Land suitability: technical methods

A technical report to the Australian Government from the CSIRO Flinders and Gilbert Agricultural Resource Assessment, part of the North Queensland Irrigated Agriculture Strategy

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Important disclaimer

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The Strategy was guided by two committees:

(i) the **Program Governance Committee**, which included the individuals David Crombie (GRM International), Scott Spencer (SunWater, during the first part of the Strategy) and Paul Woodhouse (Regional Development Australia) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; and the Queensland Government.

(ii) the **Program Steering Committee**, which included the individual Jack Lake (Independent Expert) as well as representatives from the following organisations: Australian Government Department of Infrastructure and Regional Development; CSIRO; the Etheridge, Flinders and McKinlay shire councils; Gulf Savannah Development; Mount Isa to Townsville Economic Development Zone; and the Queensland Government.

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Director’s foreword

Northern Australia comprises approximately 20% of Australia’s land mass but remains relatively undeveloped. It contributes about 2% to the nation’s gross domestic product (GDP) and accommodates around 1% of the total Australian population.

Recent focus on the shortage of water and on climate-based threats to food and fibre production in the nation’s south have re-directed attention towards the possible use of northern water resources and the development of the agricultural potential in northern Australia. Broad analyses of northern Australia as a whole have indicated that it is capable of supporting significant additional agricultural and pastoral production, based on more intensive use of its land and water resources.

The same analyses also identified that land and water resources across northern Australia were already being used to support a wide range of highly valued cultural, environmental and economic activities. As a consequence, pursuit of new agricultural development opportunities would inevitably affect existing uses and users of land and water resources.

The Flinders and Gilbert catchments in north Queensland have been identified as potential areas for further agricultural development. The Flinders and Gilbert Agricultural Resource Assessment (the Assessment), of which this report is a part, provides a comprehensive and integrated evaluation of the feasibility, economic viability and sustainability of agricultural development in these two catchments as part of the North Queensland Irrigated Agricultural Strategy. The Assessment seeks to:

- identify and evaluate water capture and storage options
- identify and test the commercial viability of irrigated agricultural opportunities
- assess potential environmental, social and economic impacts and risks.

By this means it seeks to support deliberation and decisions concerning sustainable regional development.

The Assessment differs from previous assessments of agricultural development or resources in two main ways:

- It has sought to ‘join the dots’. Where previous assessments have focused on single development activities or assets – without analysing the interactions between them – this Assessment considers the opportunities presented by the simultaneous pursuit of multiple development activities and assets. By this means, the Assessment uses a whole-of-region (rather than an asset-by-asset) approach to consider development.
- The novel methods developed for the Assessment provide a blueprint for rapidly assessing future land and water developments in northern Australia.

Importantly, the Assessment has been designed to lower the barriers to investment in regional development by:

- explicitly addressing local needs and aspirations
- meeting the needs of governments as they regulate the sustainable and equitable management of public resources with due consideration of environmental and cultural issues
- meeting the due diligence requirements of private investors, by addressing questions of profitability and income reliability at a broad scale.

Most importantly, the Assessment does not recommend one development over another. It provides the reader with a range of possibilities and the information to interpret them, consistent with the reader’s values and their aspirations for themselves and the region.

Dr Peter Stone, Deputy Director, CSIRO Sustainable Agriculture Flagship

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Shortened forms

ACLEP	Australian Collaborative Land Evaluation Project
ANZLIC	Australian and New Zealand Land Information Council
APSIM	Agricultural production systems simulator
ASC	Australian Soil Classification
ASLSFH	Australian Soil and Land Survey Field Handbook
ASRIS	Australian Soil Resource Information System
cLHS	Conditional Latin Hypercube Sampling
CSIRO	Commonwealth Scientific Industrial Research Organisation
DEM	Digital elevation model
DSITIA	Department of Science, Information Technology, Innovation and the Arts
DSM	Digital Soil Mapping
EM	Electromagnetic (electromagnetic induction instrument)
ESP	Exchangeable Sodium Percentage
FAO	Food and Agriculture Organisation of the UN
GAB	Great Artesian Basin
GDP	Gross Domestic Product
GPS	Global Positioning System
MIR	Mid Infrared
MRRTF	Multiresolution index of Ridge Top Flatness
MRVBF	Multiresolution Index of Valley Bottom Flatness
NCST	National Committee on Soil and Terrain
NIR	Near Infrared
NQIAS	North Queensland Irrigated Agriculture Strategy
PAWC	Plant Available Water Capacity
RMSE	Root Mean Square Error
RUSLE	Revised Universal Soil Loss Equation
SALI	Soil and Land Information
SGG	Soil Generic Group
SRTM	Shuttle Radar Topography Mission
USLE	Universal Soil Loss Equation
WGS84	World Geodetic System 1984
XRF	X-Ray Fluorescence

Units

MEASUREMENT UNITS	DESCRIPTION
GL	gigalitres, 1,000,000,000 litres
keV	kilo-electronvolts
kL	kilolitres, 1000 litres
km	kilometres, 1000 metres
L	Litres
m	Metres
mAHD	metres above Australian Height Datum
MeV	mega-electronvolts
mg	milligrams
MJ/m^2	megajoules per metre square
ML	megalitres, 1,000,000 litres

Geological time scales

Table 5.1: Geological timescales used in this Assessment. Note that the term 'Tertiary' will be used throughout this document to describe the geological time period from 65 – 1.806 million years ago. The Tertiary is no longer officially recognised as a formal geological period, however, it is still commonly used in soil and landscape assessments

Eon	Era	Period	Epoch	Age (Ma)	Major events
PHANEROZOIC	CENOZOIC	Quaternary	Holocene	0.01	
			Pleistocene	2.6	Major glaciations Man
		Neogene	Pliocene	5.3	
			Miocene	23	
		Paleogene	Oligocene	34	
			Eocene	56	Deep weathering in North-Eastern Australia
			Paleocene	66	Rise of East Australian highlands
	MESOZOIC	Cretaceous		145	Marine inundation of Eastern and Central Australia
		Jurassic		201	Great Artesian Basin deposited
		Triassic		252	Last major episode of orogenic mountain building (Eastern Australia)
	PALAEOZOIC	Permian		299	
		Carboniferous		359	
		Devonian		419	First land plants
		Silurian		444	
		Ordovician		485	Marine inundation of Northern and Central Australia
		Cambrian		541	
Supereon	**Eon**	**Era**		**Age**	
PRECAMBRIAN	PROTEROZOIC	Neo		1000	Oxygen rich atmsophere
		Meso		1600	
		Paleo		2500	
	ARCHAEAN			4000	Oxygen poor atmsophere

Preface

The Flinders and Gilbert Agricultural Resource Assessment (the Assessment) aims to provide information so that people can answer questions such as the following in the context of their particular circumstances in the Flinders and Gilbert catchments:

- What soil and water resources are available for irrigated agriculture?
- What are the existing ecological systems, industries, infrastructure and values?
- What are the opportunities for irrigation?
- Is irrigated agriculture economically viable?
- How can the sustainability of irrigated agriculture be maximised?

The questions – and the responses to the questions – are highly interdependent and, consequently, so is the research undertaken through this Assessment. While each report may be read as a stand-alone document, the suite of reports must be read as a whole if they are to reliably inform discussion and decision making on regional development.

The Assessment is producing a series of reports:

- Technical reports present scientific work at a level of detail sufficient for technical and scientific experts to reproduce the work. Each of the 12 research activities (outlined below) has a corresponding technical report.
- Each of the two catchment reports (one for each catchment) synthesises key material from the technical reports, providing well-informed but non-scientific readers with the information required to make decisions about the opportunities, costs and benefits associated with irrigated agriculture.
- Two overview reports – one for each catchment – are provided for a general public audience.
- A factsheet provides key findings for both the Flinders and Gilbert catchments for a general public audience.

All of these reports are available online at <http://www.csiro.au/FGARA>. The website provides readers with a communications suite including factsheets, multimedia content, FAQs, reports and links to other related sites, particularly about other research in northern Australia.

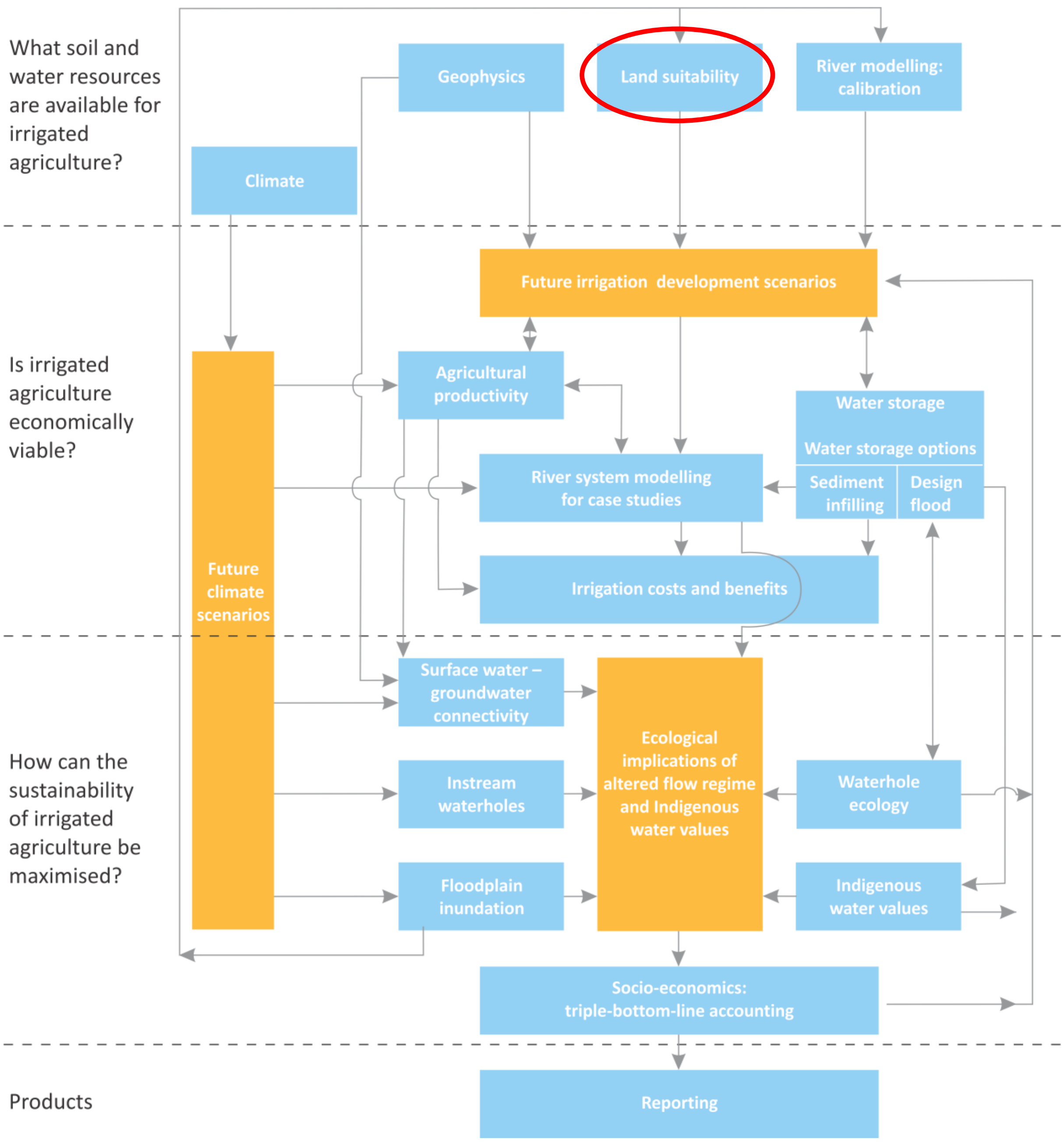
The Assessment is divided into 12 scientific activities, each contributing to a cohesive picture of regional development opportunities, costs and benefits. Preface Figure 1 illustrates the high-level linkages between the 12 activities and the general flow of information in the Assessment. Clicking on an 'activity box' links to the relevant technical report.

The Assessment is designed to inform consideration of development, not to enable particular development activities. As such, the Assessment informs – but does not seek to replace – existing planning processes. Importantly, the Assessment does not assume a given regulatory environment. As regulations can change, this will enable the results to be applied to the widest range of uses for the longest possible time frame. Similarly, the Assessment does not assume a static future, but evaluates three distinct scenarios:

- Scenario A – historical climate and current development
- Scenario B – historical climate and future irrigation development
- Scenario C – future climate and current development.

As the primary interest was in evaluating the scale of the opportunity for irrigated agriculture development under the current climate, the future climate scenario (Scenario C) was secondary in importance to scenarios A and B. This balance is reflected in the allocation of resources throughout the Assessment.

The approaches and techniques used in the Assessment have been designed to enable application elsewhere in northern Australia.



Preface Figure 1 Schematic diagram illustrating high-level linkages between the 12 activities (blue boxes)

This report is a technical report. The red oval in Preface Figure 1 indicates the activity (or activities) that contributed to this report.

The orange boxes indicate information used or produced by several activities. The red oval indicates the activity (or activities) that contributed to this technical report. Click on a box associated with an activity for a link to its technical report (or click on 'Technical reports' on <http://www.csiro.au/FGARA> for a list of links to all technical reports). Note that the Water storage activity has multiple technical reports – in this case the separate reports are listed under the activity title. Note also that these reports will be published throughout 2013, and hyperlinks to currently unpublished reports will produce an 'invalid publication' error in the CSIRO Publication Repository.

Executive summary

Soil data are considered the most important environmental factor determining the suitability of land for agriculture. There have been several land resource assessments carried out in the Flinders and Gilbert catchments over the last 50 years, however, a key recommendation common to all studies was that further soils data were needed before detailed agricultural suitability assessments could be conducted. To further our understanding of the land suitability of soils in the Flinders and Gilbert catchments three tasks were carried out as part of this study. The first was the collection of new soils data by applying a statistically robust field sampling strategy. The second was to use the existing and new soils information to produce maps of individual soil attribute layers of the Flinders and Gilbert catchments. Finally, the digital soil attribute layers were used to determine the area of land suitable for irrigated agricultural production in the two catchments.

A total of 76 irrigation land uses (crop and irrigation combinations), from 13 different land use categories, were evaluated in the Flinders and Gilbert catchments. For each of these land uses, the key limitations to production and associated soil attribute data were described. A statistically robust soil sampling design was used to determine the locations within each catchment most appropriate for new soils data collection. Soil data were collected from 451 new sites across the Flinders and Gilbert catchments. The new soils data were processed using a combination of innovative rapid techniques (e.g. mid-infrared analysis) and standard soil chemistry approaches. The prediction of soil attributes across the catchment from each data point was carried out using a spatial correlation approach. Data from a total of 1951 new and existing sites were combined with spatial covariate information and modelled using the RuleFit3 program. A range of approaches were used to quantify the reliability of the digital soil attribute layers and land suitability outputs. Independent validation of a select number of attributes was also conducted.

A total of 16 digital soil attribute layers were produced. For brevity, this report describes nine of the key attributes: pH, plant available water capacity to 1 m depth (PAWC100), minimum soil depth, soil texture, permeability, rockiness, drainage, electrical conductivity (EC) of the surface soil and exchangeable sodium percentage (ESP) of the surface soil. The distribution of soil generic groups (SGGs) across the landscape was also predicted. The model performed best for the categorical data (cross validation classification rate % from 53% to 86%) compared to the numerical data outputs (R^2 range from 18% to 54%). It is not practical to present and describe the results for each of the 76 land uses modelled, therefore a selection of 14 land uses that provide a range of crop and irrigation combinations is presented in this report (capsicum/chilli, cotton, mangos, peanuts, Rhodes grass, rice, sorghum, soybeans and sugarcane). Land suitability was described using a 1-5 class system, with class 1 being highly suitable with negligible limitations and class 5 being unsuitable. An estimate of confidence in the land suitability outputs is also provided. In the Flinders catchment, there was very little land classified as class 2 and no land classified as class 1. Based on the results (with moderate to high confidence), ~60% of the Flinders catchment is moderately suitable with considerable limitations (class 3) for cotton, soybean, sorghum, sugar, capsicum/chilli, mangos, rice, peanuts and Rhodes grass. In most cases spray irrigation was more suitable than furrow irrigation. The Gilbert catchment generally had less soil suitable for agriculture due to its dissected topography and geology. The main crops shown as moderately suitable (with considerable limitations) in the Gilbert catchment (~20% of area) were trickle irrigation on capsicum/chilli, spray irrigation on cotton, Rhodes grass, forage sorghum, soybeans and sugarcane; and furrow irrigation for peanuts. Importantly, the reliability of these data varies in space, with mapping uncertainty generally declining away from the major river systems where most of the soils data were collected. Therefore estimates of suitable land areas are considered to have high uncertainties, particularly in areas where no soil data were collected. On some of the lands classified as un-suitable, agriculture development may be possible if sufficient new technologies become available to overcome the limitations identified in the land suitability framework.

Traditional land suitability assessments take into account access to water, cost of production, flooding risk and expert opinion on issues such as secondary salinisation. In this case, the soil suitability analysis

occurred as part of a wider feasibility study within which these factors are studied in detail. Thus, this study evaluated climate, soil and local landscape drivers only. As such, extreme caution should be employed when using these maps and outputs for planning purposes. These outputs can be used for gaining a soil-centred, strategic overview of the irrigated agricultural potential in each of the catchments. Additional considerations such as water access, flooding risk, salinisation potential and economic factors are available in companion reports (Crossman et al., 2013; Dutta et al., 2013; Jolly et al., 2013; Lerat et al., 2013; Webster et al., 2013). It would be essential to conduct a detailed salinity investigation that accounts for the location of sub-surface salinity, the type of irrigation proposed, and the potential for deep drainage. This study has produced a catchment wide assessment: further detailed soil physical, chemical and nutrient analysis would be required to plan at the enterprise or property scale.

This study has established a valuable blueprint for future systematic resource evaluation over large areas at the regional scale. The study has employed resources, knowledge and expertise from State and Federal Government agencies and represents a pragmatic, yet scientifically robust approach to land and soil evaluation within limited timeframes (18 months) and over a large area (~150,000 km^2). This study now represents the largest land suitability assessment using digital soil mapping ever conducted in Australia.

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1 Introduction

Soil data are considered the most important environmental factor in determining the suitability of land for irrigated agriculture. Many soils of northern Australia are ancient and highly weathered (Reimann et al., 2012), low in available phosphorus, total nitrogen, organic carbon, soluble salts and exchangeable cations (Webb et al., 1974), and highly susceptible to erosion (Brooks et al., 2009; Pillans, 1997). There are, however, deposits of younger soils (e.g. Quaternary alluvium) that are suitable for agricultural development. To identify these areas, it is important to first understand the spatial location and characteristics of the soils and then assess this soil suitability in context with broader water, landscape, environmental and economic factors. This report describes the approaches used to assess the agricultural suitability of the soils in the Flinders and Gilbert catchments, Queensland, Australia.

1.1 Assessment area

The Assessment area encompasses the Flinders and Gilbert catchments, which drain to the Gulf of Carpentaria, North Queensland (Figure 1.1). The Flinders catchment has an area of 109,000 km^2 and a population of ~6000 people. The Flinders River is the longest river in Queensland, and the second longest Australian river course outside of the Murray-Darling Basin. The river rises in the Great Dividing Range north-east of Hughenden, nearly 1000 km from its entry to the Gulf of Carpentaria. The Gilbert catchment has an area of 46,200 km^2 and a population of ~1200 people. The Gilbert catchment is comprised of two major rivers, the Gilbert and the Einasleigh. The Gilbert River flows in a north-westerly direction from the Great Dividing Range, 150 km south-east of Georgetown and is joined by its major tributary, the Einasleigh River, downstream of Strathmore Station, before entering the Gulf of Carpentaria.

Both catchments have a maximum elevation of ~1050 m and do not have any mountains that provide notable obstruction to large-scale atmospheric circulatory systems. While the Gilbert catchment has relatively high relief in its mid-to-upper reaches, and is flat in its lower reaches, the Flinders catchment is predominately flat (Figure 1.1). The main land use by area in the two catchments is extensive cattle grazing. Major population centres are shown in Figure 1.1. The field sampling for this study was focused in the primary and secondary investigation areas shown in Figure 1.1. These areas represented the most suitable soils based on previous assessments in these catchments (see Section 1.2) and were agreed in consultation with the NQIAS Steering Committee. Some data were collected outside of these investigation areas (see Section 3.1), however, these data were largely for model validation purposes.

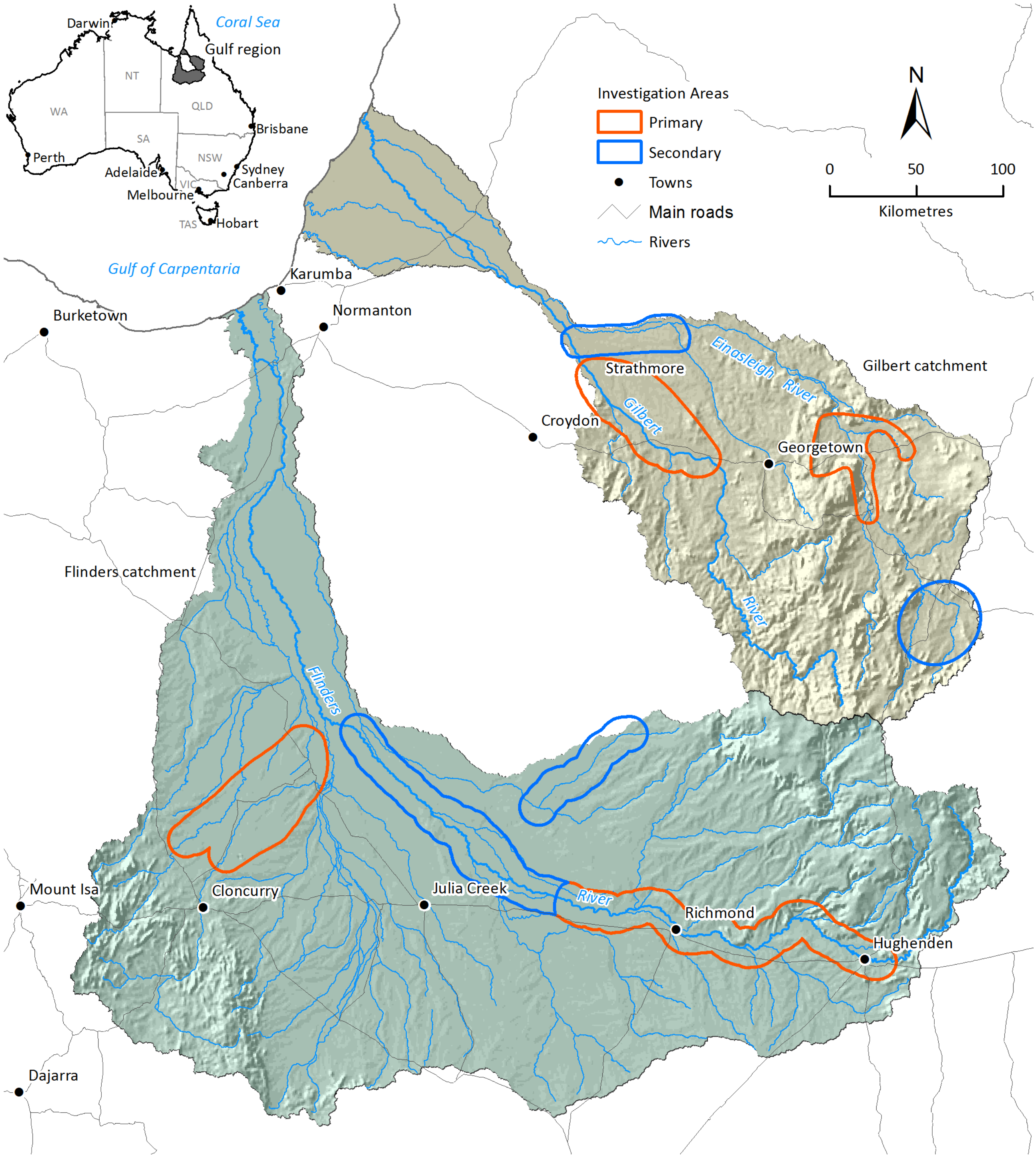


Figure 1.1 Shaded relief map of the Flinders and Gilbert catchments showing the primary and secondary investigation areas

1.2 Summary of previous soil assessments

Several land resource assessments have been conducted in the Flinders and Gilbert catchments. The broad scale CSIRO land systems work from the 1950s (Perry et al., 1964) formed the basis of subsequent agricultural investigations. An assessment of the irrigation potential in the Upper Flinders catchment was carried out by Turner and Hughes (1983), and Wilson and Philip (1999) assessed the agricultural potential of the soils in the Gulf region using new technology incorporporating radiometrics. The salinity hazard potential of the northern Gulf region, which included the Gilbert but not Flinders catchment, was carried out by Nelson and Webb (2004). An assessment of the options and demands for future land and water resource development in the region was undertaken by QDNRME (2004) and other development opportunities were investigated by MITEZ (2010). Enderlin (unpublished data) conducted soil mapping in the Gilbert River primary investigation area west of

Georgetown and in the Einasleigh town common and Maxwelton areas (data now resides in SALI). Most recently, Wilson et al., (2009) conducted a desktop assessment of the land and soil resources of northern Australia, including the Flinders and Gilbert catchments. Finally, Coventry and Pollock (2011) conducted a more focused desktop assessment of the Flinders River Agricultural Precinct near Hughenden. None of these were sufficiently comprehensive or at scale to provide a full regional assessment; a key recommendation common to all of these assessments was that further soils data were needed before detailed agricultural suitability assessments could be conducted.

1.3 Scientific approach

1.3.1 LAND SUITABILITY ASSESSMENT

Land evaluation is the process of predicting the potential use of land on the basis of its attributes (Rossiter, 1996). Generally, land evaluation requires biophysical, social and economic information (van Gool et al., 2008). This report describes only the biophysical data component as part of a broader study. The FAO Framework for Land Evaluation (FAO, 1976) describes the key principles and concepts related to land evaluation. This Assessment used a modified version of the FAO approach, coupled with digital soil mapping approaches described below. Table 1.1 lists the land use categories and crops evaluated for irrigation in this Assessment. These categories were derived following consultation with agronomists, knowledge of what crops have grown in similar tropical regions and an understanding of the commercial aspirations of local land-holders in the region.

Table 1.1 List of land use categories and crops evaluated in this study

LAND USE CATEGORY	CROP
Cereal crop	maize/corn, millet, oats, rice, sorghum (grain)
Citrus	Citrus
Food legume (pulse crop)	chickpea, mungbean (black), navy bean, soybean
Forage grazing, hay, silage	Rhodes grass, sorghum (forage)
Forage legume	lablab, lucerne
Industrial	coffee, cotton, sugarcane
Intensive horticulture (vegetables)	capsicum/chilli, cucurbit, eggplant, sweet corn, tomato
Oilseed crop	sunflower
Root crop	cassava, peanut, sweet potato
Silviculture (plantation)	African mahogany, Caribbean pine, Indian sandalwood, spotted gum, teak
Tree crop/horticulture (fruit)	avocado, banana, carambola, custard apple, lychee, mango, pineapple
Tree crop (nuts)	cashew
Vine	grape

1.3.2 SOIL ASSESSMENT

Given the size of the catchments, variability of soils and time constraints of this study, it was impractical to use traditional soil survey methods to determine the extent and agricultural suitability of the soils. In any case, soil survey methods have evolved with the expansion in computing power in recent decades allowing soil attributes (e.g. pH) collected at a specific point in space, to be related to comprehensive data on physical attributes or covariates (e.g. slope, geology) that are available over the whole spatial extent of the area. The relationship between these variables can then be extrapolated over much larger areas, which was not possible using traditional approaches (Ziadat, 2007). The process of coupling spatial data through quantitative relationships is known as digital soil mapping (DSM). It applies pedometrics, which is the use of mathematical and statistical

models that combine information from soil observations with information contained in correlated spatial variables and remote sensing images (McBratney et al., 2003). DSM is now being used for similar assessment in other parts of Australia (e.g. Kidd et al., 2012b) and around the world (e.g. Behrens and Scholten, 2006; Sanchez et al., 2009). A benefit of DSM (when compared to traditional soil mapping processes) is that it is possible to quantify the statistical (un)-certainty associated with the estimate of the soil attributes at a given point. In this study we used DSM to derive the key soil attribute layers required for land suitability assessment and to develop generic soil maps for the catchments. Such an approach allowed the assessment of a greater spatial area than in previous soil evaluations in this region with a better understanding of the quality of that assessment.

1.4 Objectives of study

The three main objectives of this study were to (i) apply a statistically robust field sampling strategy to locate sites for new soils data collection; (ii) produce digital soil attribute and generic soil maps for the Flinders and Gilbert catchments (using new and legacy data); and (iii) evaluate the irrigation land use suitability for the two catchments with a focus on the investigation areas (Figure 1.1). The methods used for the field sampling design, field data collection, lab analysis, digital soil mapping and land suitability assessments are described in Section 2. The results are presented for the Flinders and Gilbert catchments in Section 3. A synthesis of the results and implications for use are presented in Section 4.

2 Methods

2.1 Defining limitations to land suitability to focus digital soils modelling

Digital soil modelling (DSM) is carried out for a range of purposes including land suitability evaluation, soil attribute prediction (e.g. carbon) and hazard mitigation (e.g. erosion mapping) (see globalsoilmap.net). Prior to describing the DSM approach used in this study, a discussion of the growth limitations for the crops is required, as this determines which attributes are to be predicted using the DSM approach. A total of 11 limitations were identified for the Flinders and Gilbert catchment assessment (Table 2.1) based on the crops identified in Table 1.1. Crop growth restrictions related to secondary salinisation were not evaluated in this study, and restrictions related to flooding and crop growth are dealt with in other components of the Assessment (see Dutta et al., 2013; Lerat et al., 2013; Webster et al., 2013).

Table 2.1 Irrigated agriculture crop growth limitations applied in the land suitability framework. Data sets listed in Bold were modelled as part of the DSM process and used in the land suitability framework. The field observations and laboratory analysis used to derive the DSM included field observations and laboratory data conducted as part of this project (DSITIA and CSIRO), and historical records in the Queensland government (SALI) and CSIRO soil databases (ASRIS).

LIMITATION	DESCRIPTION	DATA	SOURCE
Climate	Climate conditions that are optimal for specific plant species	Average annual rainfall Frost Temperature > 40°C Temperature < 15°C	SILO (Jeffrey, 2006) SILO SILO SILO
Effective rooting depth	Adequate soil depth to support the plant and meet minimal edaphic requirements. Only physical root barriers considered	**Soil depth**	DSM from field measurements[1]
Irrigation efficiency	Applied water must match soil infiltration characteristics (avoiding excessive drainage, avoid waterlogging at top of furrow)	**Permeability**	DSM from field measurements[1]
Microrelief	Level land surface required for infrastructure and efficient machinery use	Gilgai (horizontal interval + depth)	DSM from field measurements[1]
Nutrient status	Nutrient toxicities and deficiencies to be avoided	**Soil surface pH**	DSM from field[1] and laboratory measurements
Rockiness	Minimise impact of rocks on crop management activities	**Rockiness (size + percent)**	DSM from field measurements[1]
Soil physical factors	Affects workability (ease of cultivation), seedling establishment, harvesting requirements (especially root crops) and water infiltration	**Depth of A horizon** **ESP** **Soil Generic Group** **Soil surface condition** **Soil surface texture** Soil structure	DSM from field measurements[1] DSM from laboratory analysis data DSM from field measurements[1] DSM from field measurements[1] DSM from field measurements[1] DSM from field measurements[1]
Soil water Availability PAWC 0.5 m	Relates to irrigation efficiency, the soil needs to store an adequate amount of water and make it available for plant use. Incorporates a salinity limitation to plant rooting depth. Estimated over effective rooting depth, incorporating physico-chemical restrictions to root growth.	15 bar moisture Bulk density **Clay content** Sand content **Soil depth** EC, Chloride content and ESP (physio-chemical constraints)	DSM from laboratory analysis data DSM from laboratory analysis data DSM from laboratory analysis data DSM from laboratory analysis data DSM from field measurements[1] DSM from field[1] and laboratory measurements
Soil water Availability PAWC 1.0 m	See above	As above	As above
Soil water Availability PAWC 1.5 m	See above	As above	As above
Water Erosion	Soil loss from water erosion needs to be minimised	**K factor** (soil erosion, USLE) Slope	DSM from calculated data CSIRO SRTM
Wetness	Adequate soil aeration is required for plant growth	**Site drainage** **Site permeability**	DSM from field measurements[1] DSM from field measurements[1]
Wind Erosion	Soil loss from wind erosion needs to be minimised	Average annual rainfall **Soil surface texture**	SILO DSM from field measurements[1]

[1] based on The National Committee on Soil and Terrain (2009)

2.2 Evaluation of existing soils data

As described in Section 1.2, existing soils data were available for the Flinders and Gilbert catchments based on previous studies and assessments (Figure 3.1). The ultimate goal of the sampling design was the reinterpretation of existing soils information and collection of complementary new soils information to assist with the development of appropriate digital soil attribute layers. These attribute layers were then used to evaluate the suitability of irrigated agriculture in the Flinders and Gilbert catchments. A description of the data used in each assessment (including new and legacy data) is given in Section 3.1.

2.3 Selection of spatial covariates

DSM uses spatial covariates, which are information about the landscape, soils and climate of the area of interest prepared as contiguous spatial data. The selection of spatial covariates for this study was primarily driven by the need to derive the land suitability limitations described in Table 2.1. The factors that drive land suitability are similar to those that drive soil formation. Therefore, the covariates used in this study were based on the SCORPAN framework proposed by McBratney et al., (2003) which links factors related to soil formation with landscape processes (see Table 2.2). In this framework, **s** represents soil or previously measured attributes of the soil at a point; **c** climatic properties of the environment; **o** organisms, including land cover and natural vegetation; **r** topography, including terrain attributes and classes; **p** parent material, including lithology; **a** represents age; **n** spatial or geographic position. The spatial distribution of four of the covariate layers (slope, dynamic land cover, gamma radiometric signal and weathering index) are shown in Figure 2.1 to Figure 2.4 for the Flinders and Gilbert catchments, respectively. It is common in many DSM studies to include as many spatial covariate predictor variables as possible; however, a more parsimonious approach was employed here and only those covariates that were considered critical for driving land suitability and soil formation were used. Previous studies that have utilised DSM to undertake a land suitability analysis were also consulted prior to final covariate selection (e.g. Kidd et al., 2012b). All required covariate data were created using a common mapping projection/datum. There were differences in the covariates used for the sampling design and the DSM as new data became available during the study (e.g. revised SRTM DEM). Following field visits additional covariate data sets were also added to help improve the modelling.

Table 2.2 List of covariate data used in the field sampling design (S) and DSM attribute mapping (D)

COVARIATE	PROPERTY	SOURCE OF DATA
Potassium (Airborne gamma radiometrics) (S, D)	Near surface (< 0.3 m) Potassium geochemistry	Geoscience Australia Radiometrics Map of Australia 2010
Thorium (Airborne gamma radiometrics) (S, D)	Near surface (< 0.3 m) Thorium geochemistry	Geoscience Australia Radiometrics Map of Australia 2010
Uranium (Airborne gamma radiometrics) (S, D)	Near surface (< 0.3 m) Uranium geochemistry	Geoscience Australia Radiometrics Map of Australia 2010
Total dose (Airborne gamma radiometrics) (D)	Near surface (< 0.3 m) accumulated Potassium, Thorium and Uranium geochemical response, the total radiometric signal strength	Geoscience Australia Radiometrics Map of Australia 2010
Slope percent from SRTM 1 second smoothed DEM (S, D)	Slope percent from SRTM 1 second smoothed DEM	Geoscience Australia
Weathering Index of Australia 2011 (S, D)	Index of parent material weathering intensity,	Geoscience Australia
1:1 Million surficial geology mapping (S)	Regional geology	Geoscience Australia
MultiResolution Valley Bottom Flatness based on SRTM 1 second (30m) unprocessed DEM (S, D)	Landscape zones of soil deposition, shallow and deep soils, based on SRTM 1 second (30m) unprocessed DEM	CSIRO
MultiResolution Ridge Top Flatness based on SRTM 1 second (30m) unprocessed DEM (D)	Landscape zones of soil loss, shallow and deep soils, based on SRTM 1 second (30m) unprocessed DEM	CSIRO
Prescott Index climate surface (D)	Index of moisture deficit taking into account climatic factors and terrain.	CSIRO
Profile curvature from SRTM 1 second (30m) unprocessed DEM (D)	Shape of hillslope curve in a direct line from the hilltop to valley bottom	CSIRO
Slope focal median from SRTM 1 second (30m) unprocessed DEM (D)	Surrogate for modal slope angle in a 300m radius highlighting dominant components of slope shape	CSIRO
National Dynamic Land Cover dataset (D)	Vegetation community types based on seasonal dynamics, responding to climate and soil type	Geoscience Australia

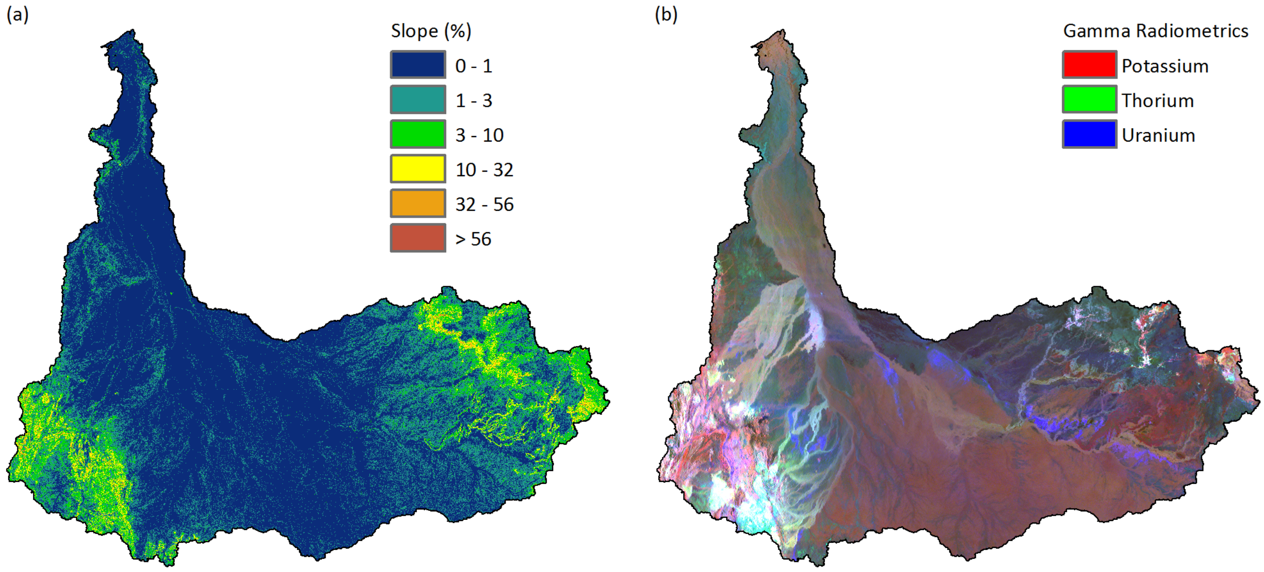


Figure 2.1 (a) % slope (b) ternary image of Potassium, Thorium and Uranium radiometric signals for the Flinders catchment (see Table 2.2 for data sources).

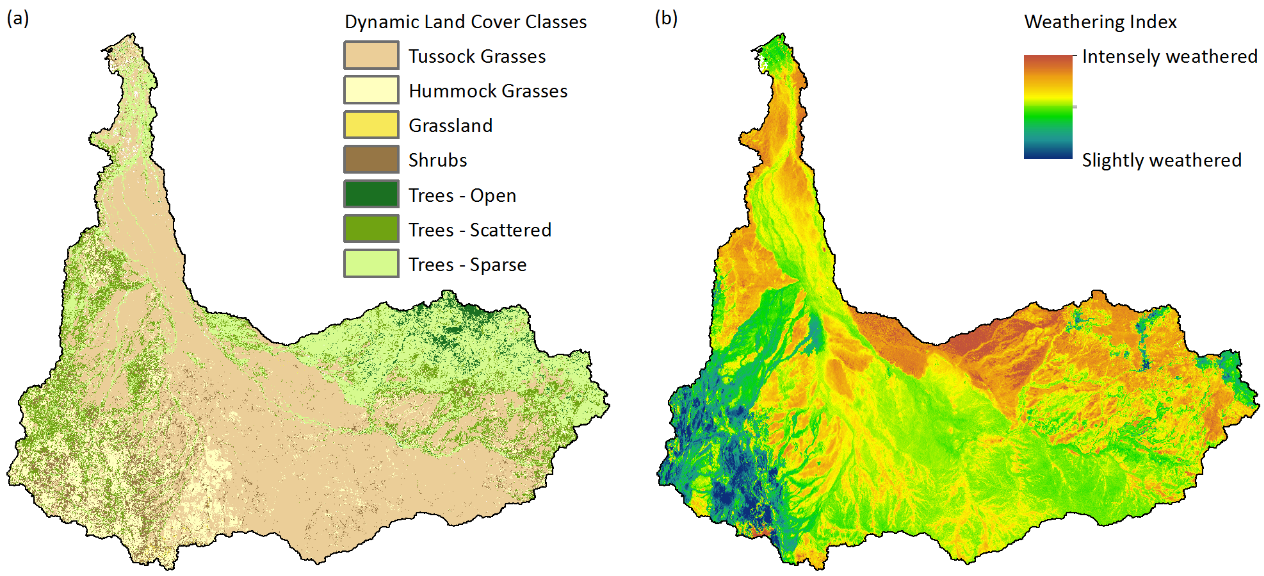


Figure 2.2 (a) dynamic land cover and (b) weathering index for the Flinders catchment (see Table 2.2 for data sources).

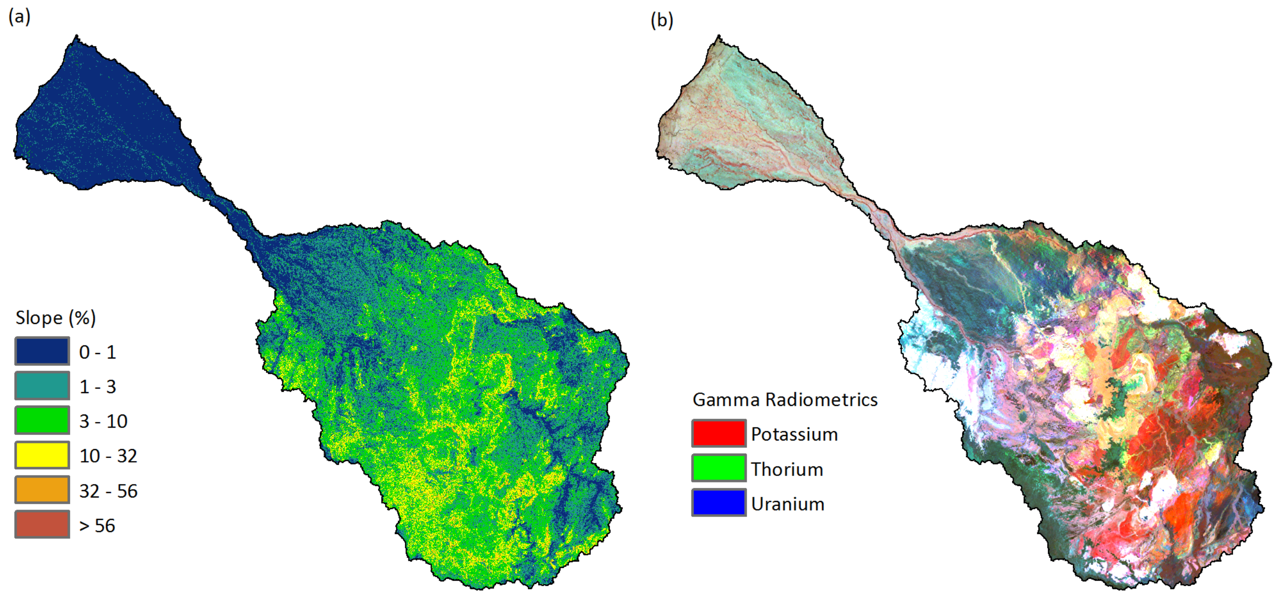


Figure 2.3 (a) % slope (b) ternary image of Potassium, Thorium and Uranium radiometric signals for the Gilbert catchment (see Table 2.2 for data sources).

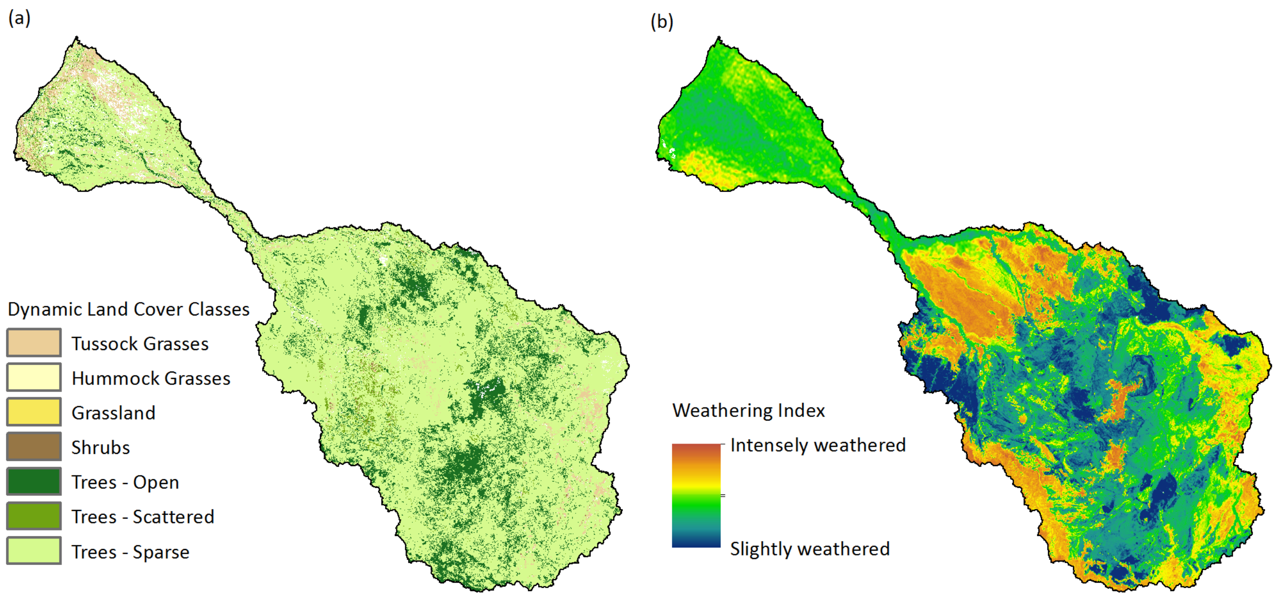


Figure 2.4 (a) dynamic land cover and (b) weathering index for the Gilbert catchment (see Table 2.2 for data sources).

2.4 Spatial soil sampling design for new data collection

A total of 451 new sites were described and sampled. The size and diversity of the catchments meant that a sampling design was required that allowed us to capture the diversity of soil and landscape types, whilst minimising logistical difficulties in accessing sites. The field sampling design in this study was based on a localised adaptation of the conditional Latin Hypercube Sampling (cLHS) approach (Minasny and McBratney, 2006; Roudier, 2011). A cLHS-based design selects sites that span the full range of soil variability found in a given set of covariates (Table 2.2). Sampling sites were selected according to the statistical distribution of covariates (i.e. covariate 'feature space') and are independent of geographic location. The practical implication of this is that sites may often be difficult to get to, hence the design may be impractical to implement particularly if distances are large and terrain rugged (Kidd et al., 2012a; Thomas et al., 2012). To overcome the spatial balance and access issues, two additional data sets were used to determine the sampling sites. The additional data included (i) distance from

each potential site (30m by 30m pixel based on SRTM-DEM) to closest prior existing site (for spatial balance); and (ii) distances from each potential site to closest road. A further pragmatic adaption incorporated in the design was to identify a ranked set of additional alternative sites nearby to each target site. While these local alternatives do not necessarily sit within the same part of the covariate space as the primary target nearby, the ultimate collection of sampled and legacy sites should span the covariate space of the region of interest. These additional sites were available as contingency if any of the primary sites were impractical to access, e.g. if they were beyond locked gates. Contingency sites were used in the knowledge that the statistically-based objectives of the overall survey would remain largely honored. A detailed description of the approach can be found in Clifford et al., (2012) and Clifford et al., (In Prep).

2.5 Field measurements

2.5.1 SOIL DATA

Based on the sampling design outlined above, field samples were collected from 451 sites by vehicle traverse over the course of a ten week field campaign. All sites were sampled using a 50 mm diameter soil corer. Sites were sampled to 1.5 m (where possible) and then described according to Australian soil survey conventions (The National Committee on Soil and Terrain, 2009). Measurements of pH, EC and dispersion were made (where possible) across standard depth intervals (0-10, 20-30, 50-60, 80-90, 110-120, 140-150 cm) at all field sites. Sub-samples taken from each of these depths were also submitted for mid-infra red (MIR) analysis (Section 2.6.2), or stored in trays for future reference. Other qualitative and quantitative information describing the soil properties were collected based on accepted standards (see The National Committee on Soil and Terrain, 2009) (Table 2.3). All site coordinates were recorded using the WGS84 system and entered into the Queensland Government Soils and Land Information (SALI) database (Biggs et al., 2000), along with the profile descriptions and laboratory data (including MIR data).

