleistocene (270-22 ka; up to Last Glacial Maximum)	Katapiri Formation	Sandy meandering river, scroll bars visible under modern alluvium; shoreline dunes; lake muds; selenite sheets and other gypsum.	Also Eurinilla, Millyera & Coomb Spring Formations. Deposited in broad valleys, which now carry present drainage. Lake depocentre now in Lake Eyre South.
	Disconformity (minor warping), depocentre now in south of the present-day Lake Eyre (the modern configuration). Climate becomes more arid.			
	mid-Pleistocene (~1.3 Ma)	Kutjitara Formation, Yandruwantha Sand	Fluvial sands, floodplain muds, and lacustrine clays and gypsum sands.	Kutjitara: Distributary palaeo-channels, trending from SE to depocentre in NW (towards northern part of Lake Eyre), now expressed as salina chains and palaeovalleys capturing present drainage in the Warburton River. Yandruwantha: eastern Strzelecki Plain.
	Disconformity (minor warping). Mid-Pleistocene (1 Ma): heightened aridity triggers beginning of the linear dunes (Simpson Desert); episodic development continues during Quaternary glacial maxima.			
	Late Neogene - early Pleistocene (~3-2 Ma)	Wipajiri, Tirari and Willawortina Formations	Sandstone, mudstone, massive gypcrete crust with celestite.	Fluvial to the south, lacustrine to the north.

Third phase (Neogene to Pleistocene) The climate became much drier (though not as dry as the present day). Surface sediments were stripped from the uplands, exposing the silcrete and forming today's stony deserts (Fuiioka et al. 2005). Fluvial and lacustrine sediments were laid down (Wipajiri, Tirari, Willawortina and Kutjitara Formations) (Table 2). The distribution and lithologies of the most recent of this group (Kutjitara Formation) indicate that in the mid-Pleistocene the lake was about 1.5 times the size of the present Lake Eyre north, and extended as far east as Lake Hydra or Lake Florence (nearly to the base of the Cooryanna Dome). Low-sinuosity palaeochannels the Kutjitara Formation rivers are still visible, extending towards the old northern depocentre, expressed in the modern landscape as elongate salt pans and claypans which lie northwesterly, cutting across the trend of the dunes (Wells & Callen 1986). The present-day valleys which carry the lower Cooper and Warburton Creeks also show this orientation (Location Map, Geology Map).

The most recent sedimentary deposit, which directly underlies modern fluvial sediments, is the Katipiri Formation (and its correlative units), dating from the late Pleistocene (~270 ka) to geologically recent times (approximately the last glacial maximum, ~18 ka) (Cohen et al. 2010). These unconsolidated, clean white crossbedded quartzose sands were deposited by sandy meandering rivers whose scroll plains and sinuous channel remnants can be seen underlying modern sediments in some satellite imagery and aerial photography (Wells & Callen 1986). The Katipiri Formation is overlaid by the Cooper Creek's floodplain muds, and (to greater or lesser degrees) by some red to orange sand dunes. This formation occupies the valley of the Cooper Creek, extending from Queensland through to the lower Cooper, and has a geomorphically important role as a dune source, a prominent landscape element, and a local aquifer.

5.3.2 Uplift, Subsidence, and the Modern Landscape

Precambrian-age metamorphic rocks expressed at surface as the Flinders Ranges are connected to or adjoin other similar rocks, in an arc extending across South Australia and into New South Wales (the Curnamona and Olary blocks, the Tibooburra Dome, the Willyama Supergoup of the Barrier Range) (Parker 1990, Sheard 2009). They are overlapped by sedimentary rocks of the Permo-Triassic Cooper Basin (extending from the SA-Qld border to Lake Blanche) and the Jurassic-Cretaceous Eromanga Basin (Alley et al 2011, Callen & Gravestock 1994, BMR 1971). Together, they have experienced sufficient uplift to create the physiographic highs which define the southwestern (Cooryanna Dome) and eastern (Benangerie Ridge) edges of the study area (BMR 1967, BMR 1971, Wopfner et al 1974, Hill 2005, Sheard 2009). Though of greater elevation than the Strzelecki Plain which they enclose, they are relatively flat and the underlying rocks are masked by regolith or sand. The role of these areas in defining the Cooper Creek and Strzelecki Creek catchments is best seen in a digital elevation model (see Location Map).

The Strzelecki Desert is divided into two sections by a hinge zone approximately along the line of Strzelecki Creek (Gravestock et al. 1995): the Strzelecki Plain in the west, and the Benangerie Ridge in the east (Fig. 3, Location Map). Although superficially similar, they differ in their elevation, tectonic history, and underlying geology. The Benangerie Ridge part of the Strzelecki Desert is a thin veneer of aeolian sediments over uplifted rocks and regolith. The dark red colour of the dunes reflects the iron-rich regolith at or near the surface, available to contribute sediments to the geologically recent sand dunes. In contrast, the Strzelecki Plain part of the Strzelecki Desert has been a long-term locus of subsidence. Iron-rich regolith is more deeply buried, and the source material for the dunes is early to mid-Pleistocene fluvial sediments (Gravestock et al. 1995).

The modern Lake Eyre Basin, and the underlying Lake Eyre (geological) and Eromanga Basins are intracratonic basins whose subsidence over such wide areas arises from continental-scale plate tectonic movements (Jansen-Schmidt et al. 1995, Quigley et al. 2010). On a smaller scale, the Australian plate experiences undulations (vertical movements on a scale of tens to hundreds of meters, across horizontal areas of hundreds of kilometers), such as the Neogene uplift which transformed a lake depocentre (Billa Kalina) into a catchment boundary (Sandiford et al. 2009). During geologically recent time the Lake Eyre depocentre has migrated from north to south (Wells & Callen 1986), which is likely to be the result of a similar vertical movement.

In the Eromanga and Lake Eyre (geological) Basins, faulting and doming was taking place concurrently with sedimentation during the Tertiary, in response to regional east-west compressional stress, differential compaction and sediment loading (Moussavi & Harami 1998). The area is thus characterised by a dome-and-basin structure in which the domes are uplifted areas and the basins are areas of subsidence (Fig. 4). The uplifted domes include the Innamincka and Gason Domes, and the basins include the Strzelecki Plain. This surface geology is strongly influenced by pre-existing structural elements: the basement highs, the dome-basin topography of the Eromanga and Cooper Basins, and underlying basement faults. Slow uplift along the ridges and domes has led to erosion and removal of sediments from their crests (Moussavi & Harami 1998, Alley 1998, Alley et al. 2011). These movements continued through the Neogene (Moussavi & Harami 1998) and their influence extends to the present day: the Innamincka Dome is rising at a rate of ~36 m/Ma (Nanson et al. 2008). The correspondence of topographic highs to anticline crests and broad river valleys to basin troughs in which sedimentation is currently occurring (Cooper Creek's widest floodplain is along the Cooper Syncline, and the Wilson River's is along the Wilson Syncline) suggest subsidence is currently active.

In the present day, there is subsidence on the west side of the Cooper floodplain (Windorah to Nappa Merrie reach), such that the channel belt has shifted to the western margin, and floodplain sediments are invading the bordering interdunes

(Knighton & Nanson 1994). The cause of this subsidence may be related to the factors creating the nearby Lake Yamma Yamma, a landform without obvious antecedents or context.

5.4 Hydrology

5.4.1 Present Day: Large Playa Lakes, Cooper Creek, Coongie Lakes

Lake Eyre receives water from the Channel Country rivers to the north and north east, and from smaller catchments such as the Neales River to the west. Lake Eyre is usually dry, occasionally receives inflow waters, and rarely fills (usually during La Niña phases of the ENSO cycle), reaching an elevation of -9.5 m AHD (Kotwicki & Allen 1998). Such fill events have been recorded for 1950, 1974, and recently. Lakes Gregory, Blanche, and Callabonna occur around the base of the Cooryanna Dome. Lakes Gregory and Callabonna are linked to Lake Blanche by small channels, so theoretically at least may receive overflow waters from Lake Blanche; Lake Callabonna is also linked to Lake Frome to the south. A small, poorly-defined channel (Warrawoocara Channel) extends from Lake Gregory towards the lower Cooper Creek.

Cooper Creek, along with the Warburton, Diamantina, Georgina, and tributary rivers, are collectively known as the Channel Country. They run from central-north Queensland down to Lake Eyre, a straight-line distance of >900 km. This great length allows these rivers to extend across climate zones: in the headwaters mean annual precipitation is ~400-500 mm, whereas around Lake Eyre precipitation is <100 mm (Knighton & Nanson 2001). The headwaters are fed by occasional monsoonal rainfall, of sufficient volume that flood pulses routinely travel as far as South Australia; the rainfall and river flows are extremely variable (Knighton & Nanson 2001, Nanson et al. 2008).

The nature of each flow event depends on rainfall volume and location within the tributary network. Hydrographs show that flow events may be single, multiple, or compound (Knighton & Nanson 2001):

- Single-peak events may be relatively small and of short duration, and tend to be locally generated.
- Multiple events show a hydrograph with more than one peak, but with progressive increases in peak magnitude toward a well-defined maximum; these events are intermediate in size, behaving more like single events at small event volumes or small basins, and like compound events if larger in scale.
- Compound events have multiple peaks which do not show progressive rise towards peak discharge; these tend to be relatively large events.

Although transmission losses from headwaters to downstream reaches can be considerable (>75% between Currareva waterhole, northeast of Windorah, and the Nappa Merrie Waterhole, at the upstream end of the study area), nonetheless flow is sustained for a great part of the year in waterholes of the Innamincka Dome (Knighton & Nanson 1994, Knighton & Nanson 2001, Silcock 2009). Complexities of flow behaviour (flow routing, and the retardation of the flood wave at greater than bankfull discharges) means that in comparison with more upstream locations, flood peaks in the waterholes of the Innamincka Dome may be lower, yet flow events may be of longer duration (Knighton & Nanson 2001). Thus, despite its location in one of the driest parts of South Australia, Cooper Creek in the Innamincka Dome area has a more dependable water supply than might be expected, commonly experiencing many flow days per year. As the Cooper Creek leaves the Innamincka Dome, it splits into three main branches: the Strzelecki Creek, the Cooper (Main Branch), and the Cooper (North West Branch).

- The main Cooper branch shows marked changes of direction, flowing northwest, west, then southwest until it reaches the narrow zone between the Gason and Cooryanna Domes. At this point it enters the Tirari Desert through the Kopperamanna floodout, then flowing west-northwest to Lake Eyre.
- The Cooper's North West Branch, located to the northeast of the main Cooper, flows northwest and dissipates among the Coongie Lakes, a RAMSAR-listed series of lakes, swamps, and interconnecting channels. These lakes may also receive inflow from high ground to the northeast, northwest, and west. Overflow from the Coongie Lakes area rejoins the Main Branch of the Cooper in poorly-defined drainages in the northwest of the Strzelecki Plain (Location Map).
- The Strzelecki Creek flows south-southwest to Lakes Blanche and Callabonna, its path defined by the Benangerie Ridge on the east and a slightly elevated part of the Strzelecki Desert on the west.

The Strzelecki Creek flows south-southwest to Lakes Blanche and Callabonna, its path defined by the Benangerie Ridge on the east and a slightly elevated part of the Strzelecki Desert on the west. The Strzelecki Creek’s more obvious down-gradient path, westwards across the Strzelecki Plain (see Statham-Lee 1994), is blocked by the northwards trend of the longitudinal dunes (Gravestock et al. 1995).

5.4.2 Geological Past: Playa Lakes and Cooper Creek

During the recent geological past, Cooper Creek carried substantially greater volumes of water than it does today. It was a relatively high-energy waterway, depositing the Katipiri Formation sands which today underlie floodplain muds in some places, and in other places are exposed at or slightly above the level of the modern river. Scroll plains and meander belts, landforms of this proto-Cooper, are visible beneath modern sediments from airphotos or satellite images (Wells & Callen 1986, Nanson 2008). The Katipiri Formation is likely to have good aquifer properties (porosity and permeability), and its potential for influencing modern floodplain vegetation is seen in the lines of heavy vegetation which trace some buried scrollbars (Maroulis 2010, unpublished data).

The volume of sediment and water discharged by the proto-Cooper Creek has varied over the Pleistocene and Holocene, as the world's climate cycled through the ice ages. Approximately 250,000 years ago the Cooper at the Innamincka Dome was 5-7 times larger than it is today (Nanson et al. 2008). Since that time there has been an overall drying trend, with periods of strongly seasonal fluvial activity at ~74-96 ka and at ~24-59 ka. There is some evidence for very large (8-9 times greater than present) but very brief catastrophic flows sometime during the Last Glacial Maximum (12-24 ka), which only affected the Innamincka Dome reaches of the river (Nanson et al. 2008).

During previous wetter climates, the large lake basins (which are in the present day dry playa lakes) were full: north and south Lake Eyre joined, and Lakes Gregory, Blanche, Callabonna, and Frome formed a single semicircular lake around the base of the Cooryanna Dome. The extent and age of these palaeolakes can be measured by the remnant beach ridges. The +10 m AHD shoreline around Lake Eyre and the +18 m shoreline around the Frome-Gregory system correspond to the wettest periods, during which Lake Gregory overflowed towards the Cooper through the Warrawoocara Channel, linking the two lake systems. These lakes were linked at ~125 ka (the last interglacial), and for the last time at 50-47 ka (De Vogel et al. 2004, Cohen et al. 2011). Subsequent moderately high lake levels in the Frome-Gregory system have occurred at ~17 ka, ~13 ka, ~5 ka, and ~1 ka. The ~17 ka event may reflect the influence of southern rainfall on the Cooryanna Dome, rather than filling from Strzelecki Creek, whereas the others may derive from northern (semitropical) moisture sources (Cohen et al. 2011). The ~1 ka event, in which the Frome-Gregory system contained water 10-12 times the volume of the 1974 event, is possibly linked to a series of extreme flows under La Niña-like conditions (Cohen et al. 2011).

6. LANDCAPE ELEMENTS

6.1 Stony and Sandy Uplands

The Strzelecki Plain is surrounded on all sides by stony and sandy uplands. The Innamincka, Cordillo, and Gason Domes are anticlines related to the dome-and-basin structure of the Eromanga Basin. The (deceptively simple) landscape conceals complex geology, from a long history (Table 2) of domal uplift, Palaeogene and Neogene sedimentation, episodes of erosion, and the deposition of silcrete and other duricrusts (Alley 1998, Alley et al. 2011).

In the Benangerie Ridge and the Cooryanna Dome, the Eromanga Basin rocks (and other, underlying sedimentary basins) and Cainozoic rocks and sediments overlie various older metamorphic and igneous rocks, whose tectonic behaviour differs from that of the Eromanga Basin. The Cooryanna Dome partially overlies the rocks of the northern Flinders Ranges (Sheard et al. 2009), a tectonically-active landscape, exhibiting relatively rapid Neogene uplift (Quigley et al. 2006). The Benangerie Ridge has a relatively thin cover of Cainozoic rocks and sediments over or abutting a complex of other geological elements, including the Eromanga and other sedimentary basins, Willyama Group metamorphic rocks which are tectonically related to the Flinders Ranges, and the Tibooburra Dome (another area of active uplift) (Hill et al 2005, Quigley et al. 2006, Sheard et al. 2009). The Benangerie Ridge has been consistently higher than the Strzelecki Plain, controlling the location of the present-day Strzelecki Creek and its geological precursors (Gravestock et al. 1995).

The surface qualities of these uplands influences the amount of runoff delivered to the plain below. Elsewhere in the Channel Country, local rainfall has been demonstrated to be an important source of recharge for unconfined surface aquifers (Tweed et al. 2011). The surface aquifers provide water at non-GAB bores (Tweed et al. 2011) and are thus economically important; they influence vegetation and are thus ecologically important.

- The Benangerie Ridge is largely covered by closely-spaced longitudinal sand dunes. Because the Ridge's elevation is not high and its surface is covered in permeable sand, there is no run-off into the Strzelecki Plain during local rain.
- The other uplands are mostly stony, covered in either outcrop or gibber plain. Some of the gibber plain is true desert pavement, with a surface layer of closely-interlocking small rocks overlying rock-free silty sediment. In places the desert pavement is self-organised into contour-parallel bands (stony gilgai). In some cases, the rocky plain is the highly-silicified or ferruginised rubble of shallowly subcropping sandstones. Gibber-covered or rocky slopes

shed water freely, and small drainages from the rocky uplands down to the Strzelecki Plain demonstrate the role of these hills in watering the Strzelecki Plain fringes during local rainfall. The hydrological properties of stony gilgai are more complex and were not examined in this study.

- Small creeks running from uplands to plain are most prominent to the south and east-northeast (the Cooryanna and Innamincka Domes respectively), which is upwind of the aeolian sand transport. They are least prominent to the west and north (the Gason and Cordillo Domes), where sand has accumulated at the slope break, and prevented water transmission into the plains.

6.2 Topography of the Strzelecki Plain

The Strzelecki Plain is surrounded on all sides by stony and sandy uplands. There are only three points where drainage networks cross the uplands: to the north east, where Cooper Creek cuts through the Innamincka Dome and water enters the Strzelecki Plain, to the south west, where Cooper Creek exits the plain via the Kopperamanna Floodout, and to the south east, where a small relict channel links Lakes Callabonna and Frome.

The topography of the Plain over a scale of hundreds of kilometers is a strong determinant of river behaviour and drainage network development. Overall, the Plain has extremely low relief. From the twin Lakes Lady Blanche and Sir Richard in the north to the Kopperamanna Floodout in the south, the elevation decreases only 20 m in 274 kilometers (0.0073% slope); along the Cooper's flow path, the downvalley gradient ranges approximately 0.002 - 0.012%. As a consequence, the component of stream power derived from downvalley slope is very low. Geomorphic activity (erosion and sedimentation) during river flows is more strongly driven by other factors: discharge, local topography over a scale of tens of kilometers (dunes and flats), and landform-scale flow effects (e.g. waterholes).

