Lake Eyre Basin Rivers Monitoring Project

Geomorphology of the Thomson River, Queensland: overview and comparison with Cooper Creek

DEWNR Technical report 2015/52

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

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

Geomorphology of the Thomson River, Queensland: overview and comparison with Cooper Creek

A Report to the Department of Environment, Water and Natural Resources, South Australia; Lake Eyre Basin River Monitoring Project

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Foreword

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

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

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

Sandy Pitcher
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

Author's Acknowledgements

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Funding for these projects has been provided by the Australian Government through the Department of the Environment Office of Water Science. See www.bioregionalassessments.gov.au for further information.

Frontispiece: Four places representing key locations in the Cooper/Thomson catchment:

Top left, Galina Waterhole (Cooper Creek); top centre, the Jundah scarp; top right, Muttaburra Broadwater (Thomson River); bottom, Lake Dunn outflow creek. Photo credits: Gresley Wakelin-King, 2014.

Table of Contents

Table of Figures

Executive Summary

This fluvial geomorphology of the Thomson River has not previously been described, and this report presents a baseline overview of the Thomson River's landforms and processes. Constrained by resources and time, the project's objectives were achieved by comparing the Thomson River with Cooper Creek (which is downvalley in the same catchment, and has been the subject of detailed research). The study is part of a series of studies within the Lake Eyre Basin Rivers Monitoring project, one of three water knowledge projects undertaken by the South Australian Department of Water, Environment and Natural Resources (DEWNR) to inform the Bioregional Assessment Programme in the Lake Eyre Basin. Funding was provided by the Australian Government through the Department of the Environment.

This project was initiated in response to concerns about the expansion of the coal and coal seam gas industry, and focuses on the area overlying the Galilee Basin. It is an important result of this investigation that the upper Thomson River reaches which overlie the Galilee Basin are the least like those reaches for which published research is available (i.e. Cooper Creek in south-east Queensland). That is, management decisions for the upper Thomson River based on the currently-available literature will be based on a river system that is unlike the upper Thomson River. These upper reaches include the lower order tributaries, in particular Aramac Creek and the uplands above the escarpment. The uplands are part of the Great Dividing Range, and include Lakes Dunn and Galilee. The landforms reflect low-energy fluvial processes, despite relatively high gradients: present-day stability is likely to rely on a low discharge flow regime. These landforms are likely to be close to the threshold of geomorphic change, with vulnerabilities at specific locations (e.g. the Lake Dunn sill) and specific processes (erosion following high-discharge flow triggering valley-floor or knickpoint incision).

In this report, research literature describing the landforms and fluvial processes of Cooper Creek are reviewed, and Cooper Creek's characteristic landforms are briefly described. Characteristic landforms and fluvial processes of the Thomson River are briefly described for the uplands, tributaries, upper Thomson River, and lower Thomson River. The Thomson River's characteristic landforms are floodways anastomosing around floodplain bars, with channels at the lowest elevations within some floodways. In the lower-order reaches, channels are small and discontinuous; channels become larger and have greater degrees of connectivity with increasing reach order (and in response to increasing discharge). The Thomson River's sediment load is dominated by mud aggregates, with some sandy bedload in low- to medium-order channels. The variable flow regime commonly includes inundation across most or all of a valley's floodways; in-channel flow is not the dominant behaviour.

Cooper Creek is a well-researched river, and knowledge of its fluvial processes will be relevant to land and catchment managers of the Thomson River at least as far upriver as Muttaburra. However, the Thomson River is not identical to Cooper Creek, and where industry or infrastructure development is planned, individual reach behaviour should be investigated. The Thomson River differs from Cooper Creek in that its alluvium is not above a local unconfined aquifer, and in its degree of valley confinement. Some reaches of the Thomson River also differ from Cooper Creek with respect to downvalley gradient and sediment load. In comparison to Cooper Creek, the Thomson River has no swamps, and a less complex channel system.

Terminology

Clast: a sedimentary particle (anything from a grain of silt up to a boulder).

Float: a term from field geology, indicating a clast sitting on or in loose sediment, in a non-depositional and non-erosional context. The implication is that the rock may have emerged from the underlying regolith (as can happen under certain circumstances).

Multithread rivers are those in which several channels coexist within a reach. **Anastomosing** and **anabranching** are multithread rivers in which channels are separated by stable, floodplain height vegetated bars. These are different from **braided** systems, in which channels are separated by mobile unvegetated bars. The terminology has developed over the last 30 years (for example, Cooper Creek's channel networks were described as anastomosing in Nanson et al. 1986, and anabranching in Nanson and Knighton 1996). The terms are probably still under discussion, and reviewing the process differences implied in the terminology is outside the scope of this report. Here, anastomosing is used to refer to multithread waterways which form a mesh-like network, and anabranching is used to refer to the main channel network which divides and rejoins.

Acronyms

GAB	Great Artesian Basin
INS	Invasive Native Scrub
LEB	Lake Eyre Basin

1 Introduction

This is the report of a study of the fluvial geomorphology of the Thomson River and Queensland reaches of Cooper Creek. This study was commissioned in 2014 by the South Australian Department of Environment, Water and Natural Resources.

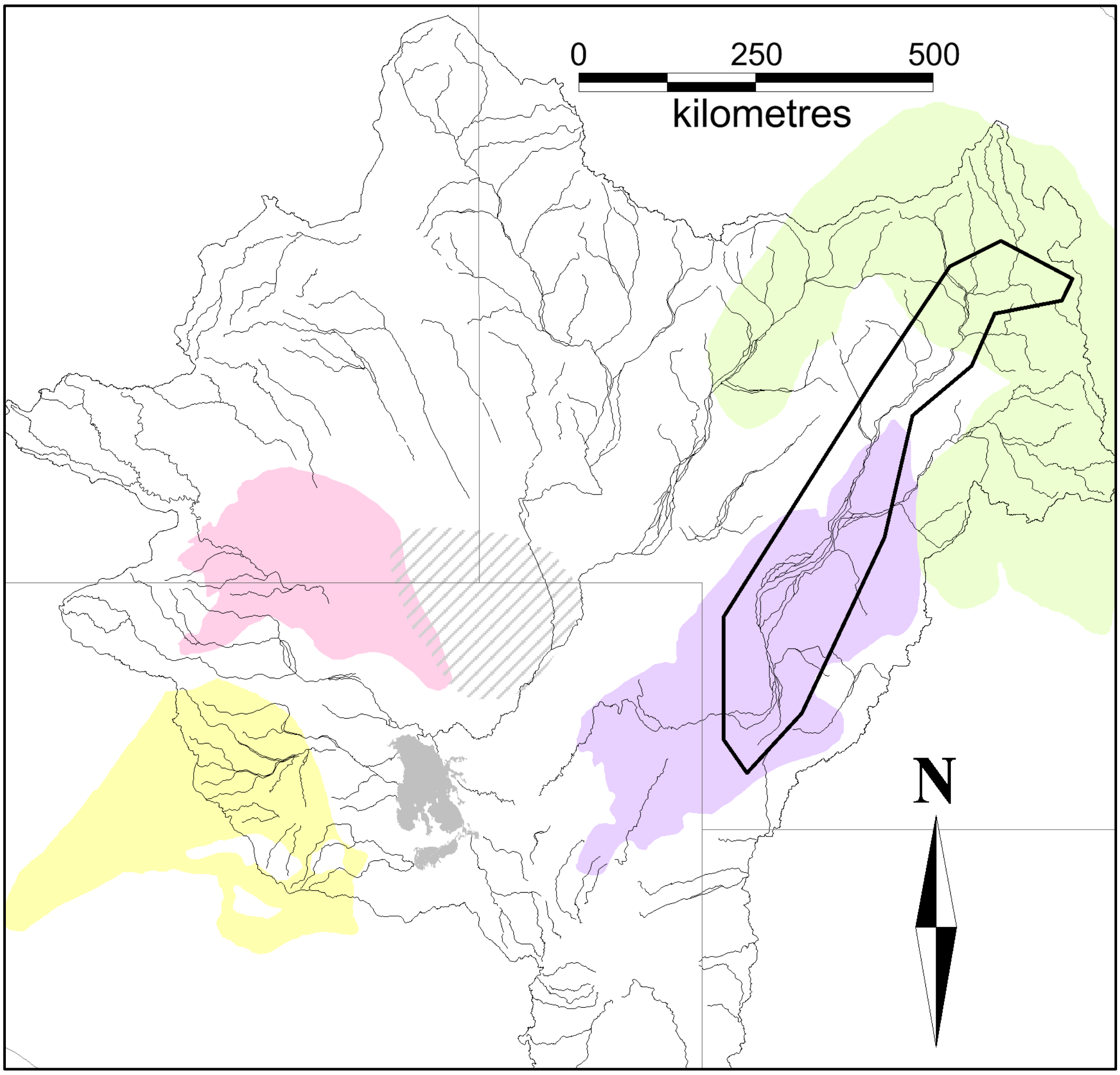

Fig. 1 Rivers of the Lake Eyre Basin, and underlying coal-bearing geological basins.

The Lake Eyre Basin showing state borders, principal drainage lines, Kati Thanda-Lake Eyre (grey), and the Permo-Triassic coal basins: Pedirka, pink; Arckaringa, yellow; Cooper, purple; and Galilee, green. The Simpson Basin (diagonal stripes) is now considered part of the Pedirka (Munson and Ahmad 2013). The study area of this report (black outline, and see Fig. 3) is the Thomson River and the Queensland reaches of Cooper Creek.

Organisational Context

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

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

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

- To provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed coal seam gas or large coal mining developments.
- To provide scientific advice to the Commonwealth Environment Minister on:
    - bioregional assessments being undertaken by the Australian Government, and
    - research priorities and projects commissioned by the Commonwealth Environment Minister.
- To publish and disseminate scientific information about the impacts of coal seam gas and large coal mining activities on water resources.

This report is part of a series of studies forming part of the Lake Eyre Basin Rivers Monitoring project, one of three water knowledge projects undertaken by the South Australian Department of

Water, Environment and Natural Resources (DEWNR) to inform the Bioregional Assessment Programme in the Lake Eyre Basin. The three projects are:

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

The Lake Eyre Basin Rivers Monitoring project’s focus areas are those parts of the Lake Eyre Basin which are underlain by sedimentary basins containing coal: the Pedirka, Arckaringa, Cooper, and Galilee geological Basins (Fig. 1). The South Australian Government sub-contracted relevant agencies from other states to contribute to this project, where project activities extended into Queensland or the Northern Territory. This study's focus is the reaches of the Thomson River which overlie the Galilee Basin. Information presented here is also relevant to parts of Cooper Creek which overlie the Cooper Basin.

1.1 About This Study

Aims and Scope

The aim of this study is to provide an overview of the geomorphology of the Thomson River, especially the focus area: those reaches which overlie the Galilee Basin, or which may be affected by coal mining or coal seam gas extraction. The intention is to provide baseline information on fluvial function as far as possible within the scope of the project. The Thomson River is described in terms of its similarity or differences with respect to reference reaches: well-researched parts of Cooper Creek, which is downvalley in the same catchment.

This study aims to establish landform-process relationships. Information is presented spatially (see ***Methods***, below) and pictorially (Google Earth images of reaches and photographs of landforms) in a way that permits readers to extrapolate from the specific areas described in this report, out to reaches in their area of interest. In other words, if a river reach is similar in valley context, sedimentology, and reach-scale landforms to one of the reaches presented here, then it is likely to be operating in similar ways.

The linear distance encompassing the field sites was 1150 km, and the total distance travelled during field work was 5613 km. To achieve the objectives and overall project deadline, this investigation was constrained to a total project length of 8.4 weeks, including less than 3 weeks of field time. Detailed examination of all the Thomson River was not possible. The author has applied prior experience of regional-scale process-based field studies in various Australian drylands rivers, and information from the better-researched Cooper Creek, to provide useable observations of the landform processes likely to be operating.

Exclusions

This study provides an overview of Thomson River's fluvial geomorphology. Since the project's scale does not permit a complete baseline documentation for the river, the target area (the Thomson River) is described in terms of its similarity to or difference from well-researched reference reaches in Cooper Creek.

Given its scope, this report does not present a definitive study or include a full literature review. The report presents comments and conclusions drawn from the author's field experience, presented in the spirit of providing maximum information, while recognising that in some places such conclusions will require further study or confirmation.

Geomorphology is the basis of habitat, insofar as ecosystems are hosted in/on landforms, but this investigation does not aim to investigate or describe physical habitats from an ecological perspective. This study focuses on the fluvial processes that create and support the landforms. In the literature review (section 3), the following areas of research lie outside the scope of the present report: links between hydrology or landforms and ecosystems or habitat (e.g. Sheldon et al. 2002, Arthington et al. 2005); the monitoring of river hydrology and aquatic biota which has taken place under the auspices of the Lake Eyre Basin Intergovernmental Agreement (the ARIDFLO and the Lake Eyre Basin Rivers Assessment programs, e.g. Cockayne et al. 2013).

The rivers of the Lake Eyre Basin (LEB) are very different from each other in character; this report reviews the literature of other LEB rivers only where it specifically applies to the subjects of this study. A basin-wide literature review was compiled for the Lake Eyre Basin Rivers Monitoring Project, Stage 1 (Miles and McNeil 2013).

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

How to Use This Report

In this report,

- section 1, the introduction, defines site locations which are referred to in the text;
- section 2 describes catchment-scale features;
- section 3 reviews the literature covering nearly 30 years' research into the reference reaches (Cooper Creek in Queensland);

- section 4 describes the landforms observed during the course of the study;
- section 5 provides an overview of the Thomson River's processes, and compares it to the reference reaches in Cooper Creek;
- section 6 presents concluding remarks on knowledge gaps and management implications;
- sections 7 contains details of references cited in this report.

It is recommended that readers primarily consult the sections which relate to their specific interests. If they wish to gain an overview of management implications or resource extraction implications they should read section 6. If they wish to understand reach-specific landform-process relationships, they will find more detail in sections 3 and 4. In particular, descriptions, pictures and Google Earth images from those sections can be compared with landforms in the reader's area of interest. Readers seeking to apply existing knowledge of Cooper Creek's flow behaviour, physical habitat or landforms to the Thomson River will find some important points of comparison in section 5.

1.1.1 Methods

Existing research has documented a great deal of information about fluvial geomorphology in the Queensland reaches of Cooper Creek. In contrast, little geomorphological research has taken place in the catchment's upper reaches (above the Thomson/Barcoo confluence). The present study uses reference reaches from the existing research (Cooper Creek) as a basis to understand the upper catchment. Reach names and locations are detailed in section 1.2 *Locations*.

The project comprised a brief desktop study (geological maps, satellite images, literature review, digital elevation models) and a field investigation. At each field site, a qualitative assessment of sediment composition and grain size was undertaken, and the spatial relationships between sediments, landforms, vegetation, and lithotypes examined. Analysis interpreted the process implications of remotely acquired and field data in the context of the published research, and identified those places and processes which most departed from the Cooper Creek reaches described in the literature.

The methodology is essentially spatial, because spatial relationships of sediments and landforms to each other results from (and gives clues to) the fluvial processes which formed them. For example, the spatial relationships between Cooper Creek's floodplain braid bars and the underlying sedimentary facies was used to determine that the braid bars were not relics of a previous geological age, but were actually part of the modern river (Nanson et al. 1986). Similarly, distribution of channels and soils across the Cooper Creek floodplain was used to investigate fluvial processes (Fagan and Nanson 2004). A more detailed discussion of spatial methodology in geomorphological studies can be found in Wakelin-King (2014).

Valley and longitudinal profiles were drawn from the Geoscience Australia 9-second digital elevation model and 5 million scale topographic drainage data. Microsoft Excel was used to quantify slope values from a linear regression, and calculate R-squared variation. River sub-sections for measurement of longitudinal profile were assessed visually, examining the whole-river profile for breaks of slope, then numerically, by determining lengths of river whose slope values had low degrees of variance.

Mud aggregate sediments are a characteristic feature of the Cooper/Thomson system: they are robust under transport, and their pellet grain size ranges from coarse silt to coarse sand (Maroulis and Nanson 1996). Viewed in the field during documentation of sediment type, the mud aggregate sediments appear to contain much more sand than they really do. Gently pouring water onto a clod of dry Cooper Creek mud causes it to rapidly break down into its component aggregates, but the aggregates themselves remain intact: only very little clay is released into suspension (Gibling et al. 1998). Vigorous treatment is required to dismantle mud aggregates into their primary grains (see Wakelin-King and Webb 2007a). For the purposes of estimating sediment composition during this project's field work, any dark-coloured or dusty sandy sediment was wetted to see if it would slake to aggregates (Fig. 2), and then the slurry mashed with a fingertip to destroy the aggregates and reveal the relative abundances of mud and sand.

Fig. 2 Wetted vertic soils slake to aggregates.

Two clods of mud aggregate sediment on a white rock. The left one has been wetted with fresh water, and has collapsed into its constituent sand-sized aggregates. A few sand- and grit-sized lithic clasts are also present. Hammer tip for scale.

1.2 Locations

The Cooper Creek catchment's headwaters are in the north-eastern edge of the Lake Eyre Basin (LEB), and it covers a large area of south-western Queensland. Its major rivers are the

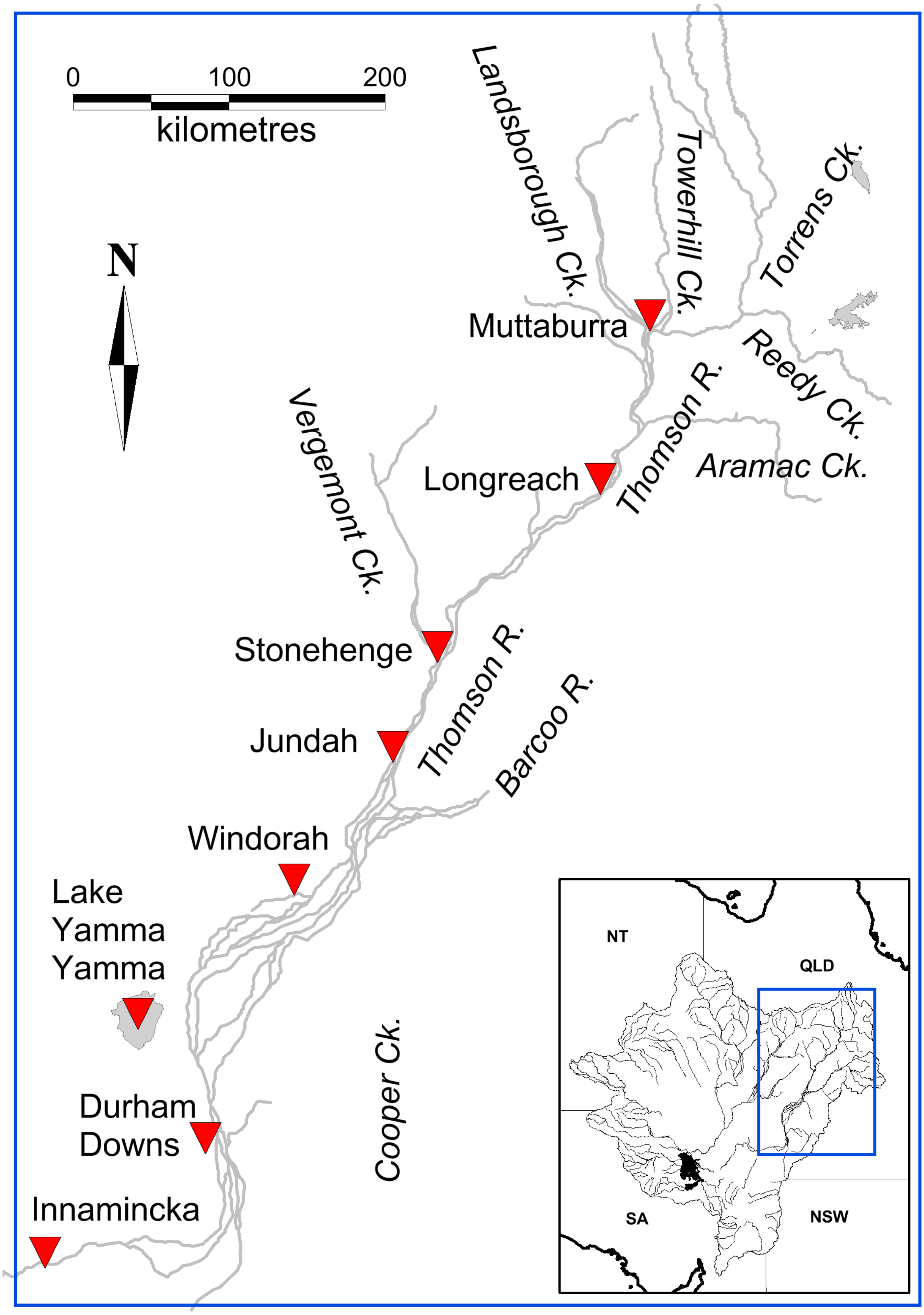

Fig. 3 Place-names in the Cooper/Thomson catchment.

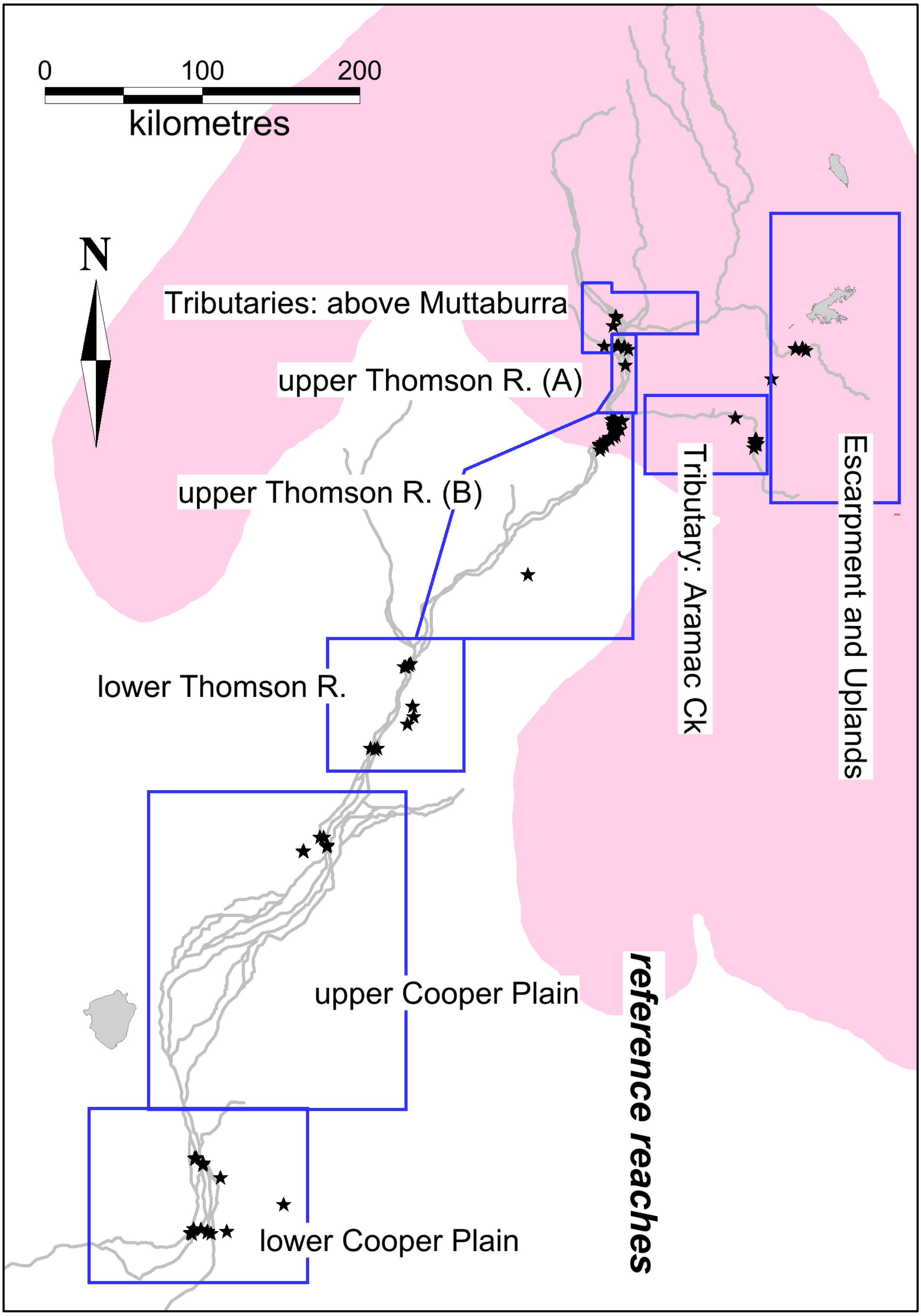

Fig. 4 Reach groups as defined in the present report.

