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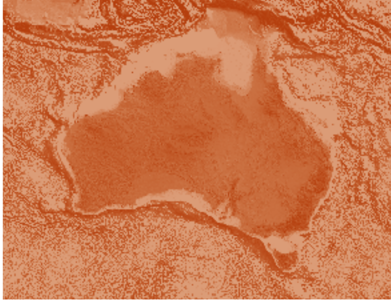

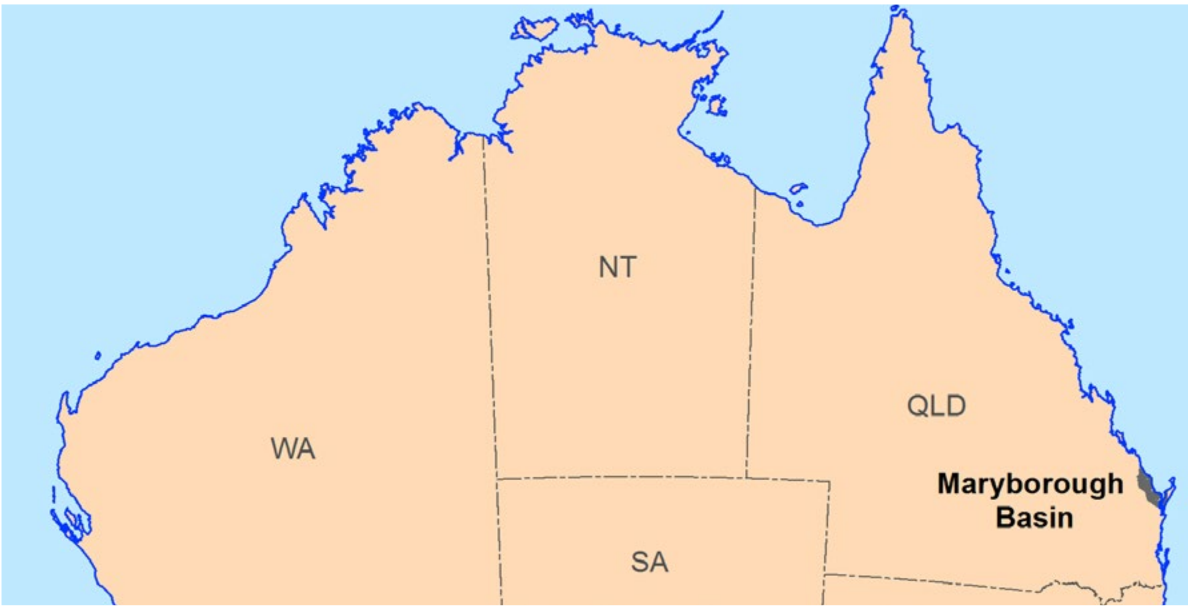

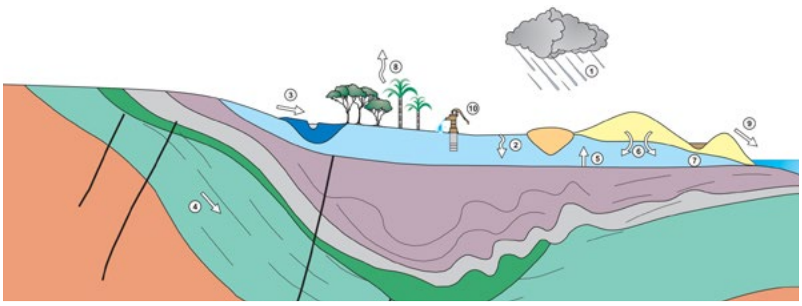

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Regional Hydrogeological Characterisation of the Maryborough Basin, Queensland

Technical report for the National Collaboration Framework Regional Hydrogeology Project

Marshall, S. K., Fontaine, K., Kilgour, P. L. and Lewis, S. J.

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Summary

The Maryborough Basin is a geological basin in South East Queensland, situated on the coastline approximately 250 km north of Brisbane. It covers an area of 24,600 km^2, of which about 37% occurs onshore. There are several major population centres within the basin, including Bundaberg, Hervey Bay and Maryborough. The geological basin is infilled by up to 9 km of Mesozoic sedimentary rocks, with two stratigraphic units containing variably thick seams of black coal (individual seams are generally less than 1 m thick). These formations are the Cretaceous Burrum Coal Measures and the deeper Jurassic Tiaro Coal Measures. The Mesozoic rocks are capped across most of the basin by relatively thin Cenozoic sediments comprising sands, silts and gravels. The Mesozoic rock strata in the basin are commonly folded and faulted, although the intensity and style of geological structures varies across the basin.

The Maryborough Basin supports major agricultural industry (especially sugar cane production) and contains environmentally significant areas such as the World Heritage-listed Fraser Island. Both agriculture and the environment rely strongly on groundwater systems within the basin. Although no coal mining or coal seam gas (CSG) extraction presently occurs, several historic coal workings and a current development application for a new coal mine (Colton Coal Mine) attest to the prospectivity of the basin. Much of the area is also covered by active petroleum (including coal seam gas) and coal exploration tenements granted to several companies. The basin is of particular economic significance because resources are near major population centres, and there is an existing gas pipeline connection to the Port of Gladstone.

Regional hydrogeological assessment of the Maryborough Basin was the primary focus of this investigation, and was required due to the lack of prior regional groundwater studies. Most previous hydrogeological work focused only around the main extraction area of the Bundaberg Groundwater Management Unit (GMU), in support of the local sugar cane industry. In addition, past studies have concentrated on the near-surface Cenozoic Elliott Aquifer, as it provides the bulk of groundwater extraction in the basin. Consequently, there is only limited data available on the hydrogeological properties and processes relevant to the deeper aquifers. This assessment involved compilation and synthesis of existing data and information (i.e., there was no new data acquisition undertaken), as well as new analytical studies to develop a basin-wide hydrostratigraphic framework and hydrogeological map. The overall objective was to improve conceptualisation of the regional groundwater system, and provide an up to date summary of existing knowledge of the basin's aquifers and aquitards, to provide a base level of understanding about the hydrogeology of the basin in the event of any future development of coal or coal seam gas resources.

A new regional hydrostratigraphic framework was developed for this project to incorporate the entire stratigraphic succession of the Maryborough Basin. This work defined nine regional hydrostratigraphic units (seven aquifers and two aquitards) on the basis of broadly similar hydrogeological parameters, with each unit having regionally consistent aquifer or aquitard characteristics. The distribution and thickness of each hydrostratigraphic unit can vary significantly across the basin, as shown on the new regional hydrogeology map (developed for this project). Understanding the spatial distribution of the hydrostratigraphic units is integral to understanding the basin-scale occurrence and characteristics of the regional hydrogeological flow systems.

The key aquifers in the Maryborough Basin (listed from youngest to oldest) are the:

1. Quaternary Coastal Aquifer;
2. Quaternary Alluvial Aquifer;
3. Quaternary Basalt Aquifer;
4. Elliott Aquifer (Cenozoic);
5. Burrum Aquifer (Cretaceous);
6. Grahams Creek Aquifer (Cretaceous); and
7. Duckinwilla Aquifer (Triassic to Jurassic).

The regional aquitards in the Maryborough Basin are the Quaternary Coastal Aquitard and the Maryborough Aquitard (Cretaceous).

The Elliott Aquifer is the main source of groundwater extracted from the Maryborough Basin, and commonly forms the uppermost hydrostratigraphic unit (the watertable aquifer). The Elliott Aquifer is an unconfined, semi-consolidated to consolidated aquifer consisting mainly of sand, silt and conglomerate. The aquifer contains discrete beds of gravel (usually in paleochannels incised into the underlying Burrum Coal Measures) that act as localised and highly transmissive conduits for relatively high volumes and rates of groundwater flow.

Across the southern and central parts of the Maryborough Basin significant volumes of groundwater are extracted from the sandier sequences of the Cretaceous Burrum Aquifer. This unit, underlying the Elliot Aquifer, also contains coal measures that are the primary targets for current (and probably future) coal and CSG exploration. The unit is lithologically heterogeneous and groundwater is stored and transmitted both within fractures of the coal and silt-bearing strata, and also in intergranular pore space within sandstone sequences. Further work is required to distinguish the main hydraulically conductive water-bearing zones at a finer scale within this hydrostratigraphic unit. The Burrum Aquifer and the Elliott Aquifer are likely to be the most significantly affected by any future coal and CSG extraction in the basin. However, the magnitude, direction and focal zones for hydraulic connection (groundwater flow) between these two main aquifer systems are largely unknown, although current evidence suggests that there is no regionally extensive confining unit (e.g., aquitard) separating these aquifers. Increased groundwater extraction as a result of coal or CSG extraction from the Burrum Coal Measures could potentially affect the hydraulic processes that currently exist in these aquifers, and may have an adverse impact on beneficial uses, as a result of changes to existing groundwater flow patterns or aquifer water quality. Consequently, any future mining developments would need to closely monitor and manage local- to intermediate-scale groundwater impacts.

The Maryborough Aquitard is a thick siltstone-dominated unit that separates the Burrum Aquifer from the underlying Grahams Creek Aquifer. Regionally, the formation acts a groundwater flow barrier although in some areas there are thin sand-rich lenses that may be locally productive for groundwater. These sands have also been a previous target for primary conventional gas resources. The exact distribution and hydraulic properties of the Maryborough Aquitard are poorly understood due to the paucity of data and scant previous work.

The Grahams Creek Aquifer has a more sporadic distribution and variable thickness than the main sedimentary aquifers in the basin, and is used as a minor source of groundwater extraction along the western margin of the basin where it occurs at relatively shallow depths. The formation consists mainly of acidic volcanic rocks, with groundwater extracted from zones of intense fracturing or weathering.

Beneath the Grahams Creek Aquifer lies the Duckinwilla Aquifer. This contains two sub-units: the Tiaro Coal Measures and the Maryborough Formation. There is very limited existing information on the hydraulic properties of both the Grahams Creek Aquifer and the Duckinwilla Aquifer and hence a comprehensive hydrogeological assessment was not possible.

The near-surface Quaternary sedimentary aquifer formations (Quaternary Coastal Aquifer and Quaternary Alluvial Aquifer) are relatively minor components of the regional groundwater system. However, these units are used for groundwater extraction in some localised settings, mainly in the modern river valleys for the alluvials and near the coast for the dunes, as they consist of highly permeable, unconsolidated to semi-consolidated sands and silts. These sand-rich units may be highly locally transmissive and contain good quality groundwater. The Quaternary Basalt Aquifer, which generally forms small-scale and localised aquifers mostly in the south of the basin, is also used at a local scale, with groundwater stored and transmitted in fractures and vesicles of the basalt. The three Quaternary aquifer systems are unlikely to be significantly impacted by the development of future coal and CSG resources because their groundwater flow systems are of local rather than regional scale. They are also unlikely to be in direct hydraulic connection with the target coal-bearing formations.

Groundwater recharge into the various Mesozoic aquifers of the Maryborough Basin occurs mainly in areas where outcropping or subcropping aquifer units occur along the western margin of the basin. In contrast, the near-surface Cenozoic aquifers are mostly recharged by diffuse rainfall recharge, or from leaking surface water bodies that are directly connected to the unconfined aquifers. For these near-surface aquifers, recharge is most effective during intense rainfall events that may cause flooding and water-logging. The variation in the height of the watertable (the hydraulic head) in the uppermost aquifer was analysed and mapped for this project. Overall, this analysis indicates that regional groundwater gradients, which can be used to infer flow directions, show changes in water levels from being higher in the recharge areas along the basin margin in the west, and lower towards the coastline in the east. The watertable elevation broadly correlates with the topography and hence the direction of flow is consistent with that of the surface water flow across the landscape, particularly the east-flowing river catchments. Previous studies have suggested that surface water systems are predominately gaining streams that mostly act as drains for groundwater (except during high-flow periods), although the mechanisms of surface water–groundwater connectivity and the volume fluxes involved are poorly understood. Stream-flow is greatest during summer, indicating that there is a strong seasonal influence on recharge. Where surface water and groundwater discharges occur along the coast, there are many important bird areas, wetlands and national parks. There are also many groundwater dependent ecosystems (GDEs) across the basin.

Given the intense structural disruption that has affected the pre-Cenozoic rocks of the Maryborough Basin, major structural faults and folds in Mesozoic aquifers are likely to play a significant role in the regional groundwater flow system. Although speculative due to the lack of critical data, this study has highlighted the potential for major structural zones to act as groundwater pathways between regional aquifers. Important groundwater processes such as recharge, discharge and flow paths may be influenced by structural features such as faults and folds. However, the detailed structural disposition of the basin is not well understood, and there are only limited detailed geophysical survey data (seismic reflection) available for the onshore basin to help constrain interpretations. Potential structural conduits and barriers for groundwater flow would be important to evaluate in greater detail, to help improve understanding of the direction and magnitude of groundwater fluxes within the basin. The influence of structure on hydrogeological systems has been conceptualised as part of this study by developing new hydrogeological cross-sections, but requires further investigation to better understand the role of geological structures on the basin’s groundwater flow systems.

A regional water balance assessment is a useful tool to facilitate the monitoring and management of groundwater in the future; this would likely be particularly important with any future development of coal and CSG resources. A new hydrogeological conceptual model was developed for the basin to communicate and assess key water balance components. The hydrostratigraphy of the basin was also assessed to determine hydraulic parameters for each hydrostratigraphic unit. Due to the absence of relevant datasets, the water balance is considered as a preliminary indicative water balance only, and is inconclusive in its findings. It would be made more robust by acquiring new data as part of targeted future investigations. To improve the conceptual model, key requirements are data pertaining to: the rate and volume of recharge; vertical hydraulic gradient (and connectivity); surface water flow volumes into the basin; variation in evapotranspiration across the basin; and groundwater and surface water discharge.

A major issue highlighted by this study is the lack of detailed and relevant data to inform hydrogeological assessment. Data is concentrated in the Bundaberg GMU and focuses on the Cenozoic Elliott Aquifer rather than deeper Mesozoic aquifers. The basin has the potential to contain a significant quantity of water available for beneficial use in deeper aquifers but there is little current understanding about the distribution and hydraulic properties of the deeper aquifers. Nevertheless, the absence of significant aquitards and extensive faulting and folding in the basin indicates that there is likely to be hydraulic connectivity between aquifers, and that significant exploitation of the basin’s coal seams may result in changes to the water level and/or quality of groundwater. Other issues for the basin include the potential of widespread seawater intrusion, which could be enhanced by increased groundwater extraction; the possibility for increased salinisation of aquifers due to additional groundwater extraction; impacts of extraction on surface water stream-flow; and the potential impact of increased extractions on significant ecosystems and environmental heritage.

The generation of a new hydrostratigraphic framework for the Maryborough Basin and the development of a basin-scale conceptual hydrogeological model have assisted with the identification of key data and knowledge gaps. These can be built on with future hydrogeological studies of the basin, which should be targeted to collect new data that can help improve current interpretations. Further work is required to elucidate the hydraulic properties of the key aquifers and aquitards, in particular those of deeper units. The development of a basin-wide groundwater testing network (with purpose-built piezometers), used for regular testing of water levels, salinity and chemistry is also suggested. In addition, geochemical investigations to determine groundwater age, residence times, flow paths (including recharge and discharge mechanisms) and connectivity between aquifers would further improve the understanding of the hydrogeology of the basin.

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Abbreviations and acronyms

ABS	Australian Bureau of Statistics
AEM	Airborne Electromagnetics
AGSO	Australian Geological Survey Organisation (former name for Geoscience Australia)
AHD	Australian Height Datum
ANRA	Australian Natural Resource Atlas
ASL	Above Sea Level
ATP	Authority to Prospect
BoM	Bureau of Meteorology
CO_2	Carbon Dioxide
CSG	Coal Seam Gas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model
DERM	Department of Environment, Resources and Mines (Queensland)
DIWA	Directory of Important Wetlands in Australia
DNRM	Department of Natural Resource Management (Queensland)
DR	Development Report
DSEWPaC	Department of Sustainability, Environment, Water, Population and Communities
EC	Electrical Conductivity
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
EL	Exploration Licence
ELA	Exploration Licence Application
EPBC	Environment Protection and Biodiversity Conservation Act
ET	Evapotranspiration
GA	Geoscience Australia
GAB	Great Artesian Basin
GDE	Groundwater Dependent Ecosystem
GIS	Geographic Information System
GMA	Groundwater Management Area
GMU	Groundwater Management Unit
GSQ	Geological Survey of Queensland
IBA	Important Bird Areas
IESC	Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
NCF	National Collaboration Framework Project Agreement

NCGRT	National Centre for Groundwater Research and Training
NGIS	National Groundwater Information System
NPA	National Partnership Agreement
NRM	Natural Resource Management
NWC	National Water Commission
OWS	Office of Water Science
Qa	Quaternary alluvium
QDEX	Queensland Digital Exploration Reports system
QDNR	Queensland Department of Natural Resources
SKM	Sinclair Knight Merz
SRTM	Shuttle Radar Topographic Mission
SWL	Standing Water Level
TDS	Total Dissolved Solids

Units

cm	centimetres
Ga	Billions of years ago
GL	Gigalitre: one billion litres (equivalent to 1,000 megalitres, ML)
gph	gallons per hour
kL	kilolitre: 1,000 litres (cubic litre: m^3)
km	kilometres
L/s	litres per second
m	metres
m/d	metres per day
m/s	metres per second
Ma	Millions of years ago
Mcf	Million cubic feet
mg/L	milligrams per litre
ML	Megalitre: one million (1,000,000) litres
Mm/yr	millimetres per year
mS/m	milli-Siemens per metre
Mt	Million tonnes
ppm	parts per million
S/m	Siemens per metre
µS/cm	micro-Siemens per centimetre

1 Introduction

1.1 Background

In response to community concerns about coal seam gas (CSG) extraction and coal mining, the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the Committee) was established as a statutory committee in 2012 by the Australian Government under the *Environment Protection and Biodiversity Conservation Act 1999 (Cth)*. The Committee provides expert scientific advice on the potential water-related impacts of coal seam gas or large coal mining proposals referred to it by Australian Government and state government regulators. This advice is provided to enable regulatory decisions on coal seam gas and large coal mining developments to be informed by the best available science.

The Committee also provides advice to the Australian Government on bioregional assessments and research priorities and projects. The research aims to strengthen the science underpinning regulatory decisions, including by informing the advice the Committee provides to regulators. It focuses on areas of risk and where there are identified knowledge gaps, and aims to address issues of national significance. These research priorities are currently arranged under four main themes:

- *Hydrology*: changes in dynamics and aquifer interconnectivity. Research under this theme addresses knowledge gaps in surface and groundwater connectivity, bore integrity, and mine site remediation. These are crucial elements to better understand potential long-term impacts on water resources.
- *Ecosystems and water:* environmental tolerances, responses and mitigation. Research under this theme improves scientific understanding of the ecological impacts caused by changes to water quantity, quality, and flow; and informs the ability to monitor and mitigate the effects of coal seam gas and coal mining on aquatic ecosystems, key species and ecological communities.
- *Chemicals:* water-related risks to environmental health. Research under this theme improves scientific understanding of coal seam gas chemicals, their movement in surface and groundwater systems, and their toxicity; and also informs decisions about the management of salts and heavy metals.
- *Cumulative impacts:* monitoring, assessment and evaluation. Research under this theme addresses knowledge gaps in cumulative impact assessment processes in light of the significant number of proposals being considered in regional contexts.

The Australian Government's research programme is closely related to the Bioregional Assessment Programme. Bioregional Assessments will strengthen the science underpinning future decisions about coal seam gas and coal mining activities and their impacts on groundwater quality, surface water resources and ecosystems. Importantly they will provide an objective basis for scientists, and non-scientists alike, to consider when debating potential coal seam gas and coal mining developments and adaptive management strategies.

The Bioregional Assessment Programme (http://www.bioregionalassessments.gov.au/) will target regions with significant coal deposits and initially focus on those regions subject to significant existing or anticipated mining pressure (Figure 1.1). The six initial bioregional assessments are:

- Lake Eyre Basin underlain by the Galilee, Cooper, Pedirka and Arckaringa coal bearing basins (QLD and SA)
- Northern Inland Catchments, including the Namoi, Border Rivers-Gwydir, Maranoa- Balonne and Macquarie-Castlereagh natural resource management regions underlain by the Gunnedah and Surat basins (NSW and QLD)
- Clarence-Moreton Basin including the South East Queensland and Northern Rivers natural resource management regions (NSW and QLD)
- Sydney Basin including the Southern Rivers, Sydney Metro and Hawkesbury-Nepean natural resource management regions (NSW)
- Northern Sydney Basin and the Gloucester sub-basin including the Hunter Central Rivers and Hawkesbury-Nepean natural resource management regions (NSW)
- Gippsland Basin.

Dedicated support for the Committee and its research priorities is provided by the Australian Government Department of the Environment.

1.2 Focus of this project

Areas that are not included in the initial six bioregional assessments may still be subject to coal mining and coal seam gas extraction (Figure 1.2). Consequently, the main focus of this project (known as the *Regional Hydrogeological Characterisation of Coal Basins Not Covered by Initial Bioregional Assessments* project) is on four medium- to smaller-scale coal-bearing basins in Australia that will not initially be investigated as part of the Bioregional Assessment Programme. This work has been undertaken to assist future management decisions and understand the potential risks posed by coal and CSG extraction to the water resources of these basins.

The coal-bearing basins of interest for this overarching project (Figure 1.2) are:

- Laura Basin, Queensland
- Maryborough Basin, Queensland
- Otway Basin, Victoria
- St Vincent Basin, South Australia.

Comprehensive knowledge of regional hydrogeological systems within these coal basins will provide an important baseline of information that is critical for understanding impacts on water resources or water-related assets caused by any future CSG or coal mining developments. These impacts may affect both surface water- and groundwater-dependent resources (and potentially the economic, environmental or socio-cultural values that rely on these water resources), and can involve local- to regional-scale hydrological flow systems. The information compiled for this overarching project will improve the understanding of the groundwater resources and hydrogeological systems within these coal basins, including recognising the key data and knowledge gaps that may significantly limit the extent of current knowledge.