There are two elements in the Strzelecki Plain with significant relief. The most important is the Cooper Creek Fan, a low-angle alluvial fan with its apex near the township of Innamincka, extending into the Plain as a half-circle abutting the Innamincka Dome and the Benangerie Ridge (Fig. 5, pale to dark green, and see Location Map). First described by geologists of the South Australian Geological Survey (Callen & Bradford 1992), the fan has since been the site of important research into previous hydrology and climates (e.g. Cohen et al. 2010). The Cooper Creek Fan has a significantly greater gradient than elsewhere in the Strzelecki Plain: most areas are approximately 0.020 - 0.027% (Fig. 50). The Cooper Creek's potential stream power (and therefore possibility of landscape change) is greater on the Cooper Creek Fan than elsewhere.

The second element of greater relief is a very low rise just to the northeast of Lake Gregory. This rise has a circular shape with an apparently low-elevation central section (Fig. 5, and see Location Map). Its elevation compared to neighboring areas is only slight (8-15 m, over several km), and is largely masked by its covering sand dunes (whose elevation above the interdune is 3-10 m, over a much shorter distance); this report is the first description of its occurrence. However it is clearly a significant influence on the existence and location of lakes such as Lake Hope (see section 3.6).

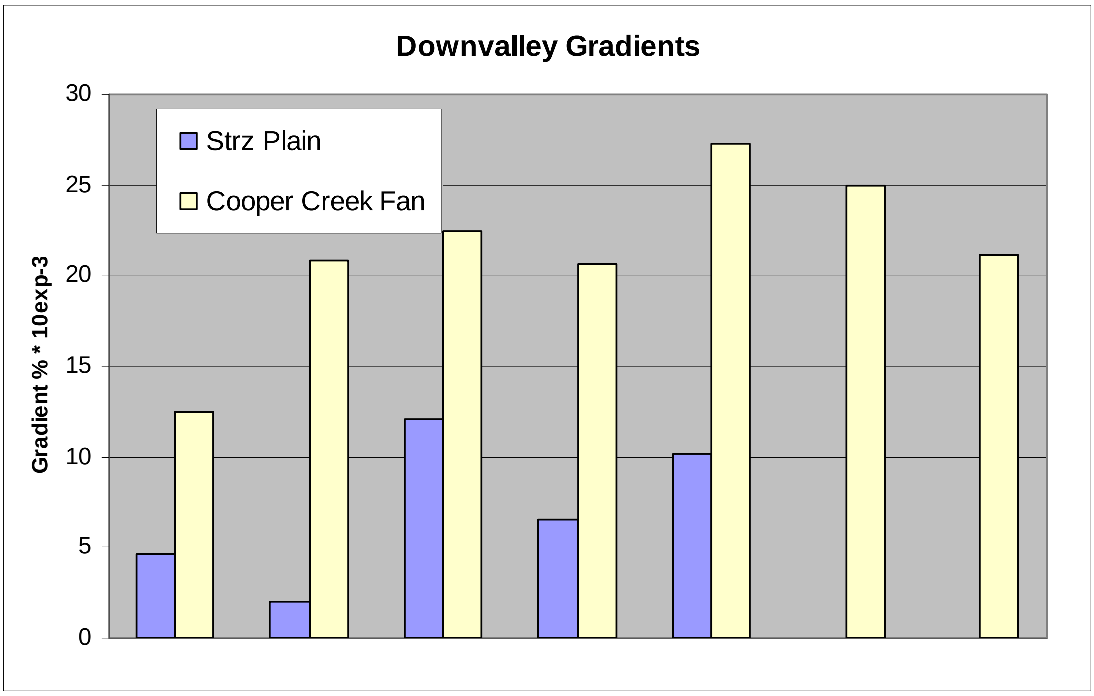


Fig. 50. Downvalley gradients of the study area.

6.3 Cooper Creek Waterholes and Channels

Owing to the exceptionally wet conditions, all water-retaining landforms of the waterholes, swamps, and river channels were inaccessible during fieldwork. In addition, travel to some locations was restricted. There was therefore no opportunity to examine the upstream or downstream ends of waterholes, waterhole and channel bedforms, and channel: waterhole relationships; and very little opportunity to examine riparian zones, levees, and splays. Fortunately, Cooper Creek is relatively well-researched (compared to other arid-zone rivers). Although much of the research describes the Queensland reaches, its observations and process interpretations are still applicable.

Unusual features of Channel Country geomorphology and fluvial processes include the origins and consequences of the floodplain's mud-aggregate sediments, and the coexistence of two different (anastomosing and braid-like) fluvial systems (Rust

1981, Rust & Nanson 1986, Nanson et al. 1986, Nanson et al. 1988, Rust & Nanson 1989, Knighton & Nanson 1994, Maroulis & Nanson 1996, Wakelin-King & Webb 2007). Because Cooper Creek is one of only two documented modern analogues for a common and economically-important lithotype, its geomorphology and sedimentology is of outstanding international importance to science, and it is likely to pass criteria for National Heritage listing (Wakelin-King & White, *in prep*.)

Published descriptions and analysis of reach-scale fluvial landforms for the Windorah to Nappa Merrie reach (Queensland) (Fagan & Nanson 2004, Knighton & Nanson 2000,Gibling et al. 1998, Knighton & Nanson 1994) are relevant to the present study area. Most are listed in Section 1.3 and shown in Fig. 5, and additional points are:

- The channel belt is the zone, within a wider floodplain, within which most fluvial activity takes place, and most channels are located. The rest of the floodplain may be rarely active, or not presently active (that is, it may be a palaeodrainage).
- Waterholes are obvious from the air and on the ground. Waterhole floors are deeper than the channels that feed into them and lead out of them, and therefore the downstream end of waterholes is characterised by a steep reverse slope. Waterhole downstream ends are often associated with a splay of sediment, and channel bifurcations. Waterholes are a self-maintaining landform created by present-day fluvial conditions, and the vegetation along the riparian zone plays a critical role in maintaining the steep banks and scoured bed that allows these waterholes to persist (Knighton and Nanson 2000).
- Waterholes in the Windorah to Nappa Merrie reach play a very important role in groundwater recharge. Abstraction of surface flow into groundwater is a major contributor to transmission loss and contributor to local ecology of plants with deep roots (Nanson et al. 2009, Cendon et al. 2010). Flood-driven scouring of the waterholes' impermeable clay lining allows water to escape and form a freshwater lens above the deeper regional saline water table, in the alluvial sediments around and down-gradient of the waterholes (Cendon et al. 2010). The groundwater does not supply the waterhole; the flow is in one direction only. At the close of flow, clays re-seal the waterhole boundaries. The size of the freshwater lens scales to waterhole size.
- The floodplain sediment is dominated by sand and silt-sized mud aggregates, derived from self-mulching vertic soils. Three different floodplain surfaces (braid-like with shallow floodways, reticulate, and unchannelled) reflect the balance between fluvial and gilgai-soil processes.
- Braid-like floodplain, experiencing relatively frequent inundation of relatively high flow energy, is crossed by broad shallow (<1 m) floodways, dividing the floodplain into braid-like bars. (Older publications refer unequivocally to a

braided floodplain or braidplain, but more recent work is less definitive.) There is limited gilgai development. The shallow floodways offer a more direct downvalley route at high flow volumes than the anastomosing main channels, and so the shallow floodways follow different (sometimes perpendicular) paths than the main channels. Cooper Creek thus has two different coexisting modes of flow behaviour.

- Reticulate floodplains experience sufficient inundation for gilgai processes to operate, without high-energy flow to erode the sediment, display a reticulate channel pattern: a dense network of densely-vegetated channels with short channel segments intersecting at high angles. Gilgai behaviour is well-developed, with gilgai mounds being the high ground between channels. In the study area many of the shallow basins (see Strzelecki Plain: “Flats”) are reticulate-channelled swamps. Although it was previously assumed that reticulate channel areas must necessarily be of lower elevation (for example backswamps), this is not the case; they merely have to be wet but low-energy.
- Unchannelled, featureless floodplains are not inundated, and so develop neither gilgai nor shallow floodways. In the Windorah to Nappa Merrie reach (Qld), these areas always occur in higher parts of the floodplain; in the present study area, they also occur in palaeodrainages which are isolated from the modern flow path.

Distributary channels are another reach-scale fluvial landform, not described from the Queensland Cooper Creek research, but investigated during the course of this present work. They are a particularly characteristic and important feature of the Cooper Creek Fan. Small creeks attached to the main channel look like they would be tributaries; in the temperate zone they would be bringing new water into the main channel. In Cooper Creek, the situation is reversed, and they are distributary, taking water and sediment from the main channel and spreading it across nearby flats.

Distributaries are created by an extended version of the same process that creates levees. Normally, as floodwaters overtop the levees, the increased roughness encountered in the riparian zone slows flow and promotes sediment deposition. This process maintains the levees. However if the difference in elevation between the levee top and the floodplain is sufficient, and other conditions exist which promote erosion (strong flow, a break in the vegetation), a breach may be created in the levee, such that the flow escapes from the main channel and splays out over the floodplain. Under the right topographic conditions, some of these splays will develop into distributary channels.

The junction where the small channel leaves the main channel is referred to in this report as the offtake. Because of the Cooper's flow variability, the offtake areas generally experience two-way flow. These processes contribute to patterns of erosion which are locally complex, and create complex landforms. The roots of bank trees demonstrate that erosion and bank retreat can be rapid around offtakes, probably as small distributaries develop into large distributaries and take increasing amounts of water from the main channel.

Landforms on a scale of meters to tens of meters are described in Gibling et al. (1998) and Knighton & Nanson (2000). The cohesive floodplain muds are very strong and capable of maintaining the very steep banks which are characteristic of the waterholes and the main channels. Anabranches and distributary channels sometimes cut through the levees. Sinuous channels may develop accretionary benches along convex banks and along straight reaches, and these may promote anabranch formation.

Within the present study area, such waterholes and channels as could be observed were consistent with the descriptions above. Layers of deposited sediment visible in gully-cut banks demonstrate that both sand and mud are transported through Cooper Creek. The absence of mud drapes at high-level flood deposits suggests that the mud is carried through the system as mud aggregates, behaving as sands, and this is consistent with the rest of the system. White to buff medium to fine quartzose sand is the dominant sediment visible in the study area, along levees, banks, and downstream sediment splays from terminating channels. The volume of mud in transport does not appear to be great, although it is likely that mud is being accumulated in places that were not accessible during this trip (swamps and lakes).

Because of Cooper Creek's wide floodplain and low gradient, flow velocity (and therefore stream power) is generally low; this predisposes the channel planform to be anabranching and anastomosing (Nanson & Huang 1999, Knighton & Nanson 2000). Waterholes are formed at points of flow convergence, such as between sand dunes, or where several anastomosing channels converge between large floodplain braid-like bars. In these areas, constriction in flow width increases flow depth and therefore stream power, allowing the scouring which first creates and then maintains the waterholes (Knighton and Nanson 1994, 2000). Knighton and Nanson (2000) considered that the waterhole scouring penetration through cohesive floodplain muds and into the easily-entrained Katipiri Formation sands was a key feature in waterhole permanence, however the existence of similar waterholes in the Neales River catchment which do not have an underlying sand body indicates that this is not the case (Wakelin-King 2010).

6.4 Strzelecki Plain: Sand Dunes

In the Strzelecki Plain, it is clear from aerial photographs, DEMs, or GoogleEarth images that the longitudinal dunes influence the river's pathway, sometimes blocking the channel from its most direct down-gradient path (Gravestock et al. 1995). However, the channels, the transverse dunes, and the longitudinal dunes co-developed over time (Stevens 1991, Cohen et al. 2010) and the relationship is not simple. Fluvial processes operated alongside aeolian processes.

- Sand in river channels was blown to form the transverse dunes,
- transverse dunes were overprinted by longitudinal dunes,
- channels avulsed and relocated as the Cooper Creek Fan developed,
- channels were deflected from one path to another by the dunes,
- the new channels later created more transverse dunes,
- and so on.

Wind power not only extended the longitudinal dunes but also carved shallow basins, which have their own affects on the river network. As has occurred elsewhere on the Cooper (in Queensland, Maroulis et al. 2007), the Strzelecki Plain records a complex history of mutual action: wind and water, dune and river.

Although it is sometimes popularly supposed that the dune fields grew from sand blown in from somewhere else on the continent, actually aeolian process do not move dune sands very far (Pell 2010). Sand is brought into the Lake Eyre Basin by large river systems, to be stored as fluvial sediments (e.g. the Katipiri Formation), or rocks (e.g. the Namba Formation) (Table 2). As the climate dries, sediment is released by corrasion and the sand is rearranged locally to form sand dunes. The underlying rocks or sediments which liberate sand to the dunefield are one of the reasons for the differences in dune colour. The dark red-orange dunes of the Benangerie Ridge lie over shallowly subcropping ferruginous Namba Formation, while the pale orange dunes of the Strzelecki Plain are sourced from younger, less iron-rich fluvial sediments such as the Yandruwantha Sand (Gravestock et al. 1995, Sheard 2009). Most of the sands transported down the modern Cooper Creek are re-mobilised Katipiri Formation, characterised by buff to bright white colour.

The dunefields in the study area are dominated by either longitudinal or compound dunes.

Longitudinal dunes crests are parallel to the dominant wind direction at the time of their formation, varying across the Strzelecki Plain from a few degrees west of north near Lake Hope, to roughly north around Moomba, to northeast on the Benangerie Ridge (see Fig. 5 and Location Map). They usually have single crests with occasional bifurcations, but may also occur with double or multiple crests, or in reticulate or other patterns (see Hesse 2010). The interdune corridors may expose the underlying older sediments or rock, and frequently host deflationary claypans (Fig. 7). In some parts of the Strzelecki Desert longitudinal dune fields, claypans occur in aligned bands, perpendicular to both wind direction and dune trend; where these are not part of compound dunes (see below), aligned claypans indicate locally strong deflationary processes related to fluctuations in wind strength (Stevens 1991). The longitudinal dune fields are of relatively recent origin (within ~200 ka, Hesse 2010), thus where their presence constraints the drainage network (such as Strzelecki Creek), the fluvial geography is also relatively young (Gravestock et al. 1995).

The Cooper Creek Fan and the Coongie Lakes area are dominated by **compound dunes**, and these are found to a lesser extent elsewhere also. Two different dune types are formed (Stevens 1991, Fitzsimmons et al. 2007, Cohen et al. 2010), presumably both driven by the same prevailing winds. **Transverse** (perpendicular to wind direction) **source-bordering dunes** are created by sediment blown northwards from rivers or lakes, and are deposited immediately adjacent to the sediment source. They may occur in sets, with the largest/highest being next to the sediment source, and size decreasing progressively downwind. Their length is scaled to the channel or lake from which they arose. The transverse dunes date back to at least 250 ka, with additional sand added during periods of fluvial activity, most recently during the Last Glacial Maximum (28-18 ka) (Cohen et al. 2010). The longitudinal dunes overprint the transverse dunes (Fig. X2) and are slightly younger in age; they form from sand taken from the transverse dunes (Fitzsimmons et al. 2007, Cohen et al. 2010), leading to wind-eroded areas in the source dunes (Fig. 9). Longitudinal dunes tend to mask the presence of older transverse dunes, which are most visible on a DEM (Fig. 8) or through aligned interdune claypans (Stevens 1991, Cohen et al. 2010).

Northwards sand transport is evident in the disposition of some dunes across the Gason Dome, and in the creation of longitudinal dunes from transverse dunes, but generally wind-driven sand transport has been limited to local areas (within a few km). Sediment dating of longitudinal dunes on the Cooper Creek Fan shows that the distance of sand transport has been small, and that longitudinal dune sediments are largely derived from neighboring interdune corridors (Cohen et al. 2010). This is consistent with the behaviour of longitudinal dunes generally: the behaviour of linear dune fields can be variable, but relatively small amounts of sand are transported downwind (Pell et al 2000, Fitzsimmons 2007, Hesse 2010). In the study area, the clear association of most longitudinal dunes to their parent transverse dunes and the relatively minor mixing of the different colour-marked grain populations both indicate limited aeolian transfer of sand from north to south (and see Fig. 23 for a dune nose that has been stable for probably tens of thousands of years). Though in the past longitudinal dune extension has influenced the creation and location of waterholes (see sections 2.3, 6.3), aeolian transport resulting in net downwind sand movement is unlikely to be an agent of geomorphic change today.

6.5 Strzelecki Plain: “Flats”

On the Strzelecki Plain, the landscape is characterised by compound dunes set amongst kilometers-wide open flat areas (“flats”). The distribution and relationships of dunes and flats are amongst the strongest determinants of ecosystems and drainage network. Whereas dunes modify the river by impeding flow, the flats give best expression of the underlying slope of the Strzelecki Plain, and allow water to be transmitted. The flats have a microtopography including low rises and shallow basins, which influences reach-scale river function and local ecology. Flats and dunes are created by coexisting fluvial and aeolian processes.

The flats may have longitudinal dunes extending into them from the south, but they are generally characterised by very flat, empty topography. Where the flats are inundated by water from Cooper Creek or from sources of local run-off, they present as swamps or lakes (Fig 10). They may also be part of the current Cooper Creek floodplain. Where the flats do not (under the current landscape and climate conditions) commonly receive water, they present as broad claypans.

The flats on the present-day flow path are dark grey to black on the Google Earth images, whereas the claypans are pale grey to white. This colour difference relates entirely to modern inundation and vegetation: the scale, shape, and other features are similar (Fig 10). Most (perhaps all) of the flats are palaeodrainages (alluvial plains, flood basins, or lakes on the same scale as the Coongie Lakes) from previous versions of the Cooper Creek flow path (Stevens 1991, Gravestock et al. 1995, Cohen et al. 2010). The previous flow path of these palaeodrainages can sometimes be traced (see Stevens 1991) through the disrupted sand dunes, using the transverse source-bordering dunes as indicators of previous rivers and lakes.