Pink colour is the subcrop of the Galilee Basin, black stars are field sites.

Thomson River (the main subject of this report), the Barcoo River, and Cooper Creek which extends from the Thomson/Barcoo confluence (Fig. 3) to Kati Thanda-Lake Eyre. Where the Thomson River and Cooper Creek are considered together in the present report, they are referred to as the Cooper/Thomson. In South Australia Cooper Creek flows past the township of Innamincka; the fluvial geomorphology of the Cooper Creek in South Australia has been described in Wakelin-King (2013).

In this report, field sites and river processes are discussed in groups according to their reach groups (Fig. 4):

1. escarpment and uplands, including Lake Dunn,
2. tributaries above the Thomson River main trunk (above the confluence just upvalley of Muttaburra where the Landsborough, Torrens, and Towerhill Creeks meet),
3. Aramac Creek, a tributary above the Thomson River main trunk,
4. the upper Thomson River main trunk (from upvalley from Muttaburra, downvalley past Longreach, to just upvalley from Stonehenge)
    - the reaches above the confluence with Aramac Creek (Upper Thomson A) are steeper than the reaches below the confluence (Upper Thomson B), see section 2.2,
5. the lower Thomson River main trunk (from Stonehenge, downvalley past Jundah and to just above the Thomson/Barcoo confluence),
6. the upper Cooper Plain (a reference area), from the Thomson/Barcoo confluence, past Windorah and extending southwards to Durham Downs,
7. the lower Cooper Plain (a reference area), from Durham Downs to the South Australian border just east of Innamincka.

These reach groups have been defined on the basis of information collected during the present study (downvalley gradient, channel planform, floodplain configuration). These are preliminary results: a more detailed study of the Thomson River may define the reach groups differently.

The Cooper Plain (that is, Queensland reaches of Cooper Creek) are reference reaches because they are well-researched. The target area of the present report are the reaches underlain by the Galilee Basin the escarpment and uplands, the tributaries, and the upper Thomson River north of Longreach. Although outside the target area, the lower Thomson River and the Cooper Plain are underlain at depth by rocks of the Cooper Basin, and are thus subject to hydrocarbon exploration interest. As such, some aspects of the present report may be relevant to these areas also.

2 Cooper/Thomson Catchment

This section describes the catchment-scale characteristics of the Thomson River and Cooper Creek.

2.1 Geology and Physiography

In non-geological circles (e.g. land or catchment management), the word 'basin' can be used to mean a topographic basin, such as the Lake Eyre Basin (LEB). In geology, 'basin' is used to mean an accumulation of sedimentary rock, for example the Great Artesian Basin (GAB) or the Galilee Basin. In this study, it is useful to envisage the basins as if they were a stack of irregularly-shaped plates, of which the top is the topographic, or river basin.

The river valleys are influenced by the geology exposed along the valley margins: hillslopes are the ultimate source of alluvial sediment, while their physical character determines the nature of rain runoff into the river system. In the study area, the surface geology falls into the following groups of units (Fig. 5):

- modern sediments, including alluvium of the Lake Eyre Basin rivers;
- In Fig. 5, the layer 'regolith' includes both Cainozoic-age sediments and sedimentary rocks, plus regolith (duricrusts e.g. silcrete and ferricrete, and heavily weathered rocks which may show reddish, mustard yellow, brown, or bleached white colours);
- Great Artesian Basin rocks.

Beneath the study area but not cropping out at surface, the rocks of the Cooper and Galilee Basins underlie the Great Artesian Basin.

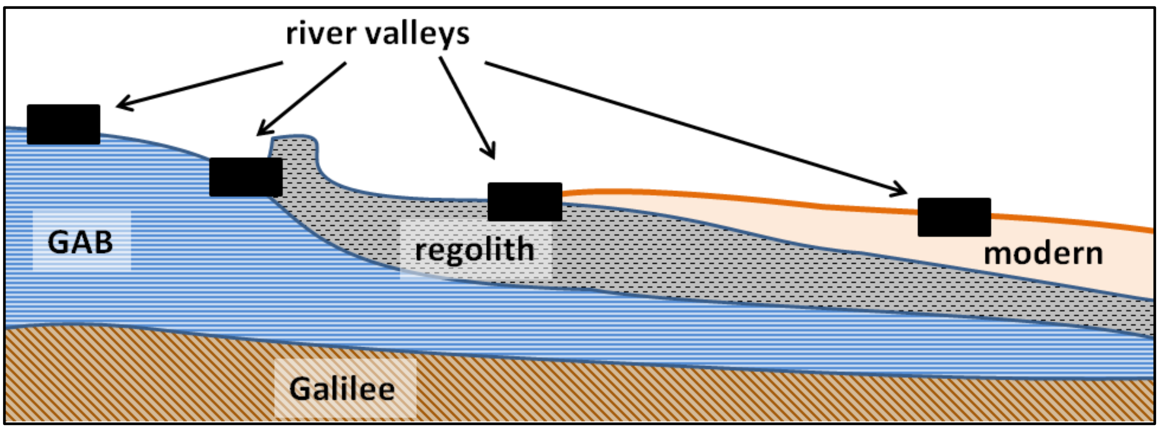

Fig. 5 Schematic geological cross-section of the study area. See text.

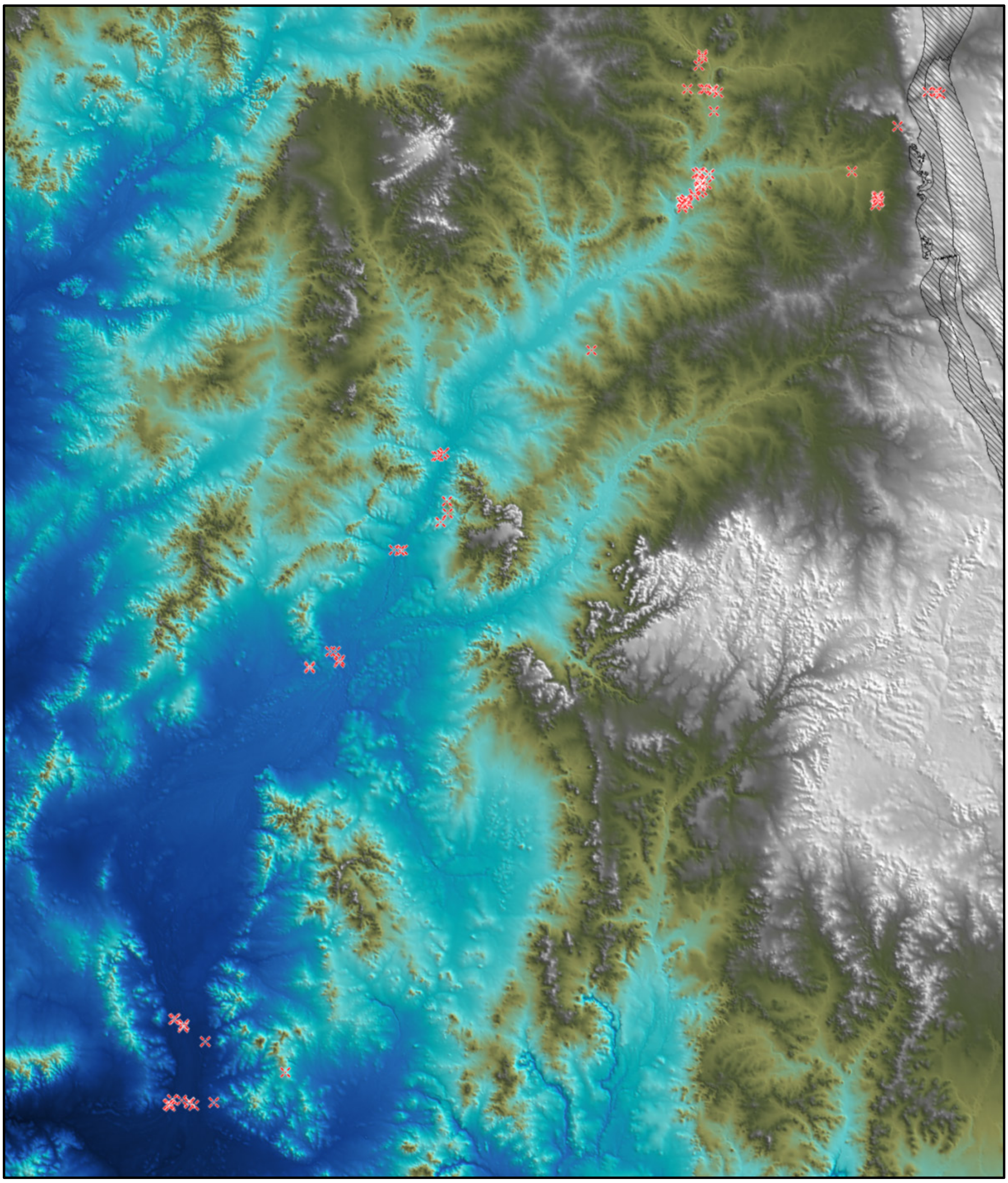

Fig. 6. Digital elevation model (DEM) of Cooper Creek and Thompson River catchments

Colours grade from black (at 30 m AHD) through blues and greens (approximately 60-250 m AHD), to grey and white at approximately 300 m AHD. Based on the AUSLIG 9-second elevation data. Field sites are red crosses, Great Artesian Basin intake beds shown with diagonal stripes in the map's north-eastern corner. Scale and map extent are approximately the same as in Figs. 9 and 10.

The Cooper/Thomson catchment is of very low relief, and slopes roughly south-west (Fig. 6). The underlying rock layers of the Great Artesian Basin dip shallowly towards a similar direction. Because of this correspondence of orientation, the ground surface intersects only a few of the rock layers. Consequently, wide expanses of the Cooper Creek catchment have very similar lithologies cropping out at surface (Fig. 7). Most of the study area is underlain by labile lithic sandstones and siltstones of the Winton and Mackunda Formations (Fig. 8). In places, these formations are overprinted by regolith (widespread weathering profiles and duricrusts), or overlain by rocks of Cainozoic age (such as the widely-extending Glendower Formation) or modern sediments (e.g. sandplains). The Cooper/Thomson catchment is thus characterised by landscape uniformity across hundreds of kilometres (Fig. 9).

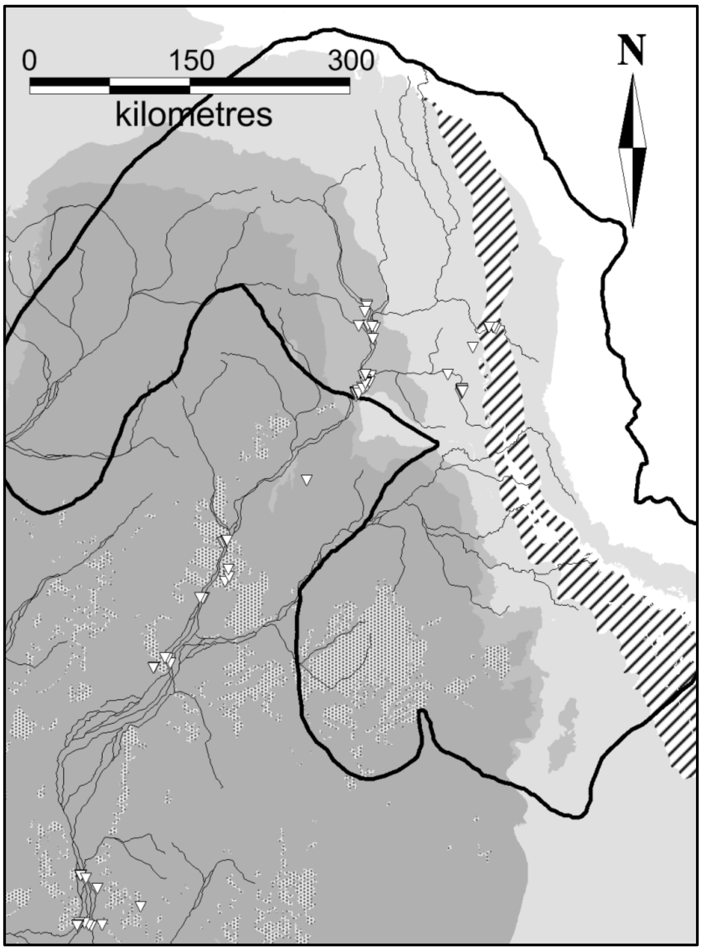

Fig. 7 Solid geology map of the Cooper/Thomson catchment.

The thick black line indicates the extent of Galilee Basin subcrop. Thin lines, drainage (1:5 million scale); white triangles, field sites. The geological units are indicated by their colour:

- grey, more or less water-confining GAB formations (dark grey, Winton Formation; medium grey, Mackunda Formation; pale grey, other formations), comprising labile lithic sandstone, siltstone, mudstone, limestone;
- diagonal stripes, aquifer units of the GAB eastern recharge area (Ronlow Beds, Hooray Sandstone, Hutton Sandstone, and others) comprising quartzose to sub-labile sandstone, with some siltstone and other lithologies;
- stipple, Cainozoic-age Glendower Formation (quartz sandstone and conglomerate, often overprinted by silcrete)

Sand and alluvium are not shown.

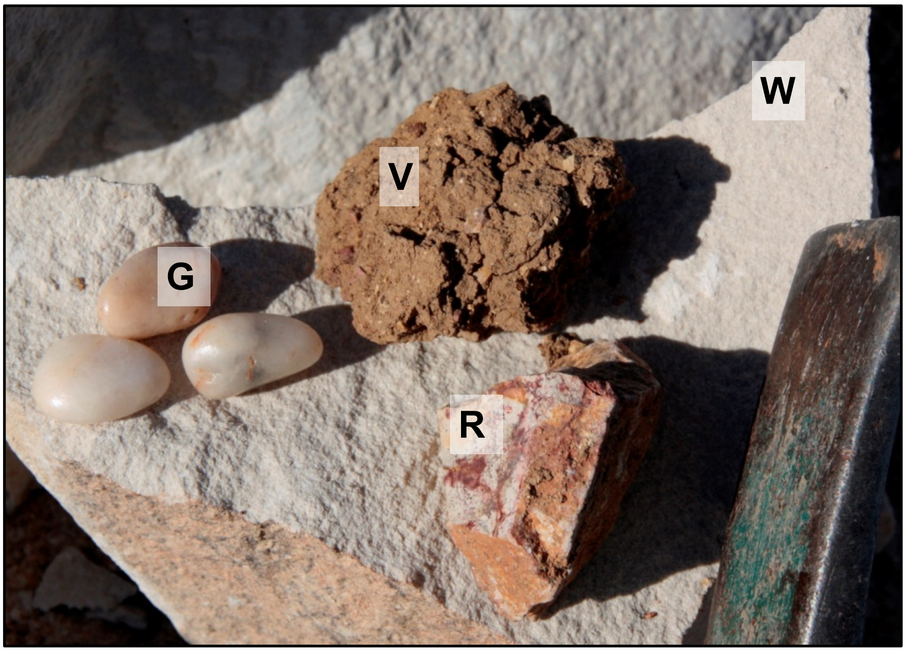

Fig. 8 Some rocks of the study area.

W, white sandstone of the Winton Formation; G, the well-rounded and very polished pebbles characteristic of Glendower Formation conglomerates; R, regolith (a mottled weathering profile); V, a clod of the floodplain's vertic soil. Hammer top for scale.

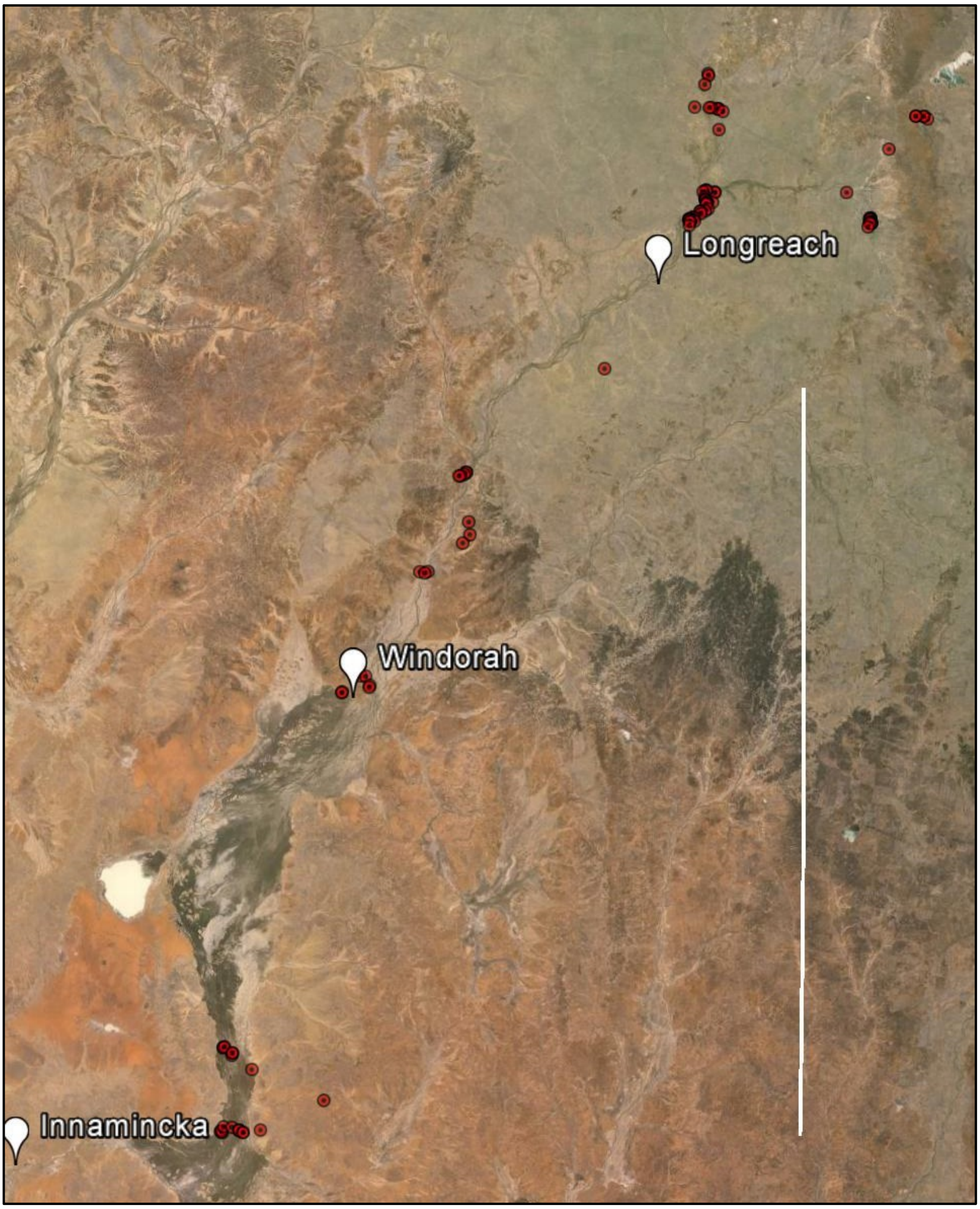

Fig. 9. Google Earth image in real colour of Cooper Creek and Thompson River.

The ground surface colour closely corresponds to the physiographic units shown in Fig. 10. Field sites, red dots; north to top, white scale bar = 400 km. Scale and map extent are approximately the same as in Figs. 6 and 10.

Physiographic mapping (Pain et al. 2011) expresses this uniformity very well. The Cooper/Thomson catchment in Queensland is dominated by three physiographic units (the Winton-Blackall Downs, the Eromanga Lowlands, and the Cooper Plain; Fig. 10). Remote imagery (Fig. 9) indicates strong contrasts in physical character between the units (see *Valley-Margins* below). However, this uniformity of geology and landscape does not extend to the most upstream parts of

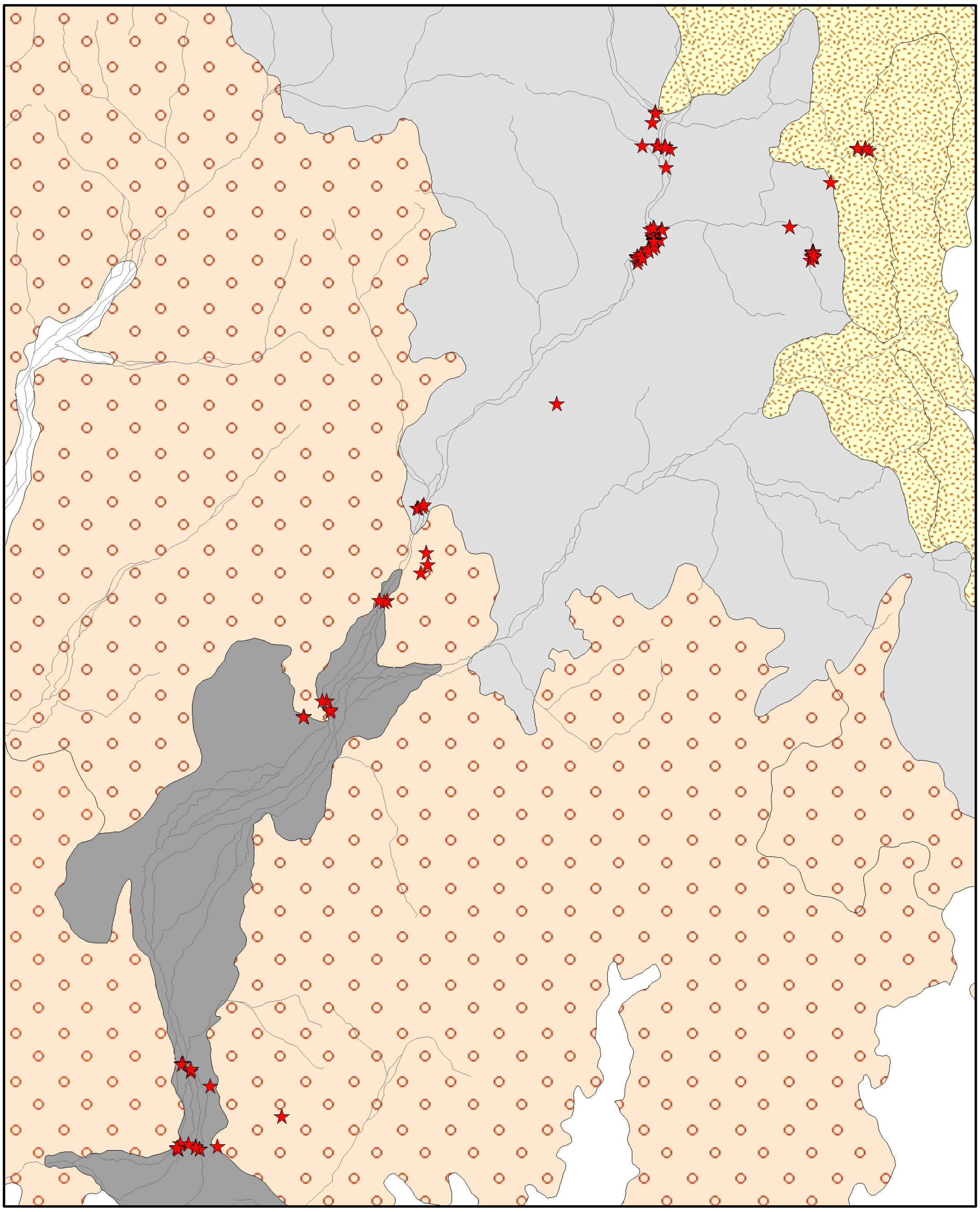

Fig. 10. Physiographic units of the Cooper Creek and Thompson River catchments.