Table 2.3 Field based soil attributes and methods of analysis. NCST =The National Committee on Soil and Terrain (2009)

QUANTITATIVE SOIL FEATURE	ATTRIBUTE	METHOD	PURPOSE
Location	Unique id, projection, datum, x, y	GPS	Location information for mapping, modelling and data management
Classification	Soil class	ASC in field or office	Defined soil class from the Australian Soil Classification, facilitates communication and correlation
Landscape	Landform element	NCST in field	Describes the landform immediately surrounding site
Landscape	Landform pattern	NCST in field	Describes the broader landform around the site
Landscape	Slope	Measured in field (clinometer)	Influences runoff, erosion, crop types and management factors
Soil surface attribute	Rock outcrop	NCST in field	Influences crop types and management operations
Soil surface attribute	Surface coarse fragments	NCST in field	Influences crop types and management operations
Soil surface attribute	Surface condition	NCST in field	Influences crop establishment, seedling development and water infiltration
Soil surface attribute	Surface structure	NCST in field	Affects infiltration, erosion and workability
Soil surface attribute	Microrelief	NCST in field	Impact on machinery operation, drainage and irrigation efficiency
Soil water regime	Drainage	NCST in field	Summarises wetness conditions likely to occur at a site
Soil water regime	Permeability	NCST in field	Describes capacity of soil profile to transmit water internally and influences soil wetness and plant root aeration
Soil water regime	Soil mottles	NCST in field	Indication of hydrological properties of soil profile
Soil physical depth for plant growth	Rooting depth	Measured in field and laboratory	Indication of chemical or physical barrier to root growth
Soil physical depth for plant growth	Soil depth restriction (before 1.5 m)	Measured in field as depth to impermeable layers or bedrock	Defining characteristic of the soil, driver for a range of other attributes including rooting depth and PAWC
Soil profile properties	Field texture	NCST in field	Influences soil physical properties and water storage capacity
Soil profile properties	Structure	NCST in field	Affects infiltration, erosion and workability
Soil profile properties	Soil colour	NCST in field	Indication of nutrient levels and soil water regime
Soil profile properties	Segregations	NCST in field	Hard segregations impact on machinery use, other segregations may indicate soil hydrologic conditions and depth of water percolation in the soil
Soil chemistry	pH	Measured in field and lab	Affects balance of nutrients in soil, including potential deficiencies and toxicities
Soil chemistry	Electrical conductivity	Measured in field and lab	Indicator of salinity; may restrict root growth.
Soil chemistry	Dispersion class	Measured in field	Indicator of potential erosion
Sample analysis	Bulk density and porosity	Measured in field and lab, and estimated by pedotransfer function	Affects rooting depth, soil permeability and drainage and soil workability
Sample analysis	Plant available water capacity	Estimated by pedotransfer function from a range of data	Capacity of soil to store moisture for plant use

2.5.2 SOIL AND LANDSCAPE ANALYSIS

The DSM process quantitatively predicted the distribution of soils in each catchment. In addition, the survey team also used geomorphic principles to assess the distribution of soils within the landscape to guide and validate the DSM process. Landscape descriptions of the major geomorphic units within the igneous, sedimentary, metamorphic and unconsolidated lithologies were described in each of the investigation areas for each catchment. This assessment also provided an estimate of the age of deposits (e.g. Quaternary, Tertiary, Mesozoic etc) and degree of weathering. Such descriptions are important for identifying deposits likely to be suitable for agriculture (e.g. Quaternary alluvium). This assessment used the collected soils data, as well as knowledge of the geology, climate, vegetation and fauna in the area. Radiometrics, which is a measure of the natural radiation in the Earth's surface, was used to help identify the relative age and weathering of soil and rock types (Figure 2.1b and Figure 2.3b). All this information is important for identifying landscape processes such as the depth of soil weathering, the potential for salinity and relative fertility of the soil. A synthesis of this work is presented in the results section and the more detailed landscape descriptions are presented in Appendix A.3 and A.4 for the Flinders and Gilbert catchments, respectively.

2.6 Laboratory analysis

2.6.1 TRADITIONAL LABORATORY ANALYSIS

Of the 451 sites sampled in the field 68 sites were analysed for soil chemical and physical properties using conventional laboratory methods at the DSITIA Chemistry Centre Laboratory at the EcoSciences Precinct in Brisbane. The specific attributes analysed in the laboratory are outlined in Table 2.4. The data were then entered into the SALI database (Biggs et al., 2000).

Table 2.4 Laboratory methods applied to 68 of the 451 samples collected

Measurement	Elements and Methods	Reference
Particle size (% clay, sand, silt)	Sieve and Hydrometer method	(Thorburn and Shaw, 1987)
Moisture	15 bar moisture	(Rayment and Lyons, 2011)
pH, EC, chloride, nitrate	1:5 soil/water	(Rayment and Lyons, 2011)
Exchangeable cations	Cation exchange capacity (CEC), exchangeable calcium, magnesium, sodium, potassium	(Rayment and Lyons, 2011)
Exchange acidity	Exchangeable aluminium, H^+	(Rayment and Lyons, 2011)
Bulk density	Ring method using oven dry weights	Modified from (Cresswell and Hamilton, 2002)
Total elements (phosphorus, potassium, sulfur)	X-Ray Fluorescence (XRF)	(Rayment and Lyons, 2011)
Total elements (total carbon and nitrogen)	Dry furnace	(Rayment and Lyons, 2011)
Extractable trace elements	Iron, manganese, copper, zinc	(Rayment and Lyons, 2011)
Surface soil fertility	Organic carbon (Walkley and Black), total nitrogen (Kjeldahl), xtractable P (Colwell), extractable potassium, extractable sulfur	(Rayment and Lyons, 2011)

2.6.2 SPECTRAL SCANNING FOR SOIL ATTRIBUTES (MID INFRARED, MIR)

Infrared spectroscopy allows for rapid, simultaneous characterisation of various soil constituents using non-destructive methods (Viscarra Rossel et al., 2006). This approach can diagnostically measure the chemical, physical and mineralogical composition of soils, and is a valuable complement to traditional methods, particularly when a large number of samples and analysis are required (McBratney et al., 2006). It can be used for rapid soil characterisation where there are effective calibration sets for a range of soil materials (McKenzie and Grundy, 2008). In this study we used mid-infrared spectroscopy (MIR) to predict the fractions of coarse sand, fine sand, silt and clay as well as electrical conductivity (EC), acidity (pH), cation exchange capacity (CEC), calcium (Ca) and 15 Bar moisture. The MIR technique was considered more suitable than the visible infrared (VIS) or near infrared (NIR) for this type of analysis due to the higher incidence spectral bands in this region as well as the higher intensity and specificity of the signal (Viscarra Rossel et al., 2006).

A total of 339 MIR sites were sampled in the field using chip trays. MIR data were not collected for validation sites. A sub-sample was taken and hand ground in an agate mortar and pestle to <0.5mm. Samples were then dried in a forced draught oven at 40 °C for a minimum of 48 h. All samples were loaded in quadruplicate onto scanning plates and the diffuse reflectance MIR (DRIFT) spectra were obtained using a Bruker Vertex 70 FTIR spectrometer (Bruker, 2011). Each replicate was scanned for 32 s (64× 0.5 s scans). Partial least squares regression (PLSR) models were then constructed between the calibration samples and chip tray samples using the Quant 2 module (Bruker, 2011 v7.0). For each determinant, optimal spectra pre-processing was determined using the Quant 2 optimise facility. Following prediction, replicate sample predictions were averaged. Results were examined for each sample and if any of the predictions were flagged as outliers the result for that sample was reported in the database as NP (no prediction). Values for the coefficient of variation and standard error of the mean were reported for the replicate averaging and the Mahalanobis distance and F statistic probability reported as a reliability measure of the prediction.

2.7 Soil attribute mapping

2.7.1 MODELLING APPROACH

A spatial correlation approach was used to estimate the value of the required soil attributes (presented in Table 2.1) using relationships between the spatial covariates (Table 2.2) and physical and chemical soil properties that were measured at points in the field (and described in Section 2.5 and 2.6). The statistical modelling for this process was carried out using RuleFit3 (http://www-stat.stanford.edu/~jhf/r-rulefit/rulefit3/R_RuleFit3.html), which is the latest implementation of the RuleFit machine learning method and interpretational tools (Friedman and Popescu, 2008) deployed using the R statistical computing platform (http://cran.r-project.org/). RuleFit3 is a rule-based data-mining algorithm for general regression and classification, and performs predictive learning using rule ensembles (Friedman and Popescu, 2008). These ensembles are linear combinations of simple rules derived from training data. The form of these rules includes decision-tree-style binary rules as well as linear terms more commonly found in linear regression. Automated model selection is carried out via cross-validation for an estimate of prediction error. The relative importance of predictors is computed based on their overall use in rules as well as through interactions with other predictors. Models vary in complexity and scale depending on the availability of data, and on the relationship between the target variable and the predictors. RuleFit3 differs from other machine learning algorithms sometimes used for DSM in terms of model construction and model form. Cubist and C5.0 by RuleQuest Research (http://www.rulequest.com/), for example, produce unconnected sets of rules together with separate linear terms for each rule set. RuleFit3 produces rules and linear terms together and model predictions are formed by summing across all terms (Friedman and Popescu, 2008). The choice of RuleFit3 over alternative data mining algorithms was due primarily to its predictive accuracy compared with other methods, but also due to the expertise of its authors in the field of statistical learning (Hastie et al., 2009), prior experience on the part of these authors with RuleFit3, and the availability of a stable implementation of the

model. RuleFit3 generates relative rankings of the contribution of covariates to each model to provide a qualitative understanding of their operation. This provides an opportunity for expert evaluation, and highlights the dominant pedogenic factors driving soil prediction models. Thus pedogenic and geomorphological assumptions can be confirmed or challenged.

In addition to the new data collected during the Assessment, all data previously measured in these catchments (legacy data) were also incorporated into the modelling (Table 3.2). RuleFit3 was deployed to model the list of target variables presented in Table 2.1, with a general regression model created when the target variable was numeric (e.g. depth of A horizon) and a classification model created when the target variable was binary (e.g. absence/presence of surface microrelief, coded as -1/+1 internally within RuleFit). Classification models for categorical layers with more than two classes (e.g. structure class), also known as multiclass classification models, were built using a one-vs-all strategy; if there are *k* classes this involves *k* binary models.

In general, all model fitting is carried out with equal weight on each data record. For some target variables additional weight is placed on important observations. For example, there are only 50 records where surface microrelief was found, and 1368 records where it was not found. When equal weights are used the model has difficulty correctly classifying sites with microrelief; by placing more weight on these samples we can reduce the number of errors (but this also increases the number of false detections of microrelief).

The relative importance of the covariate layers was evaluated by RuleFit, and serves to assist expert evaluation by testing conceptual understanding of soil formation in the Assessment area. The relative importance measure is on an arbitrary scale from 0 to 100 where 0 indicates that a covariate was not used in any of the rules and 100 is the value given to the most important covariate. An overall measure of importance is provided for multiclass classification where the individual importance values are weighted according to the number of observations within each class. All important values are rescaled so that the most important covariate has a score of 100.

2.7.2 SOIL GENERIC GROUP (SGG)

An understanding how soils are formed and distributed is important for identifying the opportunities and limitations to agricultural development. Given the constraints of time and data associated with this project, it was not possible to define and map detailed ‘soil types’. Instead, the distribution of soil generic groups (SGGs) was modelled. Soil generic groups were first used in Queensland to facilitate extension in the sugar industry, and have been slightly modified here to suit the range of soils encountered in the Gulf region. The concepts and derivation of the different SGGs is shown in Table 2.5.

The modelling approach used to predict the SGG across each catchment first involved classifying the soil at each field site according to the Australian Soil Classification (ASC) system (Isbell, 2002) and then allocating the soil to a SGG (see Table 2.5). If the ASC had not been used at historical sites, an ASC classification was interpolated using expert knowledge. Using the same RuleFit process described in Section 2.7.1, models for the SGGs were built based on the covariate layers and then the SGG was predicted across both catchments. Within each SGG, the soils have similar profile morphology and soil properties in terms of general land use potential. Thus, the SGG is very useful as a general communication tool.

Table 2.5 Soil Generic Group (SGG) classes and description

Concept	General description	Landform	Major management considerations	ASC orders used to generated SGGs
Sand or loam over relatively friable clay subsoils	Strong texture contrast between the A and B horizons, but A horizons generally not bleached. B horizon not sodic and may be acid or alkaline. Moderately deep to deep.	Undulating plains to hilly areas on a wide variety of parent materials.	The non-acid soils are widely used for agriculture; the strongly acid soils are generally used for native and improved pastures.	Chromosols and Kurosols except those with strongly bleached A horizons (the AT, AV, AY, AZ, BA or BB subgroups)
Friable non-cracking clay or clay loam soils	Moderate to strongly structured, neutral to strongly acid soils with little or only gradual increase in clay content with depth. Grey to red, moderately deep to very deep.	Plains and plateaus along with some steeper country on intermediate to basic rocks, limestone and fine grained sedimentary rocks.	Generally high agricultural potential because of their good structure, and their moderate to high chemical fertility and water holding capacity. Ferrosols on young basalt landscapes may be shallow and rocky.	Dermosols, Ferrosols and deeper Calcarosols
Seasonally or permanently wet soils	A wide variety of soils grouped together because of their seasonal or permanent inundation. No discrimination between saline and freshwater.	Coastal areas to inland wetlands, swamps and drainage depressions. Mostly unconsolidated sediments, usually alluvium.	Require drainage works before development can proceed. Acid sulfate soils and salinity are associated problems in some areas	Hydrosols and Aquic Vertosols
Red, yellow or grey loamy soils	Well drained, neutral to acid soils with little or only gradual increase in clay content with depth. Shallow to deep,	Level to gently undulating plains and plateaus.	Moderate to high agricultural potential with spray or trickle irrigation due to their good drainage. Low to moderate water holding capacity, often hard setting.	Kandosols
Deep sandy soils	Moderately deep to deep sands. May be gravelly.	Sandplains and dunes; aeolian and fluvial siliceous sediments.	Low agricultural potential due to excessive drainage and poor water holding capacity	Rudosols, Tenosols
Shallow sandy and stony soils	Very shallow to shallow <0.5m. Usually sandy or loamy, but may be clayey. Generally weakly developed soils that may contain gravel.	Crests and slopes of hilly and dissected landscapes associated with quartzose sandstone, quartz rich rocks (granites, rhyolites) or eroding lateritic scarps.	Negligible agricultural potential due to lack of soil depth and presence of rock.	Rudosols and Tenosols (shallow occurrences) and Calcarosols (shallow)
Sand or loam over intractable clay subsoils	Strong texture contrast between the A and B horizons; A horizons usually bleached. Subsoil usually sodic. Usually alkaline but occasionally neutral to acid subsoils. Moderately deep to deep.	Lower slopes and plains in a wide variety of landscapes.	Generally low agricultural potential due to restricted drainage, poor root penetration and susceptibility to gully and tunnel erosion. Those with thick to very thick A horizons are favoured.	Sodosols; bleached Chromosols and Kurosols (those with AT, AV, AY, AZ, BA or BB subgroups as described in Isbell (2002)
Cracking clay soils	Clay soils with shrink-swell properties that cause cracking when dry. Usually alkaline and deep to very deep.	Floodplains and other alluvial plains. Undulating to rolling Mitchell Grass Downs country (formed on Mesozoic fine grained sedimentary rock). Minor occurrences in basalt landscapes.	Generally a moderate to high agricultural potential. The flooding limitation will need to be assessed locally. Many soils are high in salt (particularly those associated with the Rolling Downs). Gilgai and coarse structured surfaces may occur.	Vertosols

2.7.3 MODELLED DATA COMPILATION

The soil sampling for the Assessment was concentrated in the primary and secondary investigation areas (Figure 1.1) as these represented the most suitable soils based on previous assessments in these catchments, and are the most likely areas for agricultural expansion due to the suitability of soils and distance to water and local interest. To consider other opportunities, and provide information at the catchment scale, soil data were extrapolated outside of the investigation areas. To do this, we generated three RuleFit3 models for each DSM output (target variable). The first model was based on all available data, and was used to predict our target variable (e.g. soil depth) everywhere. The second model was based on data only from focus areas of the Flinders catchment, and was used to predict the target variable only for those focus areas. The third model was based on data from the Gilbert catchment, and was used to predict the target variable only for those focus areas. The performance of each model was evaluated under multi-fold cross-validation. We recorded R-squared values for numerical targets and the classification rates derived from classification tables for binary and categorical targets. The final model was formed using the all-of-data model as the base model. We superimpose investigation area models if they lead to better performance over their respective investigation areas. This leads to four possible final models where we substitute in none, either one, or both of the investigation area models. The relative importance values associated with the environmental covariates from each of the component models are combined to form overall relative importance values. We combine the relative importance values as a weighted average based on the number of data points. The weight from a particular data point was associated with an investigation area model if the data point lies in an investigation area and that investigation area model contributes to the final prediction, otherwise the weight was associated with the all-of-data model. As the relative importance scale is arbitrary, we rescale the values so that the most important environment covariate has a relative importance value of 100.

2.7.4 STATISTICAL EVALUATION, VALIDATION AND UNCERTAINTY

We used three different approaches to evaluate the accuracy or reliability of the predictions from the DSM process. These include internal statistical cross-validation, independent field validation, and a non-parametric bootstrap assessment of the standard deviation of model predictions of numeric target variables, which we map spatially as a function of the model output.

The first approach assessed the model rigor using ten-fold internal cross-validation process for computing statistical measures of model strength (based on the process described in Section 2.7.3). Each fold is withheld from the dataset in turn, the model is built on the remainder of the data and predictions are made for the portion withheld. We compare these model predictions with the observations. Cross-validation is also important for setting model parameters such as data weights (e.g. when unequal weights are used for binary classification). For categorical targets with low record counts we performed five-fold cross-validation.

The second approach involved independently validating 10 soil attributes that were relatively quick to measure in the field (rockiness, mirco-relief, surface condition, surface texture, surface structure, permeability, drainage, depth of A horizon, surface pH and soil depth). A two week field campaign was undertaken in 2013 to using a random sampling design of sites from within and outside the primary and secondary investigation areas. These additional sites did not undergo any wet chemistry or MIR analysis. Further augmentation of the evaluation set was done by a desktop exercise with GoogleEarth™ (http://www.google.com/earth/index.html) to record coordinates of new basalt rocky areas after it was evident during the field survey that the preliminary models could be strengthened through the addition of additional rocky areas. A comparison of the predicted and observed data was evaluated and is presented in Section 3.3. Due to the size of the catchments, and the relatively sparse data available for modelling, the independent validation data were added to the existing field data and the models were re-run to produce the final attribute maps.

The third method for evaluating the rigour of the DSM was to use non-parametric bootstrapping of the DSM modelling for numerical layers. In non-parametric bootstrapping the available data were re-sampled with replacement, the model was then refit, and predictions made of the soil properties at our sampling sites. This process is repeated 1000 times which produces a bootstrap distribution of predictions for each of the sampling sites. Plots of the standard deviations of these predictions against the overall model prediction indicate that

standard deviations of the predictions change smoothly with the model predictions, see Panels 1 and 2 of Figure 2.5. Lower standard deviations were found close to where the majority of the model predictions lie (between 6 and 7 pH units). This process was repeated for the models based solely on the investigation area data. Maps of the confusion index were prepared for each of the binary and categorical layers based on the approach described by Finke (2007). The confusion index plots the ratio of the second highest classification probability to the highest classification probability at each point within the landscape and takes values in the range [0,1]. When the two values are similar this value is close to 1 and we are less sure about our predicted class; when the probability of one class is higher by a large margin, the ratio is close to zero, and we are confident in our predicted class.

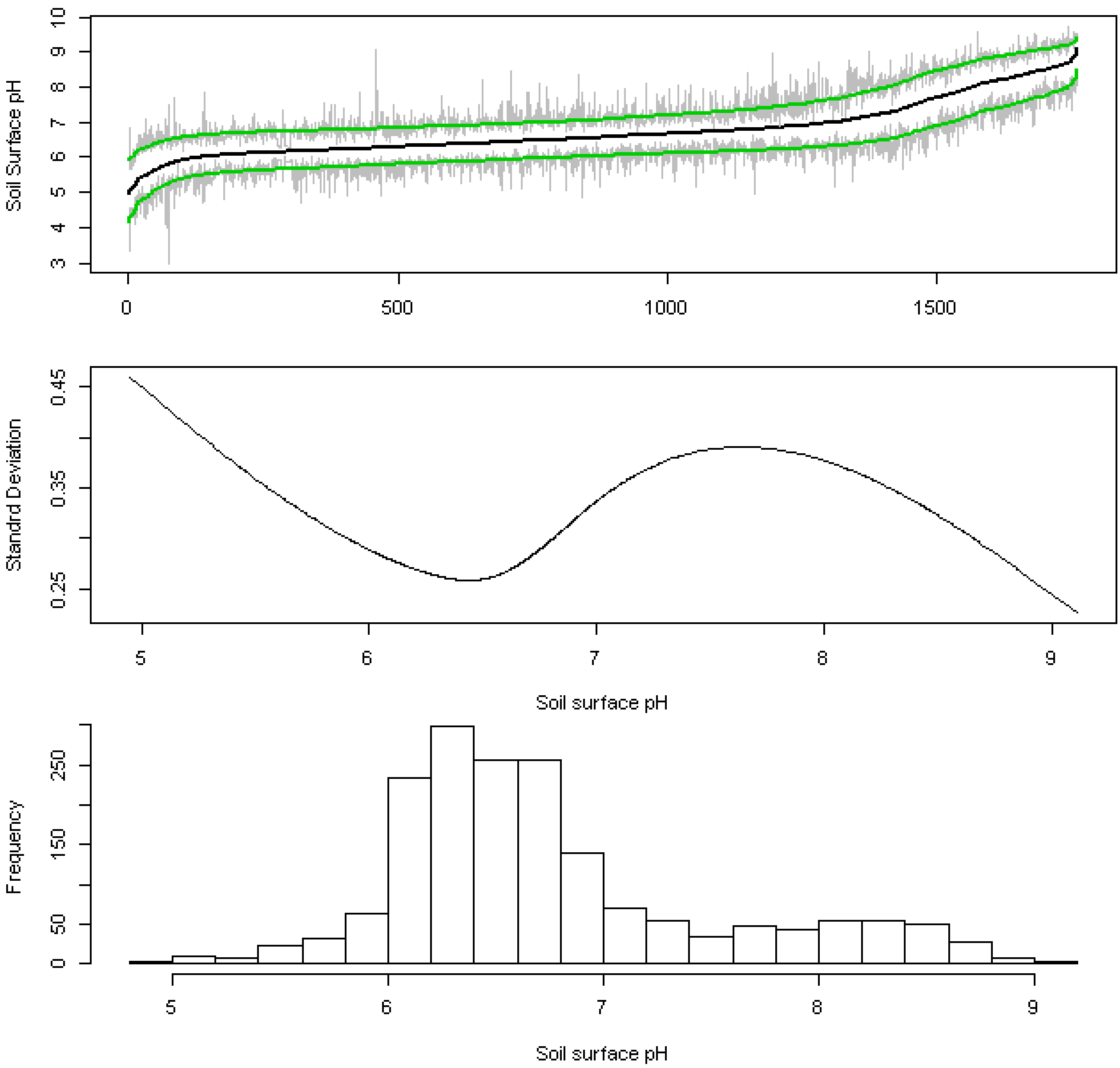


Figure 2.5 The top image contains a plot of the ordered soil surface pH predictions (black) together with bootstrapped 95% confidence intervals for each point (grey lines) and smooth confidence intervals (green lines) as found by robust smooth regression. The middle image is a plot of the standard deviation, based on the smooth confidence intervals, as a function of soil surface pH value. The lower image is a histogram of the Soil surface pH predictions showing most of the samples are predicted to lie between pH values of 6 and 7, and predictions in this range will therefore be less variable.

2.8 Land use suitability assessment

Land suitability is the fitness of a given area for a land utilisation type, commonly expressed as a set of discrete classes numbered from Class 1 (completely suited) to Class 5 (completely unsuited) as defined in Table 2.6 (van Gool et al., 2008). Suitability rules for the 40 crops outlined in Table 1.1 were developed based on the Queensland Government guidelines for land evaluation (Land Resources Branch Staff, 1990) (see Appendix A.2). The approach was adapted to include extra limitations to agricultural production that apply to certain areas of the Flinders and Gilbert catchments, in conjunction with expert agronomic opinion. The guidelines are based on land use requirements that relate to plant growth, machinery use, land preparation, irrigation and the prevention of land degradation. Attributes that contribute to less than optimal conditions for crop growth/production in a particular area are regarded as limitations. A total of 10 limitations to agricultural production have been assessed in this project (see Table 2.1).

Land is classified on the basis of a specified land use and a rating of 'suitable' assumes production is optimal with minimal degradation to the land resource and the wider environment in the long term. The land suitability classification depends directly on the severity of limitations associated with the land use being considered. These in turn are determined by the land use requirements of the crop, the inherent characteristics of the land, and the season of crop growth (i.e. 'wet' or 'dry' season for non-perennial crops). Crops are assessed individually and given a particular suitability subclass for each limitation. These are listed for all land uses and all limitations in Appendix Appendix A and A.2. The final land suitability class is determined by the most severe suitability subclass that applies in a particular area of land.

Land is considered less suitable as the severity of limitations for a land use increase, reflecting either (a) reduced potential for production, and/or (b) increased inputs required to prevent land degradation. Decreasing land suitability within a region often reflects the need for increased inputs rather than decreased potential production. The first two classes (Class 1-2) are considered suitable for the specified land use as the benefits from using the land for that land use in the long term should outweigh the inputs required to initiate and maintain production. Class 3 land is considered moderately suitable, and substantial investment may be required to sustain optimum productivity in the long term. Class 4 is considered presently unsuitable or is used for marginal land where it is doubtful that the inputs required to achieve and maintain production outweigh the benefits in the long term. More work would be needed to determine whether the effect of the limitation(s) can be reduced to achieve sustained production. Class 5 is considered unsuitable having limitations that in aggregate are so severe that the benefits would not justify the inputs required to initiate and maintain production in the long term. It would require a major change in economics, technology or management expertise before the land could be considered suitable for that land use. Some class 5 lands such as escarpments will always remain unsuitable for agriculture. Four different types of irrigation were evaluated in this study (furrow, spray, trickle and flood). A summary of the irrigation option and crop combinations is provided in Appendix Appendix A .

Each of the classifications applied are based on regionally accepted practices for each of the cropping and irrigation types (see Section 2.8.1). It is acknowledged that different practices may occur that could change the suitability rating applied beyond the scope of this regional scale study. It is important to point out that there are many reasons why a particular land unit is given a classification value of 5. For example, a rocky steep site may be classed at 5 due to slope and rockiness restrictions, whereas a flat alluvial soil may be given a class 5 for furrow irrigation due to extremely high drainage and permeability ratings, making furrow irrigation unviable at a commercial scale.

In general terms, there are a number of agronomic factors relating to irrigation potential, soil and landscape conditions, and crop type that hold for tropical north Queensland. These include, with all things being equal, that more land will be suited to spray irrigation compared to furrow irrigation as the soil and slope constraints are less severe. Other generalisations are that cotton, sugarcane and rice are more tolerant to wetter soil conditions, and therefore are better suited to heavier soils compared to other crops like cereals. Root crops are more susceptible to wet conditions. Cassava and sweet potato are unsuitable for cracking clay soils due to physical constraints, especially soil adhesiveness. Peanuts are more tolerant of soil adhesiveness, but are not recommended where the clay structure is coarse. The wetness limitation is less severe for dry season crops as they will generally not experience the seasonally wet conditions and irrigation applications can be controlled to prevent this. Heat stress is a severe limitation for high value perennial horticulture crops because the leaves and fruit are vulnerable to scorching and desiccation in hot temperatures. Small crops are generally not affected by heat as a limitation as they are grown in the cooler dry season. Avocados, custard apples and coffee are more susceptible to wet soil

conditions. Coffee and avocados require deeper soils. Finally, water erosion hazard may be mitigated by crop management practices such as crop residue retention and the growth of cover crops.

Table 2.6 Suitability classification applied in this study

Class	Description
Class 1	**(Highly) Suitable land with negligible limitations**. This is highly productive land requiring only simple management practices to maintain economic production.
Class 2	**Suitable land with minor limitations** which either reduce production or require more than the simple management practices of class 1 land to maintain economic production.
Class 3	**Moderately suitable land with considerable limitations** which either further lower production or require more than those management practices of class 2 land to maintain economic production.
Class 4	**Marginal land which is presently considered unsuitable due to severe limitations**. The long term significance of these limitations on the proposed land use is unknown. The use of this land is dependent upon undertaking additional studies to determine whether the effects of the limitation(s) can be reduced to achieve sustained economic production.
Class 5	**Unsuitable land with extreme limitations that preclude its use**. Class 5 is considered unsuitable having limitations that in aggregate are so severe that the benefits would not justify the inputs required to initiate and maintain production in the long term. It would require a major change in economics, technology or management expertise before the land could be considered suitable for that land use. Some class 5 lands however, such as escarpments, will always remain unsuitable for agriculture.

2.8.1 GENERAL APPROACH

For this assessment, a land use is defined as a combination of a crop (Table 1.1), irrigation type (furrow, spray, trickle or flood), and season of growth (wet season, dry season, perennial). For all wet season crops, irrigation will supplement natural rainfall. For dry season crops, full irrigation is assumed. A total of 76 land uses were evaluated in the Assessment (See Appendix Appendix A). The suitability framework makes the following assumptions for irrigated crops: (i) unlimited irrigation water is available to the cropping location; (ii) spray irrigation systems can deliver irrigation rates of up to 16-17 mm/day during periods of peak demand; (iii) spray irrigation systems can deliver irrigation rates of 24-25 mm/day for sugarcane crops during periods of peak demand; (iv) the applied irrigation water infiltrates sufficiently well to maintain soil water in the rooting profile sufficient for crop growth (crops not stressed); (v) spray irrigation scheduling allows sufficient time for regular maintenance; (vi) the amount of water applied does not drain below the rooting depth. A list of factors not assessed are presented at the end of this section.

2.8.2 LAND SUITABILITY MODELLING

Land suitability modelling uses the underlying assumption that the most limiting factor determines the overall suitability rating (from Section 2.8.1). The land suitability modelling in this study applied a set of rules (presented in Appendix A.2) to the spatial attribute data derived using DSM. The processing of the DSM layers into crop suitabilities was conducted in two stages using purpose built Python scripts (www.python.org). Stage 1 converted the attribute (e.g. pH) into an attribute code (e.g. Nr1 = pH 5.5-7.0, Nr2 = pH 7.0-8.5, Nr3 <5.5, Nr4 = pH >8.5). Then Stage 2 applies the crop specific suitability weighting to the layers produced in Stage 1. For example, for rice grown with flood irrigation, raster cells containing values Nr2 become a suitability 1, those containing Nr1 or Nr3 become a suitability 2, and those containing Nr4 become a suitability 3 (see Appendix A.2). The different

limitation sub-classes (e.g. for pH, soil depth and water erosion) are then used to produce a single suitability map for each crop and irrigation combination (**Error! Reference source not found.**).

2.8.3 LAND USE ATTRIBUTES AND RULES INCLUDED IN ASSESSMENT

Climate

a. Frost

Plants vary in their tolerance to frosts. Frosts can suppress the growth of sensitive crops, reduce yield through damage to flowers or fruits or kill plants. Generally, only light frosts are encountered in the study area. These are defined as days where the minimum temperature is ≤2°C. Lower lying areas such as along the creeks and drainage lines are more likely to experience localised frosts. Crops most likely to be affected by frosts are small crops (e.g. capsicum) and sensitive perennial tree crops such as cashew and coffee.

b. Heat stress

The Gulf region is noted for its exceptionally hot temperatures that occur over long periods. For example, Julia Creek has an average of 154 days per year with a maximum of >35°C. The intense solar radiation associated with high temperatures (often combined with wind) is likely to cause damage to the leaves and fruit of many crops, being particularly significant for perennial horticultural crops such as pineapples, bananas, grapes and custard apple. Small crops (e.g. capsicum) will generally not be affected, as they will be grown in the dry season when temperatures are less intense.

c. Temperature variation

Certain crops (e.g. chickpea, lychee) require cool temperatures for efficient seed/fruit set. Other crops (e.g. cassava) show a distinct preference for climates that do not include cool winters.

d. Precipitation

The amount of rain that falls during the growing season is relevant for irrigated cropping in terms of the quantity of supplementary irrigation required. However, suitability subclasses have only been determined for crops that are grown without irrigation (i.e. totally rainfed). Generally, the Flinders River catchment lacks sufficient rainfall for dryland broadacre cropping.

Irrigation efficiency (furrow irrigation)

Applied water must match the soil infiltration characteristics to minimise water loss and deep drainage. Long furrow lengths and application durations are inappropriate for soils where a significant deep drainage component is likely to occur. Waterlogging may also be a problem at the upper end of furrows if they are too long. Furrow irrigation is suitable only on land with gentle slopes and slowly permeable cracking clays soils and texture contrast soils. Spray, micro/sprinklers or drip irrigation should be used on permeable and sloping soils for even application of water, and to minimise deep percolation and thus avoid off-site seepage and watertable rise.

Microrelief

Gilgai microrelief causes water ponding that affects irrigation efficiency. It also affects the establishment of irrigation and other crop related infrastructure. Areas with gilgai microrelief must be levelled to ensure even slopes for efficient water use under furrow irrigation. Levelling of gilgai soils which contain sodic and/or saline layers close to the surface may expose these layers at the soil surface. A vertical interval (depth of depression) of >0.3 m was used as the diagnostic attribute to determine microrelief subclass limits.

Nutrient balance – pH

Soil pH affects the availability of nutrients for plant use. Strong acidity or alkalinity may lead to certain nutrient deficiencies and/or toxicities.

Rockiness

Coarse fragments (e.g. pebbles, gravel, cobbles, stones and boulders), hard segregations and rock outcrop in the plough zone can damage and/or interfere with the efficient use of agricultural machinery. Surface gravel, stone and rock are particularly important and can interfere significantly with planting, cultivation and harvesting machinery used for root crops, small crops, annual forage crops and sugar cane. Sites were assigned as being rocky based on the thresholds below, or where the combined total of any of the following field observations had an abundance greater than 50% at the surface or top 0.1 m of soil: (i) rock outcrop or boulders >2%; (ii) cobbles or stones (60 – 600 mm) >20%; (iii) coarse gravel (20-60 mm) >50% (iv) medium gravel (6-20 mm) >90%; (v) hard segregations >50%

Soil depth

The soil depth limitation generally relates to the requirement for physical support for the plant. Additional soil depth is required for certain crops (e.g. avocado) and for efficient harvesting of root crops. Uprooting of valuable tree crops is a potential problem in the Gulf Plains area in the event of severe storms which are prevalent in the summer and which are made worse by shallow soils. Shallow soils generally occur on hillcrests and steep slopes least modified by weathering processes.

Soil physical condition

Soil physical properties influence seedbed preparation, plant establishment and the harvest of root crops. The soil physical condition is related to properties such as surface condition, soil water range for working, and adhesiveness. Surface condition of the soil affects seedling emergence and establishment, and root crop development through hardsetting, crusting and coarse structure. Adhesive soils affect the harvesting operations and condition of root crops such as peanuts and cassava. Peanut crops ideally require friable soils to enable harvesting machinery to easily lift and remove crops from the soil. Most cracking clay soils are adhesive to varying degrees. In general, the degree of adhesiveness increases as clay content and/or strength increase and degree of pedality decreases. Cracking clay soils also have the capacity to shear tree roots. Silty and hardsetting surfaces also reduce infiltration from rainfall and irrigation applications. Soils with sodic and intractable subsoils covered by only a thin surface soil are generally unsuitable for broadacre cropping.

Soil water availability

Soil water availability is assessed in terms of the capacity of the soil to retain water for plant use. For irrigated land, a reduced soil water storage capacity means more frequent irrigations are required to obtain optimum yields. Plant available water capacity (PAWC) is used as the indicator of a soil’s capacity to store water throughout the effective rooting depth. In this study, PAWC was estimated at observation sites using values predicted by the pedotransfer function of Shaw and Yule (1978) as modified by Littleboy (1997). Attributes included are particle size analysis (clay, silt and sand content), 15 bar moisture measurements and the percentage of coarse fragments in the profile. Generally, soil texture, structure, clay content and clay mineralogy have the largest influence on PAWC. In this study, soil water storage has been estimated over the effective rooting depth. Plant root growth may be impeded by physico-chemical attributes of the soil, thereby limiting the volume of soil-water available to plants. The physico-chemical constraints used in this study include salinity (chloride concentration and/or soil EC) and exchangeable sodium percentage (ESP).

Water erosion

Land degradation will occur with consequent productivity decline if water erosion is not minimised. While infiltration rate, and soil permeability and other inherent soil factors largely determine the potential for runoff from a soil, the severity of soil erosion is influenced by climatic factors such as the amount, distribution and intensity of rainfall, landform factors such as gradient and slope length, and management practices such as the maintenance of surface cover. Soil properties relating to erodibility have been linked in a soil erodibility factor known as the K-factor. The K-factor was calculated by relating soil erosion (K-factor) to permeability, surface structure, particle size analysis (clay, silt and sand content) and organic carbon content (Rosewell and Loch, 2002). Suitability subclasses were determined based on a combination of K-factor and slope (Table 2.7; Appendix A.2).

Table 2.7 The four soil stability categories based on K-factor used in this study (Rosewell and Loch, 2002)

K-FACTOR	SOIL ERODIBILITY CLASS
<0.02	Very low (very stable soils
0.02-0.04	Low to moderate (stable soils)
0.04-0.06	High (unstable soils)
>0.06	Very high (very unstable soils)

Wetness

Wetness refers to excessive water on the soil surface or in the soil profile as a result of rainfall or local run-on water. The excess water is caused by inadequate site drainage due to landscape position and/or poor subsoil drainage. The wetness limitation takes into account the adverse effects of excess water on production through reduction in crop growth and quality, restrictions in machinery use and the need for reclamation works. Drainage and permeability classes (McDonald and Isbell, 2009) are combied and take into account all aspects of internal and external drainage at an observation site. The attributes used to indicate internal drainage include colour, mottles, segregations and impermeable layers. Red or brown whole colours indicate well drained soils while mottled grey soils with segregations, such as manganiferous nodules, indicate imperfect drainage. Slope and topographic position are used to assess the ease of disposal of excess water. Soil permeability, indicated by texture, pedality, grade of structure, segregation, pH and ESP (exchangeable sodium percentage) affects the supply to and removal of soil water from the root zone. Wetness limitation subclasses are determined separately for summer (wet season) and winter (dry season) land uses. The drainage and permeability classes are summarised in Table 2.8.

Table 2.8 The drainage and permeability classes used in this study. Note: the time period listed with the drainage classes is the period of time the soils (or some horizons in the soil) would remain wet after water addition. Ks refers to saturated hydraulic conductivity.

Drainage class (considers both internal and external factors at a site)		Permeability class (relates to soil aeration and porosity)	
1	very poorly drained – wet for most of the year	1	very slowly permeable (Ks <5 mm/day)
2	poorly drained – wet for several months	2	slowly permeable (Ks 5-50 mm/day)
3	imperfectly drained – wet for about a month	3	moderately permeable (Ks 50-500 mm/day)
4	moderately well drained – wet for about a week	4	highly permeable (Ks >500 mm/day)
5	well drained – wet for several days		
6	rapidly drained – wet for <1 day		

Wind erosion

Soil loss via wind erosion can occur when soils have little or no vegetation cover during dry and windy conditions. Factors such as texture, structure and roughness of the soil surface affect the susceptibility of soils. Sandy surfaced soils in arid areas (<500 mm mean annual rainfall) are vulnerable to wind erosion and assessed accordingly.

2.8.4 FACTORS NOT INCLUDED IN ASSESSMENT

Flooding

Flooding was not assessed within the land suitability framework. Hydrodynamic modelling of the streams and floodplains of the Flinders and Gilbert catchments was carried out in another component of the Assessment. Readers are directed to Dutta et al. (2013) for details on flood inundation and flood hazard mapping.

Salinity

Salt is a common feature of the soils in inland Australia. It may be present in parent rocks and therefore build up in soils during rock weathering. It may also accumulate through long-term deposition in the landscape and concentrate through hydrologic processes (rainfall or water movement below the land surface) (Bui and Moran, 2000). The Cretaceous sediments of the Rolling Downs geomorphic unit of the Flinders catchment (see Appendix 6.3.2) are noted for their salinity (Turner and Hughes, 1983). Soils of the Rolling Downs may therefore have moderate to high salinity, and possess a 'salt bulge' between 0.6 and 0.9 m depth.

In this study, soil profile salinity has been incorporated in the soil water availability limitation in terms of the general way it restricts the effective rooting depth of plants, thereby reducing the volume of soil water available to them. Where detailed observations have been made across the landscape, salinity may be evaluated as a limitation in its own right by determining a weighted mean of salinity at various depth intervals in the plant root zone. It was not possible to adopt such an approach for regional assessments in this study, due to the paucity of ground observations available. Also, after irrigation, weighted mean profile salinity is more closely related to profile drainage and the quality of the irrigation water than to the inherent salinity of the soil before irrigation is adopted.

Secondary salinisation

Agricultural development, especially irrigation, disturbs the natural hydrologic equilibrium in the landscape. Increased access to groundwater results in raised watertables, which may be saline. Where watertables approach the ground soil surface evaporative concentration of salts may occur, resulting in secondary salinisation. Salt may also accumulate in places where saline groundwater is discharged lower in the landscape.

The potential for land development to cause environmental degradation is normally incorporated into a land suitability assessment. In terms of secondary salinity, this involves the consideration of inherent natural salinity (e.g. geomorphology, existing salinity profiles and vegetation type), soil profile drainage and the position in the landscape. The intention is to delineate areas of intake (recharge) potential and outflow (discharge) potential (Land Resources Branch Staff, 1990). Due to the limited availability of soil data away from riparian areas and frontage country, and the limitations of SRTM slope data, quantitative evaluation of regional scale secondary salinisation risk was not feasible in this study.

Hence, it is important that prior to irrigation development, particularly in the Flinders catchment, that the risk of secondary salinisation be assessed. This should include a detailed salinity investigation, taking into consideration the nature of the landscape, the type of irrigation proposed and the potential for deep drainage. Techniques for the identification of potential problem areas based on geology, geomorphology, soil and vegetation are provided in SalCon (1997).

The soil assessment described in this report was complemented by a groundwater assessment, which assessed surface water – groundwater connectivity and risk of groundwater rise (Jolly et al., 2013). Further qualitative discussion of the potential risks associated with salinity for each catchment is given in Section 3.

Landscape complexity

Landscape complexity relates to the complexity of soil patterns and/or topographic dissection that may reduce the size of land portions available for cropping enterprises. Due to the scale of assessment and the low intensity of field observations, it was not possible to assess the 'landscape complexity' limitation in this suitability framework.

Economics

The economics related to the viability of operating particular irrigation systems has not been included in this study but are reported elsewhere in this Assessment (see Crossman et al., 2013; Webster et al., 2013).

2.8.5 RELIABILITY OF LAND SUITABILITY OUTPUTS

Two approaches were used to create a general reliability map for the land suitability assessment to reflect the increased certainty around intensively sampled areas and the distribution of legacy data used in this study (Figure 3.1).

The first approach employed the Mahalanobis distance (Mahalanobis, 1936) for assessing prediction reliability in the context of soil property prediction (adapted from Sanderman et al., 2011). The Mahalanobis distance is a generalised distance function that measures how similar samples are based on their covariate information. In this application it is used to represent the spatial covariate information at a given point in the landscape. If a point in the catchment is very similar to regions that were sampled then the model predictions for that point will be more reliable. In order to implement this approach k=25 sites were selected that represent all of our sites using k-medoids cluster analysis (Kaufman and Rousseeuw, 1990). The minimum Mahalanobis distance between each point and each of the 25 sites was then recorded. Lower distances correspond with greater reliability. The output then provides an overall estimate of the reliability of the soil attribute data used to drive the land suitability assessment. The output then provides an overall spatial estimate of how well the sampling has accounted for certain soils, and so, conceptually, the quality of relationship between the sampling and the soils. By extension, this then is a test of RuleFit3 model quality and mapping reliability. The maps are classified according to very low, low, medium, high and very high reliability.

The second approach included expert opinion and knowledge about landscape processes or conditions that will influence agricultural development potential in these catchments that were not captured sufficiently in the modelling process (and areas of expert opinion where the Mahalanobis method underestimates confidence). The two landscape features that require special attention are the basalt rock outcrops and secondary salinisation. In the Upper Flinders catchment basalt rock outcrops were not well captured by the covariate data. To identify the rocky landscapes, the Qld Government Regional Ecosystem 2012 mapping was used (http://www.ehp.qld.gov.au/ecosystems/biodiversity/re_introduction.html). The secondary salinisation hazard in the central Flinders catchment was not explicitly considered in the modelling as it is not a direct impediment to agricultural development. However, the Rolling Downs geological unit in the Flinders catchment (Figure 3.4a) is vulnerable to secondary salinity due to moderate electrical conductivity (EC) levels at depth (0.6-0.9 m). It is important that this region is 'flagged' as a potential management risk and extreme caution will be required to minimise the salinity risk. The Rolling Downs unit was identified using the 1: 1,000,000 surface geological survey data (Geosciences Australia; see Table 2.2). Reliability maps are presented for each catchment in Sections 3.6.1 and 3.9.1.

3 Results

3.1 Field data

Table 3.1 and Table 3.2 summarise the data used in this study which includes the new data collected as part of this project as well as the legacy data included from previous assessments. Figure 3.1 shows the spatial distribution of the sites within the catchment. Table 3.2 provides a breakdown of each of the sites according to the soil attribute. The primary soil data is available on request and is stored in the Queensland SALI data base.

Table 3.1 Summary of sites used in the DSM component of this study including new and legacy data from within the catchment and regional data from immediately outside catchment boundary

Data type	Boundary	Number of sites
Legacy data (pre FGARA)	Within catchment boundary	787
FGARA assessment (new data)	Within catchment boundary	451
FGARA assessment (new data)	Additional sites with rockiness only (within model boundary)	126
Regional data (legacy) outside catchment boundary	Adjacent to catchment (outside boundary, e.g. Einasleigh Uplands)	587
Total		**1951**

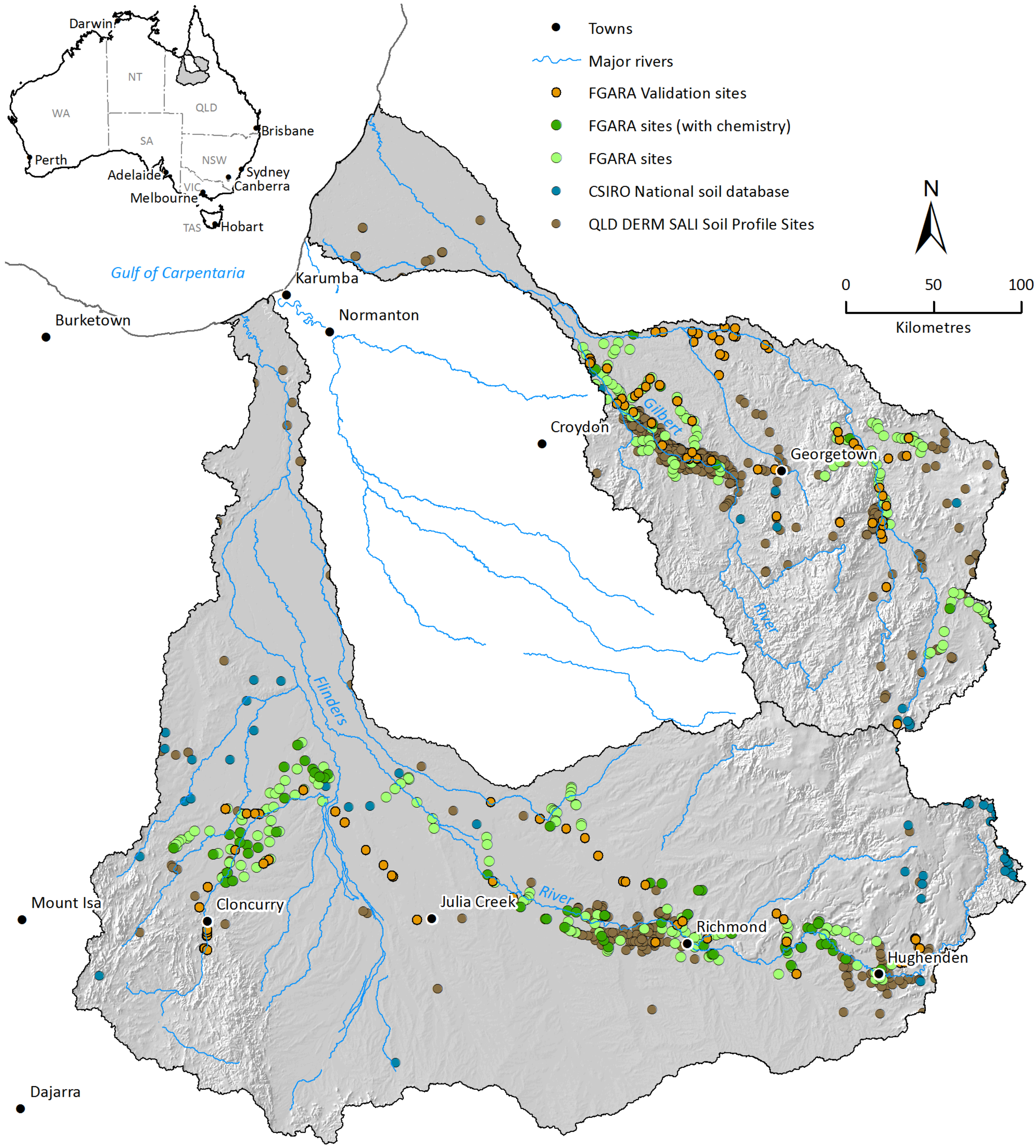


Figure 3.1 Location of soil sampling sites in the Flinders and Gilbert catchments. Sites include legacy data (from Queensland Government SALI data base and CSIRO National soil database), new FGARA sites and FGARA validation sites

Table 3.2 Summary of soil samples collated for the Flinders and Gilbert catchments as part of this project. NCST stands for The National Committee on Soil and Terrain (2009): Australian Soil and Land Survey Field Handbook

DATA	SOURCE	FLINDERS SITES	GILBERT SITES	OUTSIDE CATCHMENTS	TOTAL SITES
Clay content	Laboratory analysis	274	118	112	504
Depth of A horizon	Field measurements	443	730	543	1716
EC	Field and laboratory analysis – used in suitability not DSM	341	175	174	690
ESP	Laboratory analysis	160	62	158	380
K factor	Calculated	273	116	110	499
Microrelief	NCST codes	344	680	394	1418
Soil water availability – PAWC 0.5 m	Calculated	272	116	106	494
Soil water availability – PAWC 1.0 m	Calculated	272	116	106	494
Soil water availability – PAWC 1.5 m	Calculated	272	116	106	494
Organic Carbon	Laboratory analysis – not used in suitability or DSM	161	68	152	381
pH (soil surface)	Field measurements	477	722	564	1763
Rockiness	NCST codes	492	754	463	1709
Soil depth	Field measurements	487	734	584	1805
Soil drainage	NCST codes	492	729	585	1806
Soil generic group	Classified and allocated	492	733	585	1810
Soil permeability	NCST codes	481	724	564	1769
Soil structure	NCST codes	423	713	523	1659
Soil surface condition	NCST codes	426	704	472	1602
Soil surface texture	NCST codes	492	736	584	1812

3.2 Spectral data

The results of the MIR spectral analysis are given in Table 3.3. These results suggest there was a high degree of confidence in the data predicted using MIR with 15 Bar (moisture) having the strongest relationship (R^2 =91.64) and pH the lowest (R^2 = 77.16). As summarised in Table 2.1, MIR 15 bar was used in the PAWC estimations; particle size (sand, silt and clay content) was used in the derivation of K factor and PAWC; EC was used for PAWC and pH was used where field or lab pH were unavailable. MIR results for Ca and CEC were not used.