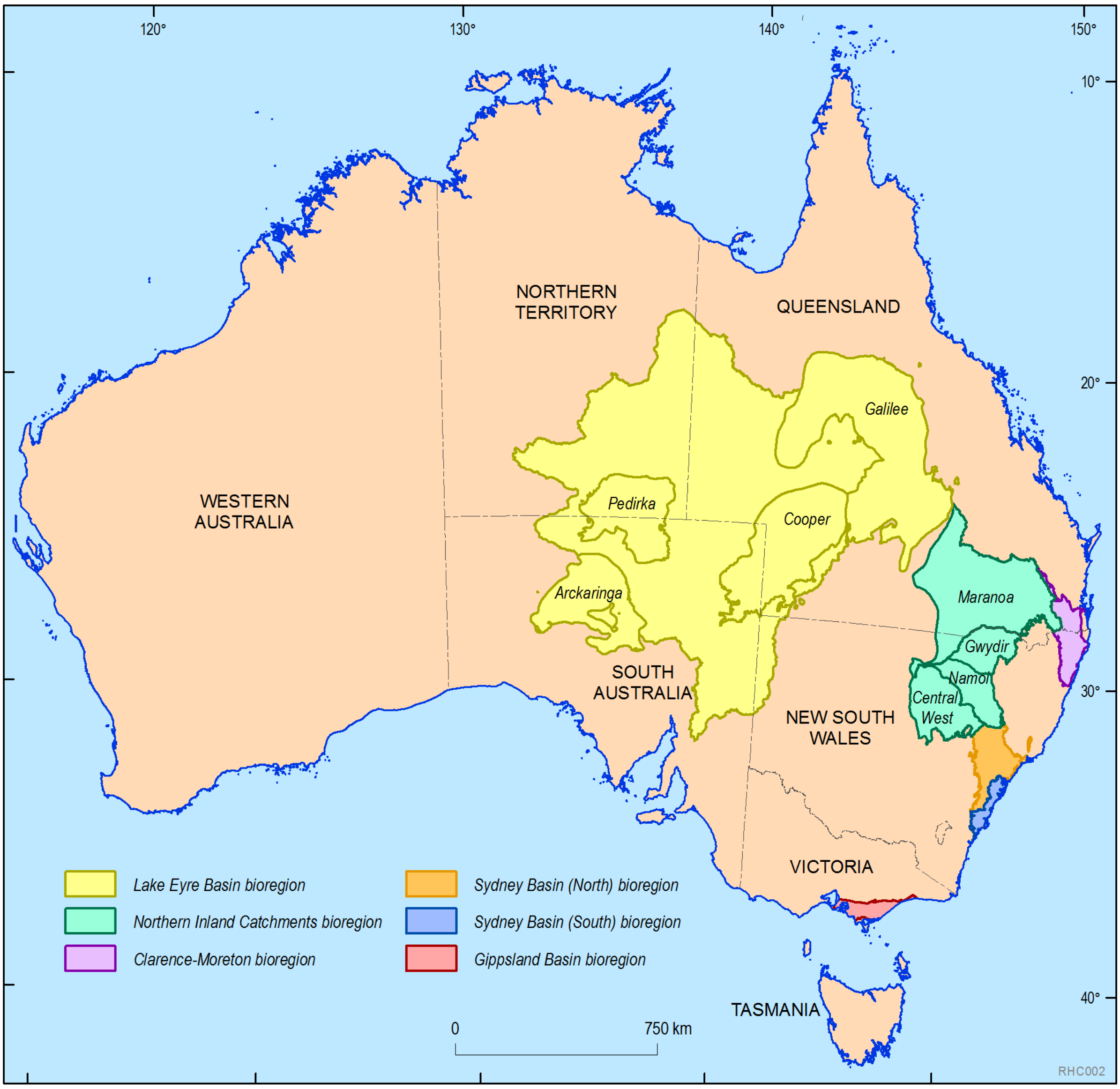

Figure 1.1 Initial bioregional assessment areas.

Source: Bioregional Assessment Programme, 2015

1.3 Project overview

This hydrogeological study of the Maryborough Basin is one of a number of research projects funded by the Department of the Environment as part of the wider programme of research into the effects of coal and CSG extraction on water resources (http://www.environment.gov.au/coal-seam-gas-mining/index.html). The overarching aim of this research programme is to increase the scientific knowledge base used to underpin regulatory decisions on CSG and large coal mining developments. The broader research program is designed to:

1. Assist better decision making, regulation, natural resource management and industry practice.
2. Build knowledge about the highest risks to water resources, land and ecosystems.
3. Help provide data and knowledge that can support bioregional assessments in priority areas.

Figure 1.2 Sedimentary basins in Australia containing identified in situ resources of brown and black coal.

Source: Jaireth and Huleatt (2012)

1.4 Geoscience Australia's role in the project

As the custodian of national geoscientific and geospatial data and knowledge Geoscience Australia is well positioned to contribute to the delivery of the IESC Committee research agenda. In recognition of this capability, the Australian Government Department of the Environment entered into a strategic partnership with Geoscience Australia by signing an overarching Collaborative Head of Agreement in April 2012. Further, a specific National Collaboration Framework Project Agreement (NCF) was developed for an integrated program of work to support the assessment of coal seam gas and coal mining developments on groundwater resources in May 2012. One of the research projects identified under the NCF Agreement was the *Regional Hydrogeological Characterisation of Priority Coal Basins Not Covered by Initial Bioregional Assessments*. This project, which focuses here on the Maryborough Basin in Queensland, aligns with the Committee's research priority 1 (aquifers).

1.5 Project objectives and outcomes

The main objective of the *Regional Hydrogeological Characterisation of Coal Basins Not Covered by Initial Bioregional Assessments* project is to present the current knowledge base, and identify the main data gaps and uncertainties that exist, for the hydrogeological and groundwater resource characteristics of coal-bearing sedimentary basins that are of strategic national importance but are not the subject of initial Bioregional Assessments. This work has focused particularly on developing an integrated basin-scale conceptual understanding of regional groundwater flow systems, including a hydrostratigraphic framework that identifies the main water-bearing geological formations (aquifers), and their key hydrogeological parameters and connectivity relationships.

1.6 Project scope

The scope of this project was restricted to desktop assessments. The work programme involved the collation, analysis and interpretation of a variety of existing geological, hydrological and other relevant datasets such as topographic, geophysical and remotely sensed data. Relevant scientific and technical literature on the study areas was collected and evaluated. Local subject-matter experts were also approached for consultation and discussion, including professionals employed by state government agencies and various universities. No new (field or laboratory) data was collected for this study and only the onshore portion of the basin was included.

1.6.1 In-scope activities

The scope of work included:

1. Provision of regional hydrogeological characterisations to support any future assessments of CSG and coal mining developments
2. Integrated and multidisciplinary evaluation of the geology and hydrostratigraphy
3. Identification of CSG and coal-mining activities with potential to impact on water resources (groundwater/surface water) if developed/extracted in the future.

1.6.2 Out-of-scope activities

The following activities were beyond the scope of this project:

1. The collation, analysis and interpretation of hydrogeological and groundwater datasets and information from areas outside of the eight coal basins specified for investigation
2. Acquisition of new field-based datasets, such as through drilling of new bores or acquisition of geophysical datasets
3. Acquisition of new groundwater analytical data through laboratory testing and analysis
4. Detailed environmental impact or vulnerability risk assessments associated with potential CSG or coal mining activities
5. Detailed analysis relating to ecology, biology, or surface water features and impacts
6. Detailed assessment of other unconventional hydrocarbon resources which may occur in the basin (such as shale gas)

7. Numerical modelling simulation of current or projected scenarios (e.g., associated with CSG or coal mine developments) for groundwater volumes/pressures (head), flow or solute transport.

1.7 Report structure and content

1.7.1 Overview of project reports

The main outputs developed by Geoscience Australia for the overall NCF work programme are a series of four technical reports focused on the regional hydrogeology and groundwater systems of the Laura, Maryborough, Otway, and St Vincent basins. These reports, which have been internally and externally peer-reviewed by senior scientists, are published as Geoscience Australia Records and are freely available as pdf files for download from the Geoscience Australia website (http://www.ga.gov.au/). Each basin report is a stand-alone document that provides analysis, interpretation and summary of existing data and information compiled on the biophysical, hydrogeological and groundwater systems. The reports are supported by a digital reference library (Endnote format) comprising relevant datasets and existing literature, such as scientific journal articles, government reports, and other technical publications.

1.7.2 Structure and content of Maryborough Basin report

This report focuses specifically on the assessment of the Maryborough Basin in Queensland. The structure of the report is:

- Investigative approach and data summary (Chapter 2), which includes study approach, data and information and the project workflow.
- Geography (Chapter 3), which includes Maryborough Basin location; physiography and land cover; climate; surface water systems; population; land use; and environmental assets.
- Geology (Chapter 4), which includes Maryborough Basin setting, geomorphology, regolith, structural geology and stratigraphy.
- Coal and CSG resources (Chapter 5), which includes the distribution and size of deposits in the basin, CSG resources, past exploration history, current exploration and development focus and information about other economic resources in the basin.
- Hydrogeology and Groundwater Systems (Chapter 6), which includes the hydrostratigraphic framework of the basin, a characterisation of the groundwater system, conceptualisation of the groundwater system and a first attempt to quantify some components of the basin’s water balance.
- Identification of the important data and knowledge gaps relevant to the geology and groundwater systems of the basin, as identified during this study (Chapter ☐).
- Summary of conclusions (Chapter 8) and potential avenues identified for future work to address the main uncertainties in the current understanding of the basin (Chapter 9).
- A glossary of geological and hydrogeological terms is included after the References.
- There are three appendices included. Appendix A provides a copy of the most up-to-date International Stratigraphic Timescale (useful for reference to the geological times mentioned in this report). Appendix B provides some background information used to contextualise groundwater management in the basin, on groundwater legislation, policy and management practices in Queensland. Appendix C contains a map with the spatial distribution of data used to inform the groundwater flow mapping presented in Chapter 6.

2 Investigative approach and data summary

2.1 Study approach

The approach used for this study initially involved an initial extensive data and literature review. Information was gathered about the geology, hydrogeology, coal and CSG resources, climate and environmental features of the Maryborough Basin. Digital versions of many of the collected resources were collated in an EndNote reference library (accompanying this report).

To undertake a hydrogeological assessment of the Maryborough Basin, existing information about the hydrogeology was reviewed. Two recent studies were identified that focus on the upper hydrostratigraphic units of the basin (Moser 2004; AustralAsian Resource Consultants (AARC) 2011), and two older studies were found on the deeper hydrostratigraphic units (Laycock 1969; Laycock 1975). All previous studies were of local scale within the basin, and there have been no hydrogeological studies of the entire basin. Developing a hydrostratigraphic framework for the basin was difficult, due to a paucity of bore data and hydraulic testing of stratigraphic units. As per the convention of Laycock (1969), aquifer units were based on stratigraphic units. Further work is required to distinguish individual aquifers and confining units within each stratigraphic unit.

To understand the spatial variability of the aquifer systems across the basin, a new regional-scale hydrogeology map was developed (as there was no detailed existing basin-scale hydrogeology map). This was created through the interpretation of bore data and relevant information from the existing literature. To improve conceptualisation of the system, cross-sections were also required. These were created by interpreting available hydrostratigraphic information, topography from the DEM and the hydrogeology map. To understand the groundwater flow conditions of the basin, a map of the hydraulic head across the basin was also constructed.

Available information was collected and analysed to provide information about the hydraulic properties of each aquifer, and the recharge and discharge mechanisms in the basin and connectivity between units. In general there were limited data or information to provide a thorough assessment and a preliminary water balance was created as a first attempt, which demonstrated that there are many data and knowledge gaps relating to inputs and outputs of the regional hydrogeological system.

A summary of the main findings and data and knowledge daps were identified and discussed. Potential options for future work have been provided.

2.2 Data and information

2.2.1 Surface water and climate data

Surface water and climate data were obtained from the Bureau of Meteorology (BoM). There are only three surface water gauges within the Maryborough Basin. Climate data from four BoM climate stations were used (as explained in Section 3.3).

2.2.2 Groundwater and geological data

Bore data from within the Maryborough Basin was obtained from the National Groundwater Information System (NGIS; BoM, 2013b) and from the Healthy Headwaters Dataset (Department of Natural Resources and Mines 2012). These datasets were compared and analysed to determine the type and relevance of information provided. The National Groundwater Information System (NGIS) data contained more hydrostratigraphic information for each bore, including bore depth, but Healthy Headwater data contained more comprehensive chemical and hydraulic head information associated with bores. Most bores are in and around the Bundaberg area and there is only relatively limited data available for the remainder of the basin.

All government and company reports were downloaded from Queensland Digital Exploration Reports (QDEX) (Department of Energy and Water Supply 2011). Three seismic studies were of use for conceptualising the hydrogeology of the basin: Swift (2001) studied the Susan River anticline; Swift and Lipski (1999) focused on one area in Maryborough and one area near Hervey Bay; and Hill (1994) investigated the offshore basin. The study by Hill (1994) provided useful information about the structure and evolution of the basin. Prior to these there were some minor onshore seismic programs in the Maryborough Basin but unfortunately with data of low quality.

2.2.3 Previous investigations of interest

Relevant scientific, technical and regulatory literature relating to the Maryborough Basin wre collated and reviewed for this project. Major hydrogeological and geological studies are outlined in Table 2.1.

Table 2.1 Previous investigations of interest in the Maryborough Basin.

Reference	Investigation type	Details
Rands (1886)	Coal geology	The Burrum, Cherwell, Isis and Gregory Rivers were traversed. The stratigraphy of the Burrum Coal Measures, Elliot Formation and Maryborough Beds was identified.
Rands (1890)	Coal geology	Differences between the Tiaro Coal Measures and Burrum Coal Measures were identified, though they were not separated stratigraphically.
Rands and Ball (1901)	Coal geology	This report is an update and review of Rands (1890). Ball investigated the geology and production quantity at the two operating collieries in the area (Burrum and Riverbank).
Dunstan (1913)	Coal geology	A compilation of all coal resources in Queensland and an examination of the state’s estimated total coal volumes. This contains only minor details of the Maryborough area coal seams.
Bryan and Massey (1926)	Coal geology	Characterised the stratigraphy of the Tiaro Coal Measures and separated it into four formations.
Siller (1955) and Siller (1956)	Petroleum geology	Geological and geophysical surveys by the Lucky Strike Drilling Company were undertaken for oil exploration. In 1954-55 this company drilled two deep wells, which has been instrumental in understanding the deep stratigraphy of the basin.
Siller (1959)	Petroleum geology	Photogeological and geological surveys were conducted in the basin for the purpose of oil exploration by the Pacific American Oil Company during the 1950s and 1960s. In 1967, the company drilled one deep exploration well.
Hawthorne (1960)	Coal geology	Information about coal exploration drilling in the Burrum Coalfield by the Queensland Department of Mines from 1950 to 1960. Cores were examined from > 60 drill holes to a depth of approximately 300 m. The area west of Howard was also explored for coal production potential

Reference	Investigation type	Details
		and the Maryborough Formation was mapped in detail.
Chiu Chong (1965)	Coal geology	This report contains the findings from a diamond drilling program in early 1964. Coal recovery in the target coal seams was 91.1%.
Ellis (1968)	Regional geology	This comprehensive report contains the sheet notes for the 1:250,000 map of the Maryborough area produced by the Geological Survey of Queensland. It includes physiography, stratigraphy, intrusions, structural geology, geological history and economic geology. It is acknowledged that little is known of the groundwater systems in the area. This report suggests stratigraphic units that have the potential to be aquifers, but this information is not based on physical evidence.
Laycock (1969)	Hydrogeology	This is a comprehensive hydrogeological investigation and of the area between Tiaro and Pialba. This was a preliminary assessment of the groundwater potential of the area. Results include lithological logs and the analysis of 177 water samples as well as conclusions regarding the extraction potential of each potential aquifer unit.
Randal (1969)	Hydrogeology	A hydrogeological survey was conducted to supplement the water supply for Childers. As a result of the investigation, the Tertiary Elliott Formation was considered to be the most productive. Three sites were proposed for test bores but no drilling or pump tests were conducted.
Laycock (1975)	Hydrogeology	Nine bores were drilled in 1971 but were unable to be tested due to heavy rain. In 1974, a further 9 bores were drilled and tested. This study located and characterised the aquifer to the east of Maryborough.
Muller and Randal (1979)	Hydrogeology	Following on from the investigation by Randal (1969), the Geological Survey of Queensland reassessed groundwater supply in Childers. This report reviews previous groundwater studies before drilling.
Muller (1979)	Hydrogeology	35 exploratory bores were drilled in the Childers area to attempt to secure another groundwater source for the town of Childers. The drilling was undertaken to assess strata, water quality and water levels. The study found that potential groundwater supplies are available both from Tertiary basalt and the Cenozoic Elliott Formation.
Cranfield (1982)	Stratigraphy	Ten deep stratigraphic bores were drilled between 1978 and 1980 by the Geological Survey of Queensland to further characterise the stratigraphy of the Maryborough Basin. This report contains detailed stratigraphy of these bores (which included wireline logs). It includes a diagrammatic cross-section derived from borehole data.
Scott (1993)	Coal seam gas and geology	This is an assessment of which formations may have the potential to produce coal seam methane (CSG) in the Maryborough Basin. These were found to be the Myrtle Creek Sandstone, the Tiaro Coal Measures and the Burrum Coal Measures. The Burrum Coal Measures were considered to be the most effective for producing methane.
Cranfield (1994)	Regional geology	An update on the Ellis (1968) notes of the Maryborough 1:250,000 sheet. This report contains details of the physiography, stratigraphy, intrusive rocks, structure, geological history and economic geology.
Hill (1994)	Offshore seismic survey	A major marine multichannel seismic reflection survey was conducted by the Australian Geological Survey Organisation (AGSO) off the coast of southeast Queensland. This investigated the structure, stratigraphy and evolution of the offshore Maryborough Basin. The information is useful and relevant for characterising the offshore portion of the basin and a portion of the onshore basin along the coast. The Tasman and Capricorn basins were also investigated.
Swift and Lipski (1999)	Onshore seismic	This seismic survey focused on two areas, one near Maryborough and one near Hervey Bay. The survey comprised three lines totalling approximately 12 km of Mini-Sosie source. It was acquired to detail potential hydrocarbon plays related to the evaluation of probable gas production in the area.

Reference	Investigation type	Details
Swift (2001)	Onshore seismic	This seismic survey high-graded the Susan River prospect and gave some indication of a deep play. The purpose was to confirm structural closure of the anticline. Data were collected along eight seismic lines totalling approximately 64 km.
Moser (2004)	Groundwater conceptualisation	Conceptualisation of the Burnett Basin for the purpose of groundwater management. This report conceptualises the hydrogeological system and assessed groundwater flow, chemistry, saltwater intrusion, discharge and recharge. It provides a conceptualisation of Cenozoic Aquifer units and the Mesozoic Burrum Coal Measures only.
Stephenson and Burch (2004)	Petroleum geology	This is a preliminary assessment of the petroleum potential of Australia's east coast, including an assessment of the Maryborough Basin. It concludes that the basin has a good potential for gas but that environmental concerns will limit offshore exploration in particular. The report is a summary of existing information and includes the basin's stratigraphy, structure and elements of its petroleum system.
Bradshaw, Spencer et al. (2009)	Carbon capture and storage	The Queensland Carbon Dioxide Storage Atlas assesses 36 basins for their carbon dioxide storage potential. The Maryborough Basin is assessed as having low prospectively for carbon dioxide storage, however it was also concluded that there was insufficient data for a volumetric assessment and additional wells were required for a definitive assessment of storage potential. The report includes information regarding basin evolution, existing resources, containment, reservoir assessment and seal assessment.
Helm, Molloy et al. (2009)	Aquifer storage and recovery	In South East Queensland, a regional assessment of Aquifer Storage and Recovery (ASR) potential was undertaken. The report acknowledged that the hydrogeology of the Maryborough Basin was not well understood and made assumptions about the key aquifer characteristics based on analogous formations in the neighbouring Nambour and Clarence-Moreton Basins.
MBA Petroleum Consultants (2010)	Shale gas	Within the Maryborough Basin, the Cherwell Mudstone Member (within the Maryborough Formation) was identified as a shale gas target.
AustralAsian Resource Consultants (AARC) (2011)	Coal mine environmental management plan	A hydrogeological study was undertaken to support an application for a coal mining permit in the Maryborough Basin. For the hydrogeological study 11 new monitoring bores and 2 production bores were drilled and monitoring bores were constructed in three existing boreholes. A range of assessments were made including groundwater chemistry, hydraulic conductivity of aquifers and groundwater levels. Cenozoic aquifers were not considered and the report focused on groundwater of the Burrum Coal Measures. The environmental management plan also contained details of other environmental and groundwater-related aspects, such as geology, flora and fauna, GDEs and soil impact. The study focused on the prospective mine area near Aldershot.
Kuuskraa, Stevens et al. (2011)	Shale gas	An international assessment of shale gas potential in 14 regions outside the United States identified the Maryborough Basin as one of four basins in Australia with major shale gas potential.
Sinclair Knight Merz (2012)	Hydrogeology and hydrology	An assessment of selected surface water basins, including the Burnett, Burrum and Kolan river catchments to advance the understanding of surface water-groundwater connectivity in the area.

2.3 Project workflow

The regional hydrogeological characterisation of the Maryborough Basin involved the identification, acquisition, assessment and interpretation of existing datasets (without collecting any new field or laboratory data). Many of the stages outlined below were similarly applied to each of the four basins assessed for the wider project.

The workflow steps for the Maryborough Basin hydrogeological characterisation study were:

1. Undertake an initial State of Knowledge Assessment and data collation exercise for the Maryborough Basin using nationally available datasets. This preliminary report provided important national-scale context for the Maryborough Basin area.
2. Following the initial contextual study, identify the potentially useful datasets that need to be acquired for regional characterisation. These data fall under broad themes such as geoscientific, hydrologic, geophysical, ecological, topographic, remotely sensed (satellite), infrastructure, land access and tenure (mining and exploration tenements), water use and management.
3. Determine the relevant data custodians for each of the datasets to be acquired. Consult with these custodians to obtain the most recent workable version of the required data in the appropriate format. The main data custodians included Geoscience Australia, other commonwealth agencies (such as the Bureau of Meteorology), and the respective state government agencies responsible for relevant data for each coal basin (e.g., state government water resource departments and geological survey departments). Useful information for this project was also provided by the Queensland University of Technology.
4. Determine the required data storage, maintenance and access requirements to support activities for the life of the project (and potentially beyond the life of current project). Develop the data storage framework, and system protocols and procedures for optimum data access and use for all staff involved in the project. Datasets included digital spatial data in both vector and raster formats (GIS geodatabase), written technical reports and scientific papers (stored in an Endnote Bibliographic file).
5. Identify the key features that relate to management of land and water. This helped provide context for current and future CSG and coal mining impacts on the basin. Activities included identifying existing legislation, policy and protocols in Queensland (see Appendix B); identifying existing water use and resource developments and the key water-dependent assets, identifying stakeholders in water management and use, and local basin issues.
6. Engage with science experts on geology and hydrogeology of the Maryborough Basin.
7. Conduct detailed desktop review and analysis of available scientific and technical literature to understand the geology (including geophysics), hydrogeology (including hydrostratigraphy, sedimentology, aquifer systems and parameters), and groundwater resources (including volumes and broad-scale water chemistry) of the basin. Other relevant fields of study were subjected to preliminary assessment only, such as ecology, surface water, and natural resource assets.
8. Identify the main components of the regional hydrogeologic system and the important hydrologic-dependent assets that occur in the basin, e.g., streams, lakes, springs, GDE. Information on the volume of water stored and taken for various purposes from any basin-scale water resource was also collated, e.g., bore extraction volumes to support agriculture, communities etc.

9. Hydrogeological analyses and data interpretation of the basin including the development of the new Maryborough Basin hydrogeology map, analysis of flow systems and a preliminary hydrogeochemical study. Recharge and discharge mechanisms and connectivity in the basin were also assessed. Although there was insufficient data to develop a detailed regional water balance, preliminary assessment of the water balance components was attempted.
10. Develop groundwater conceptual model/s based on an integrated analysis and interpretation of the existing geoscientific and hydrological data to explain the key processes of water movement, transfer and storage across the main components of the regional water cycle. Identify the main aquifers and their key relationships with other parts of the hydrologic system (surface water connectivity, aquitards, GDE etc.).
11. Compile and assess aquifer characteristics (porosity, hydraulic conductivity etc.) and groundwater parameters (e.g., piezometric levels and water chemistry compositions) from available data (particularly noting where significant gaps may occur in these datasets). The reliability and confidence in the basin-scale conceptual models depended on the extent, quality and availability of appropriate data to generate conceptual understanding of the regional system.
12. Finalise reporting requirements through multiple iterations, incorporating peer review feedback as an ongoing process in developing the regional conceptual understanding. Specific reviewing timeframes were used to ensure work was completed on-time, and to the appropriate standard.