The southern margin of some flats have shallow basins which are noticeably deeper than other nearby flats. In some places this expresses as particularly dense reticulate-channeled swamps (Fig. 8), elsewhere as claypans or lakes. These basins are generally found immediately downwind of the trailing edge of the nearby compound dunes (the most notable examples being the pair Lakes Lady Blanche and Sir Richard, and immediately to the south another pair, the Mitkacaldratillie Lakes, Fig. 51). In some cases the basins are in interdune areas (see "B" on Fig.8), or the upwind source of transverse dunes (Lake Moolionburrina, 20 km NNW of Cuttapirie Corner). Although at first it appears that these basins may result from the ponding of south-flowing water by transverse dune systems it is evident from 1) the existence of these deeper basins even when completely enclosed by dunes (see "B", Fig. 8), and 2) the relative elevation of these deeper basins in comparison with nearby flats, that the basin-dune relationship is largely independent of fluvial processes, and is causally linked with aeolian processes. It is likely that these basins are deflationary, that their occurrence relates to the vortices created downwind of an obstacle, and that the variable expression of these basins across the Strzelecki Plain relates to stochastic features such as wind velocity, dune height and approach gradient, and vortex interaction with nearby topography.

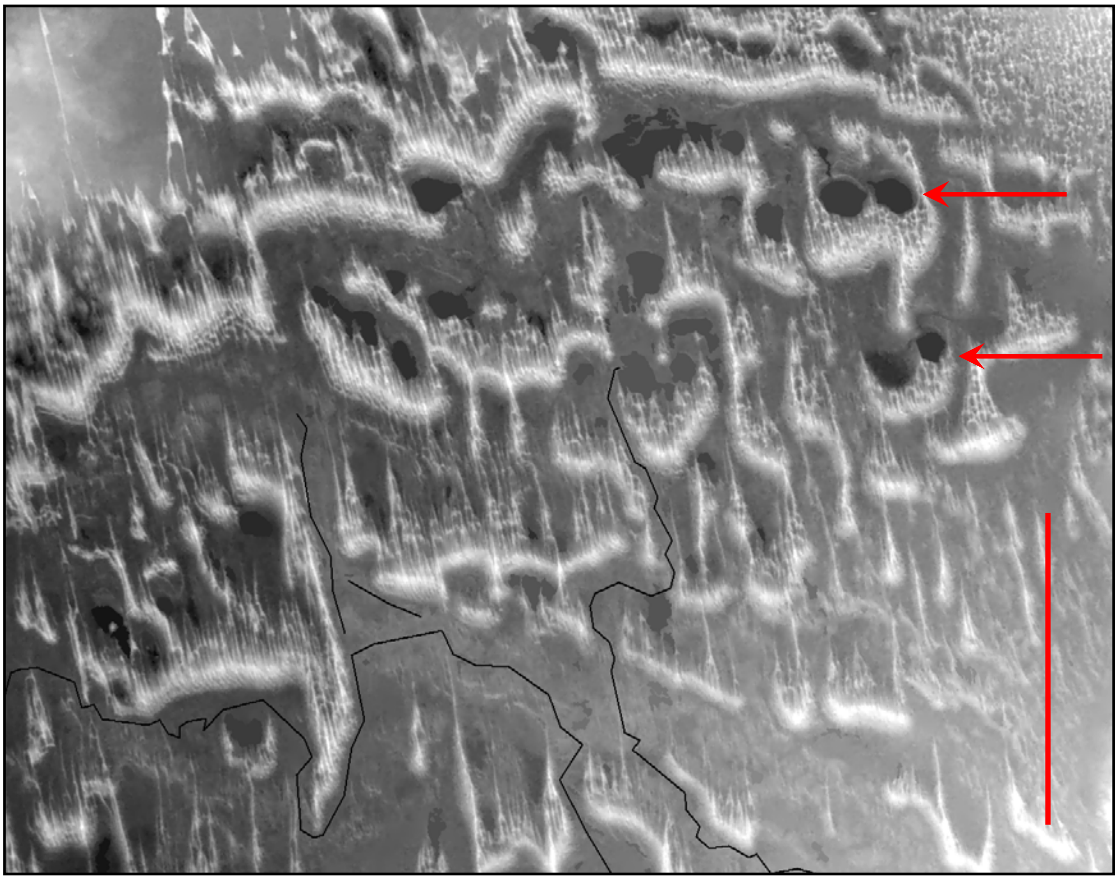


Fig. 51. Deflationary basins of the northern Strzelecki Plain

In this DEM the semicircular deflationary basins can be seen mostly downwind of dune sets, e.g. Lakes Lady Blanche and Sir Richard (top arrow) and the Mitkacaldratillie Lakes (bottom arrow). This DEM is coloured black (18 m AHD) to white (70 m AHD), and is not daylight-shaded. The bright white edges to the sand dunes demonstrates that the transverse dunes are generally the highest and widest crests in each compound dune system. North to top, red scale line is 20 km, black lines are the coarse-dataset rendering of the Main Branch and North West Branch of Cooper Creek.

7. AREA DESCRIPTIONS

The previous sections of this Technical Appendix cover general descriptions of landform elements and processes, including references to published literature. This section covers site-specific observations and analyses drawn from this study. It is a companion to section 3. The eight geomorphic management zones in this study area (see Geomorphic Management Zones Map), and the ninth in Queensland (Windorah to Nappa Merrie reach) are grouped by spatial proximity and dominant landform types. Boundaries of these geomorphic zones are not intended to correspond to hydrological management reaches or ecological zones.

7.1 Windorah to Nappa Merrie: Super-Wide Cooper Floodplain

The floodplain contains more than 300 recognisable waterholes, including many which are permanent or semi-permanent; it is one of the "wettest" reaches in the Lake Eyre Basin (Knighton & Nanson 1994, Knighton & Nanson 2000, Silcock 2009). Most waterholes occur along the major anastomosing channels; their distribution depends on local features (primarily opportunities flow concentration), and on the degree of transmission loss (therefore declining stream power) as flows move downstream (Knighton & Nanson 1994, Silcock 2009). The floodplain sediments are a relatively thin layer (several meters) of mud aggregates overlying white quartzose fluvial sands. This reach is currently affected by tectonic activity: subsidence of the western floodplain is moving the channel belt westwards (Knighton & Nanson 1994).

The most downstream waterhole of this reach is the Maapoo waterhole (Fig. 12); the Nappa Merrie waterhole is located within the Innamincka Dome (below). (Note that there is a another waterhole with a similar name, the Marpoo, near Ooranie Creek on the Cooper Creek Fan.). The floodplain around Maapoo waterhole is very flat (visible on the DEM). Immediately downvalley from Maapoo (at the edge of the Innamincka Dome) the floodplain is narrowed by strongly-outcropping rocks, and it is likely that water from extreme flow events has ponded here and deposited this flat plain. High levels of salinity were recorded here by early explorers, who did not see salinity along the Cooper within the Innamincka Dome (Piddock 2009), it is possible that the Maapoo's elevated soil salinity here relate to these hydrodynamic conditions. Alternately, there may be unrecognised Great Artesian Basin leakage.

7.2 Cooper Creek in the Innamincka Valley

Cooper Creek is confined within a valley defined by rocks of the Eromanga and Lake Eyre geological Basins (Fig. 13). The valley width is very irregular (Fig.12), responding in part to valley wall lithology. This part of the Cooper is extremely important:

- Ecologically, the main refuge waterholes are here because the high stream power in this narrow valley has scoured deeper and longer waterholes than elsewhere in the study area.
- Geologically, the path of the river through the uplifting Innamincka Dome defines the base level of the Cooper Creek for hundreds of kilometres upstream. The extremely low gradient thus created promotes the fluvial style (anastomosing channels, waterholes) and the preservation of the mud floodplain in the Windorah to Nappa Merrie reach. In this way the Cooper through the Innamincka Dome has a national (and in some ways international) level of significance (Wakelin-King & White, submitted).

In this reach, the Cooper has carried much greater flows during times of previous wetter climates than it does today. The valley here contains evidence of short extreme flood events during the Last Glacial Maximum and in the early to middle Holocene (Nanson et al. 2008), that is roughly 24-12 ka and ~5 ka. The greater flows and floods, in combination with variations of lithology (rocks which are hard all the way down, as opposed to hard gibber plains which are underlain by soft rock types) has undoubtedly influenced the disposition of the valley walls.

Using the area around Cullyamurra waterhole as an example, the broad landforms (kilometer scale) are (Figs 12, 13, 14; and see section 3.2):

- Flat-topped plains, hills and mesas are the highest landforms in the area. Innamincka township is built on this level. There are also some smaller rubbly rock outcrops within the Cullyamurra floodplain.
- The next level down is a terrace, formed of sands deposited during extreme flood events, possibly 5,000 years ago. The 2010-2011 floods did not come up to this level. The sands are white to pale buff remobilised Katipiri Formation. Innamincka pastoral station homestead is built on this level.
- There are a few small orange dunes on the high floodplain. It is not clear from this study whether the orange sand recently migrated onto this high floodplain from elsewhere, or whether the extreme floods partially buried existing dunes.
- There are shadow bars and slackwater deposits: white sand deposited at relatively high elevations in the lee of some floodplain obstacle (like rocky outcrop, see Fig. 13, or in small declivities in valley walls, such as at Cullyamurra Choke, Fig. 52). They are evidence of extreme floods, and the sands may be datable.
- Several wide palaeochannels dissect the terrace, best seen in the DEM. These may represent palaeochannels of a previous, larger version of Cooper Creek, or they may be short-term channels established across bar tops during

extreme flood events. Some of these wide palaeochannels carry smaller, inset modern channels or waterholes within them.

Fig. 52. The Cullyamurra Choke.

The rocky walls of the Innamincka Dome are very close together here, and the floodplain is narrow to non-existent. It is likely that the waterhole will be especially deep here. Strong rocky outcrop (dashed circles), boulder plain from catastrophic outwash (within black line), flow is from left to right.

- The generally high level of the terrace slopes down; some small flood channels are above the level of the modern floodplain, and evidently carry above-floodplain level flow. It is not clear whether these flood channels originate as palaeochannels, or if they are entirely a product of the modern fluvial regime.
- The modern floodplain and waterhole are the lowest levels in this area.

Upstream of Cullyamurra Waterhole is the Cullyamurra Choke (Fig. 52). The valley becomes extremely narrow and there is almost no floodplain. The western section of the Choke is flanked by strong rocky outcrop, whereas the eastern section is narrowed by a low plain of large boulders. There is a wide basin-like area to the south (purple, in Fig. 14). In the past, the extreme flood events have filled this flood basin, and at the highest water level flow exited along two overflow paths (yellow, in Fig. 14). One of these overflow paths is the boulder plain forming the narrowest section of the Cullyamurra Choke. The boulder plain is an outwash deposit, representing a catastrophic outburst flood moving many tonnes of rocky debris in a single event.

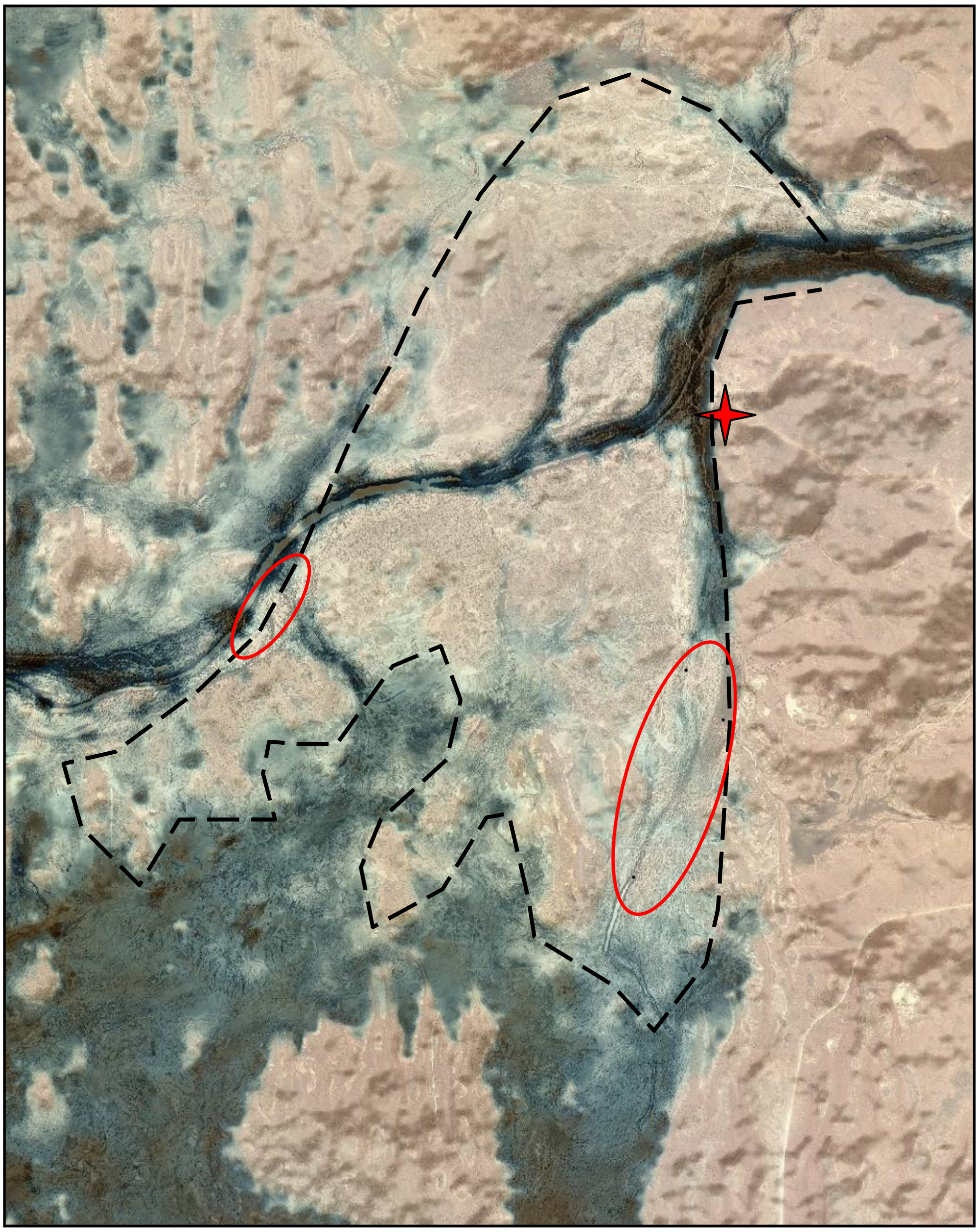


Fig. 53. Sediment wedge at the apex of the Cooper Creek Fan.

This palaeoflood deposit forms an elevated upper terrace (black dashed line). It must be overtopped before water from the Cooper can enter Strzelecki Creek. The two most prominent sills are circled (red). Near Queerbiddie Waterhole (Q) the offtake valley leading to Strzelecki Creek is just as large as that of the Cooper Creek main channel. DEM draped with a semi-transparent orthophoto, north to top, red star is Innamincka township.

7.3 THE COOPER CREEK FAN: BRANCHES AND OFFTAKES

7.3.1 Fan Apex: Queerbiddie, Town Common, and Strzelecki Ck Offtakes

In this more proximal (eastern) section of the Fan, upstream of the various offtakes and distributary channels, the volume of water discharging down the creek channels is at its greatest. The potential for geomorphic activity is therefore high, these reaches having relatively steep gradient and greater discharges (both proportional to stream power). In this reach, channel relocation is most likely to sweep over and disrupt previous landforms, blurring the sand dunes and depositing sediments over palaeodrainages. For this reason the dunes here do not have the crisp clarity that they display elsewhere.

The main channel of the Cooper is strongly defined here by riparian vegetation. On the orthophotograph the main channel is clear, however this is misleading. The DEM shows (Fig. 53) that the channel segment extending towards Strzelecki Creek is just as big and deep as the main channel. Two factors discourage water from diverting to Strzelecki Creek. Firstly, the lignum and thick riparian vegetation discourages overbank flow and maintains bank integrity by trapping sediment, and by focusing stream power to the channel center (scouring and maintaining channel depth). This keeps the Cooper Creek channel hydraulically efficient, encouraging flow to continue in the present path. Secondly, a wedge of sediment has created a sill, discouraging southwards flow except during high river levels (Fig. 53).

The apex of an alluvial fan will be a locus of bedload deposition for any very large flood where high-energy waters leave the confines of the valley and spread out. At the apex of the Cooper Creek Fan, floodwaters leaving the narrow Innamincka valley deposited a wedge of white sandy sediments, now forming a high terrace. The modern channel with Queerbiddie Waterhole cuts through it, and the 15 Mile Track travels across its high, dry terrace as far as the Minkie Waterhole turnoff (Fig. 17). It was most likely deposited during an extreme flow event (possibly the same flood that deposited the terrace near Cullyamurra). This wedge of sediment forms a localised area of relatively elevated ground (~53-55 m AHD) which is a barrier between the Cooper and Strzelecki Creeks.

There are two principal offtakes which deliver water from the Cooper into the Strzelecki Creek (Sz1, Sz2 in Fig. 17). In the offtake which starts from the Town Common and occupies a palaeochannel (Sz1), the sill (highest elevation along the flowpath) is located 3.7 km south from Sz1 rising to 52.5-53 m AHD. The sediment wedge here is ~8.3 km long, and 8.5 m high, measured along the Strzelecki Ck flow path from Sz1. The broad crest of the sill extends 3.4 km in an upstream direction from the northern end of Burlieburlie Waterhole (Fig. 53). The second offtake Sz2 is the side-channel near Ski Beach and the King memorial, 5.5 km downstream from Sz1. Its sill (elevation is 52.7 m) is close to the main channel. The potential flow paths from main channel to sill extend along Cooper Creek's left bank 2 km upstream and 2 km downstream from Sz2. Two minor offtakes (Sz3, Sz4, Fig.17) share a single sill (elevation 52.7 m AHD).

