Soil Horizons Pty Ltd, Townsville

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Irrigation potential of the soils of the Flinders River Agricultural Precinct, northwestern Queensland: a desktop study

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EXECUTIVE SUMMARY

Information derived from the published literature was used to prepare this report on the irrigation potential of the soils in the vicinity of the upper Flinders River, between Hughenden and Julia Creek. The soils occupy four land systems, each of which is recognised by its distinctive, recurring patterns of topography, soils, and vegetation. The Julia Land System is the most extensive in the upper Flinders River catchment and is characterised by treeless rolling plains with Mitchell grass *(Astrebla spp.)* pastures on cracking clay soils that are underlain by weathered, Cretaceous shales, mudstones, or limestones.

Three other land systems are underlain by clay-rich alluvial sediments of the Flinders River and lie downslope of, and are inset as younger stream deposits into the Julia Land System. Downstream of about Marathon, the older alluvial terraces of the Flinders River now form the Balbirini Land System that stands at or just above the levels attained by major floods on the river. The Georgina and Gregory Land Systems have developed in the lower, modern alluvial floodplain deposits of the Flinders River and have been deposited in drainage depressions and channels eroded into the older alluvial deposits. These predominantly clayey sediments, with some sandy stream channel and levee deposits are inundated by even small floods on the river. They define the Gregory Land System in the Hughenden-Marathon area in the east and, farther downstream, the Georgina Land System.

Discussing the land in relation to the four land systems has allowed the identification of broadly similar soil-landscapes in the region, and has offered a practical guide for assessing the irrigation potential of different parcels of land in the region.

Grey – olive brown cracking clay soils, some with gilgai microrelief, are the dominant soils of the four main land systems in the upper Flinders River catchment. The few soil chemical analyses available from the catchment, and from similar soils on the extensive rolling downs of western Queensland, indicate possible soil alkalinity, soil salinity, and soil sodicity limitations to conventional, flood-irrigated agriculture. The use of modern, well-controlled trickle irrigation or overhead travelling or centre-pivot irrigation techniques may overcome these limitations. Small areas of sandy, former stream channel and levee deposits of the alluvial land systems also hold promise for the establishment of irrigated agricultural enterprises.

The Flinders River Agricultural Precinct offers opportunities for development of irrigation infrastructure and cropping on a mosaic of smaller pockets of land rather than one large contiguous area. The mosaic design uses the best-suited soils and reduces the risk for off-site impacts, delivering productivity and environmental safeguards.

Some potential sites for irrigated agriculture have been identified by the landholders in the vicinity of the upper Flinders River, but before irrigated farm plans are prepared for them, they will require detailed, site-specific analyses of their topography, relationships with river flood heights and recurrence intervals, and soil assessments. A three stage strategy for site and soil assessment has been set out.

Glossary of technical terms used in this report

Term	Definition
Anions	Elements or compounds held in the soil solution in anionic or negatively charged forms; nitrate and phosphate anions are extremely important anions in sustaining plant growth, especially in soils of the dry tropics.
Aggregate (soil)	Many soil particles held in a single mass or cluster such as a clod, crumb, block, or prism.
Alkaline soil	See ‘Soil pH.
Alluvial terrace	A level, usually narrow plain bordering a river but standing at an elevation above the commonly attained flood level and rarely inundated.
Alluvium	A general term for all the unconsolidated material deposited by streams, including gravel, sand, silt, clay, and all variations and mixtures of these.
Calcareous	Containing lime (see ‘Lime’)
Carbonate	Usually calcium carbonate in soils. See ‘Lime’
Cation	Elements or compounds held in the soil solution in cationic or positively charged forms; the basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) and acidic cations (H^+ and Al^{3+}) are extremely important in sustaining or constraining plant growth.
Cation exchange	The interchange between a cation in the soil solution and another cation on the surface of a material such as fine clays or organic colloids (Glendinning 2000).
Cation exchange capacity (CEC)	The sum of cations that can be adsorbed onto negatively charged sites on the surfaces of colloids. The CEC of a soil provides an indication of its fertility.
Chloride content	The amount of soluble salt present in the soil as chlorides. Values exceeding 300 mg / kg (equivalent to 300 parts per million) suggest that the soil may contain sufficient sodium chloride, or common table salt, to inhibit plant growth (see ‘Soil salinity’).
Chromosol	Soils with a strong texture contrast between A horizons (topsoils) and B horizons (subsoils) and are neutral to alkaline (Isbell 1996)
Clay	A general term for fine particles of inorganic (mineral) origin in soils and of colloid size (< 0.002 mm).
Cretaceous	Pertaining to the Cretaceous Period of the geological time scale, approximately 141 – 65 million years ago; the time period at the end of the Age of Dinosaurs and preceding the Age of Mammals.
Crust	A surface layer on soils, ranging in thickness from a few millimetres to as much as 30 mm, that is much more compact, dense, hard, and brittle when dry than the material immediately beneath it.
Dermosol	Soils with structured B horizons (subsoils) and lacking a strong texture contrast between A (topsoil) and B horizons (Isbell 1996).

Term	Definition
Electrical conductivity (EC)	The capacity of a moist substance to conduct or transmit electrical current. Soil EC is measured in 1:5 soil:water suspensions in units of decisiemens per metre (dS / m) and relates to the amount of soluble salts in the soil solution. Soil EC values of more than 0.25 dS/m indicate moderately salty soils that are likely to affect the growth of many plants. Salt-tolerant plants such as triticale and barley will grow in clay soils with EC values of 0.75 – 1.28 dS/m; only extremely salt-tolerant plans such as saltbush will grow in clay soils with EC values greater than 2.03 dS/m..
Exchange complex	All the materials, primarily inorganic clays or organic humus, that contribute to the cation exchange capacity of the soil (Glendinning 2000).
Exchangeable cation	A positively charged ion held on or near the surface of a solid particle by the negative surface charges on the colloid and which may be replaced by other positively charged ions in the soil solution (Peverill *et al.* 1999). Cations of most interest in soils are the basic cations: Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}; and the acidic cations: H^{+} and Al^{3+}.
Exchangeable sodium percentage (ESP)	The amount of exchangeable sodium ions present in a soil sample as a percentage of the sum of its basic and acidic exchangeable cations: ESP = (100 x Exchangeable sodium content of soil) / Sum of cations in the soil
Floodplain	The land bordering a stream, built up of sediments deposited from the overflow of the stream and subject to inundation when the stream overtops its banks in even minor flood events.
Gilgai	The microrelief of soils produced by expansion and contraction with changes in moisture and commonly found in soils that have large amounts of the type of clay that swells on wetting and shrinks and contracts on drying.
Gypsum	Calcium sulphate [$CaSO_4.2H_2O$]
Hectare (ha)	1 hectare (ha) = 100 x 100 m = 10,000 square metres = 2.5 acres
Land system	A parcel of land that is characterised by distinctive, recurring patterns of topography, soils, and vegetation (Perry *et al.* 1964)
Leaching	The removal of soil materials in solution from the soil profile by percolating waters (Brady and Weil 2002).
Levee	A long, low, narrow ridge of sandy sediments adjacent to a stream channel and formed by the deposition of coarser sediments during flood stages of the stream.
Lime	Calcium carbonate [$CaCO_3$]
Limestone	A hard sedimentary rock that consists chiefly of calcium carbonate (lime). In the upper Flinders River catchment most of the limestones are ‘muddy limestones’ that contain up to 20% clay, silt, or fine sand.
Microrelief	Small local differences in topography, including mounds, hummocks, swales, pits, and depressions that may be as small as 1 m or so in diameter and with elevation differences of less than 2 m. See ‘Gilgai’.
Mudstone	A hard sedimentary rock that, in the upper Flinders River catchment, consists of particles of clay, silt, and fine sand; coarse sand (1 – 2 mm diameter) or gravel (coarser than 2 mm) fragments are absent. Calcareous mudstones may contain up to 20% calcium carbonate (lime).
Ped	See ‘Soil structure’.

Term	Definition
Saline soil	A soil containing sufficient soluble salts to impair its productivity. The electrical conductivity of the saturated extract is greater than 4 dS/m. (see also ‘Sodic soil’ and ‘Electrical conductivity’)
Sediment	Transported and deposited particles derived from soils, rocks, or biological materials.
Self-mulching soil	A condition of the surface soil, notably of clays, in which a high degree of aggregation is exhibited in which the aggregates, usually 2 – 10 mm diameter, fall apart, naturally, as the soil dries to form a loose, granular mulch at the soil surface. A thin crust may form over such soils following rain but the crusts are tin, fragile and readily disrupted by even weak disturbances such as the impact of light grazing.
Shale	A hard, laminated mudstone-like rock that consists predominantly of clay-sized particles and commonly with a strong cleavege that produces flat, chippy fragments usually 5 – 50 mm long.
Slickensides	Stressed surfaces in soils that swell and shrink. Slickensided surfaces are smooth, polished, and bear very shallow striations produced when one block of soil moves against another.
Sodic soil	A soil that contains sufficient exchangeable sodium to influence the development of soil properties that are adverse to plant growth. Non-sodic soils contain less than 6% exchangeable sodium; sodic soils contain 6 – 15% exchangeable sodium, and strongly sodic soils have exchangeable sodium percentages greater than 15%.
Soil fertility	The status of the soil with respect to the amount and availability to plants of nutrient elements that are essential for plant growth (Glendinning 2000).
Soil pH	A measure of acidity or alkalinity of the soil. The pH of the soil is equal to the negative logarithm of the hydrogen ion concentration in the soil. Acid soils have pH less than 6.5; neutral soils have pH 6.5 – 7; alkaline soils have pH greater than 7. Soil pH is measured by using an electrode inserted into a 1:5 soil : water suspension. Field test kits have been produced commercially and produce less accurate pH estimations based on colour changes of an indicator applied to the soil.
Soil salinity	The total amount of soluble salts present in the soil, measured in terms of the electrical conductivity and chloride content of the soil (see ‘Electrical conductivity’ and ‘Chloride content’).
Soil sodicity	An indication of the exchangeable sodium content of the soil (see ‘Sodic soil’).
Soil solution	The aqueous phase of the soil and its solutes consisting of ions dissociated from the surfaces of the soil particles and of other soluble minerals (Brady and Weil 2002).
Soil structure	The combination of soil particles into naturally occurring aggregates of similar size and shape (i.e. ‘peds’) and their arrangement in the soil profile into platy, blocky, prismatic, columnar, granulated, or crumb shapes. Lenticular peds are lens shaped and indicate that the soil has undergone some swell-shrink movement.
Subsoil	That part of the soil profile below the topsoil (see ‘Topsoil’).
Topsoil	The uppermost part of the soil, ordinarily moved by tillage, or its equivalent in uncultivated soils.
Vertosol	Clay soils with shrink-swell properties that exhibit strong cracking when dry and at depth have slickensides, and/or lenticular (i.e. lens-shaped) structural aggregates. Although many Vertosols exhibit gilgai microrelief, this feature is not used in their definition (Isbell 1996).