2.3.1 Outputs

As a result of the workflow carried out for this study, the following new outputs were developed:

1. A new regional hydrostratigraphic framework of the Maryborough Basin
2. The development of a basin-scale hydrogeology map
3. Several new hydrogeological cross-sections
4. New interpretation and understanding of aquifer hydraulic head data and a watertable contour map for the basin
5. A conceptual hydrogeological model of the basin
6. A preliminary, first-pass water balance assessment.

3 Geography

3.1 Location and population

The Maryborough Basin is a geological basin in South East Queensland, approximately 250 km north of Brisbane (Figure 3.1). The basin has an area about 9,100 km^2 onshore and 15,500 km^2 offshore. It underlies the major regional centres of Bundaberg, Hervey Bay and Maryborough. Offshore, the basin underlies Fraser Island.

The population of urban centres within the Maryborough Basin from the 2011 Census (Australian Bureau of Statistics 2013) are shown in Table 3.1. Based on these data, the total population of the Maryborough Basin is estimated at 151,000, although the actual population may be greater, as the statistics cover primarily urban areas. Tourism is an important industry for the Maryborough Basin and population is likely to increase during peak tourism periods. Population density and the urban centres are shown in Figure 3.2. The three major areas of high population are Bundaberg and Hervey Bay along the coast and Maryborough in the south. Figure 3.2 also shows major infrastructure, including the gas pipeline and railway that extends to Gladstone Port north of the basin. The major highway is the Bruce Highway, which runs from the north-west to the south-west of the basin through Childers and Maryborough.

3.1.1 Variation of interpreted basin boundary

The geological interpretation of the Maryborough Basin boundary has evolved over time. This report has used the onshore basin boundary based on information contained within the recently updated publication, *Geology of Queensland* (Draper and Bryan 2013). Prior to the current interpretation, the boundary of the Maryborough Basin was thought to extend further to the south (Figure 3.1). The offshore extent includes Fraser Island, an interpretation confirmed from a study using data from an offshore geophysical survey (Hill 1994). As this report focuses on the onshore Maryborough Basin, the offshore extent is not shown on subsequent report figures.

There has been some variation in the reported depth and stratigraphy of the basin. Draper and Bryan (2013) excluded the Lower Mesozoic Duckinwilla Group from the basin and instead suggested that these rocks are contiguous with the underlying northern Nambour Basin. All previous descriptions (e.g. Ellis 1968; Cranfield 1982; Cranfield 1994; Hill 1994; Stephenson and Burch 2004; Bradshaw, Spencer et al. 2009) include the Duckinwilla Group within the Maryborough Basin. 'Geology of Queensland' (Draper and Bryan 2013) was released mid-way through the timeframe of this project and included the Duckinwilla Group within the Maryborough Basin. Therefore, these strata were included as part of the Maryborough Basin for the purposes of this project. This is important because the Duckinwilla Group contains coal measures (Tiaro Coal Measures) that outcrop in the basin. Refer to Section 4.3 for further details of the Maryborough Basin stratigraphy.

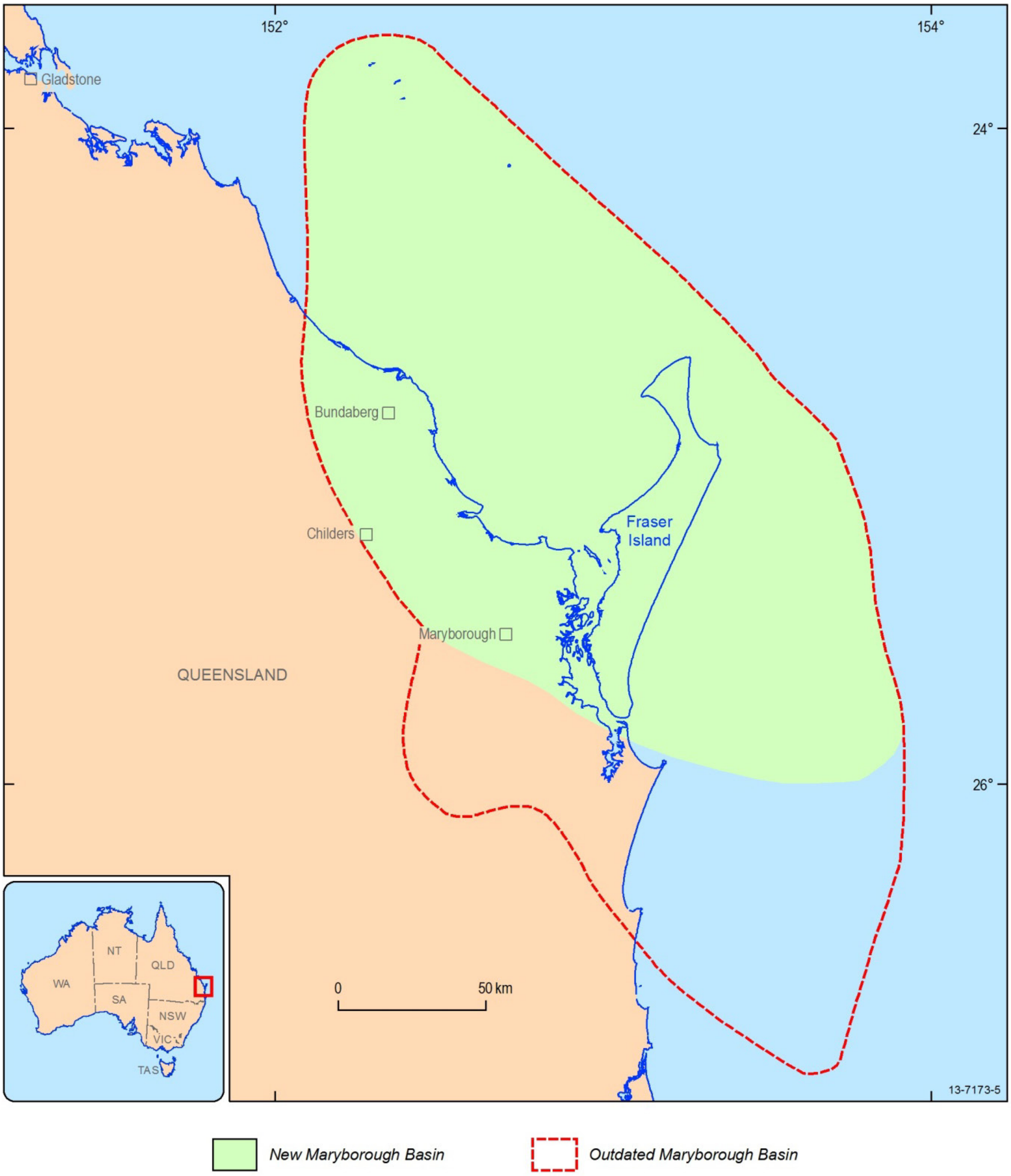

Figure 3.1 Previous and current basin boundaries for the Maryborough Basin.

Source: Previous basin boundary from Hill (1994), and current boundary after Draper and Bryan (2013)

3.2 Physiography and land cover

The Maryborough Basin is relatively flat and low-lying (Figure 3.3), with most of the topography within the basin below 100 m AHD. Sub-linear hills and ridges crop out along its western margin. Elevated terrain on Fraser Island is caused by an extensive system of parabolic sand dunes, and some of these are approximately 250 m above sea level (ASL).

Land cover in the Maryborough Basin (Figure 3.4) is mostly a mix of closed canopy tree cover, open canopy tree cover and land used for agriculture. A large portion of land is used for irrigated sugarcane agriculture, particularly around the towns of Bundaberg, Childers and Maryborough and adjacent to the Kolan, Burnett and Mary Rivers.

Table 3.1 Urban centre populations in the Maryborough Basin.

Urban Centre/Locality	Census area code	Population (2011)
Bargara	UCL313001 (UCL)	10,052
Booral	UCL321019 (UCL)	723
Bundaberg	UCL312001 (UCL)	49,750
Burnett Heads	UCL315011 (UCL)	2630
Burrum Heads	UCL315012 (UCL)	1068
Childers	UCL315019 (UCL)	1410
Cordalba	UCL322030 (UCL)	314
Craignish	SSC30442 (SSC)	1752
Dundowran	SSC30519 (SSC)	970
Dundowran Beach	SSC30520 (SSC)	1769
Elliott Heads	UCL321037 (UCL)	762
Fraser Island	SSC30624 (SSC)	194
Hervey Bay	UCL312003 (UCL)	48,680
Howard	UCL315043 (UCL)	1016
Innes Park	SSC30801 (SSC)	2031
Maryborough	UCL312004 (UCL)	21,777
Moore Park	UCL315068 (UCL)	1650
River Heads	UCL315086 (UCL)	1295
Toogoom	UCL315096 (UCL)	1872
Torbanlea	UCL322120 (UCL)	290
Woodgate	UCL321119 (UCL)	940
Total		**150,945**

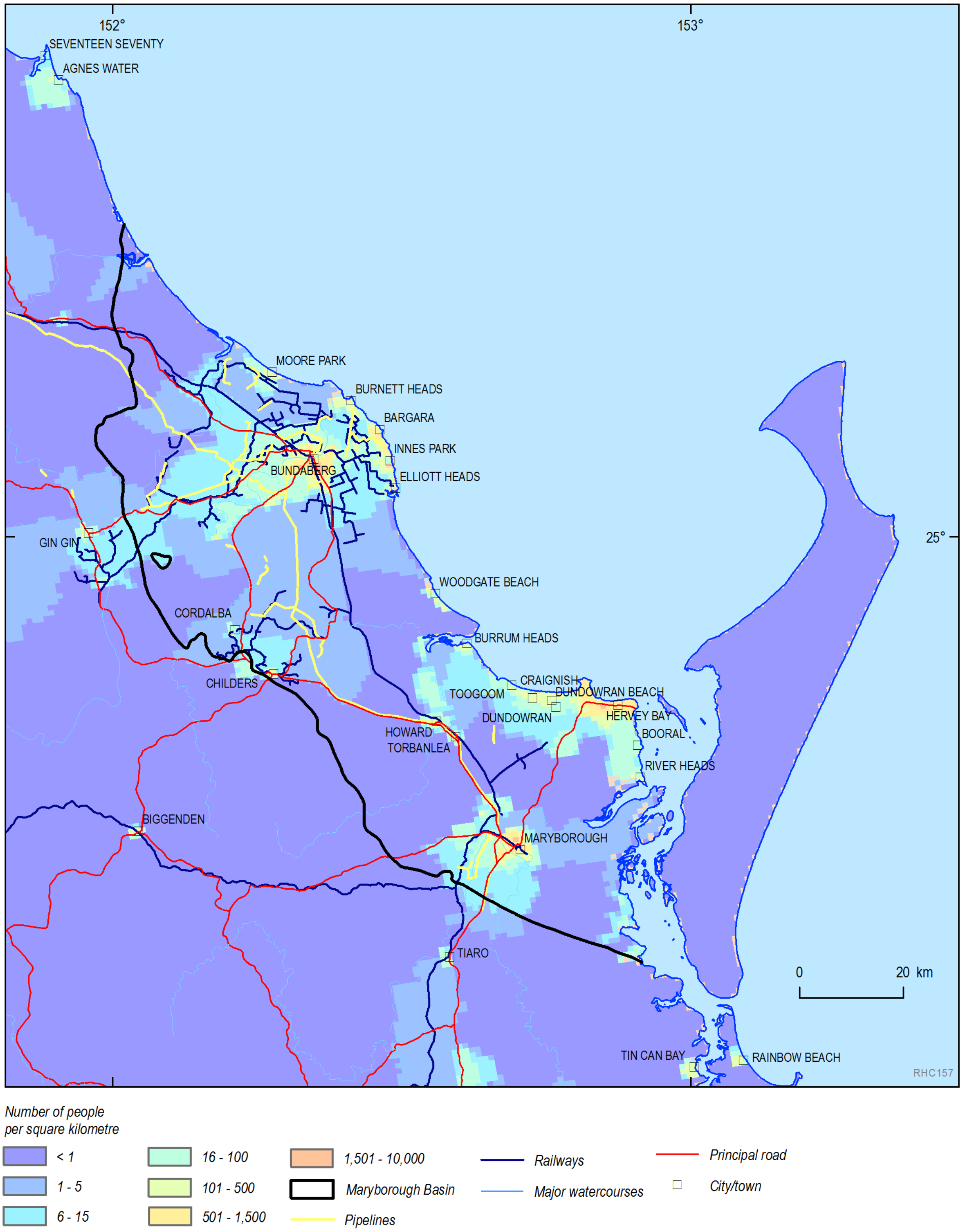

Figure 3.2 Population distribution and major infrastructure, Maryborough Basin.

Figure 3.3 Location and topographic map of the Maryborough Basin displaying regional centres.

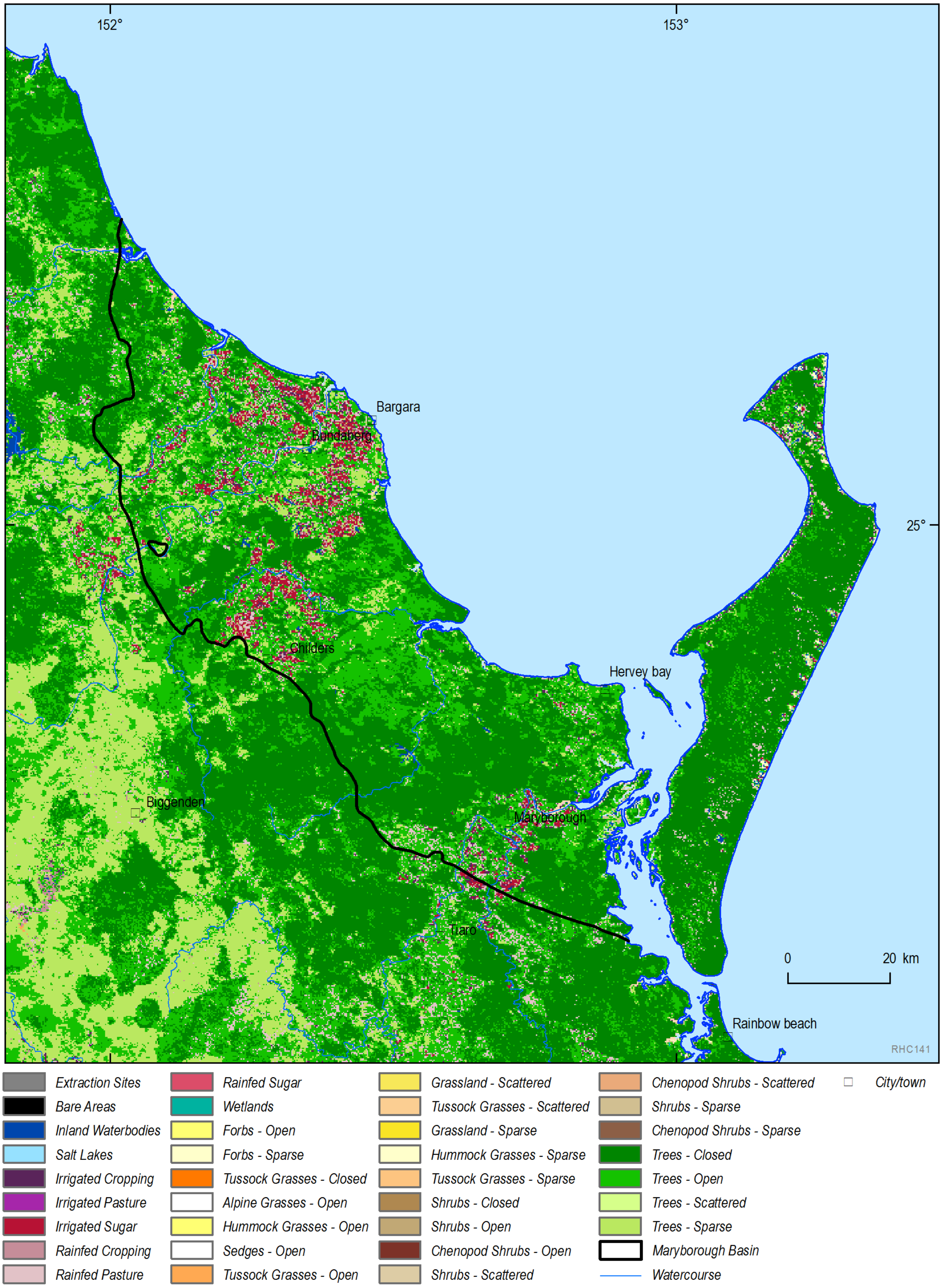

Figure 3.4 Land cover distribution in the Maryborough Basin.

3.3 Climate

The climate of the Maryborough Basin is *subtropical with no dry season* according to its Köppen-Geiger classification (Stern, de Hoedt et al. 2008). The northern tip of Fraser Island is the only part of the basin which has a separate classification and this part of the basin experiences a *tropical* climate.

Climate data was retrieved and analysed from four stations operating within the basin (BoM 2012b). These were the Maryborough Station, Bundaberg Aero Station, Hervey Bay Airport Station and Sandy Cape Lighthouse Station (Figure 3.5). These stations were chosen because they are spread geographically across the basin and contain historical data. Across the basin, the mean annual rainfall ranges from approximately 1,030 to 1,160 mm (Table 3.2). Both temperature and rainfall are higher in summer (December to February) than in winter (June to August). The average maximum temperature per month in summer is 29.8°C and the average rainfall per month is 152.7 mm, compared to 22.2°C and 62.6 mm in winter respectively.

Table 3.2 Rainfall and temperature data for stations in the Maryborough Basin (BoM 2012b).

	Maryborough	Bundaberg Aero	Hervey Bay Airport	Sandy Cape Lighthouse	Average
Time range of data	1908 - 2013 (1); 1870 - 2013 (2)	1959 - 2013 (1); 1942 - 2013 (2)	1999 - 2013 (1; 2)	1907 - 2013; 1871 - 2013 (2)	
Annual statistics					
Maximum temperature (°C)	26.9	26.6	26.2	25.8	26.4
Minimum temperature (°C)	15.3	16.4	16.7	18.8	16.8
Mean rainfall (mm)	1157.3	1031.8	1133.5	1276	1149.7
Summer statistics					
Maximum temperature (average °C/month)	30.5	29.9	29.8	29.2	29.8
Minimum temperature (average °C/month)	20.3	21.1	21.7	22.1	21.3
Mean rainfall (average mm/month)	156.6	156.0	153.5	144.6	152.7
Winter statistics					
Maximum temperature (average °C/month)	22.6	22.6	22.0	21.7	22.2
Minimum temperature (average °C/month)	9.4	10.9	10.7	14.8	11.5
Mean rainfall (average mm/month)	53.6	42.8	66.3	87.7	62.6
(1) = Time range for temperature data (2) = Time range for rainfall data					

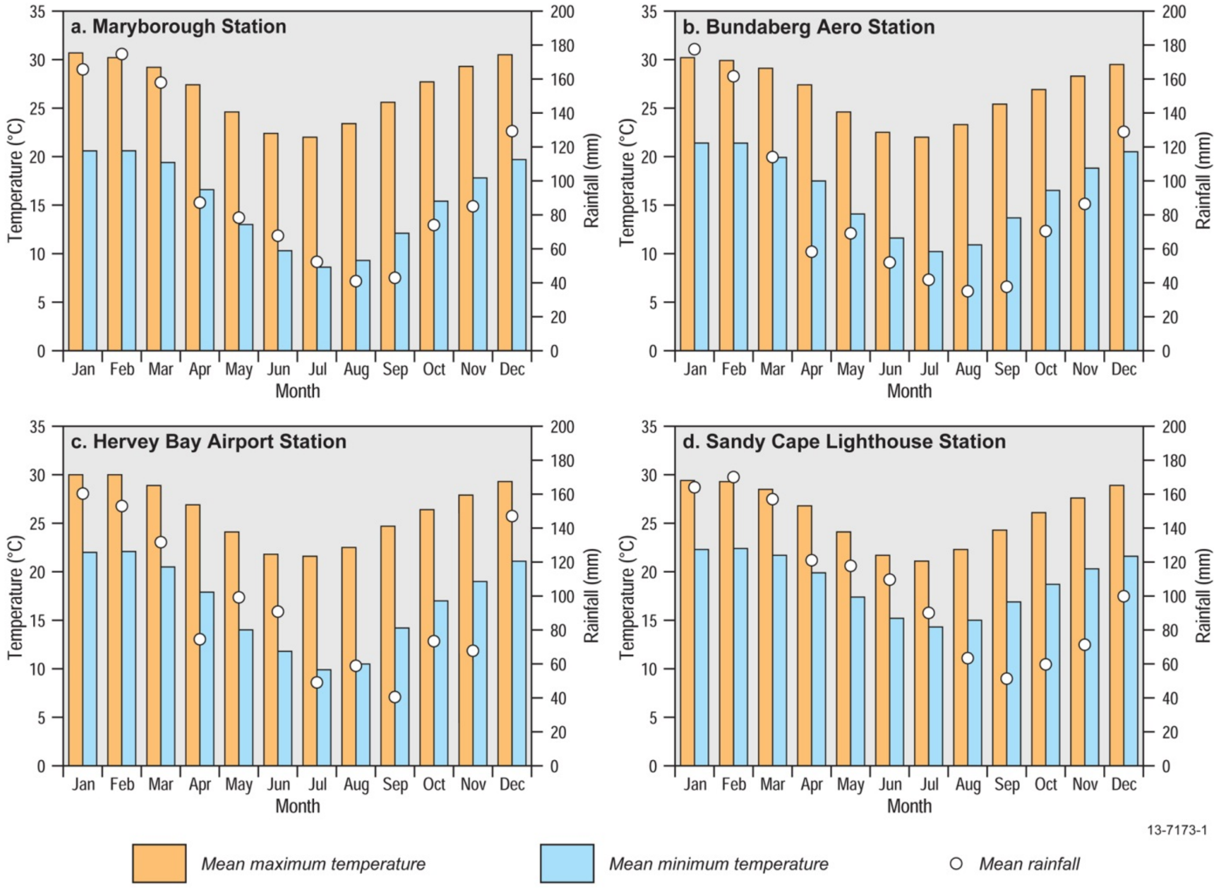

Figure 3.5 Mean monthly distribution of rainfall for four climate stations in the Maryborough Basin.

Source Bureau of Meteorology (2012b)

Estimates for point potential evapotranspiration (ET) from national-scale data in the Maryborough Basin range from approximately 800 to 1700 mm/year (BoM 2012a). This data is shown in Figure 3.6, which shows that ET is greater towards the south and in the east. Fraser Island has greater (>1500 mm/year) ET values than onshore (about 800 to 1,600 mm/year).

ET varies both temporally and spatially within the basin. This is shown when comparing the ET values (in mm per day) for the Bundaberg and Maryborough Climate Stations in 2012 (2012 is the most recent year with a complete ET dataset). ET data were available from 2009 to present for the Maryborough and Bundaberg Climate Stations (Figure 3.5). ET is shown to be slightly greater in Bundaberg, with a total annual ET of 1,561 mm in 2012 compared to Maryborough, with a total annual ET of 1,513 mm in 2012. ET is also shown to be lower (approximately 2 to 3 mm per day) in the winter months compared to the summer months (approximately 5 to 6 mm per day).