7.3.2 Palaeodrainages and Isolated Waterholes

An alluvial fan with a single source of water and sediment at its apex develops by channel relocation from one place to another over geological time. The Cooper Creek Fan has developed in this way. Terminal lakes, like the present Coongie Lakes, would have been associated with some palaeodrainages. For example, the palaeodrainage east of Lake Marroocutchanie is likely to have fed the Mitkacaldratillie Lakes (Stevens 1991) (Fig 10). The Mitkacaldratillie Lakes have deltaic sediment deposits at their inflows whose size is inconsistent with present-day hydrology, and which indicate a previous state of greater water supply.

It is likely that most or all of the flats on the Cooper Creek Fan represent palaeodrainages (many have been later modified by deflationary basins, or cut by advancing longitudinal dunes). The most recently-abandoned palaeodrainage is Christmas Creek, which used to flow from the Toonman and Chillimookoo Waterholes west, northwest, and then north towards Lake Oolgoopiarie. Sediments deposited by this channel between the compound dunes eventually attained sufficient elevation that the creek was diverted to its present course, south and around Cuttapirie Corner. The valley of this palaeodrainage slopes from south to north (Fig. 54), falling ~2 m in elevation along a length of ~28 km (0.0013% average slope).

Palaeodrainages may receive floodwaters, or local runoff, and may host isolated waterholes (e.g. Montepirie, Durrantie, Gidgealpa Waterholes). It is unlikely that these are relict in the true sense (i.e. they are not what remains of ancient palaeo-waterholes). If they support riparian vegetation and contain water often enough to be named, they are responding to present-day conditions. It would be more accurate to consider them as waterholes along what are now flood pathways, and were once the main drainage line.

Most palaeodrainages which now act as floodways receive water from distributary channels. For example, the Christmas Creek waterholes (Toonman, Chillimookoo) presently receive overflow waters from distributaries downstream of Narie Waterhole on the Main Branch. The close network of palaeodrainages and modern flow paths creates a situation in which some isolated waterholes may receive water from different directions, for example Gidgealpa Waterhole is reputed to receive water from the north and from the south. This may be related to flow routing of flood peaks.

Like others in Cooper Creek, these isolated waterholes often occur where local floodplain constrictions have focused flow and increased stream energy. They are not as deep as main-channel waterholes (Costelloe 2013), and so are not likely to retain water for very long, or act as refugia. However, their riparian vegetation indicates they are important for local plant and terrestrial ecology. If they encounter sufficient flow volumes and have sufficient riparian vegetation that self-scouring happens during flood events, then it is likely that the waterholes are also point sources of freshwater recharge for local groundwater hosted in Katipiri Formation sands. As such, they may be important for the ecology of deep-rooted plants.

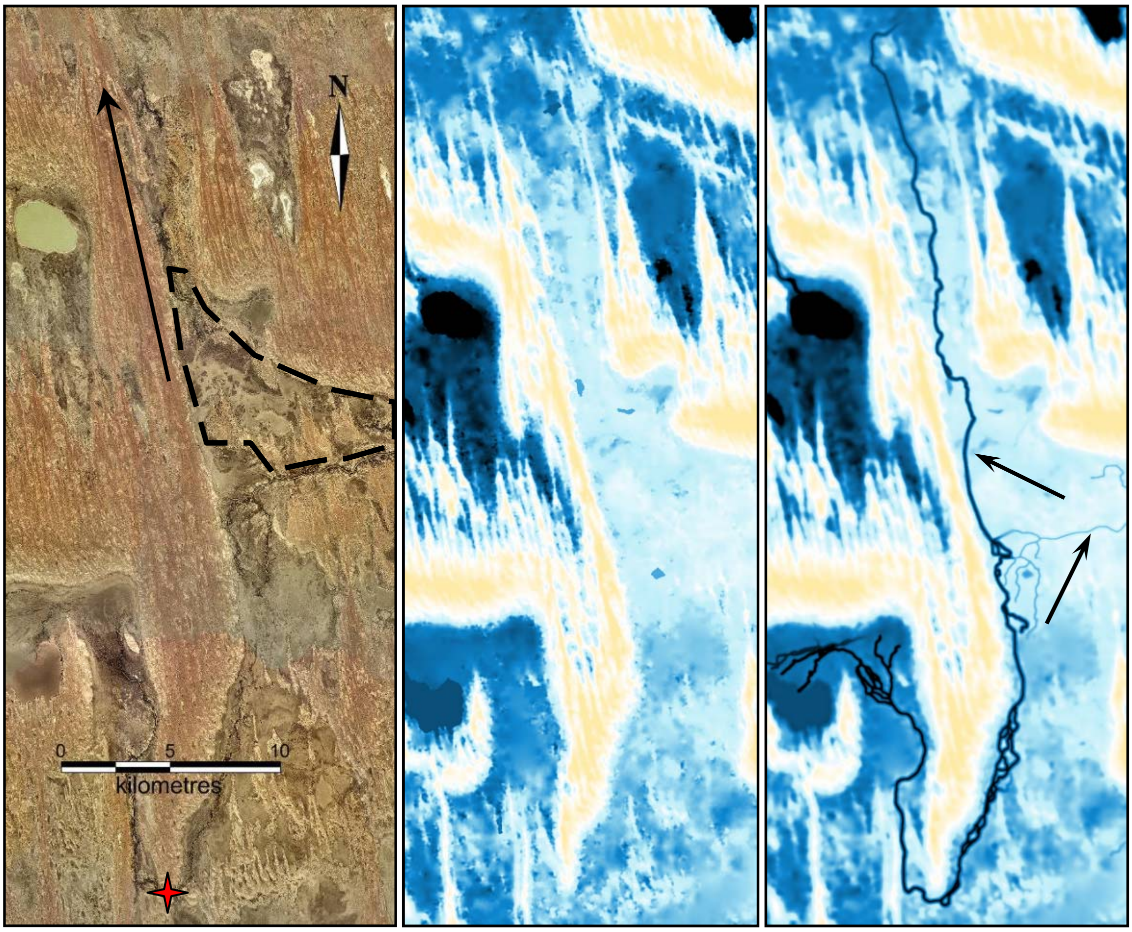


Fig. 54. Christmas Creek, at the distal edge of the Cooper Creek Fan.

Left, orthophoto, showing the present-day channel going south around Cuttapirie Corner (red star), and the palaeodrainage Christmas Creek (to the right of and parallel to the long black arrow). Dashed line encloses the highest surfaces of the sediments deposited by that palaeodrainage. Middle picture, smoothed DEM (black and dark blue low elevations, white and pale orange high elevations) of the same area. The palaeodrainage valley of Christmas Creek slopes south to north. Right picture, hydrologically forced DEM: a spurious creek line has been inserted (top arrow), and the channel bed has been given an elevation 5.5 m less than that assigned to the actually existing channel (bottom arrow). The profile of the spurious creek descends ~2m from north to south, against the actual flow direction.

7.3.3 Inner Fan: Channels, Distributaries, and Waterholes

Cooper Creek across the inner Cooper Creek Fan is sinuous to Minkie Waterhole, and meandering from there down through Tilcha and Marpoo Waterholes. As a class, meander loops have steep erosional outer banks, and gently-shelving inner banks in which progressive sediment deposition extends the land area towards the opposite bank. In this way meander loops migrate incrementally outwards.

The meandering is currently active (scroll plains exist at Wills Grave and other bends right down to the forks) but it is very slow. The width of the scroll plain at, and downstream of, Wills Grave indicates this is the most active meander on the Fan, yet it dates to 45-55 ka, with a flood chute cutting across at 35 ka (Nanson et al. 2008). Riparian tree roots exposed along meander outer-bend banks indicate only minor bank retreat. In Fig. 20, the exposed roots are largely bank-parallel (lacking the root "knees" which indicate rapid channel incision), and the main tree root with a slight knee is very thick (indicating it is very old). Elsewhere, riparian tree roots indicate general bank stability, except at the offtakes of the distributary channels, where there is often evidence of long-term bank stability followed by rapid bank retreat.

Cooper Creek can be considered to have two types of reach, waterholes and shallow complex reaches. They may correspond conceptually to the pool-and-riffle systems found in other rivers.

Many distributary channels come off the Cooper Creek main channel on the Cooper Creek Fan; they are a significant mechanism of transmission loss.

Distributary channels are created as floodwaters overtop and breach the landforms that define the main channel (typically the riparian ridge or levee, but also including other flanking sedimentary deposits). The distribution of distributary channels is uneven down the length of the main channel (Fig. 17). There are some important distributaries at the fan apex, mostly related to palaeochannels which cut through the high palaeo-floodplain. From Tilcha to Marpoo Waterholes there are some but they are only short, and it’s likely that previous splay deposits have built a sufficiently high flanking area that these reaches are rarely overtopped. From Marpoo onwards the number and length of distributary channels is greatly increased. It is clear that in these reaches there is sufficient elevation difference (main channel to distributary termination) to develop and maintain the distributary system.

Short distributaries deposit their sediment close to the main channel, just behind the levee, and also along their length down to their terminations. Pale river sand and silt builds up into sediment wedge flanking the channel (Fig. 23), sometimes partially filling interdune spaces (Fig. 17). Longer and larger distributary channels may develop their own network of distributaries, and deliver water and sediment kilometers distant from the main channel (Fig. 23). Sand is deposited close to the distributaries but water carrying mud can travel well beyond distributary terminations, as unchannelled overland flow across the flats, or through the reticulate channels of the various swamps. Thus, distributary channels are important in the pattern of sediment deposition across the Cooper Creek Fan. They create near-channel sand wedges which increase the elevation of the Fan surface, and in more distant, lower areas deposit sediments rich in clays and organic carbon.

Distributary channels and shallow, complex reaches of the main channel appear to be spatially linked, such that the offtake is often at or upstream from a shallow reach. It is likely that variations in channel bed elevation and roughness (and therefore flow efficiency) lead to some reaches being more likely to overflow during a flood peak. If offtakes and distributaries develop upstream of channel constrictions, it is likely that the removal of water would further predispose those reaches to sediment deposition and flow resistance, creating a process feedback. Downstream flow impedance may also be an explanation for the high number of distributaries immediately upstream of the forks (Fig. 17).

Vegetation is strongly tied to landform type, with landforms experiencing frequent inundation (banks, levees, scroll bars, downstream ends of distributary channels) carrying often dense vegetation, while drier landforms carry little or none. Distributary channels are critically important to local ecosystems, as they carry water and fine sediments out to the flats.

7.3.4 Outer Fan (Main and North West Branches): Channels, Swamps and Waterholes

In the outer Fan, Cooper Creek divides between three distributary channels (Figs. 17, 24). Two distributaries flow towards the southwest, taking collectively 47% of the 2012 flow (Costelloe 2013), and this is the water source for the Cooper Main Branch. The third distributary flows northwest, took 53% of the 2012 flow, and is the source of the North West branch. Distribution of flow between the distributaries is dependent on flood height, with the North West Branch taking a greater proportion at lower flows and a lesser proportion at higher flows (Costelloe 2013).

The North West Branch anabranches rejoin just upstream of Tirrawarra Swamp. The unnamed more northeasterly of these anabranches (NW2 in Fig.24; contains Eulcaminga Waterhole, Fig. 25) looks to carry less of the modern flow: there is less inundation of its floodplain, in comparison with the other anabranch’s floodplain (NW1 in Fig. 24; contains Mudrangie Waterhole Fig. 25) which has many swamps in deflationary basins. This is consistent with the measured hydrology (Costelloe 2013). On the other hand NW2 may once have experienced much higher stream energies than NW1, since Tirrawarra Waterhole's upstream end is found in NW2.

The North West Branch is a single-thread channel for the first ~23 km, maintaining the channel form across the first "flats" that it crosses. This may be an indication of relatively high stream energy through higher volume in these reaches. Around Scrubby Camp Waterhole, the channel travels through an area where alluvial sediments from palaeodrainages and from the present drainage line are filling up the interdune spaces. At Scrubby Camp, a small anabranch leaves the main channel, depositing alluvial sediments in levees and splays to form a high plain to the south of the channel, before rejoining the channel a short distance downstream (Fig. 25). At the downstream end of the Scrubby Camp reach, the North West Branch splits into two flow paths. The two flow paths rejoin where NW1 enters Tirrawarra Waterhole halfway along the waterhole's length.

Tirrawarra Waterhole terminates in a number of distributary channels, each surrounded by a pale halo of alluvial sands. This style of waterhole termination, a downstream splay surrounded by sediments, is common throughout the study area. The Waterhole extends more than one third of the way into the next "flat" (Tirrawarra Swamp). This "flat" is wholly occupied by a swamp, which is made possible by the volume of water delivered by the North West Branch. The network of anastomosing and reticulate channels shows no clear primary flow path: almost the entire swamp is flow path, making it a critical stage in water delivery to Coongie Lakes. Water re-gathers into a single channel in the north east corner of Tirrawarra Swamp, and the flow path remains as a single thread (Kudriemitchie channel) until its entry into Coongie Lake. Kudriemitchie channel is more or less constrained by dunes for its entire length. Its width varies in a way which bears no clear relationship to topography or tributary input, and the exact nature of its fluvial processes remains to be determined.

The indeterminate nature of the sills at the north end of Embarka Swamp, and the northeast end of Tirrawarra Swamp is because they have not been shaped by wave action (as is the case elsewhere).

Most of the sandy sediments transported by Cooper Creek are deposited across the inner Cooper Creek Fan, upstream of the division between Main Branch and North West Branch. A small remainder is transported beyond the division, but it is deposited at the point where the single channel divides into reticulate and anastomosing channels in the flats. Downstream from this point, any sand that is deposited around river channels (for example, the active delta prograding into Coongie Lake, see below) has been locally re-mobilised into fluvial transport from nearby sources. However, mud continues to be transported from upstream, and is deposited across the flats and floodplains.

7.4 Coongie and other Lakes

The lake groups in the study area include the Coongie Lakes, lakes in Strzelecki Plain’s northern and southwestern areas, and the overflow lakes.

In the southwest Strzelecki Plain, there are a number of small to medium-sized lakes. Some are isolated within the dune fields, and some are connected to Cooper Creek by small channels. They are not part of the Cooper Creek Fan and its palaeodrainages. Like the others in the study area, they are created by deflation, and some (including the largest, Lake Hope, Fig. 27) are related to the subtle area of elevated topography northeast of Lake Gregory. Where the lakes' longest

dimensions are at a high angle to the southerly winds, they are associated with prominent compound dunes at their downwind sides.

The overflow lakes are a small cluster of lakes and flats extending downvalley from the junction between Hamilton Creek and Alfred Creek, and include Lake Strangeways (also known as Wattiecaroonie), and Lakes Androdumpa (Fig. 55) and Oolgoopiarie at the northern end of Christmas Creek. The northern edge of the Strzelecki Plain – a narrow dunefield which slopes up to the stony uplands – is just to the north of the overflow lakes. The lakes do not receive any runoff water from the uplands, although Lake Strangeways may be influenced by the groundwater salinity which appears to be present in the small lakes of the narrow dune field. The overflow lakes have not been the focus of particular study, probably because they only fill rarely, and so do not support rich ecologies. In a wetter climate however they would be important wetlands.

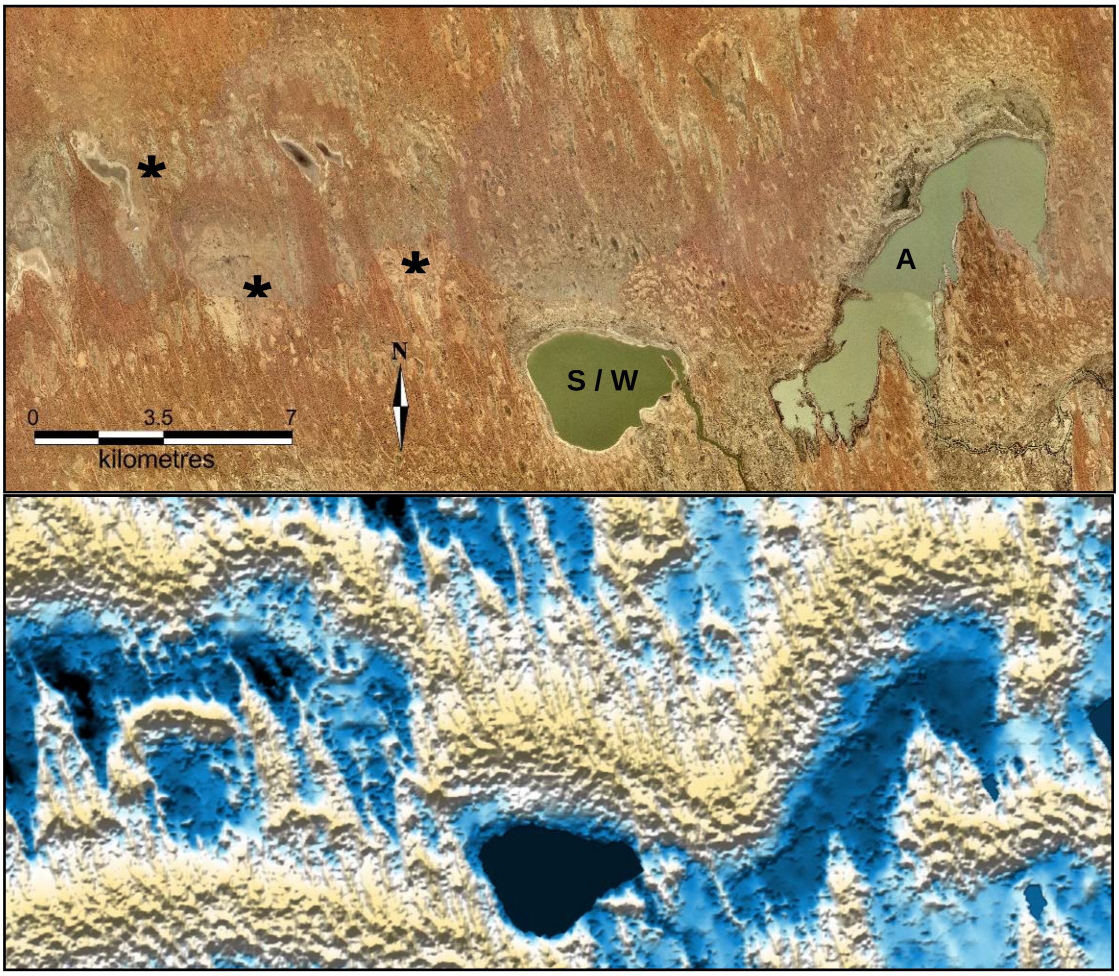


Fig. 55. Lakes and deflation basins in dry flats differ in their degree of alteration by water.