Yellow stipple: Jericho Plain, Alice Tablelands, and Maranoa Lowlands; medium grey: Winton-Blackall Downs; pale orange with brown dots: the Eromanga Lowlands and the Charleville Tableland; dark grey: the Cooper Plain. Field sites, red dots; scale and map extent are approximately the same as in Figs. 6 and 9. Derived from the Physiographic Regions of Australia dataset (Pain et al. 2011). Scale and map extent are approximately the same as in Figs. 6 and 9.

the Cooper/Thomson catchment. A prominent scarp (Fig. 11, and arrow on Fig. 12) east of the Aramac and Muttaburra reaches leads to an area of higher elevation (the Lake Dunn and upland reaches). Along the north-eastern edge of the Lake Eyre Basin, this zone of higher elevation corresponds to the outcrop of the LEB sandstone aquifer formations (Fig. 7). In the study area, outcrop of the aquifers corresponds reasonably closely to the areas upslope of the scarp (Fig. 6). A further aspect of geology is relevant to Cooper Creek's fluvial processes. The geological forces which produce anticlines and synclines in the rocks of the Great Artesian Basin are also responsible for the stony hills (e.g. the Innamincka Dome) and the valleys which they confine (reviewed in Wakelin-King 2013 section 5.3). Ongoing uplift (Nanson et al. 2008) has confined Cooper Creek into the narrow Innamincka valley, and the correspondence of the Cooper Plain valley to the Cooper Syncline and Wilson Depression (Senior, 1968) indicates that the synclines are continuing to develop. This means that the Cooper Creek valley is an accommodation space: a void into which sediments can be transported and where they are deposited. Beneath the ground surface there are Cainozoic-age sediments and sedimentary rocks to depths of hundreds of metres (Senior, 1968). Of these, the most important is the late Pleistocene quartzose sands (Katipiri Formation) deposited by a previous iteration of Cooper Creek (Gibling et al. 1998, Maroulis et al. 2007). They host groundwater which is recharged through waterhole beds during floods (Cendón et al. 2010).

Fig. 11 Looking northeast towards the scarp.

2.2 Valley Width and Downvalley Gradient

The Cooper/Thomson river system has notable variations in valley width, which correspond to physiographic units (Fig. 10). Valley widths in the Winton-Blackall Downs physiographic unit are generally narrow (approximately 1 km in the lower order tributaries, and approximately 3-5 km in the upper Thomson River; Table 1). The lower Thomson River's valley (the Jundah-Stonehenge reaches) is constrained by strongly outcropping silcretes of the Eromanga Lowlands, and is also relatively narrow (approximately 5 km). Below this, the river valley widens out to the super-wide valley of the Cooper Plain physiographic unit; this is a distinctive feature of the south-western

Table 1 Valley widths and longitudinal profile gradients on sections of the Cooper/Thomson River system; Fig. 3 shows locations of reach groups.

Reach groups (Fig. 4)		Gradient %	R^2 value	Valley Width (km)	
				range	**typical**
Uplands	above Lake Dunn	0.1708	0.9770	0.1-0.5	Not measured
	Lake Dunn	Not measured		0.1-0.7	Not measured
	scarp	Not measured		0.05-0.1	0.05-0.1
Tributaries above Muttaburra confluence		Not measured		1-4	1-4
Tributary: Aramac Creek (from below scarp foot to confluence with Thomson River)		0.0427	0.9602	0.5-3	0.5-3
Upper Thomson River A (from Muttaburra confluence to upvalley from the Aramac Creek confluence)		0.0258	0.9560	2-10	~3-5
Upper Thomson River B (from below the Aramac Creek confluence to Stonehenge)		0.0171	0.9870	2-8	~3-5
Lower Thomson River (Jundah-Stonehenge)				3-10	~5
Upper Cooper Plain		0.0195	0.9823	8-60	~55
Lower Cooper Plain		0.0146	0.9212	10—47	~15

Queensland landscape (Figs. 9, 10). Near the border with South Australia, the river valley becomes very narrow again where it is constrained by rocks of the Innamincka Dome.

The Lake Eyre Basin is a very low-relief topographic basin; this enforces on its longest rivers a very low gradient. Cooper Creek and its tributary the Thomson River have an overall gradient of 0.023%. A visual assessment of the longitudinal profile (Fig. 12) shows that the valley gradient is reasonably consistent for most of the river's length (except for the upper reaches which are steeper). On the coarse scale therefore, most of the Cooper/Thomson river system is *graded* (see Mackin 1948) or in equilibrium, with reach-scale balance between sediment input and output which reflects temporal and spatial continuity of sediment transport. Tooth and Nanson (2000) describe the central reaches of Cooper Creek as an example of an equilibrium drylands river. The relevance of this to the present study is firstly, that the anabranching fluvial style has developed in response to the river's present conditions, it is not a transitional style moving towards some different equilibrium; and secondly, that the variations in valley width are not a strong influence in the river's adjustment of its gradient.

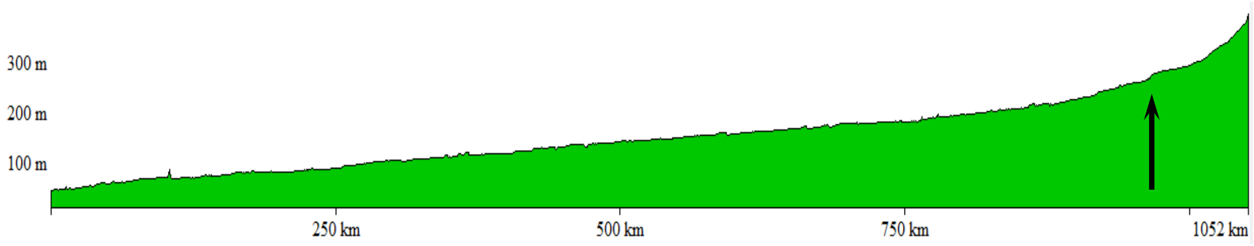

Fig. 12 Longitudinal profile of Cooper Creek and Thomson River.

Arrow indicates scarp; vertical exaggeration times approximately 400.

Primary influences on longitudinal profile will be the amount of elevation created by the underlying geology, and local changes to base level, e.g. if downriver reaches have a knickpoint (which effectively lowers local base level), or a valley constriction which limits throughput of sediment (which effectively raises local base level). Longitudinal profile will also be influenced by the scale and timing of sediment deposition. Sediment may be brought into the river trunk by tributaries, and pulses of sediment may be stranded in the river trunk at the close of flow event. Since fluvial transport is limited by the scale and frequency of flow events, river reaches may be locally not in equilibrium, if the river has not had the opportunity to remove sediment from floodplains which are above the in-grade profile, or deposit sediment into floodplains which are below it.

Examined in more detail, the Cooper/Thomson longitudinal profile shows variations along its length. Sections of river have been grouped according to their gradient (Table 1). The observations and their possible process implications are as follows:

- In the uplands above the escarpment, the creeks above Lake Dunn (not examined during this study's field work) have a gradient that is an order of magnitude higher than that of the Thomson River main axis. Stream power will be high, capable of transporting coarse sediments. The gradients of the creeks in the Lake Dunn area were measured, but the reach is short with a wide range of elevations (relating to the landforms present: see section 4). The calculated slopes therefore had a high degree of variance (low R-squared value), and are not reported here.
- The escarpment is visible as a bump in the longitudinal profile (Fig. 12, arrowed). The scarp foot zone will be a knickpoint for the streams that extend from uplands down to the main drainage network. The gradients of scarp and scarp foot were not measured.
- Aramac Creek is a lower order tributary. It has a high gradient – 1.6 times that of the upper Thomson River's main axis downvalley of Muttaburra, and nearly 3 times that of the lower Cooper Plain. It can be expected to show greater stream power (in proportion to volume of

discharge) than the upper Thomson River, and may be capable of carrying a heavier or larger grained sediment load.

- The gradients of the group of lower order tributaries upvalley from the Muttaburra confluence were not measured in this project). They are likely to be at least as great as the gradients immediately downvalley from Muttaburra.
- The upper Thomson River has a lower gradient than the tributaries and uplands. It can be divided into a relatively small steeper section, from Muttaburra to the Aramac Creek confluence (the upper Thomson River A), and a less steep section (the upper Thomson River B), which comprises most of the upper Thomson River.
- The lower Thomson River has the same gradient as the upper Thomson River B. This is somewhat surprising, as the lower Thomson River valley is confined (Jundah to Stonehenge) and encompasses the transition across three physiographic regions (Fig. 10). This indicates that whatever knickpoint had to move through these erosion-resistant rocks (see *Valley Setting* below), drainage development is now integrated along this long section of river.
- The upper Cooper Plain has a consistent gradient from above the Durham Downs reaches to above the Barcoo River confluence. This suggests that the sediment load delivered by the Barcoo River is accommodated by the existing flows, since neither the valley constrictions at Windorah and Durham Downs nor the valley expansion below Windorah seem to have created local base levels. That is, existing flows are not constrained by the valley margins. The gradient is higher than the reaches above and below, which is consistent with the possibility that sediment bought to Cooper Creek by the Thomson and Barcoo Rivers is mostly deposited from the Thomson/Barcoo confluence down to somewhere around Lake Yamma Yamma.
- The lower Cooper Plain has the lowest gradient. This is likely to reflect sediment accumulation behind the downvalley constriction caused by the Innamincka Dome. An area of very flat floodplain lies immediately upslope of the Innamincka Dome (Wakelin-King 2013).

2.3 Valley Margins

The nature of the hillslopes which flank the river system affects the rapidity of river rise during a flow event, and the percentage of rainfall which reaches the river channels. The vertic soils of the Mitchell Grass downs will absorb rainfall, whereas hard rocky country will shed it; and it is observed that a lot of rain is needed to generate flows in the Mitchell Grass downs, whereas relatively little rain is needed to generate in-channel flow in the rocky uplands (Phelps et al. 2006).

Hillslope type will also determine the nature of sediments carried by the river. Flood waters coming off the red country carry sediment of a larger grain size and reddish colour, whereas floods from the Mitchell Grass downs carry suspended clay and look milky (Phelps et al. 2007).

Eromanga Lowlands ("Red Country")

Most of the Cooper Plain is flanked by gibber-mantled hillslopes of the Eromanga Lowlands physiographic unit (Fig. 10). Surface sediments are pebbles and cobbles of silcrete and iron-rich duricrust, and orange-red to orange brown silty sand or sandy silt (Fig. 13). Gibber hillslopes will have relatively rapid rainfall runoff, especially where there is good hillslope:channel connectivity in small tributary streams (e.g. Fig. 13). Such streams can be expected to show a flashy flow pattern, which may be effective at moving coarse sediment. (This is in contrast to the main Cooper Creek axis, which has a more sustained but low-energy flow pattern.)

In some areas, such as the lowest order channels on sub-catchment drainage divides, remnant land surfaces are visible as sandy soil supporting the thin remnants of banded vegetation. The sandy soil overlies thick and extensive silcrete. On the hillslopes flanking the

Fig. 13 Gibber hillslopes of the Eromanga Lowlands.

Top, silty and pebbly sands (foreground, disturbed by roadworks), and poorly vegetated gibber plain (background). Single-width bitumen road for scale; near Jackson township. Bottom, headwards extension of lower-order creek channels cuts back into flat-topped gibber plain just west of the Durham Downs reaches. Google Earth image; white scale bar (near river channel) = 1 km.

Jundah to Stonehenge reaches, relict land surfaces are particularly well preserved. They display more intact banded vegetation communities growing on red-brown slightly silty sands. Small silcrete pebbles scattered on the surface are "float" from underlying silcretes. The scarps that face into the Jundah-Stonehenge reaches are particularly steep, and show signs of vigorous undercutting and erosion of the regolith (Fig. 14).

Banded vegetation indicates that a hillslope's drainage occurs as unchannelised sheetflow (as opposed to creeks or streams). The slope operates interactively with the vegetation communities such that rain shed from the bare interband is intercepted by the vegetated band (Wakelin-King 1999). Where the banding is intact and functioning well, banded vegetation slopes are good at intercepting rainfall; they are productive ecosystems. They are vulnerable to erosion (especially channel incision along water lanes, see Wakelin-King 1999), or devegetation which reduces the efficiency of the water-trapping vegetation bands.

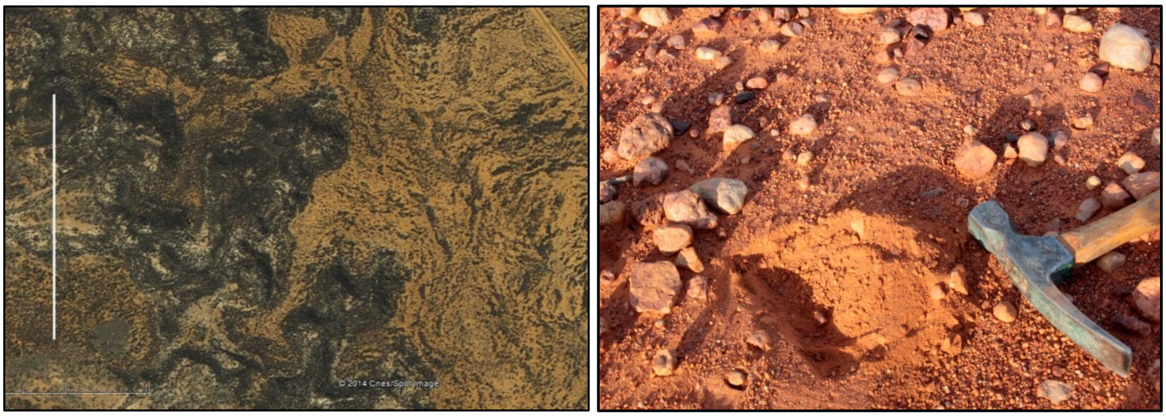

Fig. 14 The Jundah old land surface and scarp.

Top left: The relict land surface is the orange-brown surface with bands of vegetation (right side of Google Earth image). The scarp is the convoluted dark line in image left and centre. White scale bar = 1 km. Top right: Surface sediments are sandy with silcrete pebbles. Left, Looking down into the gully past the boulders at the scarp face. Person (circled) for scale.

Cooper Plain Eastern Edge

In some parts of the Cooper Plain, the channel belt is migrating towards the western valley margin, and non-fluvial sediments are encroaching into the valley from the east (Knighton and Nanson 1994). Just north-east of this study's Durham Downs reaches, tributary streams are delivering clean quartzose and lithic sands into the eastern side of the valley (Fig. 15, and see Fig. 9). At a reach scale, these sands occur as flat sand sheets with low disorganised mounds or dune remnants and local scalds (deflation hollows). Interspersed lower-elevation gilgai swamps suggest the sand is overlaying floodplain sediment.

In most reaches with sandy splays encroaching into the Cooper Plain, the splays have a classic 'river-dominated delta 'distribution of channel landforms. Only in the splay north-east of the Durham Downs reaches do flows down the main Cooper Creek axis locally redistribute the sand and affect channel disposition at the splay front (Fig. 15).

Although these sandy splays are accumulating within the valley of the Cooper Plain, they could be considered as valley-margin because the present-day creek is not constrained by them and rarely interacts with them.

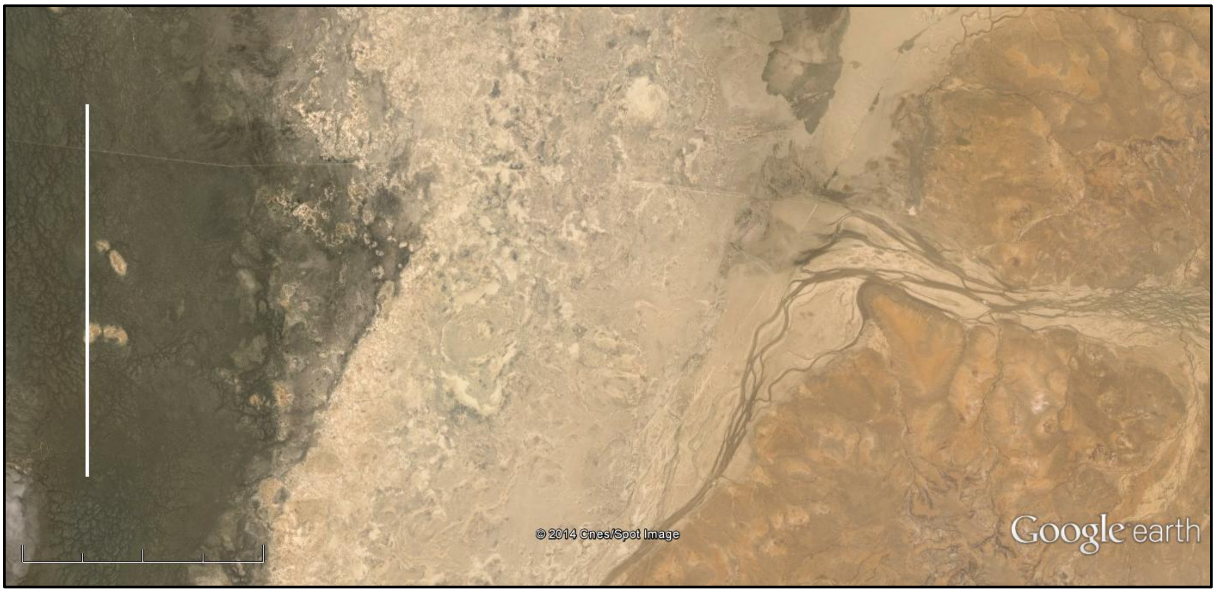

Fig. 15 Pale sands accumulating along the Cooper Plain's eastern side.

In this reach, main-axis flow has diverted the tributary channel southwards. Google Earth image, white scale bar = 10 km.

Winton-Blackall Downs ("Mitchell Grass Country")

North-east of Jundah, the hillslopes flanking the river belong to the physiographic unit Winton-Blackall Downs (which in the study area corresponds closely to the IBRA-7 bioregion Mitchell Grass Downs). They are characterised by extensive flat plains of crumbly vertic soils, known locally as black soil plains. The hillslope vegetation is predominately Mitchell grass (*Astrebla* spp.), and scattered trees on some slopes (Fig. 16). Mitchell grass is a long-lived perennial grass with deep roots (1.3-1.6 m) and a tight crown of stubble after grazing (David Phelps, Qld DAFF, pers. comm. 2014); it would be a useful element in preventing erosion and trapping sediment.

The chemistry and clay mineralogy of vertic soils gives them strong shrink-swell characteristics (see Hubble 1984). When wet, vertisols can absorb a lot of moisture; when dry, soil volume reduces greatly, leading to strongly developed cracking, and macropore development (expressed either as especially deep mud cracks, or as irregular to roughly cylindrical deep holes known locally in drylands Australia as "crabholes") (Fig. 16). The surface texture of the vertic soil may be puffy, or develop a finely crumbed texture ("self-mulching") of sand- and silt-sized mud aggregates. During the shrink-swell cycle, soil particles fall into the cracks; accumulation of fallen soil creates heave and circulation of subsoil during wet periods when the cracks close. This creates gilgai microtopography (surface undulation). Vertic soils' ability to retain moisture makes them biologically productive and economically valuable. Macropores' size and depth of penetration makes them important in groundwater recharge, though because they swell shut with rain the relationship is not simple (e.g. Costelloe et al. 2009).

Rain that falls on vertic soils, or floodwaters that travel across them, cannot run off until the macropores have either filled up or swollen shut, and until the surface aggregates have absorbed as much water as they can hold. Consequently, the Mitchell Grass downs shed very little runoff. Substantial rain is required to generate flows from these hillslopes (Phelps et al. 2006).

The black soils overlie GAB rocks and/or Cainozoic rocks and regolith. From Jundah to approximately Longreach, the underlying Winton Formation is not strongly expressed at the surface. However in reach areas # 5, 6, 7 (north of Longreach, Muttaburra, Aramac) the underlying rocks are more strongly exposed at surface. (This may be because the soil cover is thinner, or it may be because the underlying Mackunda Formation crops out more strongly.) In many places the vertic soil is a thin cover, and hills of sandstone surrounded by sandy colluvial aprons (Fig. 16) are found in valley margin positions. These rocky areas contribute quartz sand (and possibly quartzose silt) into the drainage network. Rocky or sandy colluvial areas will have different runoff characteristics to deep black soil plains, and this affects how much and how rapidly rain water enters the river. It is also possible that a thin soil cover over rock will have a different runoff characteristic than deep black soil country.

2.4 Cooper Creek Surface Hydrology

It is not within the scope of this study to review Cooper Creek's hydrology in detail. In brief, the fact that Cooper Creek's lower order reaches extend so far north allows the catchment to benefit from the influence of monsoonal rainfall (Knighton and Nanson 1994a, Knighton and Nanson 2001). This allows Cooper Creek to routinely experience flows that may last for months, and which may experience single, compound, or multiple flood peaks (Knighton and Nanson 2001). The duration and frequency of the flows allows Cooper Creek to establish equilibrium process-landform relationships (Tooth and Nanson 2000). The relative frequency of the flows allows Cooper Creek to host rich ecosystems. The high volume of some of the floods allows flood peaks to travel into the driest parts of Australia, overcoming transmission losses of 75% or more for some flows between the Windorah and lower Cooper valley reaches (Knighton and Nanson 1994b).