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1. INTRODUCTION

1.1 Irrigation and soils

Since European settlement in northwestern Queensland some 150 years ago, the region's vast savanna rangelands have been used for the grazing of native pastures by domestic livestock. Growing food, fibre, and fodder crops has occupied a tiny part of the land and, except for a few pioneering endeavours, irrigated agricultural production has been virtually negligible in the region. Small areas of irrigated fodder, cotton, small grains, and cut-flower crops have been established over the last two decades in the vicinity of the upper Flinders River; opportunities may arise in the future to expand and diversify such enterprises.

If irrigated agriculture is to be developed across the region, a basic question that must be addressed is: *If water supply were a non-limiting factor in the upper Flinders River region, are there any areas of soils with physical and chemical properties that might support irrigated agricultural production?*

A definitive answer to this question would address issues of land tenure, water rights, and economics that are beyond the scope of the present paper. However, the answer does require a sound knowledge of basic soil and agronomic issues such as:

- the nature and properties of the potentially irrigable soils (especially their soil-water properties related to infiltration, profile water storage, and plant use, and the geochemical constraints that the soils present to plant growth such as higher than desirable levels of soil acidity, alkalinity, salinity, and sodicity);

- the nature of the soil landscapes such as gilgai microrelief, soil cracking, or closely spaced stream channel sands that may influence the irrigation design (e.g. irrigation by flood, overhead travelling or centre-pivot irrigator, or trickle irrigation techniques);
- the properties of the soils that control soil drainage, wet weather trafficability, and the disposal of drainage waters;
- the suitability of the proposed crop plant to the soils and climate of the area,
- the amount and quality of the potential irrigation water supply.

This paper attempts to describe and discuss the soil issues principally involved in developing irrigated cropping in the upper Flinders River area (Fig. 1a). Irrigated agriculture, by definition, must increase the water inputs to the soil over those provided by the modest annual rainfall regime over the area (430 – 490 mm). Any water applied over the growth requirements of the irrigated plants will either evaporate from the soil surface or drain below the root zone of the crop and, eventually, will seep into drainage channels or will recharge deep aquifers below the crop. The quantitative assessment of soil suitability for irrigation is usually based on detailed soil survey results to locate parcels of land suitable for irrigated crops (McDonald 1970), followed by field approaches to measure key variables in small plots, such as water infiltration rates into the soil, soil profile water storage capacity, plant growth rates, and crop responses (Shaw and Yule 1978). But lack of resources has precluded adopting such an approach in the present project.

1.2 Nature of the present study

This study is based on the published information on the nature and properties of the mosaic of soils and landscapes in the vicinity of the Flinders River in the region between Hughenden and Julia Creek (Figs 1a, b). It has relied heavily on soil and landscape information presented in three key studies that were made at twenty year intervals over the last 50 years (Sleeman 1964; Turner and Hughes 1983, and Shields 2003). These studies have provided general descriptions of the soils and landscapes; all of their soil analytical data relate to general trends in groups of soil profiles, and no site-specific soils information has been presented. Consequently, the soil information lacks detail and is generally applicable to wide tracts of land. The data are too coarse to permit either new interpretations to be made of the nature and properties of the soils at specific sites, or a re-assessment of the irrigation potential of relatively small areas of individual soils within particular soil landscapes.

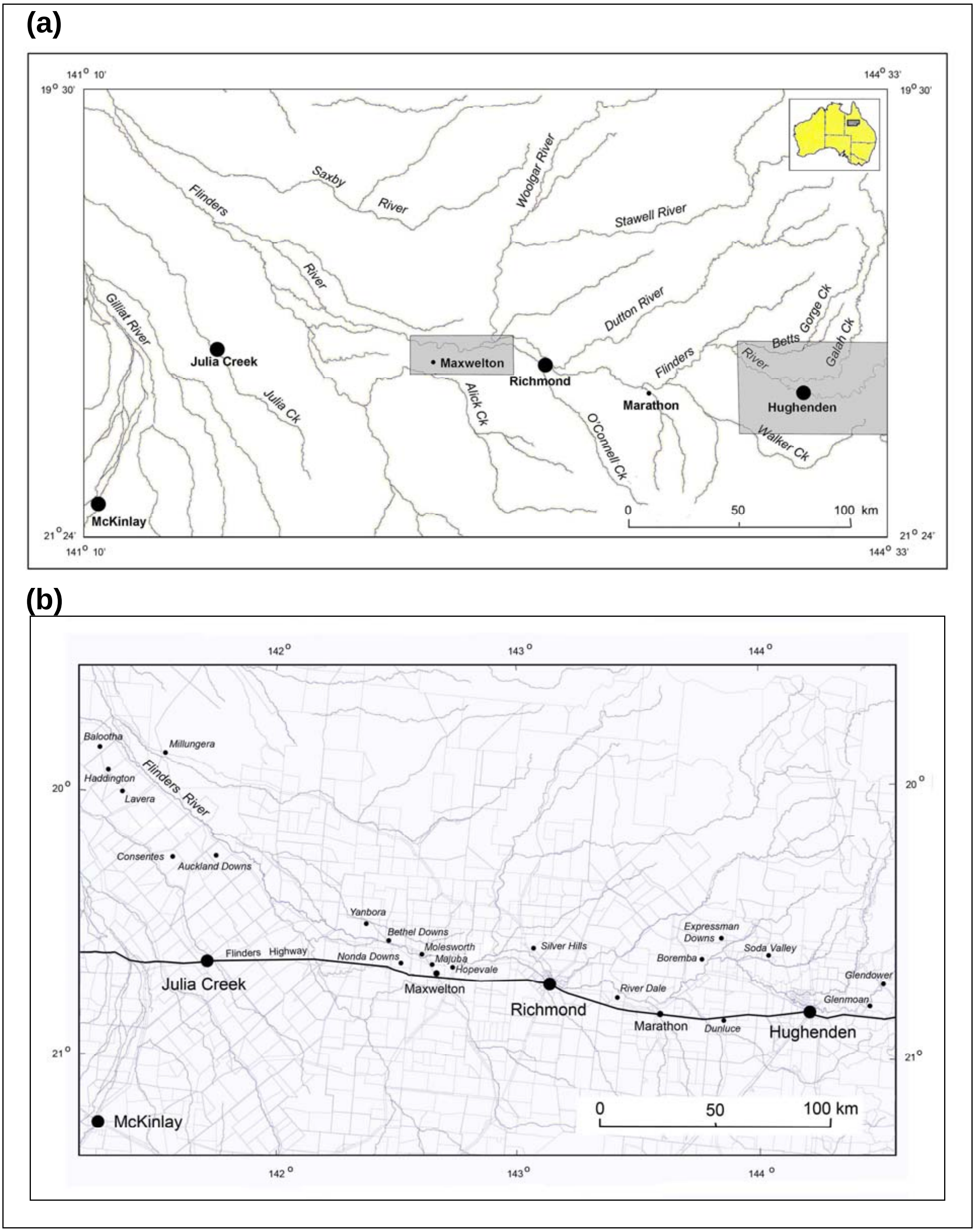

Figure 1. Location of the Flinders River Agricultural Precinct.
(a) The upper Finders River and the main streams draining the southern Carpentaria Plains. The shaded areas indicate the locations of the previous studies near Hughenden by Turner and Hughes (1983), and near Maxwelton by Shields (2003).
(b) Property boundaries and the main localities referred to in the text.
The maps were made from digital data supplied by the Queensland Department of Environment and Natural Resources and are used with permission. © The State of Queensland (Department of Environment and Resource Management) [2010].

Several regional reconnaissance soil studies have been made over parts of the catchment of the upper Flinders River, North Queensland (Isbell *et al*. 1967, Isbell and Murtha 1970, Northcote *et al.* 1975) but local data were not presented. Unpublished soil investigations have been carried out on a small area near Maxwelton (Fig. 1) by Enderlin and Christianos in the mid 1990's (limited soil data available from the Queensland Department of Environment and Resource Management) and on an irrigated cotton farm at 'Meadowlands', adjoining 'Silver Hills', 15 km north of Richmond, by Gorman (2001). Bourne and Dowling (1990) and Shields (2003) briefly discussed the history of irrigated cropping on cracking clay soils at 'Silver Hills', 20 km northwest of Richmond, where forage corn, maize, and cotton have been grown successfully. Broad agronomic assessments have been made of the soils across the upper Flinders catchment by Wilson and Philip (1999), who relied on the previously published information available at a regional level. Wilson and Philip (1999) recognised that, '… the broad descriptions of soils and their properties [provide] little in the way of analysis for agricultural potential'.

Where appropriate, information has been drawn from the soils elsewhere in central and northwestern Queensland to overcome the paucity of data specific to particular soil patterns and characteristics in assessing the feasibility of sustainable irrigation, and where the landscape suggests that irrigation may be a possibility.

This paper aims to re-interpret the properties of the soils and landscapes in terms of the opportunities and constraints to irrigated agriculture in the Flinders River Agricultural Precinct. It has not been possible to make detailed assessments of sustainable irrigation practices using conventional measures of land suitability adopted in the limited scale and site-specific evaluations undertaken to date. The imperative has been to identify general soil and landscape characteristics that may guide assessments of suitability for irrigation, and to identify where practical applications might be made. The interpretations of this report should be treated cautiously, however, because none have been tested in a pilot study in the field, which is the acid test of irrigation feasibility.

The major findings are two-fold:

- irrigated agriculture is a potentially viable operation at certain sites in the vicinity of the upper Flinders River, especially if modern, well-controlled irrigation water management techniques are established and refined through local experience which should be obtained by way of a gradual ramping up of pilot-scale implementation;

- a mosaic of small, potential irrigation areas has been identified in the area, but detailed soil and site data are required from those areas before irrigated farm plans are developed for any particular site. A strategy is recommended whereby some of the critical field data might be collected in conjunction with inputs from relevant landholders.

2. THE FLINDERS RIVER AGRICULTURAL PRECINCT

The Flinders River Agricultural Precinct is not rigidly defined, but occupies the lower landscape elements lying within about 10 km of the upper Flinders River, in a zone where water could be channelled to and away from surface storage (Fig. 1a). The river drains westwards across the southern part of the Carpentaria Plains, then northwards, across flat to gently undulating plains, ‘the rolling downs’, lying at about 260 to 320 m elevation above sea-level near Hughenden and dropping to close to sea-level near the Gulf of Carpentaria, some 500 km to the northwest. Between ‘Glendower’ (40 km upstream of Hughenden; Fig. 1b) and ‘Balootha’ (110 km northwest of Julia Creek), the rolling downs are characterised by long, gentle slopes (usually less than 3 %), less than 10 m of local relief, and extensive, essentially tree-less, Mitchell grass *(Astrebla spp.)* and Flinders grass *(Iseilema spp.)* pastures on alkaline cracking clay soils.