The orthophotograph (above) shows Lakes Apanburra (A) and Strangeways / Wattiecaroonie (S / W) have clearly defined shorelines, while to the west are some irregular flats (asterisks) crossed by longitudinal dunes. The DEM (below) shows that the lakes and the flats are equivalent in elevation. The flats have no access to Cooper Creek or other water, and have not been modified by waves and seiches.

7.4.1 Lakes: Created by Wind, Modified by Water

The great majority of the lakes were created by deflation, and so owe their existence to the consistent southerly wind. In many cases, especially the larger lake basins, the lakes are found north (downwind) of compound dunes. Their distribution and associated landforms demonstrate that lake formation is related to aeolian processes, and is largely independent of fluvial processes (see section 2.5). Some lakes are also themselves the source of their own source-bordering dunes, creating a complex topography. The depth of individual lakes is related to (inter alia) the topography of the upwind dune; that is, lake bed elevation can be unrelated to the elevation of nearby lakes or drainage channels. The intricate topography, where fluvial base levels are not created by fluvial processes, is the reason for the Coongie Lakes' complex fill pattern.

The presence of water is an important factor in landform evolution, as the deflationary basins are altered by nearshore and lacustrine processes (Fig. 55). Wind-driven waves along the shoreline create beach ridges (Fig.27). During fieldwork the weather was gentle and only ripples were seen, but the wind's persistence drove ripples through a belt of buffering vegetation (Fig. 56).

Fig. 56. At the Lake Toontoowaranie shoreline.

Even in gentle weather the breeze is strong enough to push sediment-moving ripples through a buffering belt of vegetation.

G. Overton (per. comm. 2012) describes storm winds pushing the water level 2 m higher up the beach, and also bottom currents strong enough to move anchors made from wheel rims. These reports indicate seiche processes: in an enclosed body of water, a seiche is when water sloshes backwards and forwards in response to wind or earthquakes. Technical definitions discuss standing waves, where the nodes (at shoreline and center) do not move up and down, and the water rises and falls where the wave amplitude is greatest (for example, see the Wikipedia entry). However, in real-world situations (water bodies with irregular boundaries) seiche waveforms can have amplitude along the shoreline (creating rapid rise and fall in water level), reflect off shorelines (pushing the wave-front off in another direction), and interact constructively with waveforms across its path (decreasing wave predictability while increasing wave amplitudes). Seiches create strong bottom currents, sometimes initiating fish kills when water temperature changes. On the Great Lakes (USA) shoreline seiches have reached 2-5 m in height, and killed people.

In the context of this present study, a sill is an area of slightly higher elevation which must be overtopped by increasing flood height before flow can move downstream. In a few cases the sills have a complex of landforms whose origin is not clear (e.g. the exits of Coongie Lake into Browne Creek). In many cases, the sills are just random microtopography related to erosion and sedimentation along the "flats" or river channels (e.g. the northeastern exit of Tirrawarra Swamp, the flow paths between the main Coongie Lakes and the peripheral lakes (red lines, Fig. 26), and the north-western exit of Lake Appadare). For these cases, the overtopping event is likely to be gradual, with the flood front creeping along at a gentle pace until it reaches the maximum elevation. From there, the flows move briskly downslope (J. Costelloe, J. Reid, pers. comm., 2012). These types of sills are unlikely to have landscape processes that maintain them, so alterations to their elevation (for example, erosion promoted by infrastructure development or streamwise roads) is best avoided.

Where beach ridges occur on the same side of the lake as the inflow / outflow channels, the sill they create has clear boundaries. For example, Lake Toontoowaranie receives waters from the south, transmits waters to Lake Goyder through its northeastern exit channel, and at higher flow levels also transmits water through its north-western exit channel (Fig. 28). Both channels cut through a pronounced beach ridge, although the northeastern exit channel is modified into a wave-dominated delta. At the western exit of Lake Appadare, flow cuts through a sill and a longitudinal dune; it slightly incises consolidated sediments. The sill here has a greater elevation than both lake and downstream channel (Fig. 57)

The presence of such a positive elevation to be crossed and then descended from (as opposed to just a gradually increasing elevation from one lake to the next) is interesting. If a gradual increase in water level achieved the crossing of the narrow and relatively steeply-sided sill, the sill would be likely to be eroded and a new channel formed. It is probable that two processes are in play. Firstly, nearshore processes maintain the sill, transporting sediment onto it when conditions are favourable (in the same way that beaches are maintained). Secondly, seiches are likely to be part of the overtopping process, pushing a body of water right over the sill. This would mitigate against such mid-sill gullying as might be expected from a more gradual overtopping. The implication is that the release of water down the channel might be weather-dependent or perhaps pulsed, if the wind conditions are right.

Fig. 57. The sill at the western exit of Lake Appadare

Standing on the Lake Appadare sill, looking downstream towards the Cooper (left photo) and upstream towards the northern end of Lake Appadare (right photo). The deepest section of this channel (dark mudcracked sediments) is ~1 m lower than the highest sandy sill at either end. Hana for scale (circled).

Sills developed along wave-influenced shorelines are likely to be dynamic. To maintain current hydrology, it is important that sill levels be allowed to maintain themselves naturally, so that the lake periodically accumulates sufficient water to allow nearshore wave action. Anything that acts to cut a channel through the sill to such a depth that the lake does not accumulate water may permanently reduce the lake's capacity.

The larger lake basins, such as Lakes Lady Blanche and Sir Richard, may occupy the entire interdune space available to them (Fig. 51). Rarely, the lake occupies a whole interdune space without apparent influence by deflationary basins (for example, Lake Goyder). In some of the larger flats small deflationary basins can be seen: barely visible semicircular areas with small beach ridges to the north and a thin rim of vegetation around the edges. Either the size of the basin or the frequency of inundation has been insufficient for it to develop into an obvious lake. A common circumstance is that a number of closely spaced deflationary basins will expand through shoreline processes, and merge; examples include Lakes Marroocutchanie, Toontoowaranie and Apanburra (Figs. 28, 29).

7.4.2 Lakes and Groundwater

Along Cooper Creek's Windorah to Nappa Merrie reach, waterholes contribute to groundwater only during high-flow periods, when the mud seal is temporarily scoured away and water can move from waterhole to the underlying water table within the permeable sands of the Katipiri Formation. The freshwater lens around and down-valley from the waterhole supports the ecology of local deep-rooted plant species.

The situation in the lakes is likely to be different.

- There is every likelihood that at least some lakes will receive water without accompanying muds, as much will have been abstracted during passage through upstream swamps and lakes. It cannot be assumed that a mud seal necessarily forms along lake floors.
- Although the wet conditions did not permit lake floor observations, it was seen during this study that most lake shores were clean white sands (probably Katipiri Formation equivalents), and local report indicates that at least one large lake, when dry, is sandy almost all the way to the centre (Lake Hope; Gary Overton, pers. comm., 2012). At least some lakes therefore have sandy bottoms, and it is possible that there may be open connection between lake waters and local groundwater.
- However, some mud transport was observed (possibly remobilised from previous deposits), so some lake floors are likely to be muddy. In addition it is likely that at least some lake floors are cut into less permeable older sediments. It is possible then that some lakes are not connected to their local groundwaters when there is water in the lake.
- Lake floors with vertic soils (including high porosity macropores) have different patterns of recharge and soil salinity development, according to whether the rain falls during dry or wet climate phases (Costello et al. 2009).
- In some small playa lakes, which receive neither Cooper Creek water nor collected runoff, the satellite imagery indicates surface deposits of efflorescent salts, indicating possible surface discharge of saline groundwater. (The size and distribution of these efflorescent deposits indicates this is water of local origin, not Great Artesian Basin water.)

The relationships between lakes, local groundwater, and soil salinity are likely to be very site-specific.

7.4.3 Lakes as Flow Buffers

The lakes and swamps are sumps, and act as local base levels and flow buffers. For each, flow does not proceed downstream until the local topography has been filled to a certain level. In the case of very large floods (such as 2011-2012), the surrounding low-elevation landscape is also inundated. In the Cooper Creek Fan, part of the

Cooper's flow is diverted to the Coongie Lakes, and the amount of inundation achieved depends upon the size of the flood. The other part of the Cooper's flow goes down the Main Branch. If it extends beyond the overflows area (see below) as far as the southwestern Strzelecki Plain, the entire flow is abstracted by Lakes Appadare and Hope. Flow enters Lake Appadare through its northeastern channel, which has a small delta on its entry into Lake Appadare. After a certain level, flow exits Lake Appadare through the southern channel towards Lake Hope (where it enters via a wave-dominated delta). When Lake Hope is sufficiently full, water is backed up along the linking channel (splays breaching the banks and depositing flanking alluvial sands), and Lake Appadare returns water to Cooper Creek via a poorly-defined north-western exit and a clearly defined western exit (Fig. 29).

7.5 The Northern Overflow and the Main Branch (Cuttapirie Corner)

There was no access to the Cooper downstream from Boggy Lake, or along the northern overflow, and these comments are based on the regional study.

The northern overflow is poorly-defined flat area transmitting water back to the Cooper Main Branch. During extremely wet years, water moves through the overflow lakes, becoming diffuse and unchannelled south of Lake Oolgoopiarie (Fig. 30). The flow path proceeds southwest and south, rejoining the Cooper near the Deparanie Waterhole. The flat overflow area is flanked to the northwest and southeast by dunefields containing deflationary basins. In places, these deflationary basins connect to the northern overflow via interdune corridors. Because the depths of the deflationary basins are related to the wind-driven erosion events that created them, some deflationary basins may be appreciably lower in elevation than the overflow, so the local slope from the overflow down the interdune corridors to the basins can be greater than the downvalley slope towards the Cooper Main Branch. Thus, the northern overflow is flanked by a number of well-vegetated interdune corridors, some leading to lakes which have abstracted water from the overflow (Fig. 30).

There are few parts of dryland Australia where the vegetation and landforms have not already been impacted to some degree by grazing. The Northern Overflow is reputed to have had little to no grazing because of its difficulty of access.

The Cooper Main Branch travels northwest from Embarka Swamp as a single channel. From the Narie Waterhole, the Main Branch flows northwest and west, until it enters a broad swampy area of extremely low gradient where the western flow path is completely blocked by longitudinal dunes. The main channel becomes distributary, with offtakes directing some water north but most water south into a broad irregular inundated area. Flow re-collects into channels ~7 km south of the distributaries, near Walkers Crossing. From there south the channel is small, often multi-thread and anabranching, and displaying evidence of a good deal of channel relocation. Near

Cuttapirie Corner the channel is constrained by dunes and its location is more stable. It continues around the Corner and north, with many small splays cutting through the banks and distributing alluvial sediments along the channel flanks. From there through to Deparanie Waterhole, the channel is single-thread where constrained by dunes, and follows a diffuse flow path through anastomosing channels and swamps when traversing flats.

The large longitudinal dune blocking the westward path of the present Cooper Main Branch also blocked the path of the Cooper's most recent palaeodrainage. What is now Christmas Creek was once the main flow path. It flowed from the area of Toonman Waterhole (Fig. 30) deposited alluvial sediments in the area adjacent to the large longitudinal dune, now a broad swampy area. It then flowed north towards Lake Oolgoopiarie, depositing alluvial sediments along its flanks, and at its downstream (northern) end.

7.6 Cooper Creek’s Low-Discharge Reaches

7.6.1 Southern Strzelecki Plain: Cooper Creek below Deparanie Waterhole, and Strzelecki Creek

There was no access to the Cooper downstream from Boggy Lake, and these comments are based on the regional study.

The lower Cooper beyond Coongie Lakes is the driest reach in the Channel Country, with no semi-permanent waters along its entire 340km length (Silcock 2009). Below Deparanie Waterhole, Cooper Creek is a discontinuous small channel. Because the downvalley direction is now almost the same as the trend of the longitudinal dunes, the river’s flow path tends to be abstracted down interdune corridors, and then cut westwards across the trend of the longitudinal dunes. The most striking example is just downvalley of Deparanie Waterhole, where the Cooper Creek goes across ~10 km of dune fields. The main flow path continues west then south to Murra Murrina Waterhole, however some flow is abstracted towards Cooyeeninna Waterhole and then down the Kanowana Channel. This flow path eventually terminates in a nest of swamps and flats ~37 km to the south.

Because of this continued abstraction of floodwaters, potential wetlands are common in the dunefields flanking the river, but Cooper Creek itself is small. Its reaches alternate between

- small waterholes (channel segments with clearly-defined banks supporting riparian vegetation; smaller and more shallow than the waterholes upstream, but capable of holding water at least briefly),
- single-thread channels, supporting minor riparian vegetation and with some deeper sections,

- and inundated areas (swamps, networks of anastomosing channels, small lakes).

The disposition of the channel types depends on their local topography, with inundated landforms in small flats and wide interdune areas, waterhole channel segments in flow-constricted areas where the path cuts across the trend of the longitudinal dunes (Fig. 31), and longer single-thread channels travelling down the main interdune corridors.

As with the Northern Overflow (section 7.5), the flanking dune fields contain deflation basins, and those which connect to the Cooper flow paths via interdune corridors receive water from the Cooper. The most significant of these is the Lake Appadare / Lake Hope complex, which captures the entire Cooper flow (section 7.4.3). Below Lake Hope, the channel is more continuous but there are very few waterholes, and the lakes are smaller and fewer. The channel is sinuous around the ends of longitudinal dunes.

The Strzelecki Creek on the Cooper Creek Fan, north of the Della Road, is undefined within an area of broad inundation (see sections 3.3.3 and 7.3.3). South of that, the Strzelecki is also largely discontinuous, although its primary flow path is fairly clearly defined. Single-thread channel segments with clearly defined banks supporting riparian vegetation alternate with poorly-defined anabranches with sparse vegetation, all set within a context of wide flats. South of Tilparee Waterhole, the creek becomes more constrained by the longitudinal dunefields of the southeastern Strzelecki Plain. As the creek approaches Lake Blanche, it displays channel mobility, with the present channel and signs of former channels set within a channel belt. The path of Strzelecki Creek is influenced by neotectonic movement and the geologically recent development of the longitudinal dune fields (Gravestock et al. 1995, Nanson et al. 2008).

7.6.2 The Tirari Reaches

At the southwestern corner of the Strzelecki Plain, Cooper Creek enters the Kopperamanna Floodout. In pre-European times, Kopperamanna was a major trading location for the Aboriginal drug pituri (Watson 1983).

The Cooper's flow path is very diffuse across the Kopperamanna Floodout. Channels re-form at the western end, where the flow path is increasingly constricted by small longitudinal dunes. The Cooper leaves the Floodout as a single sinuous channel, slightly inset and moderately mobile, which flows across the trend of longitudinal dunes towards its mouth into Lake Eyre). The apparent simplicity of this landscape is deceptive: two separate palaeo-Cooper Creek channel belts can be discerned in satellite images beneath the present dune field, and palaeochannels with a strong north-east trend are expressed as chains of playa lakes and flooded interdunes

(Wells & Callen 1986, Nanson et al. 2008). The trend of the lower Cooper which flows northwest from the Kopperamanna Floodout, rather than south west towards the depocentre in Lake Eyre South, (Fig. 58) is a reflection of these influences.

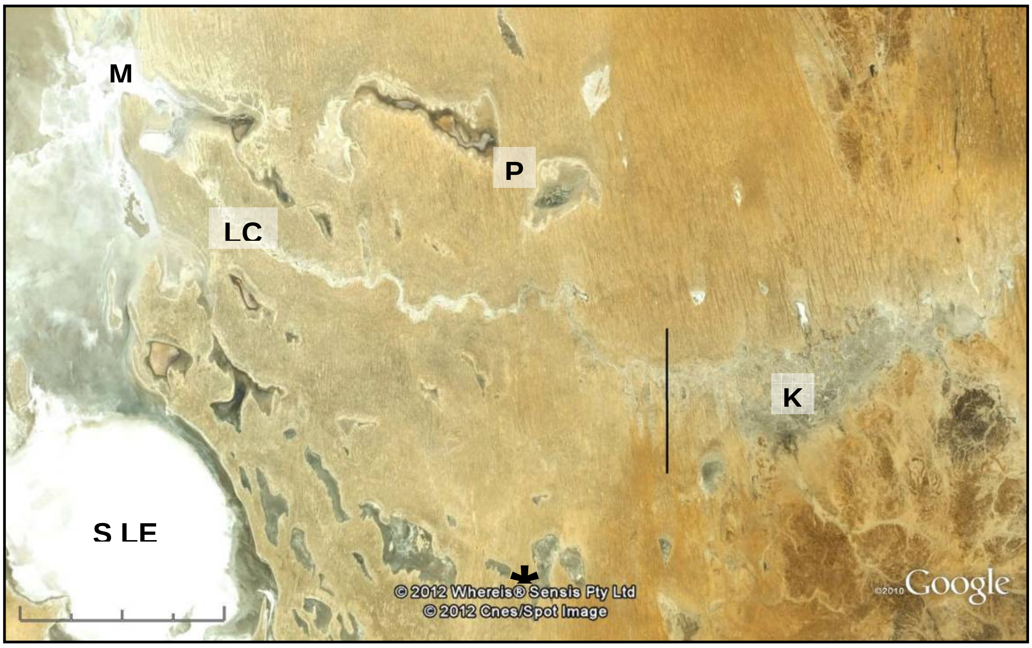


Fig.58. The lower reaches of Cooper Creek.