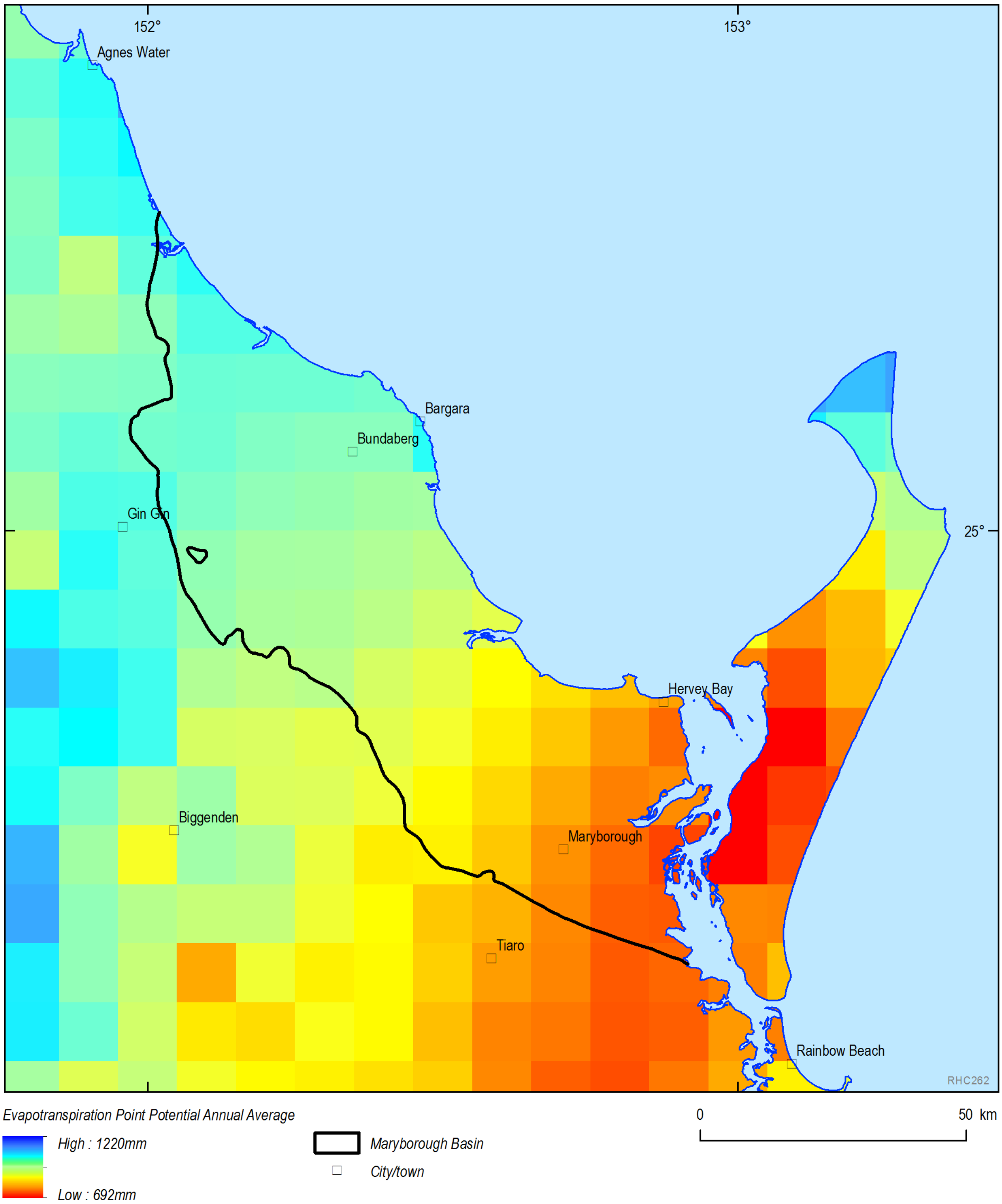

Figure 3.6 Point potential annual average evapotranspiration for the Maryborough Basin.

Source: Bureau of Meteorology (2012a)

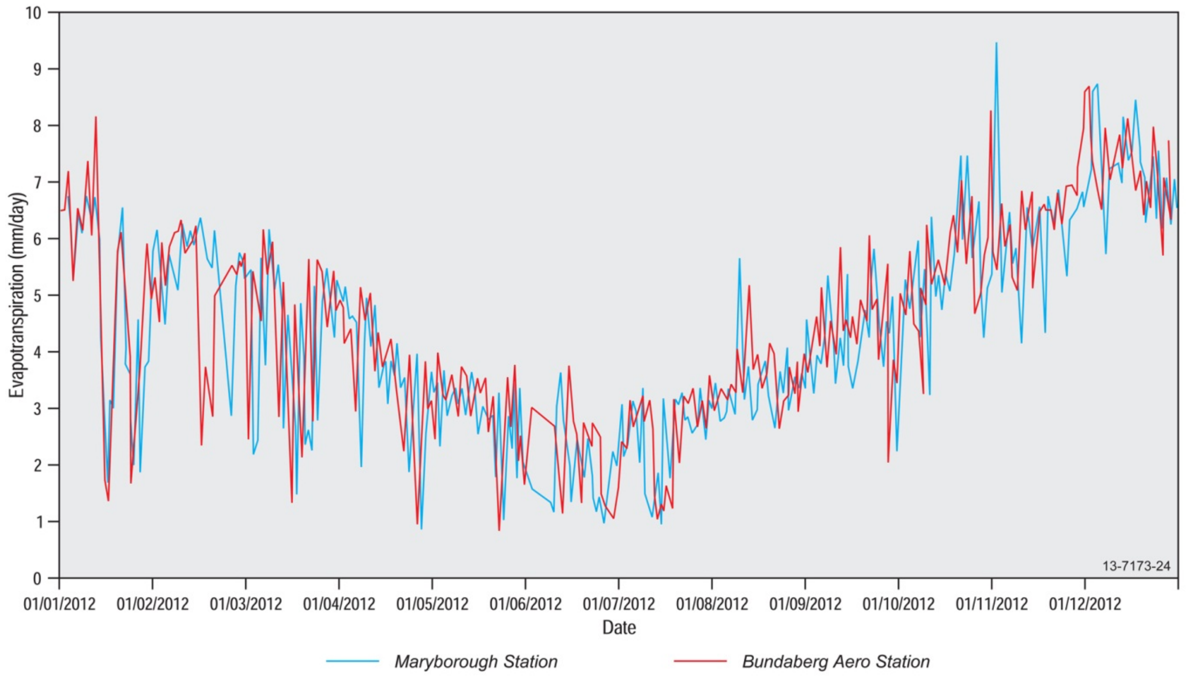

Figure 3.7 Potential evapotranspiration at the Maryborough and Bundaberg Aero climate stations (BoM 2012a).

3.4 Land use

The most common land use type in the Maryborough Basin is beef cattle grazing (Table 3.3). There are also large areas of state forest, which include the Tuan State Forest, used for plantation forestry (Figure 3.8). Horticulture and agriculture are major industries. Sugar cane plantations occur at Childers, Maryborough and Bundaberg and industries associated with sugar refining are important economically. Tourism is another major industry (Cranfield 1994).

Table 3.3 Land use in the Maryborough Basin.

Grazing natural vegetation	32.44%
Nature conservation	30.81%
Irrigated pastures and cropping	11.92%
Production forestry	5.55%
Other minimal use	5.25%
Urban intensive use	4.69%
Water	4.29%
Plantation forestry	4.03%
Irrigated horticulture	0.62%
Dryland cropping	0.27%
Dryland horticulture	0.14%

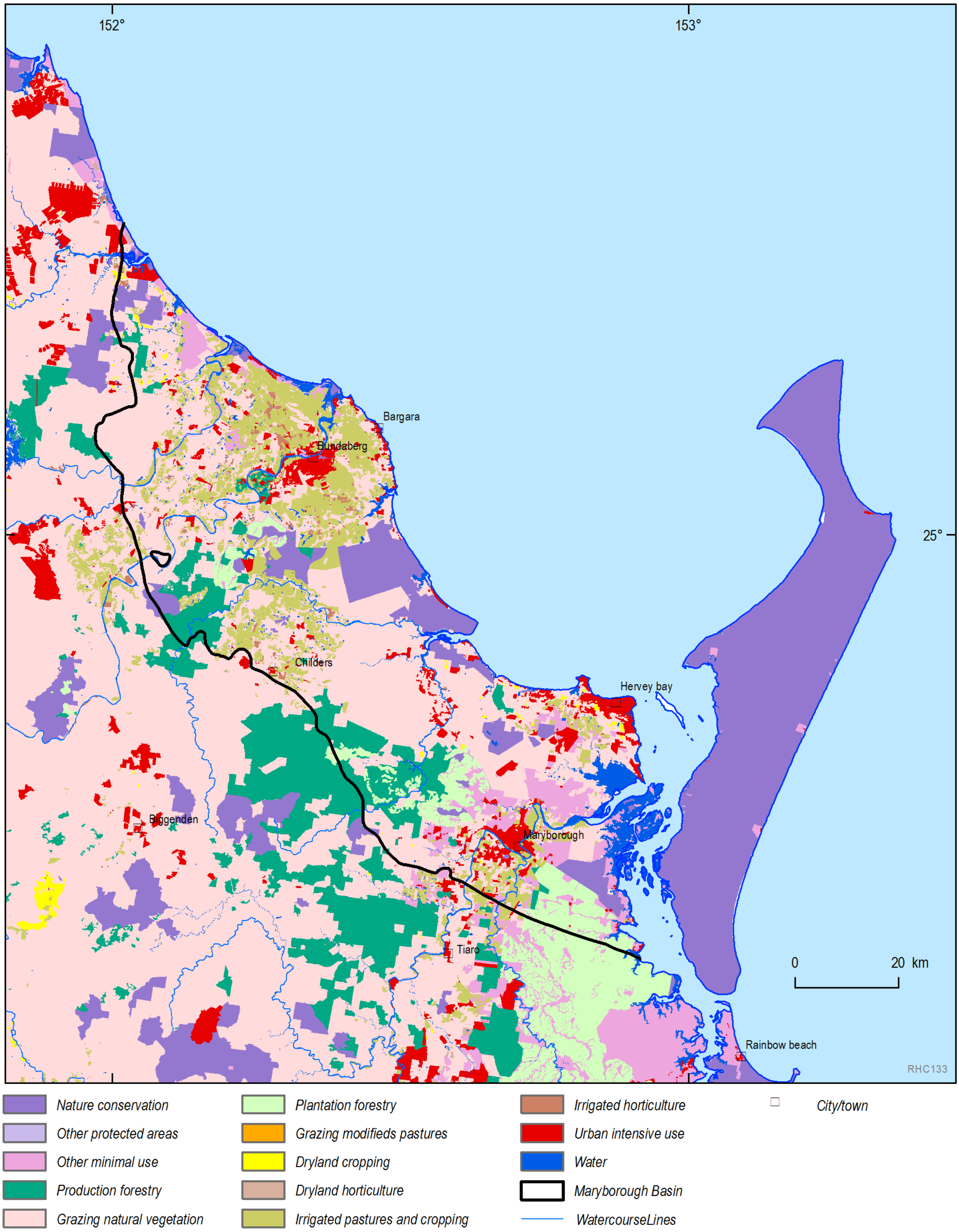

Figure 3.8 Land use in the Maryborough Basin.

3.5 Surface water systems

There are four main surface water catchments in the Maryborough Basin: the Kolan River, Burnett River, Burrum River and Mary River. These catchments contain a combination of perennial and non-perennial water courses (Figure 3.9). Watercourses drain predominately from the west to the east as they originate in the elevated terrain of the Great Dividing Range and discharge at the sea.

Figure 3.9 Surface water catchments in the Maryborough Basin.

Stream-gauge data is available for three surface water gauging stations within the Maryborough Basin (BoM 2013a): Tianana Creek (this station is up-catchment and outside the basin boundary but was included to understand surface water flow into the basin), Isis River and the Gregory River (Figure 3.9).

Annual stream flow from historical data is shown in Figure 3.10. Streamflow in the catchments varies between years and ranges from approximately 1 to 315 GL/year. The average streamflow is 23, 56 and 49 GL/year for the Tianana Creek, Isis River and Gregory River stations respectively.

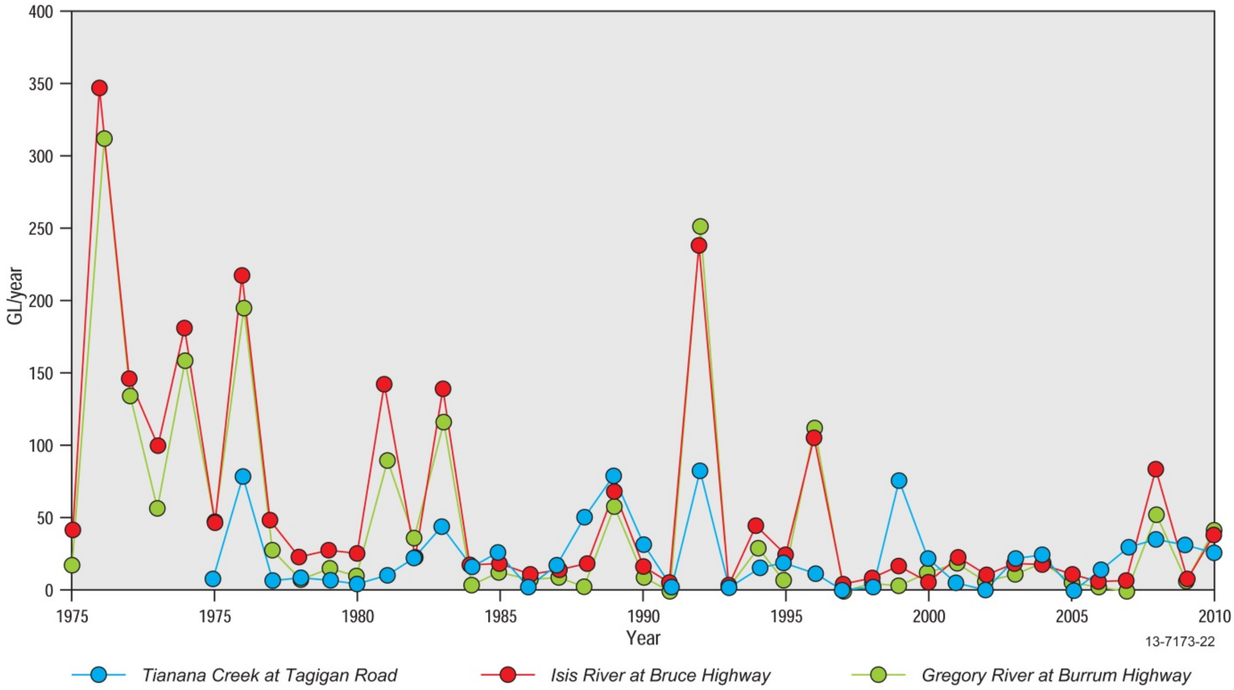

Figure 3.10 Annual streamflow values for tributaries of Maryborough surface water systems.

Source: Bureau of Meteorology (2013)

Sinclair Knight Merz (2012) conducted an analytical assessment of groundwater–surface water connectivity, as well as the impact of groundwater extraction on surface water availability for the Burnett, Burrum and Kolan river catchments. This advanced the understanding of surface water-groundwater connectivity in the area. Connectivity mapping to indicate whether streams were predominantly gaining or losing systems was not undertaken for Maryborough Basin catchments and instead analytical impact assessments were used *"to quantify the time lag and size of the impact of groundwater extractions on surface water systems at a catchment scale"* (SKM, 2012). A semi-quantitative classification of connectivity was applied to the catchments. Details of the results from this study for specific catchments are discussed in Section 3.5.1 to 3.5.4.

The Australian Natural Resource Atlas (Department of Sustainability Environment Water Population and Communities 2010) contains information regarding catchment size and water use for varying catchments or sub-catchments. Water use in the main catchments of the Maryborough Basin is outlined in the following sections, where development categories for surface water use are: <30% ('Low Development'); 30 to 70% ('Moderate Development'); 70 to 100% ('Highly Developed'); and >100% ('Overdeveloped') (Department of Sustainability Environment Water Population and Communities 2010).

3.5.1 Kolan River

The Kolan River is approximately 180 km long and discharges to the sea north of Bundaberg. A major tributary of the river is Gin Gin Creek. The lower reaches of the Kolan River are perennial and the upper reaches are non-perennial (Figure 3.9). The Kolan River Surface Water Management Area is 2,795 km^2 and its total storage volume is 1,318,760 ML. Total surface water use is estimated at 38,998 ML/year, which places it in the 'Highly Developed' category. Mean annual run-off is 631,208 ML/year and is greater during the summer months.

Sinclair Knight Merz (2012) suggested that *"streamflow and bore hydrographs show good evidence of groundwater-sustained baseflow in the Kolan River catchment".* Their modelling showed that streamflow depletion as a result of groundwater extraction would occur in the river within days and that groundwater and surface water in the catchment is *"highly connected"*.

3.5.2 Burnett River

The Burnett River catchment is the third largest on the Queensland coast (Sinclair Knight Merz 2012), and includes the Bundaberg Irrigation Scheme, which is a state government managed irrigation scheme near the towns of Bundaberg, Childers and Gin Gin (Department of Sustainability Environment Water Population and Communities 2010). The 3,720 km^2 irrigation system consists of water storages (472,305 ML total volume) and a channel distribution system. Water supply is supplemented by water transfer from the Kolan Basin. Total surface water use is 135,535 ML/year, which makes it a 'Highly Developed' surface water catchment. The mean annual run-off is estimated at 883,074 ML/year.

Modelling was undertaken by Sinclair Knight Merz (2012) to assess connectivity between surface water and groundwater in the Burnett catchment. Although this was done in Three Moon Creek, which is a tributary north-west of Bundaberg and outside of the Maryborough Basin boundary, it still provides useful information for the downstream system. Flows in Three Moon Creek occur 52% of the year and there are 'no-flow' conditions for the rest of the year. Streamflow depletion as a result of groundwater extraction is predicted to occur within days, and Three Moon Creek and its adjoining aquifers were classified as *"very highly connected".*

3.5.3 Burrum River

The Burrum River catchment lies between Bundaberg and Hervey Bay and contains four sub-catchments: Elliott River, Gregory River, Isis River and Burrum River. The Burrum, Isis and Gregory rivers converge to discharge at a single inlet at Wide Bay, south of Bundaberg. The Burrum Surface Water Management Area has a catchment size of 2,295 km^2 and its major tributaries are Duckinwilla, Harwood, Doongul, Powell and Logbridge Creeks. The major storage in the system is Lenthalls Dam, which is on the Burrum River. The total storage volume is 18,490 ML and the total surface water use is 6,134 ML/year which places it in the 'Medium Development Category'. The mean annual run-off is estimated at 222,500 ML/year.

In an assessment of the impacts of groundwater extraction on streamflow in 2012, Sinclair Knight Merz deduced that the Burrum River and the aquifers adjacent are *"very highly connected".* It was predicted that groundwater extraction would impact and reduce streamflow volumes within days.

The Elliott Surface Water Management Area has an area of 365 km^2 and is bound by the Burnett River in the north and the Gregory River in the south. Tributaries include the Elliott River and the Mahogany

Creek. The total storage volume is 22,995 ML and the total surface water use is 6,811 ML/year, which places it in the ‘Low Development’ category. Mean annual run-off is estimated at 50,300 ML/year.

The Gregory Surface Water Management Area has an area of 855 km^2.Total storage volume is 250,415 ML and the surface water use is 7,903 ML/year, which places it in the ‘Low Development’ category. Run-off averages 150,400 ML/year.

There are no data for the total storage volume of the Isis River and the total surface water use is 1,042 ML/year, which places it in the ‘Medium Development’ category. The Isis Surface Water Management Area has a catchment area of 530 km^2 and the mean annual run-off is estimated at 95,600 ML/year.

3.5.4 Mary River

The Mary River flows north-north-east and enters the Great Sandy Strait to the west of Fraser Island. The Mary Surface Water Management Area is approximately 9,595 km^2 and has a total storage volume of 308,129 ML. Total surface water use is approximately 80,722 ML/year, which places it in the ‘Medium Development’ category. Mean annual run-off is estimated at 2,042,000 ML/year.

3.5.5 Water use

Water use in the Maryborough Basin has been estimated based on surface water catchments (Figure 3.11) (Australian Bureau of Statistics 2013). A summary of surface water volumes in each of the surface water management areas that occur in the basin area is provided in Table 3.4. The greatest volume of water used in the basin is from the Burnett River Catchment, as the Bundaberg area is a large producer of sugar cane. Surface water (from rivers, creeks and lakes) use is greater than groundwater use for the Mary River and Noosa River catchments, whereas in the Burnett and Burrum River catchments groundwater use is greater than surface water use.

Table 3.4 Surface water use in the Maryborough Basin.