Table 3.3 Results of the MIR model statistics for data collected in this study

COMPONENT	CALIBRATION DATA TRANSFORM‡	NO. OF CALIBRATION SAMPLES	R^2	RMSECV	BIAS
15 bar	none	172	91.64	2.26	–0.00123
Coarse sand	log	160	76.86	0.278	–0.00118
Fine sand	log	160	89.67	0.0849	–0.000242
Silt	log	160	86.32	0.112	–0.000639
Clay	none	160	90.14	6.19	–0.0762
EC	log	233	82.31	0.38	–0.00166
pH	none	247	77.16	0.456	0.012
CEC	none	123	79.24	5.71	–0.0537
Ca	none	123	73.2	6.19	–0.163

§ **RMSECV (Root Mean Square Error of Cross Validation):** In case of a cross validation the RMSECV value can be taken as a criterion to judge the quality of the method. **Bias (mean value of deviation, also called 'systematic error'):** The bias is a systematic deviation of the measured (predicted) values from the true value due to a particular measurement method, for example. In our case, it is the difference between the average true value and the average measured value of the validation. **RPD** (Residual Prediction Deviation): The residual prediction deviation is the ratio of standard deviation to standard error of prediction. (Bruker 2011. *OPUS Spectroscopy Software Version 7 User Manual Quant* BRUKER OPTIK GmbH, Rudolf-Plank-Str. 27, D-76275 Ettlingen)
‡ **Log_{10} transforms** were applied to calibration data sets where histograms indicated that distributions were not normal.

3.3 Statistical outputs of digital soil mapping (DSM)

3.3.1 SOIL ATTRIBUTE LAYERS

Relationships were developed between the environmental covariates and the best available estimates of each soil attribute at the sample locations using the methods in Section 2.7.1. The relationships were then applied over the entire extent to produce maps of each soil attribute. The summary statistics of the DSM results for the numerical attributes for both the Flinders and Gilbert catchments are presented in Table 3.4. The R^2 statistic is the percentage of variability explained by the model. For these attributes, the model performed best for clay (R^2 = 54.3%) and pH (R^2 = 49.5%). The summary statistics for the categorical data are presented in Table 3.5. The categorical data performance is measured by the percentage of cases that are correctly classified under cross-validation. These classification rates are 85.8% for micro-relief, 80.6% for soil surface condition and 80.4% for rockiness. While a numerical comparison of R^2 values and classification rates has no formal statistical meaning, it is clear that our models of categorical attributes do better than our models of numerical attributes. This could be because of the limited number of labels used to describe each categorical attribute. If we were to create categorical attributes with ten or more layers our classification performance would drop. For this report, we have chosen to present statistical results for nine attributes that represent a combination of numerical, categorical and binary data (pH, PAWC100, texture, minimum soil depth, permeability, rockiness, drainage, EC and ESP). The spatial results for nine attributes are presented in Sections 3.5 and 3.8 for the Flinders and Gilbert catchments, respectively. Figure 3.2 shows radar plots that indicate the relative importance of the spatial covariate layers in the prediction of six soil attributes. The order of spatial covariates is dictated by overall relative importance across these six layers. The Prescott index was the most important variable of the thirteen spatial covariates.

Table 3.4 Results of the digital soil modelling (attribute mapping) for the numerical data in both the Flinders and Gilbert catchment. Root mean squared error (RMSE) is expressed as a percentage of the range of the observed values; lower values indicate less residual variance relative to the range.

ATTRIBUTE	RMSE	R^2
Clay %	13.70	54.3
Depth of A horizon	0.203	17.7
EC	0.525	18.4
ESP	2.990	24.0
K	0.013	25.8
PAWC 50	17.300	35.7
PAWC 100	29.300	24.0
PAWC 150	34.600	19.4
pH	0.705	49.5
Soil depth	0.451	27.0

Table 3.5 Results of digital soil modelling (attribute mapping) for the binary and categorical data in both the Flinders and Gilbert catchment. See Section 2.7.3 for approach.

ATTRIBUTE	CROSS-VLAIDATED CLASSIFICATION RATE (%) FOR THE BINARY AND CATEGORICAL LAYERS
Drainage	52.7
Permeability	56.0
Texture	63.0
Condition	80.6
Structure	75.8
Microrelief	85.8
Rockiness	80.4
Soil General Group (SGG)	47.9

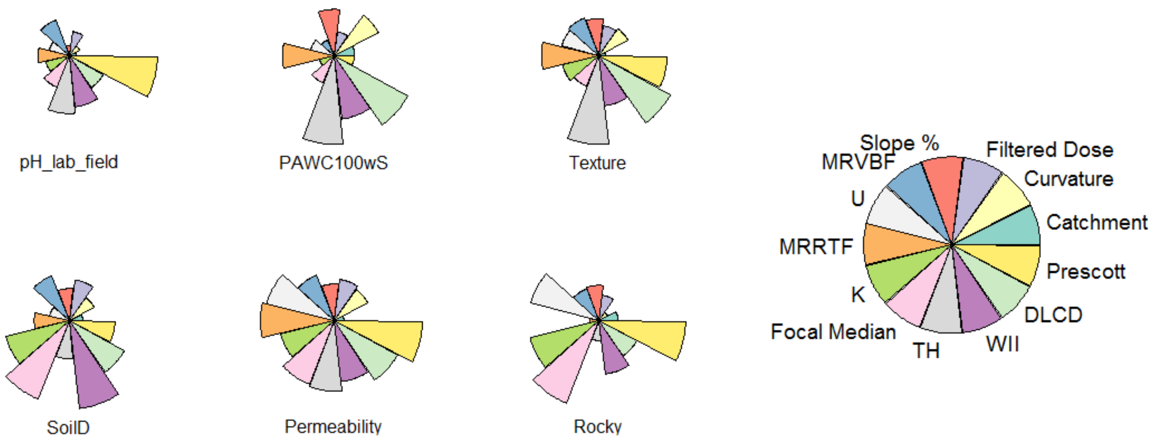


Figure 3.2 Six radar plots of the relative importance of each spatial covariate for each soil attribute. Thirteen spatial covariates are represented in each radar plot and the legend on the right hand side indicates the position and colour of each spatial covariate. K = Potassium, TH = thorium, U = Uranium, DLCD = dynamic land-cover data set, MRVBF = multiresolution valley bottom flatness, MRRTF = multiresolution ridge top flatness, WII = weathering index, Catchment = categorical mask indicating the prediction location. The other variables are described in detail in Table 2.2.

3.3.2 INDEPENDENT VALIDATION

Independent validation was conducted on 10 soil attribute variables. The results for the nine attributes are presented spatially for each catchment in Section 3.5 and 3.8 (pH, texture, minimum soil depth, permeability and rockiness, drainage, EC and ESP). PAWC was not measured on the final validation trip but we also performed independent validation of the soil generic group. Figure 3.3 present the statistical results for the two numerical layers, pH and soil depth, showing a strong fit between the observed and predicted pH (R^2 = 0.67), and a weaker, but acceptable relationship between observed and predicted soil depth (R^2 = 0.46). Table 3.6 presents the classification tables for observed vs predicted values for the categorical variables soil surface permeability, soil surface texture, rockiness and soil generic group (SGG). The classification rates for these soil attribute are determined by summing the diagonal entries and dividing by the number of validation sites. The classification rate was 63% for permeability, 78% for texture, 93% for rockiness and 57% for SGG.

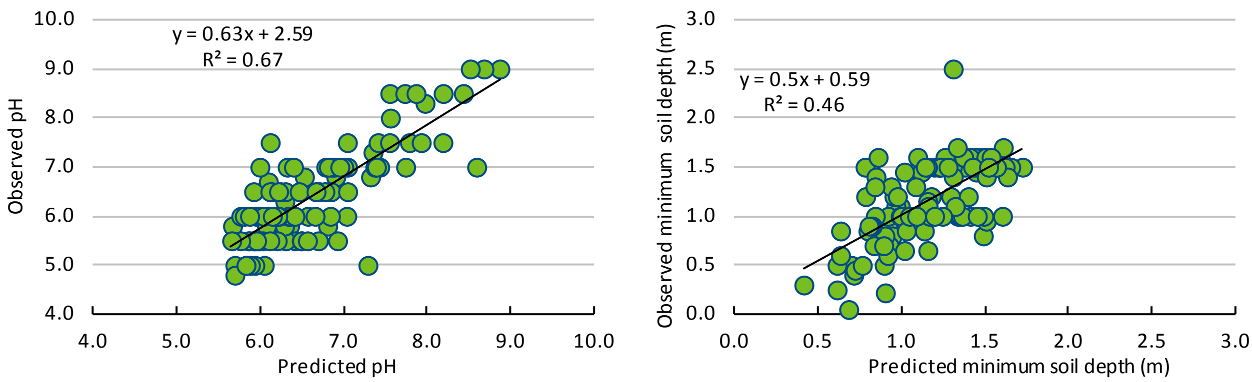


Figure 3.3 Observed (measured in the field) vs predicted (modelled) values for the surface pH and minimum soil depth (m) validation site data.

Table 3.6 Observed (horizontal) vs predicted (vertical) classification tables for (a) permeability, (b) texture, (c) rockiness and (d) soil generic group (SGG) values. The values indicate the number of validation sites for each pair of observed and predicted category. The classification rates are determined by summing the diagonal entries and dividing by the number of validation sites.

(a) Soil surface permeability

	1	2	3	4
1	1	2	3	0
2	1	37	17	0
3	0	7	27	2
4	0	2	7	5

(b) Soil surface texture

	1	2	3	4
1	42	7	0	2
2	7	9	0	3
3	1	1	2	0
4	2	1	0	34

(c) Rockiness

	1	2
1	98	4
2	4	6

(d) SGG

	1	2	3	4	5	6	7	8	9
1	9	3	0	1	0	0	0	0	1
2	4	17	0	2	0	0	0	0	2
3	0	0	0	1	0	0	0	0	0
4	7	5	0	9	0	0	0	0	1
5	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0	0	0	0	1
7	2	2	0	0	0	0	1	0	0
8	1	9	0	1	0	0	0	2	1
9	1	2	0	0	0	0	0	0	25

3.4 Flinders catchment soil and landscape interpretation

3.4.1 GEOMORPHIC LANDSCAPE DESCRIPTION

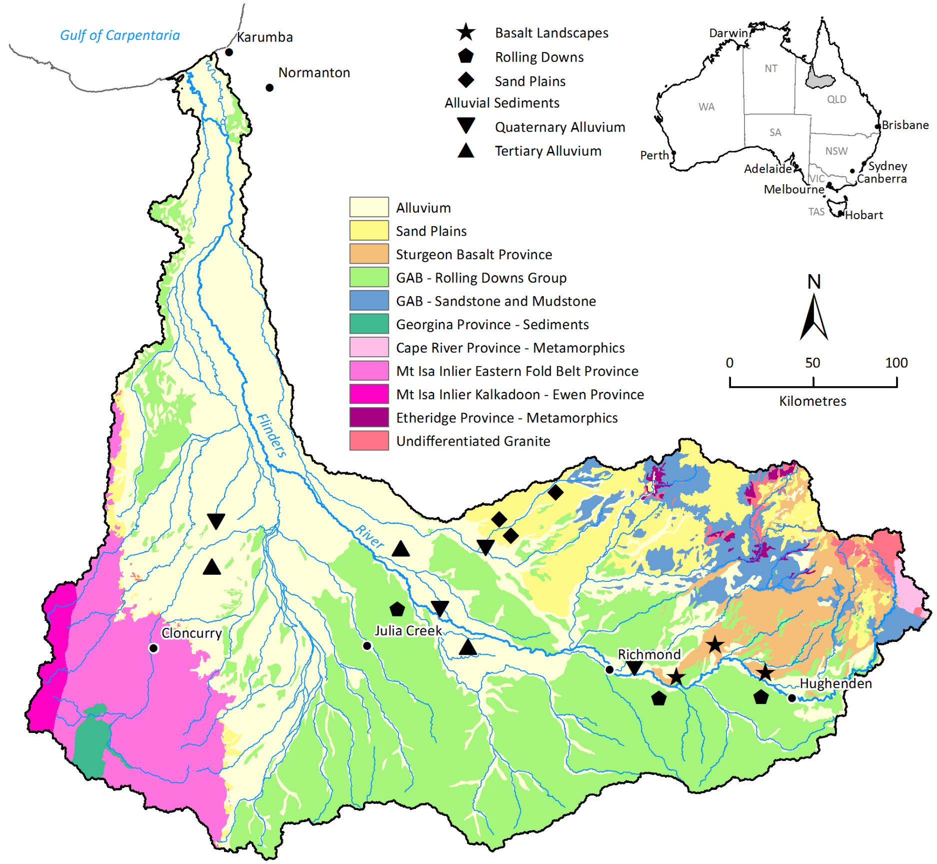
The Flinders catchment includes a range of landscapes from extensive clay plains, rolling Mitchell Grass Downs to upland areas where Porcupine Creek, a major tributary of the upper Flinders River, has carved out a dramatic gorge located in the Porcupine Gorge National Park north east of Hughenden. The upper Flinders catchment is dominated by sandy, loamy and clayey deposits originating from the coarse-grained quartz based geology in the upper catchment while the lower Flinders catchment is dominated by clay-based alluvial sediments. Four major landscape units (Figure 3.4a) were identified in the Flinders catchment based on soil data collected for this region (e.g. Enderlin, 2000; Turner and Hughes, 1983; Wilson and Philip, 1999) as well new soil survey data (Figure 3.1). The major geomorphic landscape units in the Flinders catchment include (i) Alluvial sediments, which are broken into Quaternary alluvium and Tertiary alluvium (ii) Rolling Downs; (iii) Basalt landscapes and (iv) Sand plains. Appendix A.3 describes each of the four major landscape units in more detail, and provides a description of the composition and distribution of soils within each landscape unit. It is important to note that each investigation area may contain several landscape units.

3.4.2 SOILS OF THE FLINDERS CATCHMENT: SOIL GENERIC GROUP MODELLING RESULTS

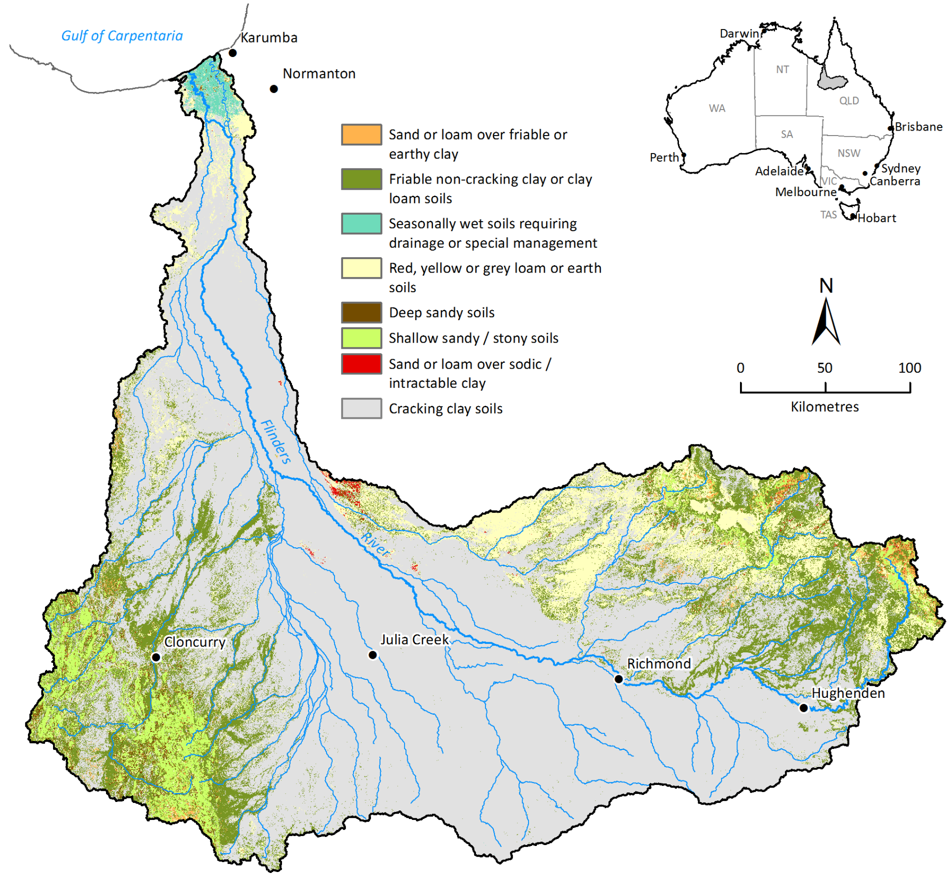
The model results, and field validation, show that the Flinders catchment is dominated by cracking clay soils (68% see Table 3.7), which almost completely cover the extensive alluvial and Cretaceous mudstones in the centre of the catchment (Figure 3.4). At the mouth of the catchment the soils are dominated by seasonally and permanently wet soils. Loamy soils dominate in the upper relief positions in these areas. To the east in the uplands, loamy soils dominate the recent (Quaternary) and older (Tertiary) colluvium slopes and alluvial parent material in the lower and upperslopes. The basalt areas are dominated by cracking clays on the elevated plains, and flanked by clay loams and non-cracking clay soils (~15%). Shallow sandy and stony soils are found on the coarse grained granodiorite and metamorphic (gneiss) parent materials (~4%). To a lesser extent, these areas have also yielded sands or loams over friable clay soils (<1%). In the western uplands, three soil groups co-dominate: shallow sandy and stony soils are associated with quartzites, sandstones, granites and granodiorites; cracking clays soils are strongly associated with metabasalts, schists, and mudstones and siltstones, and clay loam and non-cracking clay soils dominate the alluvial and channel flood plain areas draining the uplands.

Table 3.7 % area of each of the Soil Generic Group (SGG) classes predicted for the Flinders catchment

Soil generic group description	% SGG soil type in Flinders catchment*
Sand or loam over relatively friable clay subsoils	1
Friable non-cracking clay or clay loam soils	15
Seasonally or permanently wet soils	0.75
Red, yellow or grey loamy soils	10
Deep sandy soils	0.75
Shallow sandy and stony soils	4
Sand or loam over intractable clay subsoils	0.5
Cracking clay soils	68



(a)



(b)

Figure 3.4 (a) Geological and geomorphological description of the Flinders catchment (see Appendix A.3 for more detailed description), Geology based on the 1: 1,000,000 surface geology mapping, and (b) Soil generic group (SGG) modelled classes for the Flinders catchment

3.5 Flinders catchment digital soil modelling (spatial) results

The results for the nine selected digital soil mapping (DSM) outputs for the Flinders catchment are presented in Figure 3.5 to Figure 3.13. To the right of each DSM map is an associated map of model uncertainty or reliability that is quantified using the standard deviation in the case of the numeric layers, and the confusion index for the binary and categorical data.

The spatial distribution of predicted pH is shown in Figure 3.5 for the Flinders catchment. The central zone of the catchment features an extensive tract of alluvial soils and low-relief mudstones, all of which are dominated by clays. This zone features alkaline soils with slow drainage leading to pedogenic accumulation of carbonates, the most important source of alkalinity (Figure 3.5a). The pH trend in the eastern uplands and the Cloncurry region reflects the underlying lithology which is often more siliceous/quartz-rich i.e. sandstones/siltstones, and so produces coarser textured soil. Being more freely draining and leached, these soils are typically more acidic. The basalts in the eastern uplands weather to finer textured soils (clay rich) and being mafic are a source of leached base elements and are relatively alkaline. The accompanying map (Figure 3.5b) shows the standard deviation of modelled data and indicates a greater degree of confidence in the pH predictions in the eastern and western uplands, whereas the reliability is lower in the basalt-dominated and low relief central zone. This pattern is due, however, to the short range of variability as the majority of pH values (between 6 and 7 pH units) are in the low relief central catchment area. In this case more data do not result in improved model confidence. Lower confidence levels of pH predictions, i.e. of the order of approximately 0.6 standard deviations, is within the reliability of field pH testing, which is in the order of 0.5 units of pH. This indicates that the prediction errors are within typical field measurement tolerances.

The plant available water capacity in the upper 100 cm of the soil profile (i.e. PAWC 100) (Figure 3.6) was predicted to be highest across the central zone where the soils are dominated by deep clays with little or no stoniness in the soil profile. They have large capacity to hold water for plants (minimum, 41.9 mm; maximum, 130.1 mm; mean, 90 mm, and SD, 19.5). The PAWC 100 pattern matches the soil texture trend in that the coarser grained, stonier and shallower soils of the eastern and western uplands have diminished capacity to store water, hence show lower PAWC 100 values. Figure 3.6b shows the standard deviation of modelled data and indicates a reasonable degree of confidence in the PAWC predictions across most of the catchment; however, this confidence is reduced in the rocky basaltic areas in the northeast and the metasediments of the southwest.

The minimum soil depth predictions are shown in Figure 3.7. Generally, the soils were predicted to be shallower in the upland areas, reflecting the more freshly weathered soils and susceptibility to wind and water erosion; this is especially the case in the western upland area where the soils are sandier (Figure 3.7a). The deepest soils are found in the central zone, especially in the drainage systems, where soils are typically no shallower than 2 m. The soils mantling the extensive mudstones are typically between 1 and 2 m in depth. Figure 3.7b shows the standard deviation of modelled data and indicates a reasonable degree of confidence in the soil depth predictions across the central parts of the catchment, however, the model confidence is reduced (SD increased) in the headwater or upland areas of the catchment, suggesting that soil depth is less in steeper areas.

The surface texture output in Figure 3.8a shows that the catchment is dominated by clay soils, particularly in the central zone, and by loamy soils in the uplands. Again, surface textures strongly reflect parent material where soils are derived *in situ*. In other cases, soils reflect upstream/upslope processes and the parent material is derived from transported materials (i.e. alluvial and colluvial). For example, the drainage zones of the eastern uplands are generally dominated by clay soils, which are the result of deposition of the finer soil fractions from the weathered basalt and from fine grained sedimentary lithologies. In the western uplands, the texture classes relate to the complex assemblage of lithologies, with sands and loams on quartz-rich intrusive parent material, and clays over the mafic and fine-grained sedimentary lithologies. In terms of mapping reliability, the most reliable surface texture predictions are in the central zone, whilst the least reliable predictions are in the uplands and the mouth of the river (Figure 3.8b). It is probable that less reliable predictions are a result of the complex patterns of parent material and/or relief patterns.

In keeping with the soil texture patterns, the Flinders catchment is dominated by soils that are slowly permeable, particularly in the extensive clay soils of the central zone (Figure 3.9a). Zones of greater soil permeability are associated with the upland regions to the east and west, reflecting the coarser soil textures. These areas are

typically moderately permeable, with smaller areas of highly permeable soils. In terms of reliability, this is strongest in the central zone, particularly in the fine grained sedimentary rocks, and poorer in the upland and lower areas of the catchment (Figure 3.9b).

The distribution of the rocky soils strongly reflects the patterns from the previous attributes. For example, the uplands are dominated by rocky soils (Figure 3.10) and associated with slowly weathering parent materials dominated by quartz, or new parent material like basalt that have had little time to weather. Alternatively, the non-rocky soils are found in the extensive lower-lying areas of the central zone, which feature alluvial deposits, or weathered mudstones with fine textures, leaving no residual rockiness.

The Flinders catchment is overwhelmingly dominated by soils that are moderately well-drained, especially in the areas of Rolling Downs, lowland alluvium and the eastern uplands (Figure 3.11). This latter area is interspersed with areas of well-drained soils on the sand plains, and well-drained and rapidly drained soils, especially on the granites. Again, in keeping with the coarser grained textures of the parent materials in the western uplands (e.g. siliceous metamorphics and igneous), the soils are typically dominated by well-drained and rapidly-drained soils.

Figure 3.12 shows the predicted EC in the top 10 cm of the soil. Salt measurements were collected down soil profiles, however, due to minimal data, EC at depths >10 cm were not modelled. The surface soils of the Flinders catchment are broadly non-saline, with a range between 0 and 1.8 dS/m (SD 0.1). A soil is considered saline for agricultural purposes when > 2 dS/m (Soil Survey Staff, 1993). There are extensive areas of the catchment where the salt levels are more pronounced, particularly in the alluvium nearest the coast and in the extensive Rolling Downs group of the southern lowlands. The former areas are likely to be associated with the combination of coastal influence and heavy clays, ensuring poor leaching of salts, whereas in the Rolling Downs, salts are likely to be in situ in the mudstones, and again poorly leached due to the heavy clays. The soils on the basalts in the eastern uplands also show relatively elevated salinity levels, and this is likely to be derived from in situ weathering of the mafic, salt-rich material.

The mean exchangeable sodium percentage (ESP) of the surface soil is 0.9, with the maximum value of 19.3 (SD 1.7), indicating that some areas are strongly sodic (Figure 3.13) (Rengasamy and Churchman, 1999). The areas of most elevated ESP are associated with the Rolling Downs heavy clays soils derived from mudstones. These are likely to be a strong source of sodium on weathering, and the heavy texture of the soils ensures that leaching is minimal so that the sodium is retained. There are other areas with elevated ESP including the alluvial areas downstream of the eastern basalts, and the alluvial channels derived from the Rolling Downs.

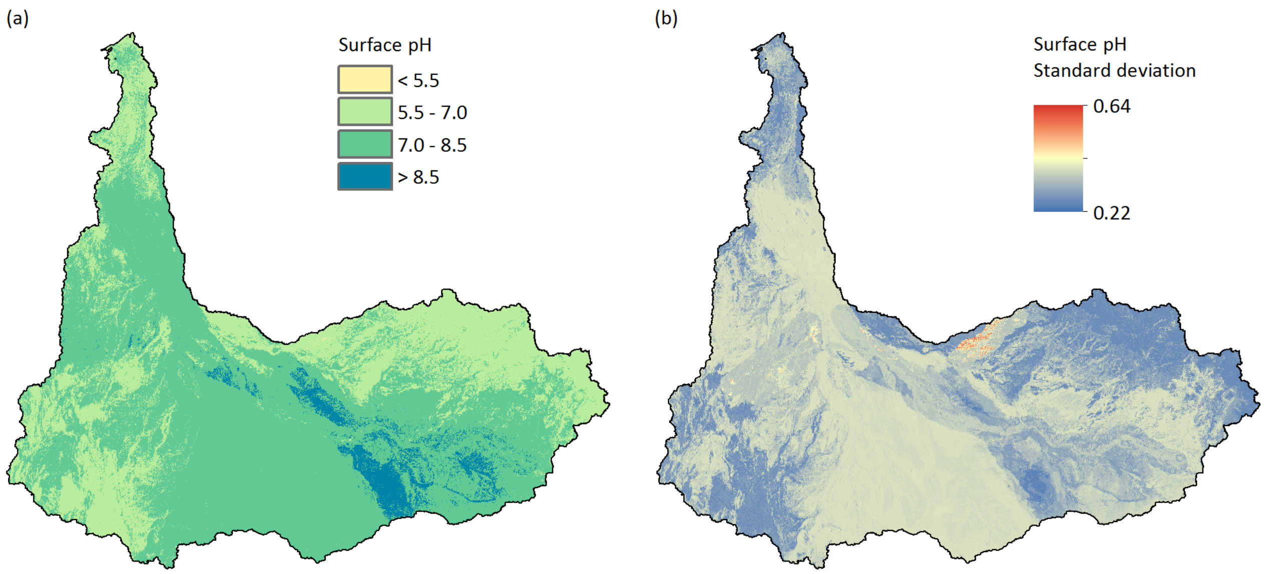


Figure 3.5 Flinders catchment digital soil mapping predicted surfaces for (a) surface pH and (b) the standard deviation around the prediction.

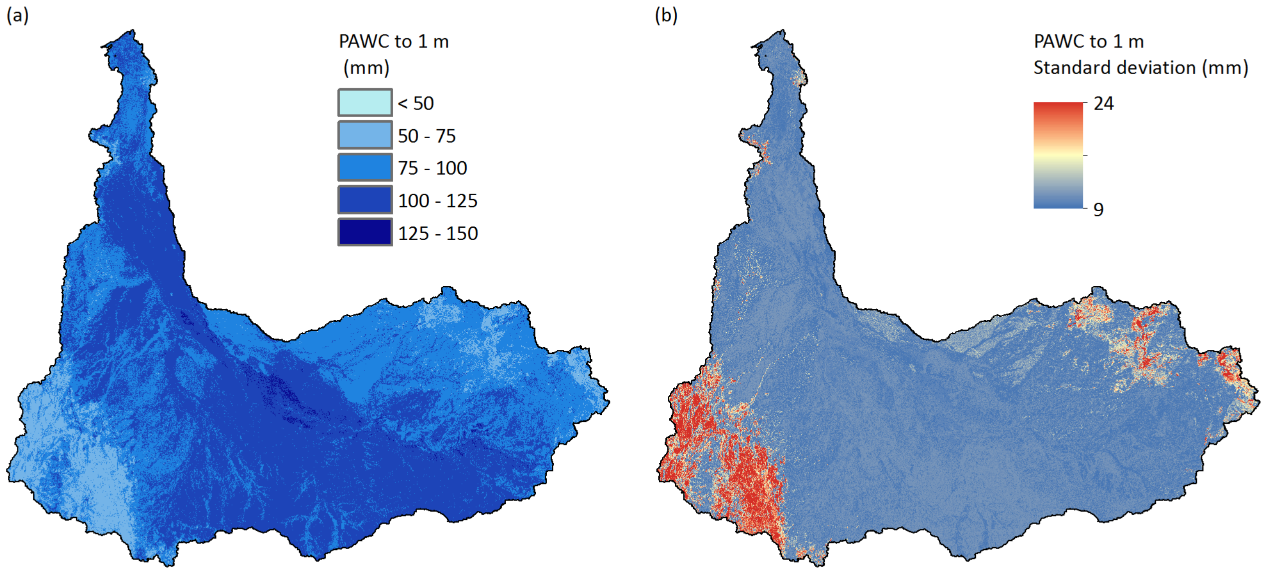


Figure 3.6 Flinders catchment digital soil mapping predicted surfaces for (a) PAWC to 1m and (b) the standard deviation around the prediction

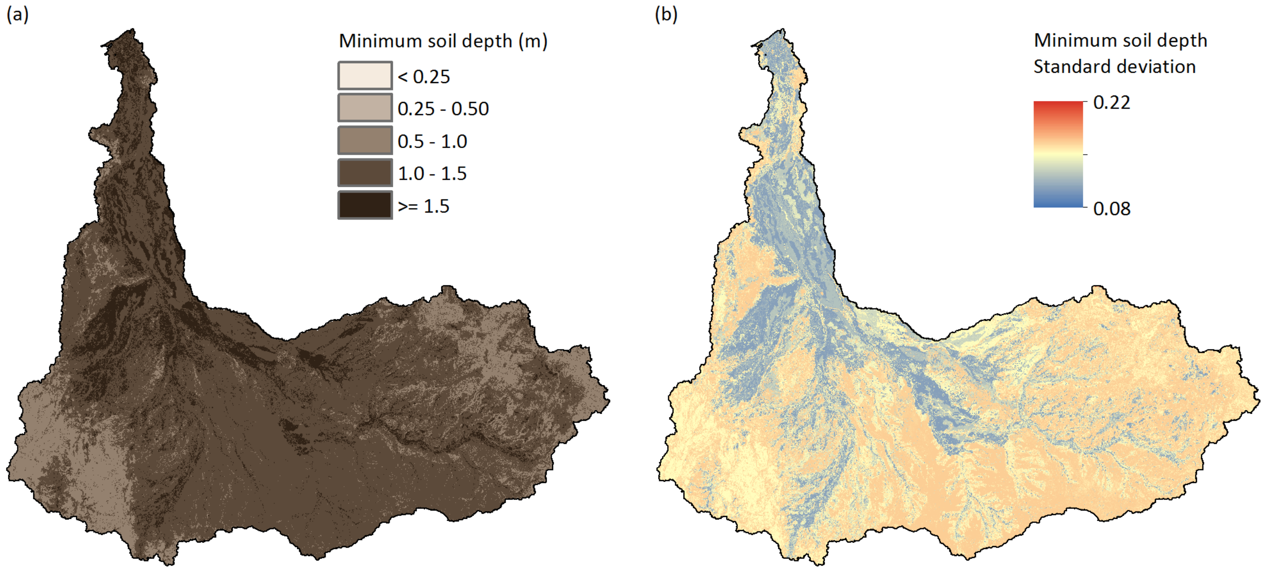


Figure 3.7 Flinders catchment digital soil mapping predicted surfaces for (a) minimum soil depth and (b) the standard deviation around the prediction.

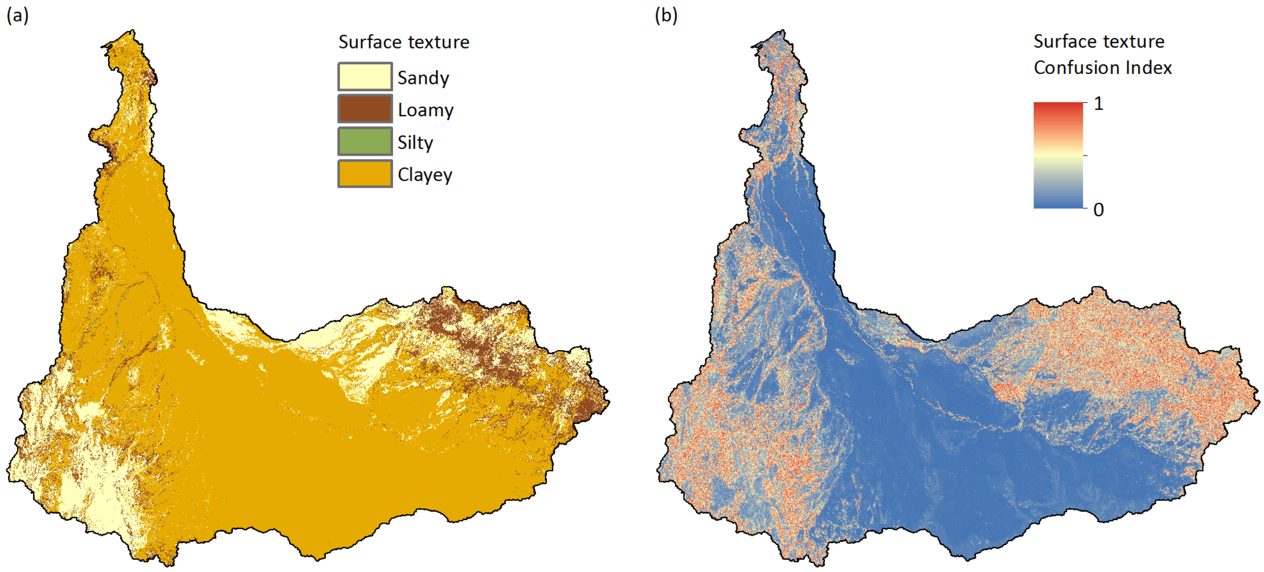


Figure 3.8 Flinders catchment digital soil mapping predicted surfaces for (a) surface texture and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

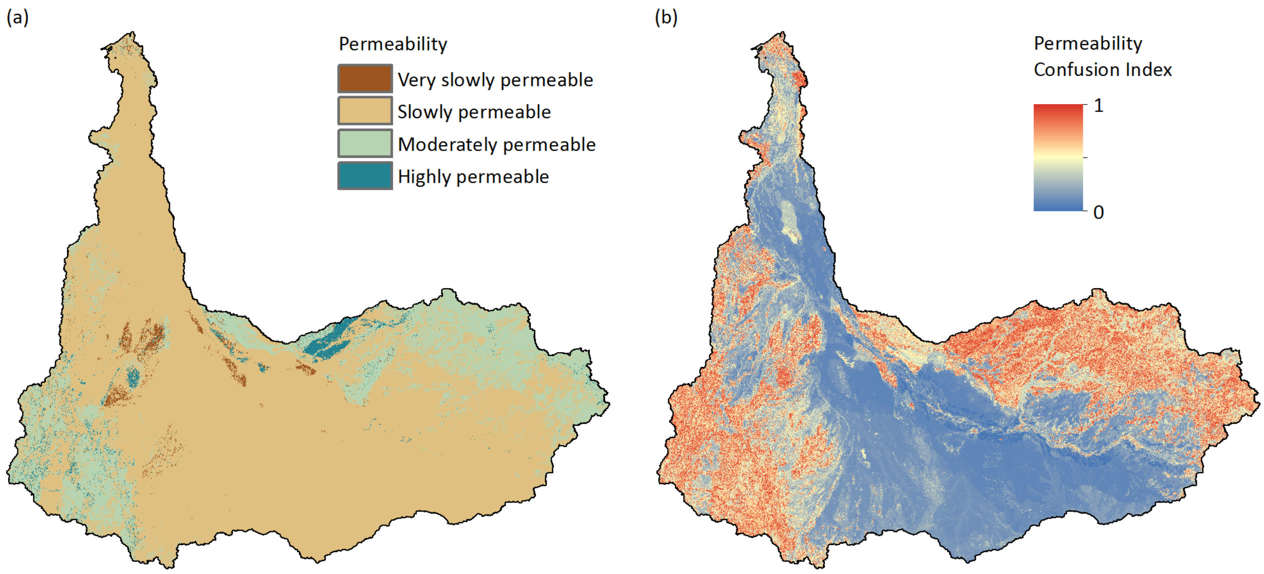


Figure 3.9 Flinders catchment digital soil mapping predicted surfaces for (a) permeability and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

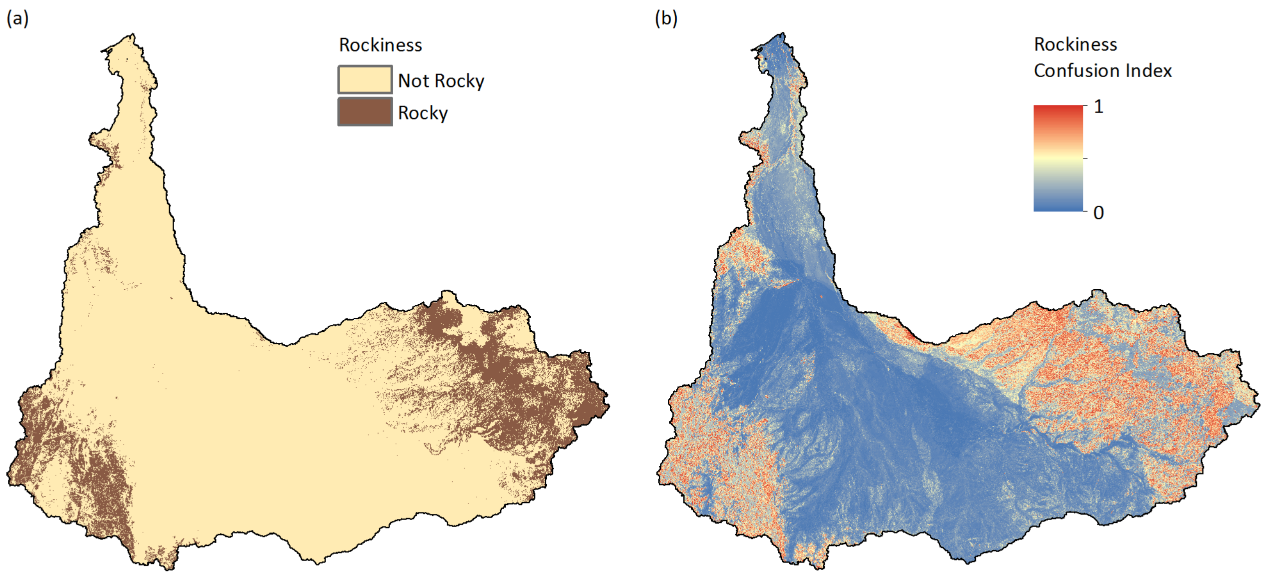


Figure 3.10 Flinders catchment digital soil mapping predicted surfaces for (a) rockiness and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

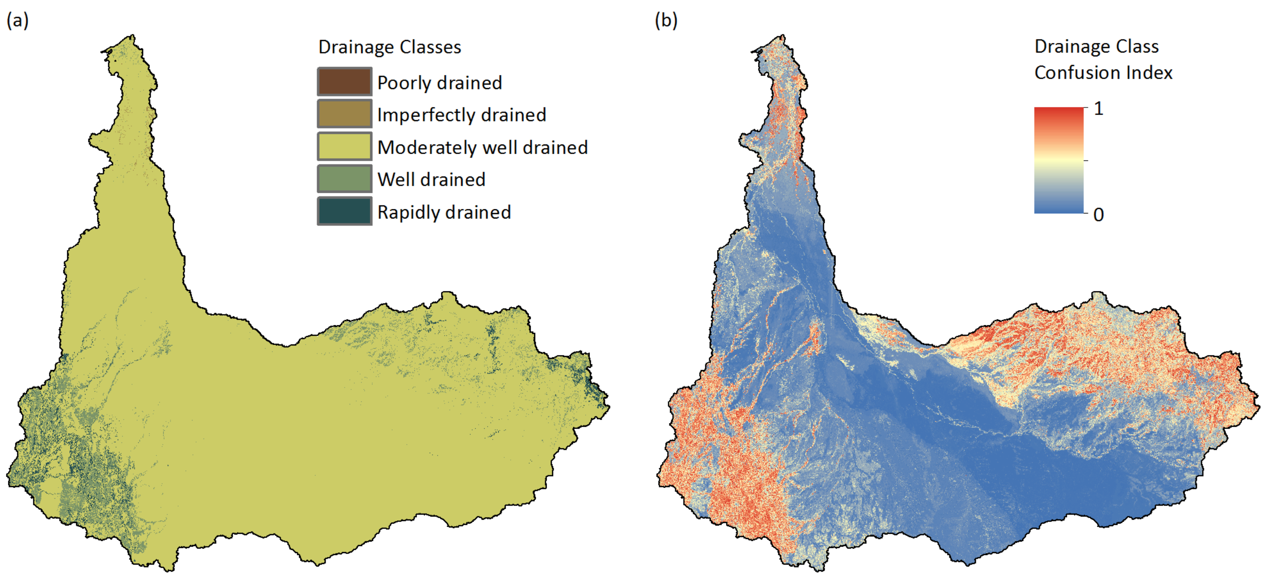


Figure 3.11 Flinders catchment digital soil mapping predicted surfaces for (a) drainage and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

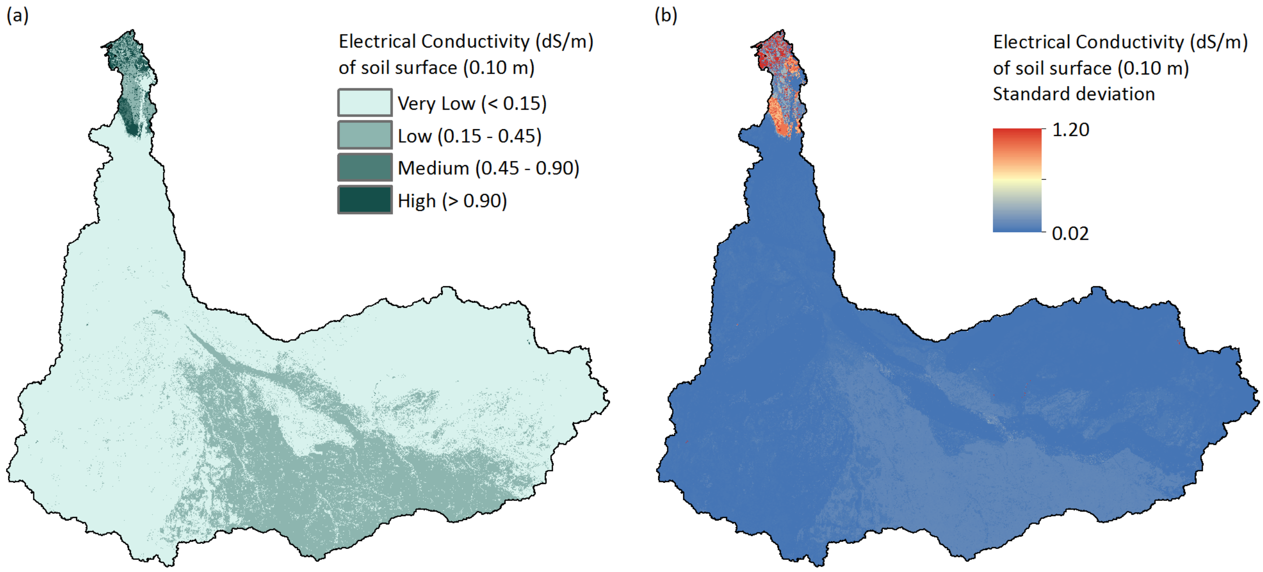


Figure 3.12 Flinders catchment digital soil mapping predicted surfaces for (a) electrical conductivity (EC) in the top 10cm of surface soil and (b) the standard deviation around the prediction

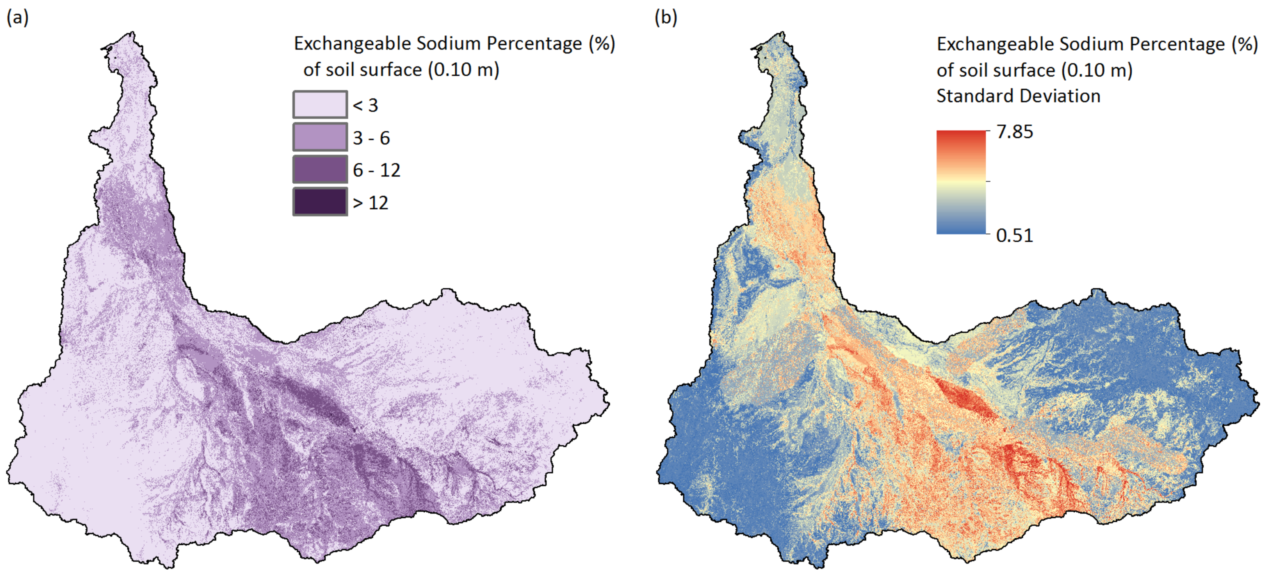


Figure 3.13 Flinders catchment digital soil mapping predicted surfaces for (a) exchangeable Sodium percentage (ESP) in the soil surface (0.1m) and (b) the standard deviation around the prediction.

3.6 Land Suitability Assessment for the Flinders catchment

3.6.1 RELIABILITY OF LAND SUITABILITY MAPS IN THE FLINDERS CATCHMENT

Figure 3.14 presents a map indicating the reliability of the land suitability mapping that was undertaken as part of the Assessment. This reliability map should be consulted when interpreting the land suitability maps presented in Section 3.6.2. The areas that have very low Mahalanobis distance values are generally more reliable, and we have higher confidence in these areas; they are generally the areas where most of the on-ground soils data were collected. The areas with medium to high Mahalanobis distance values are where we have less data and are less confident in the modelled predictions in these areas.

Not all soil attributes were modelled as part of the DSM process, and in some cases the DSM process did not fit subsequent observation or knowledge of the biophysical processes in these catchments. Figure 3.14b highlights a number of additional issues that need to be considered when evaluating the land suitability maps. These include areas that were not completely addressed by the modelling (e.g. secondary salinisation which is a landscape/ catchment /groundwater process only partly addressed with soil information) (shown in green), areas where low sampling density resulted in predictions inconsistent with observation and knowledge of landscape processes in that area (shown in red), or areas where the model did not perform well against the field data collected (e.g. rockiness in basalt landscapes; shown in purple).

In terms of the secondary salinisation issue, sampling undertaken in this assessment and previous assessments in this region (e.g. Turner and Hughes, 1983) determined that the clay soils of the Rolling downs group are sodic, and have medium to high salt levels by 60 cm and moderate chloride levels by 90 cm. Gypsum is often the dominant salt at depth and its presence could cause corrosion of irrigation infrastructure. It is possible, that the use of modern, well-controlled trickle irrigation, overhead travelling or centre-pivot irrigation techniques may overcome these limitations within the farm or paddock (Coventry and Pollock, 2011), however, the risk needs to be acknowledged and managed appropriately. There are broader catchment concerns around salinity, especially in this region. These issues are discussed in more detail in the catchment reports.

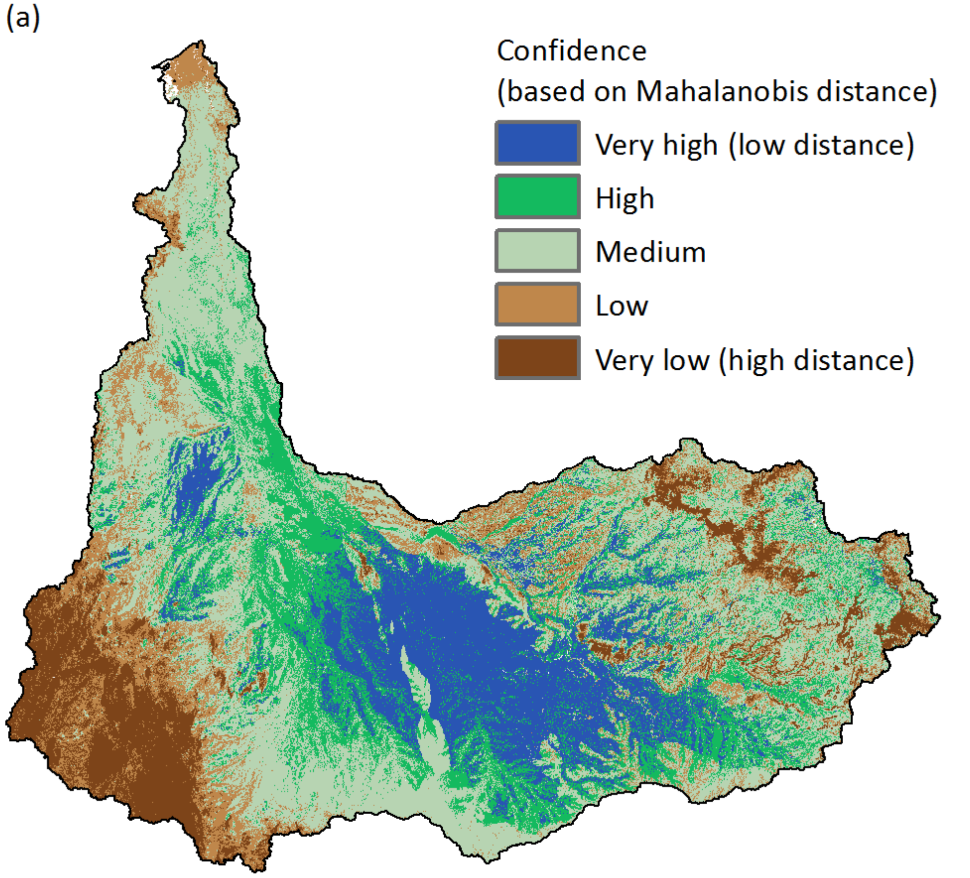


Figure 3.14 Confidence map for the land suitability outputs for the Flinders catchment (a) Mahalanobis distance values where low Mahalanobis distance values mean better or higher confidence in the land suitability outputs (b) location of the GAB area that has a known salinity risk (soils with a salt bulge between 0.6 and 0.9 m) as well as areas of low reliability based on expert opinion of landscape processes.