Annual rainfall in the area (mean: 430 – 500 mm) is strongly seasonal and highly variable from year to year. As a result, the Flinders River either fails to flow in some wet seasons (December – March), or is prone to significant intermittent flooding.

Just below ‘Glendower’ where the river emerges from a narrow gorge cut 60 – 80 m below basaltic plains of the Einasleigh Uplands (Fig. 2), it occupies a broad, shallow depression with the bed of its meandering main channel incised some 5 – 10 m below the rolling downs. It maintains this general form into the flatter country to the northwest of Richmond, where the river channel breaks into a system of much shallower, braided channels and merges with the channels of the Saxby and Cloncurry Rivers. This is broad, drainage depression that, in places, is up to 40 km wide (Fig. 1a).

During previous flood events, the river has deposited several extensive bodies of clay-rich alluvium, that include smaller, elongated areas of sandier sediments forming ancient channel sands and stream levees across the clayey alluvial plains. Each of these major bodies of river alluvium, and the surrounding rolling downs, is characterised by distinctive and different recurring patterns of topography, soils, and vegetation that define a suite of land systems that Perry *et al.* (1964) first recognised in the region. Breaking the land into land systems allows the identification of broadly similar soil-landscapes in a region, and offers a practical guide for assessing the land use potential of different parcels of land in that region. A land systems approach is used in the present report to provide a framework for describing and interpreting the soil properties across the region, and to locate parcels of land suited to irrigated agriculture within specific land systems.

3. THE GEOLOGICAL SETTING

The area is underlain by fine-grained rocks, mainly calcareous shales, mudstones, and limestones, which were deposited as muddy calcareous sediments in shallow marine environments in the Great Artesian Basin during the Lower Cretaceous period, some 140 - 100 million years ago. The rocks were uplifted towards the end of the Upper Cretaceous Period (about 65 million years ago), gently warped to produce low-angle dips towards the southwest, and have been exposed to weathering and soil formation (Vine 1970; Vine and Paine 1974). More recently in the late Tertiary and Quaternary Periods, between 5.9 and 0.9 million years ago, basaltic volcanoes actively erupted (Stephenson *et al.* 1980). At least 43 known eruption centres produced an extensive lava field to the north of the Flinders River between Hughenden and Richmond (Fig. 2).

Individual volcanoes produced basaltic lavas that flowed away from the source and down former stream lines, burying and preserving any river gravels that may have been in the stream channel. After the lava cooled and solidified, it formed a rock that was much harder than the surrounding Cretaceous mudstones and limestones and these were then preferentially eroded by post-basaltic streams draining the elevated terrain. The softer Cretaceous rocks, that had originally formed the hills and had constrained the basalt flows to shallow valleys and drainage lines, were removed by erosion. The prolonged erosion did not remove the harder basalt flows, that once lay in the lowest parts of the landscape; the ancient lava flows are now found capping many of the flat-topped ridges, and their erosional remnants, that lie immediately to the north of the Flinders River between ‘Glendower’ and Marathon. The ancient river gravels preserved beneath the lava flows indicate that most of the individual flows were 5 – 10 m thick (Coventry *et al.* 1985). The erosion processes are still continuing in the landscape, removing soils and rock, and producing the river sediments that are transported towards the Gulf of Carpentaria flood events in the modern Flinders River.

Prolonged weathering and erosion of the relatively soft Cretaceous sedimentary rocks that underlie the study area has produced the distinctive rolling downs topography of the southern Carpentaria Plains. More recent erosion by the Flinders River has excavated a broad depression across the rolling downs. Unpublished drill log data provided by the Department of Environment and Resource Management, Brisbane, indicate that alluvium transported by an ancestral Flinders River fills broad channels excavated in the Cretaceous sedimentary rocks to a depth of 5 – 25 m below the current river bed. These channels have been infilled with the river's modern load of clayey and generally fine sandy sediments.

4. LAND SYSTEMS OF THE REGION

A land systems approach offers a unifying view of the agricultural and environmental properties of parcels of land and provides a basis for assessing their constraints to economic development within a region. As is discussed below, parts of the various land systems that are underlain by alluvial sediments hold some considerable promise for irrigated agriculture in the Hughenden – Richmond – Julia Creek area.

Field mapping carried out by the CSIRO Division of Land Resources and Regional Survey in 1953-54 (Perry *et al.* 1964) shows that the most widespread land system of the upper Flinders River catchment is the Julia Land System (Fig. 2), which is characterised by treeless rolling downs with Mitchell grass *(Astrebla spp.)* pastures on cracking clay soils that are underlain by weathered, fine-grained Cretaceous rocks.

Several land systems have been defined on the clay-rich alluvial sediments that lie downslope of, and are inset as younger deposits into the Julia Land System. Downstream of about Marathon, older alluvium of the Flinders River now forms the slightly elevated Balbirini and Bylong Land Systems that lie at or above the levels attained by major floods on the river (Fig. 2). The Monstraven Land System occupies a similar landscape position in the west (Fig. 2).

Modern alluvial deposits of the Flinders River in the study area have been deposited in drainage depressions and channels eroded into the older alluvial deposits. These predominantly clayey sediments, with some sandy stream channel and levee deposits, form the current floodplain of the Flinders River and are inundated by even small floods on the river. They define the Gregory Land

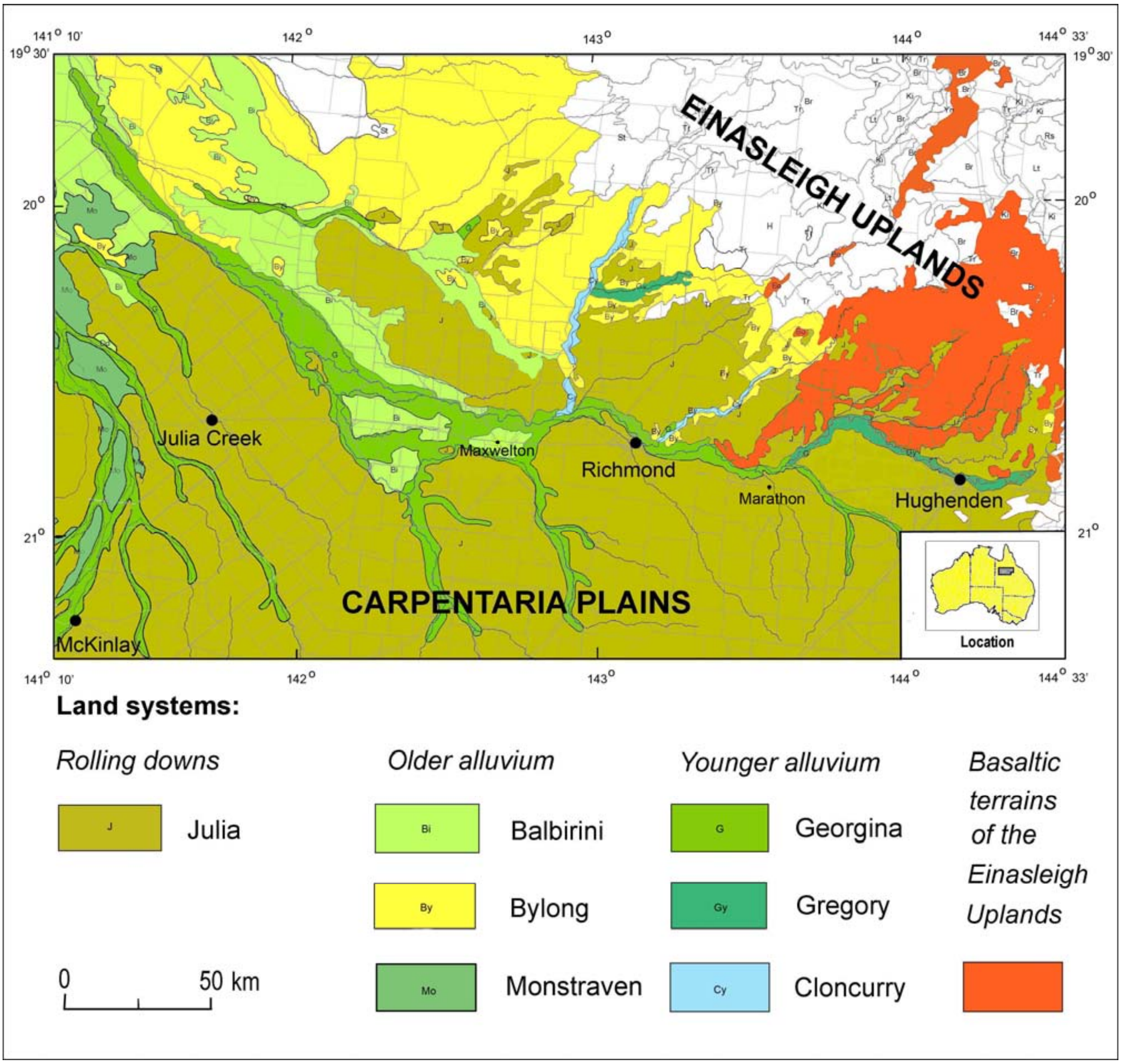

Figure 2. The distribution of the major land systems defined by Perry *et al.* (1964) in the vicinity of the Flinders River Agricultural Precinct.
Only the land systems of the Carpentaria Plains and the basaltic terrains of the Einasleigh Uplands are shown in colour. The land systems layer of this map, purchased from the Queensland Department of Environment and Resources Management, has been laid over cultural features from the digital cadastral data bases for the Flinders, Richmond and McKinlay Shires by Ms C. Herrod, Flinders Shire Council, Hughenden.
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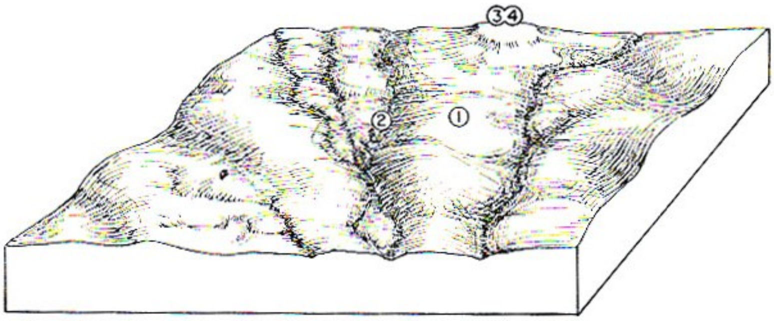
System in the Hughenden-Marathon area in the east and, farther downstream, the Georgina Land System (Fig. 2). Much sandier sediments, derived from erosion of the sandy soils of the Bylong Land System, constitute younger alluvial deposits that are restricted to the lower parts of the Stawell and Dutton Rivers where they underlie the Cloncurry Land System (Fig. 2). This land system occupies a similar landscape position to that of the Gregory or Georgina Land Systems (Fig. 2). Each of the three land systems on younger alluvial deposits lie at elevations slightly below (possibly as much as 2 – 5 m) the associated older alluvial sediments of the Balbirini, Bylong, or Monstraven Land Systems, and at a much lower elevations (possibly 5 – 8 m) below the Julia Land System.