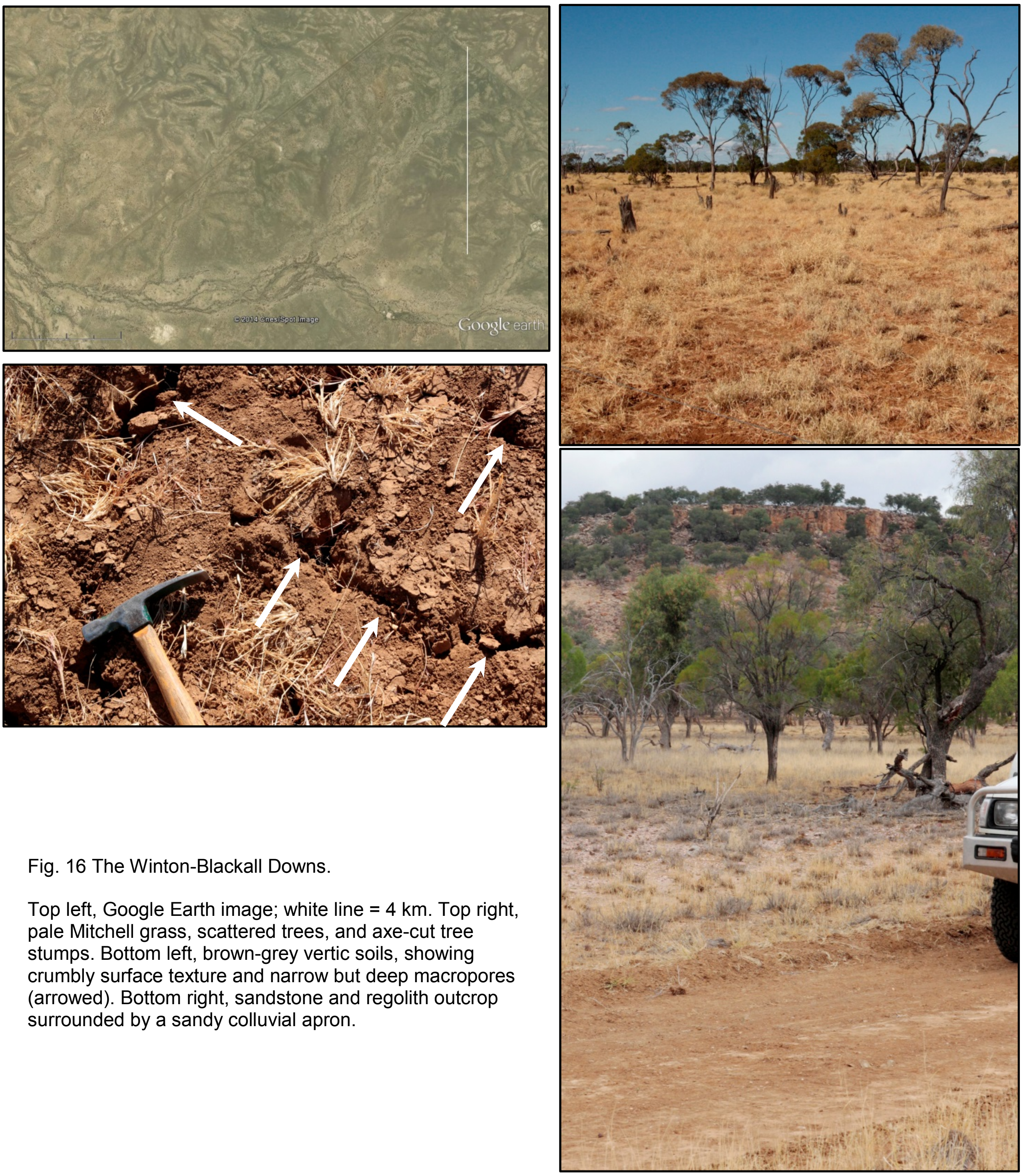

Fig. 16 The Winton-Blackall Downs.

Top left, Google Earth image; white line = 4 km. Top right, pale Mitchell grass, scattered trees, and axe-cut tree stumps. Bottom left, brown-grey vertic soils, showing crumbly surface texture and narrow but deep macropores (arrowed). Bottom right, sandstone and regolith outcrop surrounded by a sandy colluvial apron.

Despite Cooper Creek's access to water in such volumes, the system experiences an extremely high degree of flow variability, even within the context of Australia's generally variable flow regimes (Knighton and Nanson 2001, Finlayson and McMahon 1988). The river experiences long periods of drought, during which main channels experience lowered water levels, or dry out completely except for the main waterholes. Floodplains can be widely inundated during large floods, sometimes for months at a time, but they can also dry completely.

There are two gauging stations, at Longreach and Stonehenge, and data are only available for a few decades. Available discharge data demonstrates the system's variability (Fig. 17). Interestingly, the signature of the mid-1970s wet years is visible whereas the 2010-2012 wet years is not. No other measured data were available to the present study. Local reports describe qualitatively certain aspects of the river's behaviour, such as the affects of tributary asynchronicity on river behaviour (Phelps et al. 2006, 2007).

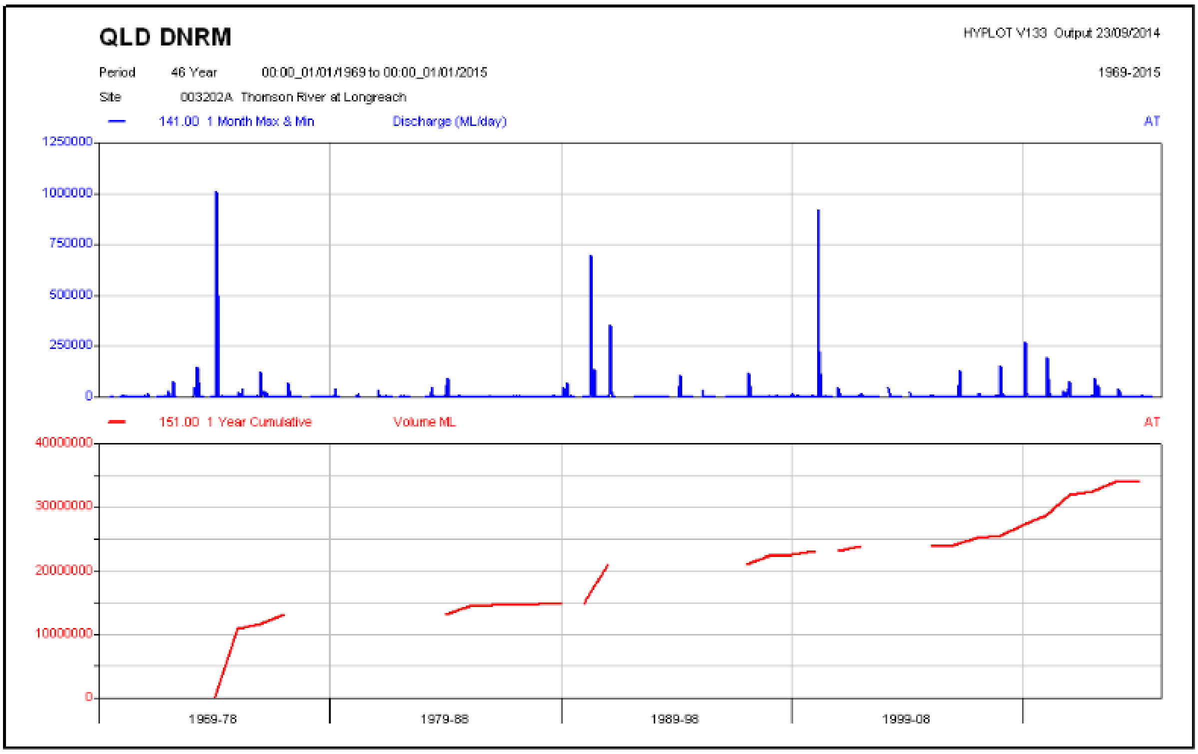

Fig. 17 Longreach discharge data 1969-2014; Queensland Department of Natural Resources and Mining

2.5 Cooper/Thomson Land Use

In broad terms, land use in the Cooper/Thomson catchment can be grouped into living areas, tourism, pastoralism and agriculture, and the resources industry (especially petroleum, coal and coal seam gas).

Towns, roadside stops, and human habitations on e.g. pastoral property require the construction and maintenance of living areas: buildings, roads, fences. Town and property water is commonly drawn from the larger waterholes. Local amenity calls for inhabitants' access to natural beauty.

The tourism industry requires the construction of living areas and access to natural beauty (waterholes, shade, vegetation, views). Tourist land use is less widespread than similar enjoyment of landscape by local inhabitants, but tends to be more intensive at certain spots, particularly along traffic corridors and at notable beauty spots.

Pastoralism (grazing of stock animals) requires living areas, and access to water and vegetation for stock feed. Pastoralism is very widespread. The intensity of the land use depends on management practices e.g. placement and control of watering points, management of grazing pressure, feral animal control, fire management and control of invasive native scrub.

Agriculture (growing crops) is not widespread in the catchment, as the climate is usually too harsh for regular cropping. However, in the 1990s there were proposals for irrigated cotton grown on Cooper Creek floodplain near Windorah, planning to extract irrigation water from surface flows. Similar proposals continue to be raised in that area from time to time. Opportunistic cropping during flood years has been known, for example attempts were made to grow cotton on Lake Yamma Yamma (Angus Emmott pers. comm. 2014), and harvesting hay during good years for drought proofing in future years is spoken of by some landholders.

The lower Cooper Plain is underlain by the Eromanga Basin (part of the GAB) and the Cooper Basin, both of which are prospective for gas and oil. South-western Queensland and north-eastern South Australia have been very important parts of Australia's hydrocarbon industry since the mid-1900s. The upper Thomson River (from Longreach east and north-east to beyond the LEB catchment boundary) is underlain by the Galilee Basin, which is prospective for coal seam gas. Resources industry requires living areas, office areas, industrial areas for the treatment of water and hydrocarbons, pipeline corridors, production wellheads and other infrastructure. Certain kinds of hydrocarbon extraction require clusters of wellheads spaced at approximately 500 m to approximately 5 km, and a coal seam gas proposal might have well densities of approximately 40 wells in an area 25 km^2. Wellhead clusters require a similar density of access roads. Hydrocarbon extraction may involve the co-production of formation water, and in particular coal seam gas production requires dewatering of the coal seam, which can produce large volumes of water. Proposals for treated formation water include beneficial use in the community (irrigation, industrial use), or discharge down natural watercourses.

Potential Risks to Be Managed

These paragraphs briefly consider the effects of human use on fluvial landscapes (note that impacts on e.g. biota, groundwater etc. are outside the scope of this report), especially negative impacts occurring where risks are not properly managed.

Potential challenges arising from human infrastructure include blocking flow paths or changing flow directions by e.g. roads and fences; creating point sources of erosion at road crossings or other flow concentrators; and water extraction from waterholes and channels.

Potential challenges arising from grazing and agriculture include water extraction for stock or irrigation; blocking flow paths or changing flow directions by e.g. roads and fences; creating a linear sources of erosion along stock routes, cattle pads, farm tracks, or graded lines; changing patterns of sedimentation or erosion by grazing to the extent that vegetation communities are depleted or changed.

Tourism is most intense along traffic corridors, which tend to follow settlement-era dispersal patterns along permanent and semipermanent waters. Tourist pressure is therefore usually greatest on the river reaches which are also most important for ecosystems. People usually desire to camp within sight of water, and like to take straight-down pathways down steep slopes to gain access to water. As a consequence, popular camping areas along waterhole banks tend to be challenged by vegetation trampling, firewood collection, and footpaths developing into gullies. Unburnt toilet paper (which does not biodegrade in arid conditions) is also an issue. Potential challenges arising from tourism also include those arising from human infrastructure.

Resource industry development must manage the challenges arising from human infrastructure (see above). Where resource industry bodies control large areas of land, they need to appropriately manage total grazing pressure, feral animals, and weeds (including an appropriate patch burning regime).Specific challenges for the coal and coal seam gas industry are managing subsidence risk (since subsidence in the Cooper/Thompson's low gradient river valley is likely to alter the flow path or flow regime of channels), and the proper disposal of formation water. Although one might imagine that drylands river landforms might be improved by, or at least not harmed by, receiving large volumes of extra water, this is unlikely to be the case. Drylands river landforms and their ecosystems are presently in equilibrium with long periods of no-flow, and change in that flow regime will certainly change both ecosystems and landforms. In the absence of research on this topic, examples of factors that may change with increased discharge are given here. Note that these examples are based on location-specific conditions.

1. *Stream power* The power of a flow to erode and transport sediment is proportional to discharge. Under Australia's present climatic regime, many drylands waterways are

underfit, occupying valleys carved by previous larger rivers (e.g. the Finke River, see Wakelin-King 2015). Rivers are often transport-limited (sediment transport limited by the flow regime of episodic and often low-energy events), and the resulting landforms include discontinuous ephemeral streams (Bull 1997), floodouts (e.g. Tooth 1999, Wakelin-King and Webb 2007a) or rivers with lobes of sediment stranded along the flow path (e.g. Arckaringa Creek, Wakelin-King 2010, Wakelin-King 2015). If stream power increases (e.g. through increased discharge), the system can move from a depositional to an erosional state, triggering valley-floor incision; this can lead to floodplain desiccation and ecosystem diminishment or death (Bull 1997, Fanning 1999, Wakelin-King and Webb 2007a).

2. *Vegetation and Flow Dynamics* Vegetation plays a key role in flow dynamics, governing qualities such as scour and sedimentation on spatial scales ranging from bedform to reach (e.g. Graeme and Dunkerley 1993). Riparian vegetation plays a role in maintaining waterhole depth (e.g. Knighton and Nanson 2000, Wakelin-King 2010), and floodplain vegetation is an important roughness element that promotes sediment deposition and maintains valley-floor integrity (e.g. Bull 1997). Drylands rivers trees (e.g. black box, coolabah, red gum, acacias) have different requirements with respect to period of inundation, groundwater salinity, or duration of waterlogging. Changes to flow regimes may diminish or kill some trees, or increase the range of others; this will alter boundary roughness and sediment erosion or deposition along the flow path.

3 Review of Geomorphological Studies of Cooper Creek

Although there is very little research into the geomorphology of Lake Eyre Basin rivers, Cooper Creek is an exception. Since the mid-1980s (Rust and Nanson 1986, Nanson et al. 1986), Cooper Creek's sedimentology, hydrology, fluvial processes, and geological history have been examined in research dominated by the University of Wollongong's Professor Gerald Nanson and his students and colleagues. The reaches from Windorah (Queensland) to the Strzelecki Plain (South Australia) have been a particular focus. Outside that research group, Phelps et al.'s (2006 and 2007) local observations on river behaviour permits fluvial processes to be interpreted in many locations through the Cooper Creek catchment, Silcock (2009) reviewed waterhole distribution in Channel Country rivers, and Wakelin-King (2013) researched the geomorphology of Cooper Creek in South Australia. In contrast, there has been no research into the geomorphology of the Thomson River.

This section summarises the literature relevant to present-day fluvial processes in the Queensland reaches of Cooper Creek, for two reasons. The scope of the present project was not sufficient to examine the Thomson River thoroughly, therefor ethe approach was taken to compare the unknown (the Thomson River) with the well-known (Cooper Creek within the Cooper Plain physiographic unit). That is, management practices are likely to be based on an assumption that all LEB rivers are like the Cooper Plain. Although the Cooper Plain is clearly highly significant, for example it houses some of the LEB's wettest reaches (greatest concentration of permanent and semipermanent waterholes) (Silcock 2009), it does not follow that what is right for the Cooper Plain will be right for the Thomson River.

Channels

The Cooper Plain is famous throughout the geological and geomorphological communities for its characteristic channel patterns. The dominant channel network is an anabranching system of 1 to 4 primary channels, together with secondary (narrower but continuous) and minor (discontinuous) channels (Knighton and Nanson 1994). Their planform is variable, from gently to highly sinuous (Fig. 18). Independent of the anabranching channels, floodplain-height wide and shallow floodways (see *Floodplains* below) separate braid-like bars. Initially, it was considered that the anabranching channels were the modern fluvial system, whose floodplain muds were draped over a relic braidplain (Rust 1981). Further investigation demonstrated this was not the case; both channel systems coexist, and are active at different flood heights (Nanson et al. 1986, Knighton and Nanson 1994).

The anabranching channels are generally narrow and deep, with moderate to steeply dipping banks which generally lack levees. Individual channels vary in their character in a longitudinal direction, such that a channel may become smaller or larger with distance downstream, as secondary channels leave or join it, or as the bed rises (channel becomes more shallow). Because individual channels are joined in an anabranching network, downstream continuity of the primary flow path is preserved (Knighton and Nanson 2000). Channels generally have well defined bankfull stages (Knighton and Nanson 2000), despite the flow variability that has many flows above or below bankfull level. The anabranch network preferentially forms towards the west of the Cooper Plain, and non-fluvial sediments are encroaching on the floodplain from the east (Knighton and Nanson 1994).

Waterholes, a characteristic feature of Cooper Creek's channel network, are channel segments which are notably wider (Fig. 18) and deeper than the primary channels. They are long-term reservoirs of water after flow has ceased and the channels and floodplains have dried out, so are

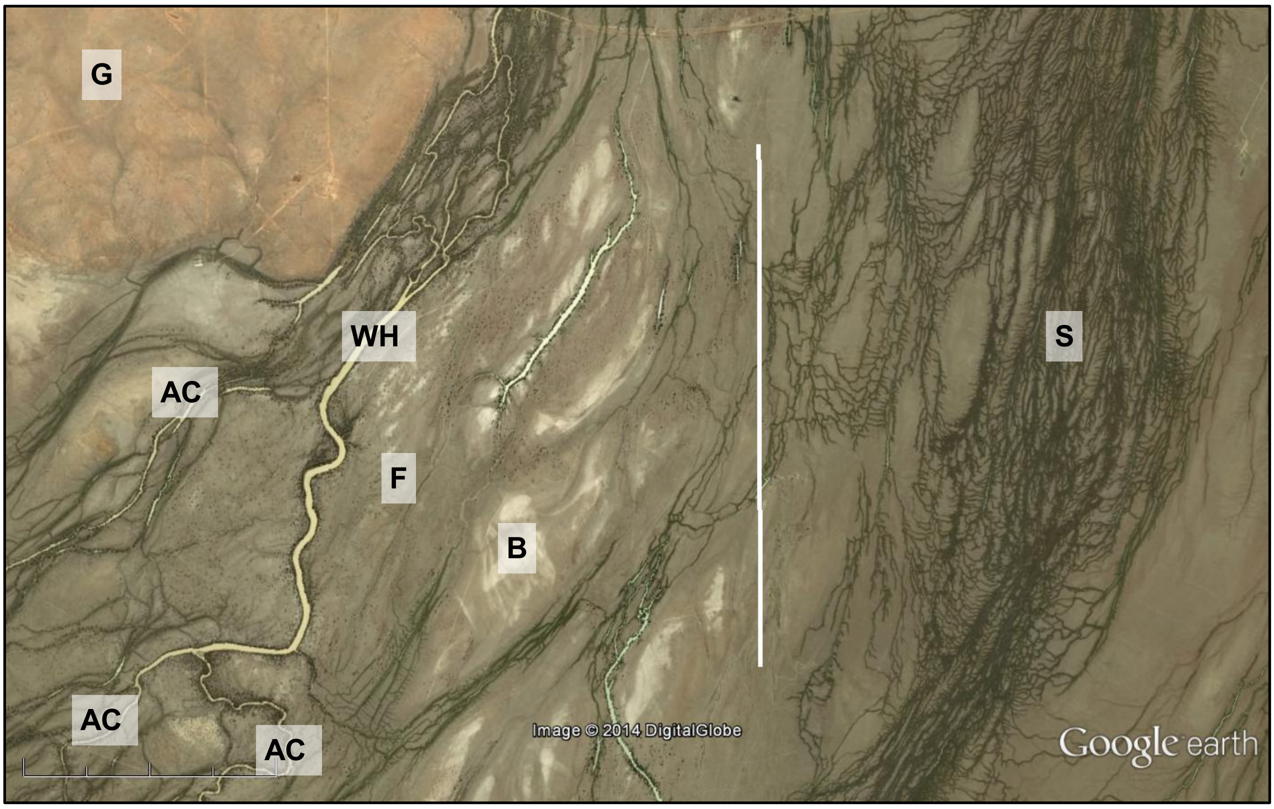

Fig. 18 The lower Cooper Plain at Goonababinna Waterhole.

The orange-brown colour is the gibber plain hillslopes (G). The floodplain is pale to dark grey. The swampy area (S) has a high density of small reticulate channels, and the dark grey colour is because of its dense vegetation. Most of the floodplain is shallow floodways (F), some of which separate the pale braid-like bars (B). The waterhole (WH) is wider than its nearby anabranching channels (AC). Google Earth image, white scale bar = 4 km.

ecologically and culturally important (Silcock 2009). Most waterholes are located along primary flow paths, and their planform is usually less sinuous than the primary channels. They tend to have steep banks of cohesive muddy sediments, which are crowned by tree-covered levees (Knighton and Nanson 1994, Knighton and Nanson 2000). Most are associated with landform configurations which will locally increase stream power: flow-path convergence or constriction, or locations along valley margins (Knighton and Nanson 1994, Knighton and Nanson 2000). Waterhole formation is linked to scouring at high flood levels, and may also be related to scour breaking through the cohesive floodplain muds and excavating into the underlying less cohesive sand layer (Knighton and Nanson 1994, Knighton and Nanson 2000, and see Silcock 2009). Waterhole longitudinal profiles have fairly steep reverse gradients at the downstream ends (as must necessarily be the case if the waterholes are deeper than the channels downstream from them). The location of the downstream reverse slope marks the end of the waterhole, and its elevation is the cease-to-flow depth (the flood stage below which water will cease to flow through the waterhole). Cease-to-flow depth governs waterhole storage volume, and is the attribute which determines whether a waterhole will be transient, semipermanent, or permanent (Knighton and Nanson 2000, Costelloe 2011).

Floodplain

The Cooper Plain floodplain has three types of surface: a braided pattern occupying 44% of the floodplain surface, swamps with reticulate channels (39% of the floodplain surface), and

an unchannelled surface (17%) (Fig. 18). The floodplain's character is strongly influenced by the vertic soil's gilgai nature (see *Sediments* below), and the distribution of surface types is determined by fluvial energy across the floodplain (Fagan and Nanson 2004). Perennial floodplain vegetation that acts to trap sediment includes waterlogging-resistant species such as blue bush, rats-tail couch, sedges and lignum (David Phelps, Qld DAFF, pers. comm. 2014).

In the braided floodplain, elongate landforms of slightly higher elevation (referred to in this report as *floodplain bars*) are separated from each other by wide shallow swales (*floodways*). The elevation difference between swales and floodplain bars is generally <1 m. Floodplain length is approximately hundreds to thousands of metres, and width tens to hundreds of metres. Floodway width is in the range of metres to a few tens of metres. Floodplain bar tops have centimetre-scale microtopography, but show limited gilgai development (see *Sediments* below). The braided floodplain pattern occurs on both high and low areas of the floodplain, and are spatially linked with the major anabranching channels (anabranching channels are never found in reticulate or unchannelled floodplain surfaces). Braid patterns occur where inundating flows have sufficiently high energy to erode and redistribute floodplain sediment, such that gilgai processes cannot proceed to their fullest expression (Fagan and Nanson 2004).

Floodplain swamps with a dense and complex network of reticulate channels are always associated with strongly-developed gilgai features, including prominent microtopography from gilgai heave. Although previously described as backswamps (e.g. Knighton and Nanson 1994) and assumed to be confined to lower elevation portions of the floodplain, the reticulate channels can occur on higher as well as lower floodplain surfaces. The swamps with reticulate channels occur in locations where inundation frequency is sufficient to develop gilgai features in the vertic soils, but where flow energy is not strong enough to move the soil particles. Linear depressions in the gilgai microtopography locally concentrates flow, creating and maintaining the reticulate channels (Fagan and Nanson 2004).

Unchannelled floodplain surfaces are always at higher elevations, and flood records demonstrate that these surfaces are rarely inundated. These surfaces neither receive enough water to move soil particles (creating the braid surface), nor enough water to develop gilgai (Fagan and Nanson 2004).

Sediments

The Cooper Plain's floodplain is dominated by black or dark grey vertic soils, which are made up of sand- and silt-sized mud aggregates. A clod of vertic soil will collapse immediately into aggregate particles on immersion in water, but the aggregates will not themselves disperse; there will be little suspended clay in the water (Gibling et al. 1998). Mud aggregates are stable under transport; flume experiments demonstrate their stability through several cycles of vigorous transport (Maroulis and Nanson 1996). Aggregate mobility declines after several days of immersion due to partial aggregate breakdown (Maroulis and Nanson 1996). Mud aggregates can be transported as bedload during floodplain inundation, and be deposited in the kinds of sedimentary structures more commonly associated with sand (Nanson et al. 1986, Maroulis and Nanson 1996, Gibling et al. 1998, and see Wakelin-King and Webb 2007b). Layering and sedimentary structures formed during the deposition of the wet mud are mostly destroyed as it dries by fragmentation of the mud back into aggregates, and/or by gilgai heave. Around remnant pools of water, bioturbation will also destroy depositional structures (Gibling et al. 1998).