3.6.2 RESULTS OF LAND SUITABILITY MODELLING IN THE FLINDERS CATCHMENT

There were 76 different land uses (crop and irrigation combinations) evaluated in this study (see Appendix Appendix A). In this section we present and discuss the results for 14 different land uses for the Flinders Catchment. These land uses represent a range of land use categories (Table 3.8). Thumbnail images for the remaining 62 land uses can be found in Appendix A.5.

Table 3.9 present the land suitability data in two formats. The first format is the amount of land in class 1 and 2 (suitable) and class 3 (moderately suitable) as directly calculated by the models (see Figure 3.15). The spatial arrangement of the land use suitability for each of the 14 land use combinations in the Flinders catchment are shown in Figure 3.17 to Figure 3.22. The second approach presented in Table 3.9 takes the model certainty or confidence into consideration. For these data, only areas where we have medium, high or very high confidence in the predicted values (based on the Mahalanobis calculations, Figure 3.14) are presented. The total area of Flinders catchment is 11,002,630 ha, however, when the areas of low and very low confidence are removed, the available area for agriculture is ~7,526,690 ha.

It is important to note that the suitability calculations have been evaluated on a catchment basis. There has been no consideration of the contiguousness of the land units, or scale of farming operation. This section presents the suitability of the soil to grow crops within the climate of the Flinders catchment. Water availability and other considerations are being dealt with in other components of this Assessment (e.g. Crossman et al., 2013; Webster et al., 2013).

Table 3.8 Land use combination of crop and irrigation type for the 14 different land uses presented. * refers to dry season cropping

		IRRIGATION METHOD			
Land use category	***Land use (Crop)***	***Furrow***	***Spray***	***Trickle***	***Flood***
Horticulture	Capsicum/Chilli*	√		√	
Industrial	Cotton	√	√		
Tree crop	Mango			√	
Root crop	Peanuts		√		
Forage	Rhodes Grass		√		
Cereal	Rice				√
Pulse crop	Soybeans	√	√		
Forage	Sorghum*		√		
Cereal	Sorghum*	√			
Industrial	Sugar	√	√		

Generally speaking, a large portion of the Flinders catchment is moderately suitable (class 3) for irrigated cropping (both spray and furrow systems), with moderate limitations (Figure 3.17 to Figure 3.22). Of the irrigation types, spray is often more favourable than furrow because the soil and slope constraints are lower. In the very flat areas, earthworks may be required to establish sufficient slopes for furrow systems. The alluvial areas in the Flinders catchment generally have moderately favourable properties for irrigation as they have deeper well drained soils. The clay soils on the Cretaceous fine grained sedimentary rocks (of the Rolling Downs group; see Figure 3.4b) are suitable but the major limitation is wetness (which is a combination of drainage and permeability) as the clay soils

are only slowly permeable. In these areas the soils are often saline relatively close to the surface (<1.0 m). Where wetness is high, the soils are shallow (e.g. Rolling Downs group), and EC is elevated (near 2.0 dS/m) there is a risk of secondary salinisation (see section 2.8.4). It would be essential to conduct a detailed salinity investigation that accounts for salinity, the type of irrigation proposed, and the potential for deep drainage. Much of the upland areas to the east and west of the catchment are unsuitable for irrigation, typically because of soil depth, rockiness and other physical limitations. Some of the more extensive alluvial areas may be suitable, particularly for spray irrigation (e.g. western uplands). By and large, much of the lower catchment has conditions suitable for irrigation for most crops but flooding may be an issue (see Dutta et al., 2013).

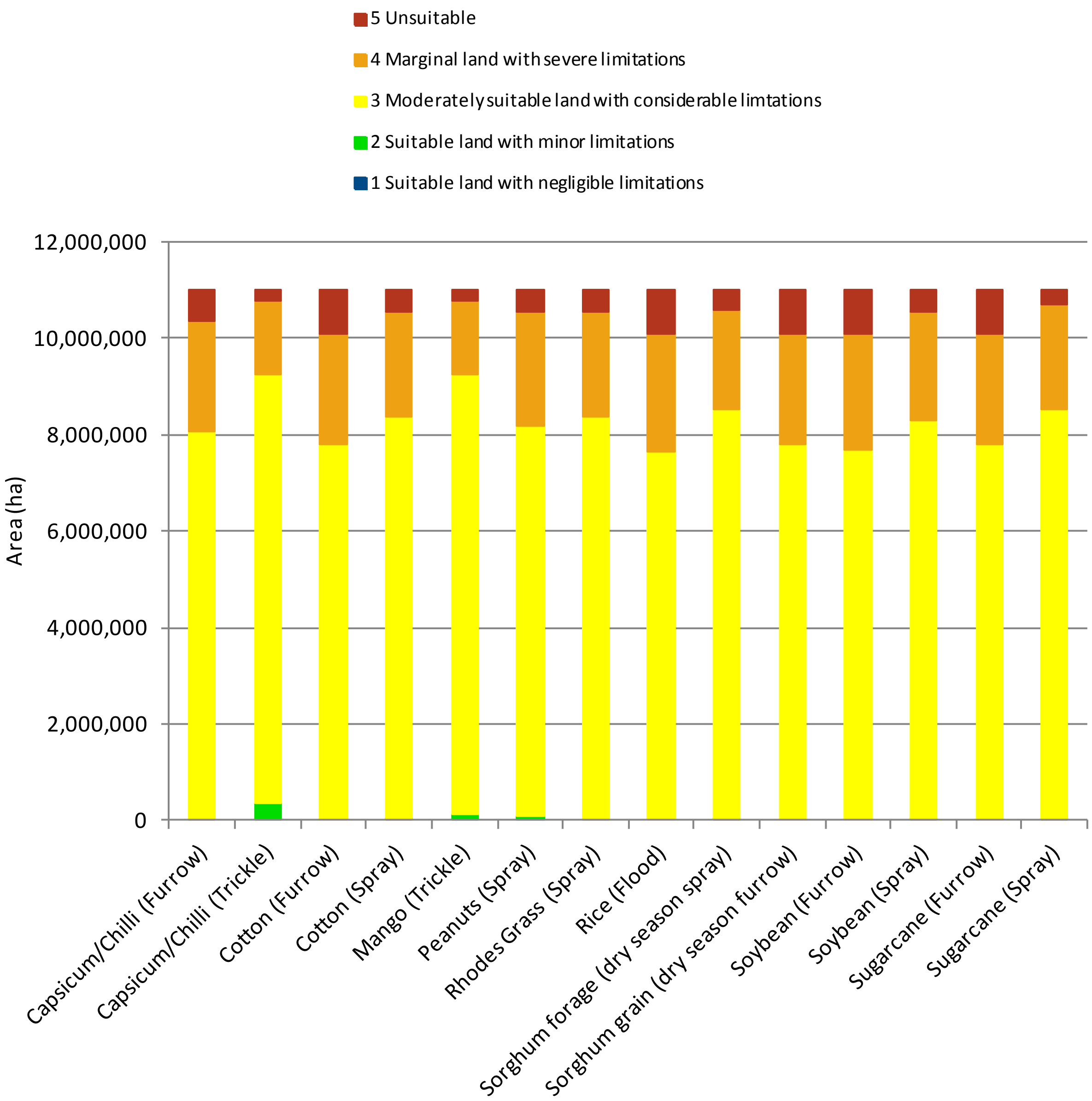


Figure 3.15 Suitability of 14 different irrigated land uses shown in this Assessment for the Flinders catchment. Model confidence not considered in data presented in this figure.

Table 3.9 Area (hectares) and % area of the Flinders catchment that has suitable (Class 1-2) and moderately suitable (class 3) land for the 14 different land uses presented. The right hand estimates of land suitability in the table have taken model confidence into consideration. * refers to dry season cropping

LANDUSE CATEGORY	LAND USE	IRRIGATION STYLE	LAND SUITABILITY (hectares, %)		LAND SUITABILITY WITH MODEL CONFIDENCE INCLUDED (hectares, %)	
			Class 1 and 2	Class 3	Class 1 and 2	Class 3
Horticulture	Capsicum/Chilli*	Furrow	18 (<1%)	8060790 (73%)	15 (<1%)	6680080 (61%)
Horticulture	Capsicum/Chilli*	Trickle	371060 (3%)	8887510 (81%)	144610 (<1%)	6992200 (64%)
Industrial	Cotton	Furrow	0	7810330 (71%)	0	6604980 (60%)
Industrial	Cotton	Spray	24630 (<1%)	8366990 (76%)	16280 (<1%)	6401680 (58%)
Tree Crop	Mango	Trickle	131390 (1%)	9120590 (83%)	30130 (<1%)	7098330 (65%)
Root Crop	Peanuts	Spray	72770 (1%)	8094570 (74%)	26560 (<1%)	6180990 (56%)
Forage	Rhodes grass	Spray	24670 (<1%)	8366950 (76%)	16320 (<1%)	6401640 (58%)
Cereal	Rice	Flood	0	7649520 (70%)	0	6491810 (59%)
Forage	Sorghum*	Spray	27060 (<1%)	8482390 (77%)	17090 (<1%)	6415260 (58%)
Cereal	Sorghum*	Furrow	0	7810330 (71%)	0	6604980 (60%)
Pulse crop	Soybeans	Furrow	0	7695410 (70%)	0	6502180 (59%)
Pulse crop	Soybeans	Spray	24670 (<1%)	8254770 (75%)	16320 (<1%)	6301260 (57%)
Industrial	Sugarcane	Furrow	0	7810330 (71%)	0	6604980 (60%)
Industrial	Sugarcane	Spray	24680 (<1%)	8485890 (77%)	16330 (<1%)	6416170 (58%)

The following sections discuss the irrigation suitability for the selected crops. With respect to capsicum and chillies, <3% were considered suitable (class 1 and/or 2) for either furrow or trickle irrigation. The area of moderately suitable land (class 3) was 73% for furrow irrigation and 81% for trickle irrigation (Figure 3.16). When areas of low model confidence are removed, the area of suitable to moderately suitable land (class 1-3) drops to 61% for furrow irrigation and 64% for trickle irrigation (Table 3.9). Furrow irrigation is more suitable on the cracking clay Vertosols and alluvial sediments. Trickle irrigation includes some class 2 land (with minor limitations) in the uplands and around Cloncurry.

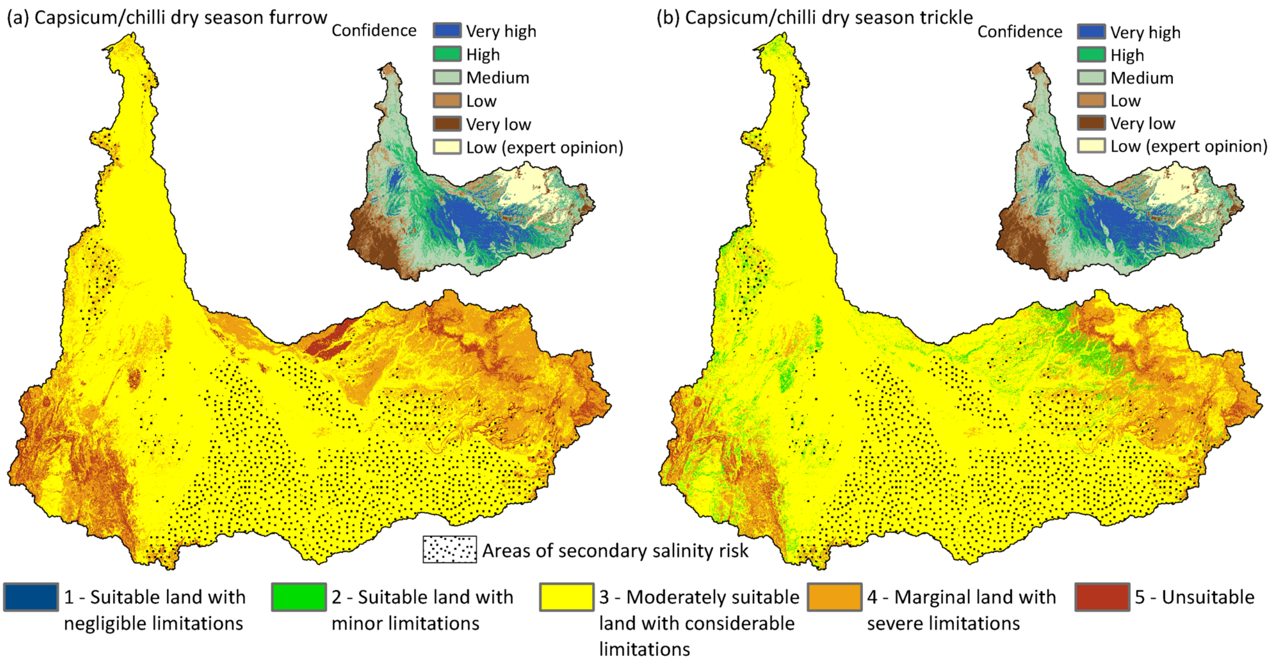


Figure 3.16 Predicted suitability for growing capsicum/chilli using (a) furrow irrigation and (b) spray irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

For the cotton land use, <1% is considered suitable (class 1 and/or 2) for either furrow or spray irrigation in the Flinders catchment (Table 3.9). This is due to issues such as potential water erosion, low soil moisture storage capacity, soil depth and rockiness. The area of moderately suitable land (class 3) was 71% for furrow irrigation and 76% for spray irrigation (Figure 3.17), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 60% for furrow irrigation and 58% for spray irrigation (Table 3.9). The central part of the Flinders catchment shows the highest potential for both irrigation types. Spray irrigation is more suitable on lighter sandy soils; hence a larger total area is suitable for spray irrigated crops. Furrow irrigation is generally only favoured on heavier soils. North of Cloncurry there is a small proportion of the area suitable for spray irrigation with minor limitations (class 2), though these areas are small, discrete and non-contiguous.

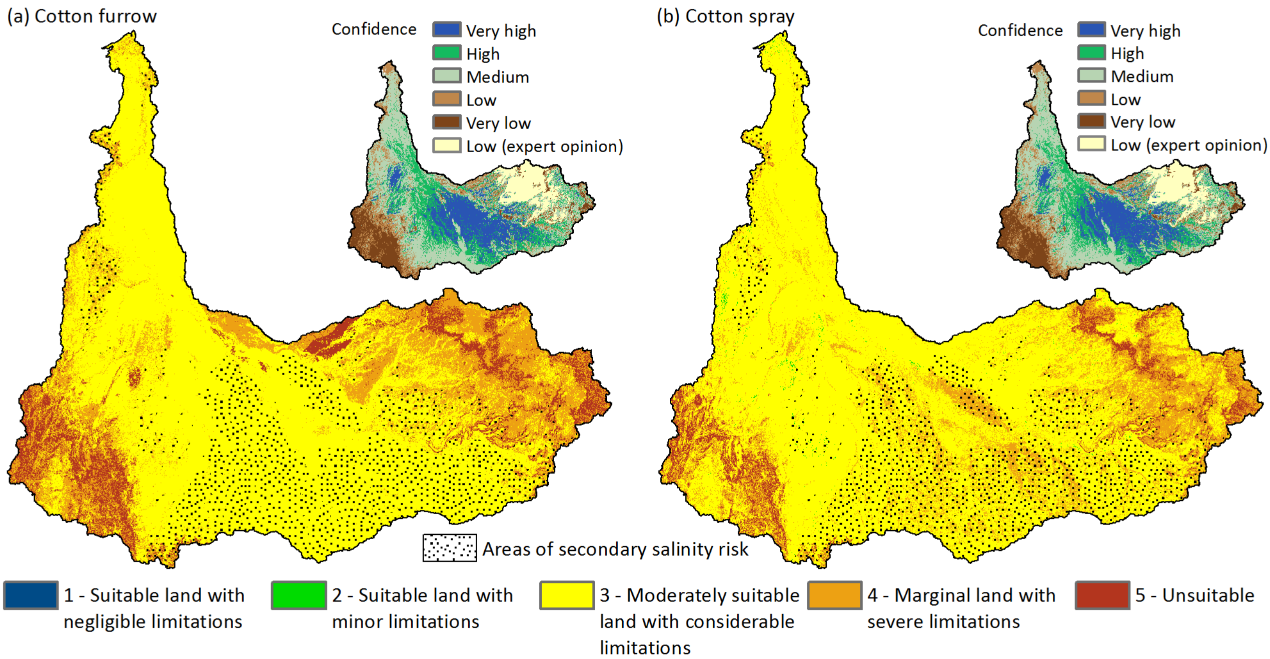


Figure 3.17 Predicted suitability for growing cotton using (a) furrow irrigation and (b) spray irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

For mangoes, ~1% is considered suitable (class 1 and/or 2) for trickle irrigation in the Flinders catchment (Table 3.9). In the north-east of the catchment, there is a large contiguous area on the lighter textured soils that are suitable for irrigated mangoes with minor limitations (Figure 3.18a). Class 2 soils are generally free draining and have loamy textures that require more frequent irrigation. The area of moderately suitable land (class 3) was 83% for trickle irrigation, however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 65% for trickle irrigation of mangoes (Table 3.9). The area of moderately suitable land occurs on the clay soils in the central part of the catchment. Mangoes do not like wet soil conditions, and a range of management practices will be required to maintain drainage and prevent waterlogging.

None of the Flinders catchment is considered suitable (class 1 or 2) for flood irrigation of rice (Table 3.9), however, there are large areas of the central Flinders that is moderately suitable (70%) (Figure 3.18b). When the areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 59%. The major limitations to flood irrigation of rice are related to slope, rockiness and permeability (slow permeability preferred).

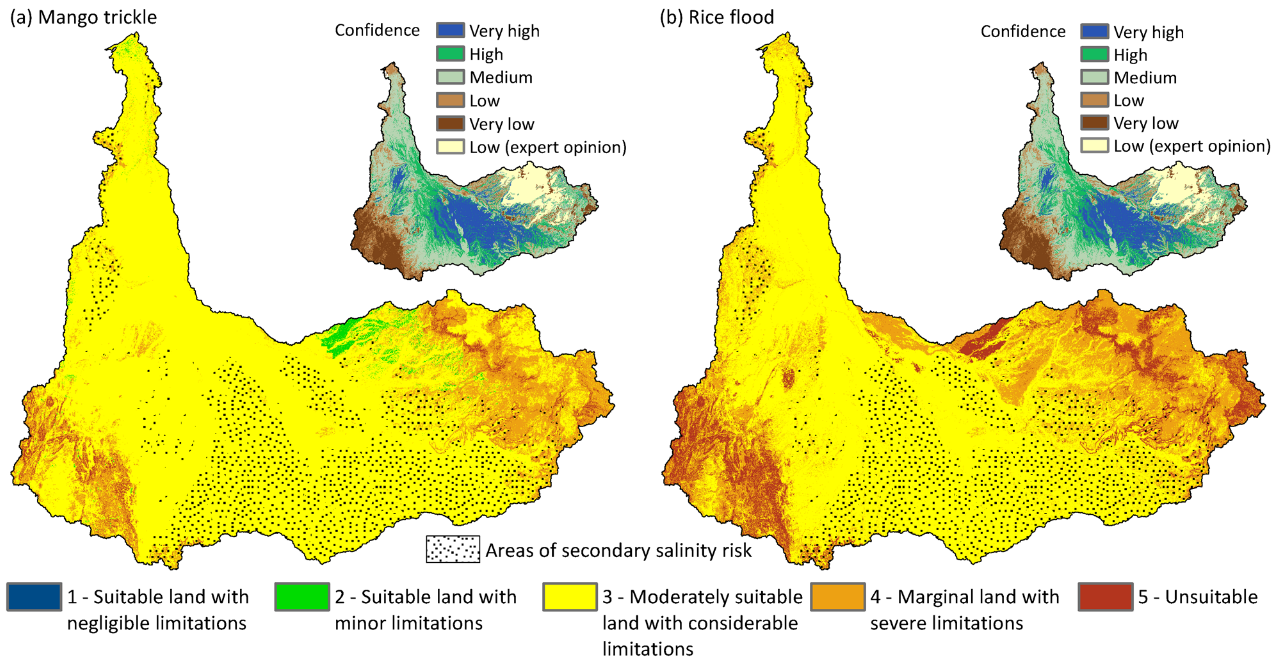


Figure 3.18 Predicted suitability for growing (a) mango using trickle irrigation and (b) rice using flood irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

There is ~1% of the Flinders catchment suitable (class 1 and/or 2) for spray irrigation of peanuts (Table 3.9). These areas correspond to the well-drained, friable soils where peanuts grow best (Figure 3.19a). There is ~74% of the catchment classified as moderately suitable land (class 3) for spray irrigation, however, when areas of low model confidence are removed, the area drops to 56% (Table 3.9). On the moderately suitable soils, soil wetness needs to be managed when growing peanuts as harvesting and machinery operations are dependent on a narrow soil moisture range for working (soil adhesiveness).

By and large, the suitability patterns for Rhodes grass under spray irrigation match those of peanuts under spray irrigation (Figure 3.19b). There is <1% of the Flinders catchment suitable (class 1 and/or 2) for spray irrigation of Rhodes grass (Table 3.9). There is ~76% of the catchment classified as moderately suitable land (class 3) for spray irrigation, however, when areas of low model confidence are removed, the area drops to 58% (Table 3.9).

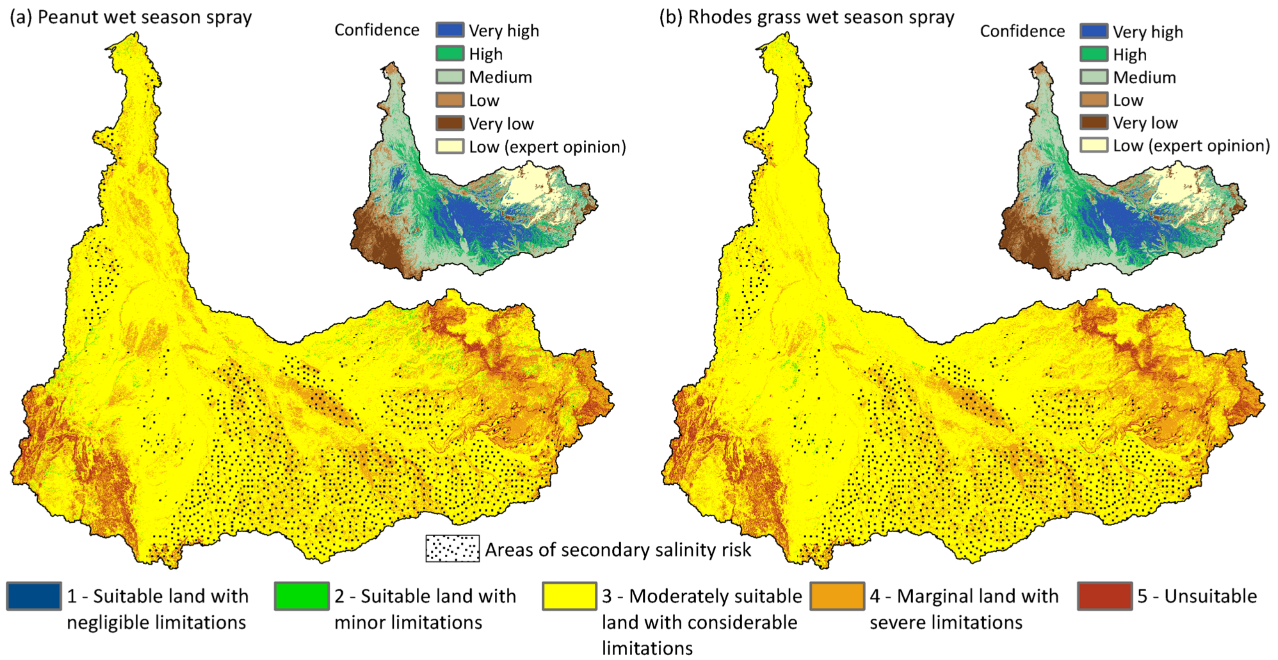


Figure 3.19 Predicted suitability for growing (a) peanuts using spray irrigation and (b) Rhodes grass using spray irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

For sorghum, <1% is considered suitable (class 1 and/or 2) for either furrow or spray irrigation in the Flinders catchment (Table 3.9). This is due to issues such as wetness, potential water erosion, low soil moisture storage capacity, soil depth and rockiness. The area of moderately suitable land (class 3) was 77% for forage sorghum under spray irrigation and 71% for grain sorghum under furrow irrigation (Figure 3.20), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 58% for spray irrigation and 60% for furrow irrigation (Table 3.9). The central part of the Flinders catchment shows the highest potential for both irrigation types, however, the spray irrigated crops will require specific management input for the hard-setting surface soils, and soils with poor water infiltration (generally soils with exchangeable sodium percentage (ESP) values > 6).

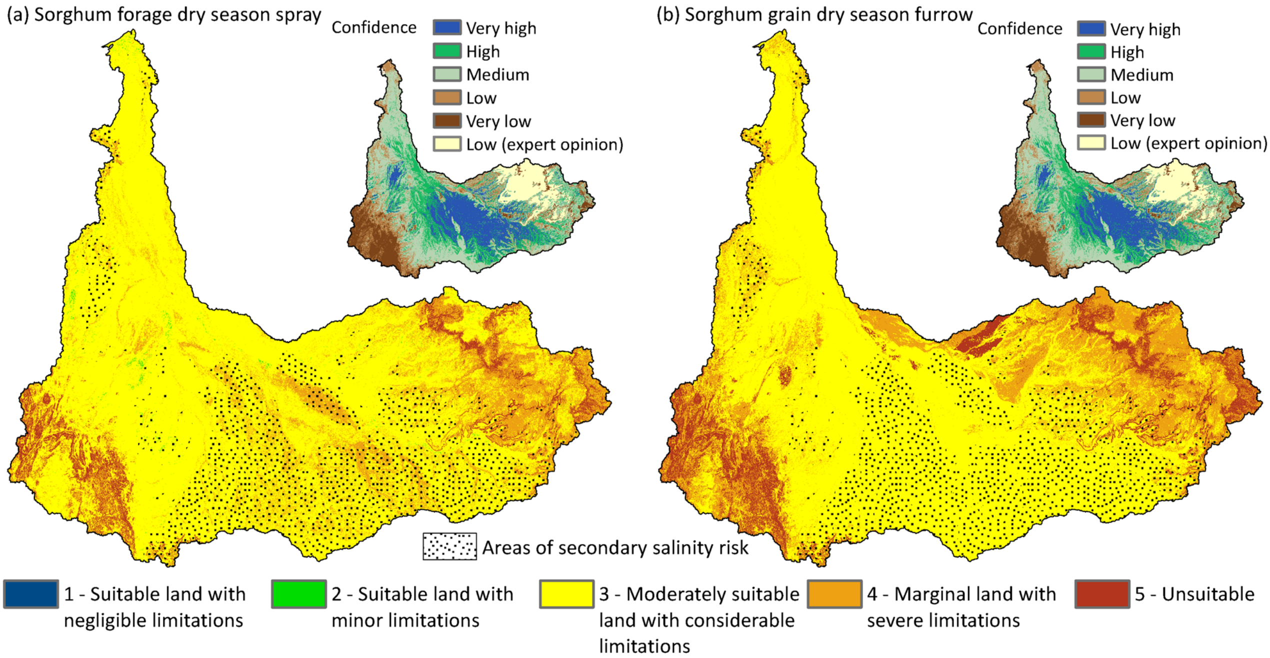


Figure 3.20 Predicted suitability for growing sorghum using (a) wet season furrow irrigation for forage and (b) wet season spray irrigation for grain in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

For soybean, <1% is considered suitable (class 1 and/or 2) for furrow or spray irrigation in the Flinders catchment (Table 3.9). This is mainly because of the wetness limitation. The area of moderately suitable land (class 3) was 70% for soybeans under furrow irrigation and 75% for under spray irrigation (Figure 3.21), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 59% for furrow irrigation and 57% for spray irrigation (Table 3.9). The cracking clay soils show the highest potential for both irrigation types.

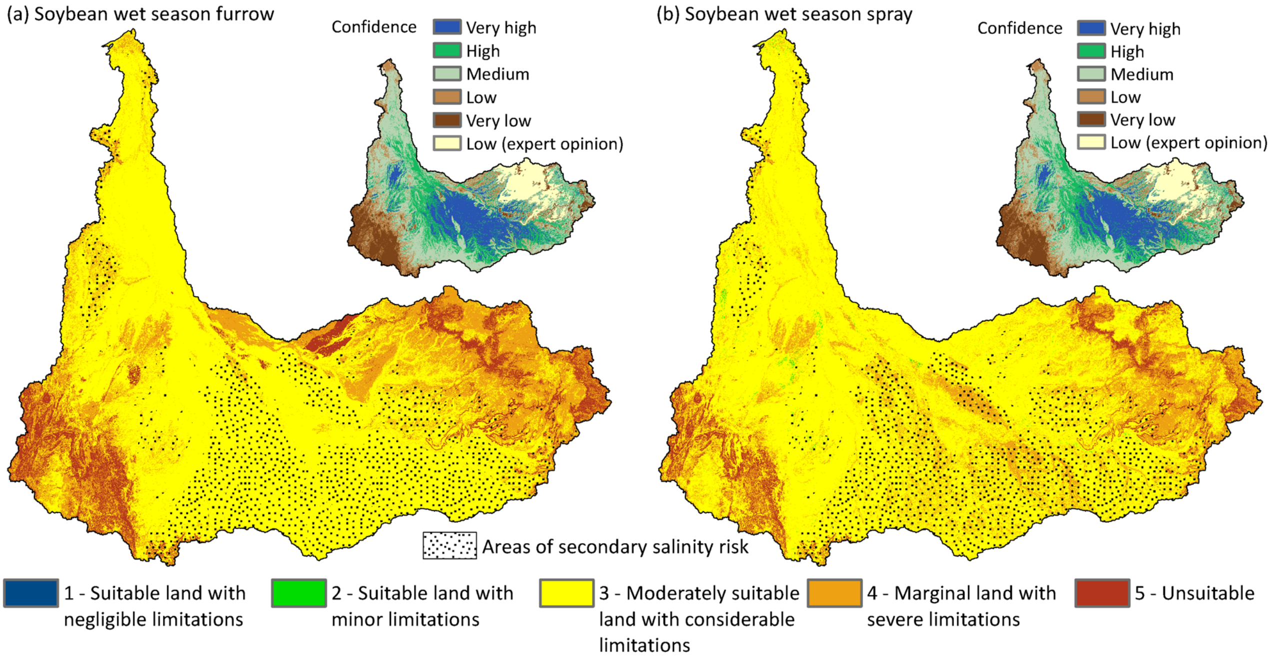


Figure 3.21 Predicted suitability for growing soybeans (wet season) using (a) furrow irrigation and (b) spray irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

For sugarcane, <1% is considered suitable (class 1 and/or 2) for furrow or spray irrigation in the Flinders catchment (Table 3.9). Although sugarcane is more tolerant of wet conditions, slowly permeable soils are still a limitation along with low soil moisture storage capacity and rockiness. The area of moderately suitable land (class 3) was 71% for sugarcane under furrow irrigation and 77% for under spray irrigation (Figure 3.22), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 60% for furrow irrigation and 58% for spray irrigation (Table 3.9). The cracking clay soils show the highest potential for both irrigation types. Slope separates the furrow and spray irrigation with flat areas unable to furrow water and steeper areas susceptible to water erosion. Furrow irrigated sugarcane is less suited to the more permeable and better drained (sandier) soils reducing irrigation efficiency and soil moisture storage capacity. Spray irrigated sugarcane requires more management input particularly on hardsetting surface soils and soils where ESP values are > 6

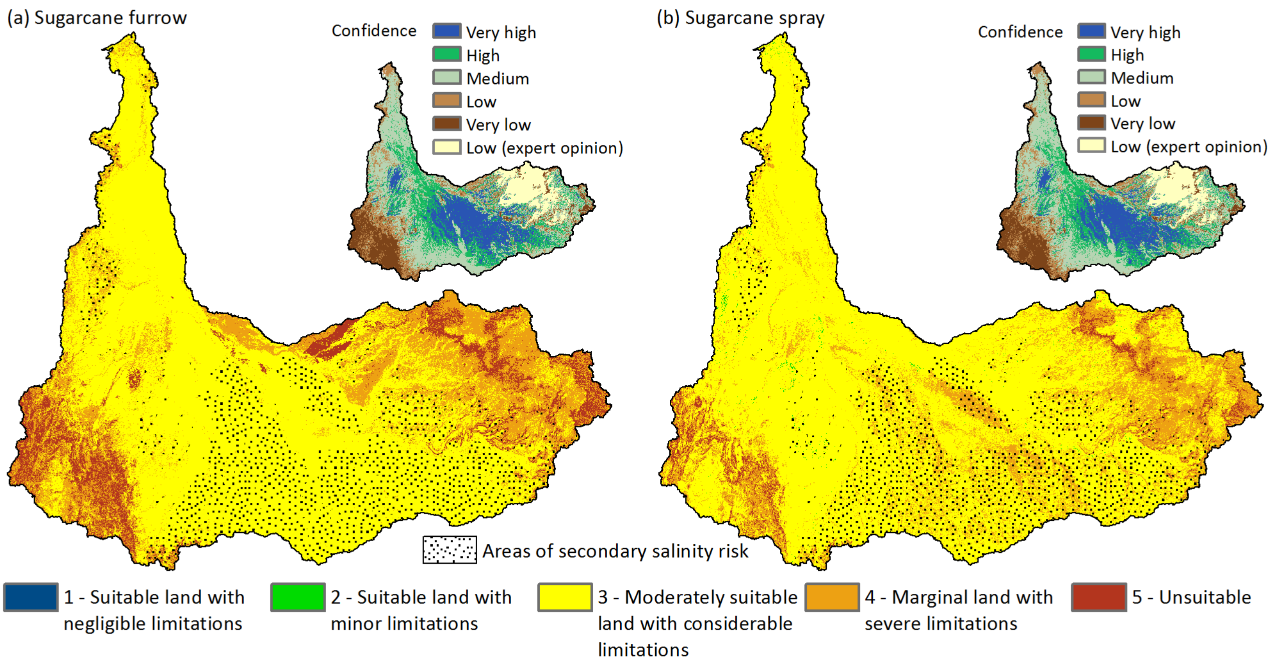


Figure 3.22 Predicted suitability for growing sugarcane using (a) furrow irrigation and (b) spray irrigation in the Flinders catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.14

3.7 Gilbert catchment soil and landscape interpretation

3.7.1 GEOMORPHIC LANDSCAPE DESCRIPTION

The Gilbert catchment is geologically diverse. It has two major tributaries, the Gilbert River in the south, and the Einasleigh River in the north. The Gilbert River catchment is dominated by metamorphic, igneous and sediments of the Great Artesian Basin. The upper Einasleigh River is dominated by igneous and basaltic geologies. Both rivers then travel westward moving through metamorphic and igneous formations before joining together in the alluvial sediments which are downstream of the deeply weathered sedimentary deposits (Figure 3.23). Five landscape units were identified in the Gilbert catchment based on data collected for this region (e.g. Enderlin, 2000; Wilson and Philip, 1999) as well as new soil survey data. The major geomorphic landscape units in the Gilbert catchment include the (i) Alluvial sediments, which are broken into upstream Quaternary alluvium, downstream Quaternary alluvium and Tertiary alluvium (ii) Basalt landscapes (iii) Igneous Landscapes, (iv) Metamorphic landscapes and (v) the deeply weathered Tertiary and Mesozoic sediments. Appendix A.4 describes each of the five major landscape units in more detail, and provides a description of the composition and distribution of soils within each landscape unit. It is important to note that each investigation area may contain several landscape units.

3.7.2 SOILS OF THE GILBERT CATCHMENT: SOIL GENERIC GROUP MODELLING RESULTS

The distribution of Soil Generic Group classes show that the lower catchment below the confluence of the Gilbert and Einasleigh River, is dominated by cracking clays and sands over friable clay, with lesser though significant areas of seasonally or permanently wet soils (~2%) (Figure 3.23b). Above the confluence, the soils strongly reflect the parent materials of the *in-situ* geology. Here shallow sandy soils are common, coinciding with the distribution of siliceous rhyolitic, granitic and grandioritic lithologies and some sand and siltstones (~24%). Large areas of clay loam and non-cracking clay soils are associated with the basalts, and to a lesser extent the grandiorites and clayey, feldspathic sandstones (24%). Sands and loams over friable clay subsoils are also associated with granodiorites and high grade metamorphic and metasedimentary rocks (~27%). These soils are also found in the channel flood (Quaternary) areas, as well as the Tertiary deeply weathered sediments. However, the Tertiary areas are dominated by loamy soils, where residual alluvium is commonly found. Areas of cracking clays are locally dominant in the alluvial areas in basalt in the eastern upland area, and in the lower catchment of the Einasleigh River (<10%). Small pockets of sands or loams over sodic clay soils are restricted to soils in or downstream from granite areas.

Table 3.10 % area of each of the Soil Generic Group (SGG) classes predicted for the Gilbert catchment

SOIL GENERIC GROUP (SGG) DESCRIPTION	% SGG SOIL TYPE IN THE GILBERT CATCHMENT
Sand or loam over relatively friable clay subsoils	27.0
Friable non-cracking clay or clay loam soils	24.0
Seasonally or permanently wet soils	2.0
Red, yellow or grey loamy soils	10.0
Deep sandy soils	0.5
Shallow sandy and stony soils	24.0
Sand or loam over intractable clay subsoils	4.0
Cracking clay soils	8.5

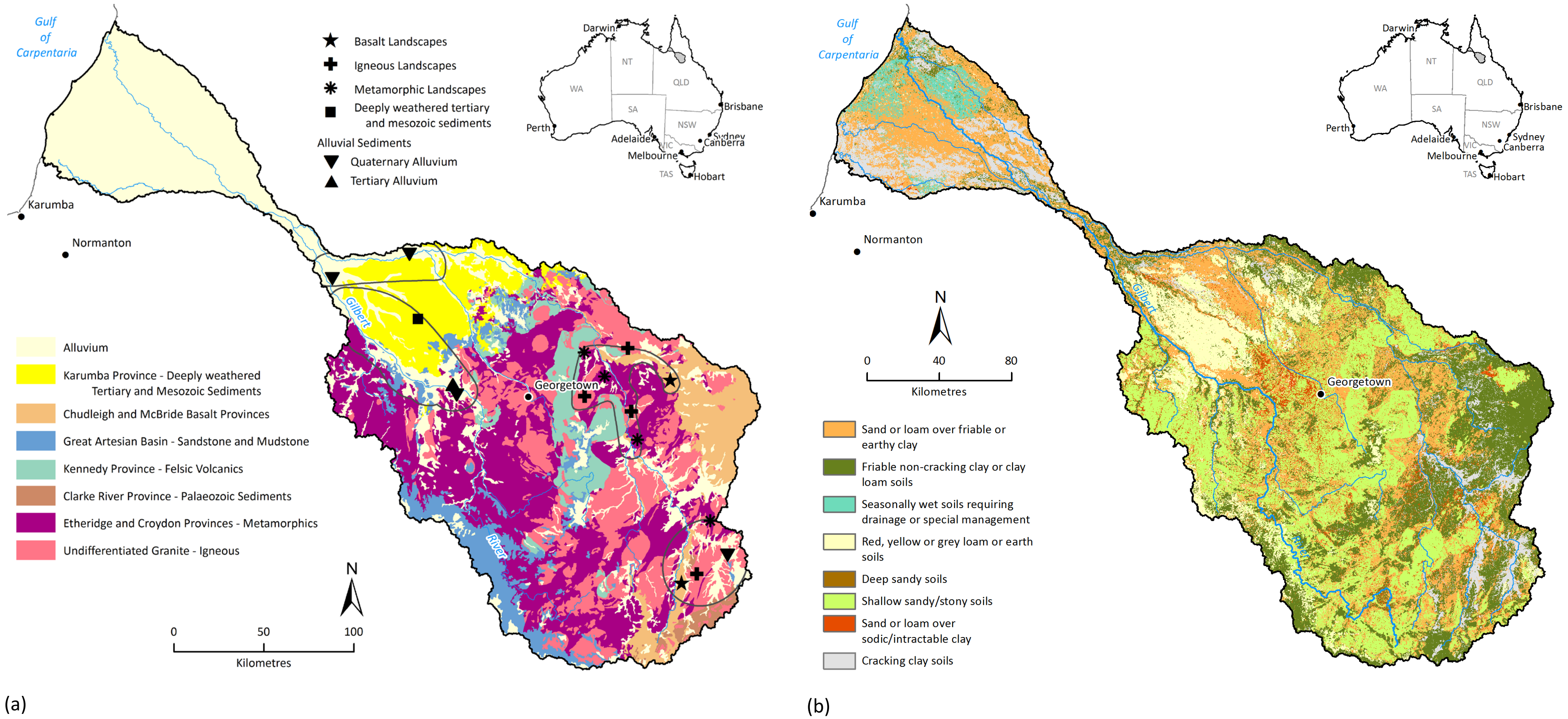


Figure 3.23 (a) Geological and geomorphological description of the Gilbert catchment (see Section A.4 for more detail); and (b) Soil generic group (SGG) modelled classes for the Gilbert catchment

3.8 Gilbert catchment digital soil modelling (spatial) results

The results for each of the nine selected DSM outputs for the Gilbert catchment are presented in Figure 3.24 to Figure 3.32. To the right of each DSM map is an associated map of model uncertainty or reliability that is quantified using the standard deviation in the case of the numeric layers, and the confusion index for the binary and categorical data.

The distribution of predicted pH is shown in Figure 3.24a. The Gilbert catchment is slightly more acidic (mean 6.1) than the Flinders catchment (mean 6.9), and the surface pH is more consistent (5.5-7.0) across the Gilbert catchment. From a pedogenic perspective this is because of the higher prevalence of coarser textured soils. The coarser, sandy soils, with higher silica content, promote leaching of base elements through freer draining profiles. More alkaline soils are often found in the lower-lying drainage/alluvial areas, which is likely to be related to the supply of base elements from upstream sources. More alkaline soils are associated with basalt which, being mafic, is inherently richer in base elements. The sharp linear boundary of modelled pH in the lower catchment may reflect the influence of the climate (e.g. Prescott Index) covariate data in the prediction. The reliability of prediction is generally good (i.e. within the range of 0.22 and 0.64 SD) and is typically within the confidence range of field pH measurements (i.e. pH 0.5) (Figure 3.24a). Reliability is strongest in the alluvium in the southern upland zone, and weakest in the lower catchment, where the apparent linear artefact is also strongly expressed, indicating that the DSM modelling has been generally weaker in this zone.

PAWC 100 was highest on the alluvial areas downstream of Gilbert and Einasleigh river junction, as well as on the clay soils formed on the southern upland alluvial areas (Figure 3.25a). PAWC 100 is typically lowest on metasediment, metamorphic, and igneous lithologies that are shallow and resistant to weathering, or highly siliceous (e.g. granitic gneiss and rhyolite) yielding soils that are gravelly or contain coarse grained quartz in the profile. The basalts (e.g. near Mt Surprise) feature higher PAWC 100 values due to the fine grained, deeper soils produced from the rapid weathering, but which also contact high amounts of rock (as recorded during the field survey). Figure 3.25b shows the standard deviation of modelled data and indicates a reasonable degree of confidence in the PAWC predictions across most of the catchment. This confidence is, however, less in the metasediments at the south edge of the catchment.

The Gilbert catchment soils were predicted to be deepest on the alluvium downstream of confluence and in the drainage areas associated with the rivers and tributaries (Figure 3.26a). Conversely, the soils are shallow in the upland areas. The finer textured, deeper soils are associated with the depositional areas. The coarse textured soils (sands and loams) are associated with the more resistant lithologies. In keeping with the weathering rates, the olivine basalt areas of the east are moderately deep (typically deeper than 0.5 – 0.8 m). The reliability of soil depth mapping is variable throughout the catchment (Figure 3.26b).

The soils upstream of the Gilbert and Einasleigh River confluence are dominated by sands and loams (Figure 3.27a). The loams are generally associated with the drainage areas, whereas the sands are associated with the higher elevation areas. Clays dominate in the eastern areas associated with the olivine basalt weathering. Downstream of the confluence of rivers, clays dominate the more elevated alluvial areas, whereas in the drainage areas lower in the landscape soils are dominated by loam and sand surface textures. This is likely to reflect the high energy of the river system in flood, which is sufficient to transport and deposit the coarser textures that dominate upstream. The reliability of surface texture class mapping is variable throughout the catchment (Figure 3.27b).

Characteristically, the predictions for permeability follow that for soil texture, as coarser grained, sandy and loamy soils will be more permeable than finer-grained, clay soils (Figure 3.28a). As such the clay-dominated areas in the alluvial areas of the lower catchment, as well as the drainage areas to the west, are typically slowly permeable. Whereas the uplands, associated with sands and loams, are moderately permeable. Soils are highly permeable in the Gilbert River channel-fringing areas above the confluence. This reflects the high energy flows and deep, coarse-grained depositions. In the lower energy drainage areas of the Einasleigh to the west soils are slowly permeable due to the accumulation of clays. The reliability of the mapping is generally poor, especially throughout the upland area, although the lower-lying river channel areas tend to be more reliable (Figure 3.28b).

The distribution of rocky soils in the Gilbert catchment strongly reflect the patterns of many of the preceding attributes (Figure 3.29a). For example, upland areas are typically dominated by rocky soils due to the occurrence of residual stones after incomplete weathering, and the presence of outcropping where the soils are also typically shallow. This is particularly the case on rhyolite and granitic parent materials that are slow to weather, and on the more recent basalt flows that have had limited time to weather. Non-rocky soils are generally found in the extensive, lower-lying areas of Gilbert catchment, including the alluvial areas of the southern uplands, the deeply weathered, residual areas above the confluence, and the extensive clay-rich alluvial areas in the lower catchment. The reliability of the rockiness predictions is variable, with more reliable predictions associated with the lower catchment, and less reliable in the northern areas above the confluence and to the west (Figure 3.29b).

The lowlands of the Gilbert catchment below the confluence are dominated by soils that are imperfectly drained (drainage class 3) (Figure 3.30). Upstream of the confluence, the clay dominated soils are moderately well-drained (drainage class 4), and the coarser (sandier) soils of the upper catchment are moderately to well-drained (class 4-5). Away from the drainage lines in the uplands, the coarser-grained soils derived from granites are typically well-drained or better. In the far east of the catchment, some of the broader alluvium is dominated by imperfectly drained soils, reflecting the higher clay content of these soils (i.e. heavier textures) with the finer particle content.

Figure 3.31 shows the predicted EC in the top 10 cm of the soil for the Gilbert catchment. Salt measurements were collected down soil profiles, however, due to minimal data at depth, EC at depths >10 cm were not modelled. The predicted salinity in the Gilbert catchment is very low, with EC values ranging between 0 – 1.2 dS/m EC (SD 0.04). A soil is considered saline for agricultural purposes when EC is > 2 dS/m (Soil Survey Staff, 1993). Saline soils exist in discrete patches in the flood plain alluvium near the mouth of the river, and in the river channel. Discrete areas of higher salinity are found in drainage channels of the uplands and in areas associated with Basalt and metamorphic lithologies.

In Australia soils are considered sodic when exchangeable sodium percentage (ESP) values are > 6 (Rengasamy and Churchman, 1999). The mean and maximum ESP values for the Gilbert are 0.02 % and 1.2 % (SD 0.04), respectively. Therefore the soils in the Gilbert catchment are not considered to be sodic. Soils with relatively elevated ESP values are associated with the alluvial clays of the coastal fringe and downstream of the confluence of the Gilbert and Etheridge rivers. In the uplands, soils with relatively elevated ESP are found associated with the sandier soils derived from igneous granites (weathered granite is typically a strong source of sodium). To a minor extent, some of the clay rich soils from the basalts (in the east) also show elevated ESP values.