4.1 The Julia Land System

The Julia Land System is characterised by gently undulating plains with long, even slopes of less than 3% (many are less than 1%) and small areas of stream channels and crests of low rises (Fig. 3). Most of the land system carries brown or grey, cracking clay soils that have formed in the underlying calcareous shales, mudstones, and limestones of Cretaceous age, or in the younger alluvial sediments that have been derived from the underlying, fine-grained rocks. The soils may have crusting or self-mulching topsoils and support productive Mitchell grass (*Astrebla* spp.) and Flinders grass (*Iseilema* spp.) pastures.

The rolling downs are essentially treeless. Few shrub species are present (Table 1) with only a few, sparse low open woodlands of native species evident (mainly whitewood *Atalaya hemiglauca,* boree *Acacia cana,* supple jack *Ventilago viminalis,* and bloodwood *Corymbia terminalis*). The widespread woody weed, prickly acacia (*Acacia nilotica*), has invaded the study area since the survey of Perry *et al.*(1964) and is concentrated in sporadic, dense thickets across the downs.



Unit	Relative Area	Landforms	Soils *	Vegetation **
1	Very large	Rolling plains	Calcareous cracking clay: *Barkly* on Cretaceous shale, mudstone; *Wonardo* on Cretaceous limestone	Mitchell grass downs; small areas of arid, sparse, low woodlands (whitewood, boree) with arid short grasses (feathertop wire, spring, and nine awn grasses)
2	Very small	Braided stream channels	Calcareous cracking clay on alluvium derived from Cretaceous sedimentary rocks *(Barkly)*	
3	Very small	Crests of low rises	Calcareous clay loam *(Tobermorey)* on Cretaceous limestone	Trees absent or arid, sparse, low woodlands (whitewood, supple jack, bloodwood, boree) with arid short grasses (kerosene, wire, and nine awn grasses)
4	Very small		Limestone outcrop – no soil	

* Soil family names are listed in italics and their characteristics are set out in Table 2.
** Common names of major species are cross-referenced with botanical names in Table 1.

Figure 3. Key elements of the Julia Land System (source: Perry *et al.* 1964).

Table 1. The distribution of plants across the Julia, Balbirini, Georgina, and Gregory Land Systems in the upper Flinders River catchment.

The species list was taken from Perry *et al.* (1964).

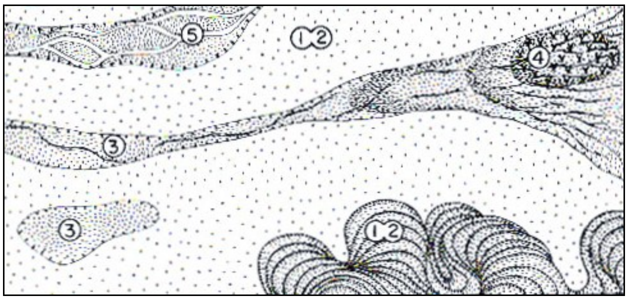
Trees and shrubs					
		Land system *			
Beefwood	*Grevillea striata*		Bi	G	
Bloodwood	*Eucalyptus terminalis*	J		G	Gy
Boree	*Acacia cana*	J			
Coolabah	*Eucalyptus microtheca*		Bi	G	Gy
Ghost gum	*Eucalyptus papuana*			G	Gy
Gidgee	*Acacia cambagei*			G	Gy
Gutta-percha	*Excoecaria parvifolia*		Bi		
River red gum	*Eucalyptus camaldulensis*			G	Gy
Snappy gum	*Eucalyptus tectifera*				Gy
Silver box	*Eucalyptus pruinosa*				Gy
Supple jack	*Ventilago viminalis*	J			
Whitewood	*Atalaya hemiglauca*	J	Bi	G	

Pasture plants					
		Land system *			
Barley Mitchell grass	*Astrebla pectinata*	J			
Blue grass	*Dichanthium fecundum*		Bi	G	Gy
Blue grass	*Dichanthium superciliatum*		Bi	G	
Browntop	*Eulalia fulva*		Bi	G	
Button grass	*Dactyloctenium radulans*			G	
Curly Mitchell grass	*Astrebla lappacea*	J	Bi		Gy
Curly windmill grass	*Chloris acicularis*			G	
Feathertop wire grass	*Aristida spp*	J	Bi		Gy
Flinders grass	*Iseilema spp.*	J			
Golden beard grass	*Chrysopogon fallax*			G	Gy
Gulf wire grass	*Aristida pruinosa*				Gy
Hoop Mitchell grass	*Astrebla squarrosa*	J	Bi		Gy
Kerosene grass	*Aristida arenaria*	J	Bi		
Mitchell grass	*Astrebla spp.*	J	Bi	G	Gy
Nardoo	*Marselia drummondii*				Gy
Native oatgrass	*Themeda avenacea*			G	
Nine awn grass	*Enneapogon spp.*	J	Bi		
Pitted blue grass	*Bothriochloa decipiens*			G	Gy
Queensland bluebush	*Chenopodium auricomum*		Bi		Gy
Reed grass	*Arundinella nepalensis*				Gy
River grass	*Chionachne cyathopoda*		Bi	G	Gy
Sesbania	*Sesbania spp.*		Bi	G	
Spider grass	*Brachyachne convergens*		Bi	G	Gy
Spring grass	*Eriochloa pseudoacrotricha*	J			
Wild rice	*Oryza australiensis*		Bi	G	Gy
Wire grass	*Sporobolus australasicus*	J			

* J: Julia Land System (soil substrate: rolling downs on weathered, fine-grained Cretaceous shale, mudstone, or limestone)
Bi: Balbirini Land System (soil substrate: higher, older alluvium),
G, Gy: Georgina and Gregory Land Systems (soil substrates: lower, modern alluvium)

4.2 The Balbirini Land System

The Julia land system merges down slope into the Balbirini, Georgina or Gregory Land Systems that are underlain by alluvial sediments by the Flinders River. The Balbirini Land System (Fig. 4) generally stands at or above the levels of the highest floods recoded since European settlement and relates to older alluvial sediments that stand several metres higher than the younger, modern sediments of the Georgina and Gregory Land Systems; the latter are related to the current flow and sediment depositional regimes of the river and are regularly flooded.



Map patterns of landform components

Unit	Relative Area	Landforms	Soils *	Vegetation **
1	Very large	Flat plains: sloping gently downstream, with meandering patterns of their depositional river systems partly preserved	Calcareous cracking clay locally with gilgai: *Barkly* and *Wonardo*	Blue grass-browntop downs; small areas of Mitchell grass; small areas of sparse woodland (coolabah, gutta-percha) with blue grass and browntop
2	Very small		Calcareous clay, gravelly and with gilgai locally: *Balootha*	Trees absent and arid, sparse low woodland (whitewood, beefwood) with arid short grasses (feathertop wire and nine awn grasses)
3	Small	Shallow depressions	Calcareous cracking clay with gilgai: *Barkly*	Blue grass-browntop downs with sparse trees (coolabah, gutta-percha; some wild rice, blue grass, and Queensland blue bush)
4	Very small	Seasonally flooded plains with numerous, braided distributary channels	Cracking clay with gilgai: *Endymion*	Blue grass-browntop downs with sparse trees (gutta-percha; some wild rice and spike-rush)
5	Very small	Braided channels and associated slopes	Calcareous cracking clay: *Barkly*	Fringing and frontage woodlands (coolabah, gutta-percha; river and spider grasses)

* Soil family names are listed in italics and their characteristics are set out in Table 2.
** Common names of major species are cross-referenced with botanical names in Table 1.

Figure 4. Key elements of the Balbirini Land System (source: Perry *et al.* 1964).

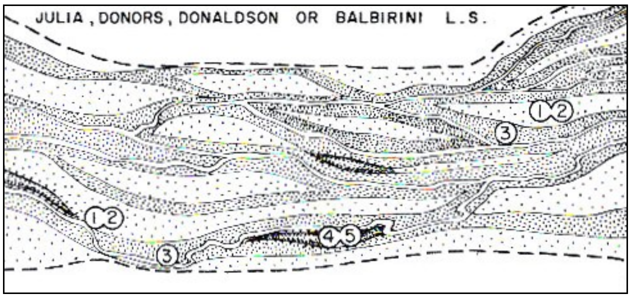
The Balbirini Land System is characterised by extensive, flat alluvial plains with slopes less than 0.5%, traversed by few shallow drainage lines, and lying just above the frequently attained flood levels of the Flinders River (Fig. 4). Table 1 indicates that the deep clay soils carry species-rich, blue grass –browntop-speargrass *(Dichanthium fecundum, Eulalia fulva, Aristida latifolia)* pastures with minor Mitchell grass *(Astrebla spp)*. There are only a few trees and sparse woodlands that include coolabah *(E. microtheca)*, whitewood *(Atalaya hemiglauca)*, gutta-percha *(Execocaria parvifolia)*, and beefwood *(Grevillea striata)*.

Occupying a similar position in the landscape to the clay-dominated Balbirini Land System, the alluvial sediments of the Bylong Land System are very sandy. This land system is restricted to gently undulating plains that form low terraces above the present flood level of the Dutton and Stawell Rivers, just upstream of their confluences with the Flinders River (Fig. 2). They are more widely distributed as the distal deposits of large alluvial fans that carried sediment from the Einasleigh Uplands along the eastern side of the Carpentaria Plains. Very uniform, pale coloured sandy soils support a low woodland of mixed species over the plains. The Bylong Land System carries conspicuous, well defined, shallow, clay-floored depressions with a lagoonal flora in the smaller ones and Mitchell grass downs in the larger ones.

4.3 The Georgina Land System

The Georgina land system includes the current, active floodplain of the Flinders River and merges with the Gregory Land System upstream of Marathon (Fig. 2). It is characterised by fine textured alluvium that is traversed by numerous braided stream channels across the level, clayey, alluvial flats and slightly higher, gently sloping, fine sandy levees (Fig. 5). Most of this low-lying land is inundated by regular flood events.

Soils are deep cracking clays on the flats and levee footslopes with deep sandy clays and sandy clay loams on abundant stream levees and in the many abandoned, braided stream channels. The vegetation is the most species rich and diverse of the three land systems of the study area. The open eucalypt woodland vegetation is heavier than on the open downs country of the Julia and Balbirini Land Systems.