Channel deposits are dominated by mud aggregates, and non-mud components up to the grain size of fine sand. Medium to coarse sands are also found in some channels, and locally gravelly channel beds occur where channels are near valley margin gibber hillslopes. Sandy sediments are deposited as sheets, 2D or 3D dunes, shadow bars, bank-attached bars or tributary junction bars (Gibling et al. 1998). Distant uplands source areas may be the origin of some in-channel sands, however the Pleistocene quartzose sands underlying modern channels were observed to be a more immediate source (Gibling et al. 1998).

Reach-Scale Fluvial Processes

An anabranching planform allows a low-energy river the most efficient possible means to transport its water and sediment load. Dividing a given water volume into several channels (rather than transporting it in a single channel) allows unit stream energy to be maximised (Nanson and Knighton 1996, Nanson and Huang 1999). The Cooper Plain's anabranching channels are a response to the low gradient and low discharge of the present-day river.

During low to moderate stages of a rising flood, the deepest anabranch channels contain the flow. As flow approaches bankfull, low-lying anabranches are conduits for water dispersal onto the adjacent floodplain. If the rising limb of the flood is rapid, channels tend to scour, whereas slower rises in flood level tend to result in sediment deposition (Phelps et al. 2007). As flow overtops the main channels, large areas of the braided and reticulate floodplain are inundated; only the highest floodplain bars and the levees of major waterholes remain unsubmerged (Gibling et al. 1998). As the flood stage rises and inundates the floodplain, flow velocity declines and transmission loss peaks because the flow front is widening and water is being abstracted to floodways and small channels (Knighton and Nanson 1994, Knighton and Nanson 2000). As the flood front travels down river, it must also fill waterholes (Knighton and Nanson 2000), floodplain swamps, and gilgai macropores.

The flowing water transports mud aggregates across the floodplain and into and along the channels. Where sediment monitoring was possible during a flood peak, bedload transport was found to be low; it is likely that most sediment transport takes place during the flood's rising limb (Gibling et al. 1998). In-channel sand and splay deposits downstream from channel ends demonstrates that quartz is also transported during flow events (Gibling et al. 1998, Knighton and Nanson 2000). Sedimentary structures indicate some channels are both aggrading and narrowing, and some floodways are aggrading (Gibling et al. 1998).

This is not a high-energy system: flow velocities are moderate in the channels and low across the floodplain. The distribution of energy from inundating flows across the floodplains is controlled by local factors: floodplain width, transmission losses and small-scale floodplain topography (Fagan and Nanson 2004). In the anabranching channels, water velocities must be variable from place to place, as the channel form, size and other factors vary from reach to reach; this is supported by measured flow velocities (Knighton and Nanson 2000). Stream power at the upstream end of a waterhole was higher than that of the entry channels and much higher than that on the adjacent floodplain. Channel surface flow velocity is lower than that at depth due to boundary roughness of bank-line vegetation, and a waterhole showed a deeply penetrative band of relatively high velocity (Knighton and Nanson 2000).

Where banks show signs of lateral mobility, the rates are relatively low in the cohesive muddy sediments (though banks intersecting the more easily entrained underlying sands have higher rates of change) (Gibling et al. 1998). Waterhole scour and cohesive banks will be a factor in maintaining waterhole stability. The fixed position of the waterholes helps to maintain stability of the multithread channel pattern (Knighton and Nanson 2000).

Catchment Scale Fluvial Processes

Local observations (Phelps et al. 2006, 2007) indicates that the more constricted valley in the Jundah-Stonehenge reach acts as a bottleneck to flow down the Thomson River; floods can back up and spread more widely above Stonehenge.

Local observations (Phelps et al. 2006, 2007) also indicate tributary asynchronicity affecting flow routing: flooding from the eastern hillslopes just below Windorah can hold up the Thomson and Barcoo floodwaters, and push floodwater into the Cooper Plain's western channels. Similarly, a big flood in the Barcoo River can push the Thomson River’s water into the western channels. If the smaller creeks (e.g. Vergemont Creek) flow first and arrive at their confluence with Thomson River before the main flow comes down, the main flow will back up and spread out.

Within a single river reach, different anabranches can carry water from different source areas (they are distinguished from each other by the different colours of the water) (Phelps et al. 2007).

4 Description: Reach Characterisations

This section contains descriptions of the river reach groups, as seen in the sites visited during the field study. Because the Cooper Plain is the reference area, against which the rest of the river is compared, Cooper Plain is described first. In subsequent sections, the reaches are described from lower order to higher order sequence.

4.1 Cooper Plain – the Reference Reaches

The Cooper Plain reaches comprise the wide valley extending from the Barcoo/Thomson confluence in the north-east (upstream) to the beginning of the narrow valley through the Innamincka Dome in the south-west (downstream) (Fig. 19). The Cooper Plain's population centres are the town of Windorah, and the Durham Downs station homestead. These reaches are reference reaches in this study, because they are the sites of existing research (see section 3). The Cooper Plain is the most downstream part of the river examined during this study. It has the lowest gradient and the widest valley.

Valley-Scale Landforms

The valley scale landforms are the silcrete-capped hills and gibber slopes of the Eromanga lowlands physiographic unit, the Cooper Plain, and the valley margin sediments deposited on the eastern edge (all described in section 2.3) (Fig. 19), and the floodplains, channels, and swamps within the Cooper Plain (described in section 3, and see Fig. 18).

The black colour of the Cooper Plain on Google Earth images denotes relatively dense vegetation (the darker colour, the more dense the vegetation). Some parts of the Cooper Plain the floodplain's colour are pale buff in colour, denoting less vegetation and/or slightly higher elevation and/or slightly sandier sediments. In particular, the Barcoo/Thomson confluence (north-east of Windorah) has a floodplain with a greater proportion of pale poorly vegetated bars, and relatively little dark-coloured swampy floodplain.

Channels and waterholes are as described in section 3. Waterhole width is in the order of 70-150 m, and length 1-17 km. Waterhole planforms typically show narrow feeder channels at the upstream end, and distributive splay channels at the downstream end. Channel width is variable on a scale of metres to tens of metres. Channel length depends on whether it is a minor or major component: primary channels are continuous, while less important channels may be kilometres to hundreds of metres long, and minor channels may be discontinuous. There is a continuity of scale and feature that blurs the distinction between landforms. Although a primary channel is clearly unlike a large swamp, some features will be co-located within a single floodplain area e.g. minor channels may travel along floodways which are swampy (retain water and are densely vegetated) (Fig. 20). If the minor channel decreases in size along its path, it becomes one of many floodway swales. A similar continuity exists with respect to floodplain bars. A high braid bar is clearly unlike a floodway, but in the floodway the lowest-elevation swales are separated by low braid bars. All become part of the floodway when the floodplain is inundated.

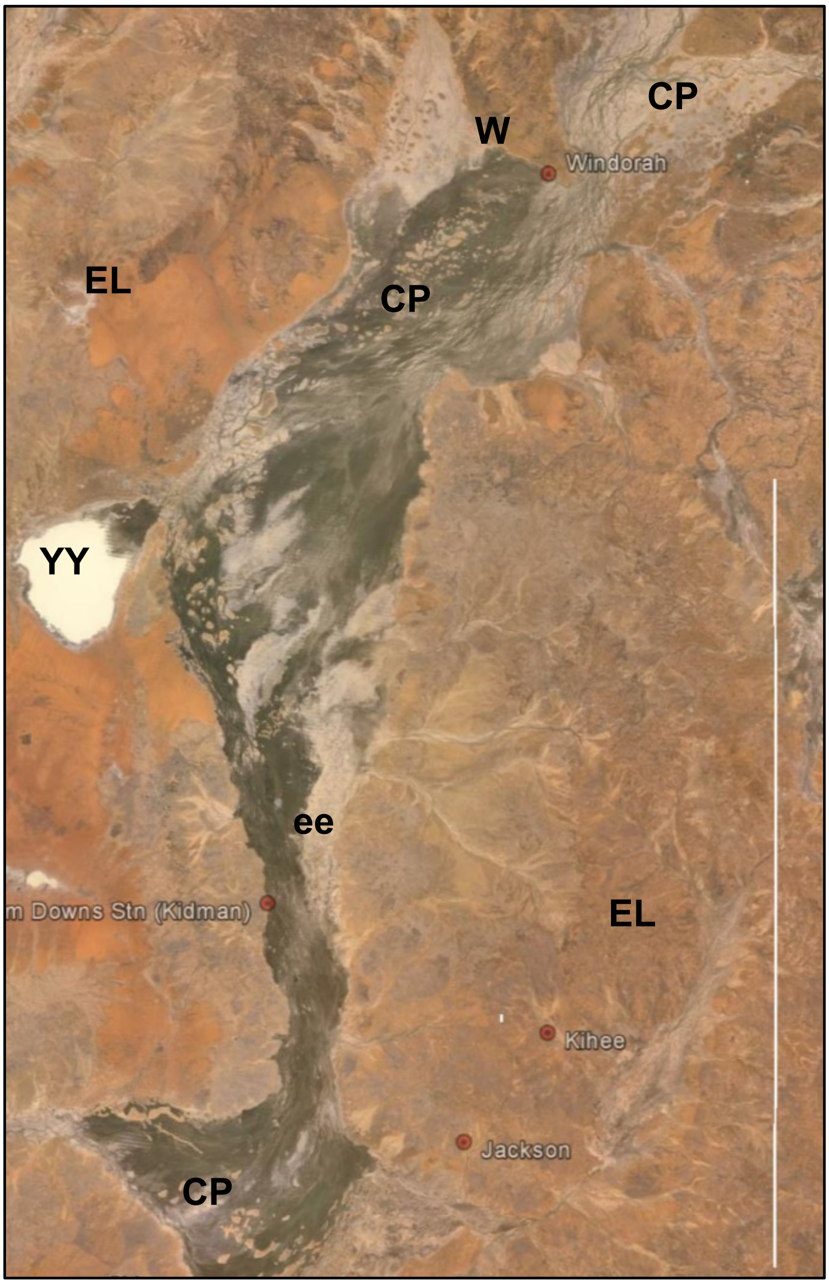

Fig. 19 Valley context of the reference reaches.

The Cooper Plain (CP) is surrounded by the Eromanga Lowlands (EL), with Windorah (W) near its northern edge, Lake Yamma Yamma (YY) on the west and sandy sediments encroaching on the eastern edge (ee). Google Earth image, white scale bar = 200 km, flow is from north to south (image top to bottom). Also see section 1.2 Figs X and AL

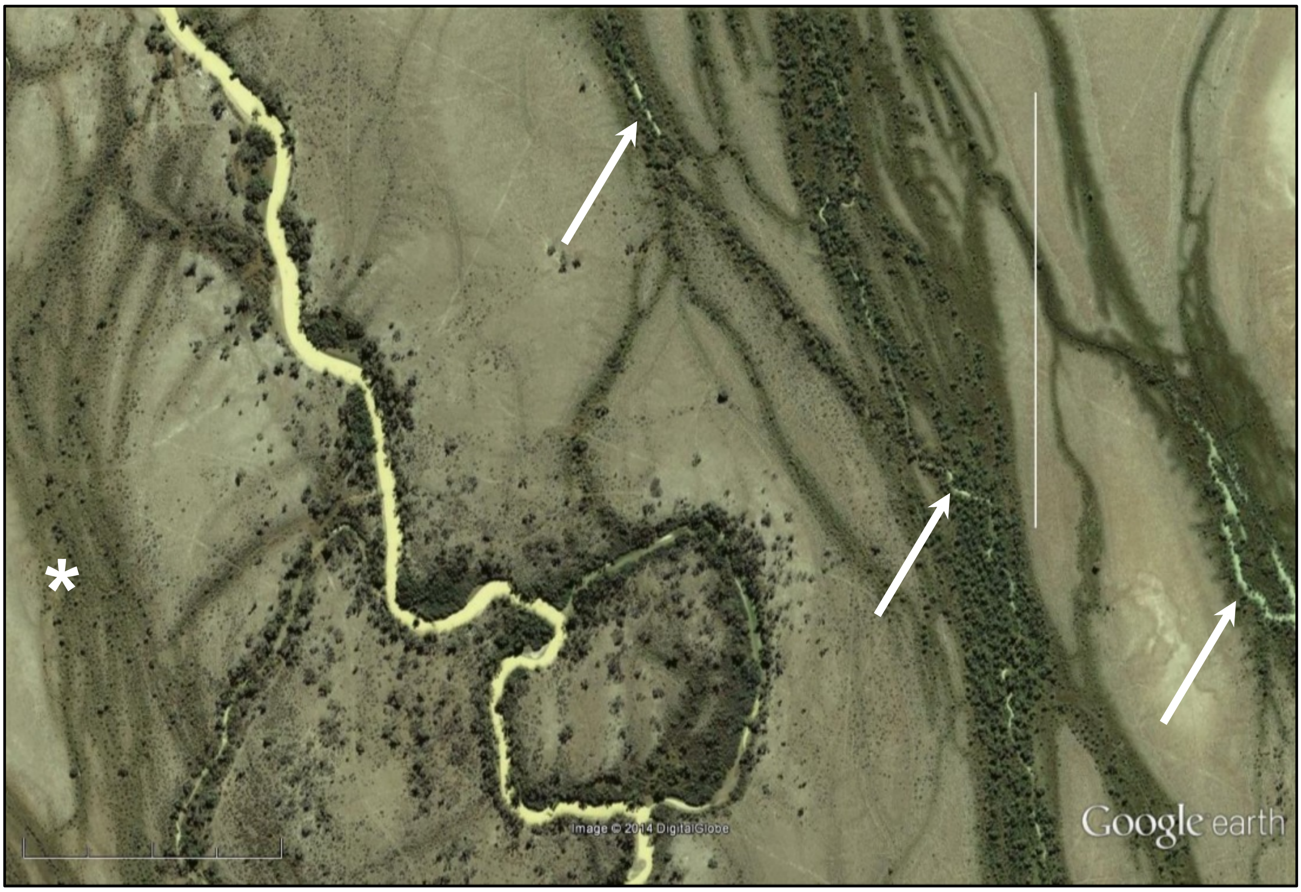

Fig. 20 Channels, floodways, and swamps on the lower Cooper Plain.

The primary channel (left of image) is continuous, with a small anabranch (bottom centre). Some minor channels (arrows) are located within swampy floodways, dark with dense lignum. Asterisk, a less densely vegetated floodway. Google Earth image, flow top to bottom, white scale bar = 0.5 km.

Reach-Scale Geomorphology

Channels' and waterholes' most characteristic feature are their banks of cohesive muds. Banks are clearly defined by topography and vegetation, making channels easy to distinguish on Google Earth images and "bankfull" clear on the ground. There is usually a sharp break of slope at the bank lip, a moderate to moderately steep slope at the upper bank which grades to a gentle slope at the lower bank (Fig. 21). Some banks are moderately steep down to the water level (a more gentle lower bank possibly concealed beneath the water). Some banks are relatively steep, especially those of sinuous small channels. In some small channels, the two-element nature of the bank slope can be resolved into the steep upper bank (which may be erosional in origin), and a lower bank-attached bar with an almost-flat upper surface and a more steep foreset (Fig. 22).

Fig. 21 Galina Waterhole bank.

White lines show approximate bank slope. A riparian coolabah on the upper bank leans out over the bank, with stubs and 'elbows' (arrows) on its lowest limbs. Looking downstream, person (circled) for scale.

The channel/waterhole riparian zone and the upper bank are vegetated by large trees (usually coolabah) and grassy understory. The tree trunks commonly lean out over the bank. Some tree limbs extend out and down, to a level where they are broken off by floodwaters; remaining portions of the limb grow up, forming a limb that extends down and then bends upwards. A bank tree may thus have a series of stubs and 'elbows' at a roughly consistent elevation (Fig. 21). This elevation may reflect maximum stream power at sub-bankfull flood stage.

The roots of channel/waterhole riparian trees are exposed in areas of bank retreat (for example the outside bank of sinuous small channels), however most of the channel and waterhole sites visited have no exposed roots, or a few large roots slightly exposed and parallel to the present bank, both conditions demonstrating bank stability.

Lignum is not present on all channel/waterhole banks, but where present clumps of lignum extend from bank lip down to a level below that of the bank trees. Riparian vegetation, particularly trees and lignum, plays an important role in trapping bank top sediments and in reducing stream power and flow velocity with increasing flow stage.

Dried sediment of the channel/waterhole bed and banks was usually so altered by desiccation and trampling that depositional bedforms were not observable. The absence of shadow bars behind or scours around riparian tree trunks suggested very low-energy flow that neither eroded or transported sediment, but the heavy degree of self-mulching made the field evidence ambiguous. An exception to this observation is that some small channels exhibited bank and thalweg scouring.

Fig. 22 A small channel set within a swampy low-elevation flow path.

This small channel feeds into Galina Waterhole. White lines show approximate bank slope. Dense lignum in foreground left, and on upper bank slope (right, near steeper white line).

Swamps are characterised by low elevation, well-developed gilgai, and dense vegetation dominated by lignum. Some swamps flank small channels and occur along floodplain flow paths (Fig. 20), and carry floodwaters as rising stages overtop the small channel banks. Swamps with the characteristic reticulate channel pattern (Figs. 18, 23) are not closely associated with the primary

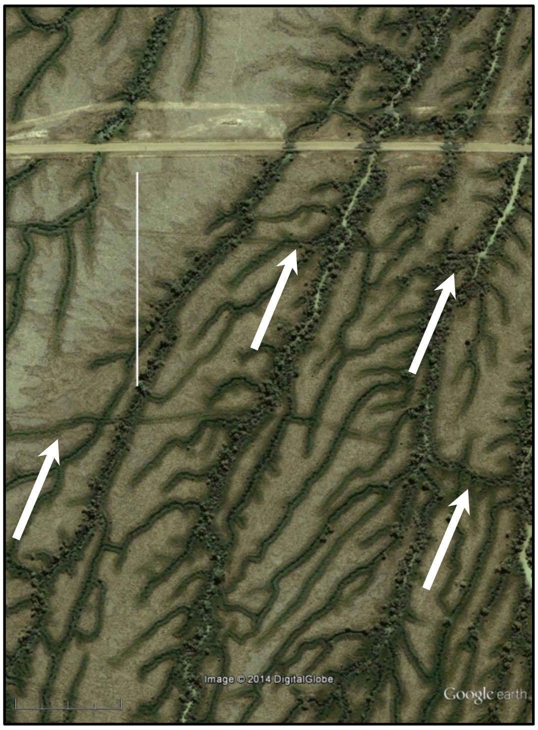

Fig. 23 Ex-roads acting as swamp channels.

The lines across the top of the photo are the present-day road and the most recent ex-road. Below them, two old roads (arrows) which crosscut the swamp channels now behave as swamp channels. Flow top right to bottom left, white scale bar = 0.25 km.

flow paths. The edges of swamps and swamp channels are usually clearly evident, but slope breaks are less distinct than those at the edges of channels and waterholes. Lignum occurs along swamp edges but not in the lowest elevation areas. Lignum growing along the banks of swamp channels may contribute to keeping the channels clear, by retarding flow in the swamp overbank areas, thus focusing stream power within the unvegetated swamp channels

Where roads cut across swamp channels, the lowered road surface becomes a focus for inundation and may in time begin to act like a swamp channel. Google Earth images show these former roads cross-cutting the trend of natural swamp channels (Fig. 23), some showing the double line that indicates bank-top lignum. In some cases, the new swamp channels divert flow from one swamp channel to another. There is no observable tendency for such flow diversions to be more effective in streamwise direction, and (unusually for roads crossing active rivers) road surfaces do not seem to be developing gullying or erosion. These observations are supporting evidence of the very low-energy nature of flood flows in these areas.

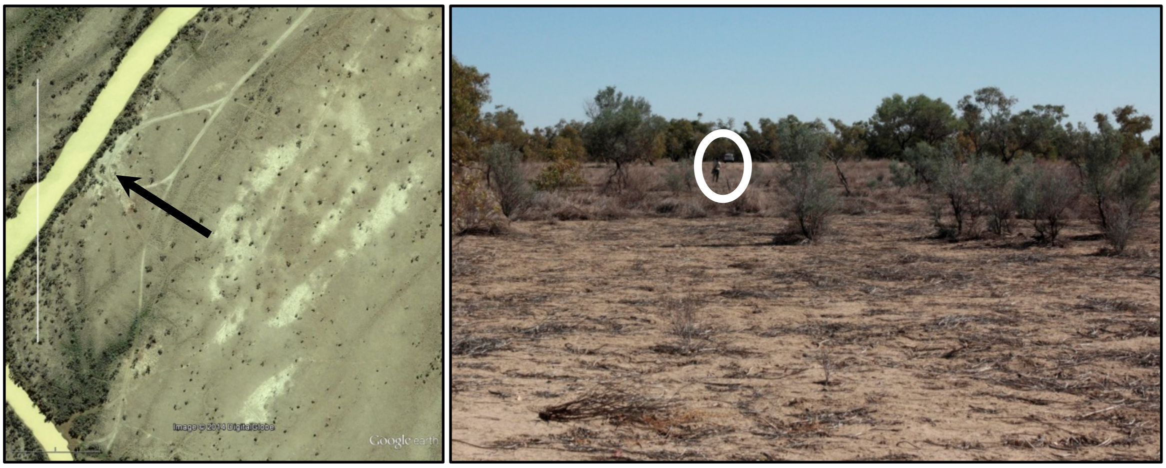

Fig. 24 Floodways near Goonababinna Waterhole.

Left, Google Earth image, black arrow indicates direction of photo view, white bar = 0.5 km, flow from top right to bottom left. Right, photo from the top of a braid bar, looking across a shallow floodway towards the waterhole. Person (in swale) and vehicle (on waterhole levee) (both circled) for scale.

The floodplain bars, or "braid bars", are somewhat featureless landforms, with very sparse vegetation, low-relief surfaces, and sparse poorly developed gilgai features. If the floodways that separate them are not swampy, they are very poorly defined and may be difficult to distinguish (Fig. 24). Floodways are characterised on the ground by slightly lower elevation and a bit more vegetation, and on Google Earth images by the grey tone of occasionally inundated floodplain, slightly more vegetation, and location within one of the flood-height flow paths.

Sediments and Depositional Landforms

The floodplain sediments in these reaches are dark grey mud aggregates, showing gilgai features (macropores, gilgai depressions, heaved surface, and either multiple cracking or self-mulching). The degree of gilgai feature development correlates with the degree to which the area is likely to be inundated: elevated floodplain bars display much less gilgai than swamp channels (Fig. 25). Most of the floodplain muds contain little sand; where present, its grain size is fine sand. Mud from a large and relatively elevated floodplain bar north of Windorah (just downvalley of the Thomson/Barcoo confluence) has a greater proportion of sand. It displays multiple cracking but no heave or deep crabholes; whether this lesser degree of gilgai features is due to elevation or sediment composition is not clear from this site.

Fig. 25 Gilgai features in floodplain sediments.

Left, large deep macropore cracks in a swampy floodway swale, Durham Downs reaches, hammer for scale. Lignum grows along the swale edges but not in its centre. Right, small macropores are present on an elevated floodplain bar near Galina Waterhole in the Durham Downs reaches, person for scale.

Fluvial Processes

The fluvial processes of the Cooper Plain as described in the research literature are discussed above in section 3. The paragraphs below are in addition to the published research.

In comparison with the rest of the Cooper Plain, the Windorah reach area has a greater proportion of floodplain bars, a lesser proportion of swamps, slightly more sandy sediments, and a greater downvalley slope. This suggests that a sandy component from the Barcoo and Thomson Rivers occurs in the upper Cooper Plain, but has not yet been transported as far as the Durham Downs reaches. It is likely that the valley constriction at Windorah is hampering downvalley sediment transport from the Barcoo/Thomson confluence.