The Lower Cooper Creek (LC) extends from where the Creek exits the Strzelecki Plain at Kopperamanna Floodout (K), to the mouth of the Cooper (M) entering Lake Eyre South (S LE). Note that the Cooper flows away from the deepest part of Lake Eyre, reflecting palaeodrainage trends which are also expressed in strings of playa lakes (P). Flow is from right to left, 20 km scale bar.

7.7 Lakes Gregory, Blanche, Callabonna, and the Warrawoocara Channel

Lakes Gregory, Blanche, and Callabonna are located at the southern margins of the Strzelecki Plain (Fig. 2, Location Map). At their most full Lake Gregory overflowed down the Warrawoocara Channel (Fig. 34) towards the Kopperamanna Floodout (last occurrences ~125,000 and ~47,000 years ago). Within the last 18,000 years (since the Last Glacial Maximum) there have been some episodes of partial filling, but under the present climatic conditions these lakes are usually dry. At least some episodes of partial filling are likely to be sourced from the north (down Strzelecki Creek).

Of the three lake floors, Lake Gregory has the highest elevation, and Lake Callabonna the lowest (Fig. 34, Location Map); Lake Frome, to the south of Lake Callabonna, also has a lake floor of higher elevation than Lake Callabonna. Furthermore, the inter-lake sills also decrease in height away from Warrawoocara Channel. Based on the one second SRTM data, the Lake Gregory overflow towards Kopperamanna must exceed 16 m AHD; the Gregory to Blanche sill is 9-12 m, Blanche to Calabonna 7.5 m, and Calabonna to Frome is 10m. For Lake Gregory to fill enough to overflow to the Cooper, all the other lakes would have to fill first, which would call for a completely different hydrological setting than occurs today.

The landforms in this area include

- Alluvial fans along the edges of the Cooryanna Dome feed sediment and rainfall runoff directly into the lakes and the inter-lake channels. The surface is covered with gibber plain and fine silty sediment, and outcrop or shallow subcrop, including some very iron-rich Cainozoic sedimentary rocks.
- The lakes consist of lake bed, hard up against the alluvial fans on their southern or southwestern sides, and edged by W-NW-SE trending source-bordering dunes around the northern edges. The source-bordering dunes define the sizes of the palaeolakes, and may occur in sets, representing the recession of the drying lakes. Many of the dunes occur as lunettes (clay- and gypsum-bearing dunes related to drying-lake stages) overlying transverse dunes (Sheard & Callen 2000). Some longitudinal dunes have N-trending longitudinal dunes extending from them. The source-bordering dunes are pale to white, indicating their sand derives from the underlying equivalents of the Katipiri Formation.
- Longitudinal dunes extend over most of the southern Strzelecki Plain. They are white to pale adjacent to and northwards of white source-bordering dunes, indicating northward sand transport. Dune colour deepens to pale orange and then mid-orange with distance away from the lakes.
- Warrawoocara Channel extends from Lake Gregory downslope towards the Kopperamanna Floodout. Its shape in DEM/satellite image is somewhat masked by two closely-spaced longitudinal dunes that run partway along its western side. It was difficult to access during field season, being too wet to travel off-road, however the intersection of road and channel showed small poorly-defined drainage ways (Fig. 59), confirming the DEM/satellite image investigation results that this channel does not currently carry overflow from Lake Gregory. Furthermore, the Warrawoocara Channel is poorly defined on DEM, and the local geology is a thin layer of fine sandy silts with some gilgai features, overlying shallow subcrop of iron-rich Cainozoic sandstones. These are all indications that the Channel was not a locus for substantial flow, but has occupied near-shore lacustrine facies for most of its lake-full geological history.
- There are several strings of small elongate playa lakes aligned parallel or semi-parallel to the larger lakes (Fig. 34). These are likely to be wind-eroded basins, related to the low hills and other topographic elements.

- There is a slightly elevated area north and north east of Lake Gregory (section 2.2). The elevation difference is largely masked by the dunefield, and is only visible with close interrogation of the DEM . The origin of these low hills is not clear. However, it is possible that the factors which keep Strzelecki Creek in its present course include not only the northwards-trending dunes (Gravestock et al. 1995), but also this topography.
- Strzelecki Creek flows south and SSW, and enters Lake Blanche on the lake's south eastern side through a delta.

Fig. 59. Warrawoocara Channel, not currently an overflow.

The only waterway in the Warrawoocara Channel is a small poorly defined channel and some accompanying swales. It carries local runoff from the alluvial fans to the south and southwest. These small drainages show no evidence of overflow from Lake Gregory, however the disposition of the drainage network indicates receipt of runoff waters from the gibber plains to the south west, and it remains a potential toad migration path.

8. HUMANS AND GEOMORPHOLOGY

8.1 Introduced Animals

8.1.1 Cane Toads: Life, Habitat and Spread

The daily cycle of the adult cane toad revolves around hydration and sheltering from desiccation. Toads are nocturnal: they spend daylight hours out of sight, sheltering in small confined spaces (burrows, deep soil cracks in black-soil country, small gaps between rocks) or beneath the cover of vegetation (Tingley & Shine 2011). Their refuge spaces can include apparently quite unfavourable situations (such as hiding beneath a sheet of corrugated iron exposed to the sun, Steve Wilson, ex-Desert Channels Queensland, pers. comm., 2012). At dusk toads emerge from their shelters, to rehydrate by immersing their ventral surfaces in shallow water (they don't drink), and to move around either locally (established populations) or away from the day's refuge site (advancing invasion front). During the night's movement, the toads feed (primarily on insects, but they will eat anything; CSIRO 2003). Males may congregate around a suitable breeding location (open ground around the edge of shallow water) and call to attract females; females may be more widely dispersed away from the breeding locations. Cane toads are known to be very successful at exploiting human environments for shelter and rehydration, utilising sub-floor spaces, pet-food bowls, and drip patches beneath air-conditioners or leaking taps (Matt Greenlees, University of Sydney, pers. comm., 2012).

Cane toad life cycles are dependent upon the availability of warmth and water, but it is important to note that

- the adults are largely terrestrial and their original native range includes seasonal dryness,
- in Australia, they are increasingly occupying zones where conditions are more extreme than those of their native range (Urban et al. 2007),
- their adaptive behaviours have allowed them to be increasingly well-adapted to seasonal drought in the Top End (Brown et al. 2011),
- they have demonstrated plasticity in cold tolerance, allowing them to invade colder regions of south eastern Australia (Kolbe et al. 2010),
- and (most importantly) cane toads at the invasion front also display genetic adaptability, displaying longer legs (fast forward progress, therefore better access to new breeding sites) (Philips et al. 2007), enhanced dispersal abilities (Alford et al. 2009) and greater ability to deal with arid conditions

(more rapid water uptake, better ability to travel long distances while dehydrated; Tingley et al. 2012).

Thus, the cane toad life cycle described below should be recognised as being derived from places where the cane toad currently exists. It does not represent factors that can be assumed to limit the toads' ability to expand into South Australia's Arid Lands.

The cane toad life cycle moves through the following stages: amplexus (breeding), eggs, tadpoles, metamorphs, adult toads. Unless otherwise referenced, this information is pers. comm., Matt Greenlees, University of Sydney, 2012.

1. **Amplexus** (breeding). Toads will seek out a suitable breeding site: a body of still or slow-flowing water, with a shallow edge and little surrounding vegetation. They will preferentially seek such a site (Semeniuk et al 2007), even if it requires they move away from the main river (David Peacock, PIRSA, pers. comm., 2012; and see Doody et al. 2006). Males congregate around the edge, calling for females; females range more widely away from the breeding site, and will come in if attracted by a male's call. Amplexus is when the male clasps the female's back, in order to externally deposit sperm on the eggs as the eggs are laid. Ideally this takes place in shallow water with a gently-shelving incline. Amplexus can take place in a vegetated riparian zone, but it is less common. It can take place in deeper water, or on a more steeply inclined bank, however the female toad risks being drowned. Toad breeding sites are characteristically described as shallow ponds, farm dams, roadside culverts, and shallow streams and billabongs (Philips et al. 2007, Kearney et al. 2008, KBT1 2012). Parameters: the likelihood of a breeding event is restricted by minimum temperature; maximum temperature has not been known to be a controlling factor.

2. **Eggs** are laid in shallow water: the female toad's feet are touching the ground when she lays the eggs, and her head is above water. The eggs are laid in long neat strings of non-toxic gelatinous material containing pairs of very toxic tiny black eggs. It is not known whether the egg strands are sticky; it is possible that eggs might float free, or become entwined around vegetation, and they have been known to become stranded by falling water levels. It is unlikely that the eggs would remain viable if they are out of the water for very long. Two possibilities arise if egg strings become detached from the breeding site and transported elsewhere (for example, by a flood pulse). Firstly, the eggs may be transported to a new hatching location. This will be detrimental if toad control is being targeted around known breeding sites. Secondly, the eggs may end up in deeper water, bringing their toxin within the depth range of larger waterhole fish or turtles. To date, there have been no reports of egg detachment, however the locations of previous studies have not been on rivers whose water levels fluctuate on a day-to-day basis (whereas the Lake Eyre Basin channel country

rivers are characterised by complex hydrology and multiple flood peaks). Parameters: the time needed between laying and hatching is generally 2-3 days, however that will be temperature dependent, and there are indications that toads are adapting to cooler temperatures. The effect of water salinity and acidity on the eggs is currently being investigated.

3. **Tadpoles** will move between shallow and deep water but are most often seen as swarms in shallow water (close to the ideal metamorph habitat). The time needed between hatching and metamorphosis can be as little as 17 days or as much as 6 months (CSIRO 2003). The amount of time they spend in this stage affects their adult fitness. If they spend a short time as tadpoles, they turn into little metamorphs and are thus less resistance to desiccation, and their fitness as adults is also compromised. Parameters: this stage is affected by temperature, feeding, competition, and the presence of predators (fear pheromones lead to faster development, therefore the tadpoles are smaller when they turn into metamorphs). Tadpoles will live amongst emergent vegetation. Tadpole swarms caught up in flowing water might result in dispersal, however if they're not at the water's edge during metamorphosis the metamorphs will drown. The effect of water salinity and acidity on tadpoles is not known.

4. The **metamorphs** are tiny black toadlets. They are very prone to dehydration, and cluster near muddy gently-sloping banks near the edge of shallow water. They don't need to enter water to rehydrate, just press their ventral surface against damp ground. They don't swim well and might drown in flowing water, however they are unlikely to enter the water. If conditions are dry their daily shelter spot needs to be within a couple of metres of their rehydration spot, however if conditions are moist they can go ~100 m from water. Unlike native frogs, they are not known to shelter in toilet cisterns or bowls. There is no information on the limiting parameters of water temperature, air/ground temperature, water salinity or acidity, or length of time to develop into adult toads.

5. **Adult toads** need to rehydrate regularly, but the length of time between hydration depends on activity levels, temperature, and humidity. Toads that are travelling (invasion front) will be in trouble if they can't rehydrate every 2-3 days, whereas toads that are sheltering have apparently been observed to last two weeks without water (KTB1 2012). Toad activity in the Top End is at a maximum in warm, wet, and windy nights (Philips et al. 2007). Because moisture and warmth is so strongly correlated in the Top End, where most of the research has taken place, there is little information on other temperature/moisture conditions, however since toads are ectotherms, minimum temperature is likely to be a limiting parameter. Toads move an average of 50-150 m per night (with much higher maximum distances) so

presumably the daytime shelter doesn't have to be very close to the rehydration site.

While there is clear evidence that toads hitchhike in vehicles (Shine Research Group 2011a, NT News Photo Gallery 2012), the most recent invasion wave across the Top End has taken place by the efforts of the toads themselves. Toads expanding into new territory along the invasion front move from one water source to another, so tending to travel long moisture corridors such as river primary flow paths. However they travel overland (not by swimming, although they can swim across strongly flowing streams), and can cross very dry or otherwise difficult country (rocky, densely vegetated, very steep, dry black-soil plains) (Schwartzkopf & Alford 2005, Matt Greenlees pers. comm. 2012). Daily travel distances are typically <100-200m, but vary widely according to conditions. Individuals have been tracked at single-night or average-per-night distances of >200m, 750 m, 1 km, 1.3 km, (Schwartzkopf & Alford 2005, Phillips et al. 2007), and toads have been observed colonising artificial watering points up to 9.5 km from permanent natural waters (Florance et al. 2011) . Invasion front toads tend to travel in approximately straight lines, away from their natal pond. They also tend to keep a distance from other pioneer toads, so the end result is a lot of toads all moving in the same direction. Toads prefer to travel along clear pathways such as roads or cleared fencelines, and travel more slowly in heavier vegetation. The toad populations along the invasion front are different in age/size, gender balance, behaviour, and genetics from those resident in established toad territory, and the complex travel patterns appear to differ along gender lines (Schwartzkopf & Alford 2005, KTB2 2012).

A number of studies have attempted to predict the eventual distribution of cane toads in Australia by matching their known habitat preferences and limiting parameters (temperature, water requirements, etc.) to Australian climate zones (Kearney et al. 2008, Urban et al. 2007, Urban et al. 2008, Florance et al. 2011). While well-grounded in literature on toad ecology, they are inadequate as predictive tools because their understanding of arid-zone landforms and hydrology is minimal. A study on the role of artificial watering points as potential toad habitat (Florance et al. 2011) develops a valuable methodology, but its results are compromised because its data sources (intended to show the locations of permanent natural waters) are incomplete and were not ground-truthed. Sophisticated computer models matching toad physiology to bioclimatic conditions (Urban et al. 2007, Kearney et al. 2008) assesses presence/absence of suitable breeding sites in such an extremely simplistic fashion that the Cooper Creek's permanent waterholes and RAMSAR-listed wetlands are presumed to not exist. Indicative lengths of water retention of some Cooper Creek landforms are shown in Table T1. These publications will disadvantage the South Australian Arid Lands Natural Resources Management Board in competitive funding applications on a national level, since they falsely indicate the SAAL NRM area is unlikely to be in danger of cane toad invasion. While the authors would rightly point out that a model is not supposed to be taken seriously beyond the limitations of its input data, the fact remains that readers unfamiliar with or unaware of those limitations will take the conclusions at face value. This has already occurred (see Peacock 2007, Urban et al. 2008, Phillips et al. 2008, Beckman & Shine 2009, Shine 2010, Florance et al. 2011).

Potential toad habitat in Cooper Creek

The key cane toad habitat requirements are water for rehydration while travelling, daytime shelters, and suitable breeding habitat.

For toads to successfully expand downstream Cooper Creek, rehydration water sites must be no more than 3-4 days toad-travel apart. Any patch of shallow water (or a shallow edge to deep water) is sufficient for adult toad rehydration, so the availability of sites for toad rehydration depends on the current hydrology of the system. In wet years, water is continuous along the channel network and in places the floodplains are inundated, so there would seem to be few limits to toad expansion down and across the Cooper's fluvial network. In light of the recent flow events (2010-2012) (Costelloe 2013), it would be desirable to actively seek information on the current location of the toad invasion front in Queensland.

In more dry years, the likely expansion corridors would be more limited. It would be possible to map and prioritise likely dispersion pathways for high-flow and low-flow hydrological scenarios by firstly defining the locations of suitable water by combining:

- geomorphic information (flow paths, permanent and semi-permanent waterholes, primary and secondary channels, and using gilgai morphology to map more and less-inundated floodplains)
- hydrological data (Costelloe 2013), and
- landholder data, and historical records of waterhole permanence (Silcock 2009).

Water locations would then have buffer zones established around them to indicate toad-travel distances. Where buffer zones intersect, a potential pathway of toad travel would exist. A simplistic model based on the travel distances measured from the Top End would make that distance 3.9-5.2 km. (More sophisticated models incorporating temperature and other biophysical conditions are described in the literature. To apply them accurately it would be desirable to have specific information from the south-western Queensland toad populations to see what distances are travelled, and over what weather conditions.) If it is intended that toad populations should be managed before they get to high-value waterholes in South Australia then it would be desirable to work with the Queenslanders to create such a database. The database could be used to identify those parts of the primary flow path which (during dry years) have the furthest-apart water sources; these would be high-priority targets for cane toad control.

An important factor in toad dispersion pathways is the location of artificial water points. The most important thing to understand about cane toad habitat in South Australia is that even where natural waters are only transient, they may be sufficient to allow invading toad populations to reach artificial permanent waters, from whence they can re-infect the system in the next wet year. In the Strzelecki Plain, there are substantial artificial permanent waters, including

- pastoral dams
- water treatment ponds created to service the hydrocarbon extraction industry.

The location of all artificial waters should be included in potential expansion corridors database.

Wherever there is water in the fluvial system, there would be no shortage of suitable places for a toad to shelter during the day, including:

- the tangles of exposed coolabah roots along the waterhole banks
- beneath fallen branches and logs along waterhole banks, and in channel beds
- beneath vegetation in gullies cutting through waterhole and channel banks
- dense lignum thickets along the edges of swamps, or some channel and waterhole banks
- within the deep cracks and crabholes of the black soil swamp country
- under the clusters of boulders, where rocky outcrop is close to the water (for example, at Cullyamurra and Nappa Merrie)
- beneath or within human infrastructure: demountable offices, accommodation blocks, toilet blocks, sheds, storehouses, stockpiles on pallets, shipping containers, garden-supply bins
- in or under human objects: shoes, the holes in bricks and bessa-blocks, cars, piles of mulch, scraps of building materials.
- It would be desirable to examine the Channel Country cane toad populations at the invasion front (currently near Jundah), to ground-truth these assumptions.