Map patterns of landform components

Unit	Relative Area	Landforms	Soils	Vegetation
1	Large	Flat plains	Calcareous cracking clay: *Barkly* on shale, mudstone, and alluvium, *Wonardo* on limestone	Trees absent or sparse woodlands (coolabah); Mitchell grass downs and blue grass-browntop downs; small areas of gidgee low woodlands
2	Medium		Calcareous clay, frequently gravelly: *Balootha*	Trees absent or sparse woodland (whitewood, beefwood) with arid short grass (spider and button grasses); some Mitchell grass downs; small areas of gidgee low woodlands
3	Small	Flood channels	Calcareous cracking clay: *Barkly;* cracking clay with gilgai: *Endymion*	Fringing woodlands (coolabah; native oatgrass, wild rice); small areas of gidgee low woodlands
4	Very small	Stream levees	*Manbulloo* on fine sands	Frontage woodlands (river red gum; golden beard and pitted blue grasses)
5	Very small	Backslopes of stream levees	Alluvial soil on stratified loams	Frontage woodlands (bloodwood, ghost gum; curly windmill grass)
6	Medium	Braided river channels	No soil – raw, unweathered sediment of current stream beds	Fringing woodlands (river red gum, coolabah; river and pitted blue grass)

* Soil family names are listed in italics and their characteristics are set out in Table 2.
** Common names of major species are cross-referenced with botanical names in Table 1.

Figure 5. Key elements of the Georgina Land System (source: Perry *et al.* 1964).

4.4 The Gregory Land System

Like the Georgina Land System, the fine- and coarse-textured alluvial sediments of the Gregory Land System lie at, or just below, the modern flood levels of the Flinders River. It is confined to a narrow alluvial plain along the river between Hughenden and Marathon where the Georgina Land System is largely absent and, similarly, along a short length of the lower Saxby River, 80 km north of Julia Creek (Fig. 2).

The soils are predominantly cracking clays on the alluvial plains and carry Mitchell grass *(Astrebla spp.)* or blue grass- browntop *(Dichanthium fecundum – Eulalia fulva)* pasture and small patches of gidgee *(Acacia cambageii)* woodland. Much sandier soils supporting eucalypt woodlands *(Eucalyptus microtheca, E. papuana, E. tectifica)* occur on the much less abundant and coarse sandy stream channels and associated fine sandy levee deposits (Fig. 6).

Map patterns of landform components

Unit	Relative Area	Landforms	Soils *	Vegetation **
1	Large	Flat plains	Calcareous cracking clay: *Barkly* with associated *Wonardo*	Mitchell grass downs or blue grass-browntop downs; small areas of gidgee low woodland in Mitchell grass downs
2	Medium		Calcareous clay: *Balootha*	Arid, sparse, low woodland with arid short grass (feathertop wire grass) or Mitchell grass downs; areas of no trees
3	Small	Linear depressions, periodically flooded	Calcareous cracking clay: *Barkly*	Sparse woodland (coolabah) with blue grass-browntop and Mitchell grass downs; small areas of blue grass-browntop downs without trees
4	Medium	Stream levees	Fine sands: *Manbulloo*	Frontage woodland (snappy gum, ghost gum, bloodwood, silver box, coolabah); frontage grass (golden beard grass, blue grasses, feathertop wire grasses)
5	Very small	Abandoned stream channels	Loamy alluvial soils	Frontage woodland (bloodwood, ghost gum, snappy gum, coolabah) with frontage grass (feathertop wire grasses, pitted blue grass)
6	Very small	Modern braided stream channels and associated slopes	No soil – raw, unweathered sediment of current stream beds	Fringing woodland (river red gum, coolabah) with frontage grass (spider, river, feathertop wire, and reed grasses

* Soil family names are listed in italics and their characteristics are set out in Table 2.
** Common names of major plant species are cross-referenced with botanical names in Table 1.

Figure 6. Key elements of the Gregory Land System (source: Perry *et al.* (1964)

5. THE SOILS OF THE REGION

The landscape of the upper Flinders River catchment has been dramatically altered by geological processes that have driven erosion and sediment deposition. The highly erodible, fine grained Cretaceous rocks that underlie the whole region have weathered to form extensive areas of soils were originally classified by Sleeman (1964) as grey and brown soils of heavy texture, then as grey, brown and red clays by Stace *et al.* (1968), or grey self-mulching cracking clays, Ug 5.2 and Ug 5.3 soils, by Northcote *et al.* (1975; following the soil classification scheme of Northcote 1979). In a localised study of the soils near Maxwelton, the cracking clay soils were classified most recently by

Shields (2003; following the scheme of Isbell 1996), as Self-mulching Grey and Brown Vertosols with much smaller areas of Crusty Grey Vertosols, Grey Dermosols, and Red Chromosols.

The cracking clay soils, first named by Sleeman (1964) as the Barkly Soils, and the closely related Wonardo, Endymion, Balootha, and Tobermorey Soils, are the dominant soils of each of the land systems in the vicinity of the Flinders River (Table 2). In the absence of individual soil profile descriptions, it is very difficult to relate the soil groups recognised in the more recent studies of Turner and Hughes (1983) and Shields (2003) to the original groups of Sleeman (1964). Hence only ‘probable correlatives’ are assigned in Table 2 to those soil groups.

Despite their uncertain taxonomic relationships, the cracking clay soils in the study area have formed in:

- the widespread Cretaceous rocks, especially in mid-slope and upper slope sites of the rolling downs (Julia Land System; Table 2),
- the clay-rich sediments that have been eroded from the Cretaceous rocks (or from the sedentary soils formed in the rocks) and deposited in lower slope sites on the rolling downs (Julia Land System),
- the clay-rich parts of the various alluvial plains of different ages that were deposited by the upper Flinders River (Balbirini, Georgina, and Gregory Land Systems; Table 2).

Not only are the cracking clay soils the dominant soils of the upper Flinders River catchment, they are extremely widespread over the rangelands of western Queensland and are remarkably similar in their profile characteristics over large areas. While their properties may differ in detail from site to site, they generally conform to the descriptions set out in Sections 5.1 and 5.2 (below). The descriptions summarise the published information from the sources listed in the previous section. These data have been supplemented by observations and chemical analyses of similar cracking clay soils of the rolling downs of western Queensland, mostly from sites lying outside the catchment of the Flinders River (Soil Horizons Pty Ltd, unpublished data).

The soils of the less extensive, sandier components of the various land systems of the older and younger alluvial plains of the upper Flinders River are discussed in Section 5.3 (below).

Table 2. Characteristics of the soils of the upper Flinders River catchment in the Hughenden – Julia Creek area.

Sources: Sleeman (1964), Turner and Hughes (1983), and Shields (2003)

Soil Family (Sleeman 1964)	Land system *				Brief description	Soil pH	Soil surface condition	Soil structure	Comments ** (T&H) = Turner and Hughes (1983) (S) = Shields (2003)
	Julia	**Balbirini**	**Georgina**	**Gregory**					
Barkly	D	D	D	D	Dark grey – olive brown, cracking clays; shallow on fine-grained, calcareous shale, mudstone, and limestone, and deeper on the clayey alluvium derived from those rocks	Alkaline throughout	Usually self- mulching, occasionally crusted	Subangular blocky to massive at depth; deep cracks	Lime nodules and/or gypsum crystals within 30 cm of surface. ***Probable correlatives:*** Sussex and Nicoleche Soils (T&H); Self-mulching Grey and Brown Vertosols and Crusty Grey Vertosols or Dermosols (S)
Wonardo	m	S	m	m	Similar to Barkly Soil, but reddish grey – dark reddish brown, cracking clay	Alkaline throughout	Thicker self-mulching surface than Barkly	Subangular blocky to massive at depth; deep cracks	Similar to Barkly Soil, but redder and with a thicker self-mulch layer. ***Probable correlatives:*** Self-mulching Grey and Brown Vertosols (S)
Endymion		m	m		Cracking clay with mottled reddish grey and olive brown subsoil	Acid topsoil, neutral subsoil	Weaker structure and poor internal drainage	Deep cracks and gilgai microrelief	Periodically flooded. ***Probable correlatives:*** Coolibah and Mt Devlin Soils (T&H)
Balootha		m	S	S	Similar to Barkly and Wonardo Soils	Neutral topsoil, alkaline subsoil	Vesicular, massive sandy loam – sandy clay surface soil	Dense, massive, very slowly permeable subsoil	Deep carbonate nodules. ***Possible correlatives:*** Mt Beckford Soil (T&H); Brown Dermosols (S).
Tobermorey	m				Shallow, pale-coloured, silty loam to clay textured calcareous soil	Alkaline throughout	Crusting surface soil	Weak platy structure in topsoil, subsoil weak angular blocky	*Underlain by limestone at 30 – 90 cm depth.* ***Probable correlatives:*** Ellington Soils (T&H), Red Chromosols if formed on limestone (S).
Manbulloo			m		Light brown – reddish brown, micaceous, fine sand	Neutral to slightly acidic	Soft to firm; some loose	Massive – single grain	Soil profile dominated by sedimentary properties of parent material. ***Probable correlative:*** Red Chromosols (S).
Cullen				m	Uniform, red, yellow, or grey coarse sands	Strongly acid to neutral	Loose, soft, or firm	Massive – single grain	Soil horizons are poorly differentiated
Alluvial soils			m		Pale coloured, laminated sand, silt, and clay layers	Variable	Soft to firm; some loose	Massive – single grain	No soil features in layered sediments. ***Probable correlative:*** Glenmoan Soil (T&H)
Solodic soils				M	Footnote to Gregory Land System description of Perry *et al.* (1964), with no further elaboration in their report: *‘Moderate areas of solodised soils occur in the Gregory Land System near Hughenden.* Probable correlative: Rosevale Soil (Turner and Hughes 1983); the chemical data of these sodic, texture contrast soils were used by Turner and Hughes (1983) to typify the alluvial terraces of the Flinders River near Hughenden where other less sodic soils are known to occur.				

* D: dominant soil, S: subdominant soil, M: moderate area, m: minor soil

** The absence of soil profile data permits only broad correlations with the soil groups defined by Turner and Hughes (1983) and Shields (2003).

5.1 Morphological properties of the cracking clay soils

The cracking clay soils of the upper Flinders River catchment have uniform, fine-textured, strongly structured profiles that range from 1 m to 3 m deep, and swell and shrink on wetting and drying. They crack significantly when dry, forming cracks 5 – 100 mm wide at the ground surface and extending for at least 30 cm, to more than 1 m deep (Figs 7a, 7b). Typically, the dark brown – grey surface soils are strongly self-mulching and, on drying, form a loose, very well aggregated, 20 – 100 mm thick layer of clayey crumbs and granules of about 2 – 6 mm (just a little larger than a match head). If the aggregated self-mulching layer is rained on or irrigated, it may form a thin, fragile crust 2 – 5 mm thick over the granular layer (Fig. 7c), and the crust is readily disrupted by even weak disturbances such as the movement of grazing animals over the soil surface (Fig. 7b).