	Size (km^2)	Total storage volume (ML)	Total storage volume (ML/km^2)	Total surface water use (ML/year)	Total surface water use ($ML/year/km^2$)	Run off (ML/year)	Run off ($ML/year/km^2$)	Development category
Kolan River Surface Water Management Area	2,785	1,318,760	473.5	38,998	14.0	631,208	226.6	High
Bundaberg Irrigation Area	3,720	472,305	127.0	135,535	36.4	883,074	237.4	High
Burrum Surface Water Management Area	2,295	18,490	8.1	6,134	2.7	222,500	96.9	Medium
Elliott Surface Water Management Area	365	22,995	63.0	6,811	18.7	50,300	137.8	Low
Gregory Surface Water Management Area	855	250,415	292.9	7,903	9.2	150,400	175.9	Low
Isis Surface Water Management Area	530	No data	n/a	1,042	2.0	95,600	180.4	Medium
Mary Surface Water Management Area	9,595	308,129	32.1	80,722	8.4	2,042,000	212.8	Medium
Total	20,145	2,391,094	118.7	277,145	91.4	4,075,082	1267.9	n/a
Mean		398,515	166.1	39,592	13.1	582,154	181.1	n/a

Source: after DSEWPaC (2010)

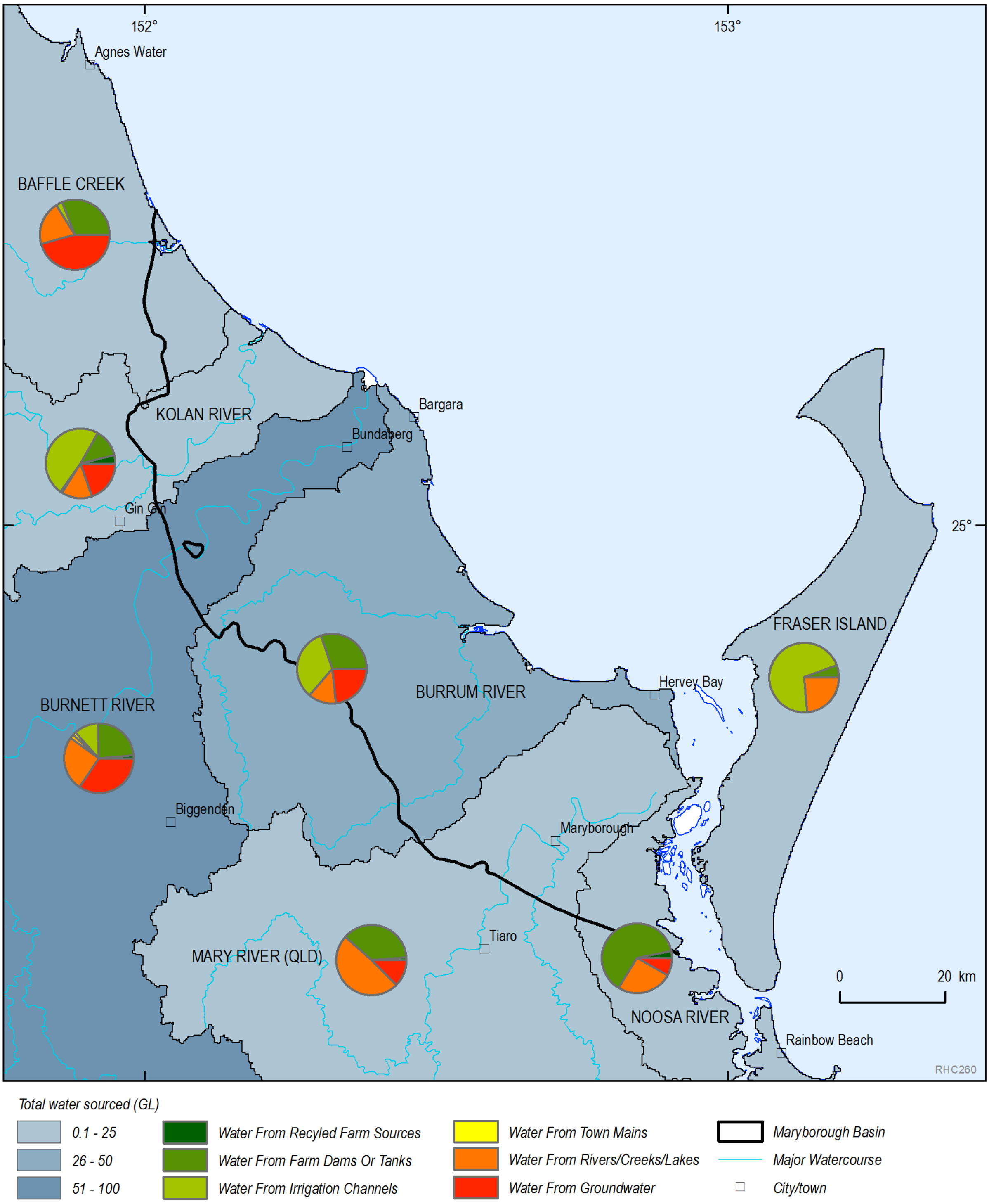

Figure 3.11 Source of water used in the Maryborough Basin, based on surface water catchment.

Source: after Australian Bureau of Statistics (2013)

3.6 Environmental assets

The Maryborough Basin contains diverse native flora and fauna. Along the coast there are mangroves and saltbush, which provide habitat for macro-invertebrates and fish species of commercial, recreational and ecological value. The Maryborough Basin contains many flora and fauna of conservation and ecological value. These include the Queensland Lungfish, currently listed as vulnerable under the *Environment Protection and Biodiversity Conservation Act 1999,* which inhabits the Burnett and Mary River systems.

Natural protected areas of the Maryborough Basin can be seen in Figure 3.12. State forest reserves flank the western part of the basin and Fraser Island is World Heritage Listed for its pristine natural environment. There are a number of national parks within the onshore portion of the basin including the Burrum Coast National Park. Marine parks include the Woongarra Marine Park and the Maaroom Fish Habitat Area. The Great Barrier Reef, which is both a World Heritage Area and a Marine Park, is just north of the offshore Maryborough Basin.

Wetlands are important to maintain for their natural environmental functions as water purification areas, nutrient retention zones, maintenance of watertables, storm protection, flood mitigation, shoreline stabilisation, erosion control and groundwater recharge (Environment Australia 2001). They are also important because they contain high biodiversity. Directory of Important Wetlands in Australia (DIWA) areas are wetlands that were catalogued through the National Wetlands Program and are *"areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres"* (Environment Australia 2001). The most important wetlands in the Maryborough Basin are along the coastline and include the Burrum Coast, Great Sandy Strait and the Fraser Island wetlands.

In addition to the DIWA areas, the Convention on Wetlands of International Importance (also known as the Ramsar Convention) identifies wetlands of international significance (Ramsar, 2014). In the Maryborough Basin, the Great Sandy Strait is considered a Ramsar Wetland (Figure 3.13). This covers an area of about 930 km^2 (Ramsar, 2014).

Important Bird Areas (IBA) are sites of global bird conservation importance. They must adhere to one or more of the following conditions (BirdLife International 2013):

- contain a significant number of one or more globally threatened species
- be one of a set of sites that contains a suite of restricted-range species or biome-restricted species
- have large numbers of migratory or congregational species.

Important Bird Areas within the Maryborough Basin include the Cooloola and Fraser Coast and Great Sandy Strait IBAs (Figure 3.13).

The Groundwater Dependent Ecosystem (GDE) Atlas is currently the most complete inventory of the location and characteristics of GDEs in Australia (National Water Commission, 2012). Within the GDE Atlas, GDEs are characterised into two classes: ecosystems that may rely on the surface expression of groundwater (all surface water ecosystems that may have a groundwater component such as rivers, wetlands and springs) and ecosystems that may rely on subsurface presence of groundwater (includes all vegetation ecosystems). The locations of these types of GDE are shown in Figure 3.14 and Figure 3.15 respectively. The Maryborough Basin has a number of both categories of GDEs, but overall has more GDEs that mostly rely on surface expression of groundwater (Figure 3.14). GDE that may rely on subsurface expression of groundwater are mostly in the central part of the basin and in the north of Fraser Island (Figure 3.15).

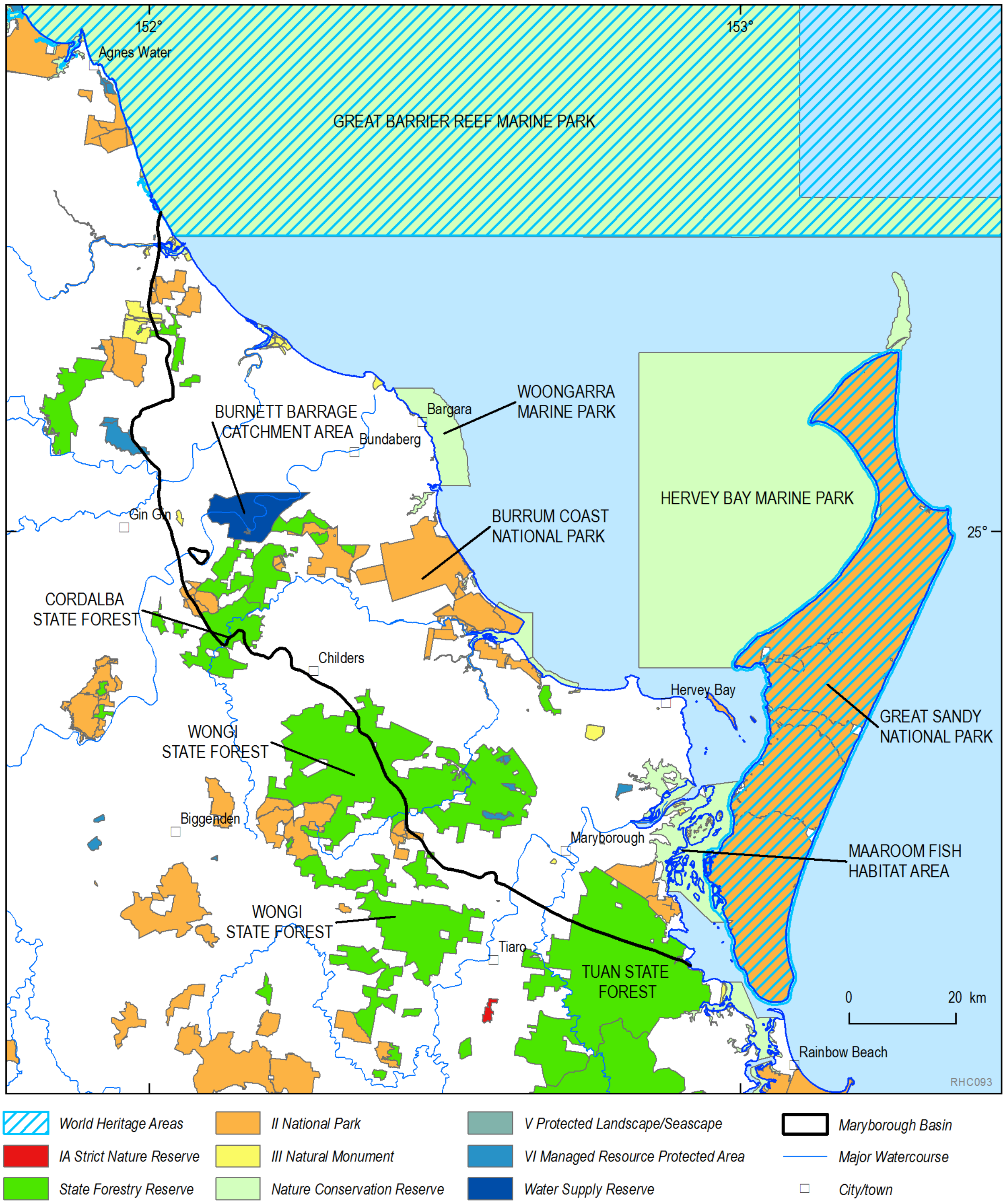

Figure 3.12 Natural protected areas within the Maryborough Basin.

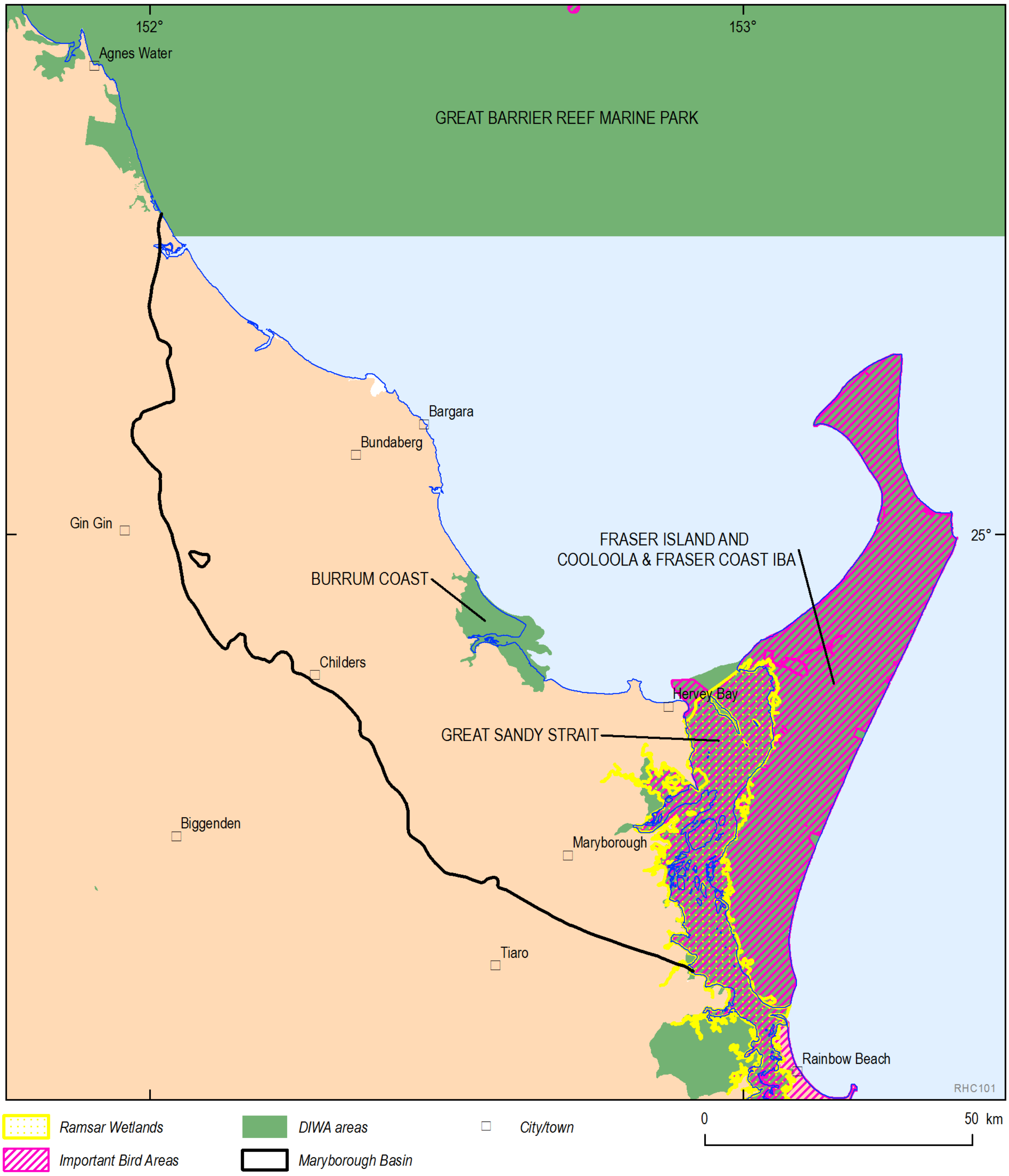

Figure 3.13 Maryborough Basin Ramsar Wetlands, DIWA Important Wetlands and Important Bird Areas.

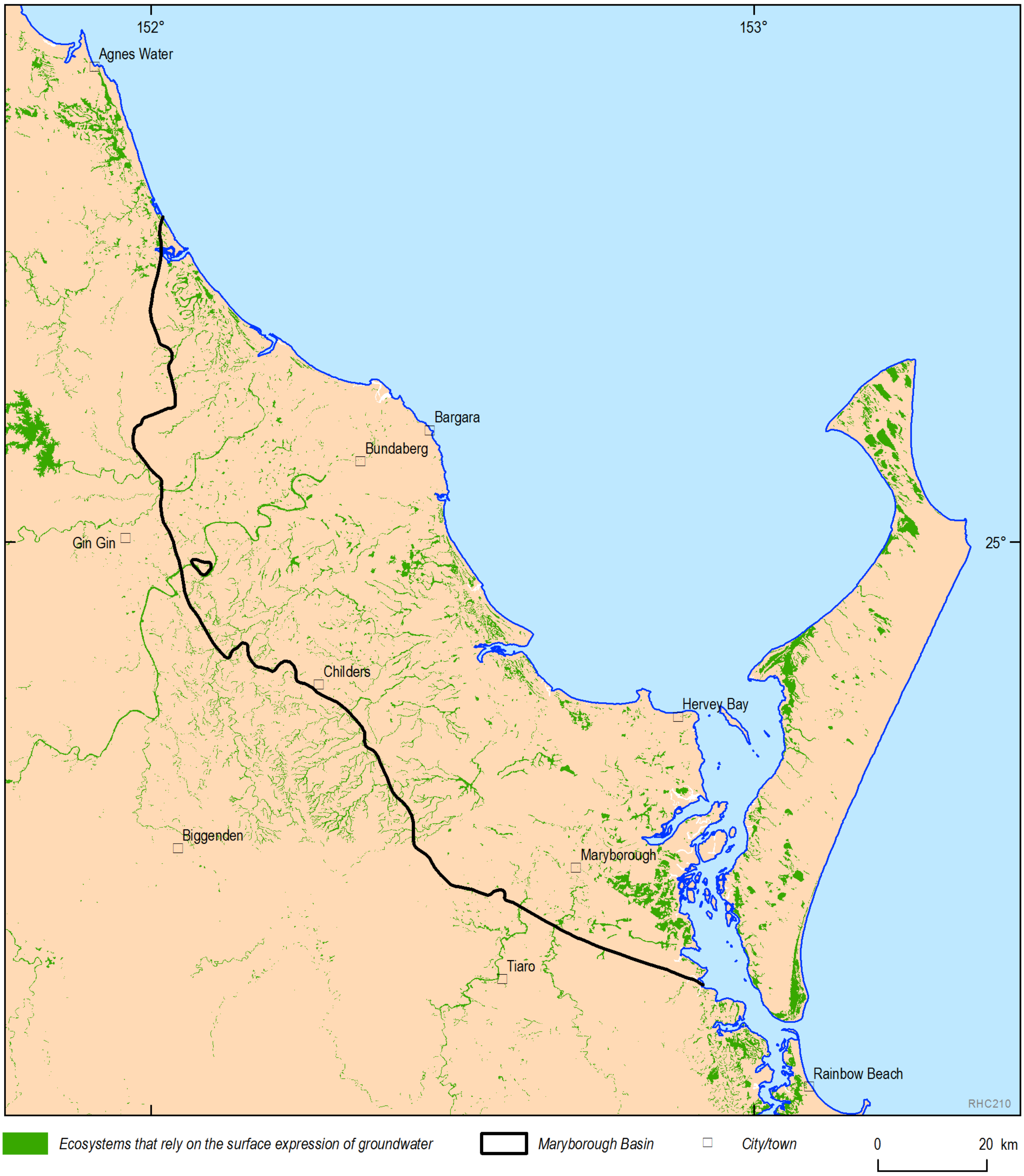

Figure 3.14 Groundwater dependent ecosystems that may rely on surface expression of groundwater in and around the Maryborough Basin.

Source: after National Water Commission (2012)

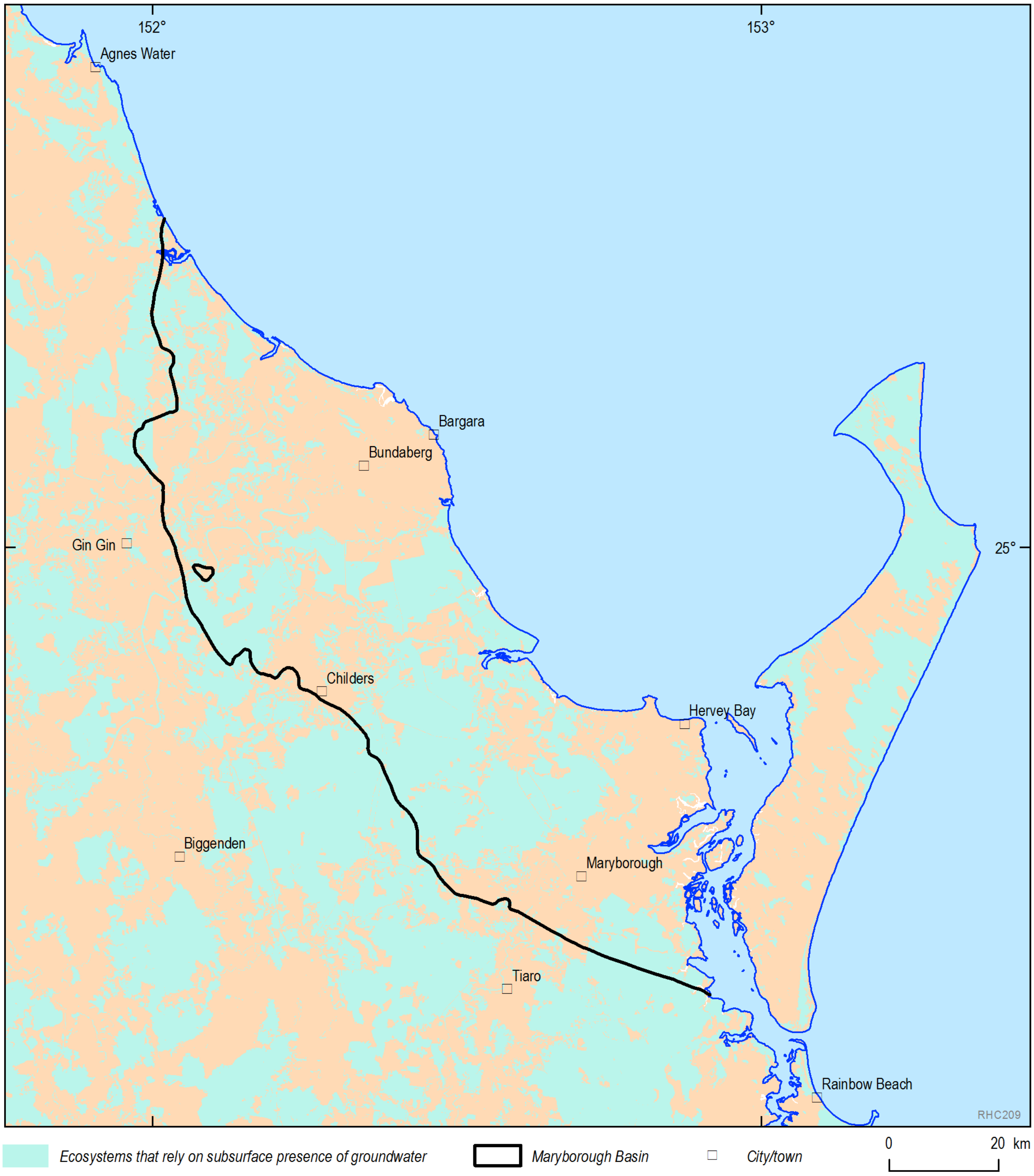

Figure 3.15 Groundwater dependent ecosystems that may rely on subsurface expression of groundwater in and around the Maryborough Basin.

Source: after National Water Commission (2012)

4 Geology

4.1 Basin evolution

The Maryborough Basin formed in the Late Jurassic to Early Cretaceous, during the New England Orogeny (Figure 4.1). Plutonic activity initiated by crustal subduction caused the basin structure to develop, which then began to fill with coarse-grained clastic sediments. As basin development continued, sediments fined-upwards to fine-grained sands, silts and coal measures (Harrington and Korsch 1985; Hill 1994). The Duckinwilla Group was deposited during this time.

Deformation of the Maryborough Basin was likely linked to convergent tectonism at a plate boundary located at New Caledonia (Hill 1994). During the Early Cretaceous, approximately 140 Ma, a pre-existing NNW-trending fault system was reactivated by transcurrent movement that displaced Triassic and Jurassic sedimentary rocks as well as the underlying basement rocks. As a result of this transtensional rifting, acid- to intermediate-type volcanism occurred (Hill 1994) and the Grahams Creek Formation was formed.

Following the transtensional rifting of the Early Cretaceous, marine transgression occurred and shallow marine clastic sediments were deposited. Thermal relaxation resulted in basin sag, providing increased accommodation space for clastic material. By the beginning of the Upper Cretaceous, the basin was developing into a foreland basin and volcanic material was being shed into the basin from an arc to its east (Hill 1994). This tectonic episode resulted in the deposition of the Maryborough Formation and the Burrum Coal Measures.

In the mid Cretaceous, regional tectonics shifted to a compressional regime. This resulted in basin inversion, folding and reactivation of steep faults. Uplift in the basin also occurred as a result of magmatic underplating and rift-flank uplift associated with Tasman Sea rifting. As a result, the current structure of sequential, broad northwest-trending synclines and anticlines were formed (Hill 1994). Basin inversion was succeeded by peneplanation, removing a large portion of the Mesozoic sedimentary sequence and causing the current manifestation of the basin as an erosional remnant of a much larger basin. The erosional products of the basin are thought to be now incorporated into the shelfal wedge and at the base of the continental slope in the adjacent Tasman Basin (Hill, 1994).