The final factor in whether or not cane toads can colonise the Cooper Creek catchment relates to suitable breeding sites. Toads prefer small shallow ponds, which would dry quickly under north-east South Australia's dry climate. Assuming such ponds are fed by local runoff, modeling using SA's rainfall:evaporation ratio has assessed north-east South Australia as being at no risk of cane toad invasion (Kearney et al. 2008, Urban et al. 2007, Urban et al. 2008, Florance et al. 2011). However this assessment is incorrect: Cooper Creek is not dependent upon local run-off for its water supply, so rainfall: evaporation ratio is only one of several deciding factors. In fact, upstream from Coongie Lake (Northwest Branch) and Embarka Waterhole (Main Branch) there are a string of essentially permanent waterholes all the way up to the upper catchment; downstream of these locations, there are waterbodies which would hold water for a time, before drying. The Coongie Lakes are drought refugia and Ramsar-listed high-value aquatic ecosystems.

Small ponds are not the only landforms which can supply the desirable features for cane toad breeding sites (shallow still water, gentle slope, relatively unvegetated water's edge). Suitable landforms are available throughout the Cooper:

- upstream and downstream edges of feeder channels and splay channels of the permanent waterholes
- margins of secondary and minor channels, also flood chutes, palaeochannels and anabranches
- offtakes and distributary channels along the Cooper Creek Fan
- lake edges
- lake input and offtake channels
- swamp edges
- sandy benches where dunes meet channels, or where stock pads come down to the water's edge
- dam edges
- borrow pits
- culverts and under-bridge areas
- flare pits and evaporation ponds of the hydrocarbon extraction industry.

Furthermore, it has not been established that the absence of ideal spots will completely prevent toads from breeding; their adaptability may include using less ideal sites.

Some landforms may be less suitable for cane toads. Heavily vegetated water's edge areas (like some downstream edges of splay channels) may be less desirable as breeding sites (though toads have been observed calling in well-vegetated ponds). Steep waterhole banks may be poor breeding sites, because of the risk of drowning. Lake shorelines exposed to wave action may be undesirable environments for metamorphs and tadpoles, although the sandy beaches associated with those shorelines may be very desirable as breeding sites. Acidity (low pH) is associated with poor health in fish (D. Schmarr, pers. comm. 2012), and heavily vegetated swamp areas (such as Tirrawarra swamp) with brown peaty water may be unsuitable for tadpoles or eggs. Increasing salinity with decreasing water level or with increasing down-valley distance is also likely to be detrimental.

Toads exploit specific microhabitat in their breeding sites (Semeniuk et al 2007). If specific waterholes or lakes are to be the subject of targeted toad control, it may be desirable to undertake detailed geomorphological mapping as an aid to identifying target habitat areas.

Cane toad control

Cane toad control mechanisms are beyond the scope of this report, however at present the indications are that

- "toad busting" (concentrated removal of toads from particular breeding sites or refuge areas) has not halted the invasion front in the Top End, but may (or may not) have slowed it briefly, and has apparently been successful in clearing specific sites, or reducing toad impact at specific sites (Sawyer & Taylor 2005, Peacock 2007, Shine research group 2011b, KTB2 2011, KTB3 2011);
- biological controls do not currently exist, though work is being done on existing cane toad parasites (Shine research group 2011c) and other things (Shannon and Bayliss 2008), while other avenues remain unexplored (Peacock 2006);
- toads can be successfully excluded from small areas by fencing (Stop The Toad 2010, Florance 2011), although the method will be problematic for many fluvial locations, and may not be economically feasible for pastoralists;
- toads are successfully preyed upon by aquatic insects (Cabrera-Guzman et al 2012), meat ants (Shine research group 2011d), crabs (Matt Greenlees pers. comm. 2012; so possibly they might be preyed upon by yabbies), and especially cane toads prey upon each other;
- toad tadpoles are attracted to toad pheromones (in a predator-prey relationship), and tadpole traps might make it possible to clear tadpoles from waterholes (Crossland et al 2012);
- it is possible that a combined strategy of toadbusting plus tadpole pheromone traps may manage toads in specific places, reducing impact on local predator populations;
- however toadbusting is a very labour-intensive operation which must be repeated regularly – it is outside the scope of pastoral station operations, instead requiring staff or dedicated volunteers, and external funding.

Toad busting of adult toads may be more successful in slowing the invasion front in the Queensland (Windorah to Nappa Merrie) reach of Cooper Creek than it has been in the Top End, since the invasion front would only be as wide as the Cooper floodplain. If the “weakest link” locations could be identified in the primary dispersion pathways, where isolating a few water sources would make it very difficult for the front to progress, it may be possible to slow or hold the toad front. Dry-year toad busting and tadpole trapping along key landforms in the dispersion paths would need to be an ongoing effort, with extra resources allocated during/after wet years.

It would be extremely detrimental if the toads were to invade as far as the high-value waterholes within the Innamincka Dome (Nappa Merrie and Cullyamurra), as they would have access to permanent water in these sites, as well as impacting on refuge fish populations. However, these waterholes are tightly constrained between waterless uplands. The pinch points (where the hills most closely constrain the creek, and the floodplains are narrowest) may represent the best places for toad call monitoring, and the best opportunities for defensive toad busting and tadpole trapping.

If cane toads get past Innamincka, and encounter the distributary channel network of the Cooper Creek Fan, they will be much harder to control. They are likely to be able to extend down both branches of the Cooper, into the Coongie Lakes, Kanowana channel, Lake Hope, Strzelecki Creek, Kopperamanna Floodout, and possibly the margins of lakes Frome, Blanche, Gregory. How permanent those populations are will depend on year-to-year hydrology, and water chemistry (salinity, pH) in the various locations. Across these areas, they are also likely to inhabit permanent artificial waters, particularly in the oilfields.

8.1.2 Stock Grazing

The analysis of Fig. 38’s evidence of grazing effects is as follows. There are several possibilities why there is a difference between the two halves of the image.

1. The difference may be apparent, caused by a boundary between two different satellite images placed along this fenceline. This is discounted because Google Earth doesn't trim its images to infrastructure.
2. Therefore the paler colour on the eastern side of the fence relates to a decrease in vegetation density. This may be caused by the blocking of flow, starving some of the vegetation of water. However, this is unlikely since the water source is on the eastern (devegetated) side.
3. Stock paths are visible in the eastern (devegetated) area. It seems most likely that the grazing pressure was much more intense on the eastern side of the fence.

While this degree of grazing pressure was not common in the 2007 images available for the remote study, it demonstrates that grazing pressure can have an effect on swamp vegetation.

8.2 Infrastructure and Civic Development

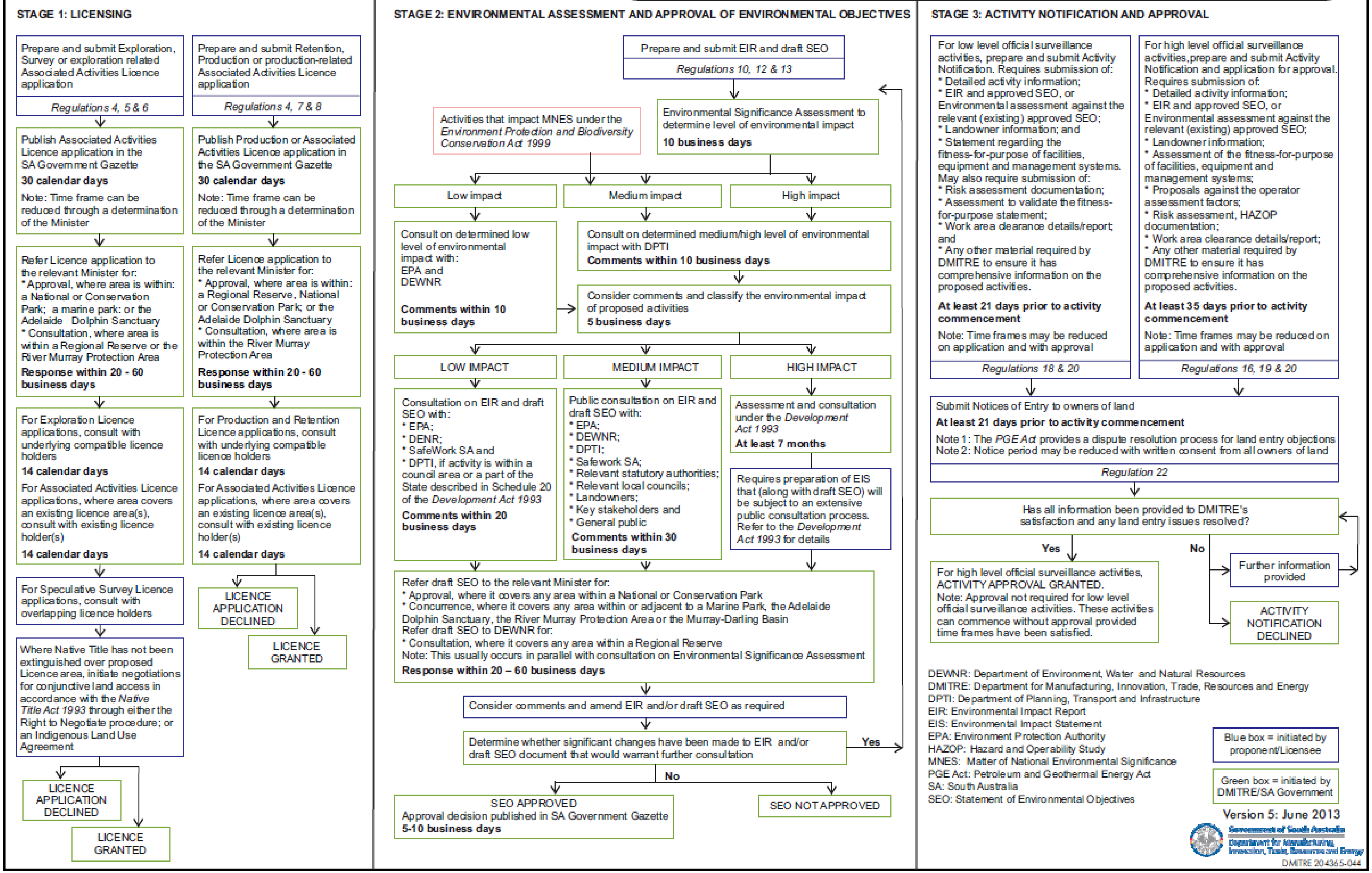
Fig. 60. The flowchart of the application and approval process required by the Petroleum and Geothermal Energy (PGE) Act 2000. (see next page)

www.pir.sa.gov.au › Petroleum › Legislation & Compliance, follow the link entitled *Guide to the licensing and approvals process for exploration, retention, production and associated activities*. Accessed April 2013.

GUIDE TO THE LICENSING AND APPROVALS PROCESS FOR EXPLORATION,RETENTION, PRODUCTION ACTIVITIES

PETROLEUM AND GEOTHERMAL ENERGY ACT (PGE) ACT 2000

The PGE Act process consists of three stages. Firstly, a licence is granted authorizing the licensee to carry out the specific activity to which the licence relates. Environmental assessments are then required to develop environmental objectives and assessment criteria for approval. Finally, a location-specific activity notification is submitted for assessment and approval where required. Each stage is shown independently in this flowchart and all stages are required to be completed before regulated activities can commence. In reality, it will be possible for some aspects of the separate stages to occur in parallel - this is best discussed with DMITRE early in project planning. References to appropriate sections of the PGE Regulations are provided where these will assist the proponent.



STAGE 1: LICENSING

Prepare and submit Exploration, Survey or exploration related Associated Activities Licence application

Regulations 4, 5 & 6

Publish Associated Activities Licence application in the SA Government Gazette

30 calendar days

Note: Time frame can be reduced through a determination of the Minister

Refer Licence application to the relevant Minister for:
* Approval, where area is within: a National or Conservation Park; a marine park: or the Adelaide Dolphin Sanctuary
* Consultation, where area is within a Regional Reserve or the River Murray Protection Area

Response within 20 - 60 business days

For Exploration Licence applications, consult with underlying compatible licence holders

14 calendar days

For Associated Activities Licence applications, where area covers an existing licence area(s), consult with existing licence holder(s)

14 calendar days

For Speculative Survey Licence applications, consult with overlapping licence holders

Where Native Title has not been extinguished over proposed Licence area, initiate negotiations for conjunctive land access in accordance with the *Native Title Act 1993* through either the Right to Negotiate procedure; or an Indigenous Land Use Agreement

LICENCE APPLICATION DECLINED

LICENCE GRANTED

Prepare and submit Retention, Production or production-related Associated Activities Licence application

Regulations 4, 7 & 8

Publish Production or Associated Activities Licence application in the SA Government Gazette

30 calendar days

Note: Time frame can be reduced through a determination of the Minister

Refer Licence application to the relevant Minister for:
* Approval, where area is within: a Regional Reserve, National or Conservation Park; or the Adelaide Dolphin Sanctuary
* Consultation, where area is within the River Murray Protection Area

Response within 20 - 60 business days

For Production and Retention Licence applications, consult with underlying compatible licence holders

14 calendar days

For Associated Activities Licence applications, where area covers an existing licence area(s), consult with existing licence holder(s)

14 calendar days

LICENCE APPLICATION DECLINED

LICENCE GRANTED

STAGE 2: ENVIRONMENTAL ASSESSMENT AND APPROVAL OF ENVIRONMENTAL OBJECTIVES

Prepare and submit EIR and draft SEO

Regulations 10, 12 & 13

Activities that impact MNES under the *Environment Protection and Biodiversity Conservation Act 1999*

Environmental Significance Assessment to determine level of environmental impact

10 business days

Low impact

Medium impact

High impact

Consult on determined low level of environmental impact with:
EPA and
DEWNR

Comments within 10 business days

Consult on determined medium/high level of environmental impact with DPTI

Comments within 10 business days

Consider comments and classify the environmental impact of proposed activities

5 business days

LOW IMPACT

MEDIUM IMPACT

HIGH IMPACT

Consultation on EIR and draft SEO with:
* EPA;
* DENR;
* SafeWork SA and
* DPTI, if activity is within a council area or a part of the State described in Schedule 20 of the *Development Act 1993*

Comments within 20 business days

Public consultation on EIR and draft SEO with:
* EPA;
* DEWNR;
* DPTI;
* Safework SA;
* Relevant statutory authorities;
* Relevant local councils;
* Landowners;
* Key stakeholders and
* General public

Comments within 30 business days

Assessment and consultation under the *Development Act 1993*

At least 7 months

Requires preparation of EIS that (along with draft SEO) will be subject to an extensive public consultation process. Refer to the *Development Act 1993* for details

Refer draft SEO to the relevant Minister for:
* Approval, where it covers any area within a National or Conservation Park
* Concurrence, where it covers any area within or adjacent to a Marine Park, the Adelaide Dolphin Sanctuary, the River Murray Protection Area or the Murray-Darling Basin
Refer draft SEO to DEWNR for:
* Consultation, where it covers any area within a Regional Reserve
Note: This usually occurs in parallel with consultation on Environmental Significance Assessment

Response within 20 – 60 business days

Consider comments and amend EIR and/or draft SEO as required

Determine whether significant changes have been made to EIR and/or draft SEO document that would warrant further consultation

Yes

No

SEO APPROVED
Approval decision published in SA Government Gazette
5-10 business days

SEO NOT APPROVED

STAGE 3: ACTIVITY NOTIFICATION AND APPROVAL

For low level official surveillance activities, prepare and submit Activity Notification. Requires submission of:
* Detailed activity information;
* EIR and approved SEO, or Environmental assessment against the relevant (existing) approved SEO;
* Landowner information; and
* Statement regarding the fitness-for-purpose of facilities, equipment and management systems.
May also require submission of:
* Risk assessment documentation;
* Assessment to validate the fitness-for-purpose statement;
* Work area clearance details/report; and
* Any other material required by DMITRE to ensure it has comprehensive information on the proposed activities.

At least 21 days prior to activity commencement

Note: Time frames may be reduced on application and with approval

Regulations 18 & 20

For high level official surveillance activities,prepare and submit Activity Notification and application for approval. Requires submission of:
* Detailed activity information;
* EIR and approved SEO, or Environmental assessment against the relevant (existing) approved SEO;
* Landowner information;
* Assessment of the fitness-for-purpose of facilities, equipment and management systems;
* Proposals against the operator assessment factors;
* Risk assessment, HAZOP documentation;
* Work area clearance details/report;
* Any other material required by DMITRE to ensure it has comprehensive information on the proposed activities.

At least 35 days prior to activity commencement

Note: Time frames may be reduced on application and with approval

Regulations 16, 19 & 20

Submit Notices of Entry to owners of land

At least 21 days prior to activity commencement

Note 1: The *PGE Act* provides a dispute resolution process for land entry objections
Note 2: Notice period may be reduced with written consent from all owners of land

Regulation 22

Has all information been provided to DMITRE's satisfaction and any land entry issues resolved?

Yes

No

For high level official surveillance activities, ACTIVITY APPROVAL GRANTED.
Note: Approval not required for low level official surveillance activities. These activities can commence without approval provided time frames have been satisfied.