While the large channels and waterholes appear to be stable, small channels exhibit signs of geomorphic activity (scouring, bank retreat, and multiple channels as might result from avulsion).

Inundated large vegetation is an important roughness component, for example in-channel gum trees can contribute as much as half the Manning's *n* values during a flow event (Graeme and Dunkerley 1993). Increased roughness leads to lower flow velocities and lower stream power. Flow encountering vegetation will be likely to deposit sediment. The channel and waterhole riparian vegetation and the lignum along swamp channel edges are likely to play an important role in encouraging sediment deposition, maintaining the bank lip and the steepness of the upper bank. Riparian vegetation intercepting high-level flood flow creates a shear zone between bank and channel (Zong and Nepf 2010) and this is also likely to play a role in maintaining the steep sides of waterholes and channels. Additionally, riparian vegetation is an important protector of bank integrity during floods, even quite major floods (Zawada and Smith 1991, Hubble and Rutherfurd 2010.).

4.2 Escarpment and Uplands (including Lake Dunn)

These reaches are the most upstream reaches of the study area. They lie along an elevated belt which forms the catchment divide between the Lake Eyre Basin and the Burdekin catchment (Fig. 26). They are bounded to the west by a scarp (Fig. 11).

Valley-Scale Landforms

Due to the project's time frame, only Lake Dunn and its outlet creek were visited. Descriptions of other landscape elements are based on the remote study.

Lake Dunn occurs in a broad uplands area which is part of the Great Dividing Range (Fig. 26, and see Fig. 10 and Fig. 7). It sits within a small valley set into the uplands, as does nearby Lake Galilee. Both lakes drain towards the west. The smooth transition from one colour to another in the DEM of the lakes' subcatchments indicates that there is currently relatively little active incision or erosion taking place (as opposed to the headwaters of the Belyando River, Fig. 26). Google Earth image of the Lake Dunn sub-catchment indicates that its surrounds are open low-relief hillslopes with discontinuous drainage or possibly chain of ponds type drainage, or a wide areas of banded vegetation (red-brown on Google Earth images) (Fig. 27). Banded vegetation hillslopes appears to lack drainage networks, but in fact are unchannelled sheetflow watercourses (Wakelin-King 1999).

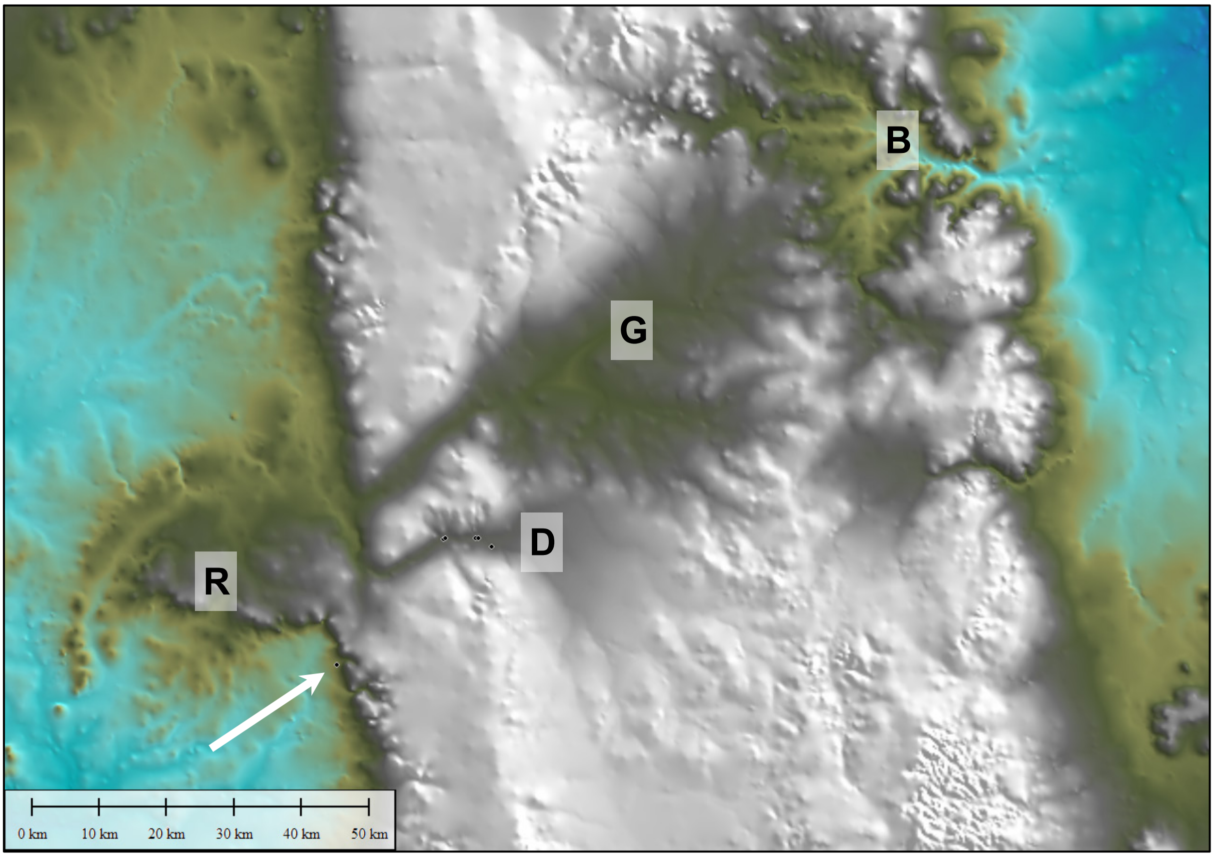

Fig. 26 DEM of the Thomson River uplands.

The uplands extend in a north-south belt (white) into which several valleys have been incised (grey, dark green and pale green). Blue colours are lower-elevation areas of the Cooper catchment (west) and the Burdekin catchment (east). Arrow, the escarpment shown in Fig. 11; G, the valley of Lake Galilee, D, the valley of Lake Dunn; B, the headwaters of the Belyando River (Burdekin catchment); R, Reedy Creek.

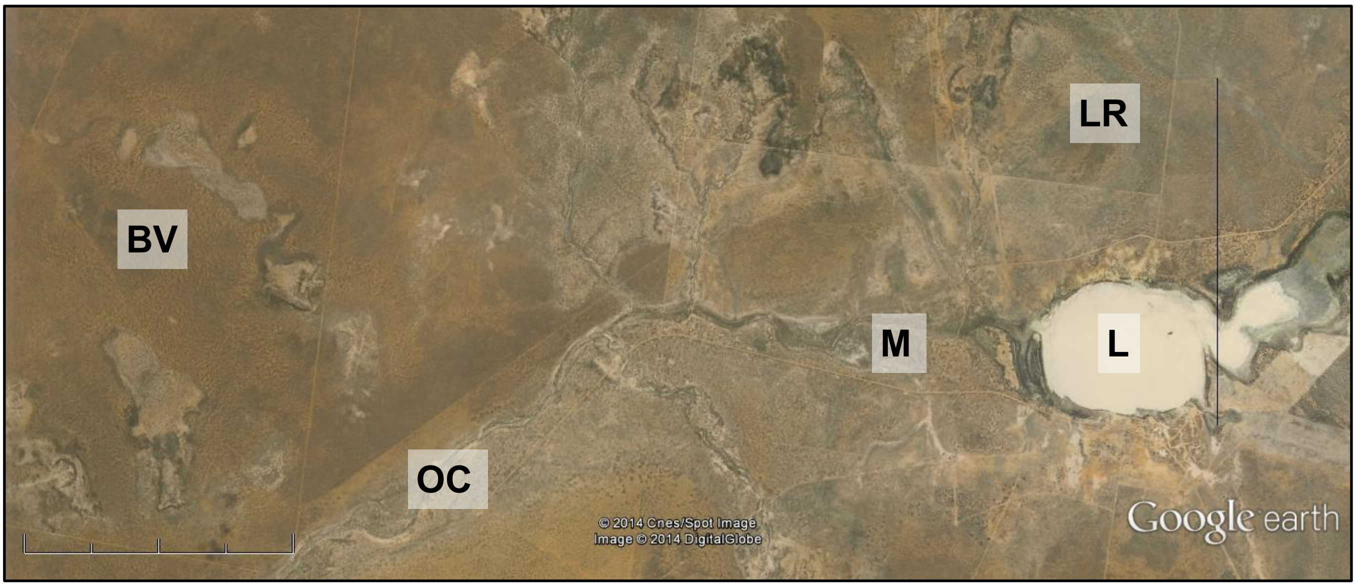

Fig. 27 Lake Dunn and the uplands.

L, Lake; M, marsh; OC, sandy outflow creek; LR, low relief uplands, BV, banded vegetation plans. Google Earth image, flow right to left, black scale bar = 4 km.

Lake Dunn receives inflow from the uplands on its east, and overflows westwards through a wide swamp which narrows to a linear marsh (Fig. 27), a wide swale with a poorly defined discontinuous channel. A few kilometres downvalley from the lake, the linear marsh receives tributary input from creeks entering from the north and south and the watercourse becomes a continuous channel confined within a narrow fluvial valley.

A scarp (Figs. 10, 11) separates the uplands from the Mitchell Grass country of the Winton-Blackall Downs physiographic region. The scarp is cutting back into quartz-rich sandstones, and at the scarp foot are colluvial aprons of coarse sandy sediment. The Lake Dunn outflow creek flows over the scarp and into Reedy Creek.

Sediments and Reach-Scale Geomorphology

Lake Dunn is a large freshwater lake whose sandy beaches show evidence of nearshore processes such as wave-driven sediment transport. The shoreline is fringed with trees and backed in places by shallow lagoons. The lake drains into its outflow marsh through a freshwater swamp behind its western beach ridges. The area is densely vegetated with stands of mature eucalypts and is biologically very productive (Fig. 28). A series of disconnected marshy low spots carries outflow, but there is no clear channel structure. The marsh's sediments were somewhat muddy, but were not the deep soft sticky mud that would have been found if the sediments were the vertic

Fig. 28 The swamp west of Lake Dunn.

muds of the Thomson River and Cooper Creek. The sediments were obscured by standing water and dense vegetation, and within the timeframe it was not possible to make any further examination. The valley-margin hillslopes flanking the linear marsh were observed to be red-brown sand and silt.

Fig. 29 The sandy and gravelly outflow channel of Lake Dunn.

Downvalley from the marsh, the outflow creek is a small channel of low sinuosity set within a small sandy valley. The creek's sediments are moderately sorted medium fine to medium quartzose and lithic sand. Some bars in the creek were pebble and cobble conglomerate, containing clasts of sandstone, mudrock, silcrete, and a few clasts of metamorphic or igneous basement (vein quartz, weathered granite, metasediments). The conglomerate was imbricated with some cluster bedforms present. Conglomerate clasts were rounded to sub-angular, and of low to moderate sphericity: the sediment provenance is local but not immediately nearby. Sediment grain size and texture would be consistent with outcrop somewhere in the upper catchment but not in the creek's or lake's banks. Unlike other reach groups, no mud aggregate sediments were observed to be present.

At the site examined, the creek had multiple channels with beds of different elevations. The channels had moderate to steep banks (Fig. 29), some vertical cut banks, and flood debris on the vegetated bar tops. Where a fenceline had been installed across the creek's path, localised intense bank erosion and channel shifting had taken place.

Fluvial Processes

Many landscape features in the uplands suggest that river behaviour is characterised by low energy or low discharge or both. On the hillslopes, banded vegetation indicates a low-energy context. Lake Dunn rarely contributes water into the Cooper system (Phelps et al. 2006). It receives water from poorly-defined waterways extending across an apparently low-relief surface, and its outlet is through a densely vegetated, unchannelled swampy area. Lake Dunn's western edge must have a sill or topographic elevation of some kind which contains the lake's water. The sill must be regularly overtopped, since the downvalley area is marshy, but evidently outflowing water does not develop sufficiently high stream power to incise through the sill.

The low-energy suite of landforms is in contradiction to the creek's evident relatively high-energy flows (sufficient stream power to transport coarse sediment and initiate erosion) and high gradient (an order of magnitude greater than downvalley gradients anywhere else in the system). The remote study suggests that Lake Dunn and its outflow creek occupies a partially infilled palaeovalley, and field evidence suggests that although its topography has the potential to provide valley-scouring flow, the present day flow regime does not usually supply sufficient discharge to trigger erosion (stream power is proportional to the product of discharge and slope: in the Lake Dunn area, the creeks have low discharge but high slope).

These reaches are currently geomorphically stable in a system of low-energy drainage that allows water to be retained in local hillslopes, supporting local ecosystems. However, they are likely to be close to the threshold of geomorphic change, from intact valley floor to incised valley floor. Typically, valley-floor incision leads to floodplain desiccation and ecosystem death (Prosser and Slade 1994, Bull 1997, Fanning 1999, Wakelin-King 1999, Wakelin-King 2010). Increased discharge that leads to erosion across Lake Dunn's sill, or establishes connectivity along the outflow creek and over the scarp's knickpoint, risks triggering self-perpetuating incision, leading to valley-floor incision or the initiation of gully networks. Similarly, banded vegetation hillslopes which experience flow concentration can become gullied and lose landscape function entirely (e.g. Tongway and Ludwig 1990). Increased discharge could take the form of a single event (e.g. an intense local storm) or a long-term change (e.g. artificial discharge of formation waters down the creek line). The degree of vulnerability depends on the natural present-day boundaries to lake and river flow. If the boundaries are landforms composed of unconsolidated sediments, then the resistance to erosion is only as great as the vegetation density and the sediment cohesion or grain size. If the boundaries are bedrock, then the resistance to erosion is as great as the rock's strength. The present project's field investigation found no outcrop along channel floor or margins in these upland reaches.

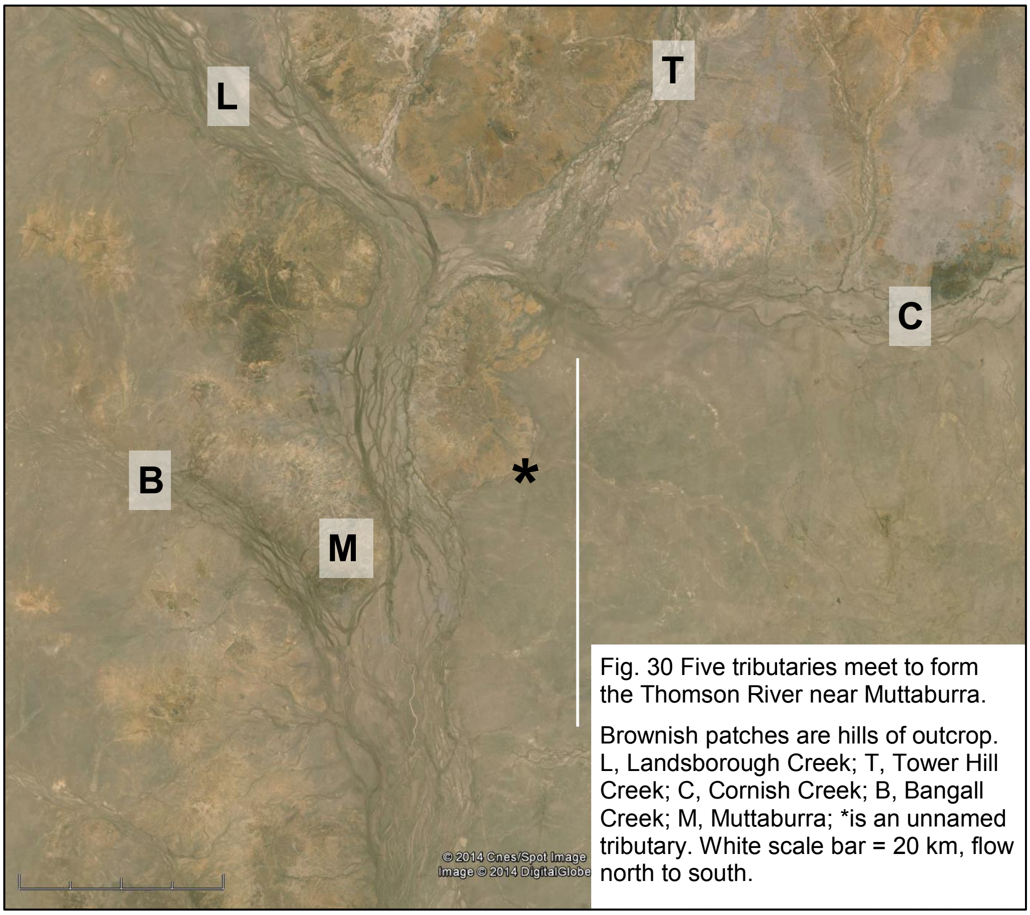

Fig. 30 Five tributaries meet to form the Thomson River near Muttaburra.

Brownish patches are hills of outcrop. L, Landsborough Creek; T, Tower Hill Creek; C, Cornish Creek; B, Bangall Creek; M, Muttaburra; *is an unnamed tributary. White scale bar = 20 km, flow north to south.

4.3 The Tributaries (near Muttaburra)

The Thomson River's most upstream reach is just north of Muttaburra, at the confluence of two large tributaries (Landsborough and Towerhill Creeks) and a smaller tributary Cornish Creek from the escarpment area (Fig. 30). A little further downstream two other tributaries join the Thomson River: an un-named small one from rocky hills to the east, entering just north of Muttaburra, and Bangall Creek, entering the Thomson River from the west just south of Muttaburra. Tributaries were examined only briefly.

Valley Scale Landforms

The five tributaries are set within a landscape in which low hills with outcropping sandstone and sandy colluvium (Fig. 30) emerge from a layer of grey vertic soils. In places the soil is thin and the sandstone or sandy colluvium is close to the surface, elsewhere the vertic soils are thick. The disposition of the hills has been a strong influence on the development of the drainage network: where the distances between hills are wide, tributaries are widely spaced in a dendritic network of low-order channels, whereas where the flow path is constrained between hills, the tributaries are forced into confluences. Below the confluence, channels from the individual tributaries maintain their individual character during flow events in which the entire floodplain is not activated, and/or in which only one or two tributaries carry flow (see section 4.5).

Within the alluvial valleys of some tributaries, the major landscape elements are floodways and floodplain bars, with few channel segments. In other tributaries, there is a small continuous channel. The sub-catchments drained by the five tributaries differ in size, gradient, valley width, and geology, and this undoubtedly governs differences in the creeks' natures.

Reach-Scale Geomorphology

In Landsborough and Bangall Creeks, the river valley is occupied by floodplain bars and floodways (Fig. 31), which are broad vegetated swales. Groups of floodways are set within broad, lower-elevation areas which are separated by a pale floodplain bars. There are no continuous channels. Instead, floodways include discontinuous channel segments with small riparian trees exhibiting exposed roots.

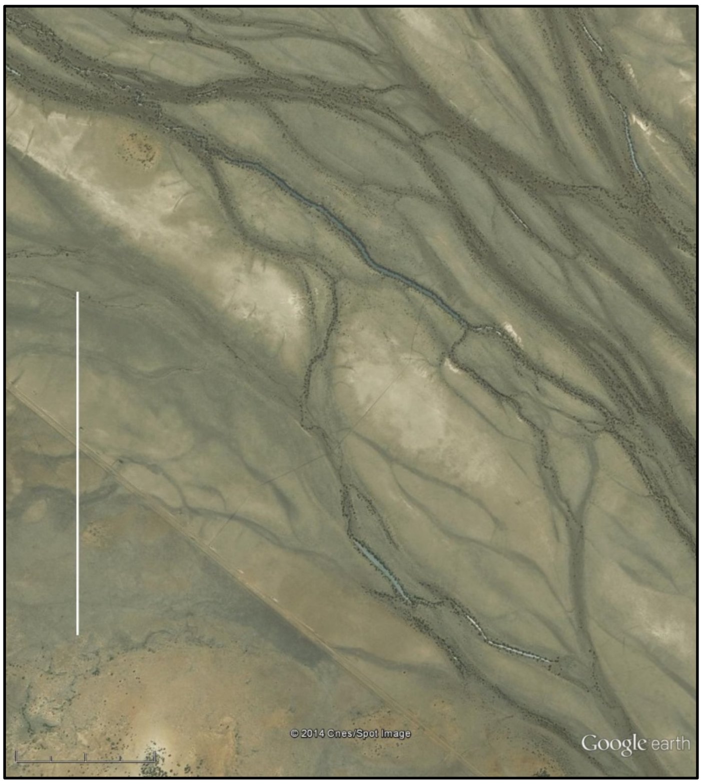

Fig. 31 Floodways in Landsborough Ck, scale 2 km.

Sediments and Depositional Landforms

The tributaries carry different sediment loads. Remote data indicate that Cornish Creek and the unnamed creek, which are relatively unconstrained, carry muddy sediments, whereas Towerhill Creek, which is flanked by outcrop, is very sandy. In Landsborough Creek, floodplain bars were covered with small gravel gibber, and floodways contained deeply cracked vertic mud.

Fluvial Processes

The tributaries of the Thomson River are each likely to have relatively small discharges, since they do not contain continuous channels or a significant waterholes. Their varying fluvial styles probably reflect differences in their flow behaviours. They are likely to have in common that different scales of flow event will inundate different fluvial landforms: the smaller (higher recurrence interval) flow events will inundate the floodways, larger flow events will also inundate the low-elevation ground amongst which groups of floodways are set, and only the largest flows will cover floodplain bars. Channel segments within floodways are likely to be created and maintained during large flow events. Their size is not indicative of flow volume, as most of the discharge is accommodated by floodways.

4.4 The Tributary Aramac Creek

Aramac Creek is a tributary joining the Thomson River approximately 40 km south of Muttaburra. Some aspects of its geomorphology are sufficiently different to the rest of the Thomson River that it is considered separately here; it would benefit from a more detailed study.

Valley-Scale Landforms

The upper reaches of Aramac Creek are located just west of, and just downslope from, the scarp and its colluvium. Hillslopes flanking the river valley have muddy vertic soils supporting Mitchell Grass communities interspersed with sandy patches, some affected by deflation (wind erosion). Aramac Creek is set within a poorly-defined valley in which relatively densely vegetated floodways anastomose around less well vegetated floodplain or floodplain bars. The 1:250,000 topographic map sheet also shows Aramac Creek as forest or scrub (c.f. the Thomson River, which is not so shown). In some places, relict palaeochannels indicate that channel relocation has taken place (Fig. 32). Within the floodways, the primary flow path is defined by a continuous line of dense vegetation containing widely separated short waterholes (Fig. 32).

Reach-Scale Geomorphology

The waterholes' planforms are similar to others in Cooper Creek and the Thomson River: a narrower upstream channel widens to become the waterhole; the waterhole finishes abruptly in the downvalley terminal splay in which the single waterhole channel becomes multiple smaller channels.

Fig. 32 Waterhole in upper Aramac Creek.

Arrow, waterhole input channel, * the waterhole's downstream terminal splay. Dark area is dense gidgea scrub in the flow path, pale areas are sandy hillslope sections, black dashed line is possible palaeochannel. Google Earth image, flow south to north, white scale bar = 1 km.

In other respects these waterholes are dissimilar. In many places along the river valley the gidgea scrub is extremely dense. The waterholes have shallow very gently-sloping banks, in which the riparian trees are set well back from the water's edge. The waterline (as expressed by water level and lignum line) is high with respect to the riparian tree bases and the overhanging limbs (Fig. 33).

Fig. 33 A waterhole on upper Aramac Creek.

The banks are very gently sloping, and trampled by stock. The trunk of the riparian tree is well back from the waterline (right arrow) and the water level is as high as the tree's 'elbow' (left arrow) (c.f. Fig. 21).