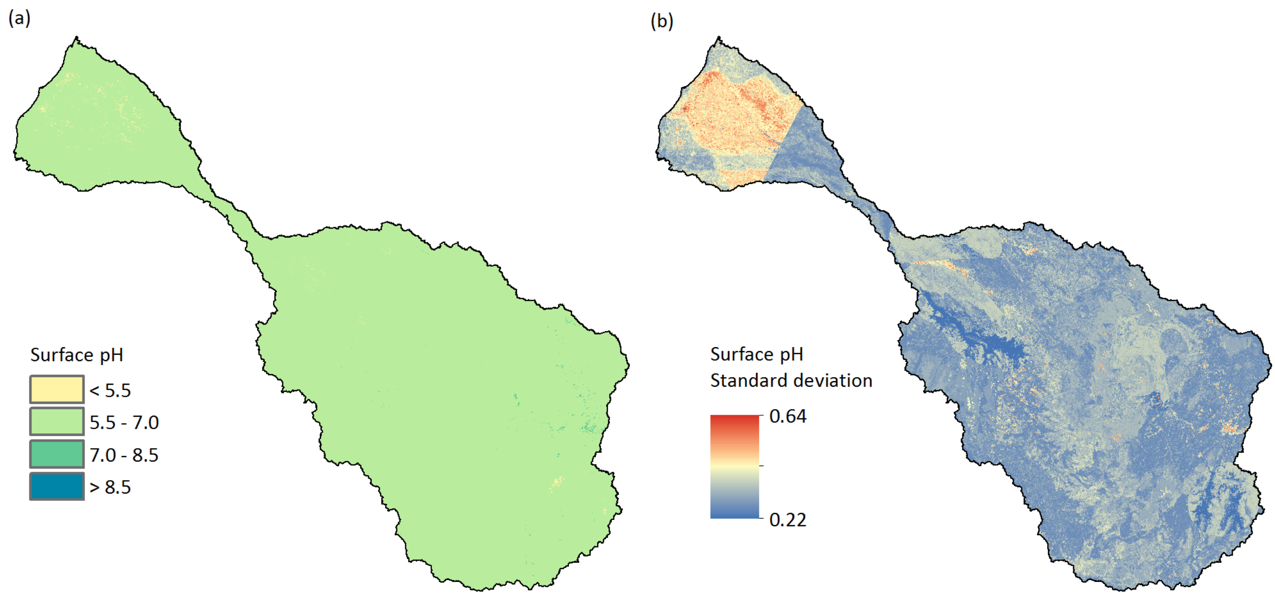


Figure 3.24 Gilbert catchment digital soil mapping predicted surfaces for (a) pH and (b) the standard deviation around the prediction

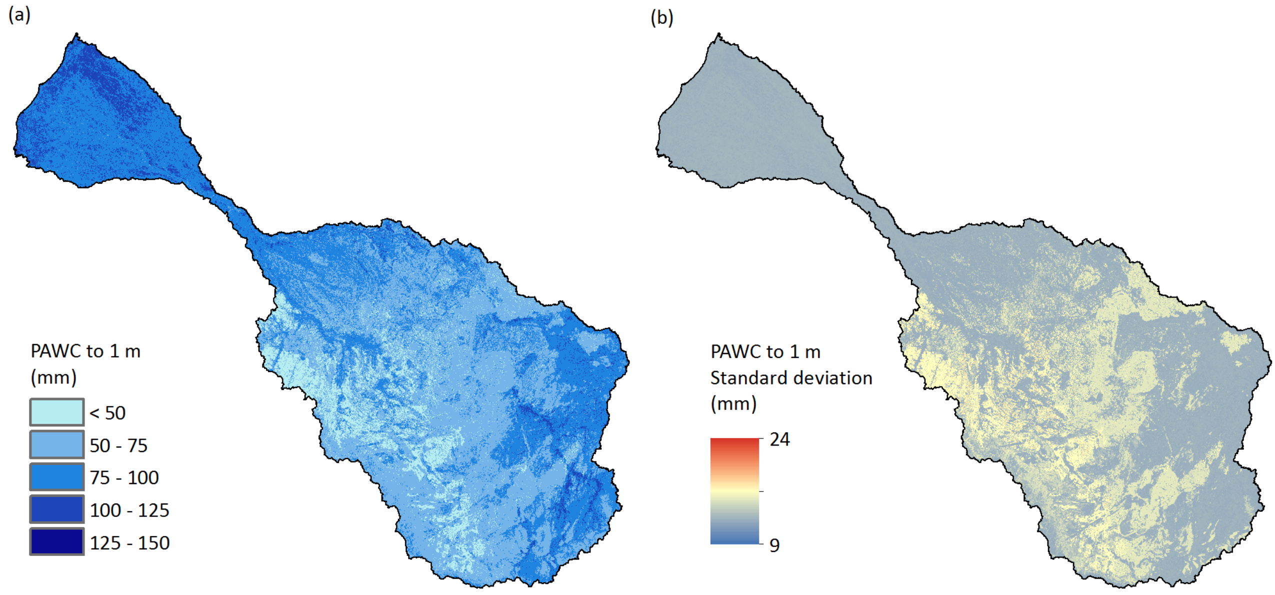


Figure 3.25 Gilbert catchment digital soil mapping predicted surfaces for (a) PAWC and (b) the standard deviation around the prediction

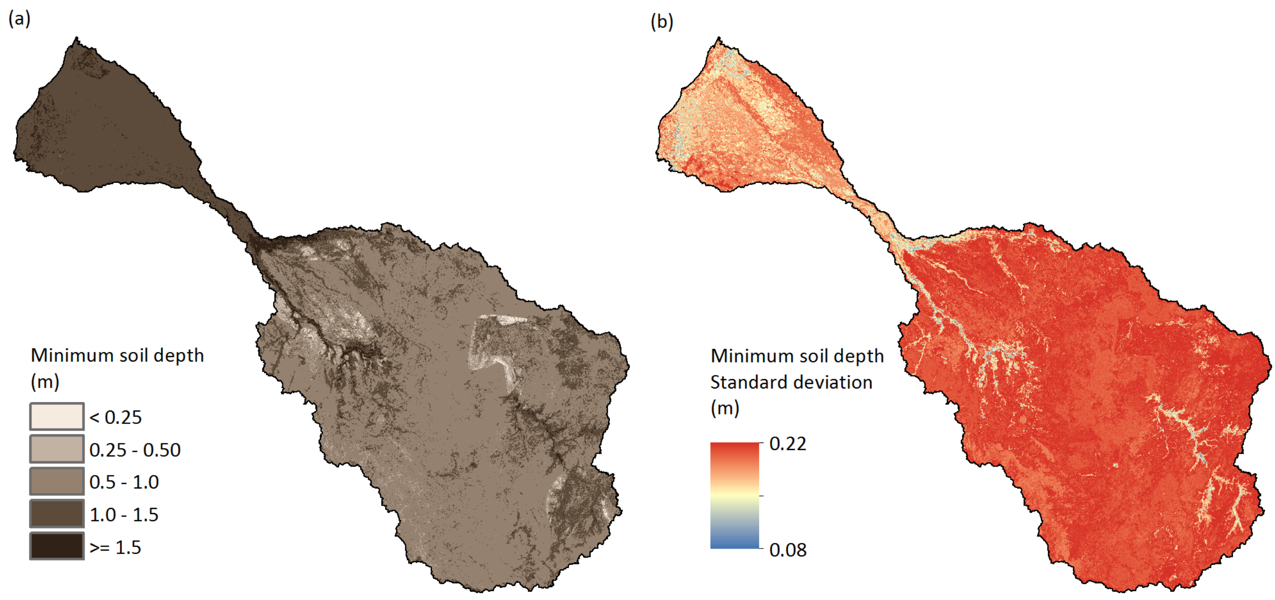


Figure 3.26 Gilbert catchment digital soil mapping predicted surfaces for (a) minimum soil depth and (b) the standard deviation around the prediction

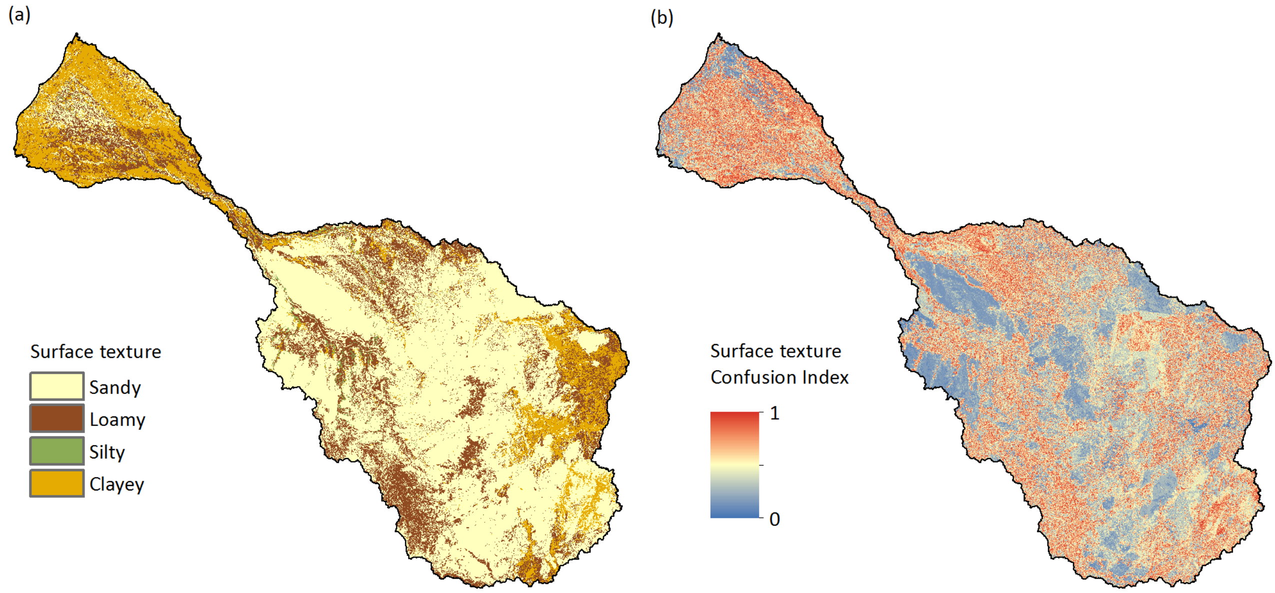


Figure 3.27 Gilbert catchment digital soil mapping predicted surfaces for (a) surface texture and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

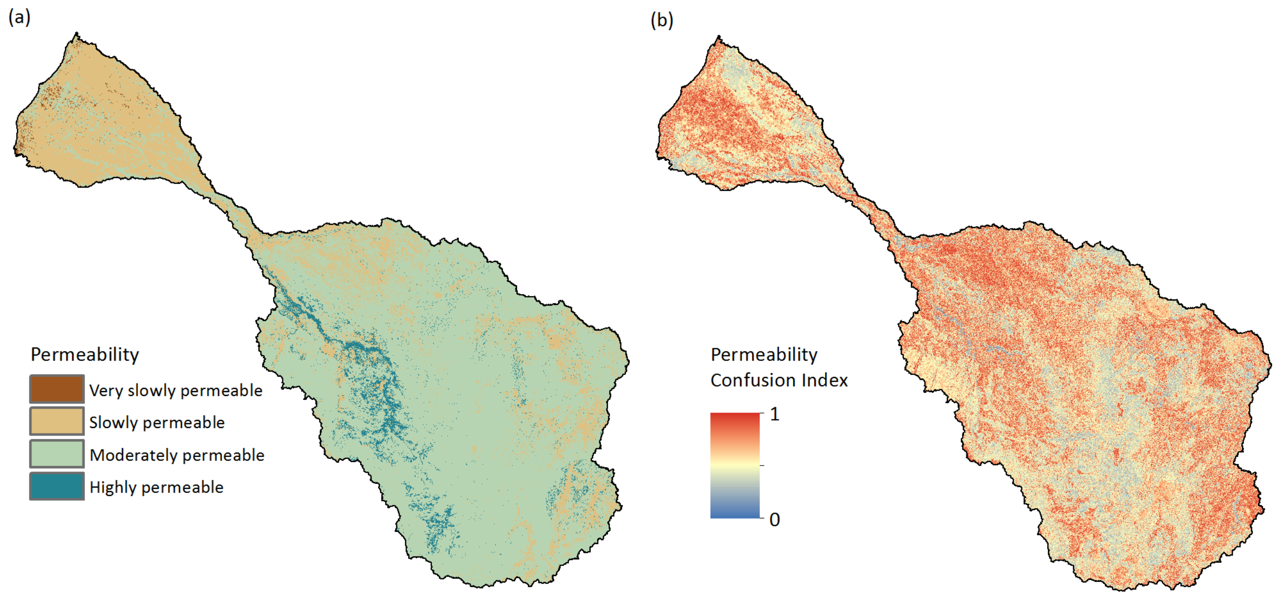


Figure 3.28 Gilbert catchment digital soil mapping predicted surfaces for (a) permeability and (b the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

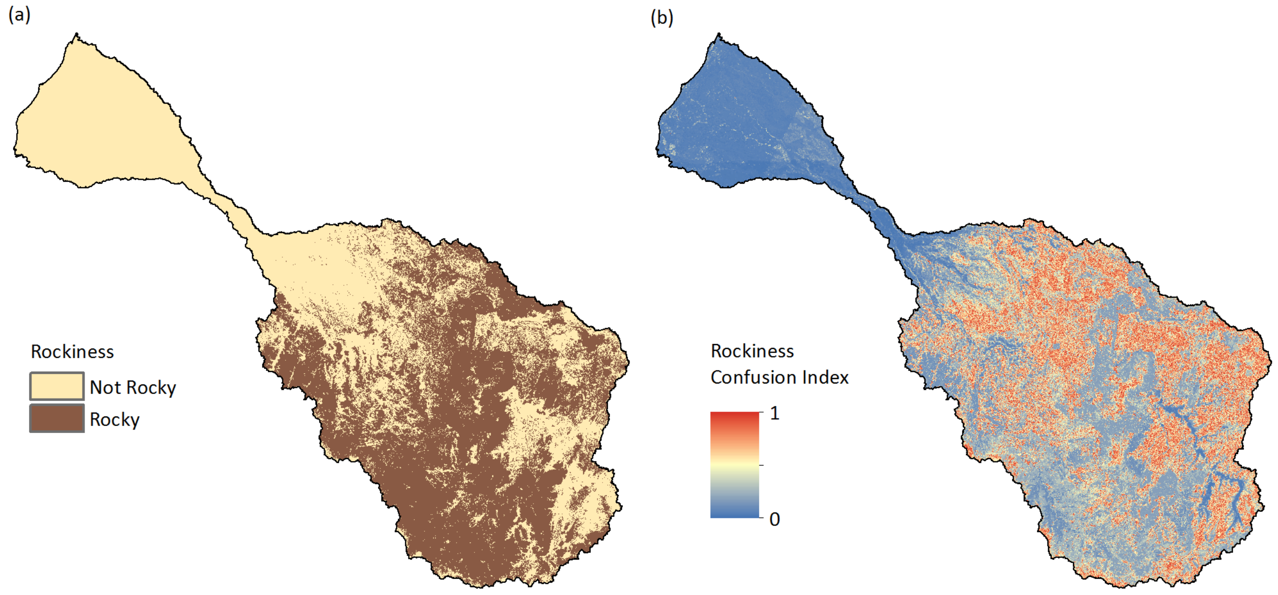


Figure 3.29 Gilbert catchment digital soil mapping predicted surfaces for (a) rockiness and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

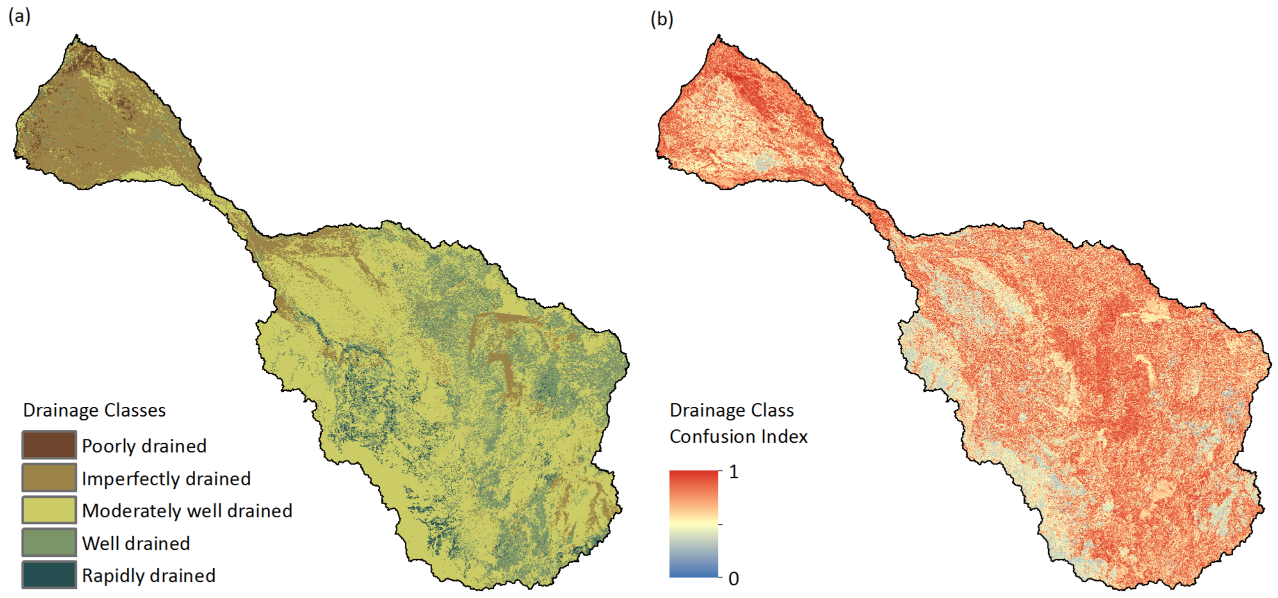


Figure 3.30 Gilbert catchment digital soil mapping predicted surfaces for (a) drainage and (b) the confusion index represents the reliability of the prediction (see Section 2.7.4 for description of confusion index calculations).

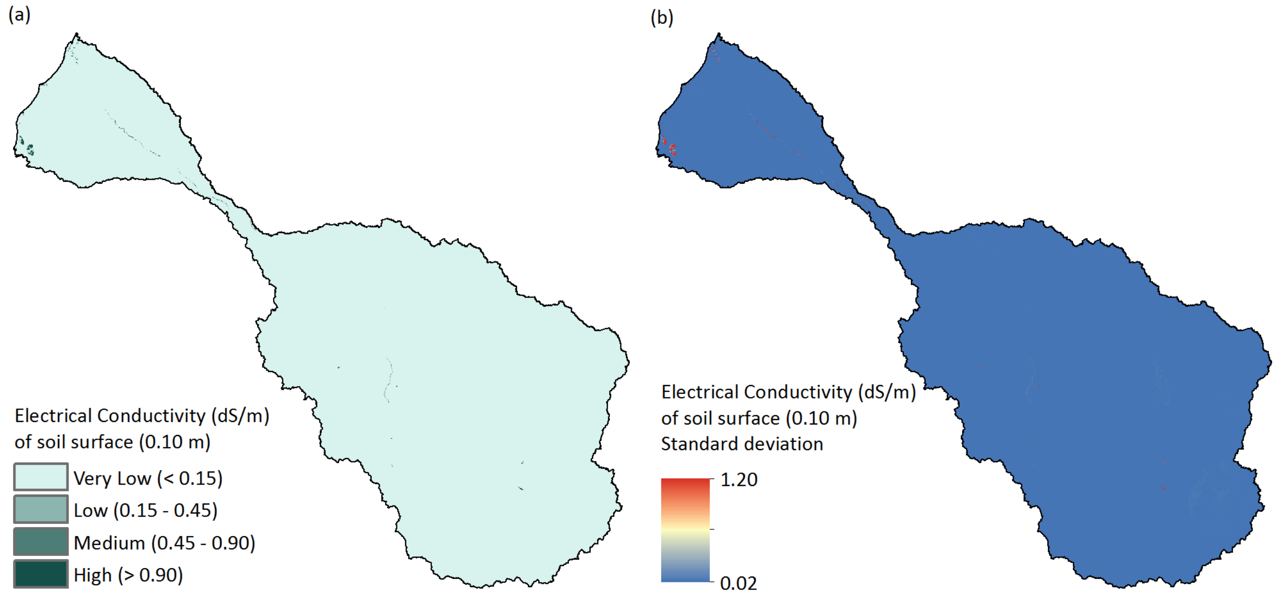


Figure 3.31 Gilbert catchment digital soil mapping predicted surfaces for (a) electrical conductivity (EC) in the top 10cm of surface soil and (b) the standard deviation around the prediction

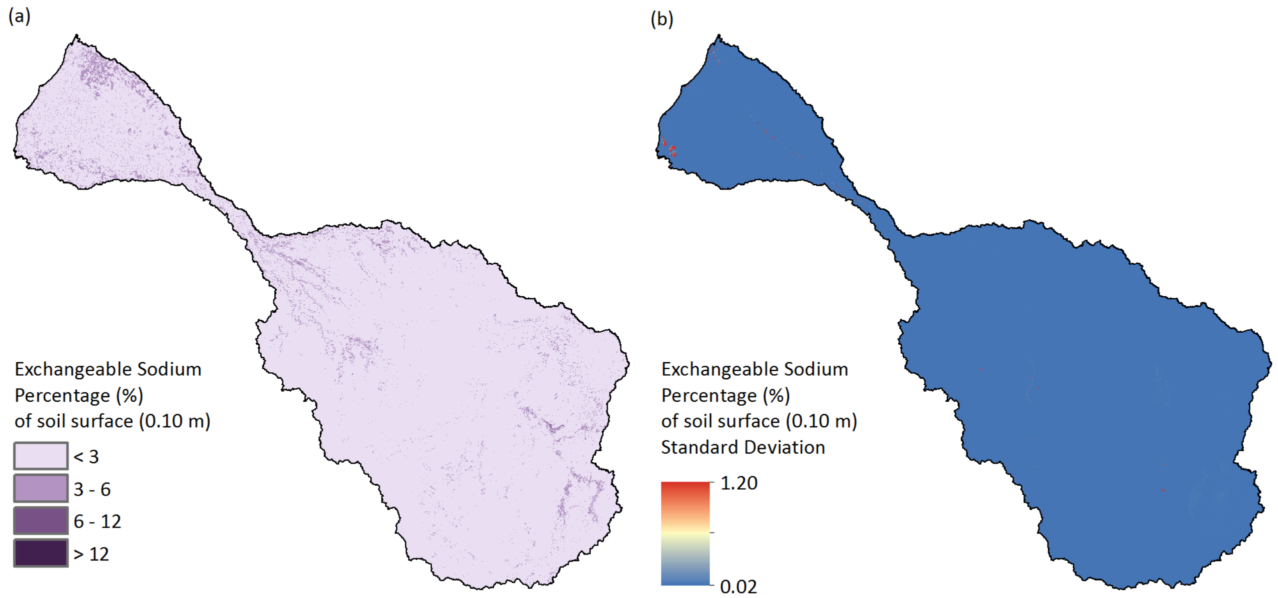


Figure 3.32 Gilbert catchment digital soil mapping predicted surfaces for (a) exchangeable sodium percentage (ESP) and (b) the standard deviation around the prediction

3.9 Land Suitability Assessment for the Gilbert catchment

3.9.1 RELIABILITY OF LAND SUITABILITY MAPS IN THE GILBERT CATCHMENT

Figure 3.34 presents a map indicating the reliability of the land suitability mapping that was undertaken as part of the Assessment. This reliability map should be consulted when interpreting the land suitability maps presented in Section 3.9.2. Figure 3.34(a) shows the Mahalanobis distance values based on the DSM predictions. The areas that have very low Mahalanobis distance values are more reliable, and we have higher confidence in these areas; they are generally the areas where most of the on-ground soils data were collected. The areas with medium to high Mahalanobis distance values are where we have less data and are therefore less confident in the modelled predictions in these areas.

Not all soil attributes were modelled as part of the DSM process. Examples of features that were not modelled include sub-surface restrictive layers (e.g. pans and sub-surface gravel layers). Discontinuous restrictive layers were identified in the area between the Gilbert and Einasleigh Rivers during soil survey. These areas contain soils dominated by ferruginous nodules and are part of the deeply weathered Tertiary and Mesozoic sediments of the Karumba Province (identified using the 1: 1,000,000 Geology; this is represented by the expert opinion label on Figure 3.23b and all subsequent confidence maps). Figure 3.34(b) shows the location of the sub-surface nodules, gravels and pans that were not predicted by the DSM, and images from the field survey are presented in Figure 3.33. Identifying this area as poor confidence (Figure 3.34b) does not preclude its development; rather it highlights that more information about the extent and agronomic implications of these sub-surface features is required. If these layers are continuous and occur within the top 25 cm of the soil profile then this may restrict machinery operations. If these layers are continuous and reside below 25 cm then they are indicative of water logging issues in low-lying landscape positions. A more detailed description of this landscape can be found in Section A.4.5.

The risk of secondary salinisation is not as widespread in the Gilbert as in the Flinders catchment; however, secondary salinity risks should still be considered (e.g. on the cracking clay soils of the GAB sandstones and mudstones; see Figure 3.23 for location) and readers are directed to previous studies for a more detailed discussion (Nelson and Webb, 2004; PPK Environment & Infrastructure Pty Ltd, 1999)..

(a) (b)

Figure 3.33 (a) and (b) Examples of the ferruginous nodules found through the soil profile on the Tertiary and Mesozoic sediments of the Karumba Province (see Figure 3.34b). Nodules are generally 1-3 cm in diameter and are found ~40 cm below the surface; however, where erosion has occurred they may be expressed higher in the soil profile.

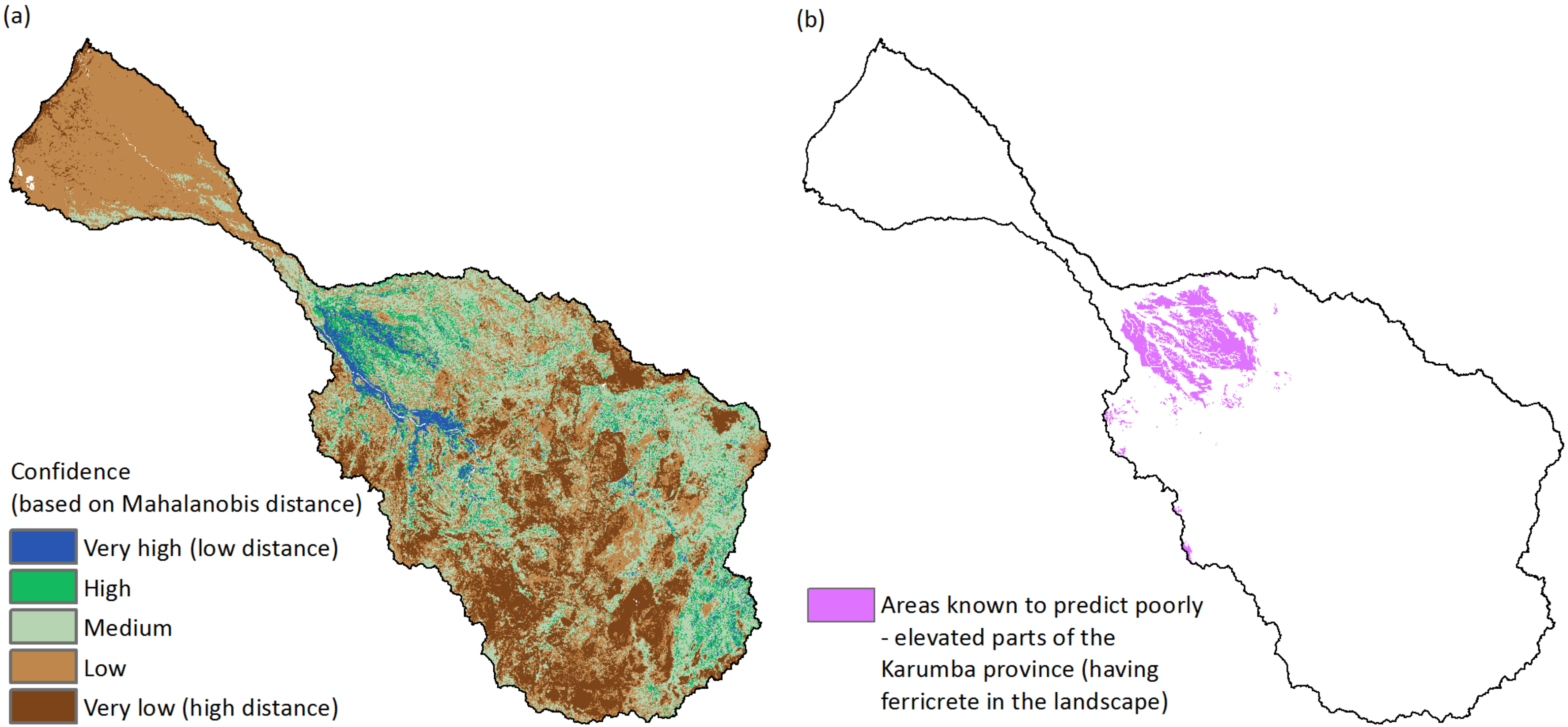


Figure 3.34 (a) Reliability map for the land suitability outputs for the Gilbert catchment. Low Mahalanobis distance values mean higher confidence in the land suitability outputs and vice versa; and (b) location of the areas of low DSM reliability based on expert opinion of landscape processes. The rocky (ferricrete) formations of the Karumba province in the lower Gilbert were poorly predicted by the models.

3.9.2 RESULTS OF LAND SUITABILITY MODELLING IN THE GILBERT CATCHMENT

There were 76 different land uses (crop and irrigation combinations) evaluated in this study (see Appendix Appendix A). In this section we present and discuss the results for 14 different land uses for the Gilbert Catchment. These land uses represent a range of land use categories (Table 3.8). Thumbnail images for the remaining 62 land uses can be found in Appendix A.6.

Table 3.11 present the land suitability data in two formats. The first format is the amount of land in class 1 and 2 (suitable) and class 3 (moderately suitable) as directly calculated by the models (see Figure 3.35). The spatial arrangement of the land use suitability for each of the 14 combinations in the Gilbert catchment is shown in Figure 3.36 to Figure 3.42. The second approach presented in Table 3.9 takes the model certainty or confidence into consideration. For these data, only areas where we have medium, high or very high confidence in the predicted values (based on the Mahalanobis calculations, Figure 3.14) are presented. The total area of Gilbert catchment is 4,606,820 ha, however, when the areas of low and very low confidence are removed, the available area for agriculture is ~1,740,335 ha.

It is important to note that the suitability calculations have been evaluated on a catchment basis. There has been no consideration of the contiguousness of the land units, or scale of farming operation. This section presents the suitability of the soil to grow crops within the climate of the Flinders catchment. Water availability and other considerations are being dealt with in other components of this Assessment (e.g. Crossman et al., 2013; Webster et al., 2013). Areas downstream of the junction are highly susceptible to flooding, however, this has not been considered in the land suitability assessment for the Gilbert catchment.

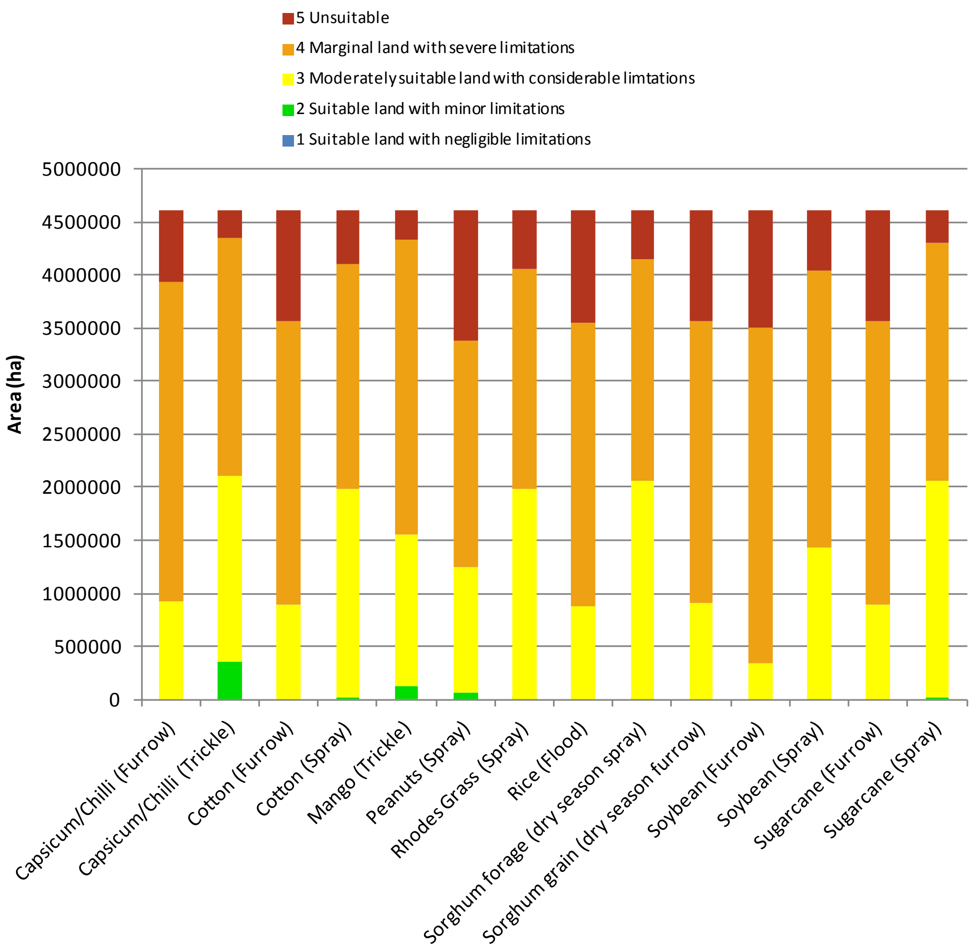


Figure 3.35 Suitability of 14 different irrigated land uses shown in this Assessment for the Gilbert catchment

Table 3.11 Area (hectares) and % area of the Gilbert catchment that has suitable (Class 1-2) and moderately suitable (class 3) land for the 14 different land uses presented. The right hand estimates of land suitability in the table have taken model confidence into consideration. * refers to dry season cropping

LANDUSE CATEGORY	LAND USE	IRRIGATION STYLE	MODELLED LAND SUITABILITY (hectares, %)		MODELLED LAND SUITABILITY WITH MODEL CONFIDENCE INCLUDED (hectares, %)	
			Class 1 and 2	Class 3	Class 1 and 2	Class 3
Horticulture	Capsicum/Chilli*	Furrow	0	931700 (20%)	0	326730 (7%)
Horticulture	Capsicum/Chilli*	Trickle	352180 (8%)	1761730 (38%)	178530 (4%)	815540 (18%)
Industrial	Cotton	Furrow	0	892800 (19%)	0	307010 (7%)
Industrial	Cotton	Spray	15290 (<1%)	1969200 (43%)	5990 (<1%)	9150220 (20%)
Tree Crop	Mango	Trickle	125600 (3%)	1430440 (31%)	69250 (2%)	815520 (18%)
Root Crop	Peanuts	Spray	68120 (1%)	1181310 (26%)	34810 (1%)	701490 (15%)
Forage	Rhodes grass	Spray	9050 (<1%)	1975440 (43%)	4410 (<1%)	916600 (20%)
Cereal	Rice	Flood	0	882675 (19%)	0	294890 (6%)
Forage	Sorghum*	Spray	11100 (<1%)	2054860 (45%)	5800 (<1%)	956650 (21%)
Cereal	Sorghum*	Furrow	0	902760 (20%)	0	307040 (7%)
Pulse crop	Soybeans	Furrow	0	342353 (7%)	0	194860 (4%)
Pulse crop	Soybeans	Spray	8990 (<1%)	1429410 (31%)	4360 (<1%)	807230 (18%)
Industrial	Sugar	Furrow	0	892800 (19%)	0	307010 (7%)
Industrial	Sugar	Spray	15390 (<1%)	2042150 (44%)	5990 (<1%)	957410 (21%)

The following sections discuss the irrigation suitability for the selected crops. With respect to capsicum and chillies, no land was considered suitable (class 1 and/or 2) for furrow irrigation, however, between 4 and 8% of the Gilbert catchment is suitable using trickle irrigation (without and with model confidence, respectively). The suitable (class 2) soils are generally sandy and loamy deep soils that are free draining, yet they have clay at depth and thus better soil moisture storage capacity. The area of moderately suitable land (class 3) was 20% for furrow irrigation and 38% for trickle irrigation (Figure 3.36). When areas of low model confidence are removed, the area of suitable to moderately suitable land (class 3) drops to 7% for furrow irrigation and 18% for trickle irrigation (Table 3.11).

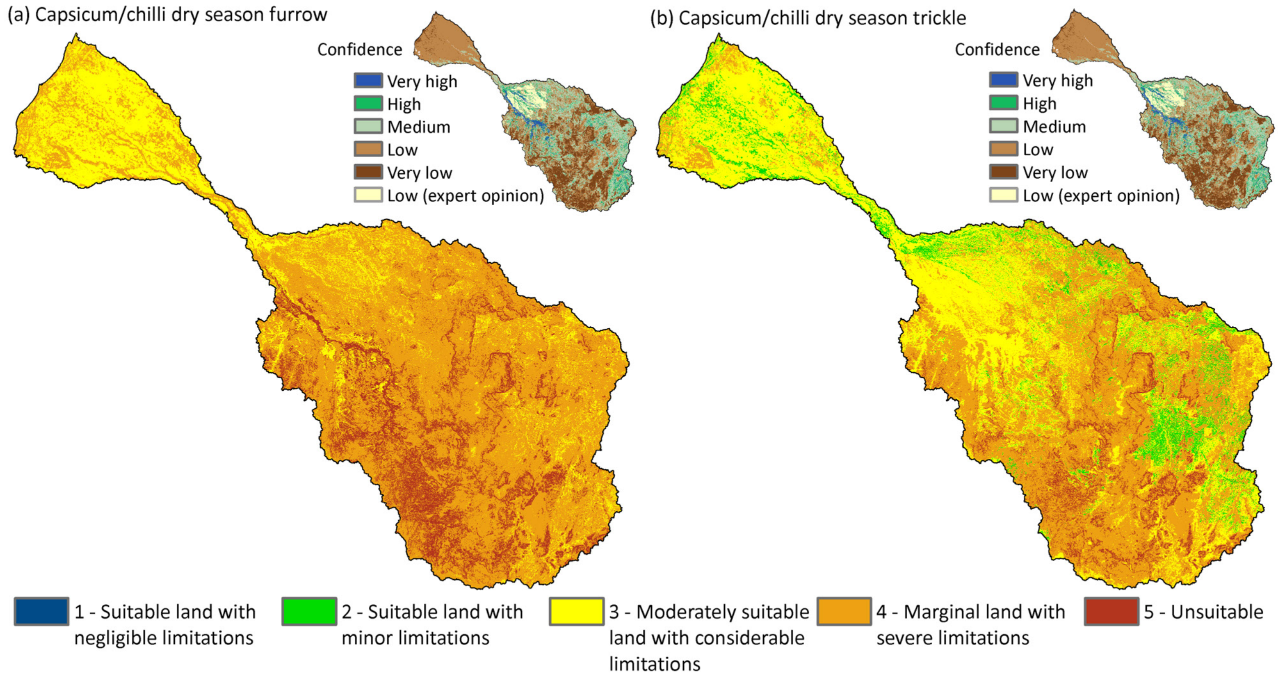


Figure 3.36 Predicted suitability for growing capsicum/chilli using (a) furrow irrigation and (b) spray irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

For the cotton land use, <1% is considered suitable (class 1 and/or 2) for either furrow or spray irrigation in the Gilbert catchment (Table 3.11). This is due to issues such as rockiness, potential erosion (slope) and soil moisture storage capacity (due to shallow and/or light-textured soils). The area of moderately suitable land (class 3) was 19% for furrow irrigation and 43% for spray irrigation (Figure 3.17), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 7% for furrow irrigation and 20% for spray irrigation (Table 3.11). Most of the upland areas to the south are not suitable, being either marginal with severe limitations or unsuitable. There are, however, significant contiguous areas that are moderately suitable with for spray irrigation cotton in the larger alluvial areas, and on some of the basalt. The main limitation here is that the soils are sandier and free draining, thus requiring more frequent irrigation applications.

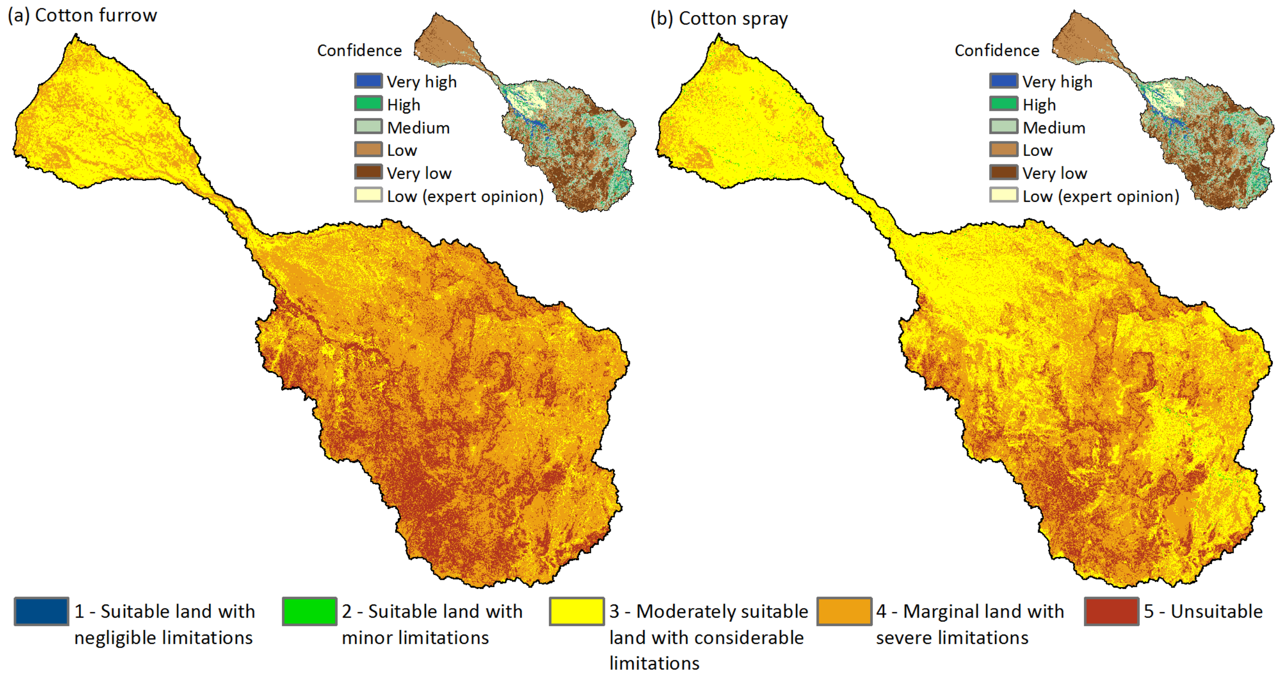


Figure 3.37 Predicted suitability for growing cotton using (a) furrow irrigation and (b) spray irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

For mangoes, ~3% is considered suitable (class 1 and/or 2) for trickle irrigation in the Gilbert catchment (Table 3.11). Narrow patches of alluvium on both the Gilbert and Einasleigh Rivers have lighter textured soils that are suitable for mangoes with minor limitations (Figure 3.38a). The area of moderately suitable land (class 3) was 31%, however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 18% for trickle irrigation of mangoes (Table 3.11). An area of moderately suitable land occurs on the deeply weathered tertiary and Mesozoic sediments between the Gilbert and Einasleigh Rivers which are favourable loamy soils (although depth is inconsistent and variable). Mangoes do not like wet soil conditions, and a range of management practices will be required to maintain drainage and prevent waterlogging.

None of the Gilbert catchment is considered suitable (class 1 or 2) for flood irrigated rice (Figure 3.11), however, there are some areas, largely downstream of the confluence of the Gilbert and Einasleigh Rivers, that are moderately suitable for rice (19%) (Figure 3.38b). When the areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 6%. The major limitations to flood irrigation of rice are related to slope, rockiness and permeability (slow permeability preferred).

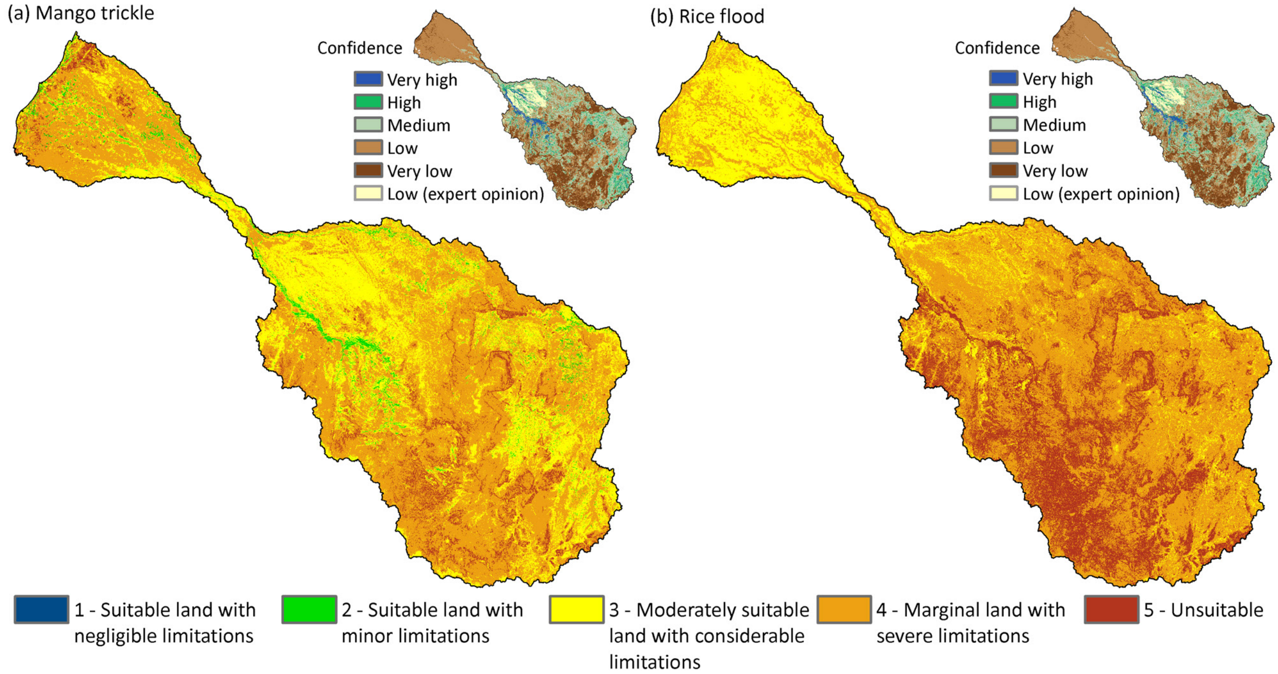


Figure 3.38 Predicted suitability for growing (a) mango using trickle irrigation and (b) rice using flood irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

There is ~1% of the Gilbert catchment suitable (class 1 and/or 2) for spray irrigation of peanuts (Table 3.11). These areas correspond to the well-drained, friable soils where peanuts grow best (Figure 3.39a). There is ~26% of the catchment classified as moderately suitable land (class 3) for spray irrigation, however, when areas of low model confidence are removed, the area suitable drops to 15% (Table 3.11). On the moderately suitable soils, soil wetness needs to be managed when growing peanuts as harvesting and machinery operations are dependent on a narrow soil moisture range for working (soil adhesiveness).

There is <1% of the Flinders catchment suitable (class 1 and/or 2) for spray irrigation of Rhodes grass (Figure 3.39b). There is ~43% of the catchment classified as moderately suitable land (class 3) for spray irrigation, however, when areas of low model confidence are removed, the suitable area drops to 20% (Table 3.11). Most of the moderately suitable land is on the alluvial sediments downstream of the confluence with the Gilbert and Einasleigh Rivers, or upstream of the confluence on the loamy soils. In these areas the occurrence of flooding will need to be taken into consideration.

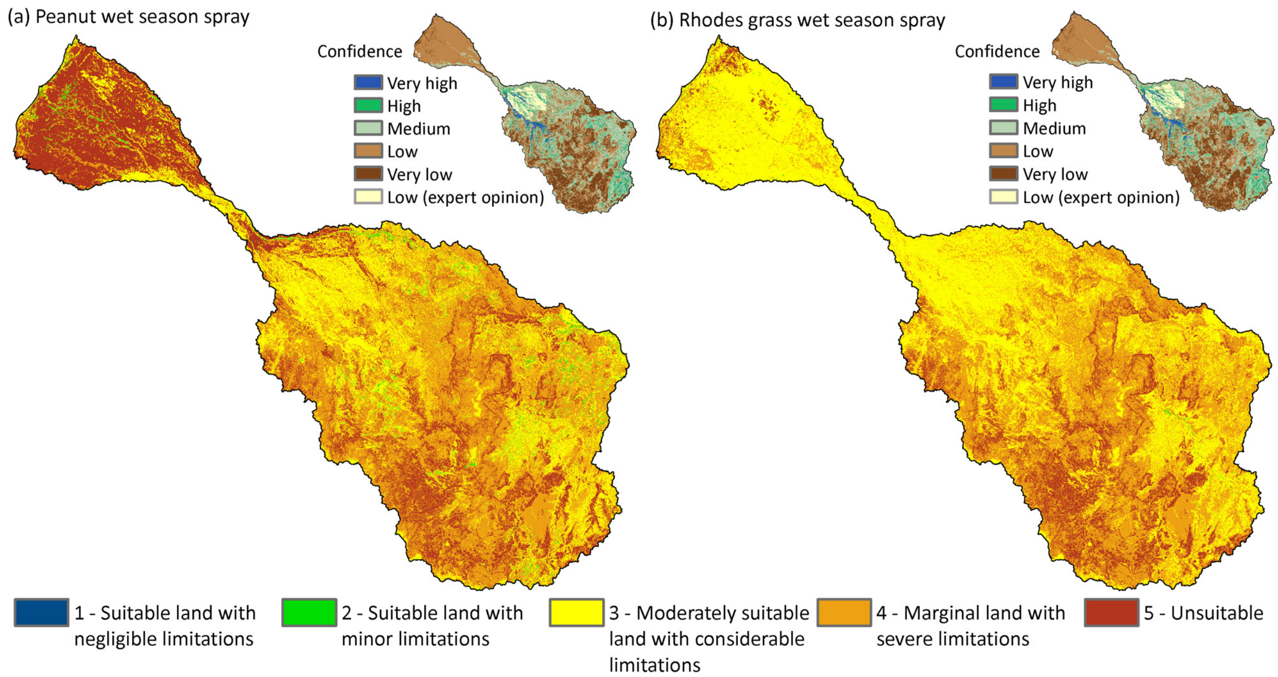


Figure 3.39 Predicted suitability for growing (a) peanut using spray irrigation and (b) Rhodes grass using spray irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

For sorghum, <1% is considered suitable (class 1 and/or 2) for either furrow or spray irrigation in the Gilbert catchment (Table 3.11). This is due to issues such as slope (which increases potential water erosion), low soil moisture storage capacity, soil depth and rockiness. The area of moderately suitable land (class 3) was 45% for forage sorghum under spray irrigation and 20% for grain sorghum under furrow irrigation (Figure 3.40), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 21% for spray irrigation and 7% for furrow irrigation (Table 3.11). The areas up and downstream of the confluence of the Gilbert and Einasleigh Rivers have large areas of contiguous moderately suitable land. These areas are relatively well drained with clay subsoils and thus good soil moisture storage capacity. However, specific management input will be required for the hard-setting surface soils, and soils with poor water infiltration.

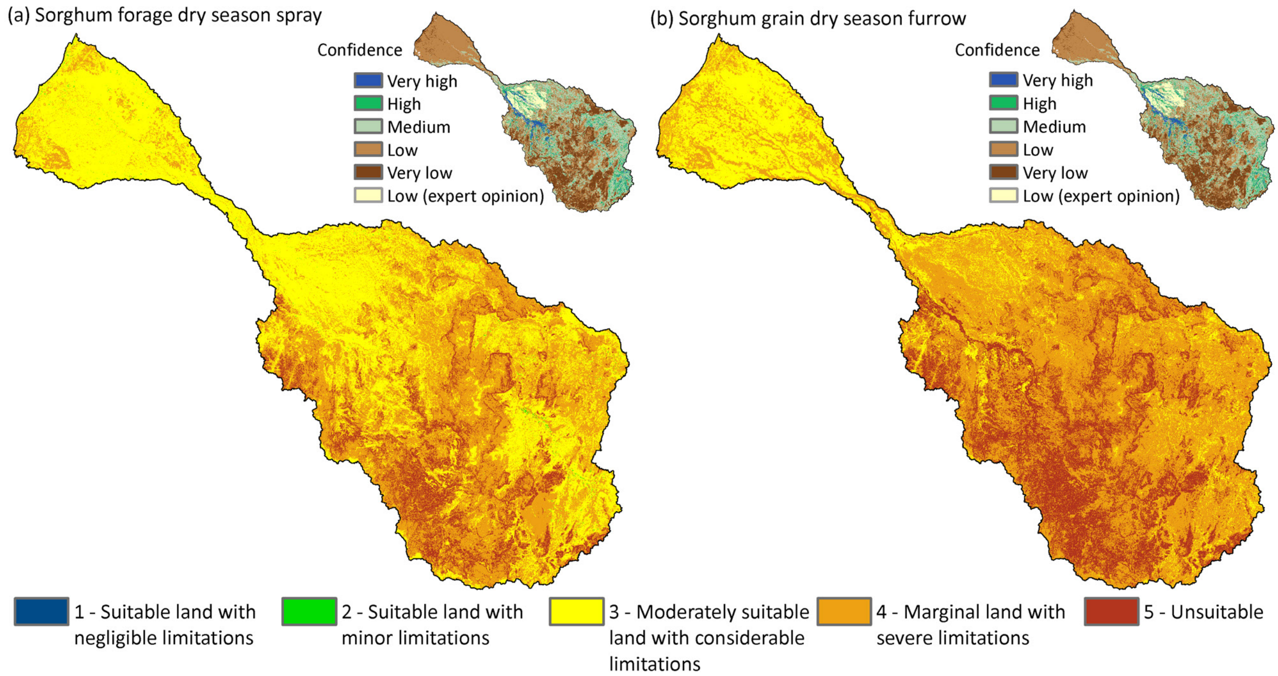


Figure 3.40 Predicted suitability for growing sorghum using (a) wet season furrow irrigation for forage and (b) wet season spray irrigation for grain in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

For soybean, <1% is considered suitable (class 1 and/or 2) for furrow or spray irrigation in the Gilbert catchment (Table 3.11). Again the main limitations are slope (water erosion hazard) and rockiness. The area of moderately suitable land (class 3) was 7% for soybeans under furrow irrigation and 31% for under spray irrigation (Figure 3.41), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 4% for furrow irrigation and 18% for spray irrigation (Table 3.11). The soils moderately suitable for spray irrigation are mainly sandy and loamy soils that are unsuitable for furrow.