Further information provided

ACTIVITY NOTIFICATION DECLINED

DEWNR: Department of Environment, Water and Natural Resources
DMITRE: Department for Manufacturing, Innovation, Trade, Resources and Energy
DPTI: Department of Planning, Transport and Infrastructure
EIR: Environmental Impact Report
EIS: Environmental Impact Statement
EPA: Environment Protection Authority
HAZOP: Hazard and Operability Study
MNES: Matter of National Environmental Significance
PGE Act: Petroleum and Geothermal Energy Act
SA: South Australia
SEO: Statement of Environmental Objectives

Blue box = initiated by proponent/Licensee

Green box = initiated by DMITRE/SA Government

Version 5: June 2013

Government of South Australia
Department for Manufacturing, Innovation, Trade, Resources and Energy

DMITRE 204365-044

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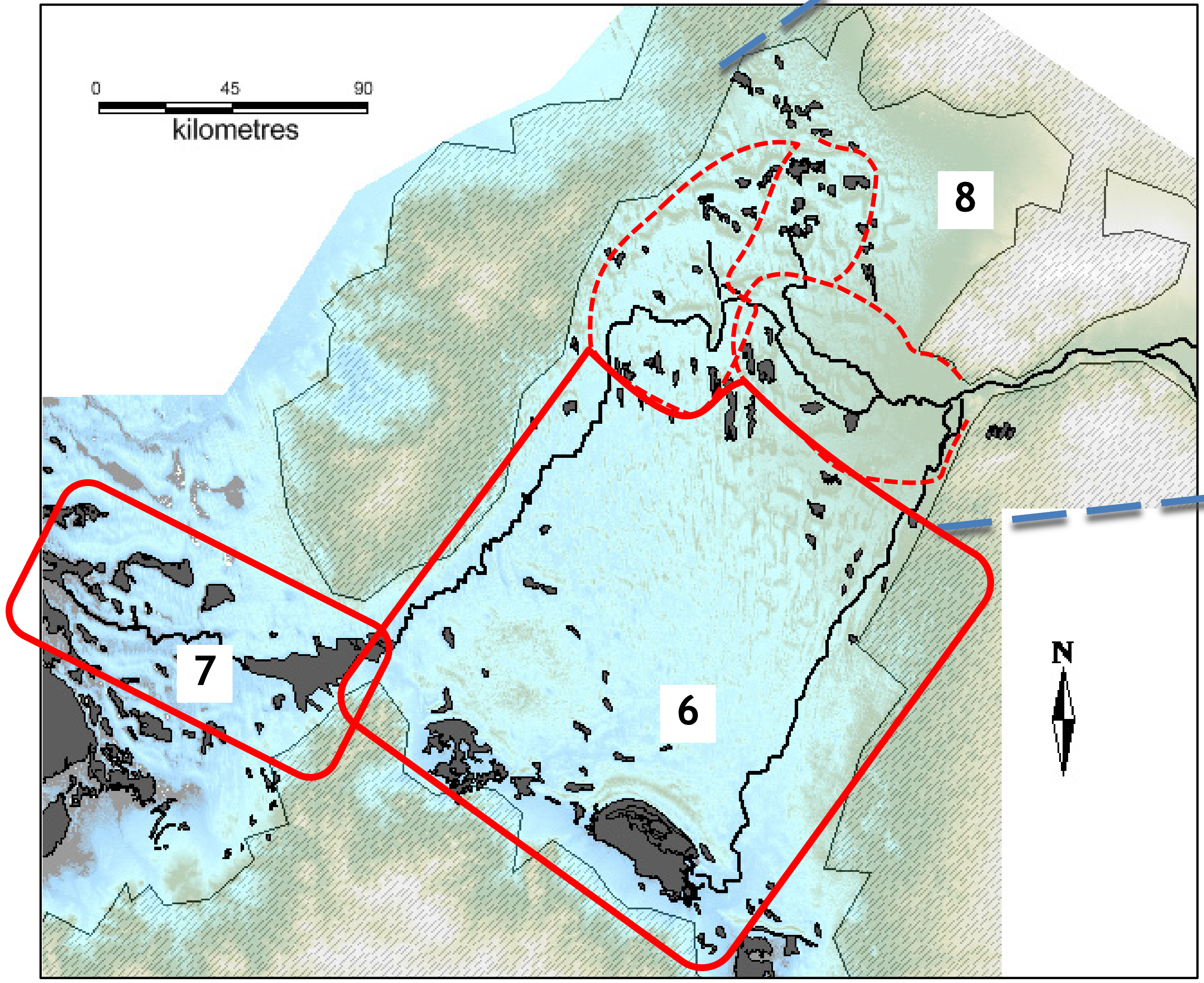
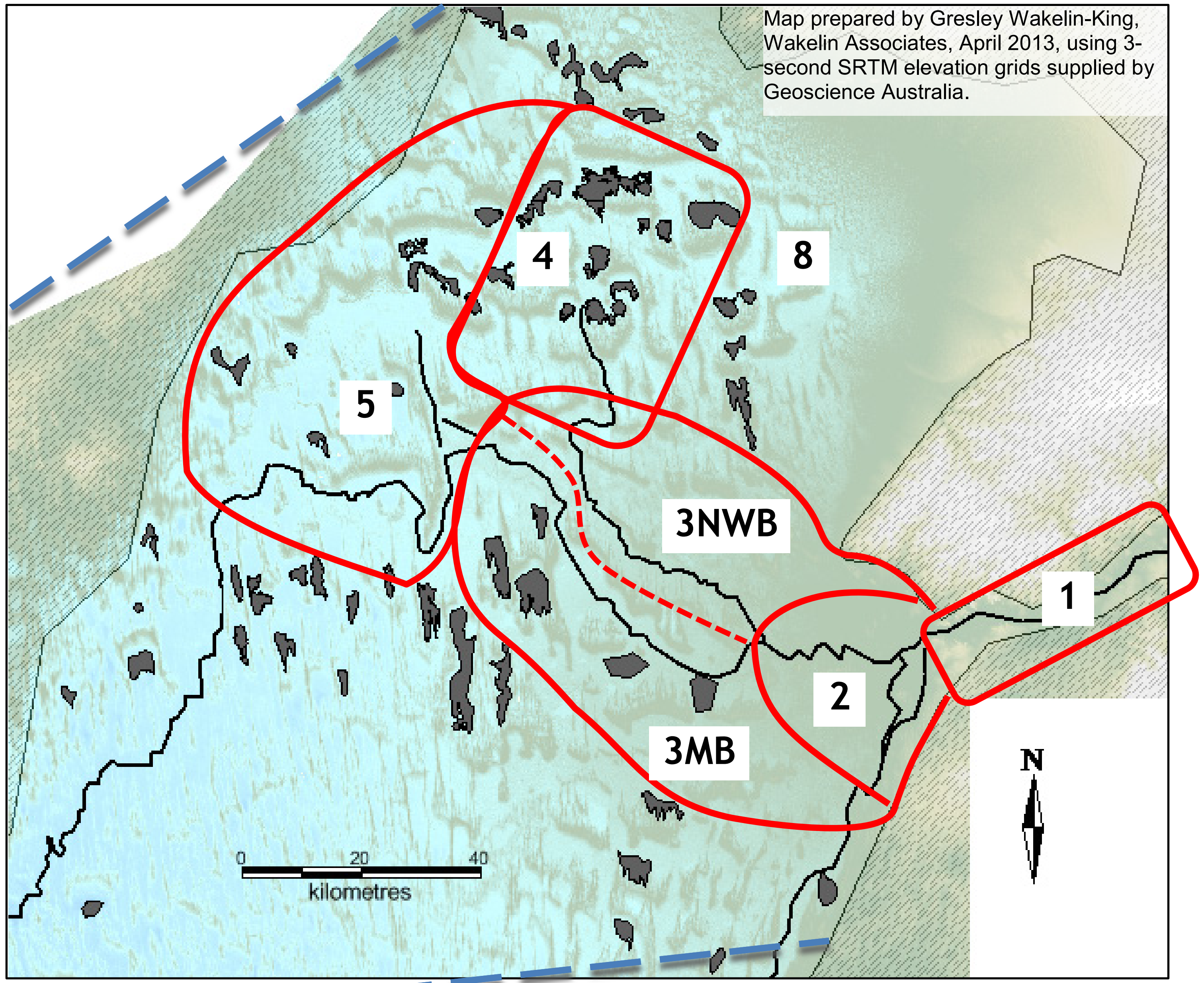
Geomorphic Management Zones of Cooper Creek in South Australia




Map prepared by Gresley Wakelin-King, Wakelin Associates, April 2013, using 3-second SRTM elevation grids supplied by Geoscience Australia.

1. Innamincka valley
2. inner Cooper Creek Fan (including Fan Apex)
3. outer Cooper Creek Fan (3MB = Main Branch, 3NWB = North West Branch)
4. Coongie Lakes area
5. northern overflow, where the North West Branch rejoins the Main Branch
6. southern Strzelecki Plain
7. Kopperamanna Floodout and the Tirari Desert reaches
8. northern Strzelecki Plain

Cooper Creek locations

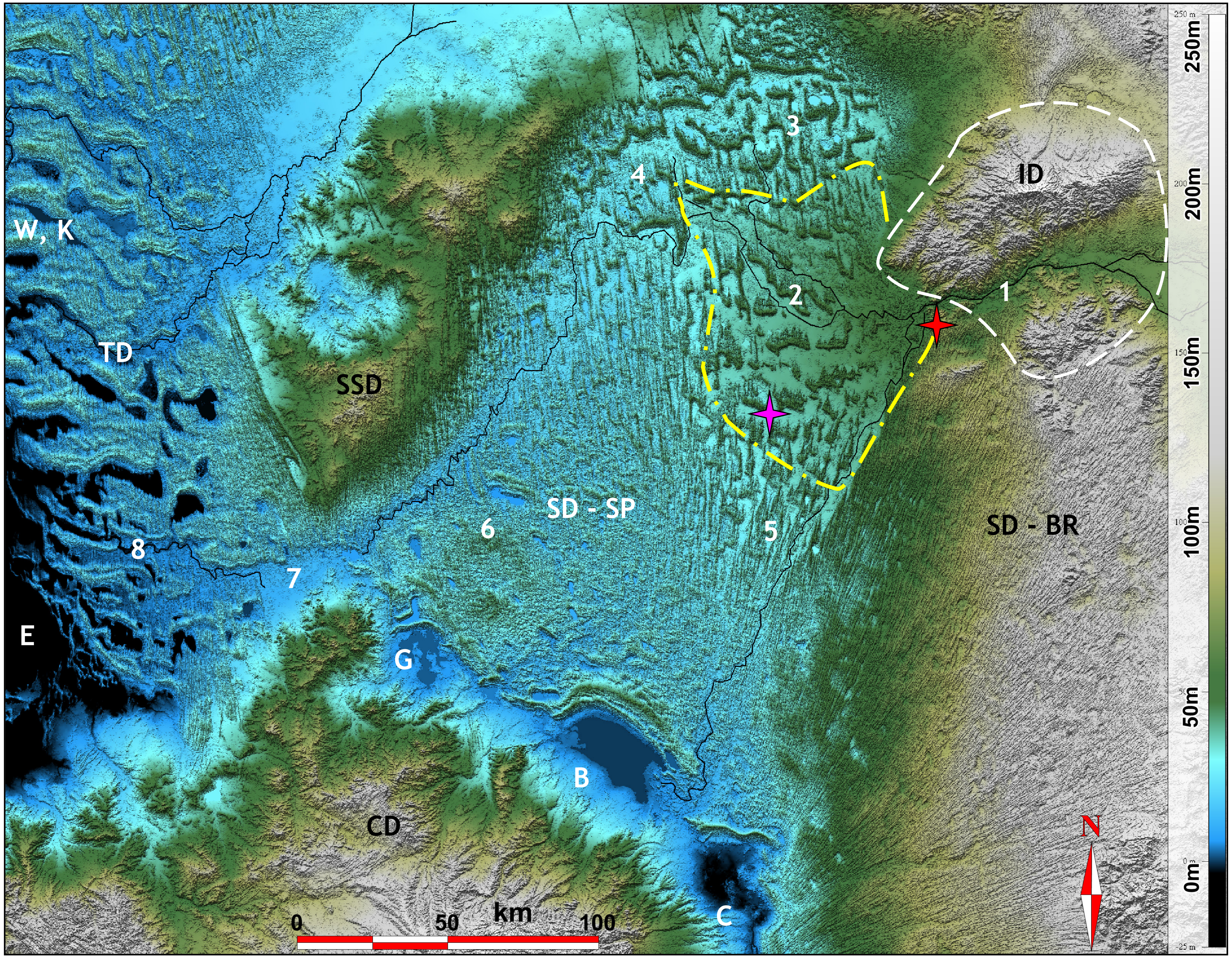
1 the Innamincka Dome (white line), cut by Cooper Creek’s valley
2 the Cooper Creek Fan (yellow dash-dot line)
3 Coongie area: lakes and swamps
4 Cooper Creek northern overflows
5 Strzelecki Creek
6 southwestern Strzelecki Plain: lakes and small channels
7 Kopperamanna Floodout
8 the lower Cooper
✦ ✦ Innamincka, Moomba townships

Sandy or Stony Uplands

- SSD: Sturt’s Stony Desert
- ID: Innamincka Dome
- SD-BR: in the Strzelecki Desert, the Benangerie Ridge
- CD: Cooryanna Dome

Lowlands

- E: Lake Eyre
- G: Lake Gregory
- B: Lake Blanch
- C: Lake Callabonna
- SD-SP: in the Strzelecki Desert, the Strzelecki Plain
- TD: the Tirari Desert
- W,K: the Warburton and Kallakoopah Creeks

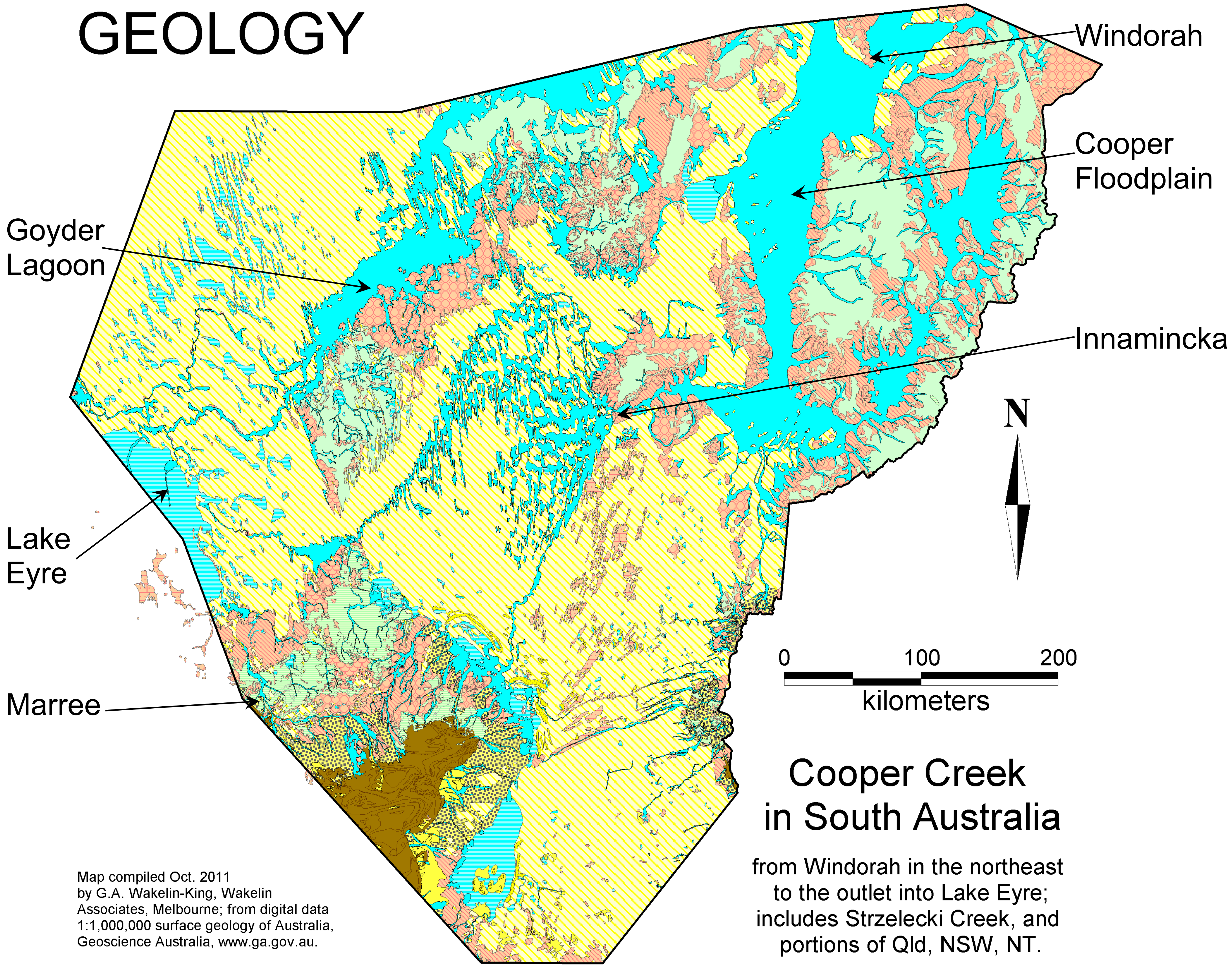


Elevation Scale: black <-3.5 m, blues to 45m, dark green to 85m, khaki to120m, grey to 250m, white >250m

Digital Elevation Model and Locations within the Tirari and Strzelecki Deserts

Map prepared by Gresley Wakelin-King, Wakelin Associates, July 2012, using 1-second SRTM elevation grids supplied by Geoscience Australia.

GEOLOGY



Cooper Creek in South Australia

from Windorah in the northeast
to the outlet into Lake Eyre;
includes Strzelecki Creek, and
portions of Qld, NSW, NT.

Map compiled Oct. 2011
by G.A. Wakelin-King, Wakelin
Associates, Melbourne; from digital data
1:1,000,000 surface geology of Australia,
Geoscience Australia, www.ga.gov.au.

- Alluvium 🟦
- SandDunes ▨
- Lunettes 🟨
- Lakes ▤
- Sediments (Quaternary age) 🟨
- Colluvium (Quaternary age) ▩
- Sand Plain (Tertiary age) ▨
- Silcrete (Tertiary age) ▩
- Sediments (Tertiary age) ▩
- Etadunna & Namba Formations (mid-Tertiary age) ▦
- Eyre & Glendower Formations (early Teriary age) ▩
- Winton Formation (GAB, Cretaceous) 🟩
- other GAB rocks (Cretaceous) ▤
- Igneous rocks (Pre-Mesozoic) 🟫
- Sedimentary rocks (Pre-Mesozoic) 🟫