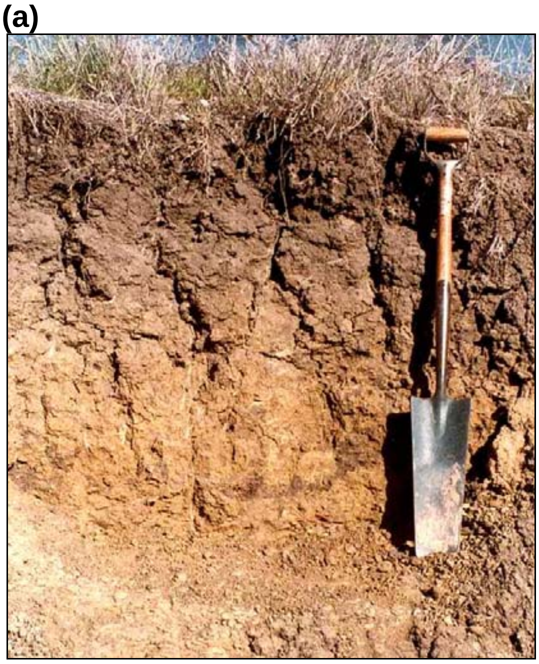
The dark grey, olive brown, and occasionally red, subsoils crack when dry and are moderately to strongly structured, changing from medium angular blocky to coarse blocky or polyhedral structure with depth. Evidence of swelling and shrinking are evident in most soil profiles as lenticular peds, diagonal slip planes with smooth or striated surfaces or ‘slickensides’ where two blocks of soil have rubbed alongside each other, and / or gilgai microrelief on the ground surface.

Gilgai, originally an Aboriginal word meaning “small waterhole”, defines the patterns of small hummocks and hollows, or the ‘microrelief’ of the ground surface, produced by swelling and shrinking of the soil with moisture changes (Hubble *et al.* 1983). The phenomenon is of variable occurrence and expression in the clay soils of the study area. On some of the cracking clay soils, gilgai patterns are absent, on others the amplitude of the gilgai microrelief may range from only a few centimetres difference in height between the top of the puff, bank, or mound (the elevated part of the gilgai topography) and the bottom of the depression, to as much as 1.5 m on deep clays supporting gidgee *(Acacia cambagei)* woodlands.

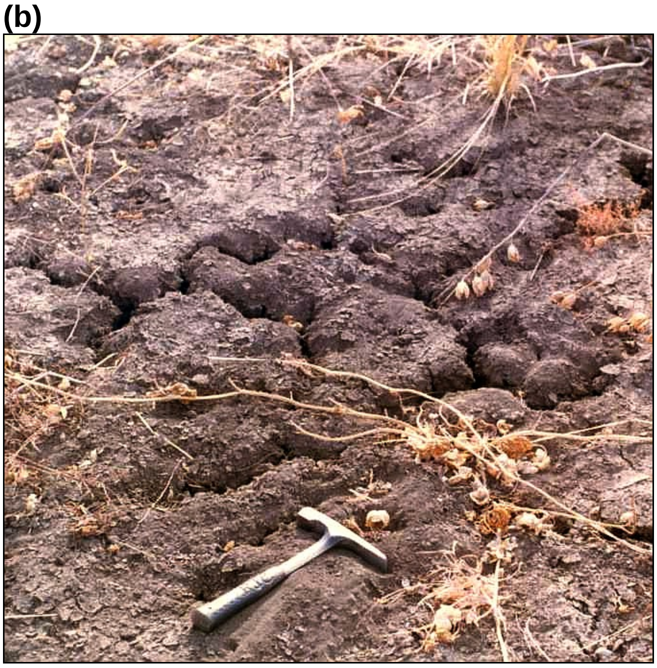
Gilgai microrelief in clay soils encourages the ponding of rain water in depressions for prolonged periods during, and after, the wet season and promotes the growth of plant species adapted to swampy or lagoonal conditions such as *Marsilea spp.* (nardoo fern) or *Eliocharis spp.* (spike rush), and the development of quite acidic topsoils (pH 4.5 – 5.0). These conditions contrast strongly with those of the well drained mounds where strongly alkaline subsoils have been pushed up to the ground surface by swell-shrink processes, and the soil is usually strongly alkaline (pH is often greater than 8.0) and contains lime nodules.

The topographic and soil chemical differences between gilgai mounds and depressions are generally of little concern to livestock grazing, but may present significant constraints to the successful management of irrigated cropping systems. Experience with land forming to infill the gilgai depressions and create smooth, long slopes suitable for furrow irrigation on cracking clay soils in the Burdekin River Irrigation Area, near Ayr, have not been successful. The soils continue to swell and shrink in response to seasonal rainfall regimes and ongoing earthworks are usually required to sustain furrow designs for flood-irrigated small crops.

(a)



(b)



(a) An olive brown cracking clay soil typical of the Julia Land System. Surface cracks continue down the profile to the Cretaceous shale parent material that lies at a depth of 0.95 m (about halfway up the spade blade).

(b) Dry, self-mulching, cracking clay topsoil.

(c) A 5 mm thick crust that had formed over the well aggregated self-mulching surface of this grey clay soil has been removed from the lower left part of this image. Fragments of the crust have been turned on their edges to demonstrate their thinness.
Diameter of coin: 24 mm.

(c)

Figure 7. Features of the olive brown – grey cracking clay soils (Vertosols) of the Julia Land System. Soils with similar properties, but formed on thick deposits of clayey alluvial sediments, are the dominant soils of the Balbirini, Georgina, and Gregory Land Systems of the upper Flinders River catchment.

5.2 Chemical properties of the cracking clay soils

Site-specific soil profile descriptions and analytical data are not available from any of the previously published soil reports, so it is difficult to make an independent assessment of the generalised field and laboratory data presented. However, Turner and Hughes (1983) and Shields (2003) have provided averaged profile analytical data for groups of soil profiles. The numbers of profiles included in the group, the variability of the results within any group, and the locations of the soil profiles within each land system are all unknown.

Field descriptions and limited analytical data were obtained in an electronic format from the Queensland Department of Environment and Resource Management, Brisbane, for 43 of the 50 cracking clay soil profiles described by N. Enderlin and N. Christianos (unpublished data) from sites near Maxwelton. Field soil pH data were available for samples from 39 of those soil profiles, soil electrical conductivity data (a surrogate estimate of soil salinity status) were available from 17 of them, and soil sodicity data (exchangeable sodium percentages) were available from only 4 of the profiles. Gorman (2001) collated chemical properties of soils that had been levelled and cultivated for irrigation for several years, where sustainable irrigation management practices have been developed (C Tritton, Silver Hills, pers. comm.). No other analytical data are available from individual soil profiles in the Flinders River Agricultural Precinct.

While the soil analytical data provide an overview of the properties of the cracking clay soils, it is not known how well they represent the soils that have formed in particular parts of the four major land systems of the present study. It is possible that the cracking clay soils formed on the Cretaceous rocks will have some chemical properties that differ from those of soils withy similar morphologies but formed in clayey sediments of different ages within the land systems on the older and younger alluvial bodies of the Flinders River. These differences cannot be teased out of the coarse, generalised data that have been published to date.

5.2.1 Soil pH (soil acidity and alkalinity)

The pH of the topsoils across the study area was variable (acidic, neutral, or alkaline), but the subsoils were almost invariably alkaline to strongly alkaline (soil pH 7.5 – 9.2). These soil alkalinities are sufficiently high to discourage the growth of many crops. However, the native vegetation species found on the rolling downs, especially the deeply-rooted Mitchell grasses *(Astrebla spp.)* and certain introduced pasture species are well adapted to such conditions.

5.2.2 Soluble salts

Commercial soil testing laboratories use electrical conductivity values of a 1 : 5 soil to water suspension greater than 0.25 dS / m, and soil chloride contents greater than 300 mg/kg, as indicators of a soil salinity level that is likely to impact on the growth of salt-tolerant plants.

Soil electrical conductivities ranging from moderate (0.3 dS / m) to extremely high (greater than 3 dS/m) were commonly encountered in the soils of the study area below depths of 30 – 50 cm, suggesting that soluble salt contents were high in the subsoils. But chloride contents, where measured in clay subsoils at a range of sites across the rolling downs (Soil Horizons Pty Ltd, unpublished data), were found to be extremely variable from very low to very high (less than 60 mg / kg to 2200 mg / kg) in soils with high electrical conductivities. At sites where the soil electrical conductivities were very high (greater than 2 dS / m), the chloride contents were also very high, and commonly lay in the range of 600 – 2200 mg / kg (Soil Horizons Pty Ltd, unpublished data). This finding suggests that some, but not all, of the soil samples with high electrical conductivities were associated with high contents of sodium chloride in saline soils, as is usually the case in Australian soils.

Gypsum (calcium sulphate) crystals were commonly found in abundance in the heavy clay subsoils of the rolling downs (Soil Horizons Pty Ltd, unpublished data). It is possible that some of the high soil electrical conductivity readings may be related to the presence of readily soluble gypsum that is capable of supplying calcium cations and sulphate anions to the soil. Such was also raised as a possibility by Shields (2003). In the absence of chloride content data from specific soil profiles presenting high soil electrical conductivities, it is unwise to attribute the high soil electrical conductivities to high soil salinities without considering other possible causes for the relationship.

5.2.3 Soil sodicity

Sodic soils occupy about one third of Australia (Isbell *et al.* 1983), and are widespread among the cracking clay soils of the rolling downs (Soil Horizons Pty Ltd, unpublished data). They present a range of properties that are adverse to plant establishment and growth. Clods of sodic soils will break down and slake when placed in water to produce sawdust-like particles in the bottom of the water container; dispersive sodic soils also break down in water but they produce a cloud of much finer soil particles that give the water a turbid, muddy appearance.

The abundant fine colloids liberated from dispersive soil aggregates are moved by any waters running off the surface of sodic soils or percolating into the soil profile. Some of the colloids will precipitate in the soil pores, blocking pathways for subsequent water movement through the soil matrix (Isbell *et al.* 1983). Very poor plant growth can result from a range of adverse properties of sodic soils, including:

- surface crusts and poor topsoil structure,
- little surface protection from rain, wind, and overland flow,
- slow water infiltration into topsoil and subsoil horizons,
- poorly structured subsoil horizons inhibiting plant root elongation
- groundwater perching within the upper part of the soil profile,
- tunnel and piping erosion,
- poor soil stability and poor load-bearing characteristics,
- undermining and failure of roads and other hard engineering structures,
- strong susceptibility to erosion by ripples and waves on the foreshores of natural or artificial water bodies,
- fine colloids that remain suspended for prolonged periods (months to years) and producing muddy, brown waters in waterholes, dams, and lakes.