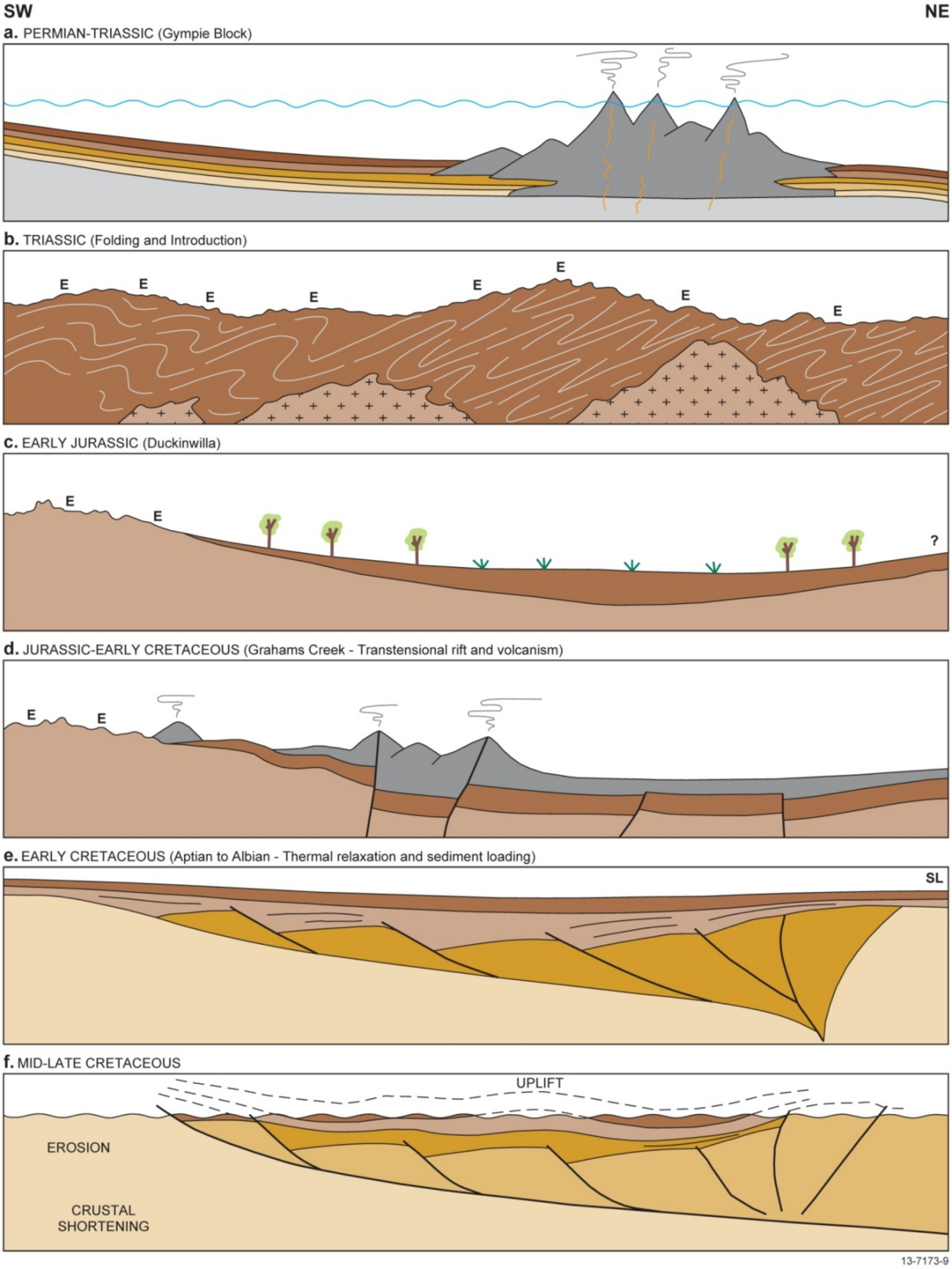

Figure 4.1 Schematic diagram of Maryborough Basin evolution. Each colour is not intended to represent an individual geological unit and shows conceptual change in the system over time.

Source: adapted from Grimes (1992) and Stephenson and Burch (2004)

4.2 Basin setting

The Maryborough Basin contains a mixed succession of Mesozoic and Cenozoic sedimentary rocks (Figure 4.3 and Figure 4.2). The Electra Fault System flanks the basin's western margin, where older geological units outcrop, and separates the basin from the Gympie Block to the west. Most of the basin extent is now covered by Cenozoic sediments of the Elliott Formation, which are dissected by Quaternary alluvial sediments associated with modern rivers. In the south of the basin, there is a repetition of units from the west to the east, which is associated with the major syncline structure in the area. Folding is tight to isoclinal in the south of the basin and more open in the north. Along the coast, Holocene dune sands occur in a NE to SW-trending linear system. These are interspersed with estuarine, deltaic and other coastal deposits (sands and muds). Fraser Island comprises a series of Pleistocene and Holocene parabolic sand dunes.

Intrusive rocks within the Maryborough Basin strata occur mostly at basin margins, where they outcrop, or lie beneath sedimentary cover. They are Mesozoic in age. Intrusive rocks range from ultramafic to granitic in composition and their exact distribution beneath sedimentary cover is unknown, although they are thought to intrude the Duckinwilla Group. There are intrusive rocks in the basin known from outcrop, including undifferentiated Late Jurassic to Early Cretaceous diorite and granite bodies. Small isolated outcrops of these intrusive rocks occur in the Maryborough Formation, mostly intruding the deeper sedimentary units.

Volcanic rocks occur in the central basin and along the coastline and are predominantly Cenozoic. The most dominant extrusive rocks within the basin are the:

1. Hummock Basalt (near Bundaberg): olivine basalt flows, minor scoria, agglomerate; and the
2. Gin Gin Basalt: Olivine basalt, formed as continental basalt flows, although no vent system has yet been recognised.

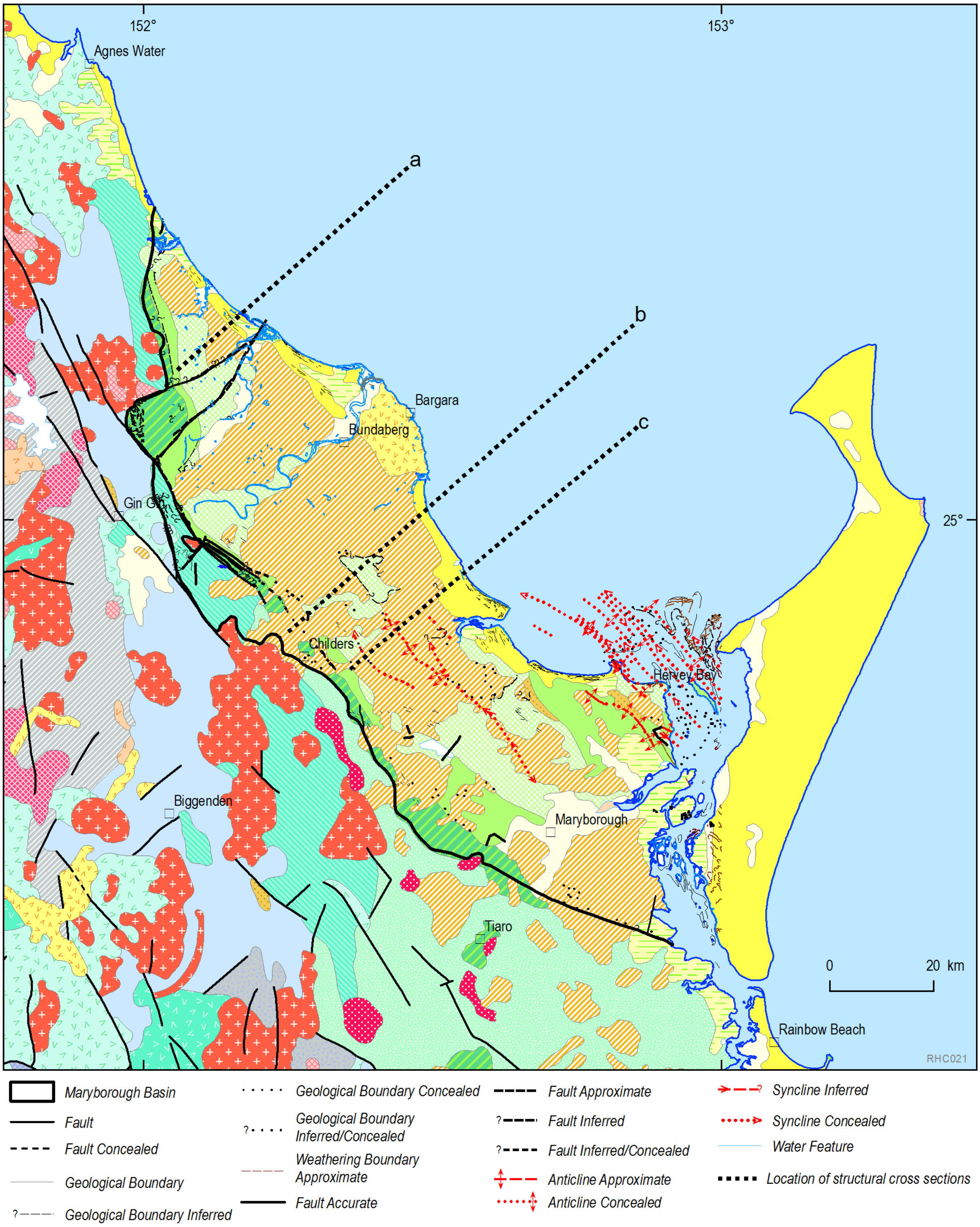

Figure 4.2 Geology map of the Maryborough Basin.

Note: Structural cross sections for lines a, b and c are shown in Figure 4.9

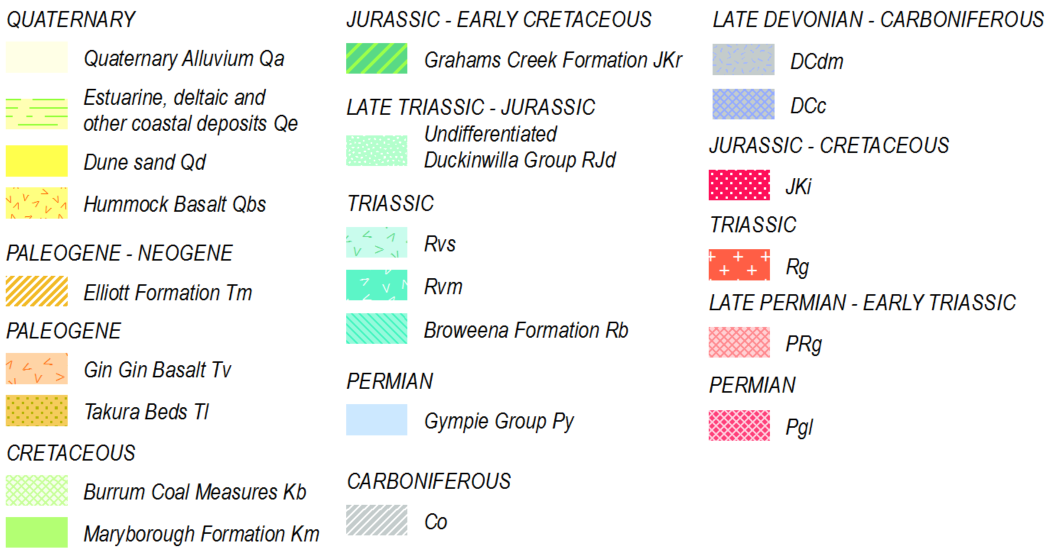

Figure 4.3 Legend for the geology map of the Maryborough Basin.

4.3 Stratigraphy

The stratigraphy of the Maryborough Basin is shown in Figure 4.4. The lower units of the Maryborough Basin are known as the Duckinwilla Group. These are Late Triassic to Middle Jurassic in age and are overlain by the Early Cretaceous rocks of the Grahams Creek Formation, Maryborough Formation and the Burrum Coal Measures. The Early Cretaceous section is truncated by a strong erosional unconformity and has been overlain by Cenozoic sediments that thicken towards the coast. The sedimentology, depositional environment and characteristics of stratigraphic units are described in the following section, which has largely been derived from Cranfield (1994). Although thicknesses of stratigraphic units are estimated in this section, they may vary considerably in the basin due to the variable nature of folding and faulting.

4.3.1 Duckinwilla Group

The Duckinwilla Group has two recognised units and is interpreted to have been deposited in a fluvial environment, likely to have been within a fluvial upper plain, fluvial lower plain or a fluvio-lacustrine setting (Ellis 1968).

Myrtle Creek Sandstone

The lower-most unit of the Duckinwilla Group in the Maryborough Basin is known as the Myrtle Creek Sandstone. These rocks were deposited during the Late Triassic to Early Jurassic in a high energy fluvial environment. The unit is formed from quartzose sandstone and contains large-scale cross bedding. It contains siltstone and shale at its base and minor tuffaceous beds. The unit is variably 60–800 m thick.

Tiaro Coal Measures

Overlying the Myrtle Creek Sandstone are the Early Jurassic Tiaro Coal Measures. These were deposited in a low energy alluvial to lacustrine environment. The sequence consists mostly of shale, mudstone, siltstone, sandstone, volcanics, minor coal and a lesser amount of limestone (Ellis 1968). The thickness of the unit is estimated to be about 800 m.

4.3.2 Grahams Creek Formation

The Grahams Creek Formation was deposited during the Jurassic to Cretaceous and unconformably overlies the Tiaro Coal Measures. It is a volcanic unit deposited terrestrially as a result of eruption from a series of vents in the western part of the basin. The formation contains volcanics and volcaniclastic sediments, trachyandesite, andesite and trachyte. It is up to 1200 m thick.

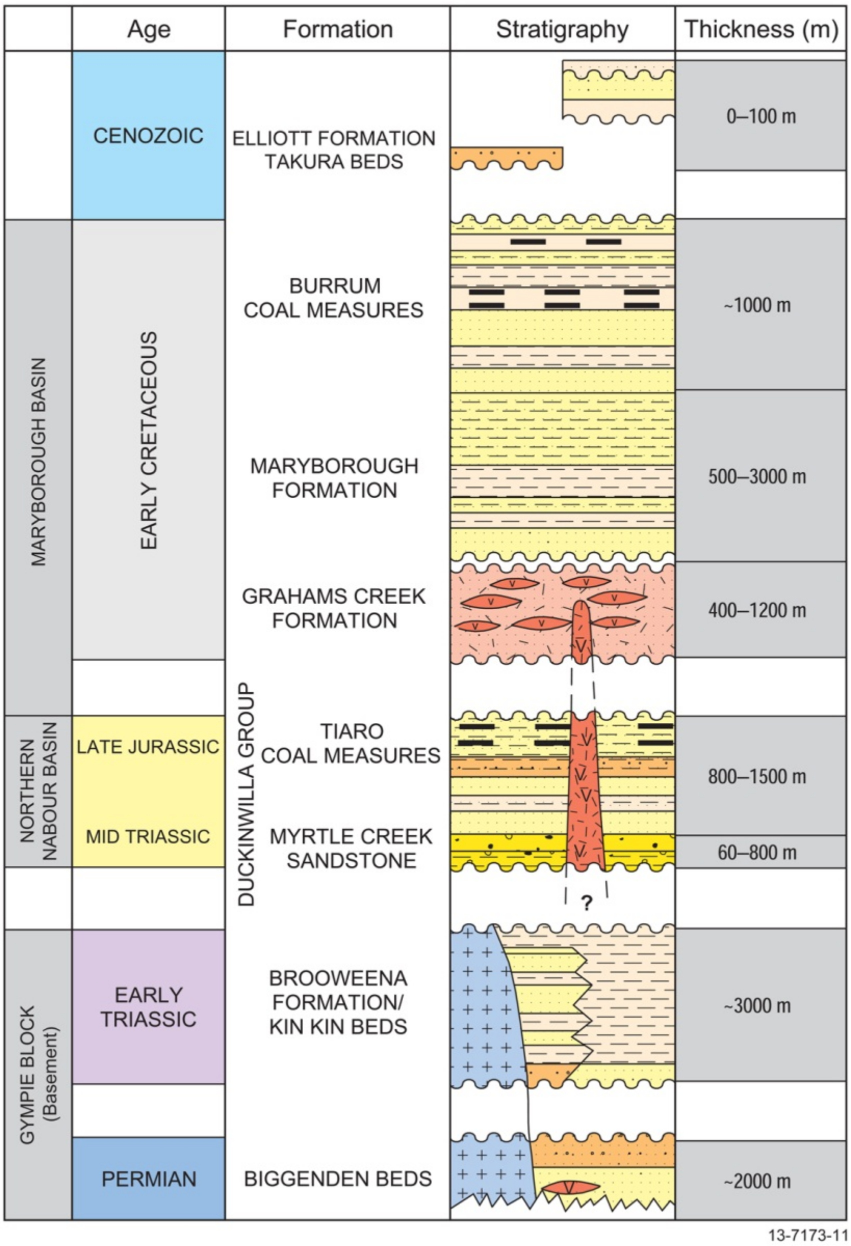

Figure 4.4 Stratigraphic chart of the Maryborough Basin.

The Duckinwilla Group has been recently re-classified as Northern Nambour Basin rather than Maryborough Basin (Draper and Bryan 2013) although for the purpose of this project has been included in the Maryborough Basin.

4.3.3 Maryborough Formation

The Maryborough Formation disconformably overlies the Grahams Creek Formation and was deposited during the Early Cretaceous. Figure 4.5 and Figure 4.6 are time-structure maps of the base, and top of the Maryborough Formation, respectively, and indicate relative thickness across the basin. Time-structure contours are derived from seismic surveys, and can be converted to depth if lithological properties are understood. The depositional environment of the Maryborough Formation was continental, followed by marine incursion. At its base, there is a mixed unit known as the Gregory Sandstone Member. The unit is very heterogeneous and consists of mudstone, siltstone, sandstone, minor conglomerate, tuff and limestone. It has an estimated maximum thickness of at least 3000 m.

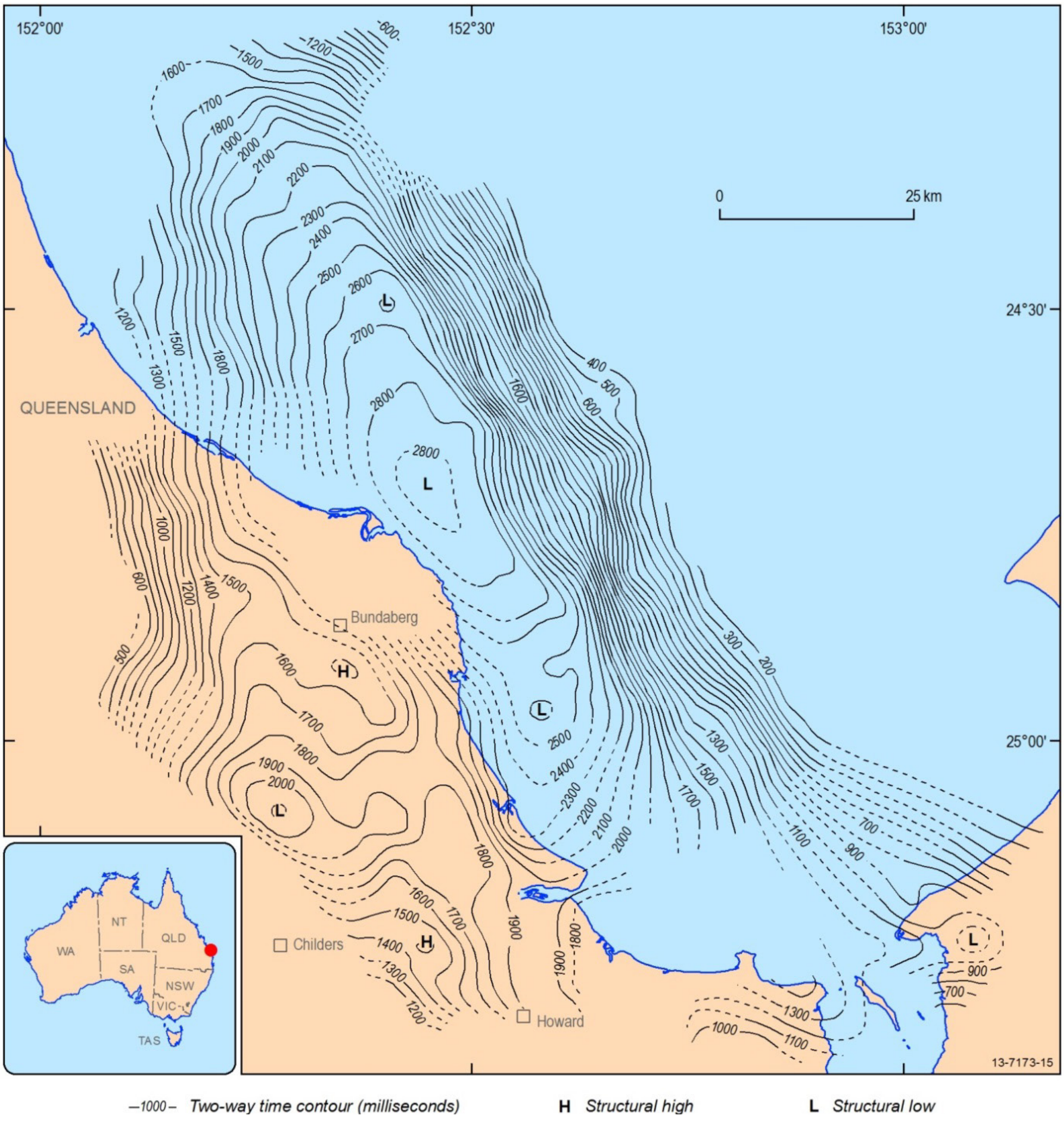

Figure 4.5 Time-structure map of the base of the Maryborough Formation (top Grahams Creek Formation) showing the approximate combined thickness of the Elliott Formation, Burrum Coal Measures and Maryborough Formation.

A major NNW-trending syncline occurs off the west coast of Hervey Bay and folds predominantly plunge towards the NNW. The units shown here are two-way time (twt); actual depth in metres is approximately double but lithological properties (interval velocities) are required for accurate conversion (adapted from Hill 1994).