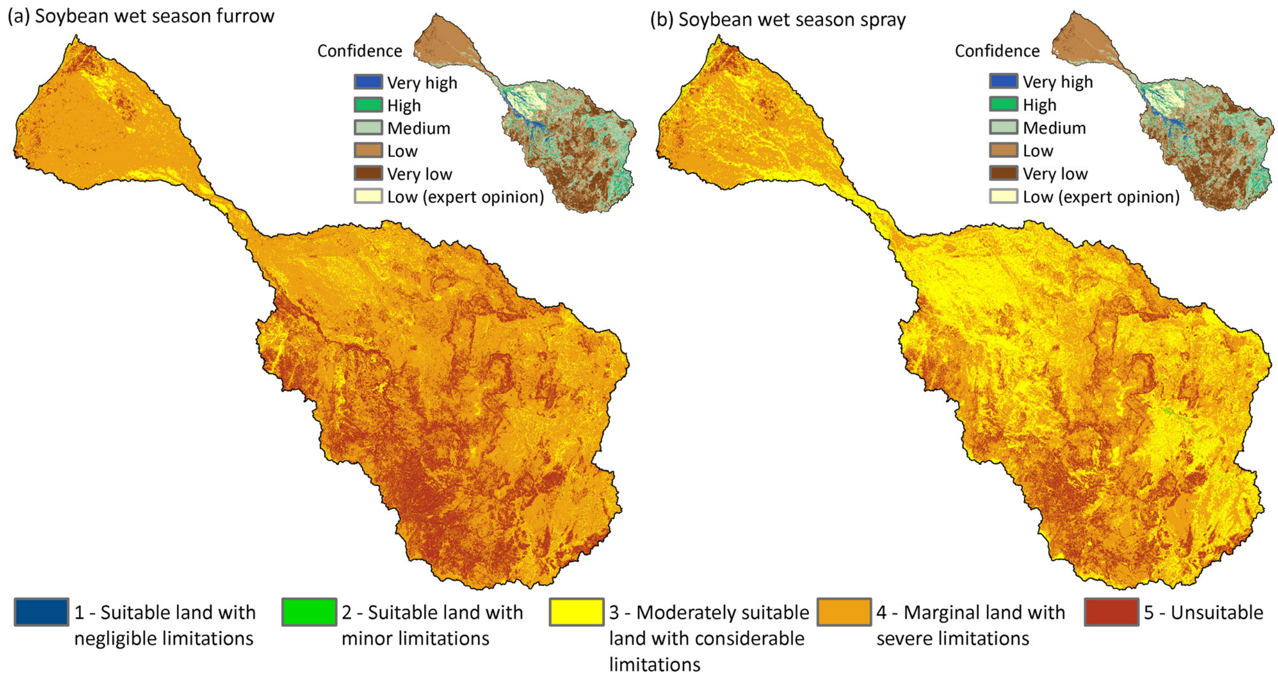


Figure 3.41 Predicted suitability for growing soybean using (a) furrow irrigation and (b) spray irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

For sugarcane, <1% is considered suitable (class 1 and/or 2) for furrow or spray irrigation in the Gilbert catchment (Table 3.11). Although sugarcane is more tolerant of wet conditions, slowly permeable soils are still a limitation along with low soil moisture storage capacity and rockiness. The area of moderately suitable land (class 3) was 19% for sugarcane under furrow irrigation and 44% for under spray irrigation (Figure 3.42), however, when areas of low model confidence are removed, the area of moderately suitable land (class 3) drops to 7% for furrow irrigation and 21% for spray irrigation (Table 3.11). Slope separates the furrow and spray irrigation with flat areas unable to furrow water and steeper areas susceptible to water erosion. The moderately suitable (class 3) soils of the river alluvium and delta areas have clay subsoils with good soil moisture storage capacity but may require more management input when these coincide with hardsetting surface soils. The large areas of undulating to rolling hilly country in the upper catchment make a large proportion of the catchment marginal (class 4) and unsuitable (class 5) for irrigated sugarcane due to shallow or rocky soils, low soil moisture storage capacity and potential for erosion largely driven by slope.

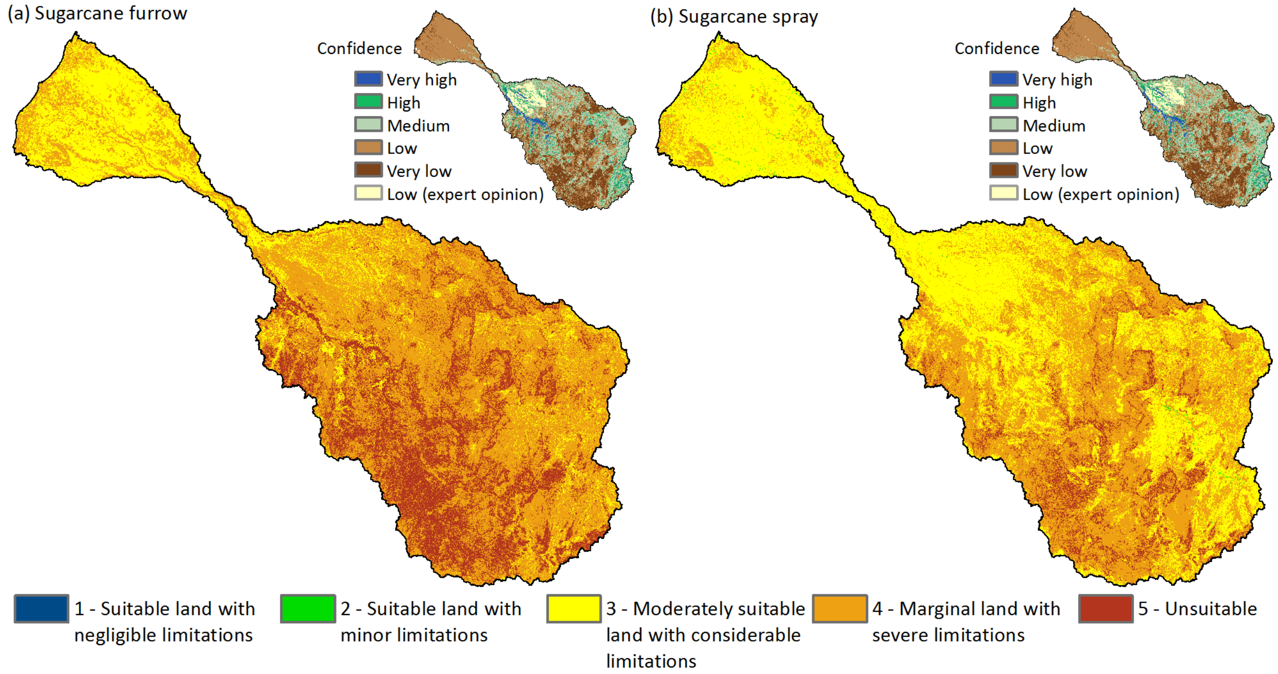


Figure 3.42 Predicted suitability for growing sugarcane using (a) furrow irrigation and (b) spray irrigation in the Gilbert catchment. The confidence map is based on the Mahalanobis calculation described in Section 2.8.4 and shown in Figure 3.34

4 Synthesis and recommendations

Soil data are the most important environmental factors in determining the suitability of land for irrigated agriculture. To further our understanding of the land suitability in the Flinders and Gilbert catchments three main tasks were undertaken in this study. The first was the collection of new soil data using a statistically robust field sampling strategy. The second was to use this new soil information, along with previously collected data, to produce digital soil attribute and soil maps of the Flinders and Gilbert catchments. Finally, the digital soil attribute layers were used to determine the area of land suitable for agricultural production in the two catchments. This report outlined the methods and results for each of these tasks. This study now represents the largest land suitability assessment using digital soil mapping ever conducted in Australia. Combined with the other studies in the overall Assessment, the information tools for regional planning have been significantly enhanced.

A total of 76 irrigation land uses (crop and irrigation combination), from 13 different land use categories (Table 1.1), were evaluated for their irrigated agriculture potential in the Flinders and Gilbert catchments. For each of these land uses the key limitations to production, and associated soil attribute data, were described. A statistically robust soil sampling design based on the conditional Latin Hypercube Sampling (cLHS) approach was used to determine the areas of the catchment most appropriate for new soils data collection. This was a pragmatic design that took into account distance from roads and other access issues. Soil data were collected from 451 new sites across the Flinders and Gilbert catchments. A sub-set of the new soil data were processed using MIR analysis and conventional laboratory analysis. The new information was put into a landscape context following the development of geomorphic catchment descriptions (Appendix 6.3 and 6.4).

The prediction of soil attributes from each data point in the catchment was carried out using a spatial correlation approach. A total of 1951 soil sites, including new and legacy data, were combined with the spatial covariate data and spatial attribute layers to predict the spatial distribution of key soil functional attributes (using the RuleFit3 program). A total of 16 digital soil attribute layers were produced. For brevity, this report presented the spatial results for 9 of the key attributes: pH, plant available water capacity at 1 m depth (PAWC100), minimum soil depth, surface texture, permeability, rockiness, drainage, electrical conductivity (EC) of the surface soil and exchangeable sodium percentage (ESP) of the surface soil. The results for the other attribute layers (% clay, depth of A horizon, K factor, PAWC50 and PAWC150, soil surface condition, soil surface structure and micro-relief) are available on request (see Section 4.1.1). The distribution of soil generic groups (SGG) across each landscape was also derived. Two different approaches were used to quantify the uncertainty or reliability of the digital soil attribute layers for the numerical and categorical data sets, respectively. Independent validation of a select number of attributes was also conducted. The DSM developed in this study worked well for the categorical data (correct % classification ranges from 53% to 86%) and was generally acceptably for the numerical data outputs (r^2 range from 18% to 54%). The spatial distribution of uncertainty was also presented for each attribute. The rockiness layer was considered one of the weakest outputs of the assessment – and is often challenging to map well.

It was not practical to present and describe the results for each of the 76 land uses modelled, therefore a selection of 14 land uses, that provide a range of crop and irrigation classes, was presented in this report. Land suitability was categorised in five classes with class 1 being highly suitable with negligible limitations and 5 being unsuitable. While there were only small areas of class 1 or 2 lands, the Flinders catchment had large areas of moderately suitable land (~60%) for cotton, soybean, sorghum, sugar, capsicum/chilli, mangoes, rice, peanuts and Rhodes grass. The limitations to development are 'considerable' and vary with land use and location. In most cases spray irrigation was more suitable that furrow irrigation. The Gilbert catchment generally has less soils suitable for agriculture due to its dissected topography and complex geology. The main crops shown as moderately suitable (with considerable limitations) in the Gilbert catchment (~20% of area) were trickle irrigation on capsicum/chilli, spray irrigation on cotton, Rhodes grass, forage sorghum, soybeans and sugarcane; and furrow irrigation for peanuts. It is important to note that class 5 land does not preclude the growth of a crop in that area. On some of these lands, if sufficient resources are available to overcome the limitations identified in the land suitability framework, then agriculture development is possible.

Although this study evaluated the suitability of the land for agricultural development, there are large differences in the reliability of the data used in this assessment. Thus considerable care is required when using these maps and other outputs for fine scale planning purposes. This Assessment focused on the 'regional scale' and could be used at the strategic level to identify prospective or unsuitable areas for agricultural development. Subsequent studies are required to identify precise land areas suitable for farming, and the associated positioning of infrastructure. We advise strongly against the use of these maps at the property or paddock scale. The broader considerations around land suitability involve proximity to irrigation water, environmental sustainability, access to markets and infrastructure, farm economics and social and cultural dimensions. In this case, the soil assessment is part of a broader assessment and the results need to be used in context with the conclusions from those studies.

This study has been an important blueprint for future systematic resource evaluation over large areas at the regional scale. This study has employed resources, knowledge and expertise from State and Federal Government agencies and represents a pragmatic, but scientifically robust approach based on limited time (18 months) over a large area (~150,000 km^2).

4.1.1 DATA MANAGEMENT, STORAGE AND ACCESS

This soil and land suitability assessment is based on historical soil site and map data which has been augmented by new soil data collected as part of this project activity. Historic soil data and ancillary data sets (digital elevation models, terrain derivatives, gamma radiometrics etc) are owned by third party government agencies and are not included as part of the data deliverables of the Assessment.

Soil site data from the Assessment, including (i) field based profile descriptions and laboratory analytical results, (ii) interpreted soil data products, and (iii) spatial layers of soil attributes and suitability, will be managed by CSIRO within the Australian Soil Resource Information System (ASRIS, see www.asris.csiro.au). Where appropriate, data will be made visible through the ASRIS map viewer.

The soil data collected as part of the Assessment will be described with standard ANZLIC meta-data and be made searchable and downloadable under Creative Commons Attribution 3.0 licensing, through the CSIRO Data Access Portal (DAP – see https://data.csiro.au). Project soil data will also be maintained by the Queensland Government within the Soil and Land Information System (SALI) and made available through a range of applications.

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Appendix A

A.1 Land use combinations for land suitability analysis

Apx Table A.1 Crop and irrigation combinations for land suitability analysis

LAND USE	SEASON (wet, dry, perennial)	CODE
African mahogany irrigated	P	AfrMahog_irr
African mahogany rainfed	P	AfrMahog_rain
Avocado trickle	P	Avocado_tric
Banana spray	P	Banana_spray
Banana trickle	P	Banana_tric
Capsicum/chilli dry furrow	D	CapsChili_dry_fur
Capsicum/chilli dry spray	D	CapsChili_dry_spray
Capsicum/chilli dry trickle	D	CapsChili_dry_tric
Carambola trickle	P	Carambola_tric
Caribbean pine irrigated	P	CaribPine_irr
Cashew trickle	P	Cashew_tric
Cassava wet furrow	W	Cassava_wet_fur
Cassava wet spray	W	Cassava_wet_spray
Chickpea dry furrow	D	Chickpea_dry_fur
Chickpea dry spray	D	Chickpea_dry_spr
Citrus trickle	P	Citrus_tric
Coffee trickle	P	Coffee_tric
Cotton wet furrow	W	Cotton_fur
Cotton wet spray	W	Cotton_spray
Cucurbit dry furrow	D	Cucurbit_dry_fur
Cucurbit dry spray	D	Cucurbit_dry_spray
Cucurbit dry trickle	D	Cucurbit_dry_tric
Custard apple trickle	P	CustApple_tric
Eggplant dry furrow	D	Eggplant_dry_fur
Eggplant dry trickle	D	Eggplant_dry_tric
Grape trickle	P	Grape_tric

Indian sandalwood irrigated	P	IndSandlWd_irr
Lablab wet furrow	W	Lablab_wet_fur
Lablab wet spray	W	Lablab_spray
Lucerne wet spray	W	Lucerne_wet_spray
Lychee trickle	P	Lychee_tric
Maize/corn wet furrow	W	Maize_wet_fur
Maize/corn wet spray	W	Maize_wet_spr
Mango trickle	P	Mango_tric
Millet wet furrow	W	Millet_wet_fur
Millet wet spray	W	Millet_wet_spr
Mungbean wet furrow	W	Mung_wet_fur
Mungbean wet spray	W	Mung_wet_spr
Navy bean wet furrow	W	Navy_wet_fur
Navy bean wet spray	W	Navy_wet_spr
Oats dry furrow	D	Oats_dry_fur
Oats dry spray	D	Oats-dry-spr
Peanut wet furrow	W	Peanut_wet_fur
Peanut wet spray	W	Peanut_wet_spr
Pineapple spray	P	Pineapple_spray
Pineapple trickle	P	Pineapple_tric
Rhodes grass wet spray	W	Rhodes_wet_spray
Rice wet flood	W	Rice_flood
Rice wet furrow	W	Rice_fur
Sorghum forage dry spray	D	Sorg_forg_dry_spr
Sorghum forage wet spray	W	Sorg_forg_wet_spr
Sorghum grain dry furrow	D	Sorg_gr_dry_fur
Sorghum grain dry spray	D	Sorghum_gr_dry_spr
Sorghum grain wet furrow	W	Sorg_gr_wet_fur
Sorghum grain wet spray	W	Sorg_gr_wet_spr
Soybean wet furrow	W	Soy_wet_fur
Soybean wet spray	W	Soy_wet_spray
Spotted gum irrigated	P	SpotdGum_irr
Spotted gum rainfed	P	SpotdGum_rain
Sugarcane furrow	P	Cane_fur
Sugarcane spray	P	Cane_spray

Sugarcane trickle	P	Cane_tric
Sunflower wet furrow	W	Sunflwr_fur
Sunflower wet spray	W	Sunflwr_wet_spr
Sweet corn dry furrow	D	SwtCorn_dry_fur
Sweet corn dry spray	D	SwtCorn_dry_spr
Sweet corn dry trickle	D	SwtCorn_dry_tric
Sweet corn wet furrow	W	SwtCorn_wet_fur
Sweet corn wet spray	W	SwtCorn_wet_spr
Sweet corn wet trickle	W	SwtCorn_wet_tric
Sweet potato wet furrow	W	SwtPot_wet_fur
Sweet potato wet spray	W	SwtPot_wet_spray
Teak irrigated	P	Teak_irr
Tomato dry furrow	D	Tomato_dry_fur
Tomato dry spray	D	Tomato_dry_spray
Tomato dry trickle	D	Tomato_dry_tric

A.2 Land suitability rules

Climate – precipitation

The amount of rain that falls during the growing season is relevant for irrigated cropping in terms of the quantity of supplementary irrigation required.

Code	Description	Suitability subclasses for land uses
	Mean annual rainfall	**A**
Cp1	Annual rainfall >1000 mm	2
Cp2	Annual rainfall 800-1000 mm	3
Cp3	Annual rainfall 600-800 mm	3
Cp4	Annual rainfall 500-600 mm	4
Cr5	Annual rainfall <500 mm	5
		African mahogany Spotted gum

Climate – heat stress

The Gulf Plains region is noted for its exceptionally hot temperatures that occur over a long period. For example, Julia Creek has on average ~150 days with a maximum of >35°C. The intense solar radiation associated with high temperatures (often combined with wind as well) is likely to cause damage to the leaves and fruit of many crops, being particularly significant for horticulture crops. Small crops (e.g. capsicum) will generally not be significantly affected, as they will be grown in the dry season when temperatures are less intense.

Code	Description	Suitability subclasses for land uses						
		A	B	C	D	E	F	G
Ch1	Low heat stress (<5 >40°days)	1	1	1	1	1	1	2
Ch2	Moderate heat stress (5-20 >40°days)	1	1	2	2	2	3	4
Ch3	Severe heat stress (≥20 >40°days)	2	3	2	3	4	4	4
		Cane_fur Cane_spray Cane_tric Cotton_fur Cotton_spray Rice_flood Rice_fur SorgGrain_wet_fur SorgGrain_wet_spr SorgGrain_dry_fur SorgGrain_dry_spr Millet_wet_fur Millet_wet_spr Sunflwr_fur Sunflwr_wet_spr Oats_dry_fur Oats_dry_spr SorgForag_wet_spr SorgForag_dry_spr Rhodes_wet_spray Lablab_wet_fur Lablab_spray Lucerne_wet_spray Chickpea_dry_fur Chickpea_dry_spr Soy_wet_fur Soy_wet_spray Mung_wet_fur Mung_wet_spr Navy_wet_fur Navy_wet_spr SwtCorn_dry_fur SwtCorn_dry_spr SwtCorn_dry_tric Cucurbit_dry_fur Cucurbit_dry_spray Cucurbit_dry_tric CapsChili_dry_fur CapsChili_dry_spray CapsChili_dry_tric Tomato_dry_fur Tomato_dry_spray Tomato_dry_tric Eggplant_dry_fur Eggplant_dry_tric Peanut_wet_fur Peanut_wet_spr SwtPot_wet_fur SwtPot_wet_spray Cassava_wet_fur Cassava_wet_spray CaribPine_irr AfrMahog_irr AfrMahog_rainfed SpotdGum_irr SpotdGum_rainfed IndSandlWd_irr	Mango_tric	Maize_wet_fur Maize_wet_spr SwtCorn_wet_fur SwtCorn_wet_spr SwtCorn_wet_tric	Teak_irr	Pineapple_spray Pineapple_tric Lychee_tric Cashew_tric Banana_spray Banana_tric Carambola_tric	Citrus_tric Grape_tric Avocado_tric	Coffee_tric CustApple_tric

Climate – frost

Frosts occur in the Gulf Plains region, but these are usually light. However, it is likely that frost would need to be considered in site selection and the management regime for certain frost sensitive crops.

Code	Description	Suitability subclasses for land uses A	B	C	D
Cf1	Frost free	1	1	1	1
Cf2	Occasional frost (<2 days)	1	1	2	2
Cf3	Regular light frosts (≥2 days)	2	3	2	3
		Cane_fur Cane_spray Cane_tric Cotton_fur Cotton_spray Rice_flood Maize_wet_fur Maize_wet_spr SorgGrain_wet_fur SorgGrain_wet_spr SorgGrain_dry_fur SorgGrain_dry_spr Millet_wet_fur Millet_wet_spr Sunflwr_fur Sunflwr_wet_spr Oats_dry_fur Oats_dry_spr SorgForag_wet_spr SorgForag_dry_spr Rhodes_wet_spray Lablab_wet_fur Lablab_spray Lucerne_wet_spray Chickpea_dry_fur Chickpea_dry_spr Soy_wet_fur Soy_wet_spray Mung_wet_fur Mung_wet_spr Navy_wet_fur Navy_wet_spr SwtCorn_wet_fur SwtCorn_wet_spr SwtCorn_wet_tric SwtCorn_dry_fur SwtCorn_dry_spr SwtCorn_dry_tric Cucurbit_dry_fur Cucurbit_dry_spray Cucurbit_dry_tric Peanut_wet_fur Peanut_wet_spr	CapsChili_dry_fur CapsChili_dry_spray CapsChili_dry_tric Tomato_dry_fur Tomato_dry_spray Tomato_dry_tric Eggplant_dry_fur Eggplant_dry_tric SwtPot_wet_fur SwtPot_wet_spray Cassava_wet_fur Cassava_wet_spray	Rice_fur Pineapple_spray Pineapple_tric Lychee_tric CaribPine_irr SpotdGum_irr SpotdGum_rainfed	Cashew_tric Mango_tric Banana_spray Banana_tric Carambola_tric Citrus_tric Grape_tric Coffee_tric Avocado_tric CustApple_tric AfrMahog_irr AfrMahog_rainfed Teak_irr IndSandlWd_irr

Climate – temperature variation

Certain crops (e.g. chickpea) require cool temperatures for efficient seed set. Other crops (e.g. Cassava) show a preference for climates that do not include cool winter temperatures.

Code	Description	Suitability subclasses for land uses					
		A		B	C	D	E
Ct1	Mean min. monthly temperature <15° for 4 months or more	1		1	1	2	3
Ct2	Mean min. monthly temperature <15° for 3 months or less	1		2	3	1	1
		Cane_fur	Lucerne_wet_spray	Citrus_tric	Chickpea_dry_fur	Cucurbit_dry_fur	Cassava_wet_fur
		Cane_spray	Soy_wet_fur	Grape_tric	Chickpea_dry_spr	Cucurbit_dry_spray	Cassava_wet_spray
		Cane_tric	Soy_wet_spray	CustApple_tric	Lychee_tric	Cucurbit_dry_tric	
		Cotton_fur	Mung_wet_fur			CapsChili_dry_fur	
		Cotton_spray	Mung_wet_spr			CapsChili_dry_spray	
		Rice_flood	Navy_wet_fur			CapsChili_dry_tric	
		Rice_fur	Navy_wet_spr			Tomato_dry_fur	
		Maize_wet_fur	SwtCorn_wet_fur			Tomato_dry_spray	
		Maize_wet_spr	SwtCorn_wet_spr			Tomato_dry_tric	
		SorgGrain_wet_fur	SwtCorn_wet_tric			Eggplant_dry_fur	
		SorgGrain_wet_spr	SwtCorn_dry_fur			Eggplant_dry_tric	
		SorgGrain_dry_fur	SwtCorn_dry_spr			Cashew_tric	
		SorgGrain_dry_spr	SwtCorn_dry_tric			Mango_tric	
		Millet_wet_fur	Peanut_wet_fur			Banana_spray	
		Millet_wet_spr	Peanut_wet_spr			Banana_tric	
		Sunflwr_fur	SwtPot_wet_fur			Carambola_tric	
		Sunflwr_wet_spr	SwtPot_wet_spray			Coffee_tric	
		Oats_dry_fur	Pineapple_spray			Avocado_tric	
		Oats_dry_spr	Pineapple_tric			AfrMahog_irr	
		SorgForag_wet_spr	CaribPine_irr			AfrMahog_rainfed	
		SorgForag_dry_spr				SpotdGum_irr	
		Rhodes_wet_spray				SpotdGum_rainfed	
		Lablab_wet_fur				IndSandlWd_irr	
		Lablab_spray				Teak_irr	

Moisture availability – irrigated crops

Adequate water storage in the soil profile relates to irrigation efficiency (i.e. the frequency of water application required).

Description	**Suitability subclasses for land uses. Different soil depths apply for various crop groups.**										
	PAWC to 0.5 m soil depth		PAWC to 1.0 m soil depth					PAWC to 1.5 m soil depth			
	Code	**A**	**Code**	**B**	**C**	**D**	**E**	**Code**	**F**	**G**	**H**
			M7	1	1	1	1	M1	1	1	1
PAWC >100 mm	M13	1	M8	1	1	1	1	M2	1	1	1
PAWC 75-100 mm	M14	1	M9	1	2	2	2	M3	1	1	2
PAWC 60-75 mm	M15	2	M10	2	2	2	3	M4	2	3	3
PAWC 40-60 mm	M16	3	M11	3	3	3	3	M5	3	3	4
PAWC <40 mm	M17	4	M12	4	3	4	4	M6	4	4	4
		Cucurbit_dry_fur Cucurbit_dry_spray Cucurbit_dry_tric CapsChili_dry_fur CapsChili_dry_spray CapsChili_dry_tric Tomato_dry_fur Tomato_dry_spray Tomato_dry_tric Eggplant_dry_fur Eggplant_dry_tric Peanut_wet_fur Peanut_wet_spr SwtPot_wet_fur SwtPot_wet_spray Cassava_wet_fur Cassava_wet_spray Pineapple_spray Pineapple_tric		Millet_wet_fur Millet_wet_spr	SwtCorn_wet_fur SwtCorn_wet_spr SwtCorn_wet_tric SwtCorn_dry_fur SwtCorn_dry_spr SwtCorn_dry_tric	Lychee_tric Cashew_tric Mango_tric Banana_spray Banana_tric Carambola_tric Citrus_tric Grape_tric CustApple_tric	Cane_fur Cane_spray Cane_tric Cotton_fur Cotton_spray Rice_flood Rice_fur Maize_wet_fur Maize_wet_spr SorgGrain_wet_fur SorgGrain_wet_spr SorgGrain_dry_fur SorgGrain_dry_spr Sunflwr_fur Sunflwr_wet_spr Oats_dry_fur Oats_dry_spr SorgForag_wet_spr SorgForag_dry_spr Rhodes_wet_spray Lablab_wet_fur Lablab_spray Lucerne_wet_spray Chickpea_dry_fur Chickpea_dry_spr Soy_wet_fur Soy_wet_spray Mung_wet_fur Mung_wet_spr Navy_wet_fur Navy_wet_spr		Coffee_tric Avocado_tric CaribPine_irr AfrMahog_irr SpotdGum_irr Teak_irr IndSandlWd_irr	SpotdGum_rain	AfrMahog_rain

Nutrient balance – pH

Soil pH affects the availability of nutrients for plant use. Strong acidity or alkalinity may lead to certain nutrient deficiencies and/or toxicities.

Code	Description	Suitability subclasses for land uses					
		A		B	C	D	E
Nr1	pH 5.5-7.0	1		1	1	1	3
Nr2	pH 7.0-8.5	1		1	1	2	1
Nr3	pH <5.5	2		2	3	2	4
Nr4	pH >8.5	2		3	3	3	2
		Cane_fur	Navy_wet_fur	Peanut_wet_fur	Cotton_fur	SwtPot_wet_fur	Teak_irr
		Cane_spray	Navy_wet_spr	Peanut_wet_spr	Cotton_spray	SwtPot_wet_spray	
		Cane_tric	SwtCorn_wet_fur	Pineapple_spray		Cassava_wet_fur	
		Rice_flood	SwtCorn_wet_spr	Pineapple_tric		Cassava_wet_spray	
		Rice_fur	SwtCorn_wet_tric	Cashew_tric		Carambola_tric	
		Maize_wet_fur	SwtCorn_dry_fur	Banana_spray		Lychee_tric	
		Maize_wet_spr	SwtCorn_dry_spr	Banana_tric		Mango_tric	
		SorgGrain_wet_fur	SwtCorn_dry_tric	Citrus_tric			
		SorgGrain_wet_spr	Cucurbit_dry_fur	Grape_tric			
		SorgGrain_dry_fur	Cucurbit_dry_spray	Coffee_tric			
		SorgGrain_dry_spr	Cucurbit_dry_tric	Avocado_tric			
		Millet_wet_fur	CapsChili_dry_fur	CustApple_tric			
		Millet_wet_spr	CapsChili_dry_spray				
		Sunflwr_fur	CapsChili_dry_tric				
		Sunflwr_wet_spr	Tomato_dry_fur				
		Oats_dry_fur	Tomato_dry_spray				
		Oats_dry_spr	Tomato_dry_tric				
		SorgForag_wet_spr	Eggplant_dry_fur				
		SorgForag_dry_spr	Eggplant_dry_tric				
		Rhodes_wet_spray	CaribPine_irr				
		Lablab_wet_fur	AfrMahog_irr				
		Lablab_spray	AfrMahog_rainfed				
		Lucerne_wet_spray	SpotdGum_irr				
		Chickpea_dry_fur	SpotdGum_rainfed				
		Chickpea_dry_spr	IndSandlWd_irr				
		Soy_wet_fur					
		Soy_wet_spray					
		Mung_wet_fur					
		Mung_wet_spr					

Physical restrictions (part one)

The physical condition of soil affects a range of cropping activities such as; plant establishment, the timing of cultivation and the harvesting of root crops.

Code	Description	Suitability subclasses for land uses						
		A	B	C	D	E	F	G
Ps1	No restriction: surface condition loose	1	1	1	1	1	1	1
Ps2	Surface condition firm/hardsetting and light textures of sands and loams	1	1	1	1	1	1	1
Ps3	Surface condition firm/hardsetting and heavy texture of clay	1	1	1	1	1	2	2
Ps4	Cracking clay soils with fine structure	3	3	3	4	4	2	2
Ps5	Cracking clay soils with coarse structure	3	3	3	4	4	2	3
Ps6	ESP ≥6 or surface condition firm/hardsetting and silty surface texture	3	3	4	3	4	3	3
Ps7	Depth of A horizon <=0.2 m AND the Soil Generic Group – "Sand or loam over intractable clay subsoils"	3	4	3	3	3	3	3
		CaribPine_irr AfrMahog_irr	Teak_irr IndSandlWd_irr	AfrMahog_rainfed	SpotdGum_irr	SpotdGum_rainfed	Cane_fur Cane_tric Cotton_fur Rice_flood Rice_fur	Maize_wet_fur SorgGrain_wet_fur SorgGrain_dry_fur Millet_wet_fur Sunflwr_fur Oats_dry_fur Lablab_wet_fur Chickpea_dry_fur Soy_wet_fur Mung_wet_fur Navy_wet_fur SwtCorn_wet_fur SwtCorn_wet_tric SwtCorn_dry_fur SwtCorn_dry_spr SwtCorn_dry_tric Cucurbit_dry_fur Cucurbit_dry_spray Cucurbit_dry_tric CapsChili_dry_fur CapsChili_dry_spray CapsChili_dry_tric Tomato_dry_fur Tomato_dry_spray Tomato_dry_tric Eggplant_dry_fur Eggplant_dry_tric

Physical restrictions (part two)

The physical condition of soil affects a range of cropping activities such as; plant establishment, the timing of cultivation and the harvesting of root crops.

Code	Description	Suitability subclasses for land uses							
		H	I	J	K	L	M	N	O
Ps1	No restriction: surface condition loose	1	1	1	1	1	1	1	1
Ps2	Surface condition firm/hardsetting and light textures of sands and loams	1	1	1	1	1	2	2	2
Ps3	Surface condition firm/hardsetting and heavy texture of clay	2	2	3	3	4	2	2	3
Ps4	Cracking clay soils with fine structure	2	2	3	4	4	2	3	3
Ps5	Cracking clay soils with coarse structure	3	3	4	4	4	3	3	3
Ps6	ESP ≥6 or surface condition firm/hardsetting and silty surface texture	3	4	4	4	4	3	3	3
Ps7	Depth of A horizon <=0.2 m AND the Soil Generic Group – “Sand or loam over intractable clay subsoils”	4	4	5	5	5	3	3	4
		SwtCorn_wet_spr	Cane_spray Cotton_spray Maize_wet_spr SorgGrain_wet_spr SorgGrain_dry_spr Millet_wet_spr Sunflwr_wet_spr Oats_dry_spr SorgForag_wet_spr SorgForag_dry_spr Rhodes_wet_spray Lablab_spray Lucerne_wet_spray Chickpea_dry_spr Soy_wet_spray Mung_wet_spr Navy_wet_spr	Peanut_wet_fur Peanut_wet_spr	SwtPot_wet_fur SwtPot_wet_spr	Cassava_wet_fur Cassava_wet_spr	Pineapple_spr Pineapple_tric Banana_spr Banana_tric	Lychee_tric Cashew_tric Mango_tric Carambola_tric Citrus_tric Citrus_tric Grape_tric	Coffee_tric Avocado_tric CustApple_tric

Soil depth

The soil depth limitation generally relates to the requirement for physical support for the plant. Additional soil depth is required to fulfil the requirements for certain crops e.g. avocado. Additional soil depth is required for efficient harvesting of root crops.

Code	Description	Suitability subclasses for land uses							
		A	B	C	D	E	F	G	H
Pd1	Very deep (>=1.5 m)	1	1	1	1	1	1	1	1
Pd2	Deep (1.0-<1.5 m)	1	1	1	1	1	1	1	2
Pd3	Moderate (0.5-<1.0 m)	1	1	1	2	2	2	3	4
Pd4	Shallow (0.25-<0.5 m)	2	3	4	2	3	4	4	4
Pd5	Very shallow (< 0.25 m)	4	4	5	4	4	5	5	5
		Cane_fur	Cotton_fur	Peanut_wet_fur	SwtCorn_dry_fur	SorgGrain_dry_fur	Rice_flood	Lychee_tric	Coffee_tric
		Cane_spray	Cotton_spray	Peanut_wet_spr	SwtCorn_dry_spr	SorgGrain_dry_spr	Rice_fur	Cashew_tric	Avocado_tric
		Cane_tric	SorgForag_wet_spr	SwtPot_wet_fur	SwtCorn_dry_tric	Oats_dry_fur	Maize_wet_fur	Mango_tric	
		Millet_wet_fur	SorgForag_dry_spr	SwtPot_wet_spray		Oats_dry_spr	Maize_wet_spr	Banana_spray	
		Millet_wet_spr	Rhodes_wet_spray	Cassava_wet_fur		Chickpea_dry_fur	SorgGrain_wet_fur	Banana_tric	
		Cucurbit_dry_fur	Lablab_spray	Cassava_wet_spray		Chickpea_dry_spr	SorgGrain_wet_spr	Carambola_tric	
		Cucurbit_dry_spray	Lucerne_wet_spray			SwtCorn_wet_fur	Sunflwr_fur	Grape_tric	
		Cucurbit_dry_tric				SwtCorn_wet_spr	Sunflwr_wet_spr	CustApple_tric	
		CapsChili_dry_fur				SwtCorn_wet_tric	Lablab_wet_fur	CaribPine_irr	
		CapsChili_dry_spray				Pineapple_spray	Soy_wet_fur	AfrMahog_irr	
		CapsChili_dry_tric				Pineapple_tric	Soy_wet_spray	AfrMahog_rainfed	
		Tomato_dry_fur					Mung_wet_fur	Teak_irr	
		Tomato_dry_spray					Mung_wet_spr	IndSandlWd_irr	
		Tomato_dry_tric					Navy_wet_fur		
		Eggplant_dry_fur					Navy_wet_spr		
		Eggplant_dry_tric					Citrus_tric		
							SpotdGum_irr		
							SpotdGum_rainfed		

Water erosion (part one)

Soil loss from water erosion needs to be minimised. Suitability subclasses were also determined for 'very stable' soils (K-factor <0.02), but using the digital soil mapping techniques, none of these soils were predicted.

Code	Description	Suitability subclasses for land uses						
		A	B	C	D	E	F	G
E11	Stable soils: K factor 0.02-0.04 and slope <0.5%	1	1	1	1	1	1	1
E12	Stable soils: K factor 0.02-0.04 and slope 0.5-1.0%	1	1	1	2	2	2	2
E13	Stable soils: K factor 0.02-0.04 and slope 1-2%	1	1	1	3	2	3	3
E14	Stable soils: K factor 0.02-0.04 and slope 2-3%	1	1	1	3	2	3	3
E15	Stable soils: K factor 0.02-0.04 and slope 3-5%	1	2	2	3	3	3	4
E16	Stable soils: K factor 0.02-0.04 and slope 5-8%	2	2	3	3	3	4	4
E17	Stable soils: K factor 0.02-0.04 and slope 8-12%	3	3	4	4	4	4	5
E18	Stable soils: K factor 0.02-0.04 and slope 12-15%	3	3	4	4	4	5	5
E19	Stable soils: K factor 0.02-0.04 and slope 15-20%	3	4	5	5	5	5	5
E20	Stable soils: K factor 0.02-0.04 and slope >20%	4	5	5	5	5	5	5
E21	Unstable soils: K factor 0.04-0.06 and slope <0.5%	1	1	1	2	2	2	2
E22	Unstable soils: K factor 0.04-0.06 and slope 0.5-1.0%	1	1	1	3	3	3	3
E23	Unstable soils: K factor 0.04-0.06 and slope 1-2%	1	1	1	3	3	3	3
E24	Unstable soils: K factor 0.04-0.06 and slope 2-3%	2	2	2	3	3	3	4
E25	Unstable soils: K factor 0.04-0.06 and slope 3-5%	2	2	3	3	4	4	4
E26	Unstable soils: K factor 0.04-0.06 and slope 5-8%	3	3	4	4	4	4	5
E27	Unstable soils: K factor 0.04-0.06 and slope 8-12%	3	3	4	4	5	5	5
E28	Unstable soils: K factor 0.04-0.06 and slope 12-15%	3	4	5	5	5	5	5
E29	Unstable soils: K factor 0.04-0.06 and slope 15-20%	4	5	5	5	5	5	5
E30	Unstable soils: K factor 0.04-0.06 and slope >20%	5	5	5	5	5	5	5
E31	Very unstable soils: K factor >0.06 and slope <0.5%	1	1	1	2	2	2	2
E32	Very unstable soils: K factor >0.06 and slope 0.5-1.0%	2	2	2	3	3	3	3
E33	Very unstable soils: K factor >0.06 and slope 1-2%	2	2	2	3	3	3	3
E34	Very unstable soils: K factor >0.06 and slope 2-3%	2	2	3	3	3	3	4
E35	Very unstable soils: K factor >0.06 and slope 3-5%	3	2	4	3	4	4	4
E36	Very unstable soils: K factor >0.06 and slope 5-8%	3	3	4	4	5	5	5
E37	Very unstable soils: K factor >0.06 and slope 8-12%	4	4	5	5	5	5	5
E38	Very unstable soils: K factor >0.06 and slope 12-15%	4	4	5	5	5	5	5
E39	Very unstable soils: K factor >0.06 and slope 15-20%	5	5	5	5	5	5	5
E40	Very unstable soils: K factor >0.06 and slope >20%	5	5	5	5	5	5	5
		CaribPine_irr AfrMahog_irr AfrMahog_rain SpotdGum_irr SpotdGum_rain Teak_irr IndSandlWd_irr	Lychee_tric Cashew_tric Mango_tric Banana_tric Carambola_tric Citrus_tric Grape_tric Coffee_tric Avocado_tric CustApple_tric	Banana_spray	Cane_spray Cane_tric	Oats_dry_spray Chickpea_dry_spray	Cotton_spray Maize_spray Sorghum_spray Millet_spray Sunflwr_spray SorghumForg_spray Rhodes_spray Lablab_spray Lucerne_spray Soy_spray Mung_spray Navy_spray	Cane_fur Rice_fur

Water erosion (part two)

Minimise land degradation due to soil erosion by water. Suitability subclasses were also determined for ‘very stable’ soils (K-factor <0.02), but using the digital soil mapping techniques, none of these soils were predicted.

Code	Description	Suitability subclasses for land uses						
		H	I	J	K	L	M	N
E11	Stable soils: K factor 0.02-0.04 and slope <0.5%	1	1	1	1	1	1	1
E12	Stable soils: K factor 0.02-0.04 and slope 0.5-1.0%	2	2	2	2	2	2	2
E13	Stable soils: K factor 0.02-0.04 and slope 1-2%	3	3	2	2	2	2	2
E14	Stable soils: K factor 0.02-0.04 and slope 2-3%	3	4	3	3	3	3	3
E15	Stable soils: K factor 0.02-0.04 and slope 3-5%	4	4	3	3	3	3	4
E16	Stable soils: K factor 0.02-0.04 and slope 5-8%	4	4	3	3	4	4	4
E17	Stable soils: K factor 0.02-0.04 and slope 8-12%	5	5	4	4	4	4	5
E18	Stable soils: K factor 0.02-0.04 and slope 12-15%	5	5	4	5	5	5	5
E19	Stable soils: K factor 0.02-0.04 and slope 15-20%	5	5	5	5	5	5	5
E20	Stable soils: K factor 0.02-0.04 and slope >20%	5	5	5	5	5	5	5
E21	Unstable soils: K factor 0.04-0.06 and slope <0.5%	2	2	2	2	2	2	2
E22	Unstable soils: K factor 0.04-0.06 and slope 0.5-1.0%	3	3	2	2	2	2	2
E23	Unstable soils: K factor 0.04-0.06 and slope 1-2%	3	3	2	3	2	2	2
E24	Unstable soils: K factor 0.04-0.06 and slope 2-3%	4	4	2	3	3	3	4
E25	Unstable soils: K factor 0.04-0.06 and slope 3-5%	4	4	3	3	4	4	4
E26	Unstable soils: K factor 0.04-0.06 and slope 5-8%	5	5	4	4	4	4	5
E27	Unstable soils: K factor 0.04-0.06 and slope 8-12%	5	5	4	5	5	5	5
E28	Unstable soils: K factor 0.04-0.06 and slope 12-15%	5	5	5	5	5	5	5
E29	Unstable soils: K factor 0.04-0.06 and slope 15-20%	5	5	5	5	5	5	5
E30	Unstable soils: K factor 0.04-0.06 and slope >20%	5	5	5	5	5	5	5
E31	Very unstable soils: K factor >0.06 and slope <0.5%	2	2	2	2	2	2	2
E32	Very unstable soils: K factor >0.06 and slope 0.5-1.0%	3	3	2	2	3	2	3
E33	Very unstable soils: K factor >0.06 and slope 1-2%	3	3	3	3	3	3	3
E34	Very unstable soils: K factor >0.06 and slope 2-3%	4	4	3	3	3	4	4
E35	Very unstable soils: K factor >0.06 and slope 3-5%	5	4	4	4	4	5	5
E36	Very unstable soils: K factor >0.06 and slope 5-8%	5	5	5	5	5	5	5
E37	Very unstable soils: K factor >0.06 and slope 8-12%	5	5	5	5	5	5	5
E38	Very unstable soils: K factor >0.06 and slope 12-15%	5	5	5	5	5	5	5
E39	Very unstable soils: K factor >0.06 and slope 15-20%	5	5	5	5	5	5	5
E40	Very unstable soils: K factor >0.06 and slope >20%	5	5	5	5	5	5	5
		Cotton_fur Maize_fur Sorghum_fur Millet_fur Sunflwr_fur Oats_fur_dry Lablab_fur Chickpea_fur_dry Soy_fur Mung_fur Navy_fur	Rice_flood	SwtCorn_tric_wet SwtCorn_tric_dry Cucurbit_tric CapsChili_tric Tomato_tric Eggplant_tric Pineapple_tric	SwtCorn_spray_wet SwtCorn_spray_dry Cucurbit_spray CapsChili_spray Tomato_spray Pineapple_spray	Peanut_spray SwtPot_spray Cassava_spray	SwtCorn_fur_wet SwtCorn_fur_dry Cucurbit_fur CapsChili_fur Tomato_fur Eggplant_fur	Peanut_fur SwtPot_fur Cassava_fur

Wetness (part one)

Adequate soil aeration is required for plant growth. Crops grown entirely in the dry season (e.g. all intensive horticulture crops, oats, chickpeas) are less affected by this limitation as they will not generally experience very wet conditions.

Code	Description	Suitability subclasses for land uses											
		A	B	C	C	D	E	F	G	H	I	J	K
W1	Rapidly drained	1	1	1	1	1	1	1	1	1	1	1	1
W2	Well drained and highly permeable	1	1	1	1	1	1	1	1	1	1	1	1
W3	Well drained and moderately permeable	1	1	1	1	1	1	1	1	1	1	1	2
W4	Well drained and slowly permeable	1	1	1	1	1	1	1	1	1	1	2	2
W5	Well drained and very slowly permeable	2	2	2	2	3	3	3	3	3	3	4	3
W6	Moderately well-drained and highly permeable	1	1	1	1	1	1	1	2	2	3	3	2
W7	Moderately well-drained and moderately permeable	1	1	2	1	1	1	2	3	3	3	3	2
W8	Moderately well-drained and slowly permeable	2	2	3	2	2	2	3	3	3	3	4	3
W9	Moderately well-drained and very slowly permeable	3	3	3	4	3	4	4	3	4	4	4	4
W10	Imperfectly drained and highly permeable	2	2	3	4	2	4	4	3	4	4	4	4
W11	Imperfectly drained and moderately permeable	3	3	3	4	3	4	4	3	4	4	4	4
W12	Imperfectly drained and slowly permeable	3	4	4	4	4	4	4	4	4	4	5	5
W13	Imperfectly drained and very slowly permeable	4	4	4	4	4	4	5	4	4	5	5	5
W14	Poorly drained and highly or moderately permeable	4	4	5	4	5	5	5	5	5	5	5	5
W15	Poorly drained and slowly or very slowly permeable	4	5	5	5	5	5	5	5	5	5	5	5
W16	Very poorly drained	5	5	5	5	5	5	5	5	5	5	5	5
		AfrMahog_irrig AfrMahog_rainfed	CaribPine_irrig SpotdGum_irrig SpotdGum_rainfed		Teak_irr IndSandlWd_irr	Pineapple_spray Pineapple_tric	Banana_spray	Carambola_tric Citrus_tric	Lychee_tric Cashew_tric Mango_tric	Banana_tric	Grape_tric	Coffee_tric Avocado_tric CustApple_tric	SwtPot_wet_fur SwtPot_wet_spray

Wetness (part two)

Adequate soil aeration is required for plant growth. Crops grown entirely in the dry season (e.g. all intensive horticulture crops, oats, chickpeas) are less affected by this limitation as they will not generally experience very wet conditions.

Code	Description	Suitability subclasses for land uses									
		L	M	N	O	P	Q	R	S	T	U
W1	Rapidly drained	1	1	1	1	1	1	1	1	1	1
W2	Well drained and highly permeable	1	1	1	1	1	1	1	1	1	1
W3	Well drained and moderately permeable	2	2	2	2	2	2	2	2	2	2
W4	Well drained and slowly permeable	2	2	2	2	2	2	2	2	2	2
W5	Well drained and very slowly permeable	3	3	3	3	3	3	3	3	3	3
W6	Moderately well-drained and highly permeable	2	2	2	2	2	2	2	2	2	2
W7	Moderately well-drained and moderately permeable	3	2	2	2	2	2	2	2	2	2
W8	Moderately well-drained and slowly permeable	3	3	3	3	3	3	3	3	3	3
W9	Moderately well-drained and very slowly permeable	4	3	3	3	3	3	3	3	4	4
W10	Imperfectly drained and highly permeable	4	2	2	2	2	2	3	3	3	3
W11	Imperfectly drained and moderately permeable	4	2	2	2	2	3	3	3	3	4
W12	Imperfectly drained and slowly permeable	5	3	3	3	3	3	4	3	4	4
W13	Imperfectly drained and very slowly permeable	5	3	4	4	3	4	4	3	4	4
W14	Poorly drained and highly or moderately permeable	5	3	3	4	3	4	4	3	4	4
W15	Poorly drained and slowly or very slowly permeable	5	4	4	4	4	5	5	4	5	5
W16	Very poorly drained	5	5	5	5	5	5	5	5	5	5
		Peanut_wet_furrow Peanut_wet_spray Cassava_wet_furrow Cassava_wet_spray	Cucurbit_dry_fur Cucurbit_dry_spray Cucurbit_dry_tric CapsChili_dry_fur CapsChili_dry_spray CapsChili_dry_tric Tomato_dry_fur Tomato_dry_spray Tomato_dry_tric Eggplant_dry_fur Eggplant_dry_tric	Cane_fur Cane_spray Cane_tric	Cotton_furrow Cotton_spray	SorgGrain_dry_furrow SorgGrain_dry_spray Oats_dry_fur Oats_dry_spr SorgForag_dry_spray Chickpea_dry_furrow Chickpea_dry_spray SwtCorn_dry_furrow SwtCorn_dry_spray SwtCorn_dry_tric	Sorg_forag_wet_spr Rhodes_wet_spray Lablab_wet_fur Lablab_spray SwtCorn_wet_fur SwtCorn_wet_spr SwtCorn_wet_tric	Maize_wet_fur Maize_wet_spr SorgGrain_wet_fur SorgGrain_wet_spr Sunflwr_fur Sunflwr_wet_spr Lucerne_wet_spray Soy_wet_fur Soy_wet_spray	Rice_flood Rice_fur	Mung_wet_fur Mung_wet_spr Navy_wet_fur Navy_wet_spr	Millet_wet_furrow Millet_wet_spray

Wind erosion

Sandy surfaced soils in arid areas (<500 mm annual rainfall) are vulnerable to wind erosion.