Sodic soils, with exchangeable sodium percentages greater than 6% of the cation exchange capacity, usually present unstable physical conditions, and slake or disperse significantly when wet, with the breakdown of soil aggregates and the release of fine clay particles from the aggregates (Hazelton and Murphy 2007). Exchangeable sodium percentages greater than 15% indicate a strongly sodic soil condition (Isbell *et al.* 1983), and stable, non-sodic soils have exchangeable sodium percentages that are lower than the critical threshold of 6% of the cation exchange capacity.

The four soil profiles analysed by Enderlin and Christianos (unpublished data) showed generally low, acceptable soil sodicity levels down to 30 cm depth, but with extremely sodic subsoils occurring at soil depths of 0.5 – 0.9 m. A wider range of soils from the rolling downs of western Queensland had non-sodic topsoils with exchangeable sodium percentages of 2 – 6%, and subsoil sodicities commonly of 6 – 15% with a few subsoil values ranging up to 32% (Soil Horizons Pty Ltd, unpublished data).

Such conditions in the soils of the upper Flinders River catchment could adversely affect the establishment and growth of certain irrigated crop varieties, but seems to have had little effect on the native vegetation of the cracking clay soils. Either the native plants have a high tolerance of alkaline, sodic, and possibly saline subsoil conditions, or the adverse soil conditions are not widespread across all niches of each land system.

5.3 Soils of the alluvial land systems

5.3.1 Sandy soils

Little has been documented about the properties of the soils of the sandier components of the land systems of the alluvial plains of the upper Flinders River catchment. No soil sampling and analysis appears to have been carried out on these soils that occupy a “small” to “medium” part of the Georgina and Gregory Land Systems (Figs 5 and 6). The actual extent of these soil units was not defined by Perry *et al.* (1964).

It is likely, however, that the sandy soils of former stream channels and levees will have allowed the rapid infiltration of rain or river flood waters, and the ready drainage of excess water from the soil profile, carrying any soluble salts as leachates from the soil profile. The sandy soils will have low clay contents and, therefore, low cation exchange capacities; the build up of excessive sodium cations in the cation exchange complex is improbable. Hence, the sandy soils of the Georgina and Gregory Land Systems are unlikely to be either saline or sodic; their chemical properties should be assessed.

5.3.2 Solodic soils: Rosevale Soil Family

Turner and Hughes (1983) analysed an unknown number of soil profiles from their Rosevale Family of solodic soils that have sandy loam – silty loam topsoils that sharply overlie sodic subsoils of heavy clay texture. Perry *et al.* (1964), in a footnote to their description of the Gregory Land System, recognised that solodic soils occupy “moderate areas” of the Gregory Land System, but also indicated the occurrence of other sandy soils such as the Manbulloo Fine Sand occupying “medium areas” of stream levees in that land system (Fig. 6); their actual extent has not been estimated.

It is unfortunate, indeed, that Turner and Hughes (1983) chose to use the solodic soils of the Rosevale Family to characterise the soil chemical properties of the alluvium of the Gregory Land System in the vicinity of Hughenden. They showed that the soil group is not suited to irrigated agriculture because of the limitations posed by subsoil sodicity. It is probable, however, that the sandier soils of the Gregory Land System may be non-saline and non-sodic. Detailed, site-specific studies of the potential for irrigated agriculture on the sandier soils of the Gregory and Georgina Land Systems appear to be worthy of further investigation.

6. IRRIGATION POTENTIAL OF THE SOILS

Two soil-related factors are critical in the assessment of the irrigation potential of any parcel of land:

- the nature and properties of the potentially irrigable soils (especially their soil-water properties related to water infiltration, profile water storage and plant use, drainage of excess soil water, and geochemical constraints that the soils present to plant growth such as extremes of soil alkalinity, salinity, and sodicity);
- the nature of the soil landscapes such as gilgai microrelief, flood frequency, or soil variability related to closely spaced stream channel sands that may influence the irrigation design (e.g. irrigation by flood, overhead travelling or centre-pivot irrigator, or trickle irrigation techniques).

They are discussed below in relation to the soils of the four main land systems in the vicinity of the upper Finders River catchment.

Wilson and Philip (1999) identified a range of soil limitations to irrigated agriculture in northern and western Queensland, and suggested that the key limitations are: low wet season trafficability, extensive clay plains with poor drainage characteristics, and adverse soil chemical conditions including strong soil alkalinity, high soil sodicity, and high soil salinity. In addition to these limitations, Turner and Hughes (1983) identified the risk of erosion by flowing water, shallow soil depth, and a poor plant nutrient supply.

Other limitations discussed by Shields (2003) included: soil salinity, climate, water availability, rockiness, risk of flooding, soil wetness, soil physical condition, landscape complexity, furrow infiltration, and water erosion hazard. Of these Shields (2003, p. 25) considered the risk of flooding and soil wetness as the most important constraints to irrigated agriculture on the 74,600 ha of clay soils he surveyed near Maxwelton, where 71% of the area of clay soils was found to be suitable for a variety of crops including cotton, forage crops, Rhodes grass / lucerne, small crops, and tree crops.

6.1. The cracking clay soils

6.1.1 Water infiltration and drainage

The most widespread soils across the rolling downs and the alluvial terraces of the upper Flinders River catchment are the cracking clay soils. Most of these soils in the vicinity of Hughenden were rated by Turner and Hughes (1983) as *'suitable for irrigation with moderate or severe limitations'* and possible crops included field crops of grain sorghum, wheat, cotton, and oil seeds.

In an irrigation assessment in a part of the Balbirini and Georgina Land Systems in the vicinity of Maxwelton, Shields (2003) rated the soils of the 29,800 ha mapped as *'moderately deep clays on mudstone as suitable for all forms of irrigated cropping except growing tree crops. The moderately deep clays have few limitations but shallow clays on mudstone are included within the mapping unit. The shallow soils are unsuitable for all forms of irrigated cropping due to several limitations including wetness, soil depth, rockiness and water erosion hazard. However, the shallow soils cover less than 5% of the mapping unit and overall limitations for the suitable crops are minor except for a moderate water erosion hazard associated with small cropping.'*

When dry, the clay soils present moderately deep to deep, dense subsoils with numerous, deep, wide cracks that act as sinks for runoff water immediately after rainfall events. Infiltration rates are extraordinarily high for the entry of the first flush of rain and runoff water ponded on the soil surface, but diminish rapidly as the soil wets up, swells, and its cracks and pores begin to close up. Water infiltration rates as high as 20 mm / hr have been measured on such soils at Karumba, but reduce to less than 2 mm / hr as quickly as a half an hour after the water application commenced (Coventry 2009). Under prolonged wet conditions, the surface pores and cracks remain closed and the topsoils are effectively impermeable. Renewed water infiltration will occur only after the soils have dried out sufficiently to form a self-mulching surface or deeper soil cracks.

Field observations of the cracking clay soils made towards the end of the dry season, and some 6 months after any significant rain, have shown that the consistence of topsoils in the upper Flinders River catchment (and elsewhere on the rolling downs) gradually changes from dry and hard to moist and plastic with increasing soil depth below 60 – 80 cm. Under such conditions, the subsoils are often sufficiently moist to have allowed the reactive clay minerals to swell and severely reduce the permeability of the subsoil. Hence, it is unlikely that there will be any significant deep profile drainage through the moist deep subsoils of the cracking clay soils into the underlying weathered rock or buried, more permeable layers of alluvium. Management of this phenomenon through appropriate water inputs matching plant water use offers a mechanism to control deep drainage of "excess" irrigation water from the soil profile.

The lack of deep drainage from the cracking clay soils explains the origin of their alkalinity, salinity, and possible sodicity at specific, lower sites in the landscape. There has been insufficient drainage of soil water from the profile over very long (geological) time periods to have leached lime, gypsum, and other soluble salts, and sodium cations from the soil. The bulk of the water losses from the soil profile have been by evapotranspiration and not deep drainage. This is an asset in irrigation planning in that the water to be supplied to the crop has to match only the plant needs and evaporation from the soil surface; under low infiltration rates, only the bare water requirements for plant growth need to be supplied. There is little likelihood, under these conditions, of generating large quantities of drainage water from over-irrigation and excessive profile drainage.

6.1.2 Soil chemical issues

The alkalinity, salinity, and sodicity of the cracking clay soils may present significant soil chemical challenges to the establishment and growth of irrigated crops on the cracking clay soils.

The soil alkalinity may be addressed by growing a crop suited to alkaline soils, or by using nitrogenous fertilisers (especially ammonium sulphate), or incorporating legumes and their residues into the cropping regime. In severe cases, it is possible to incorporate agricultural or prilled sulphur, ferrous sulphate, or phosphoric acid into the soil,. Practically, the beneficial amelioration of high soil alkalinity in the root zone is achieved progressively through prolonged farming practice, with leaching of alkaline components from the soil (mainly lime) giving rise to local acidifying effects.

Soil salinity can only be ameliorated in the long term by leaching the soluble salts from the soil profile. As is evident from the previous section of this report, such is unlikely to occur under irrigation in the heavy clay soils of low permeability. Trickle irrigation may be used in saline soils, with the trickle tape installed at, or close to, the soil surface. The irrigation water should then be applied in the small amounts needed for plant survival, and at such a rate as to maintain a slight hydraulic head, which will dissolve any soluble salts in the upper part of the plant root zone and move them downwards with the wetting front to be deposited in the subsoil beyond the bulk of the root zone of the crop (Fig. 8).

The use of trickle irrigation, or modern, well-managed overhead irrigation by travelling or centre-pivot irrigators may well allow a re-thinking of the irrigation modelling that was carried out by Shields (2003), and a reduction in the assessment of the severity of soil salinity risk.

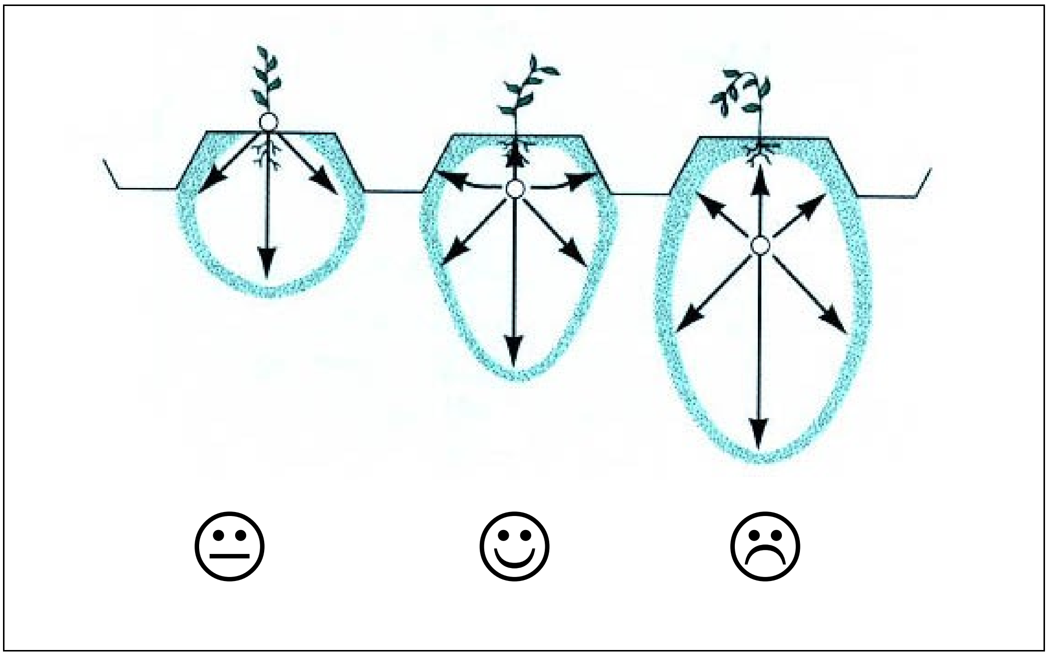


Figure 8. Use of drip or trickle irrigation to re-distribute soluble salts in the soil.
Arrows indicate possible irrigation water pathways, forming a wetting front in the soil, and carrying soluble salts (broad fuzzy line) away from the root zone of the plants. The effectiveness of the irrigation system to leach salts from the root zone of plants depends on the depth at which the water supply tube is placed.
Source: Brady and Weil (2002, p. 397).