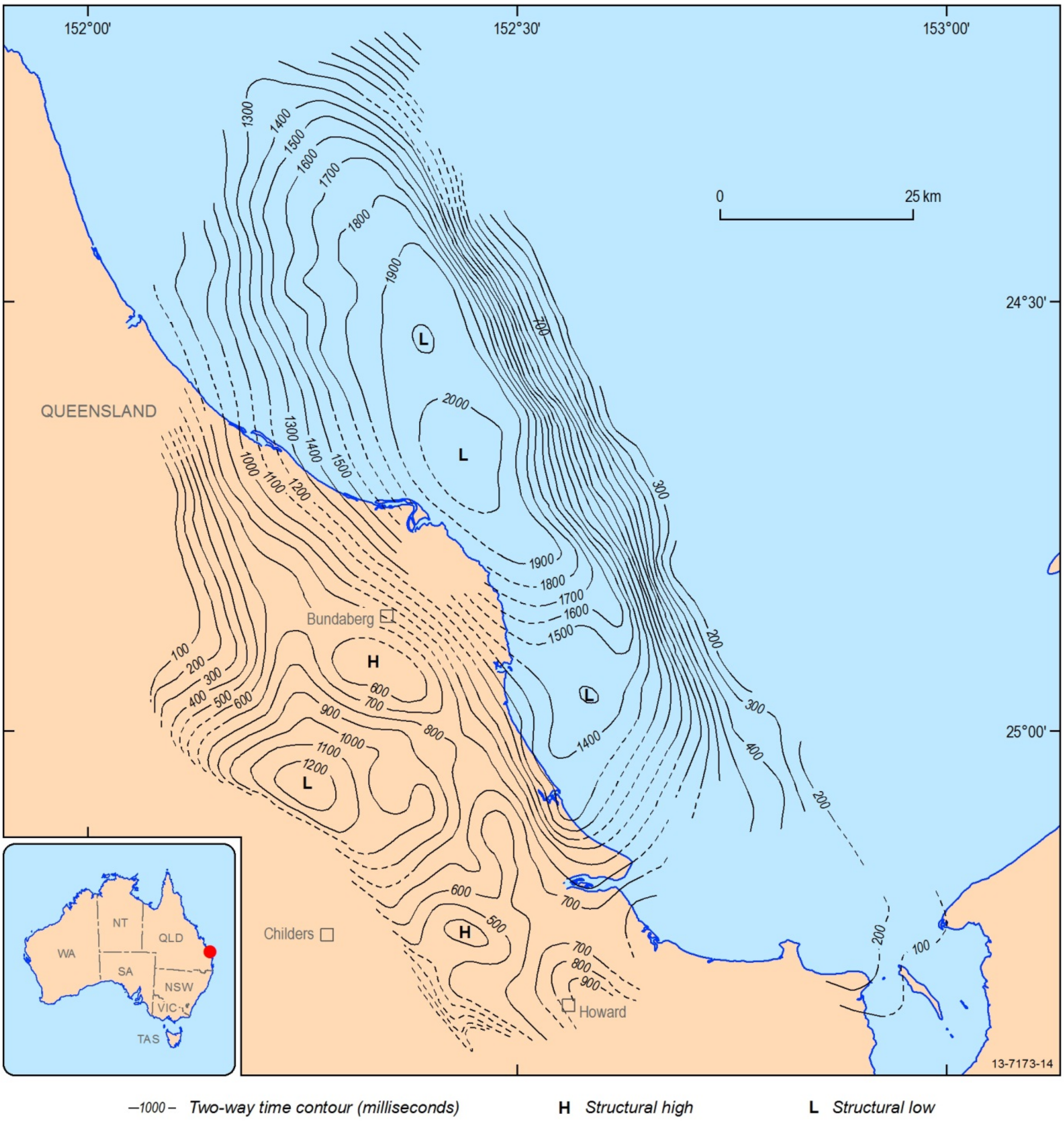

Figure 4.6 Time-structure map of the top of the Maryborough Formation, showing the approximate thickness of the Elliott Formation and Burrum Coal Measures.

Steep dips and potential overturning of the strata occur in the south-west. The units shown here are two-way time (twt); actual depth in metres is approximately double but lithological properties (interval velocities) are required for accurate conversion (adapted from Hill 1994).

4.3.4 Burrum Coal Measures

The Burrum Coal Measures conformably overlie the Maryborough Formation and these rocks were also deposited during the Cretaceous. A time structure map of the top of the Burrum Coal Measures, to indicate its relative thickness across the basin is shown in Figure 4.7. The depositional environment was fluvial to deltaic. Lithology is heterogeneous and can be divided into upper, middle and lower sections. The upper and lower sections are mostly sandstone and siltstone with minor shale and conglomerate, and lack economic coal seams. The middle section of the unit is dominated by shale and minor siltstone with thin, inter-fingering (economic) coal seams. The formation is approximately 1000 m thick. Surface exposure of the Burrum Coal Measures is poor.

4.3.5 Cenozoic units

In the Maryborough Basin the most widespread unit of Cenozoic age is the Elliott Formation. The Elliott Formation consists of sandstone, siltstone with minor mudstone, conglomerate and shale. It has a variable thickness but its maximum thickness is about 55 m. The formation is alluvial and is dated as Late Oligocene to Early Miocene based on geochronology of mammalian bones and plant fossils.

The Cenozoic units have experienced periods of deep weathering which occurred largely during the Paleogene and Neogene. This caused sediments to become mottled, iron-rich or bleached and developed a distinctive duricrust appearance (Cranfield 1994). The duricrust is generally pisolitic, has an ironstone soil profile; is mottled and deeply weathered. It may have formed as a result of several superimposed weathering events as it may occur on various levels within one formation.

The Takura Formation (also known as the Takura Beds) is only present in discrete parts of the basin between Maryborough and the coast from Hervey Bay to the Mary River. In this area it forms a ridge adjacent to the resistive top of the Maryborough Formation. The unit is thin (6 to 10 m thick) and consists of scree deposits derived from silicified mudstone at the top of the Maryborough Formation (Cranfield 1994).

There are several different dune sand formations in the Maryborough Basin. These mostly comprise of quartz sand and may form aeolian dunes up to 100 m high. Pleistocene dunefields are differentiated from Holocene dunefields by their well-developed B soil horizons. Pleistocene sand dunes are generally more degraded than Holocene dunes, due to pre-Holocene erosion.

A number of alluvial systems have deposited Quaternary sediments across the Maryborough Basin. Alluvial sediment deposits may exceed 20 m thickness but are generally about 10 m thick. These have formed at varying river terrace levels during previous times of higher sea level. There are three dominant facies within the alluvial units:

1. Modern, active, stream channels and levees with coarse-grained sand, gravel and silt
2. Older, higher stream terraces (beyond present floods), with sand, silt, clay and gravel
3. Alluvial swamps with sand and peat.

Recent sediments in the basin are those currently in the process of being deposited and re-worked along the coastline. These include alternating muds and sands of fluvial-deltaic origin, estuarine muds and sands and Holocene beach sands.

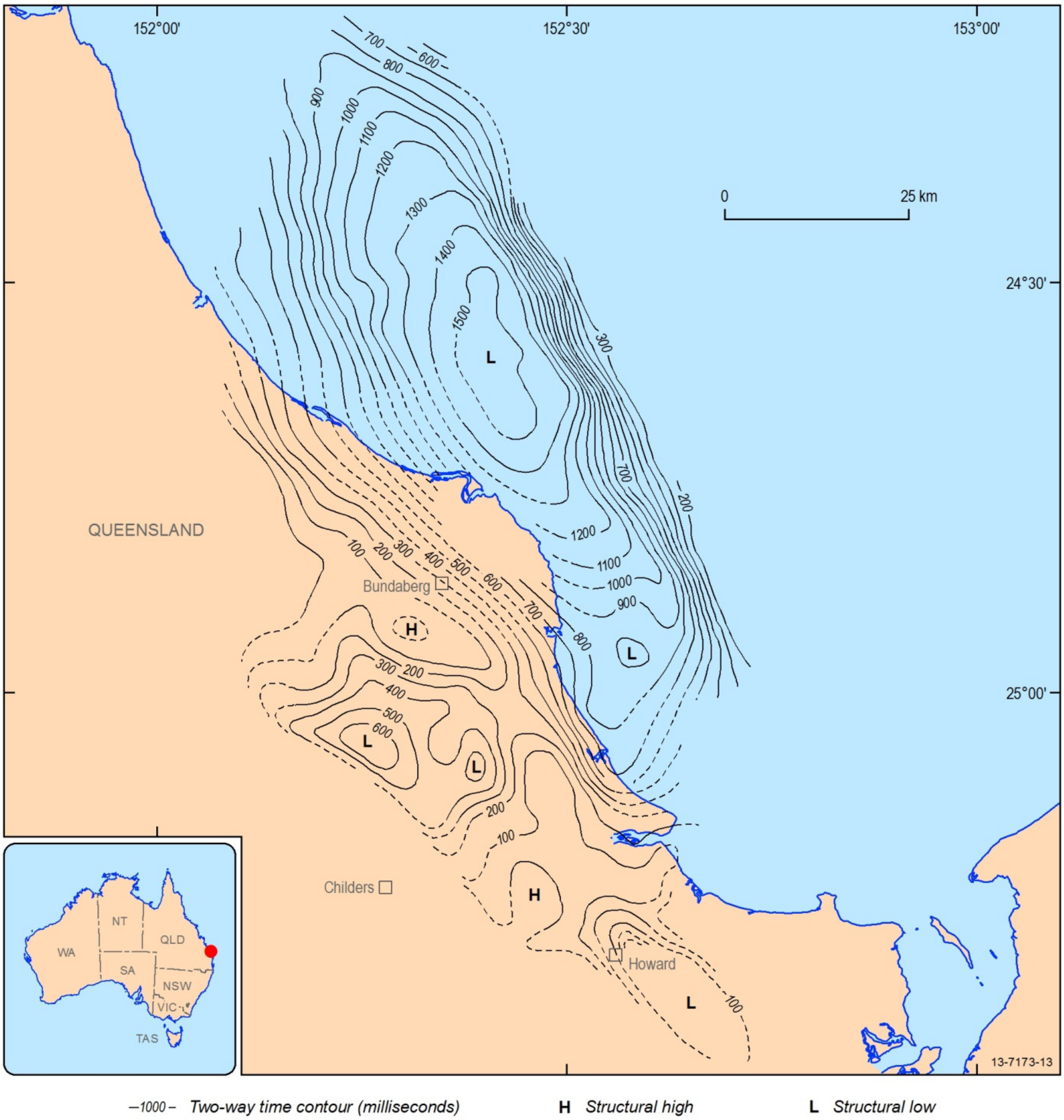

Figure 4.7 Time structure map of the top of the Burrum Coal Measures showing the approximate thickness of Elliott Formation in the basin.

A NNW-trending syncline is evident offshore, with a steep ENE limb, and onshore, the structure is more complex with multiple synclines and anticlines. The units are two-way time (twt); actual depth in metres is approximately double but lithological properties (interval velocities) are required for accurate conversion (adapted from Hill 1994).

4.4 Structural geology

The uppermost basement formation underlying the Maryborough Basin is formed by the folded Lower Triassic Brooweena Formation. The Brooweena Formation outcrops along the western margin of the basin. It is part of the Gympie Block, which lies to the west of and beneath the Maryborough Basin. The basin is bound in the west by the Electra Fault System (Ellis 1968). The north and north-eastern bounds of the basin are defined by the northwest-trending Bunker Ridge, which is a zone of elevated basement rocks (Hill 1994).

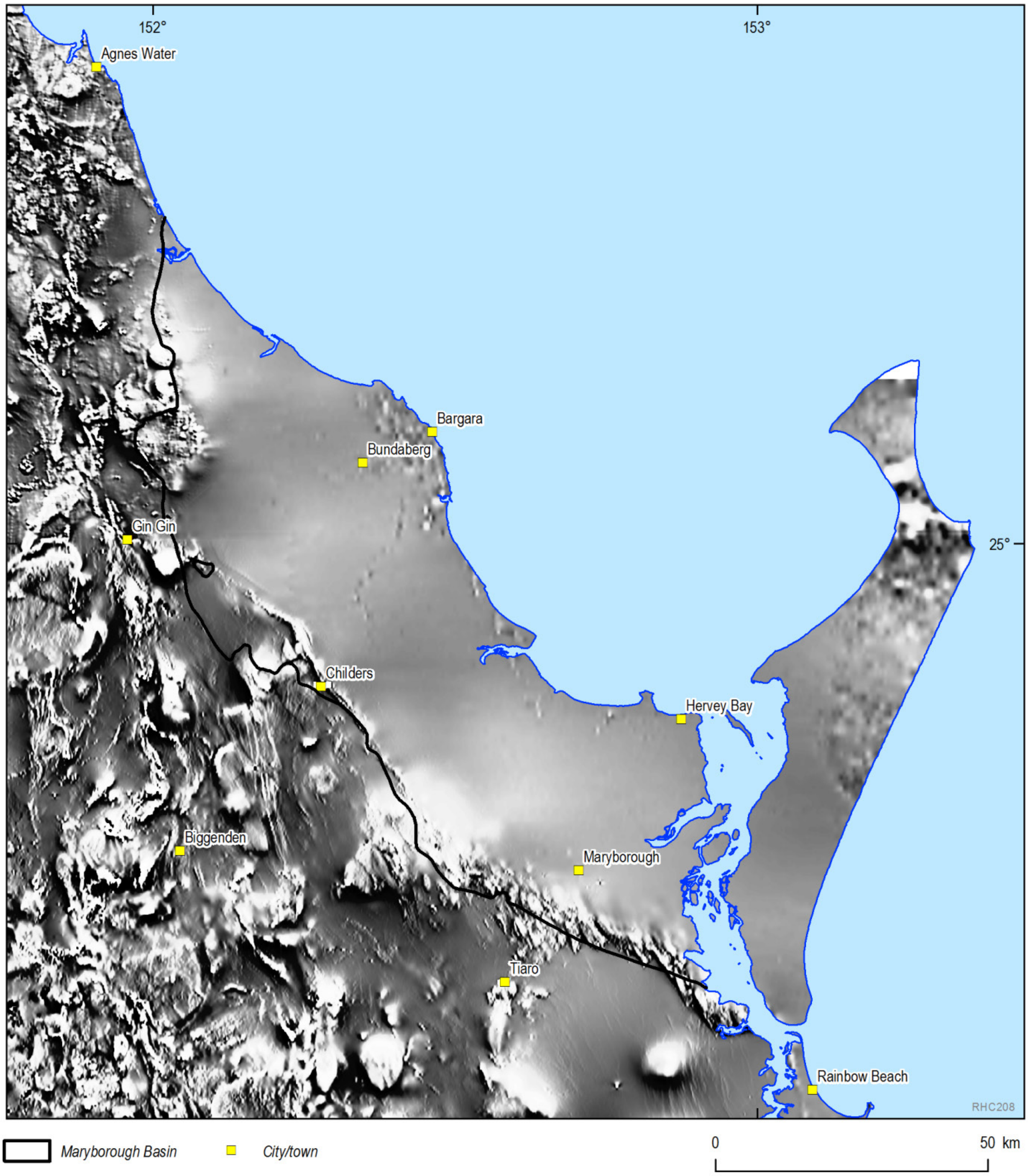

Figure 4.8 First vertical derivative of national-scale airborne magnetic data for the Maryborough Basin.

Subsidence of the basin is thought to have been controlled by structural elements of the basement, namely the Electra Fault System and the Perry Fault, which have a north-westerly trend. Normal fault movements characterised these faults, as their down-throw is to the east (Ellis 1968).

The dominant structural orientation of the Maryborough Basin is north-north-west, parallel to the regional structure of the New England Fold Belt (Figure 4.3). The regional magnetics data shown in Figure 4.8 clearly indicate the 'smooth' magnetic signal typical of sedimentary basins (due to the general lack of shallow magnetic rocks), and the 'coarse' signal where basement rocks occur (i.e.

along and away from the basin margins). The basin structure is an asymmetrical half-graben that formed as intracratonic sag basin in a foreland setting. The basal strata of the basin (Duckinwilla Group) were deposited in a fault-controlled half-graben, whereas the overlying rocks were deposited during subsidence and intracratonic down-warp. Consequently, the structural deformation of the post-Duckinwilla rocks is less intense. However, ongoing faulting and deformation has affected all of the Mesozoic strata.

The basin is defined by a series of broad, open folds and associated zones of deformation (Hill 1994). The sedimentary rocks within the basin are generally moderately to highly deformed. An important feature of the folding is that the intensity increases in the east and south-east of the basin. In the north, folds are reasonably open but in the east and south-east they can be tight to isoclinal with well-developed axial planar cleavage (Cranfield 1994; Hill 1994).

Figure 4.9 shows three cross-sections through the Maryborough Basin, including the offshore portion of the basin (adapted from Hill 1994). The locations of these cross-sections are shown on Figure 4.2. The cross-sections show the broad asymmetric synclinal structure of the basin, with the steeper limb of the syncline in the north-east. The axis of the deepest synclinal structure, which is the deepest part of the basin, is located approximately 30 km offshore.

The basin is characterised by high angle, normal and reverse faults. The throws (displacement) of the faults are typically about 1 m but can be up to 20 m. The style and distribution of faulting varies across the basin, e.g., in the south-east of the basin, west-block-down normal faults are common. Reverse faulting associated with either folding or strike-slip tectonics occurs in the north-east limb (Section a) of Figure 4.9. The high-angle faults have formed flower structures (characterised by a series of upwards branching and propagating faults), which may have formed as a result of strike-slip movement during or after compression. It can be difficult to separate folding and faulting events, as the structures are superimposed upon one another (Cranfield 1994).

One structure that dominates the basin is known as the Burrum Syncline. It has a north-west to south-east axis that plunges to the north-west. The Burrum Syncline has approximate dimensions of 20 by 6.5 km, with limb dips of approximately 7 to 25° (AustralAsian Resource Consultants (AARC) 2011).

The basement structure of the Maryborough Basin can be seen in Figure 4.10, which is a map of the depth to predicted economic basement (FrOG Tech Pty Ltd 2005). This shows that the margins of the basin are shallowest, and the deepest portion of the basin is in the central zone and offshore. The depth to the base of the Duckinwilla Group (defined base of the basin) has not been explicitly characterised due to lack of detailed geophysical data across the basin, particularly onshore. The current estimates are largely derived from one seismic survey in the offshore Maryborough Basin. At its deepest, the sedimentary thickness is estimated to be approximately 9.5 km. However, most of the basin sedimentary infill sequence is between 3 to 5 km thick (Hill 1994).

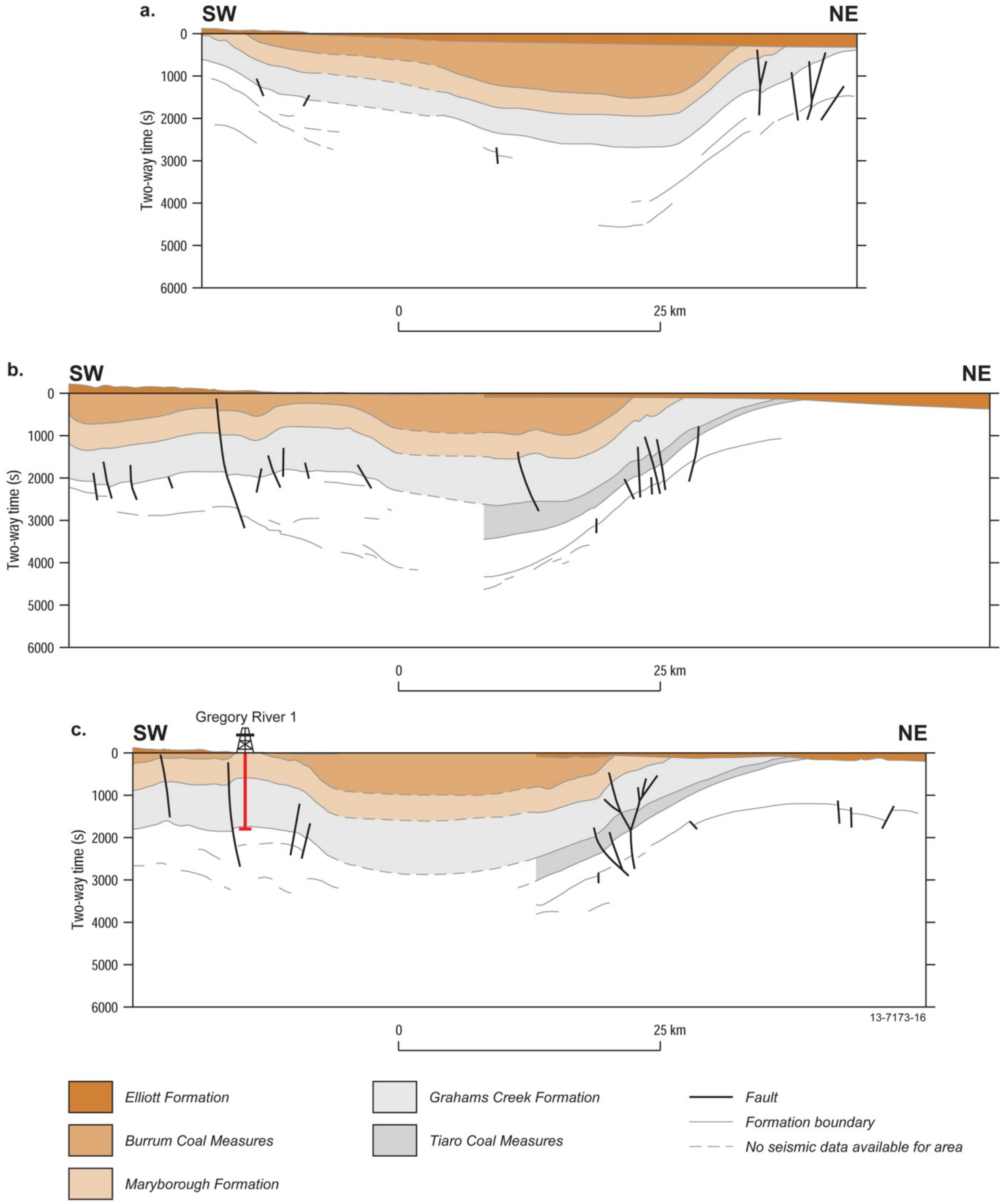

Figure 4.9 Structural cross-sections through the Maryborough Basin.

Section (a) is for the north of the basin, section (b) in the centre, and section (c) in the south. Location of the cross-sections is shown in Figure 4.2. The units shown here are seismic velocities measured in two-way time (twt); actual depth in metres is approximately double but lithological properties (interval velocities) are required for accurate conversion.

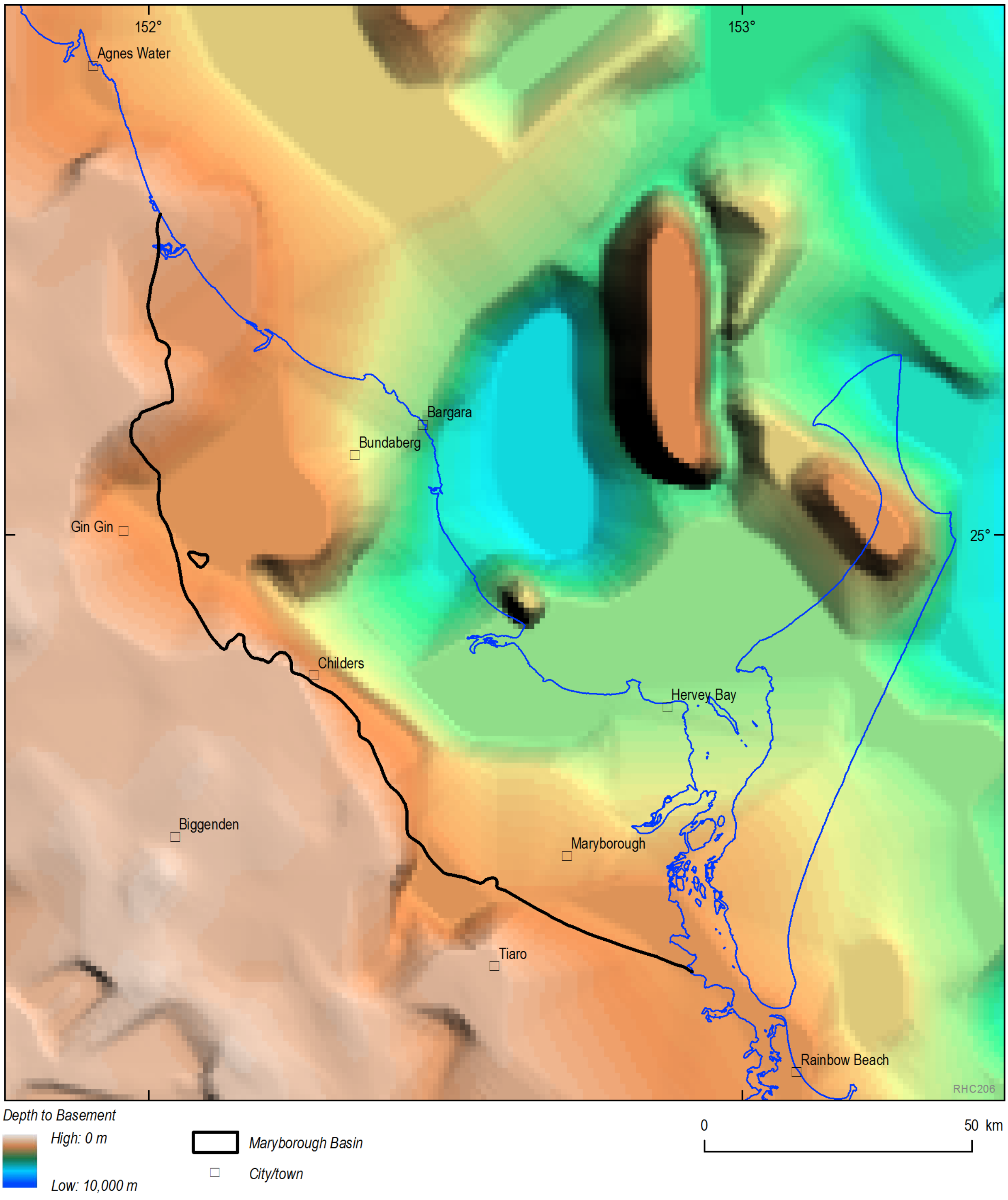

Figure 4.10 OZSEEBASE depths to geological basement for the Maryborough Basin and surrounds.