Code	Description	Suitability subclasses for land uses			
		A		B	
Ew1	No restriction: annual rainfall >= 500 mm OR surface texture not sandy	1		1	
Ew2	Annual rainfall <500 mm AND surface texture class 1 (sandy)	2		3	
Ew3	Annual rainfall <500 mm AND surface texture class 1 (sandy) AND the Soil Generic Group – “Sand or loam over intractable clay subsoils”	3		4	
		SwtCorn_wet_fur	Lychee_tric	Cane_fur	Lablab_wet_fur
		SwtCorn_wet_spr	Cashew_tric	Cane_spray	Lablab_spray
		SwtCorn_wet_tric	Mango_tric	Cane_tric	Lucerne_wet_spray
		SwtCorn_dry_fur	Banana_spray	Cotton_fur	Chickpea_dry_fur
		SwtCorn_dry_spr	Banana_tric	Cotton_spray	Chickpea_dry_spr
		SwtCorn_dry_tric	Carambola_tric	Rice_flood	Soy_wet_fur
		Cucurbit_dry_fur	Citrus_tric	Rice_fur	Soy_wet_spray
		Cucurbit_dry_spray	Grape_tric	Maize_wet_fur	Mung_wet_fur
		Cucurbit_dry_tric	Coffee_tric	Maize_wet_spr	Mung_wet_spr
		CapsChili_dry_fur	Avocado_tric	SorgGrain_wet_fur	Navy_wet_fur
		CapsChili_dry_spray	CustApple_tric	SorgGrain_wet_spr	Navy_wet_spr
		CapsChili_dry_tric	CaribPine_irr	SorgGrain_dry_fur	Peanut_wet_fur
		Tomato_dry_fur	AfrMahog_irr	SorgGrain_dry_spr	Peanut_wet_spr
		Tomato_dry_spray	AfrMahog_rain	Millet_wet_fur	SwtPot_wet_fur
		Tomato_dry_tric	SpotdGum_irr	Millet_wet_spr	SwtPot_wet_spray
		Eggplant_dry_fur	SpotdGum_rain	Sunflwr_fur	Cassava_wet_fur
		Eggplant_dry_tric	Teak_irr	Sunflwr_wet_spr	Cassava_wet_spray
		Pineapple_spray	IndSandlWd_irr	Oats_dry_fur	
		Pineapple_tric		Oats_dry_spr	
				SorgForag_wet_spr	
				SorgForag_dry_spr	
				Rhodes_wet_spray	

Gilgai microrelief – all crops

Severe gilgai microrelief affects machinery use and irrigation efficiency.

Code	Description	Suitability subclass
Tm1	No gilgai or vertical interval <0.3 m	1
Tm2	Vertical interval >0.3 m	4

Irrigation efficiency – all furrow irrigated crops

Applied water must match soil infiltration characteristics to minimise water loss and deep drainage. Waterlogging may also be a problem at the upper end of furrows if they are too long.

Code	Description	Suitability subclass
If1	Very slowly permeable	1
If2	Slowly permeable	3
If3	Moderately permeable	4
If4	Highly permeable	5

Rockiness – all crops

Surface rockiness affects machinery and harvesting operations.

Code	Description	Suitability subclass
R1	Not rocky or not significantly rocky	1
R2	Rocky	4

A.3 Flinders Geomorphology descriptions

The major geomorphic landscape units in the Flinders catchment include the:

(i) Alluvial sediments, which are broken into
- Quaternary alluvium and
- Tertiary alluvium

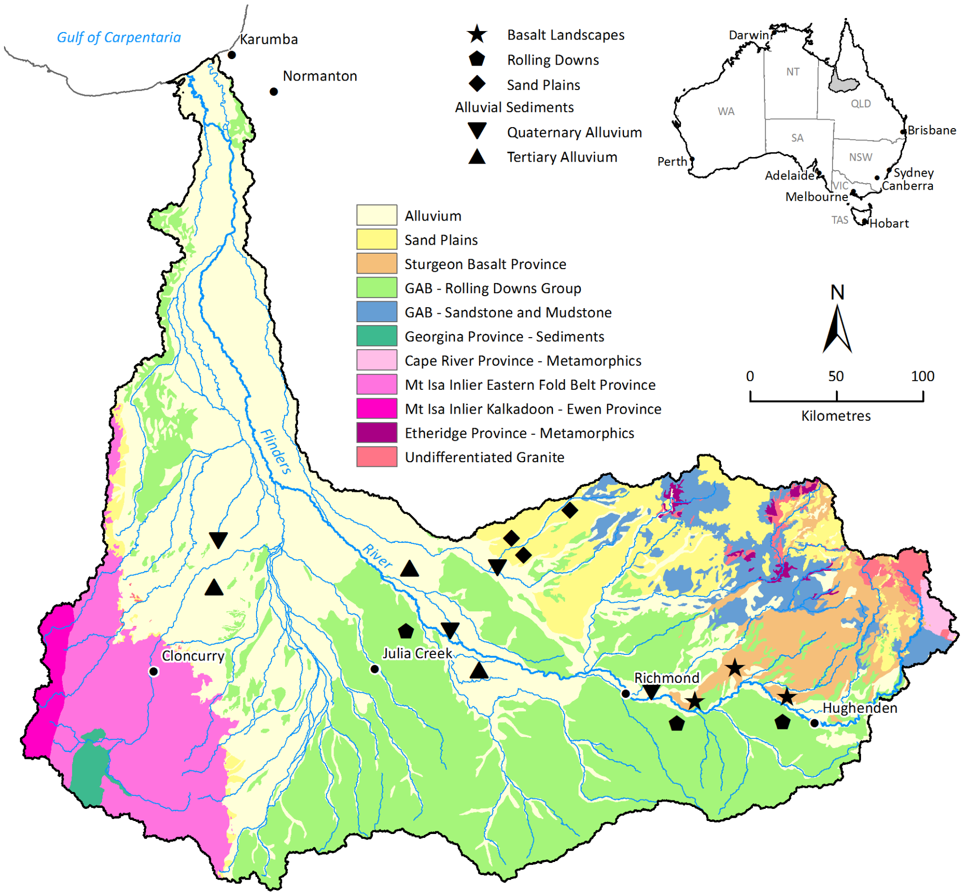
(ii) Rolling Downs

(iii) Basalt landscapes and

(iv) Sand plains

Given the proximity of the investigation areas to the main drainage lines, alluvial sediments dominate the landscape, and range from Quaternary to Tertiary in age. Radiometrics or gamma-ray spectrometry, is a measure of the natural radiation in the Earth's surface, and was used to help identify the distribution and relative age of soil and rock types (Figure 2.2). The age of the sediment is important for identifying the potential salinity and relative fertility of the soil.

Sections A.3.1 to A.3.4 describe each of the four major landscape units in more detail, and provide a description of the composition and distribution of soils within each landscape unit. It is important to note that each investigation area may contain several landscape units.



Apx Figure A.1 Location of four major landscape units (Basalt, Rolling Downs, Sand Plains, Alluvial sediments) in the Flinders catchment

A.3.1 ALLUVIAL SEDIMENTS

Tertiary and Quaternary alluvial sediments dominate the Flinders catchment. Several alluvial landscape units are present and can be distinguished based on the origin and age of the sediments, frequency of flooding and soil properties.

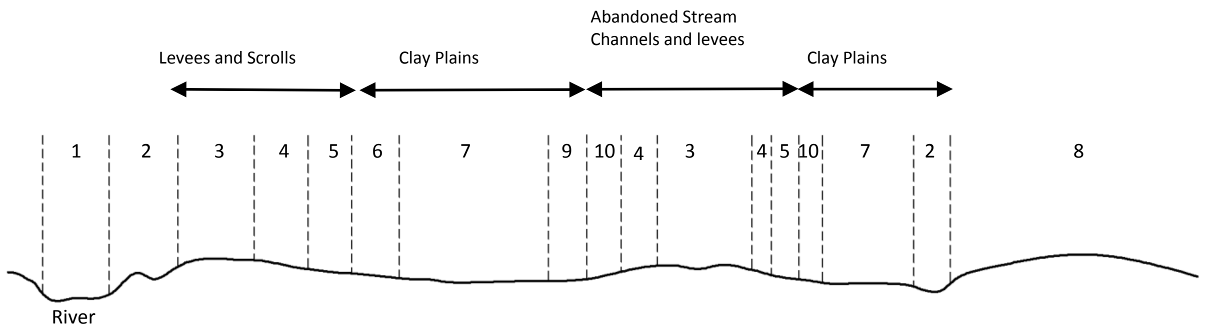
Quaternary Alluvium

The Quaternary Alluvium (QA) consists of unconsolidated sand, loam and clay sediments associated with current stream channels, prior stream channels, levees and floodplains originating from a range of geologies. A consistent series of soils occur across the landscape in varying extents and are recognised based on the origin of sediments, frequency of flooding and soil properties (Apx Figure A.2). Deeply incised main river channels, river banks and active flood drainage channels have alluvial Rudosols (units QA1 and QA2). There are sandy to loamy Brown Kandosols and Dermosols on the levees (unit QA3). These levee soils grade to levee backslopes with sandy to loamy surface Dermosols and Chromosols (unit QA4) grading to sandy to loamy surface Brown Sodosols across backslopes and alluvial plains (unit QA5). These sandy to loamy surface soils are subject to wind erosion. On the flood plains, which often have with a dense network of branching stream channels, soils are dominated by self mulching to pedal Brown, Grey and minor Black Vertosols (unit QA7) with very high salt levels at 0.5-1.0 m reflected in the rooting depth. Scalded red and brown Dermosols and Brown Vertosols with a dispersive, coarse-structured, sodic surface over vertic, strongly sodic subsoil with very high salt levels at 0.3 to 0.4 m (unit QA6).

These scalded clay soils are common in the Saxby and Flinders River area. Landscape units 3 – 6 and 9 are susceptible to wind erosion particularly around disturbed areas e.g. watering points.

Slightly elevated rarely flooded alluvial plains of (unit QA8) are predominantly Brown, Grey, Black or occasionally Red Vertosols (Cloncurry area) that have weakly to moderately self-mulching surfaces over calcareous sodic subsoils with a salt layer at 0.6 to 0.9 m. The self mulching floodplain Vertosols (unit QA7) together with a dense network of branching stream channels (unit QA10) make up large areas of the Flinders River alluvium. Initial field assessments suggest that large areas of this landscape type may be suitable for a range of irrigated agriculture.

Apx Figure A.2 Brown vertosol, north of Cloncurry Australia (CSIRO, DSITIA)



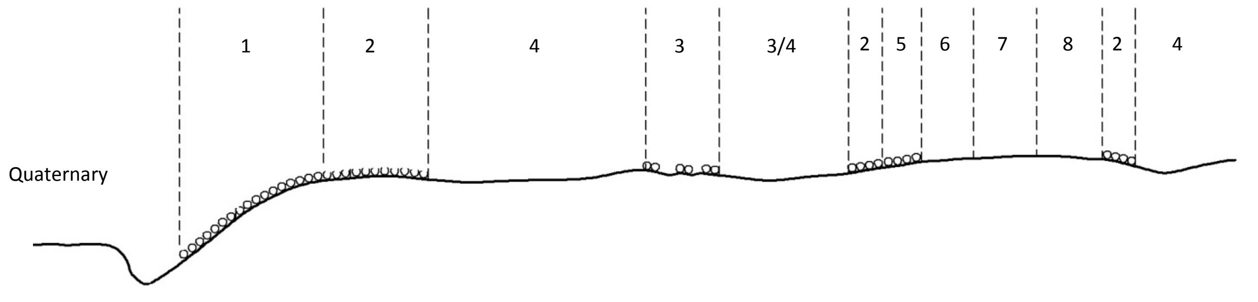
Unit	Lithology	Landform	Soils	Sites
QA1	Unconsolidated Quaternary alluvium	Stream channel	Very deep Rudosols	
QA2	Unconsolidated Quaternary alluvium	Stream bank	Stratic Rudosols	126, 136
QA3	Unconsolidated Quaternary alluvium	Levee	Very deep, loamy or sandy Brown Kandosols and Dermosols	30, 39, 46, 56, 105, 106, 124, 188, 180
QA4	Unconsolidated Quaternary alluvium	Levee backslope	Very deep, sandy and loamy Dermosols and Chromosols	117, 120, 127, 158, 159
QA5	Unconsolidated Quaternary alluvium	Alluvial plain	Very deep, loamy Brown Sodosols	157, 162
QA6	Unconsolidated Quaternary alluvium	Alluvial plain and levee backslopes	Scalded, very deep Red Dermosols mainly in the Cloncurry investigation area	118, 119, 125, 163, 166, 179
QA7	Unconsolidated Quaternary alluvium	Floodplain and alluvial plain	Very deep, self-mulching Brown and Grey Vertosols and minor Black Vertosols on the floodplain	8, 9, 29, 34, 51, 57, 58, 66, 400, 401, 402, 407, 408, 409, 421
QA8	Unconsolidated Quaternary alluvium	Alluvial plain	Very deep, Brown and Grey Vertosols and weak self-mulching Red Vertosols (in the Cloncurry Investigation area)	4, 41, 45, 59, 61, 62, 63, 67, 71, 72, 73, 109, 111, 121, 122, 123, 131, 160, 161, 173, 176, 404, 431, 439
QA9	Unconsolidated Quaternary alluvium	Floodplain	Scalded very deep Brown Vertosols, Grey Vertosols and Brown Dermosols	3, 5, 10, 24, 38, 42, 70, 78, 403, 417, 427, 435
QA10	Unconsolidated Quaternary alluvium	Floodplain with numerous branching stream channels	Very deep Grey Vertosols and Brown Vertosols with minor Black Vertosols	13, 52, 55, 430, 438

Apx Figure A.3 Schematic diagram describing the Quaternary alluvium (QA) landscape units

Tertiary alluvium

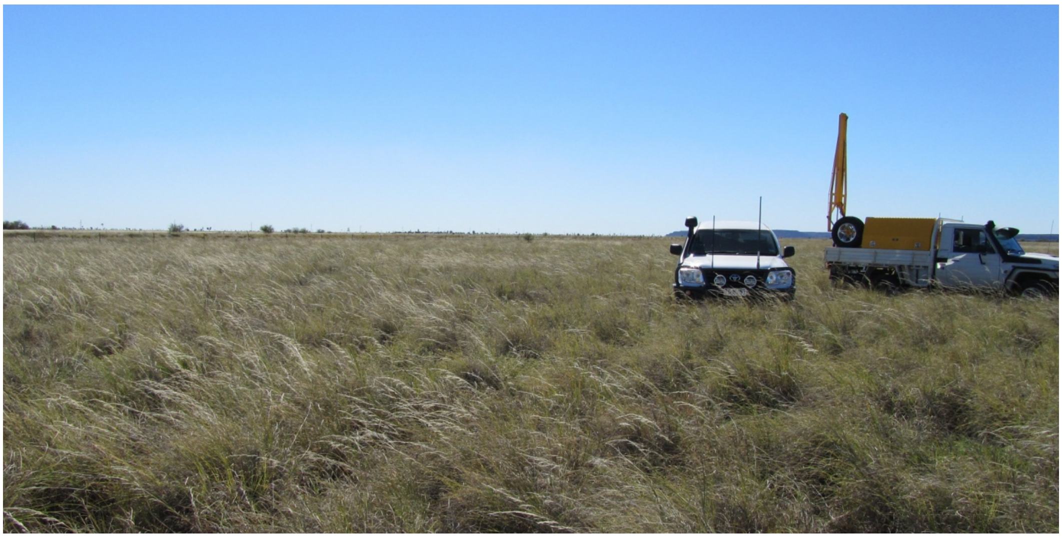
The older Tertiary alluvium (TA) is represented by elevated grasslands of clay, gravel and minor sand deposits (Apx Figure A.3). It is differentiated from the younger Quaternary alluvium by a low radiometric signature indicating a different age and origin of sediments. These extensive, elevated, non-flooded, level to gently undulating plains include incisions of recent Quaternary alluvium and all soils contain mixed gravels ranging from 2 mm to 250 mm derived from various origins. Soils are predominantly very deep, pedal, strongly sodic Grey Vertosols and minor areas of Brown Vertosols (unit TA4) with gypsum segregations and a rooting depth of 0.6-0.8m (corresponding to a salt layer). Similar, deep, pedal, strongly sodic Grey and Brown Vertosols or sometimes Black Vertosols with gypsum segregations and a rooting depth of 0.4 to 0.6 m (corresponding to a salt layer) occur on plains (unit TA2) characterised by gilgai and gravel (unit TA2). A group of gravelly, vertic, sodic Grey Dermosols (unit TA3) exist in a range of gilgai, scalded or dispersive sealing surfaces and in complexes with unit TA4. Lower slopes and areas adjacent to the Quaternary alluvium are gravelly, Red Chromosols or Sodosols or mottled Brown Dermosols (unit TA1).

To the north and north-east of Cloncurry are extensive, slightly elevated plains that lack drainage patterns are have gravelly, mottled, Brown Dermosols (unit TA5). Unit TA6 has loamy to sandy surface, mottled Brown Dermosols and Brown Chromosols; unit TA7 slightly elevated mottled Yellow and Red Kandosols (unit TA7); and unit TA8 deep Red Kandosols. These level plains support Spinifex communities and minor sheet and rill erosion occur on gentle slopes. Large areas of this landscape unit appear to have the potential for a range of irrigated agriculture.



Unit	Lithology	Landform	Soil	Sites
TA1	Unconsolidated Tertiary alluvium	Lower slopes and fans	Gravelly Red Chromosols or Sodosols or deep mottled Brown Dermosols	20, 68, 100, 150, 419, 426, 428
TA2	Unconsolidated Tertiary alluvium	Gilgaied plains	Grey Vertosols and Brown Vertosols	156, 171, 189
TA3	Unconsolidated Tertiary alluvium	Plains	Very deep, vertic Grey Dermosols	14, 167, 182, 420, 423
TA4	Unconsolidated Tertiary alluvium	Level plains	Very deep, pedal ,sodic Grey Vertosols, some minor Brown and Black Vertosols	15, 18, 19, 25, 53, 101, 102, 103, 104, 108, 116, 151, 153, 168, 181, 183, 406, 418, 422
TA5	Unconsolidated Tertiary alluvium	Plains	Gravelly mottled Brown Dermosols (Cloncurry area)	115, 170
TA6	Unconsolidated Tertiary alluvium	Plains	Loamy or sandy surfaced, mottled Brown Dermosols and Chromosols (Cloncurry area)	112, 113, 177, 190, 191
TA7	Unconsolidated Tertiary alluvium	Slightly elevated plains	Mottled Yellow and Red Kandosols (Cloncurry area)	114, 169
TA8	Unconsolidated Tertiary alluvium	Slightly elevated plains	Deep Red Kandosols (Cloncurry area)	152

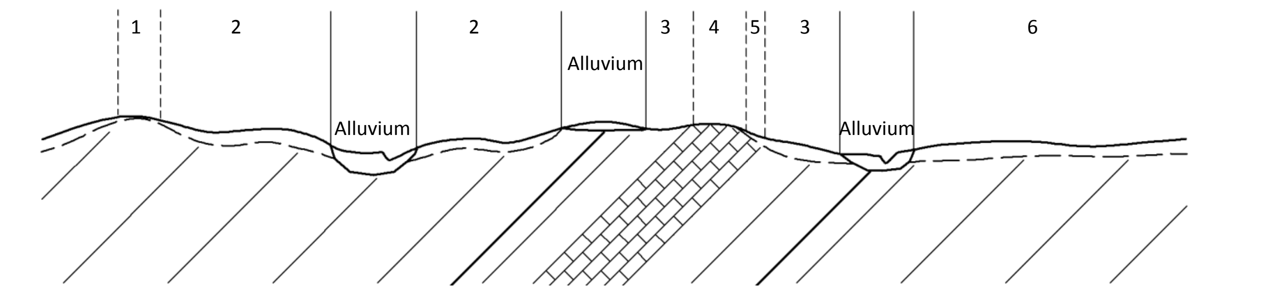
Apx Figure A.4 Schematic diagram describing the Tertiary alluvium (TA) landscape units



Apx Figure A.5 Grey Vertosol, north east of Cloncurry Australia (CSIRO, DSITIA)

A.3.2 ROLLING DOWNS

The Cretaceous sediments of the central Flinders catchment near Richmond and part of the Cloncurry River catchment comprise mudstones, siltstones, limestone, shale and some sandstone (Apx Figure A.4). Together these form extensive areas of gently undulating plains and rises with slopes of 1-5%. Large areas of fine-grained sediments are dominated by moderately deep, self mulching Brown Vertosols with strongly sodic subsoils and a salt layer at 0.5 to 0.9 m often containing gypsum and carbonate segregations. The rooting depth of these soils is limited by the depth at which very high salt levels occur (unit RD2). Similar soils to this Brown Vertosol with the salt layer varying in depth between 0.3-0.8 m (unit RD3) occur on limestone. Minor areas of similar Brown Vertosols on mudstones have the salt layer at 0.2 to 0.4 m (unit RD6). Minor gully erosion is evident on steeper slopes (>3%), and moderately deep Brown Dermosols occur on slight rises or where the underlying sediments are slightly harder (unit RD1). Shallow to very shallow Calcarosols occur on limestone ridges (unit RD4). Sheet erosion is evident on the shallow ridges. A moderately deep Brown Dermosol, an intergrade soil (unit RD5), occurs between land units 3 and 4. Due to the very high salt levels in the soil profile, deep drainage from irrigation may mobilise the salts and cause secondary salinisation on lower slopes.



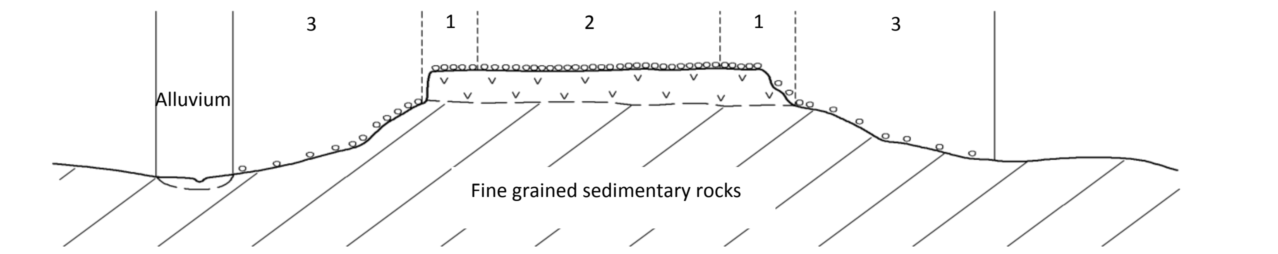
Unit	Lithology	Landform	Soils	Sites
RD1	Mudstone, siltstone, labile sandstone and limestone	Gently undulating plains and rises	Shallow Brown Dermosols	11
RD2	Mudstone, siltstone, labile sandstone and limestone	Gently undulating plains and rises	Moderately deep to deep self-mulching Brown Vertosols	16, 17, 21, 22, 23, 32, 35, 65, 69, 405
RD3	Limestone and calcareous shale	Gently undulating plains and rises	Moderately deep to deep self-mulching Brown Vertosols, minor Red Vertosols	47, 48, 49, 74, 75, 76, 415
RD4	Limestone and calcareous shale	Gently undulating plains and rises	Shallow to moderately deep Calcarosols	50, 416
RD5	Limestone and calcareous shale	Gently undulating plains and rises	Moderately deep gravelly Brown Dermosols	12
RD6	Mudstone, calcareous siltstone	Very gently undulating plains	Deep Brown Vertosols	1, 44

Apx Figure A.6 Schematic diagram describing the Rolling Downs (RD) landscape units

Apx Figure A.7 Rolling downs Vertosols, west of Hughenden Australia (CSIRO, DSITIA)

A.3.3 BASALT LANDSCAPES

In the Upper Flinders catchment, to the north of Richmond and Hughenden, there are areas of Tertiary and Quaternary basalt that form plains, undulating rises, plateaus and dissected tablelands (Apx Figure A.5). The basalt flows are characterised by extensive rock outcrops and well-developed scarps which have evolved due to erosion of the easily weathered, soft underlying Cretaceous sediments, and subsequent collapse of the hard resistant basalt cap. On the edges and scarps of the plateau and tablelands, there are shallow to very shallow, rocky Black Dermosols (unit B1). Soils on the level plateaus and plains are dominated by extremely rocky (greater than 90% boulders) moderately deep Black Vertosols with weakly developed gilgai (unit B2). The colluvial basaltic material on the lower slopes below the scarps has developed very rocky, moderately deep Brown and Grey Vertosols with a salt layer at 0.5 to 0.7 m (unit B3). Erosion rills and gullies are common. There are likely to be limited locations for irrigated agricultural due to the terrain, rockiness and salinity in this landscape type.



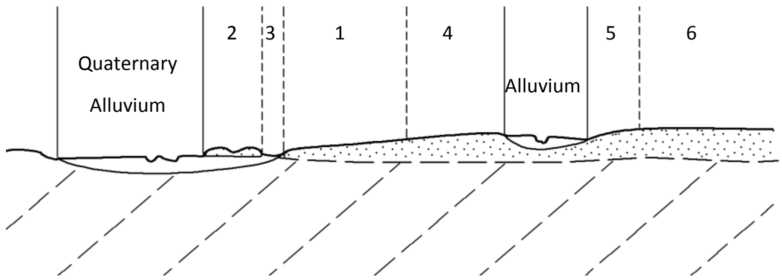
Unit	Lithology	Landform	Soils	Sites
B1	Tertiary-Quaternary basalt	Flat edges and scarps of plateau and dissected tablelands	Shallow to very shallow, rocky Black Dermosols	26, 54
B2	Tertiary-Quaternary basalt	Lava plains, undulating rises, plateaus and dissected tablelands	Rocky, gilgaied moderately deep Black Vertosols	36
B3	Tertiary-Quaternary basalt colluviums over Cretaceous sediments	Pediment	Moderately deep to deep Brown and Grey Vertosols	6, 7, 28, 37, 43

Apx Figure A.8 Schematic diagram describing the Basalt (B) landscape with 3 distinct landscape units

Apx Figure A.9 Basalt slope and (b) rocky surfaced plateau, north of Hughenden Australia (CSIRO, DSITIA)

A.3.4 SAND PLAINS

In the Saxby River investigation area extensive sand plains composed of sand and loamy alluvium developed during the Tertiary and Quaternary period following erosion and weathering of the Jurassic quartzose sandstones and geologies to the east of the Saxby River. These sediments have since formed alluvial fans, plains and stream deposits (Apx Figure A.6). Typical features of the alluvial fan sediments are the occurrence of deep sandy soils, mainly Yellow Tenosols (unit SP6); sandy surfaced mottled Brown Dermosols and Sodosols (unit SP1); and Red Kandosols (unit SP4) with minor mottled Yellow Kandosols (unit SP5). The landscape has a low gradient with undulating plains, often with internal drainage depressions and a lack of distinct relict drainage patterns. Some minor, low, wind-blown sand deposits occur on and adjacent to Quaternary alluvium (unit SP2). These wind-blown sands have Red Tenosols with relatively thin (less than 2 m) sand deposits overlying saline, hard setting, strongly sodic, poorly drained Grey Vertosols in the internal drainage depressions (unit SP3). There are likely to be limited areas with potential for irrigated agriculture within this landscape unit.



Unit	Lithology	Landform	Soils	Sites
SP1	Unconsolidated Tertiary and Quaternary alluvium	Paleo- alluvial fans, levees and stream deposits	Very deep, mottled Brown Dermosols or Chromosols or Sodosols	20, 68, 419, 426, 428
SP2	Unconsolidated (wind blown) quaternary sand	Sand plain	Very deep, Red-orthic Tenosols	436
SP3	Unconsolidated Tertiary and Quaternary alluvium	Drainage depressions	Very deep hard setting Grey Vertosols	437
SP4	Unconsolidated Tertiary and Quaternary alluvium	Paleo-alluvial fan	Very deep, Red Kandosols	429
SP5	Unconsolidated Tertiary and Quaternary alluvium	Paleo-alluvial fan	Very deep, mottled Yellow Kandosols	434
SP6	Unconsolidated Tertiary and Quaternary alluvium	Paleo-alluvial fan	Very deep, Yellow-orthic Tenosols	432, 433

Apx Figure A.10 Schematic diagram describing the Sand Plains (SP) landscape units

Apx Figure A.11 Deep sandy soils, Saxby River Australia (CSIRO, DSITIA)

A.4 Gilbert geomorphology descriptions

The major geomorphic landscape units in the Gilbert catchment include the:

(i) Alluvial sediments, which are broken into
- Upstream Quaternary alluvium
- Downstream Quaternary alluvium and
- Tertiary alluvium

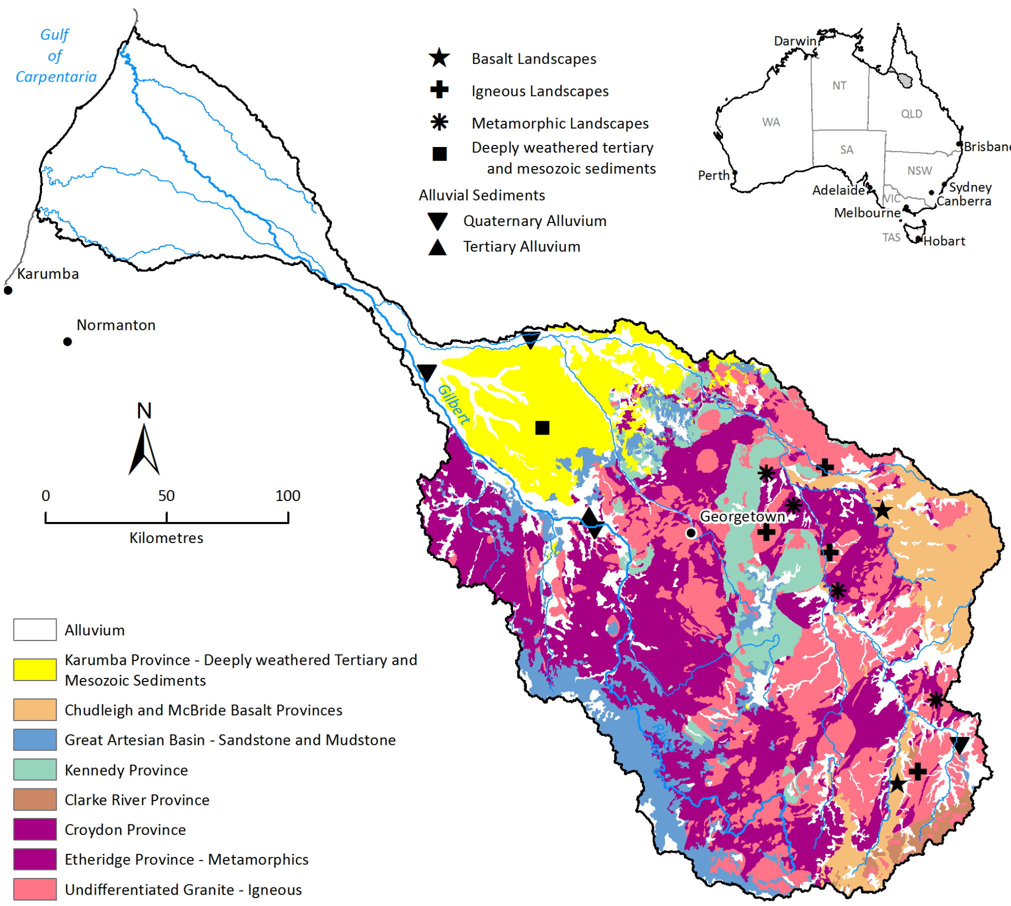
(ii) Basalt Landscapes

(iii) Igneous Landscapes

(iv) Metamorphic Landscapes and

(v) Deeply weathered tertiary and Mesozoic sediments

The soils with the greatest irrigation potential in the investigation areas lie within the alluvial sediments and range from Quaternary to Tertiary in age. These alluvial sediments are co-located with the main tributaries of the various river systems and consequently some irrigation developments already take advantage of this. The alluvial sediments in the Gilbert investigation area are not as extensive as those found in the Flinders as they are laterally constrained to a larger extent, by older geological landscapes with greater relief and shallow, rocky soils of low irrigation potential. Some areas of loamy and clayey soils offer irrigation potential outside the Primary and Secondary investigation areas with the clayey soils requiring care in management due to a salt layer at 30cm. Sections A.4.1 to A.4.5 describe each of the five major landscape units in more detail, and provide a description of the composition and distribution of soils within each landscape unit. It is important to note that each investigation area may contain several landscape units.



Apx Figure A.12 Location of five major landscape units (Basalt, Igneous, Metamorphic, Tertiary and Mesozoic sediments and Alluvial sediments) in the Gilbert catchment

A.4.1 ALLUVIAL SEDIMENTS

The Alluvial Sediments are characterised by current and relict channels, levees, alluvial plains, back plains and drainage depressions of the Gilbert and Einasleigh Rivers. These unconsolidated materials were deposited from the Tertiary to Quaternary period**.**

The Tertiary and Quaternary alluvium are differentiated by radiometric signature with high potassium coinciding with the Quaternary alluvial profiles. Increased exposure time and weathering has elluviated some of the potassium resulting in lower radiometric responses in Tertiary alluvia.

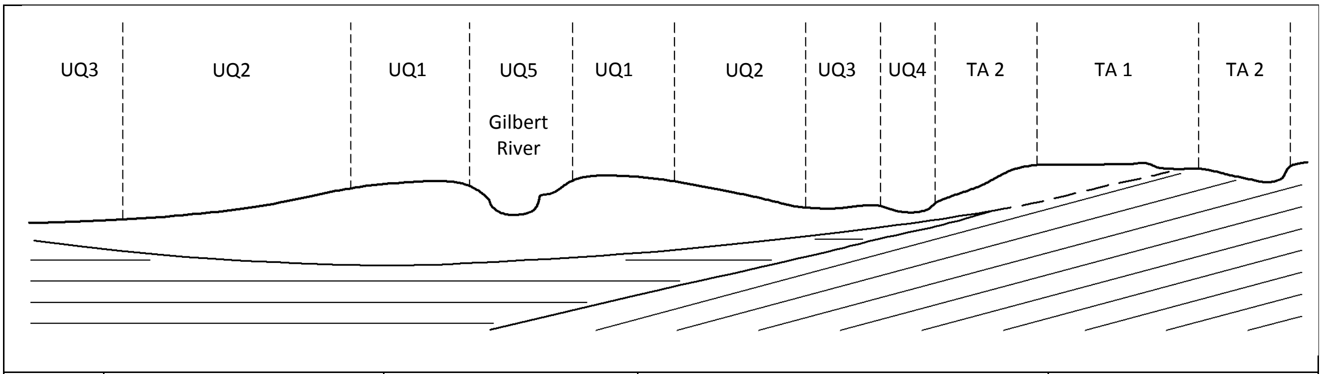
Quaternary alluvium occurs along the lower Gilbert and Einasleigh Rivers upstream of their confluence with the Gilbert River alluvium and has two distinct components. The 'Upstream' component is from the Pillars, mapped by Enderlin (Unpub) to about 30km downstream of the Georgetown-Croydon Road crossing. The 'Downstream' component continues downstream from this 30km point to the confluence with the Einasleigh River. In the 'Downstream' section the floodplain is wider, the landform elements are topographically much less distinct with more dissection by minor stream channels, and soils are generally less well drained than in the 'Upstream' section.

Upstream Quaternary Alluvium

The Upstream Quaternary Alluvium (UQA) consists of unconsolidated sand, loam and clay sediments associated with current stream channels, levees, plains, backplains and drainage depressions originating from a range of geologies (Apx Figure A.13). Outwards from the sandy, gravelly stream channels (unit UQ5) are levees of slopes 1 - 3% with very deep, well drained Brown Kandosols (unit UQA1). The levees grade to plains of 1 – 2% slope. The transition soils from the upslope levees are Red and Brown Kandosols. The larger plains areas are very deep, well drained Brown and Red Dermosols (unit UQA2). Downslope there can be backplains, although they are not always present in the sequence. They have slopes of < 1%, and have very deep, mottled, sodic Brown Dermosols. Sodicity is most likely a result of reduced drainage relative to the more elevated surrounds. A number of Brown and Black Sodosols and minor Chromosols are also found (unit UQA3). Drainage depressions and swamps are located in the lowest lying parts of the alluvial landscape. They sometimes mark the boundary between the Quaternary and Tertiary alluvial units. This unit comprises mainly very deep, mottled Brown Sodosols and Sodic Dermosols with minor Chromosols and Grey Vertosols (unit UQA4).

Tertiary Alluvium

Adjacent to sections of the 'Upstream' quaternary alluvium are discrete areas of more elevated Tertiary alluvium (Apx Figure A.13). These occur as level to gently undulating plains and rises dominated by deep, whole coloured, well drained Red Dermosols and Chromosols with some Kandosols with slight gravel (unit TA1). Backplains of slope < 1% occur in the lowest parts of the Tertiary alluvium with deep, mottled Brown Dermosols and Chromosols with common ferromanganiferous segregations. Other minor soils present are Red, Yellow and Grey Dermosols, Chromosols and Kandosols (unit TA2).



Unit	Lithology	Landform	Soil	Sites Enderlin* soil name and sites in brackets GARA sites in bold
UQA 1	Unconsolidated Quaternary Alluvium	Levees	Very deep Brown and minor Red Kandosols. Well drained and whole coloured often with underlying sequential sedimentary layers	**220 (sampled).** [Pleasant - 324 (sampled), 4-7, 17, 44, 71, 73, 102, 103, 110, 118, 119, 122, 123, 130,145, 151, 166, 180, 192, 210, 211, 217, 226, 228, 231, 234, 301]
UQA 2	Unconsolidated Quaternary Alluvium	Plains (Back slopes of Levees)	Dominant very deep whole coloured Brown and Red Dermosols. Very few coarse fragments or segregations. Minor Red or Brown Kandosols Underlying sequential sedimentary layers are common	[Venture 9, 24-26, 31-32, 49, 72, 75, 79, 87, 96, 98-100, 111, 112, 124, 130, 135, 136, 167, 177, 178, 181, 183, 193, 208, 218, 223-225, 227, 229, 230, 232, 244, 267, 268, 270, 271, 293]
UQA 3	Unconsolidated Quaternary Alluvium	Backplains	Very deep Brown (minor black) Dermosols mostly mottled and sodic. Underlying sequential sedimentary layers are common. Brown and Black Sodosols Minor Brown Chromosol and Kandosol	[Toby - 209 (sampled), 51, 91, 182, 241, 245, 253, 254, 259, 262, 272, 277 184 (sampled), 8, 274 45, 242]
UQA 4	Unconsolidated Quaternary Alluvium	Drainage Depressions, minor swamps	Very Deep Brown Sodosol (mottled) Very Deep Brown Dermosol (mottled, sodic) Deep Grey and Brown Chromosols Grey Vertosols	[Toby - 2, 74 86 68, 233] [Prestwest - 248, 308]
UQA 5	Unconsolidated Quaternary Alluvium	Channels, minor stream beds and banks	Deep Clastic Rudosol	**271** (riverbed)
TA 1	Unconsolidated Tertiary Alluvium	Elevated Plains	Deep Red Dermosols and Chromosols and minor Kandosols	[Gulfroad - 11, 15, 114, 115, 121, 137, 149, 161, 173, 185, 188, 203, 212, 214, 314, 321, 325(sampled)] [Brandyhat - 18, 80, 128, 143, 200, 289, 295, 297, 304, 305, 311 (sampled)]. [Boretrack - 36] [Lynch - 222 (sampled), 316, 199]
TA 2	Unconsolidated Tertiary Alluvium	Backplains	Deep mottled Brown (minor red, yellow and grey) Dermosols and Chromosols with minor Kandosols. Many profiles with ferromanganiferous segregations	[Gulfroad - 198 Boretrack - 10, 12, 20, 33, 170, 202, 206, 213, 294, 296, 298, 323. Lynch - 159, 169, 201, 204]

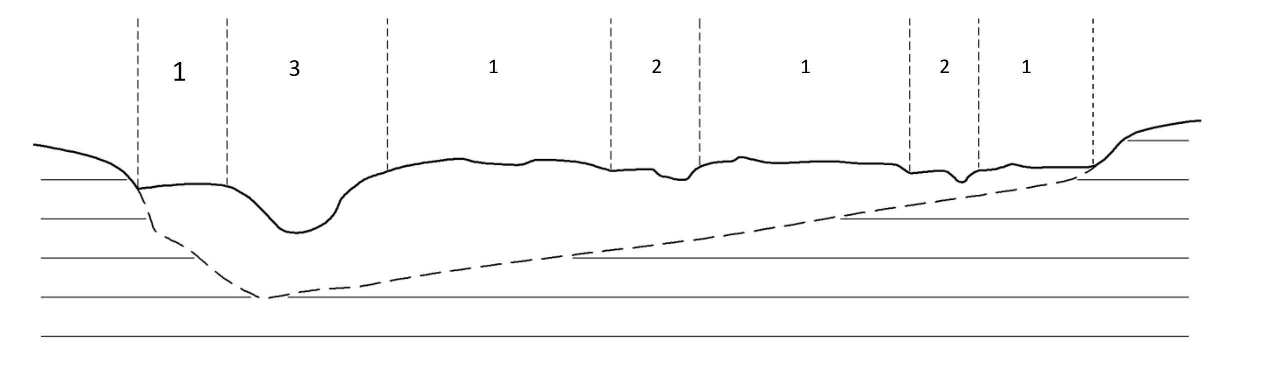
Apx Figure A.13 Schematic diagram describing the Upstream Quaternary (UQA) and Tertiary Alluvial (TA) landscape units

Apx Figure A.14 Upstream quaternary alluvium, Gilbert River Australia (CSIRO, DSITIA)

Apx Figure A.15 Tertiary alluvium, Gilbert River Australia (CSIRO, DSITIA)

Downstream Quaternary Alluvium

The downstream alluvial landscape is broader with less relief and is more dissected by overflow channels (Apx Figure A.16) than the upstream alluvium. These differences in landscape features point to contrasting hydrological conditions and flood characteristics between the upper and downstream alluvial landscapes. Outwards from the sandy, gravelly stream channels (unit DQA3) are floodplains of soils displaying indications of periods of waterlogging – mottling, darker colours and segregations. Mottled Brown Dermosols, mottled Grey Chromosols and a mottled Yellow Kandosol occupy the Gilbert River floodplains (unit DQA1) with Vertosols more extensive on the Einasleigh River floodplain. The lower wetter drainage depressions are Hydrosols and an Aquic Vertosol (unit DQA2).



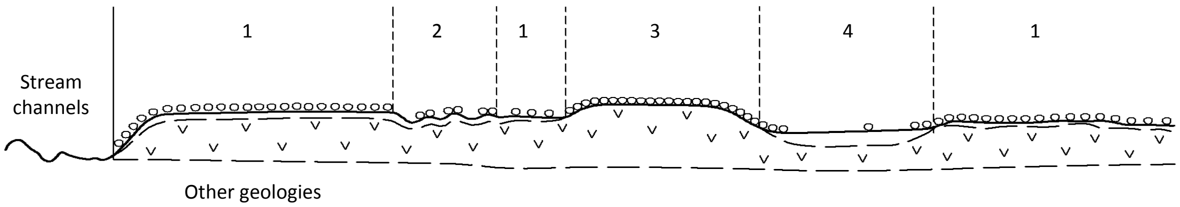
Unit	Lithology	Landform	Soil	Sites
DQA 1	Unconsolidated Quaternary Alluvium	Flood plain	Mottled Brown Dermosols, Grey Chromosol, Mottled Yellow Kandosol, Grey Vertosol	202-204, 257, 261, 269
DQA 2	Unconsolidated Quaternary Alluvium	Drainage Depression	Hydrosol	254
DQA 3	Unconsolidated Quaternary Alluvium	Stream bed	Rudosol	271

Apx Figure A.16 Schematic diagram describing the Downstream Quaternary Alluvium (DQA) landscape units

Apx Figure A.17 Harvested dryland sorghum on downstream quaternary alluvium, near the junction of the Gilbert and Einasleigh Rivers Australia (CSIRO, DSITIA)

A.4.2 BASALT LANDSCAPES

The Mt Surprise, Einasleigh and Lynd areas have Quaternary basalt occurring as undulating rises and plains with low scarps adjacent to stream channels and associated springs and spring fed wetlands (Apx Figure A.18). These basalt flows are characterised by extensive rock outcrop. Soils are dominated by rocky Red Ferrosols (unit B1), with shallower Red Ferrosol outcrops representing unit B3. Black Vertosols with gilgai (unit B2) are associated with the Ferrosols, while very deep Grey Vertosols occur in drainage depressions (unit B4). There are limited areas for agriculture due to the rockiness of the landscape.



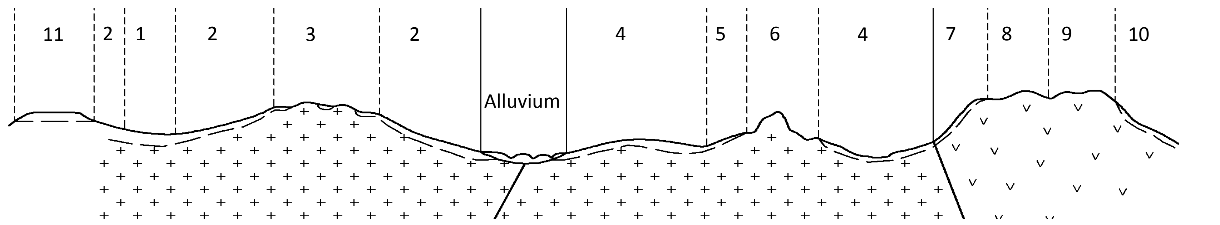
Unit	Lithology	Landform	Soil	Sites
B1	Quaternary basalt	Lava plain	Moderately deep Red Ferrosol	327, 328
B2	Quaternary basalt	Lava plain	Gilgaied deep Black Vertosol	321
B3	Quaternary basalt	Lava plain	Shallow Red Ferrosol, Black Dermosol	330, 451
B4	Quaternary alluvium	Drainage depression	Deep Grey Vertosol	304, 332

Apx Figure A.18 Schematic diagram describing the Basalt (B) landscape units

Apx Figure A.19 Basalt landscape, north of Mt Surprise Australia (CSIRO, DSITIA)

A.4.3 IGNEOUS LANDSCAPES

A range of acid, intermediate and basic intrusive and extrusive igneous rocks are widespread throughout the upper catchment (Apx Figure A.20). Acid intrusive (granites) typically have very shallow, sandy, bleached Tenosols or occasional sandy Kandosols with rock outcrop on the upper slopes (unit I3), deep sandy surface, mottled Brown Sodosols on lower slopes (unit I2) and deep bleached Tenosols in drainage depressions (unit I1). The acid volcanics (rhyolites) of the Newcastle Range have shallow bleached Tenosols (unit I7). Intermediate intrusives (granodiorite, tonalite) have shallow Red Chromosols/Dermosols (unit I5) and abundant rock outcrops with Bleached Tenosols on upper slopes (unit I6) grading to moderately deep to deep, sandy surface, Brown Sodosols on lower slopes (unit I4). The intermediate volcanics (andesites) of the Newcastle Range have shallow Red/Brown Dermosols (unit I10). Isolated areas of Tertiary alluvium are elevated remnants of gently sloping undulating rises originating from adjacent Newcastle Range Acid Volcanics. Soils have indurated outcrops on eroded slopes where the weathered Tertiary alluvium contacts with the underlying fresh granite geology (unit I11). Units I8 and I9 are rock outcrops. The soils that have formed on the Igneous geologies are generally shallow, sandy, prone to erosion and relatively steep, and thus there are few areas suitable for irrigated agriculture.



Unit	Lithology	Landform	Soil	Sites
I1	Acid intrusive (granites)	Drainage depressions	Deep Bleached-orthic Tenosols	319
I 2	Acid intrusive (granites)	Mid to lower hillslopes on rises and low hills	Moderately deep Yellow or Brown Sodosols	453, 458
I 3	Acid intrusive (granites)	Upper hillslopes on rises and low hills	Very shallow to shallow Bleached Tenosols	305, 306, 307, 309, 317, 318, 320
I 4	Intermediate intrusive (granodiorites, tonalities)	Mid to lower hillslopes on undulating rises and low hills	Moderately deep Brown Sodosols	302
I 5	Intermediate intrusive (granodiorites	Upper hillslopes on undulating rises and low hills	Shallow to moderately deep Red or Brown Chromosols or Dermosols	333, 352
I 6	Intermediate intrusive (granodiorites	Hill crests on undulating rises and low hills	Rock outcrop or shallow Bleached Tenosols	353, 354
I 7	Acid volcanic (rhyolites)	Steep hills	Shallow Bleached Tenosols	
I 8	Acid volcanic (rhyolites)	Steep hills and hill crests	Rock outcrop	350
I 9	Intermediate volcanic (andesite)	Steep hills and hill crests	Rock outcrop	
I 10	Intermediate volcanic (andesite)	Steep hills	Shallow Red or Brown Dermosols	
I 11	Tertiary alluvium fan deposits	Dissected undulating rises with very gently sloping west-east ridge crests	Indurated soils	

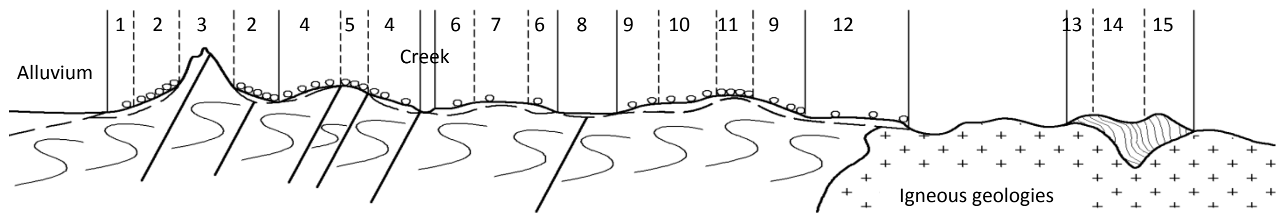
Apx Figure A.20 Schematic diagram describing the Igneous (I) landscape units

Apx Figure A.21 Igneous granite landscape (a) moderately deep Brown Sodosol (b,) west of Mt Surprise Australia (CSIRO, DSITIA)

A.4.4 METAMORPHIC LANDSCAPES

Large areas of the Einasleigh Uplands have been subject to multiple episodes of metamorphism of a range of geologies. Metamorphosed geologies are recognised based on evidence of recrystalisation and or lamination (Apx Figure A.21). Folding and faulting has produced short range variability and a complex arrangement of soils and landforms across the metamorphosed sedimentary, volcanic and intrusive geologies . Soils are dominated by moderately deep to deep Red Dermosols on the basic metamorphics (units M2, M9 and M11) varying in landscape position, soil depth, amount of gravels and rock outcrop. Deep mottled Yellow/Brown Dermosols randomly occur in association with these units and relate to changes in lithology and landscape position (unit M1 and M10). Soils formed on acid metamorphics are shallow to moderately deep Red Dermosols with abundant quartz gravels (unit M4). On hill-crests soil comprise of shallow Bleached Tenosols with abundant rock outcrops (unit M5). Intermediate metamorphics have deep Red Dermosols with sodic vertic subsoils on upper slopes (unit M7) and Brown Dermosols with sodic vertic subsoils on lower slopes (unit M6). Areas of Quaternary alluvium are represented by Vertic Brown Dermosols on local alluvial plains (unit M8) and very deep Tertiary alluvium of Red and Brown Dermosols containing quartz gravels (unit M12). The folded quartzose sandstones include sandy Bleached-orthic Tenosols on hillcrests and upper slopes (unit M13) and sandy surfaced mottled Kurosols on mid to lower slopes (unit M14). Units M3 and M15 are rock outcrops. There are limited areas of irrigated agricultural potential in these areas due to steep slopes and the presence of gravels throughout the soil profile.