6.2 The sandy soils

In the absence of specific site data, the sandy soils of the Balbirini, Georgina, and Gregory Land Systems of the upper Flinders River appear to offer many fewer constraints to irrigated agriculture than the associated clay soils. Water infiltration and deep drainage should be rapid with few impediments. The chemical properties of the soils are also unlikely to present problems to plant growth caused by excessive amounts of soluble salts, high exchangeable sodium contents, or extremes of soil pH that could be expected in the heavier cracking clay soils (Section 5.3.1, above).

The major limitations to irrigated agriculture on these soils was found to be the small, disconnected and fragmented nature of parcels of suitable land on alluvial soils, and their sensitivity to erosion by water (Turner and Hughes 1983). This, in part, is the motivation for the mosaic approach to irrigation in the Flinders River Agricultural Precinct, where the locations of individual off-takes and storages could be readily designed to allow the cultivation of the better suited, sandy soils. Erosion control practices in sandy soils have come a long way in the last 30 years and there is a number of strategies that have been used successfully in sandy soils around the world.

6.3 Solodic soils: Rosevale Soil Family

The solodic soils of the Rosevale Family were regarded by Turner and Hughes (1983) as unsuitable for irrigation as a consequence of their ‘scalded surfaces’, which are possibly crusted surfaces formed by the dispersion of the sodic clay topsoils under raindrop impacts, shallow topsoils, poor water infiltration properties, and poor drainage characteristics. In many ways, the solodic soils occupying parts of the Gregory Land System behave like the more sodic components of the cracking clay soils, discussed above (Section 6.1.1). There are treatments available now, based on the incorporation of gypsum and / or organic matter to manage the poor structure of ‘scalded’ surface soils.

6.4 The soil landscapes

6.4.1 Gilgai microtopography

There is insufficient detail in the published soil reports to be able to assess, in the present paper, the site conditions on parcels of land with the potential for irrigated agriculture in the upper Flinders River catchment. Gilgai microrelief has been noted by Perry *et al.* (1964) in the Balbirini and Georgina Land Systems (Figs. 4 and 5); it is likely to occur on similar clay soils in the Julia and Gregory Land Systems. The size and amplitude of the mounds and depressions, and the distribution of affected land within any component of the land systems of the upper Flinders are unknown. The amplitude of the gilgai could be as little as a few centimetres in the Mitchell grass plains to much as 1.5 m in areas of cleared gidgee woodlands, and such would certainly influence the ponding and drainage of rainwater, flood waters, or irrigation waters.

Experience in cropping lands in clay soils of the lower Burdekin River catchment show that gilgai topography will re-form in response to soil wetting and drying regimes after laser levelling and land forming operations have been carried out. Therefore, any earthworks required to facilitate the supply, delivery, infiltration, or drainage of irrigation water to crops growing on cracking clay soils with gilgai microrelief should be carried out only in the knowledge that their reconstruction is likely to be required after significant soil wetting and drying cycles driven by strongly seasonal rainfall regimes.

6.4.2 Soil variability

Large, continuous areas of uniform soils and slopes present few problems to the irrigation manager. But the more variable the soils, and the smaller the areas of individual soils within a paddock, the greater the requirements for crop selection, and the greater the management inputs needed by the soils, the crop, the paddock, and irrigation strategies.

The clay soils of the Julia Land System offer large areas of relatively uniform slopes and soils, whereas the clay soils of each of the land systems on the alluvial deposits of the upper Flinders River are traversed by sandy stream channel and levee deposits as shown in Figure 5. Similar, relatively small patches of sandy sediments occur within the three alluvial land systems (Balbirini, Georgina, and Gregory) of the Flinders River Agricultural Precinct. While there are patches of potentially irrigable sandy soils on these stream sediments, they are often of relatively limited extent and discontinuous along the river. Nevertheless, the soils are likely to present few limitations to irrigated agriculture and offer good prospects for producing well adapted crops from paddocks perhaps as small as 5 - 50 ha.

6.4.3 Terrace elevation

Opportunistic cropping is possible on relatively small parcels of land on sandy alluvium close to the upper Flinders River where a water supply can be assured. However, the alluvial sediments of the Gregory and Georgina Land Systems define the river’s modern floodplain and lie at elevations that are flooded by normal wet season flood events. Hence, any irrigated farming infrastructure established this close to the river could be regularly inundated.

The Balbirini Land System lies at elevations that are a few metres higher than the modern river floodplain and its alluvial terraces are flooded only in exceptional floods. The recurrence interval of these larger floods cannot currently be determined in the absence of detailed topographic and river flood data, but possibly relates to 1 in 20 to 1 in 50 year flood levels. Because of its less frequent flooding and favourable soils, irrigated agriculture is most likely to be developed on the sandy soils of the Balbirini Land System.

6.5 Planning for irrigated agriculture

It is undoubtedly the case that current and prospective cropping, either in dryland rainfed systems or under irrigation, is presented with the same challenges found in much of inland Queensland. Ahern (1988) listed these as:

- a semiarid climate,
- high levels of soil alkalinity and sodicity below the topsoil,
- difficulties with water infiltration and plant available water capacity from deeper in the soil profile and,
- in places, high soil electrical conductivity which may be associated with high chloride levels.

Conditions such as these are well documented in the management of ‘Vertisols’, or clay soils, in semiarid conditions across much of the world’s agriculture and have been the subject of extensive research in several scientific and agricultural agencies (*e.g.* Latham and Ahn 1987; Kirchhoff and So 1996).

In general, the issues considered likely to be encountered in the Flinders River Agricultural Precinct will involve rapid changes of water infiltration shifting the soil from a dry, cracked state to a moist, more plastic state as the moisture content increases, associated problems with surface trafficability when wet, crop plant rooting depth restricted by adverse subsoil chemical properties (soil alkalinity, sodicity, or salinity), and high osmotic potentials with dissolved salts (chlorides and sulphates), and less than desirable drainage from the plant root zone with restrictions to soil internal hydraulic conductivity.

It is important to realise that the characteristics of soils of the Flinders River Agricultural Precinct, the soil parent materials, and the processes that have led to these formations have not been studied extensively. As for much wider tracts of Australia, there is much to learn about how to best manage cropping and potential cropping on the soils that are alkaline cracking clays with strongly sodic subsoils and high electrical conductivity. Practically, this knowledge and experience will only come about by the gradual development of farming systems on a pilot scale to suit the local soil and climatic conditions.

This paper has shown that there may be unrealised potential for irrigated cropping in the upper Flinders River catchment on extensive areas of cracking clay soils on the rolling downs and along the terraces of the river between Hughenden and Julia Creek. The sandier channel and stream levee deposits that cut across the alluvial terraces offer potentially good soils for irrigated agriculture, but the sandy soils of the modern floodplain of the river may be too frequently flooded to warrant the investment in permanent irrigation infrastructure.   The sandier sediments and the better clay soils (less alkaline, less saline, and less sodic) of the somewhat higher river terraces of the Balbirini Land System hold much promise for opportunistic irrigated cropping.

With the advent of the Gulf Water Resource Plan (Queensland Government 2007) and the Gulf Resource Operations Plan (Queensland Government 2010), there is considerable interest in accessing water during peak river flow periods for harvest for irrigation, and in matching feasible access to water with good quality agricultural land. To date, river dams, off-stream storages, on-farm ring tanks, and non-artesian aquifers have been considered in various water-harvesting options. Small-scale irrigated cropping has been successful and is currently producing a range of crops and fodder.

The Flinders River Agricultural Precinct offers opportunities for the development of irrigation infrastructure and cropping on a mosaic of smaller pockets of land rather than large contiguous areas. The mosaic design uses the best-suited soils, and reduces the risk for off-site impacts, while delivering productivity and environmental safeguards.

7. CONCLUSIONS

The major findings of this paper are:

- irrigated agriculture is a potentially viable operation at certain sites in the vicinity of the upper Flinders River, especially if modern, well-controlled irrigation water management techniques are used;
- a mosaic of small areas is likely to be suitable for irrigated agriculture, but detailed soil and site data are required from those and other areas before irrigated farm plans are developed for any particular site.

The majority of the area that is potentially irrigable is underlain by sandier soils interspersed with cracking clay soils of the Julia, Balbirini, Georgina, and Gregory Land Systems. Previous soil survey work has provided very little soil chemical analytical data from the sandier, potentially irrigable soils. However, the cracking clay soils are known to be moderately to strongly alkaline at the surface and in the upper subsoil, with pH declining slightly in the lower subsoil and becoming mildly to moderately alkaline in the weathered bedrock. Limited soil profile chemical analysis shows increasing salinity, electrical conductivity, and soil sodicity at depth in the moderately deep clays.

As in all irrigation projects, soil salinity and groundwater levels will require careful management to ensure that irrigation practices do not contribute to a developing salinity problem. Irrigation best-management practices would necessarily ensure optimal water delivery and scheduling, matching water availability to crop plant needs, and minimising ground water accession in an environment where there is likely to be little, if any, deep drainage from the clay soils.

The area of soils suitable for irrigated cropping cannot be determined until a more detailed site assessment, involving topographic and soil chemical analysis, is made at specific locations on particular properties. Some of the costs involved in such an assessment should be borne by the landholders who would be the major beneficiaries from any irrigated cropping developments on their properties.

There is clearly a relatively large area of land available in the upper Flinders River catchment for irrigated cropping under modern, well-controlled water management inputs that are unlikely to cause short- or long-term environmental problems. As with all irrigation prospects, in all soil types, there is a range of factors and potential constraints to be more extensively examined to determine the most sustainable land and soil management practices that should be adopted.

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