Many of the riparian trees show signs of burial. The waterhole edges are heavily trampled by stock. The landholder indicates that the waterholes have silted up and shallowed: one waterhole near the homestead was 24 feet deep in 1946 and is now 10 feet deep. Old photographs apparently show the waterholes with steep banks and riparian trees with exposed roots (similar to other waterholes seen in Cooper Creek and Thomson River) (D. And A. Stent Smith pers. comm. 2014).

Fluvial Processes

The landholders consider the dense gidgea scrub to be a post-European development, attributing it to over-intensive sheep grazing and an absence of firestick management (D. and A. Stent Smith pers. comm. 2014). If this is the case, this area will be similar to the Cobar Peneplain where Invasive Native Scrub (INS) has expanded by a similar process (overgrazing displacing the vegetation community from grass to Acacia scrub, which also changes the fire regime in a way that further advantages scrub). The landholders also consider that the creek no longer flows fast enough to scour out the waterholes, and that large amounts of sediment have come down from upstream (D. and A. Stent Smith pers. comm. 2014).

In the present day, the indications are that the creek flows with less energy than other Thomson River tributaries. Long-time local resident Graham Moffatt (pers. comm. 2014) says that Aramac Creek flows slowly, which is consistent with its heavily vegetated nature. Aramac Creek's greater degree of vegetation than other Thomson River tributaries (see section 4.3) is consistent with the possibility of INS. On the Cobar Peneplain, INS is most dense on infilled palaeochannels, a similar landform type to the Aramac Creek valley. INS in the primary flow path would certainly slow flow and decrease its ability to scour waterholes. The conditions that promote INS are also likely to promote increased sediment reaching the creek, which will shallow the waterholes. Sediment deposition across the river valley as a whole would raise the cease-to-flow level, and promote sediment deposition on the bank tops and slopes. Although trampling of the bank by stock is detrimental to the bank's integrity, it seems unlikely that that alone is responsible for waterhole shallowing. It is quite possible that such trampling is a secondary effect of other changes that shallow the banks and make them more accessible to stock.

4.5 The Upper Thomson River A (Muttaburra)

At the confluence of Towerhill Creek, Cornish Creek, and Landsborough Creek, the Thomson River begins. The upper Thomson River extends downvalley 260 km from this confluence, however approximately the first 60 kilometres has a steeper gradient (Table 1), and so is considered separately here.

Valley-Scale Landforms

The upper Thomson River A is flanked on the west by low hills of sandstone outcrop partially overlain by vertic soils, and on the east by low rises of vertic soils (Fig. 30). The river valley does not appear to be constrained by the hills (c.f. section 4.7), although it is not possible within the scope of this project to be definitive.

Fig. 34 Channels and floodways of the Thomson River at Muttaburra.

Flow north to south, white scale bar = 2 km. Top, the road crossing into Muttaburra township. The three channels are the Landsborough, Thomson, and Cornish (west to east). An anabranch takes water from the Thomson channel at the Pump Hole offtake (arrow), and feeds it into the Landsborough channel near the township. Bottom, Muttaburra Broadwater (western side) and the Thomson channel with a number of short discontinuous channel segments in the floodway on the eastern side. The Broadwater shows evidence of channel relocation (arrow).

The river here is dominated by floodways and floodplain bars (Fig. 34). The floodways appear (on Google Earth images) to be relatively lightly vegetated, and most contain short sections of discontinuous small channels. There is only one continuous channel: it extends from the Landsborough/Towerhill confluence to below Muttaburra. From about the level of Muttaburra and continuing downvalley, floodways are more likely to contain small waterholes and sections of continuous channel. Small channels can be gently sinuous to very sinuous.

The Thomson River at the Muttaburra Road crossing has three channels. Although they occur within the same river valley and the 1:250,000 topographic sheet refers to it all as the Thomson River, local information is that the different channels flow from different upstream reaches: the Landsborough channel, which is filled by an offtake (at Pump Hole) from the central Thomson channel, and on the east the Cornish channel (Kerry Robinson pers. comm. 2014) (Fig. 34). The channels are differentiated on the basis of tributary asynchronicity: rain events occurring within a particular subcatchment will fill a particular channel. The fact that this behaviour is a common enough pattern that it forms part of local knowledge, despite the flows' origin in interconnected floodways, is a strong statement on fluvial behaviour.

Downvalley from the Thomson/Bangall confluence, the Landsborough channel widens to form a substantial waterhole: the Muttaburra Broadwater (Fig. 34). It is 6.6 km long in a gently sinuous planform and approximately 44 m wide at its widest point. Unlike the waterholes in the reference reaches or the rest of the Thomson River, the Muttaburra Broadwater's upstream and downstream ends are gradual rather than abrupt transitions from the ordinary channel width. In this area the Thomson channel is approximately 15 m wide.

Reach-Scale Geomorphology

The largest channel, the Muttaburra Broadwater, is similar in many respects to other waterholes in the Thomson River and Cooper Creek, having a moderate to moderately steep bank (frontispiece), with a gently sloping bank-attached bar at the base (in some places). The bank top and upper bank slopes are crowned by mature coolabah trees, but the riparian zone had no understory. Lignum was not seen during the field examination, but some melaleucas occur along the water's edge. Although the floodplain and bank top was heavily trampled by cattle, there was less signs of trampling on the bank slopes. The Muttaburra Broadwater is a significant local camping area, for both tourist amenity and travelling locals. A loop from the main road brings travellers to a series of many camping sites along the bank top. Many small gullies extend from vehicle turnarounds down to the water's edge, far more than was seen in non-campsite waterholes during this field study.

The small channel at Pump Hole showed steep to vertical banks with evidence of rapid undercutting (exposed roots, toppled trees) on curved reaches' outside bends (Fig. 35). Inner bends were lower in elevation, showed ridge-and-swale topography and sandy substrate, all demonstrating floodplain development through active meandering. There was a strong association between river red gum trees and sandy floodplain sediment (river red gum trees were not seen elsewhere during this study).

The anabranch connecting the Thomson channel to the Landsborough channel showed similar characteristics, however indicators of flow direction (bedform orientation, erosion patterns) were ambiguous.

Fig. 35 Looking downstream at the sinuous Thomson channel, Muttaburra.

Sediments and Depositional Landforms

Floodplain bars contained trampled and self-mulching vertic muds. In some floodplain surfaces concentrations of gravel and small cobbles occurred amongst the mud. These were not near valley margins, and it is likely they originated as high-energy gravel bars during a previous wetter climate.

In the small sinuous channels near Pump Hole, the channel banks were dominantly cohesive floodplain muds, whereas the bedload was very clean medium quartz sand, in some places containing up to 10% pebbles. Bedforms included bank-attached backwash bars, shadow bars and 2D dunes up to 1.5 m amplitude, implying flow energies greater than those seen in downstream reaches of the Thomson River. In one location an exposed bank showed a layer of muddy sand or sandy mud coarsening upwards to a sharp boundary and overlain by >1 m floodplain muds. This is most likely to indicate channel migration and floodplain development, although it may also reflect a change in the energy of the river system as a whole.

Fluvial Processes

It is only below the Landsborough/Towerhill confluence that the Thomson River gathers sufficient discharge (and therefore stream power) to generate and maintain waterholes and continuous channels that are big enough to be reliable water resources. The Thomson River carries water in an anastomosing network of floodways, some of which contain inset channels or channel segments. The broader Thomson River floodplain at Muttaburra does not behave as a homogenous unit: flow from individual sub-catchments is sometimes identifiable.

Flow in smaller channels is sufficiently active to transport sandy bedload and develop sinuosity despite the cohesive nature of the floodplain muds. Flow occurs both in-channel and in floodways at higher elevations. Where floodways in channels intersect, flow patterns can be complex, as is demonstrated at Pump Hole. Rising flow leaving the Thomson channel heads southwest along an anabranch, feeding into the Landsborough channel. If the Landsborough channel fills before the Thomson channel, it is possible that the anabranch will backfill and flow go in the opposite direction. At flood peak stage, the floodway from the north will feed into the anabranch at a high angle to the anabranch's flow direction. Waning flow may drain back into the Thomson channel.

Local information is that the Muttaburra Broadwater is shallowing (D. Stent-Smith, pers. comm. 2014), and it is possible that gullies from campsites may be a contributor. Gullying and bank erosion is associated with human use in other LEB rivers (Wakelin-King 2010), and sediment entering waterholes from gullies may contribute to this process (Costelloe 2011).

4.6 The Upper Thomson River B (downvalley from the Aramac Creek confluence)

From below the Aramac Creek confluence to the beginning of the lower Thomson River, the upper Thomson River exhibits a consistent gradient (Table 1) and suite of landforms. Owing to the project's time constraints it was not possible to examine the whole upper Thomson River: the field sites are located on the reaches north of Longreach (Figs. 3, 4), because these areas overlie the Galilee Basin.

Valley-Scale Landforms

In the reaches examined during field study, the upper Thomson River B is flanked on the south-east by low rises of vertic soils and a few low hills of sandstone outcrop, and on the north- west by low rises of vertic soils. Downvalley from the field sites, the river cuts through the line of outcrop so at Longreach the river valley's north-western margins are flanked by rocky hills and the south eastern margin by vertic hillslopes. The river valley does not appear to be constrained by the hills (c.f. section 4.7), although further investigation of hillslope-floodplain spatial relationships would be needed to confirm this.

In the field site reaches, some sections are dominated by floodways, and the main channel (hosted within one of the floodways) is only small. Some sections have fewer and more narrow floodways; these sections are dominated by floodplain bars, and in these the main channels tend to be large

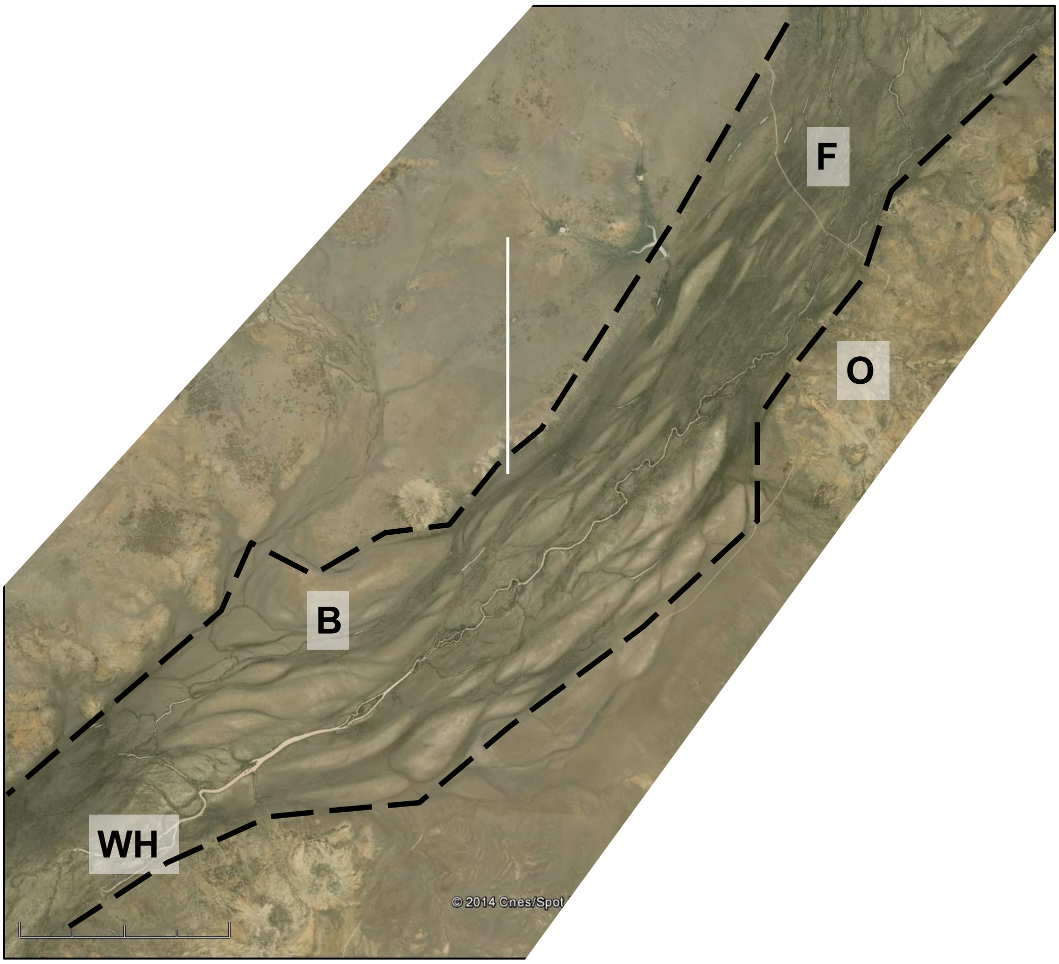

Fig. 36 Thomson River valley at Goodberry Waterhole.

The valley margin (black dashed line) is partially flanked by rocky hills of outcrop surrounded by sandy colluvial aprons (O). The north-eastern reaches are dominated by floodways (F). The south-western reaches, where Goodberry Waterhole (WH) is located, are dominated by floodplain bars (B). Flow top right to bottom left, white scale bar = 4 km. The Thomson/Aramac confluence is just to the north-east of this image's boundaries.

enough to host a waterhole (e.g. Goodberry Waterhole) (Fig. 36). The largest waterhole, Goodberry Waterhole, is 3.2 km long and 80 m wide, set within a discontinuous channel 10-30 m wide and 22 km long. Other waterholes are smaller, e.g. Galah Waterhole is 600 m long and 30 m wide. Waterholes are usually gently curved in planform, while channels are sinuous or locally anabranching in places. Smaller channels tend to be discontinuous, with a low-sinuosity planform. Floodplain bars tend to be highly elongate; their orientation and that of the floodways is approximately parallel to overall flow direction (as indicated by valley orientation). Although there are some places where channel orientation is at a high angle to the overall flow direction and the floodway orientation, in most places channel orientation is approximately similar to the overall flow direction.

Reach-Scale Geomorphology

Floodplain bars have broad planar tops with minor gilgai features, are poorly vegetated, and may have flood debris at the break of slope (Fig. 37). Floodways are moderately densely vegetated are of lower elevation. By visual estimate, the bar-floodway elevation difference is greater than is the case in the Cooper Plain. Most floodways are broad open swales, but some have a more distinct channel-like form and are likely to be a gradational to discontinuous channels in both form and process. In places, shadow bars behind floodway vegetation encourage germination and survival of other plants, so streamwise ridges of plants and sediment mounds are created. Where floodways host small channels, the floodway surface near the channels is likely to be sculpted into numerous small swales.

Fig. 37 Floodplain bar (right), floodway swale (left), and shadow bar ridge (arrow) with flood debris.

Channel and waterhole bank slopes vary from moderate to steep. The steepest slopes are in areas of geomorphic activity (anabranch nodes or sinuous small channels) where bank retreat is part of channel development. Indications of geomorphic activity included bank retreat exposing riparian tree roots, sediment deposition on bank tops and bank slopes, and small scour holes around riparian tree trunks. Many bank tops showed small swales or channels where floodwaters flowed from the floodplain into the channel, or from the channel out onto the floodplain, or both. In some places these in/outflow areas were expressed as sculpted bank tops and exposed tree roots, whereas in others more definite channels were developed (Fig. 38).

Fig. 38 Camoola Waterhole bank with an inflow/outflow channel (arrowed).

Vegetation is within the scope of this study insofar as vegetation affects landforms (by promoting sedimentation or suppressing erosion), or is affected by them. In field sites of the upper Thomson River, vegetation generally seems to be relatively sparse, and in particular there seems to be little to no riparian understory. In comparison to the Cooper Plain, the floodplains appear to have more bluebush and less lignum; gidgea scrub looks to be the dominant tree group in the floodplains, although coolabah continue to be dominant in riparian zones. Bean trees are also sometimes present. In these field sites, some riparian coolabah exhibit a growth habit in which the main trunk lies down the bank slope, as if a mature tree had been undercut and toppled forward, but then stabilised in this new growth position (Fig. 39). This was not a single occurrence: no trees like this were observed in the Cooper Plain or lower Thomson River, whereas a number of trees like this were seen in these reaches of the upper Thomson River.

Sediments and Depositional Landforms

Small valley-margin channels cut into hillslope vertic muds carry thin stringers of sandy bedload which has been transported from the colluvial slopes above. Since the larger channels and waterholes had water in them during the field component of this study, it is not known whether these sandy sediments are transported in-channel during present-day flow.

Fig. 39 A coolabah with its trunk extending down the bank slope.

Hillslope and floodplain sediments of crumbly grey-brown (apparently) silty and fine-sandy muds proved to be almost entirely mud aggregates upon testing with fresh water (minor components of fine sand or silt were present in some samples). The type and degree of expression of the gilgai features (heave topography, crabholes, self-mulching, and multiple cracking) is variable. Float of rounded pebbles, sub-rounded pebbles, and sub-rounded cobbles was common, not only on black-soil hillslopes near valley margins, but also in some floodplain bars. The lithologies indicated probable provenance of Glendower Formation or equivalent Cainozoic units, and regolith-overprinted GAB rocks. The distribution of these large clasts suggests two independent modes of occurrence: local clast movement through thin soil cover on the hillslopes, and fluvial transport and deposition from the high-energy flows.

The self-mulching nature of the vertic soils largely destroys depositional sedimentary structures. Trampling by stock is an additional factor. Signs of trampling were common in riparian zones, and where channel and waterhole banks were not steep, they were generally heavily trampled also.

Fluvial Processes

In the upper Thomson River, the disposition of the fluvial landforms arises from the river's variable flow regime. Above floodplain-level floods are an ordinary part of the river's behaviour: in at least some reaches, floods fill to the valley margins (given local variations in the alluvial valley width, it is not clear from the present research whether all reaches fill to a similar proportion from flow events of the same recurrence interval). In these floods, the largest floodplain bars are emergent, and most of the flow is accommodated within the floodways (Fig. 40). Channels are likely to be volumetrically insignificant during floods. In comparison with floodways, channels' greater depth and their roughness profile (higher in the riparian zones but much less in the channel centre) suggest that they will be a focus of greater stream power. In reaches dominated by floodplain bars, the flow's stream power is focused so that larger and longer channel segments are formed. In reaches dominated by floodways, the flow's stream power is distributed widely and channel segments are small and short. The corollary of this is that in different reaches, a single flow event will have different expression in terms of the proportion of water carried in-channel.

Fig. 40 Floodways, bars, and channels in the upper Thomson River.

Photo right, the river in flood; photo left, the river with water in the channels but not in the floodways. Google Earth image, central white scale bar = 4 km.

The inflow/outflow channels connecting channels and waterholes to the wider floodplain suggest that flows overtopping the banks of the primary channels may be an important method of water delivery to the floodplain. In some places, inflow/outflow channels were associated with small anabranches, and they may represent part of the process of anabranch formation. Geomorphic activity is also indicated by the presence of 'lying-down coolabah' in these reaches: their most likely process of formation is intermittent rapid bank retreat leading to tree collapse, followed by long-term bank stability.

Plant communities can influence the dynamics of sediment deposition during river flows, since riparian vegetation promotes bank top sedimentation and affects the distribution of in-channel stream power. From this point of view it would be valuable to know whether the absence of riparian understory was a grazing effect or a consequence of soil composition. The differences between the vegetation communities observed in the upper Thomson River and those in the reference reaches (the Cooper Plain) may relate to differences in fluvial function, landforms or soils, although they may also be influenced by land management practices.

In these reaches, the relatively small channels and waterholes with their relatively gentle bank slopes are more accessible to stock than larger channels or waterholes with steeper banks. Trampling by stock may make the bank tops more prone to erosion. It might not affect bank-slope resistance to erosion, since the sediment would be self-mulching into smaller particles anyway. Trampling by stock at the water's edge may affect bank integrity.

Gravel and cobble components in floodplain soils arise from two separate causes: excision of valley-margin segments by flood-level expansion of the drainage network, and deposition of gravelly bars from a high-energy flow. Both processes are likely to have happened during previous wetter climates.

The variation in hillslopes flanking the river valley (outcrop, subcrop with a shallow soil cover, and deep soil) may be reflected in differing hillslope runoff coefficients, affecting the amount and speed of delivery of rainfall into the river network. The distribution of outcrop is also likely to have affected development of the drainage network: the upper Thomson River and its tributary Aramac Creek are semi-confined by hills, whereas the unconfined black soil plains showed little river development.

4.7 The Lower Thomson River

The lower Thomson River is the reaches from Stonehenge (upvalley) to approximately 20 km below Jundah (downvalley). Below Jundah, the alluvial valley widens out into the Cooper Plain. At the Cooper/Barcoo confluence, approximately 44 km below Jundah, Cooper Creek begins.

Valley Scale Landforms

The lower Thomson River's valley is relatively narrow (Table 1, Fig. 41), in strong contrast to the wide valley of the Cooper Plain (Fig. 9). The alluvial valley is flanked by gibber plains and silcrete-capped hills of the Eromanga Lowlands physiographic unit (Fig. 10), which have relatively steep gradients down to the river valley. To the east, the hillslopes rise up to the Jundah scarp (Fig. 14). The major landscape elements are floodplain bars, floodways, channels and waterholes.

Channels are set within an anastomosing network of floodways. Within this floodway network, individual channels may be anabranching or single. Channel width is generally < 30 m, but varies along the flow paths, so that a channel may be discontinuous or continuous, and its width can change abruptly over a relatively short distance. The alluvial valley generally contains one to several primary channels and a number of minor channels. Wider channels tend to be of low sinuosity, but minor channels may be sinuous, especially if their flow path is at an angle to the overall reach flow direction (Fig. 41). Waterholes are part of this continuum of varying channel widths; they can be 30-75 m wide, and up to 4.5 km long (although most are shorter).

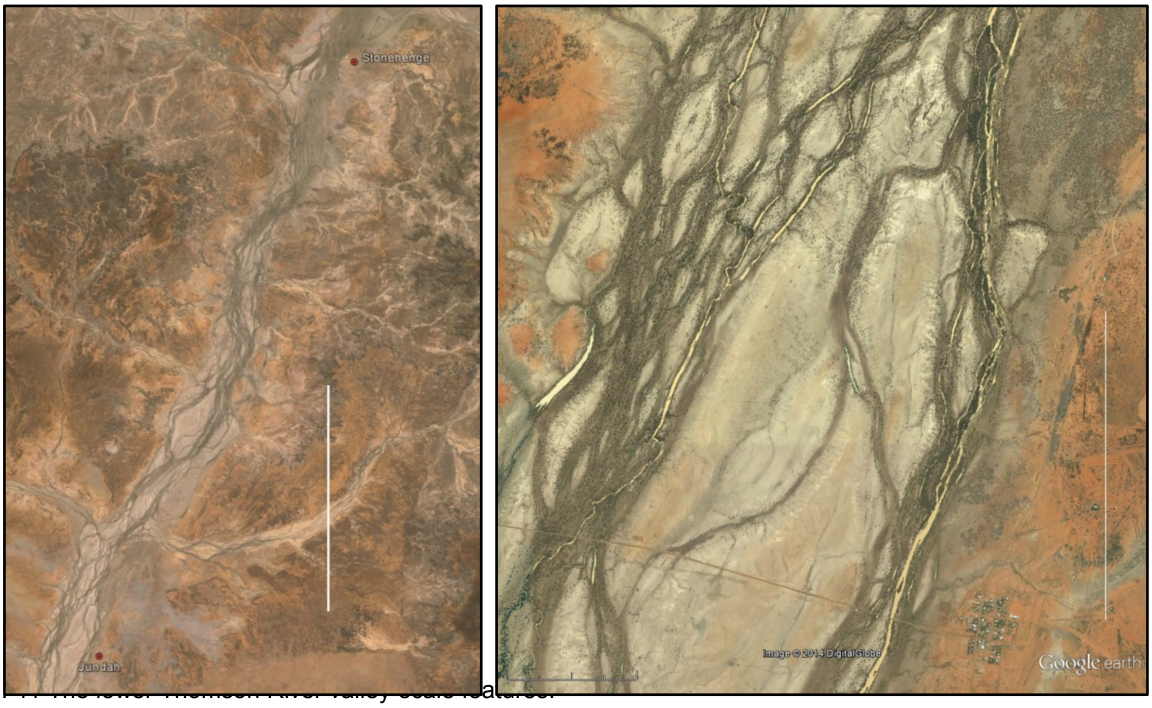

Fig. 41 The lower Thomson River valley scale features.