Unit	Lithology	Landform	Soil	Sites
M1	Basic metamorphic with quartz outcrops	Lower slope of pediment	Deep mottled Brown Dermosol	331
M 2	Basic metamorphic with quartz outcrops	Upper slope of pediment	Deep Red Dermosol with abundant quartz gravels	325, 329
M 3	Basic metamorphic with quartz outcrops	Steep low hills and hills	Rock outcrop	
M 4	Acid metamorphic (granite gneiss, schist, quartz veins)	Hillslopes on undulating rises and low hills	Shallow to moderately deep Red Dermosols with abundant quartz gravel	334
M 5	Acid metamorphic (granite gneiss, schist, quartz veins)	Upper hillslopes on undulating rises and low hills	Very shallow to shallow Red Dermosols with abundant quartz gravel and rock outcrop	300, 316, 466
M 6	Intermediate metamorphic (diorite gneiss, schist)	Lower hillslopes on gently undulating rises	Deep Yellow or Brown Dermosols	452, 462, 464
M 7	Intermediate metamorphic (diorite gneiss, schist)	Upper hillslopes on gently undulating rises	Moderately deep to deep Red Dermosols	460
M 8	Unconsolidated Quaternary alluvium	Alluvial plain	Very deep Brown Dermosol	303, 313, 314, 459, 465
M 9	Basic metamorphic (gabbro gneiss, biotite schist)	Hillslopes on undulating rises and low hills	Deep Red Dermosols with scattered quartz gravels	315
M 10	Basic metamorphic (gabbro gneiss, biotite schist)	Hillslopes on undulating rises and low hills	Deep mottled Brown Dermosols with scattered quartz gravels	308, 310, 312, 335, 351, 355
M 11	Basic metamorphic (gabbro gneiss, biotite schist)	Upper hillslopes on undulating rises and low hills	Shallow to moderately deep Red Dermosols with scattered quartz gravels and rock outcrop	301
M 12	Unconsolidated Tertiary alluvium	Very gently undulating plains and dissected rises	Very deep Red or Brown Dermosols	456
M 13	Folded quartz sandstone	Hillslopes on undulating rises and low hills	Shallow to moderately deep Bleached-orthic Tenosols	457
M 14	Folded quartz sandstone	Hillslopes on undulating rises and low hills	Moderately deep mottled Yellow Kurosols	
M 15	Folded quartz sandstone	Steep low hills	Rock outcrop	311

Apx Figure A.22 Schematic diagram describing the Metamorphic (M) landscape units

Apx Figure A.23 Rocky Red Dermosol, Talaroo road west of Mt Surprise Australia (CSIRO, DSITIA)

A.4.5 DEEPLY WEATHERED TERTIARY AND MESOZOIC SEDIMENTS

The Tertiary sediments from the Wyaaba Beds and Bulimba Formation overlie Mesozoic sediments of Wallumbilla Formation (Cretaceous Rolling Downs Group) and the Gilbert River Formation (Late Jurassic-Cretaceous (Apx Figure A.24). The Gilbert River Formation is more dominant in the south-east, the Wallumbilla Formation is found in small areas in the north east and the Tertiary elements dominate in the centre towards the confluence of the Gilbert and Einasleigh Rivers. Together they form north-west inclined landforms of near planar to very low undulating rises with moderately inclined (3-10%) slopes in the south-east to gentle (1-3%) slopes in the north-west. Local relief ranges from up to 30m towards the south-east to less than 10m in the north-west. Colluvial slopes throughout this landscape grade to alluvial channels. Soils on rises in the Tertiary sequences often exhibit hardened ferricrete and silcrete pans and less compacted ferruginous nodular layers. Ferruginous segregations/gravels are common in soils across the entire landscape.

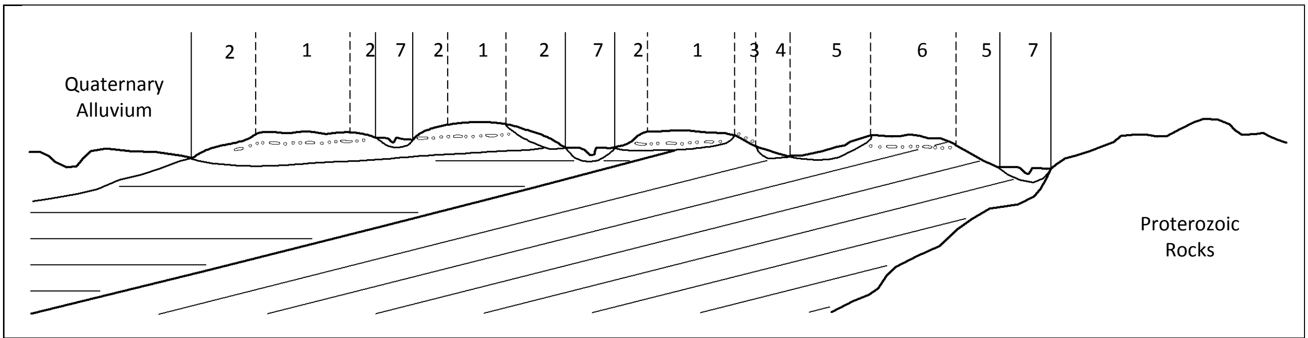
Large areas of upper slopes and crests of the very low undulating rises of the ferruginised tertiary sediments are dominated by Tenosols with ferruginous nodular layers (unit TM1); minor areas of shallow Rudosols and Kandosols had similar nodular material. Soils on undulating Tertiary colluvial rises of 3 - 6% slope are variable. Grey, Red and Brown Kandosols are most common. Grey Dermosols and Yellow Kurosols are present. The lower slopes include Grey Kurosols, Grey Chromosols and Hydrosols. Ferruginous segregations are common in most profiles (unit TM2).

A small area in the north eastern part of the study area on Abingdon Downs is the Cretaceous Wallumbilla formation. Colluvial pediments have moderately deep Brown Dermosols with ferruginised gravels derived from Tertiary sediments upslope (unit TM3). Also restricted to the Wallumbilla formation are dissected plateaus and scarps developed due to erosion of the resistant, deeply weathered, ferruginised Tertiary sediments upslope and exposed Cretaceous mudstones on lower slopes. Soils on these mudstones are deep

Black Vertosols with strongly sodic B horizons, a salt bulge (>1dS/m) beginning at 0.3m and residual surface gravel materials derived from weathered Tertiary sedimentary sequences upslope (unit TM4).

These low undulating rises include very shallow to moderately deep Brown Kandosols, Dermosols and Chromosols, Yellow Kurosols and Rudosols (unit TM5). The sandstone crests of very low undulating rises above slopes of up to 10% of unit TM5 are shallow Rudosols (unit TM6).

Significant soil variability occurs on the levees and backplains of the locally sourced alluvium reflecting source material beyond this landscape. Tenosols, Kandosols, Dermosols, Rudosols and Hydrosols are present (unit TM7).



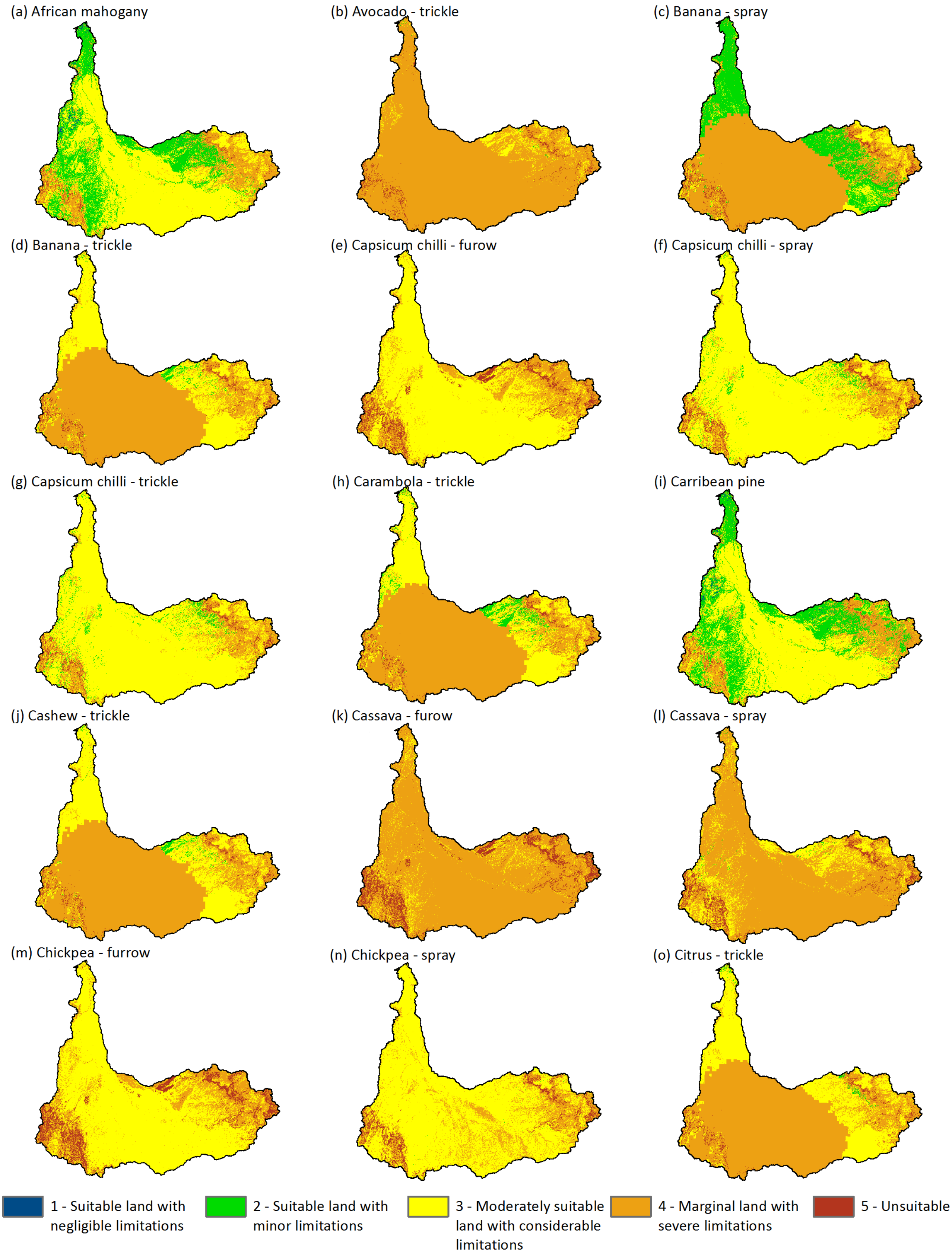
Unit	Lithology	Landform	Soil	Sites
TM 1	Tertiary sediments of the Wyaaba beds (Tmpy*) and Ferricrete formation (Tf)	Upper slopes and crests of very low undulating rises	Soils dominated by ferruginous nodules and pans (duricrusts). Dominantly shallow with some moderately deep Tenosols and Rudosols with minor Kandosols	205-210, 219 (sampled) 256, 268, 274, 278, 279
TM 2	Tertiary colluvium associated with the Wyaaba beds (Tmpy), Bulimba beds (Ti), Ferricrete formation (Tf) and Colluvium (Tqr>Tqf>JKgy)	Upper middle to lower slopes of very low undulating rises	Deep to very deep Grey Kandosols with minor red and Brown Kandosols, Dermosols and Kurosols, Chromosols and a Hydrosol. Ferruginous nodules common	200, 201, 211, 216-218, 252, 260, 264, 270, 273, 277.
TM 3	Cretaceous Wallumbilla Formation mudstone (Ku)	Pediments of very low undulating rises	Moderately deep Brown Dermosol on colluvial pediment	715
TM 4	Cretaceous Wallumbilla Formation mudstone (Ku)	Upper middle to lower slopes of very low undulating rises	Deep Black Vertosol	714
TM 5	Cretaceous sandstones and siltstones (Arenite-Mudrock) of the Coffin Hill Member (Kgf) and late Jurassic Yappar Member (JKgy). Ferruginised in places	Mid to lower slopes and foot-slopes of undulating rises	Variable. Very shallow to moderately deep Brown Kandosol, Yellow Kurosol, Brown Dermosol and a Rudosol. Brown Chromosol on a foot-slope	224, 225, 227, 250, 263
TM 6	Cretaceous sandstones and siltstones (Arenite-Mudrock) of the Coffin Hill Member (Kgf) and late Jurassic Yappar Member (JKgy). Ferruginised in places	Crests of undulating rises	Rudosols	228
TM 7	Locally sourced Quaternary alluvium	Levees and backplains	Variable. Tenosols, Red, Brown and Grey Kandosols, Yellow and Grey Dermosol, Rudosol and a Hydrosol	212, 213(sampled), 214, 253, 255, 258, 259,262, 266, 267, 272

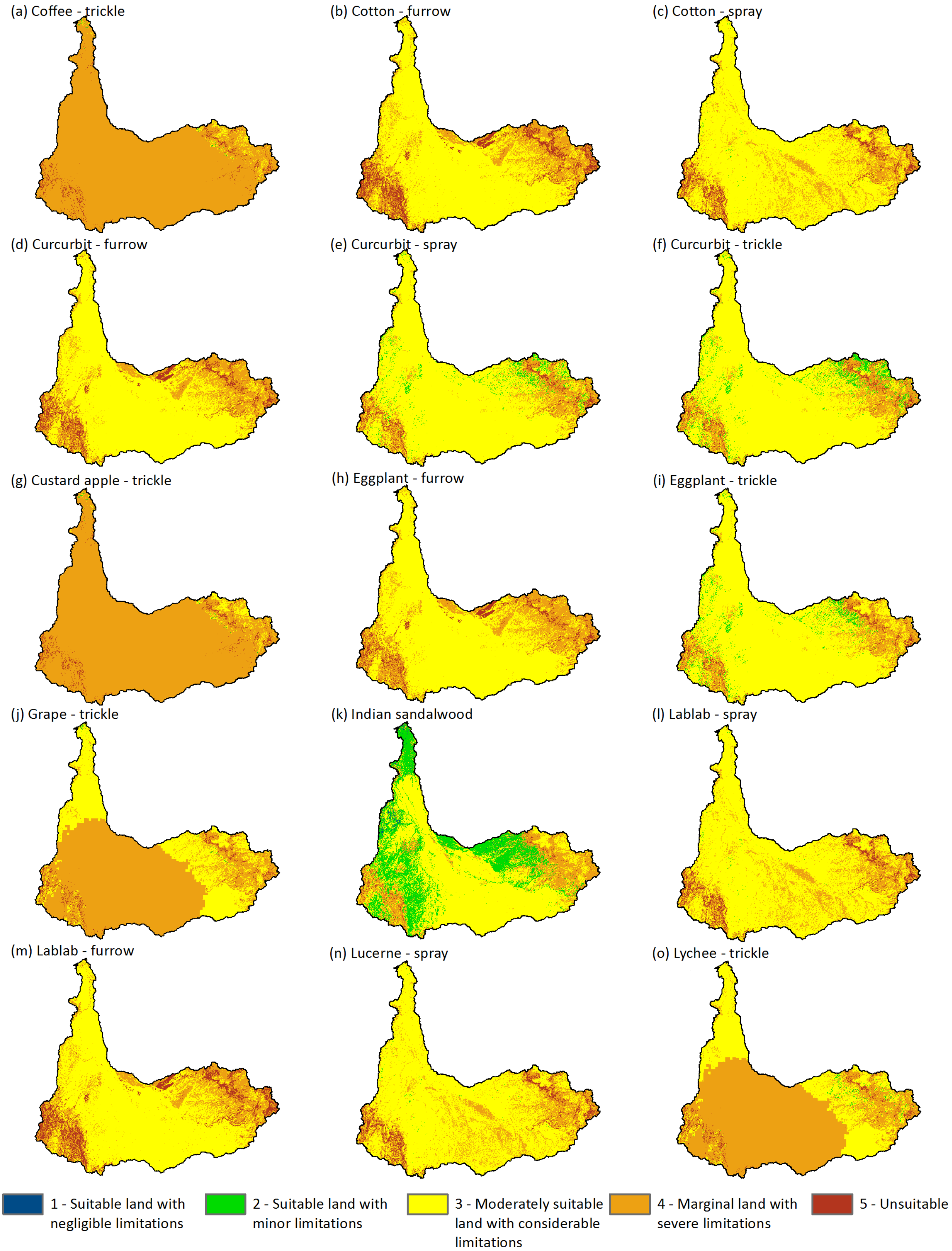
Apx Figure A.24 Schematic diagram describing the Deeply Weathered Tertiary and Mesozoic Sediments (TM) landscape units. *Geological mapping codes from 1:100k or 1:250k Queensland geology maps

Apx Figure A.25 Loamy surface textured (a) and sandy surface textured (b) Kandosols, west of Georgetown Australia (CSIRO, DSITIA)

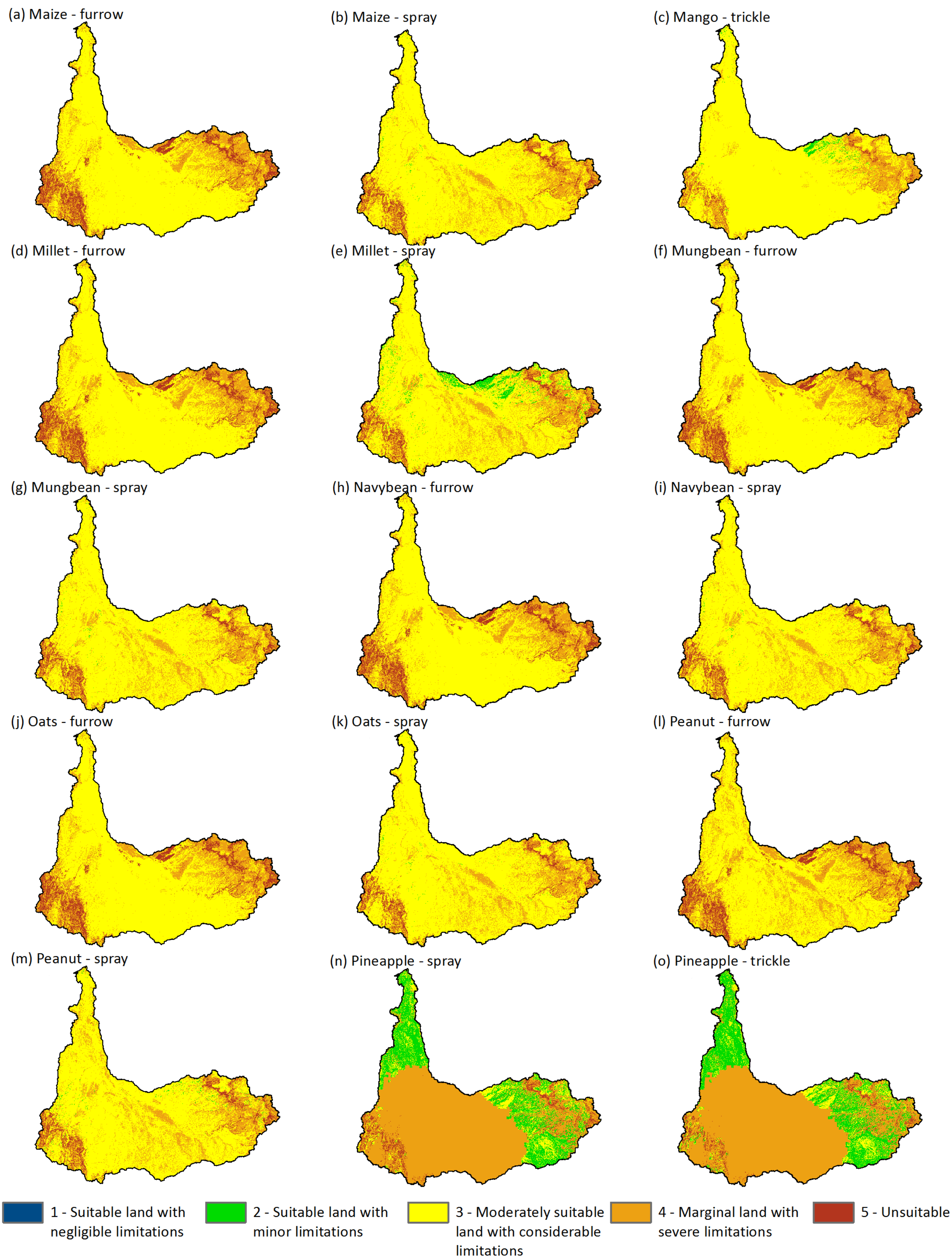
Apx Figure A.26 Ferricrete on the surface of the elevated Kandosols, west of Georgetown Australia (CSIRO, DSITIA)

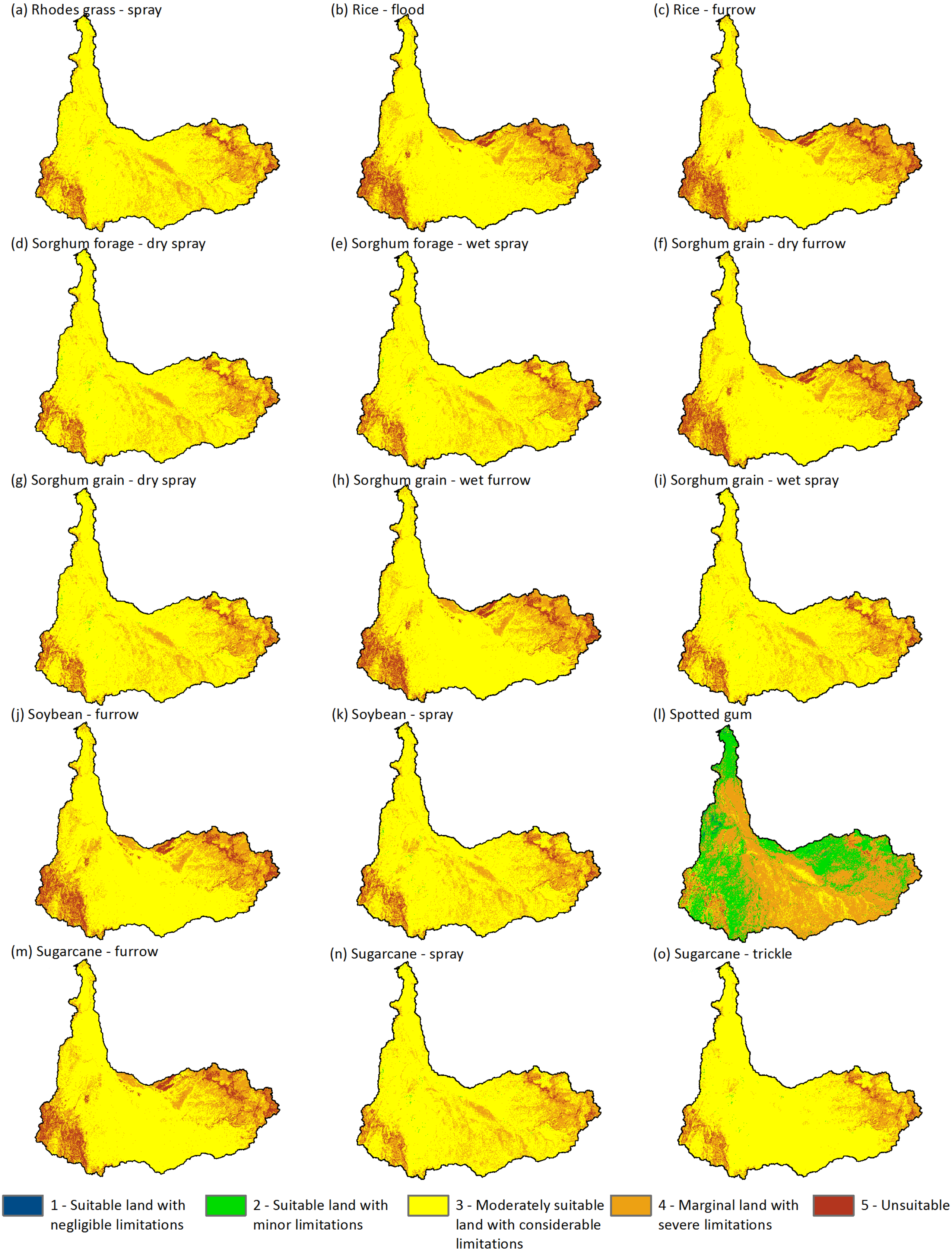
A.5 Land suitability thumbnail maps of all land uses for the Flinders Catchment

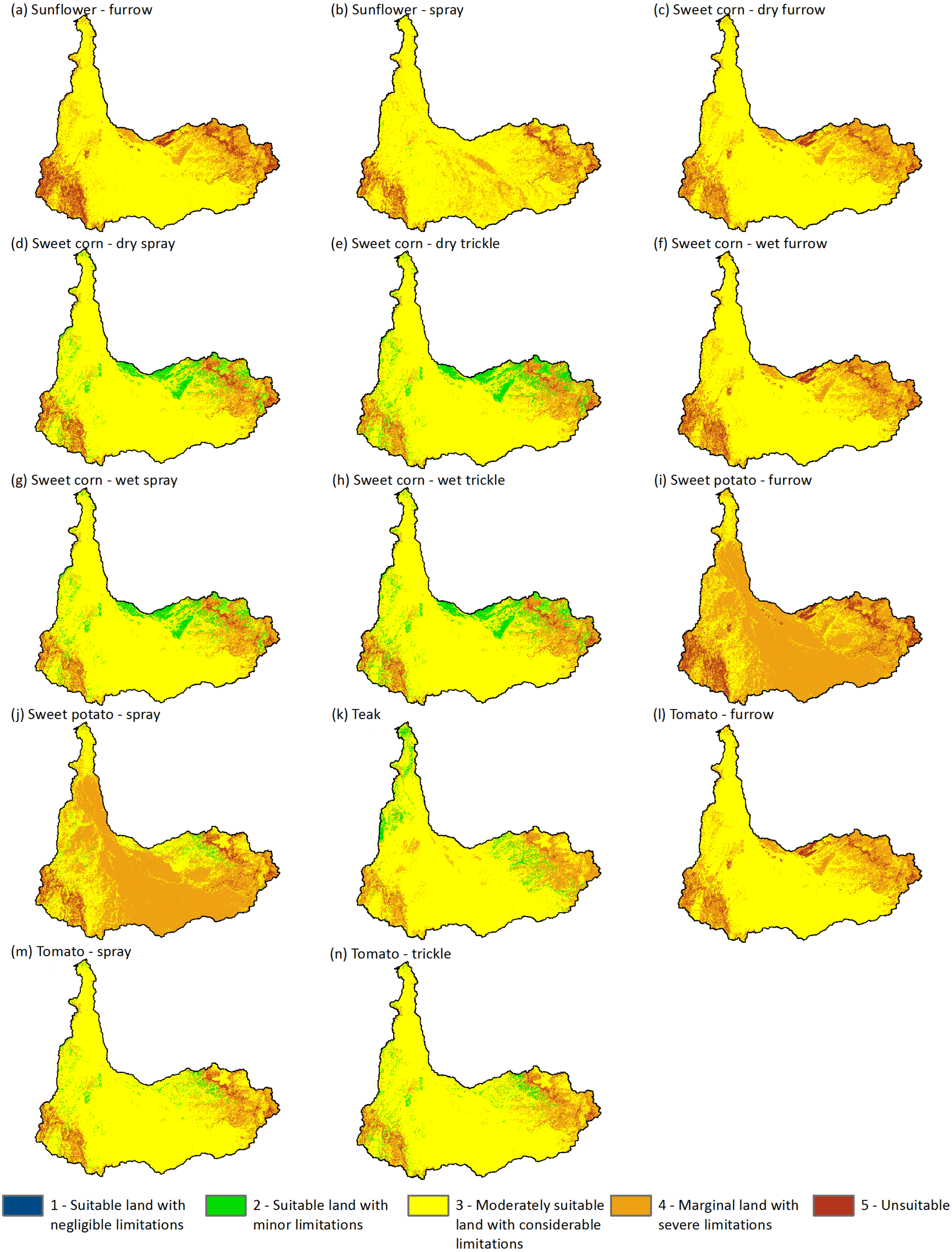




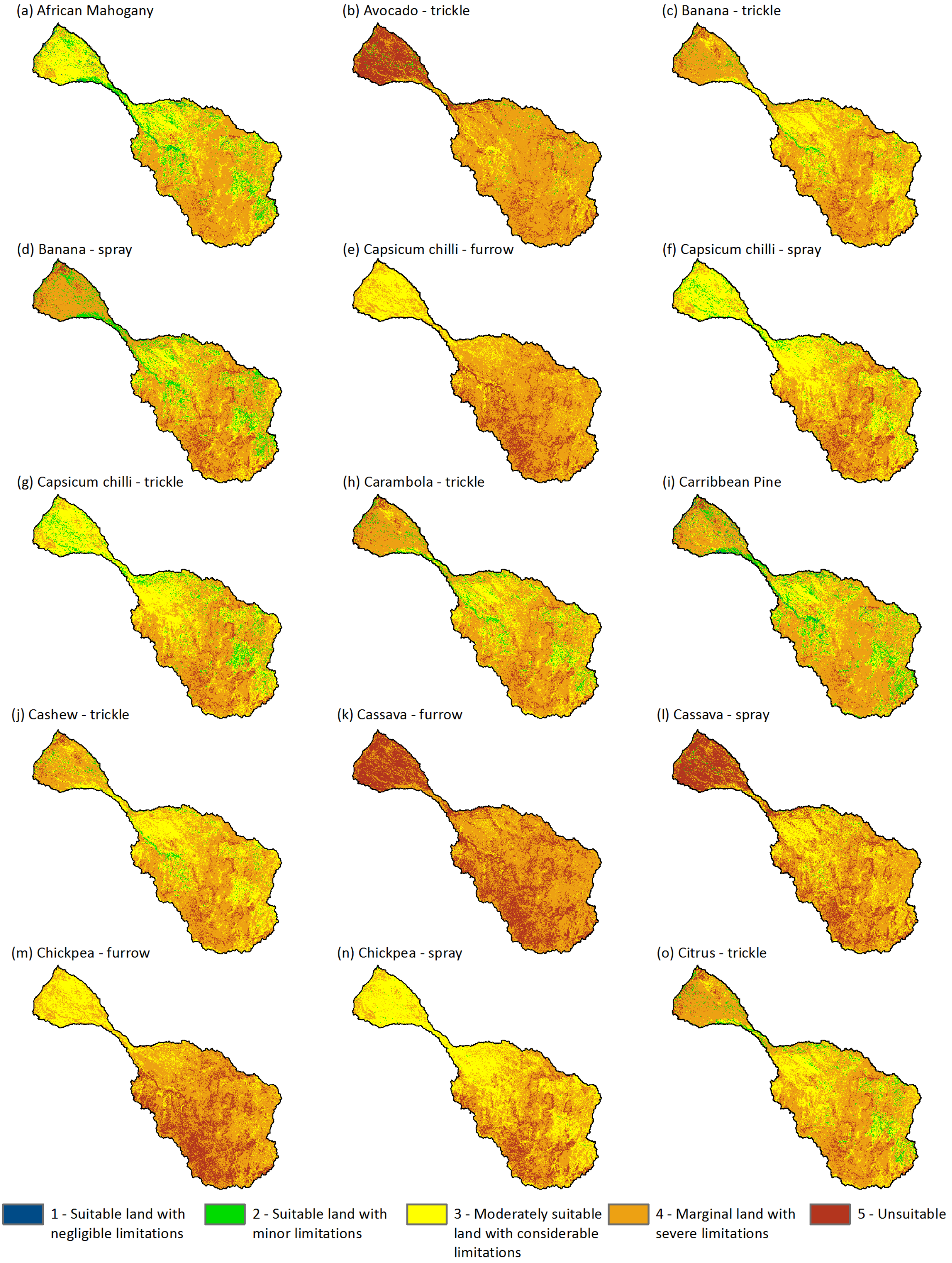
(a) Coffee - trickle
(b) Cotton - furrow
(c) Cotton - spray
(d) Curcurbit - furrow
(e) Curcurbit - spray
(f) Curcurbit - trickle
(g) Custard apple - trickle
(h) Eggplant - furrow
(i) Eggplant - trickle
(j) Grape - trickle
(k) Indian sandalwood
(l) Lablab - spray
(m) Lablab - furrow
(n) Lucerne - spray
(o) Lychee - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable

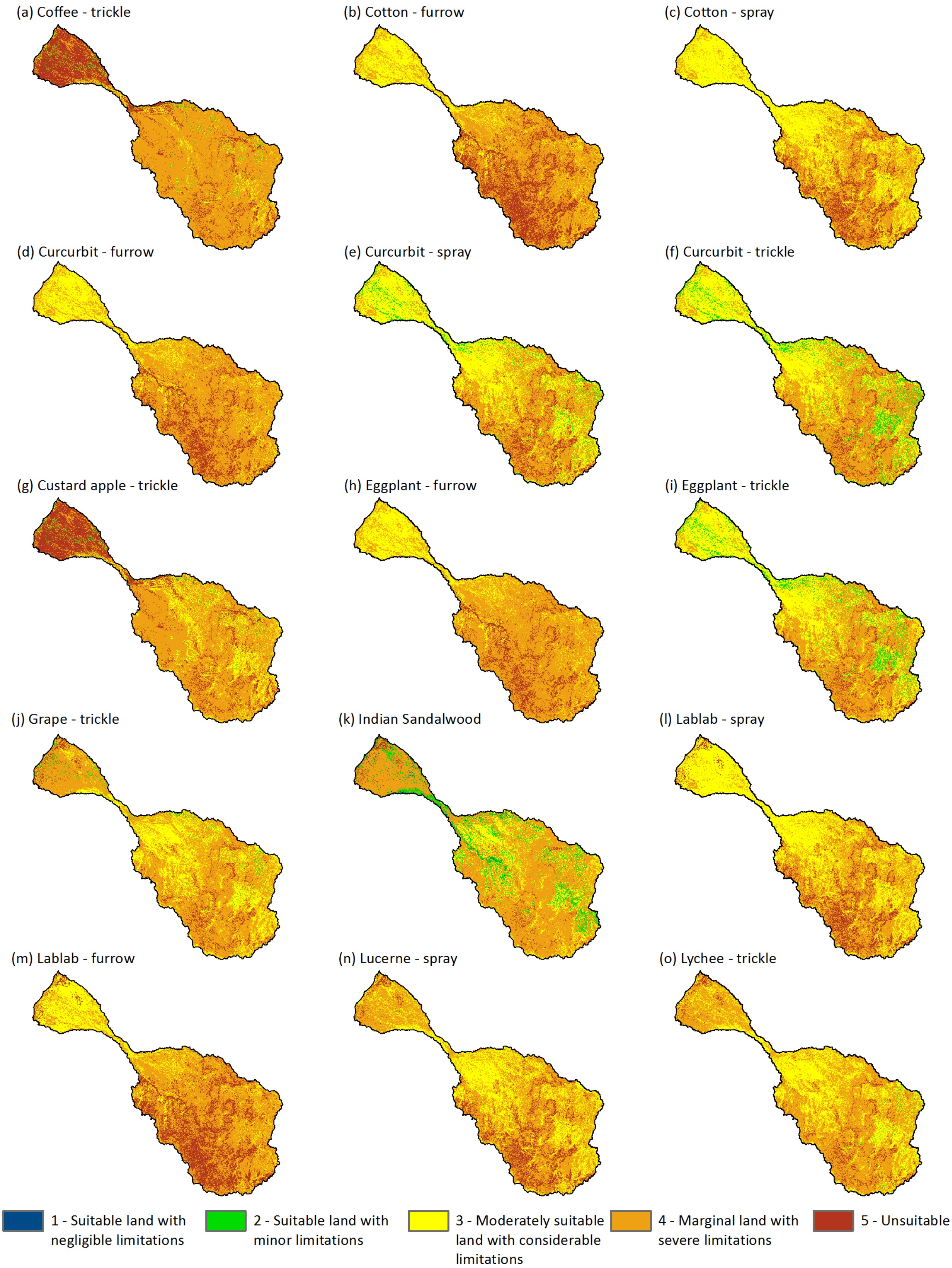

(a) Maize - furrow
(b) Maize - spray
(c) Mango - trickle
(d) Millet - furrow
(e) Millet - spray
(f) Mungbean - furrow
(g) Mungbean - spray
(h) Navybean - furrow
(i) Navybean - spray
(j) Oats - furrow
(k) Oats - spray
(l) Peanut - furrow
(m) Peanut - spray
(n) Pineapple - spray
(o) Pineapple - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable

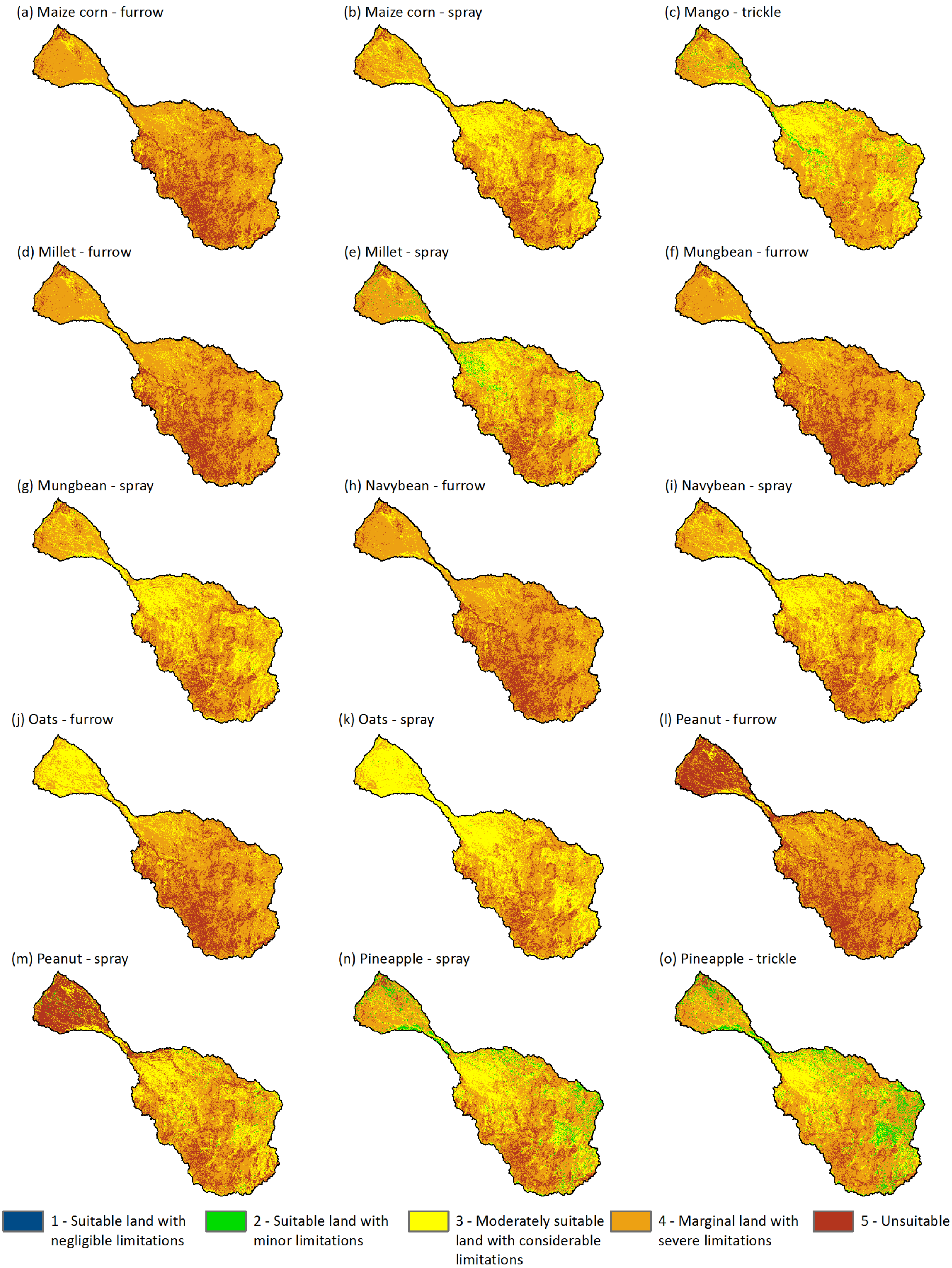

(a) Rhodes grass - spray
(b) Rice - flood
(c) Rice - furrow
(d) Sorghum forage - dry spray
(e) Sorghum forage - wet spray
(f) Sorghum grain - dry furrow
(g) Sorghum grain - dry spray
(h) Sorghum grain - wet furrow
(i) Sorghum grain - wet spray
(j) Soybean - furrow
(k) Soybean - spray
(l) Spotted gum
(m) Sugarcane - furrow
(n) Sugarcane - spray
(o) Sugarcane - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable

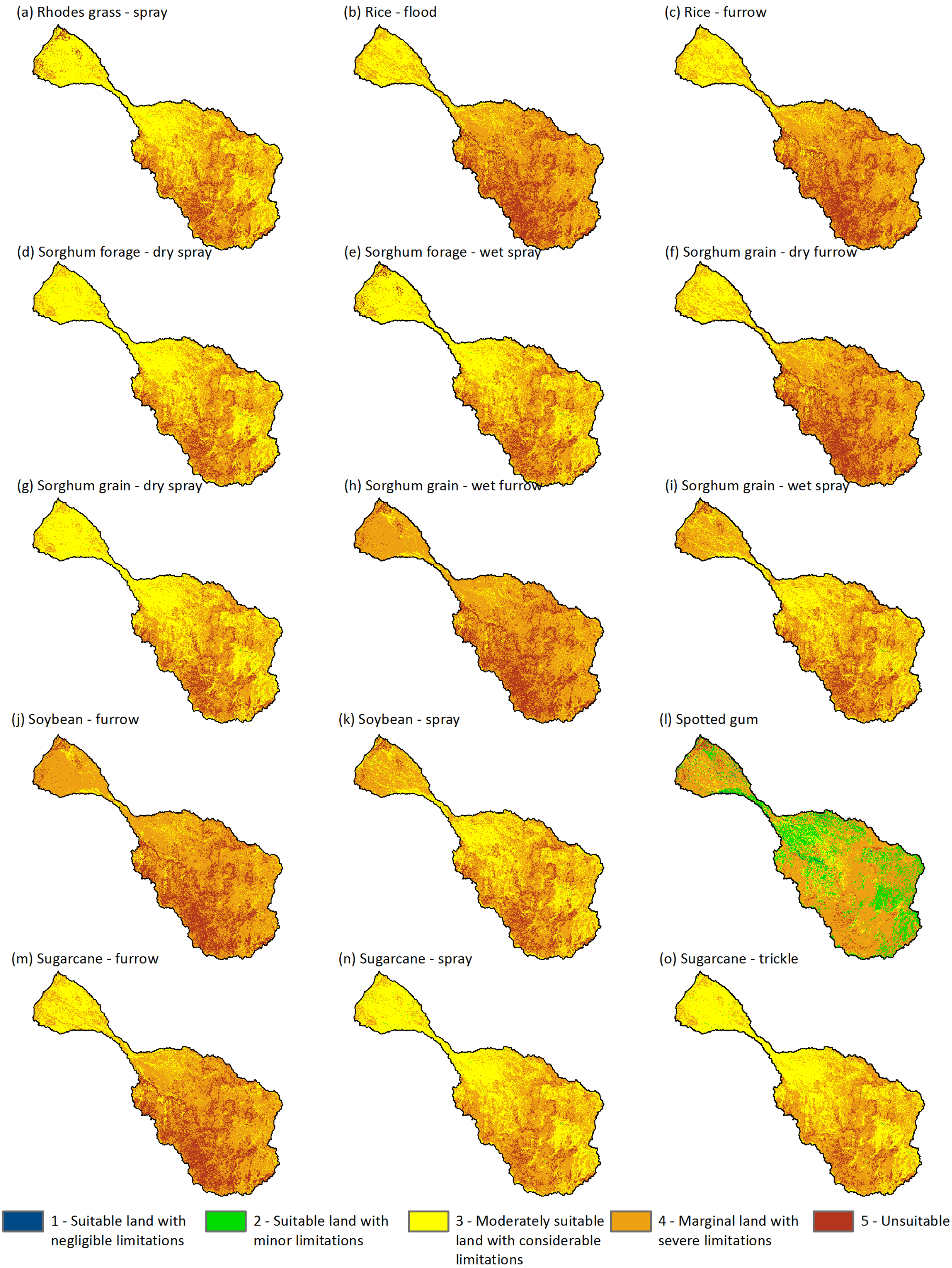

(a) Sunflower - furrow
(b) Sunflower - spray
(c) Sweet corn - dry furrow
(d) Sweet corn - dry spray
(e) Sweet corn - dry trickle
(f) Sweet corn - wet furrow
(g) Sweet corn - wet spray
(h) Sweet corn - wet trickle
(i) Sweet potato - furrow
(j) Sweet potato - spray
(k) Teak
(l) Tomato - furrow
(m) Tomato - spray
(n) Tomato - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable

A.6 Land suitability thumbnail maps for all land uses in the Gilbert Catchment




(a) Coffee - trickle
(b) Cotton - furrow
(c) Cotton - spray
(d) Curcurbit - furrow
(e) Curcurbit - spray
(f) Curcurbit - trickle
(g) Custard apple - trickle
(h) Eggplant - furrow
(i) Eggplant - trickle
(j) Grape - trickle
(k) Indian Sandalwood
(l) Lablab - spray
(m) Lablab - furrow
(n) Lucerne - spray
(o) Lychee - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable


(a) Maize corn - furrow
(b) Maize corn - spray
(c) Mango - trickle
(d) Millet - furrow
(e) Millet - spray
(f) Mungbean - furrow
(g) Mungbean - spray
(h) Navybean - furrow
(i) Navybean - spray
(j) Oats - furrow
(k) Oats - spray
(l) Peanut - furrow
(m) Peanut - spray
(n) Pineapple - spray
(o) Pineapple - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable


(a) Rhodes grass - spray
(b) Rice - flood
(c) Rice - furrow
(d) Sorghum forage - dry spray
(e) Sorghum forage - wet spray
(f) Sorghum grain - dry furrow
(g) Sorghum grain - dry spray
(h) Sorghum grain - wet furrow
(i) Sorghum grain - wet spray
(j) Soybean - furrow
(k) Soybean - spray
(l) Spotted gum
(m) Sugarcane - furrow
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(o) Sugarcane - trickle
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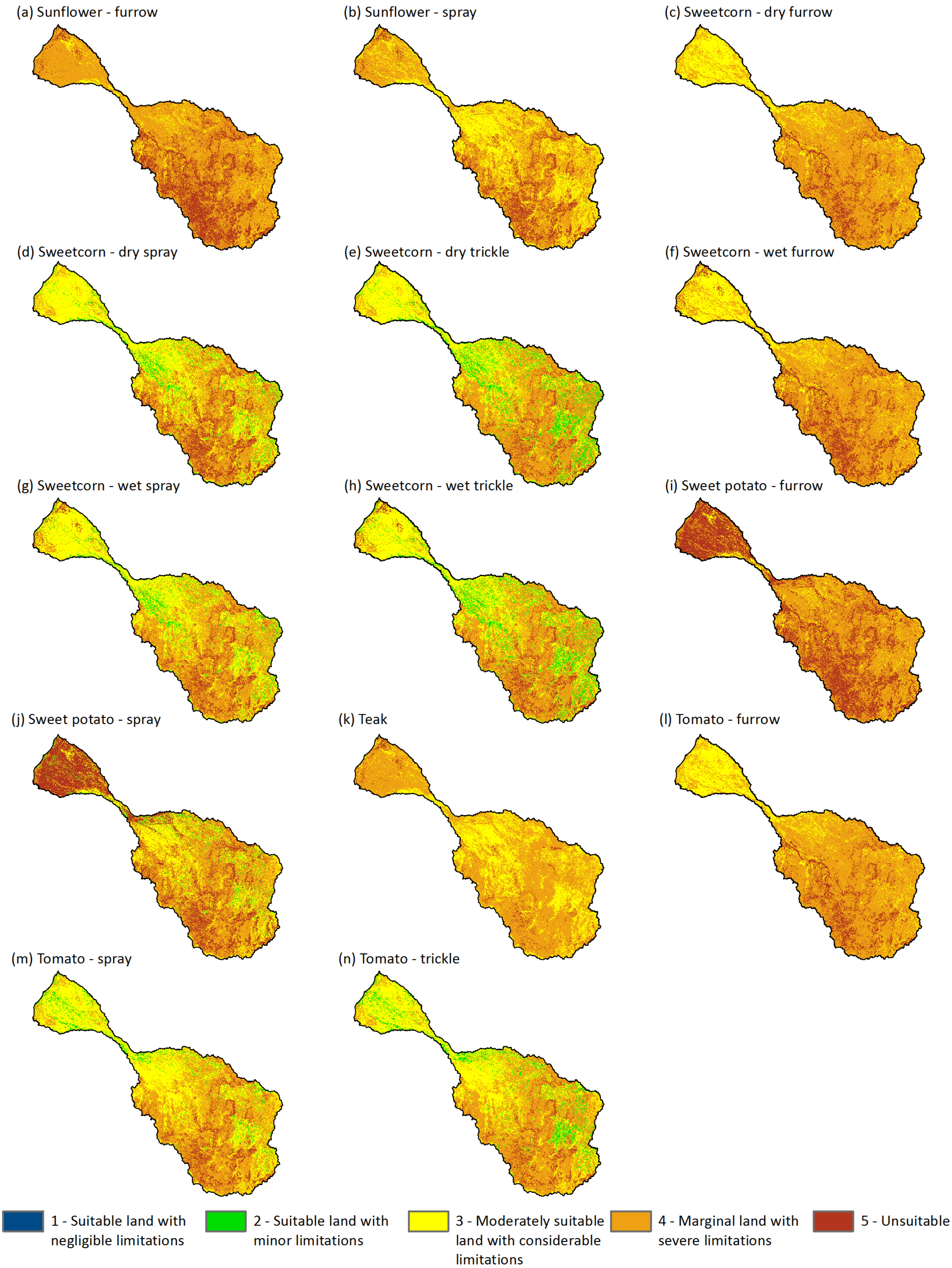
5 - Unsuitable


(a) Sunflower - furrow
(b) Sunflower - spray
(c) Sweetcorn - dry furrow
(d) Sweetcorn - dry spray
(e) Sweetcorn - dry trickle
(f) Sweetcorn - wet furrow
(g) Sweetcorn - wet spray
(h) Sweetcorn - wet trickle
(i) Sweet potato - furrow
(j) Sweet potato - spray
(k) Teak
(l) Tomato - furrow
(m) Tomato - spray
(n) Tomato - trickle
1 - Suitable land with negligible limitations
2 - Suitable land with minor limitations
3 - Moderately suitable land with considerable limitations
4 - Marginal land with severe limitations
5 - Unsuitable

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