Left, orange-brown and dark grey gibber hills flank the river valley (pale, with dark grey flow paths). Google Earth image, white scale bar = 20 km, flow top to bottom. Right, the river valley at Jundah contains floodplain bars (pale grey to very pale orange), anastomosing floodways (medium grey), and discontinuous channels and waterholes (white to very pale grey, from light reflecting from the water's surface). White scale bar = 3 km, flow top to bottom.

The river valley's most prominent features are the floodplain bars and the floodways. Remote imagery (Google Earth) indicates that there are some aspects of the these landforms which are unlike similar landforms in the Cooper Plain: there is a more unambiguous visible distinction between floodplain bars and floodways; many floodplain bars are slightly gullied at the edges, giving them a scalloped or crenelated appearance; many of the floodplain bars have pale orange tinge on the upper crest.

Fig. 42 The primary channel at Jundah.

Two smaller channels on either side of the left-hand arrow combine to form this larger channel. The banks are steep to vertical and eroded (beneath circled figure for scale). The floodplain has metre scale topography from the floodway swales (right-hand arrow).

Reach Scale Geomorphology

Two reach areas were visited during fieldwork. At Stonehenge, approximately 90% of the valley width is occupied by floodways. There are 2-4 channels, all small, and no waterholes. The channel that was examined showed evidence of active meandering (outer bank erosion, inner bank floodplain construction) with in-channel deposition of concave bars.

At Jundah, approximately 30% of the valley width is occupied by floodways. There are two channels, one of which is relatively large. The primary channel is along the eastern valley margin (Fig. 41). It is wider than the channels feeding into it from immediately upstream (60 m vs 15-25 m) (Fig. 42), and maintains that width for several kilometres. These factors and location of the township nearby indicate that this reach serves as the local waterhole. The banks are steep to vertical, with common cut faces and exposed tree roots. The tree roots are thin and show right-angled 'knees' (Fig. 43), indicating that bank retreat is recent and that the previous bank also had a vertical face. The channel is set within a floodway (Fig. 41), thus the ‘floodplain’ on either side of the channel is sculpted into minor swales (approximately 10 metres wide, approximately 1.5 metres deep) with moderately steep banks.

The floodplain bars have a fairly flat upper surface showing only poorly-developed gilgai features. They are separated by floodways of lower elevation. In comparison with the Cooper Plain, the bar-edge slope between bar top and floodway is steeper: either the elevation difference is greater, or the bar-floodway transition takes place across a shorter distance, or both. A consequence of this steeper gradient is that floodplain bar edges are gullied. The gully networks are not extensive and

Fig. 43 Exposed root 'knees' and conglomerate layer.

most do not appear to be actively self-propagating; bar-top flood runners or chutes are uncommon. This suggests that floods rarely overtop the larger bars, or if they do their stream energy is low.

Geology, Sediments and Depositional Landforms

At Stonehenge, a quarry in the valley-mansion hillslope exposed colluvium overlying white rock, while the surface sediments showed polished pebbles and heavily iron stained siliceous small pebbles. At Jundah, valley-margin channel banks exposed mud overlying a pale medium to coarse sandstone overprinted by a mottled weathering profile. The rock was softened by exposure to water, and appeared to be liberating sand into fluvial transport. Floodplain bars (which on Google Earth images showed an orange tinge, Fig. 41) consistently showed float of pebbles of silcrete and well-rounded polished vein quartz (see Fig. 8). A floodway swale near Stonehenge also showed angular, low-sphericity cobbles of iron-stained medium grained sandstone. They showed no evidence of having been deposited from fluvial transport, nor that flood waters scoured around them. The disposition of rock and regolith demonstrates that the lower Thomson River valley is incising into bedrock (consisting of GAB Winton Formation overlain by Cainozoic Glendower Formation, and a weathering profile which includes bleaching, mottling, and iron and silcrete impregnation).

The channels contains some elements of coarse bedload: sandy as well as muddy convex bars are accreted onto the banks of sinuous small channels, and some bank-attached conglomerate bars occur in the main Jundah waterhole. The conglomerate bars were not far downriver from rocky outcrop, and were in a reach that probably experiences relatively high stream power (just downstream from the confluence of two smaller channels). This suggests that channel energy is usually only high enough to locally redistribute pebbles and cobbles. The distribution of pebble and cobble clasts on floodplain bars and in one of the floodways also indicates that coarse sediments are not transported under current flow conditions. However, flow energy is sufficient to transport sand-sized bedload.

The floodplain sediments are paler in colour than those of the Cooper Plain, and appear to have a significantly higher proportion of sand. However, examination indicated that these sediments consist almost entirely of mud aggregates. The floodplain muds of the lower Thomson River contain a minor amount of fine to medium-coarse quartzose sand.

Landscape History and Modern Fluvial Processes

In the geological past, the river has cut across a band of erosion-resistant Cainozoic rock and silcrete. The river valley is narrow and valley widening is still an active process. There is now not a knickpoint within these reaches (the lower Thomson River has the same gradient as most of the upper Thomson River), however the floor of the river valley is still incising into bedrock. Since flows are intermittent and the Thomson River's flow energy is generally low (the river does not carry cobbles very far), it is likely that incision is not rapid.

The lower Thomson River's narrow valley cross-section is not big enough to contain the larger flow events of the present-day climate , and flows back up the valley from the bottleneck at Stonehenge (Phelps et al. 2006, 2007). Landforms and sediments suggest that lower Thomson River flow energies are higher than in reaches up- or down-valley (upper Thomson River or the upper Cooper Plain). Since the lower Thomson River's gradient is the same as that in the upper Thomson River, and lower than that of the upper Cooper Plain, the higher flow energy is not a response to slope. It is likely that the lower Thomson River's steep valley-margin hillslopes act more strongly to constrict the fluvial valley, leading to greater depth of flow and therefore higher stream power.

Some of the Jundah-Stonehenge reaches are occupied almost entirely by floodways but have only small channels, whereas others have more channel and less floodway. That is, in some reaches a greater proportion of flow is carried in floodways, while in others channels carry a greater percentage of the flow. This will reflect reach-scale variations in flow energy.

If the river valley is underlain by rock, it is possible that the proportion of discharge lost to infiltration (transmission loss) may be small (less than that of the Cooper Plain, which is underlain by porous sands of the Katipiri Formation).

5 Thomson River: Overview and Comparison

Thomson River Overview

The Thomson River drainage network as examined in the present study comprises headwater reaches in the uplands above the escarpment, the tributaries, and the main river axis which itself includes the upper Thomson River (Thompson River A, a relatively short stretch which is transitional in nature from tributaries, and Thompson River B, the main drainage axis), the lower Thomson River, and Cooper Creek (Queensland reaches).

The factor that is common through the study area is the variable flow regime and its interface with a diverse set of landforms. Flow patterns vary from long periods of no-flow, to floods which inundate substantial parts of the floodplain; flows in which water occurs only in-channel are regarded as minor by local stakeholders (Phelps et al. 2006, 2007). Flows can enter the main river axis from all tributaries or only a few; flows don't have to begin at the top of the drainage network or be continuous to the bottom. At the same time, the landforms through which the flows pass have not formed solely in response to fluvial processes, for example valley width is highly variable (see below). The consequence of this is that some fluvial processes may not occur in systematic top-to-bottom sequences. For example, downvalley sediment transport is likely to be intermittent firstly because flow pulses only travel a certain distance before their stream energy declines below sediment transport thresholds, and secondly because flow pulses may move from a more-confined to a less-confined setting imposed by pre-existing landforms, causing stream energy to decline and sediment loads to be dropped.

Valley width is highly variable down the system. In the uplands, some of the tributaries, and those parts of the main river axis which are flanked by the vertic soil hillslopes, the alluvial valley is probably mostly unconfined. Some parts of the upper Thomson River axis and some of the tributary junctions are partly confined by low hills. The lower Thomson River is strongly confined by relatively steep hillslopes of erosion-resistant rock. It acts as a bottleneck, against which large flows are sometimes impounded. The Cooper Plain has an extremely wide valley, within which the river is entirely unconfined. The lack of confinement in the Cooper Plain expresses itself in the presence of the many swamps, and in the way in which channel and floodplain bar orientations are more divergent from the overall flow direction (in comparison to landform orientation in the more confined reaches).

There are two components to the river's sediment load, sand and mud aggregates. The river system above the escarpment appears to be entirely sandy (however there were only few field sites in this area), but does not appear to contribute sediments into fluvial transport. Sandy sediments enter the river system from the colluvial aprons beneath the escarpment and surrounding the rocky hills flanking the upper Thomson River, and from valley-flank erosion in the lower Thomson River. There is some evidence that sand is under transport and present in some of the channels in the tributaries and the upper Thomson, whereas it is apparently much less common in the lower Thomson and the Cooper Plain. However, the scope of this project was insufficient to determine the spatial distribution of coarse bedload, especially since its distribution is likely to be complicated (as described above). Vertic soils overlie the rocks in the upper catchment, and hillslopes flanking the upper Thomson River are the source of the mud aggregate sediments which are such a characteristic part of the Thomson and Cooper Rivers. Mud aggregates travel as sand-sized particles, and the primary grain size of their components is disguised by their aggregate nature (Wakelin-King and Webb 2007a). Primary particle size is not acted upon by fluvial processes, and so is unlikely to vary systematically with downstream distance The gilgai soils which are the mud aggregate deposits have variable expression (of colour, macropore type and size, etc.) which relates to inundation frequency (Fagan and Nanson 2004) as well as sediment composition (observations from this present study).

Gradient is usually an important component of a river's stream power, however in the Cooper/Thomson system it may be subordinate to other factors. In the uplands, the gradients are the steepest in the catchment, but the system is dominated by low-energy landforms. The gradients are also relatively steep in the tributaries and the upper Thomson River A, yet these reaches have only small disconnected channels and no sizeable waterholes. The Cooper Plain has gradients which are the same as, or lower than, the upper Thomson River, yet the Cooper Plain has multiple continuous channels and many large waterholes.

Stream power in the Cooper/Thomson Rivers is more strongly driven by flow volume. At a coarse scale, the size of the river system as a whole and the size of individual elements (channels and waterholes) increases with distance downstream, reflecting the addition of tributaries draining large catchment areas. In the uplands, the low-energy landforms are likely to be the result of low flow volumes. Continuous channels and ecologically important waterholes do not occur in the main drainage axis until below the confluence of a number of tributaries. The Cooper Plain has the most substantial channels and waterholes, and it is downvalley of the Thomson/Barcoo confluence. Stream power in the lower Thomson River is likely to be related to flow depth. Its more erosive landforms (in comparison to reaches up- or down-valley) are unlikely to be related to discharge (since there is relatively little opportunity for substantial tributary input or transmission loss in these reaches), but are probably the result of increased flow depths as the river is constrained between steep valley hillslopes.

Thomson River in Comparison to Cooper Creek Reference Reaches

This section considers how much of the Thomson River can be understood from the existing research on Cooper Creek. The reference reaches (Cooper Plain, Fig. 10) are the standard because they have been the site of all the existing geomorphological research in this catchment (Queensland section).

Within the reference reaches, the river's behaviour is shaped by its large potential discharge (most of the major tributaries have joined the river by this stage), low gradient, very wide valley (most of the river is unconstrained by the valley margins), sediment load of robust mud aggregates, and underlying Cainozoic sand aquifer (into which the river discharges flood waters, thus one of the factors in transmission loss).

Within this context, Cooper Creek transmits flow down a network of anabranching major and minor channels, and a coexisting network of anastomosing floodplain-height floodways or swales, which wind around braid-like floodplain bars. The anabranch channels include waterholes, which are substantial aquatic ecosystems. The floodplain includes extensive swamps, subject to inundation but away from the primary flow path, and these are biologically very productive. These are also aquatic ecosystems: though neither lotic nor lentic, they are dependent on inundation, which places them within the definition of an aquatic ecosystem (Aquatic Ecosystems Task Group 2012). The anabranching channels distribute water from major channels to minor channels and swamps, and floods inundate the braidplain. Distribution of water across this wide area is another factor in transmission loss. Variation in stream power across the Cooper Plain is a key factor in landform maintenance, particularly with respect to the steep channel and waterhole banks, and the distribution of swamps. Channel and waterhole banks are generally stable.

The uplands (including the Lake Dunn reaches) are unlike the Cooper Plain in every respect. The gradient is an order of magnitude greater than that of the Cooper Plain. There is no vertic soil (in the reaches examined), and both hillslopes and creek are dominated by coarse sandy sediments. Despite the high gradient, most landforms indicate low-energy fluvial processes. It is likely that the present day landforms are a result of low flow volumes operating within a context of partially infilled palaeovalleys. Because of the relatively steep gradients and the nearby low base level at the foot of the escarpment, the landforms are vulnerable to erosion and incision if they experience greatly increased discharges. In a worst-case scenario, an erosion event moving the landforms across the threshold of geomorphic change may lead to self-perpetuating valley floor incision with concomitant ecosystem desiccation.

Lower order tributary creeks have very small landform elements, reflecting a small discharge. They are dominated by floodways and floodplain bars. Unlike the Cooper Plain, they lack swamps and have few and small channel segments. Landforms and sediment load of tributaries vary according to the sub-catchments.

Aramac Creek is a lower order tributary creek, unusual in its very heavily vegetated nature and its flow pattern which is said to be 'slow'. Its downvalley gradient is more than double that of the Cooper Plain. Waterholes in the upper Aramac Creek appear to be silted up and with a raised cease-to-flow level, and it is possible that Invasive Native Scrub may have affected the flow regime. The hillslopes around Aramac Creek are rich in quartz sand, in some places only thinly covered or not covered by the vertic soils. Unlike the Thomson River, deflation of the sandy soils is a management issue here.

Five tributaries come together near Muttaburra, and this is the beginning of the Thomson River. There is a short transitional zone in the upper Thomson River, where reaches have steeper gradients than the Cooper Plain. Although the Thomson River is a single alluvial valley in these reaches, flow from different tributary sub-catchments can still be differentiated. In comparison with the reference reaches, landform elements are smaller, there are few waterholes, only one of which is large, and two or three small channels. Unlike the Cooper Plain, there are some indications of channel relocation.

Most of the upper Thomson River has a gradient which is the same as that of the lower Thomson River, and is intermediate between the upper and lower Cooper Plain. The main landform elements are floodways, floodplain bars, channels and waterholes. Unlike the Cooper Plain, the landform elements are smaller in scale and less likely to be oriented at an angle to the overall flow direction. The floodplain bars are more likely to be elongate with axes parallel to the river valley, and the channels and waterholes are oriented approximately parallel to the river valley. There are no swamps of the kind occurring in the Cooper Plain. In comparison to the Cooper Plain, the upper Thomson River channel and waterhole banks showed more evidence of geomorphic activity.

In the upper Thomson River, and unlike the Cooper Plain, small scour holes occur around riparian tree trunks. Also in these reaches, inflow/outflow channels connecting channels and waterholes to the wider floodplain were common; these may be a feature in which these reaches are unlike the Cooper Plain. In the Cooper Plain, water is delivered from channel to floodplain via the network of small channels (see section 3), whereas in the upper Thomson River there seems to be a greater role for flows overtopping the banks of the primary channels. If this is a case, this is a significant difference in fluvial process between these reaches and the Cooper Plain. However, it is also possible that inflow/outflow channels exist on the Cooper Plain, in areas outside those visited in the field study. Despite this geomorphic activity, banks do not show the degree of rapid erosion that was evident in the lower Thomson River.

Compared with the Cooper Plain, upper Thomson River hillslope and floodplain vertic soils are more variable in the type and degree of expression of the gilgai features (heave topography, crabholes, self-mulching, and multiple cracking). Trampling by stock was seen to be more common in these reaches than in the Cooper Plain or the lower Thomson River. It is not known whether this was a result of higher stocking rates or some other factor. In the larger channels and waterholes in reach areas downstream, many of the banks were too steep to be heavily used by cattle, whereas stock have much more access to water in the upper Thomson River.

The lower Thomson River's alluvial valley is narrow and constrained by relatively steeply-rising rocky hillslopes. The landforms indicate relatively high stream power, including indications of fairly rapid bank erosion, scalloped edges to the floodplain bars, and steeper bar-edge slopes. The main landform elements are floodways, floodplain bars, channels and waterholes. They are not dissimilar to those in the Cooper Plain, except in being much reduced in scale, and more likely to have gullies and bank erosion. There were some indications of intermittent bank retreat, suggesting a less stable channel network than is the case in the Cooper Plain. Unlike the Cooper Plain, these reaches contain no swamps. The alluvial valley is cutting down into outcrop, so the river is not underlain by the Cainozoic aquifer, and this may mean that transmission loss is less in these reaches. The absence of swamps and smaller valley width to be occupied by floodways and minor channels may also decrease transmission loss.

6 Conclusions

This report presents the first investigation of the Thomson River's fluvial geomorphology. This baseline overview expands the information available to land and catchment managers, describing the relationships between fluvial processes and landforms, and suggesting areas of further investigation. This report presents the Thomson River alongside information from published research on the reference reaches (the Queensland reaches of Cooper Creek) which are used to interpret the Thomson River landforms. The reference reaches are considered in this report primarily because publications about the reference reaches are commonly used by stakeholders as a knowledge base for land management and risk management, and the comparisons and contrasts are important. The greater detail of studies in the reference reaches also provides useful information which can be applied where such detail was not possible within this project.

A key outcome of this investigation is that the Thomson River is similar but not identical to Cooper Creek, and the similarities decrease with distance upstream. The most upstream reaches can be very dissimilar:

> The uplands are dominated by coarse sediments and are capable of high-energy flow behaviour in a way that makes them susceptible to potentially serious ecosystem damage. Since it is the uplands that overlie potential coal or coal seam gas deposits, it is important to note that there are limitations to the applicability of the existing published Cooper Creek research.
>
> In the uplands, base level lowering in or high-energy flows across vulnerable landscape elements will increase the possibility of valley floor incision. Vulnerable areas are likely to include the scarp knickpoint, the lake sill, or the banded vegetation hillslopes. The most likely scenario for high energy flow is increased discharge down the existing relatively steep gradients.
>
> The tributary Aramac Creek is unlike the other Thomson River tributaries in ways that may be relevant to rangeland management (if they are a result of grazing management), or to understanding lower-order tributary flow behaviour (if they arise from Aramac Creek's sedimentary and topographic context).

The Thomson River's fluvial landforms are shaped to deliver a highly variable flow regime down a low-gradient drainage network. The fundamental landforms are broad floodways anastomosing around floodplain bars. Channels exist within some floodways but for much of the Thomson River they are not the dominant landforms of flow transmission. With increasing distance downstream from the lower-order tributaries, the river carries increased discharge and experiences higher stream power, and channels become increasingly significant (wider, longer, greater degrees of connectivity, and more and larger waterholes).

Management Implications and Knowledge Gaps

This study's goal was to provide baseline investigation into the Thomson River's fluvial processes. Incidental to this goal some knowledge gaps and management implications have been identified.

This is the first investigation of the Thomson River's geomorphology: it is a starting point for more detailed work. Description and analysis of a wider range of landforms in the different reach areas will give a better understanding of channel formation and evolution, floodway: channel relationships, and the level of geomorphic activity promoted by flows of different recurrence intervals. Reach areas which are particular geomorphology knowledge gaps are the Barcoo/ Thomson confluence, Aramac Creek, the uplands, and the low-order tributaries. Investigation of coarse sediment distribution down the Thomson River and into the Cooper Plain is likely to show interesting links with valley confinement and channel distribution. Aramac Creek is likely to yield significant information on either fluvial processes or land management history, depending on which factors are links to its differences from other Thomson River tributaries.

Currently, the most widespread observed effects of humans on the river system was seen to be small-scale road crossings occluding flow paths and the cutting of tree limbs for firewood at popular camping spots (riparian zones of waterholes). Waterhole riparian zones may also be being subjected to trampling and grazing by stock, and trampling and gully initiation by humans. Information on what constitutes good-condition riparian communities in the Thomson River, and waterhole-bottom topography and depth in e.g. Muttaburra Broadwater, would be useful in documenting the Thomson River's fluvial processes. If this information is not currently being collected, it is a knowledge gap.

Potential new effects of humans on the river system may arise from development of coal resources. (Please note that this section is not saying that subsidence or artificial discharge *will* occur as a result of resource development: it is indicating the ways in which, *if* such events should occur, its effects may manifest in the landforms).

- Flow paths are complex within the alluvial valleys. The downvalley flow path of a particular flow event can be affected by subtle factors of gradient, the distribution of anabranch nodes, or tributary asynchronicity. Subsidence that expresses itself within an alluvial valley may alter the flow paths, which may have effects extending far downriver. Similarly, road structures that occlude or divert flow from one path to another will have detrimental effects on downvalley ecosystems.

- Subsidence lowering local base level can create a knickpoint, leading to upstream-migrating channel or floodplain incision, and (depending on the valley context) lateral erosion up the valley flanks. Downstream-propagating erosion can also occur, if sediment-poor flows emerge from the downstream end of a newly-created depositional void.
- If subsidence fractures the rock or regolith underlying the alluvium, this may change surface-groundwater interactions.
- Artificial discharge of water down a drylands river is unlikely to be beneficial to river condition. Such discharge is likely to change vegetation communities, which will directly affect landforms (by changing sedimentation and erosion). Investigation of Aramac Creek may clarify the likely processes.
- The experience of landholders in the Cobar Peneplain is that Invasive Native Scrub infestations can be managed using (amongst other tools) patch burning. If this proves to be the case in the Lake Eyre Basin, commercial infrastructure will need to be designed to accommodate this practice.
- The river's ordinary flow behaviour includes floods which can be very widespread, routinely filling much or all of the valley floor. This information should be part of the design criteria for resource infrastructure, especially large works such *as* open-cut pits, storage ponds, overburden piles, etc.
- Vegetation is not just an ecological element, it is also an important element in fluvial processes. This is especially the case in drylands rivers, where substantial vegetation occurs along important flow paths (including in-channel trees in some places). Depending on the landform context, vegetation acts to maintain channel banks, promote channel stability, provide roughness elements that can be important in mediating flows, preserve valley floors against erosion and incision, and provides many other services to the fluvial system. Vegetation clearing or thinning during infrastructure development has implications for the fluvial processes, and these aspects should be considered in the planning process.

Hydrologic models (rainfall-runoff routing models) are sometimes used to provide river-scale flood frequency analysis. They use algorithms to route the flow through a simplified model of the flow path (e.g. a link-node network). They output discharge values on a multi-reach or whole-river scale, and are calibrated to real flow occurrences (e.g. Ryu et al. 2014). If hydrologic modelling was to take place on the Thomson River, the following factors may be relevant.

- The degree of hillslope-alluvial valley connectivity is likely to be different between the Cooper Plain, the lower Thomson River, and the upper Thomson River.

- The physical characteristics of the hillslopes bordering the alluvial valleys are likely to be different between the Cooper Plain reaches and the lower Thomson River, and within the Winton Blackall Downs physiographic unit where the soil thickness and depth to rocky subcrop may vary.
- The Cooper Plain is underlain by a porous aquifer, but other river reaches are not.
- In the Muttaburra reaches, the single alluvial valley may contain flow pathways that operate semi-independently.

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