Source: after FrOGTech Pty Ltd. (2005)

4.5 Regolith and soils

The present geomorphology of the Maryborough Basin has been described by Cranfield (1994) as containing three main elements: Remnant Surfaces, Erosional Terrain and Depositional Landforms. This has formed as a result of the influence of climate and erosion over time. Remnant Surfaces are characterised by duricrust soil profiles and contain high proportions of ferricrete. Erosional Terrain ranges in elevation from approximately 15 to 70 mASL and its morphology varies due to varying lithology of the basin. Less resistant rocks (such as shales) form depressions and more resistant rocks form outcrop and steep-sided plateaus. Depositional Landforms are Quaternary surfaces formed from volcanic rocks, as coastal depositional features (such as coastal plains, marine banks and spits), or from alluvial processes. Tidal deltas occur along the coastline depositing fluvial sediments from inland. A map showing key geomorphologic features of part of the basin is shown in Figure 4.11.

Common soil types include deep red soils derived from Cenozoic basalt; shallow red soils derived from Pleistocene basalt; and sandy loams associated with river flood plains (Ellis 1968). The latter are relatively infertile and require heavy fertilisation for sugar cane production.

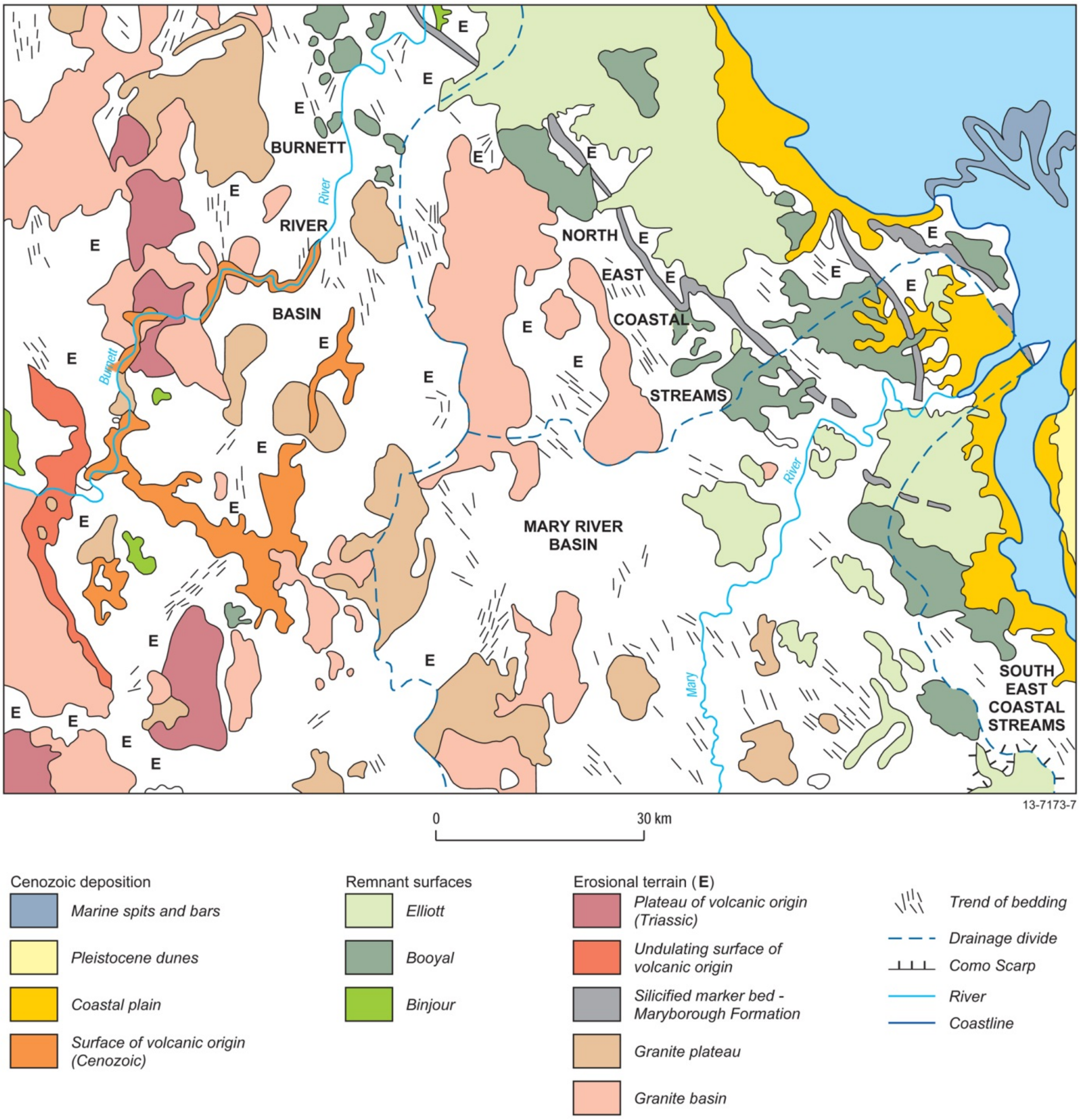

Figure 4.11 Physiography of the Maryborough Basin, showing the distribution of Remnant Surfaces, Erosional Terrain and Depositional Landforms.

Source: after Cranfield (1994)

5 Coal and coal seam gas resources

5.1 Distribution and size of coal deposits

There are three sedimentary rock formations in the Maryborough Basin with coal and CSG potential: the Myrtle Creek Sandstone, Tiaro Coal Measures and Burrum Coal Measures (Scott 1993). The economic gas prospectivity of the Myrtle Creek Sandstone is very low, as it contains only minor thin coal seams. The Tiaro Coal Measures have never been mined for coal although they have been the focus of previous exploration. This chapter discusses details of the Burrum Coal Measures and the Tiaro Coal Measures as there are no data associated with the Myrtle Creek Sandstone coal seams.

During the 1950s and 1960s, the Queensland Department of Mines undertook a drilling program to determine coal resources in the Maryborough Basin. At this time, *in situ* underground resources were estimated to be 6 million tonnes (Mt). By June 1985, 9.3 Mt had been extracted and *in situ* resources were estimated at 15 Mt. No reserve estimate was provided (Thornton 1995). The current total resource estimate of the Colton deposit in the Burrum Coal Measures is estimated to be 76 Mt. There is no current reserve estimate for the basin.

The quality of the coal resources is shown in Table 5.1. The coal has a high specific energy and high vitrinite content of 79% (Thornton 1995). Coals from the Burrum Coal Measures were predominantly used for steam raising and minor gas making (power generation). Coals from the Tiaro Coal Measures are generally low rank with Rv_{max} of approximately 0.08%. The Tiaro Coal Measures have also in places been affected by contact metamorphism, causing local alteration of the coal to anthracite and graphite (Thornton 1995).

5.1.1 Tiaro Coal Measures

The Tiaro Coal Measures are Early to Middle Jurassic. They are considered to be an equivalent unit to the Walloon Coal Measures in the Surat Basin (Hawthorne 1960). The coal occurs in stratigraphic sequences dominated by sandstone and shale (with minor oolitic limestone). The entire unit is approximately 1200 m thick, and the maximum coal seam thickness is 3 m. The depositional environment of the coal was likely to have been lacustrine to fluvial and deltaic.

The Tiaro Coal Measures is not considered to be highly prospective for either coal or coal seam gas, because it has been extensively intruded by various igneous rocks in the geologic past. In some areas that lack extensive intrusions, the Tiaro Coal Measures may produce some gas as they are classified as medium-volatile bituminous coal which may yield some minor economic quantities of methane (Scott 1993).

In the southern part of the basin, the Tiaro Coal Measures are shallower than in the north. Here, the basin sequence is generally shallower and many of the overlying Mesozoic units have been eroded away prior to the deposition of the Cenozoic Elliott Formation. Past exploration work, which included drilling, the acquisition of seismic data and high-resolution airborne geophysical data to explore for the potential viability of extracting coal from the Tiaro Coal Measures was unsuccessful and no coal of commercial quality was encountered. The coal measures were also considered not to be a viable target for extraction because of their complex geological structure (McLean and Mutton 2010).

Table 5.1 Coal analyses for the Maryborough Basin.

	Burrum Coal Measures			Tiaro Coal Measures
	Burrum Syncline	Goodwood Syncline	Pig Creek Syncline	
Sample type	raw	washed at S.G.1.6	raw	raw
Moisture %	2.2*	2.4*	2.3*	>6.0
Ash % (dry basis)	12.50	8.40	4.40	18.00
Volatile matter (dry basis)*	30.00	28.30	31.30	29.30
Volatile matter % (dmmf)	33.40	30.30	32.40	31.60
Sulphur % (dry basis)	0.67	0.52	0.79	0.50
Phosphorus %	0.17	0.04	0.01	N/A
Specific energy (MJ/kg)	35.75	no data	no data	26.51
Crucible swell number	8.50	8.00	8.50	N/A
Gray-King coke type	G7	N/A	N/A	N/A
Hardgrove grindability	82.00	N/A	N/A	N/A
Classification	644 (3)	54_(2)	54_(2)	5_(4)

** values measured at 105°C*
Source: after Thornton (1995)

5.1.2 Burrum Coal Measures

The Burrum Coal Measures are considerably shallower than the Tiaro Coal Measures and are locally confined to synclinal structures within the basin (Hawthorne 1960). This is because large portions of the basin were eroded away during basin inversion and synclinal structures have preserved the relatively shallow Burrum Coal Measures. The measures contain black coals, thought to have formed in lacustrine to fluvial and deltaic environments. The total unit thickness is approximately 1,700 m. The coal seams occur in a sedimentary sequence dominated by sandstone and shale. The upper and lower sections of the Burrum Coal Measures are classified as the least productive sections, as the coal is less laterally extensive and seams are thinner. However, the middle section (about 500 m thick) contains economically viable coal seams. Individual seams are mostly thinner than 1.5 m, with eight economically important seams recognised: the Quentin (Churchill), Portland No. 1, Portland No. 2 (Globe), Ellangowan, Jewel, Jubilee, A_1 and A_2 seams (Chiu Chong 1965). The typical distribution of coal seams within part of the Burrum Coal Measures stratigraphic sequence is shown in Figure 5.1.

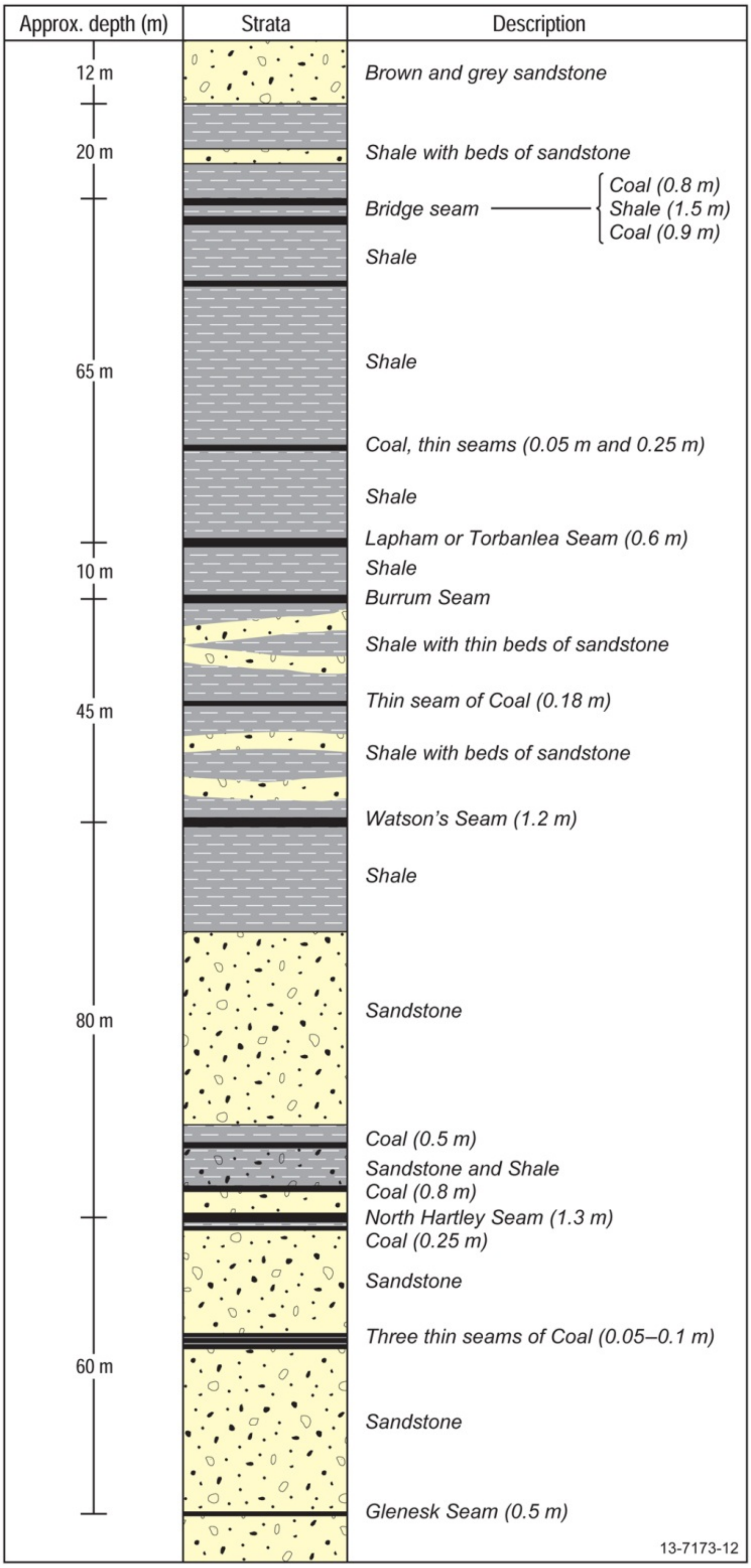

Figure 5.1 Typical distribution of coal seams in shale- and sandstone-dominated section of the Burrum Coal Measures.

Source: adapted from Chiu Chong (1965)

5.2 Coal seam gas resources

At the time of writing, two wells have been drilled in the Maryborough Basin to explore for CSG (Enter and Grant 2007a; Enter and Grant 2007b). These wells were also drilled to assess coal quality. The drilling program (by Magellan Petroleum Pty Ltd) was conducted based on previous reports that the Burrum Coal Measures were gaseous and therefore may contain recoverable quantities of methane. The wells, Burrum-1 and Burrum-2 were 438.09 m and 535 m deep respectively. Both wells encountered a thin veneer of Elliott Formation underlain by heterogeneous sedimentary units of the Burrum Coal Measures.

A total thickness of approximately 9 m of coal was intersected during drilling. Of this, seams ranged in thickness from 0.2 to 1.5 m (Enter and Grant 2007a; Enter and Grant 2007b). Details of coal quality in the Burrum Coal Measures are shown in Table 5.2.

In the Burrum-2 well, gas desorption testing and gas composition analysis was conducted for sixteen samples at varying intervals from 144.82 to 355 m depth (Table 5.3).

The coal seam gas exploration program conducted by Magellan Petroleum Pty Ltd was discontinued following the initial testing program. Although the wells demonstrated that the Burrum Coal Measures have gas-producing potential, neither well was shown to produce sufficient quantities of methane and as such, a viable resource was unable to be defined. Consequently, the wells were abandoned (Enter and Grant 2007a; Enter and Grant 2007b).

Table 5.2 Coal quality results for the Burrum-1 well samples from coal seam gas exploration drilling.

Sample number	Mass (kg)	Moisture (%)	Ash (%)	Volatiles (%)	Fixed carbon (%)
BU101CQ_1	0.83	1.8	21.6	25.2	51.4
BU102CQ_1	2.58	2.7	62.6	14.3	20.4
BU102CQ_2	0.77	1.6	7	29.9	61.5
BU103CQ_1	0.08	1.5	8.7	28.8	61
BU103CQ_2	6.3	3.1	78.8	8.5	9.6
BU104CQ_1	3.73	2.3	34	21.8	41.9
BU105CQ_1	5.21	3	67.7	11.4	17.9
BU106CQ_1	5.44	3.2	70.2	10.9	15.7

Source: after Enter and Grant (2007a)

Table 5.3 Gas sample compositions (as percentages) for Burrum-2 well sampled during exploration. Source: after Enter and Grant (2007b)

Sample number	N_2	CH_4	CO_2	Ar	C_2H_6	Other
BU201:A	0.00	99.22	0.77	0.00	0.00	0.01
BU201:B	0.00	99.25	0.74	0.00	0.00	0.01
BU202:A	0.00	99.05	0.94	0.00	0.00	0.01
BU202:B	0.00	99.28	0.71	0.00	0.00	0.01
BU203:A	0.00	99.05	0.94	0.00	0.00	0.01
BU203:B	0.00	99.28	0.71	0.00	0.00	0.01
BU203:Z	0.00	98.99	0.88	0.12	0.00	0.01
BU204:A	0.00	99.18	0.80	0.00	0.00	0.01
BU204:B	0.00	98.91	1.06	0.00	0.01	0.02
BU205:A	0.00	99.57	0.41	0.00	0.01	0.01
BU205:B	0.00	99.53	0.47	0.00	0.00	0.01
BU206:A	0.00	99.75	0.22	0.01	0.00	0.01
BU206:B	0.00	99.73	0.00	0.00	0.08	0.18
BU207:A	0.00	99.77	0.21	0.00	0.00	0.01
BU207:B	0.00	99.72	0.25	0.00	0.01	0.02
BU208:A	0.00	99.82	0.16	0.00	0.00	0.01
BU208:B	0.00	99.74	0.24	0.00	0.01	0.01
BU209:A	0.00	99.83	0.16	0.00	0.00	0.01
BU209:B	0.00	99.74	0.21	0.00	0.01	0.04
BU210:A	0.00	99.85	0.13	0.00	0.01	0.01
BU210:B	0.00	99.79	0.19	0.00	0.01	0.01
BU211:A	0.00	99.61	0.36	0.00	0.01	0.02
BU211:B	0.00	99.73	0.20	0.00	0.02	0.04
BU212:A	0.00	99.88	0.11	0.00	0.00	0.01
BU212:B	0.00	99.78	0.20	0.00	0.01	0.01
BU213:A	0.00	99.87	0.12	0.00	0.00	0.01
BU213:B	0.00	99.77	0.20	0.00	0.01	0.02
BU214:A	0.00	99.81	0.18	0.00	0.01	0.01
BU215:A	0.00	99.81	0.18	0.00	0.01	0.01
BU215:B	0.00	99.82	0.17	0.00	0.00	0.01
BU216:A	0.00	99.82	0.16	0.00	0.01	0.01
BU216:B	0.00	99.84	0.14	0.00	0.01	0.01
Average composition	0.00	99.59	0.37	0.00	0.01	0.02

5.3 Past exploration history

The Maryborough Basin has a long history of coal and (conventional) hydrocarbon exploration. Coal was first noticed outcropping along the Burrum River in 1865 and the Burrum Coalfield was the second producing field in Queensland. Once the government allowed the use of land for coal mining, the Burrum Colliery was opened by the Queensland Land and Coal Company. This was followed shortly by the opening of the Torbanlea Colliery. Coal was originally transported down the Burrum River before development of a railway in 1884. The railway system allowed for the expansion for the coal fields and the number of miners increased from 31 to 182 in 1886. The exploration and production of shallow seam coal continued and in 1960 three companies were operating five collieries and produced approximately 133,000 tonnes of coal near Torbanlea, Colton, Takura and Howard (Hawthorne 1960).

The first government report to describe and characterise the Burrum Coalfields was produced in 1886 (Rands 1886). In 1910 the Burgowan Colliery was opened approximately 3 miles north-east of Torbanlea. Coal exploration since the 1890s focused on the Burrum Coal Measures and exploration was in seams associated with the discovery by Rands. Economic coal deposits were not found in the Tiaro Coal Measures (Hawthorne 1960). Figure 5.2 shows historical exploration coverage of the Maryborough Basin from 1960 until today. Between 1964 to 1988, there were four groups of explorers and all failed to find economic coal deposits (Whiteside and Mutton 2012). Detailed aeromagnetic data released in 2005 provided data to analyse the tectonic regime and structure of the basin. Zones of intrusive rock were able to be mapped and potential targets were sought for thick coal occurs in structurally undisturbed areas (Whiteside and Mutton 2012).

Petroleum exploration within the Maryborough Basin began in 1923. Three wells were drilled by Isis Petroleum Syndicate, though no records are available. These wells were unsuccessful and were found to be dry. They were shallow wells, with the deepest drilled to just 180 m (Stephenson and Burch 2004).

Exploration for oil recommenced during the 1950s by Lucky Strike Drilling Company (Kamon 1953). Field mapping, aerial photograph interpretation, magnetometer and gravity surveys, 108 line km of single fold seismic and drilling of two exploration wells was completed. The two wells that were drilled were LSD Cherwell (1954) and LSD Susan River (1955). These wells were subsequently plugged and abandoned as they were unsuccessful. The tenements were relinquished in 1959 (Blue Energy Ltd 2011).

From 1959 to 1968, Pacific American Oil Company (in association with other companies) explored numerous tenements across the basin. Exploration techniques included photogeological interpretation, aeromagnetic surveying, field mapping, gravity surveys, and onshore and offshore seismic surveys.

Early exploration in the Maryborough Basin focused on conventional hydrocarbon reservoirs within the Gregory Sandstone Member of the Maryborough Formation and the deeper Myrtle Creek Sandstone. The Tiaro Coal Measures have more recently been explored for the potential of extracting coal seam gas (Blue Energy Ltd 2011). Historical petroleum tenements in the basin from 1950 to today are shown in Figure 5.3 and details of deep exploration wells drilled in the Maryborough Basin are contained in Table 5.4.

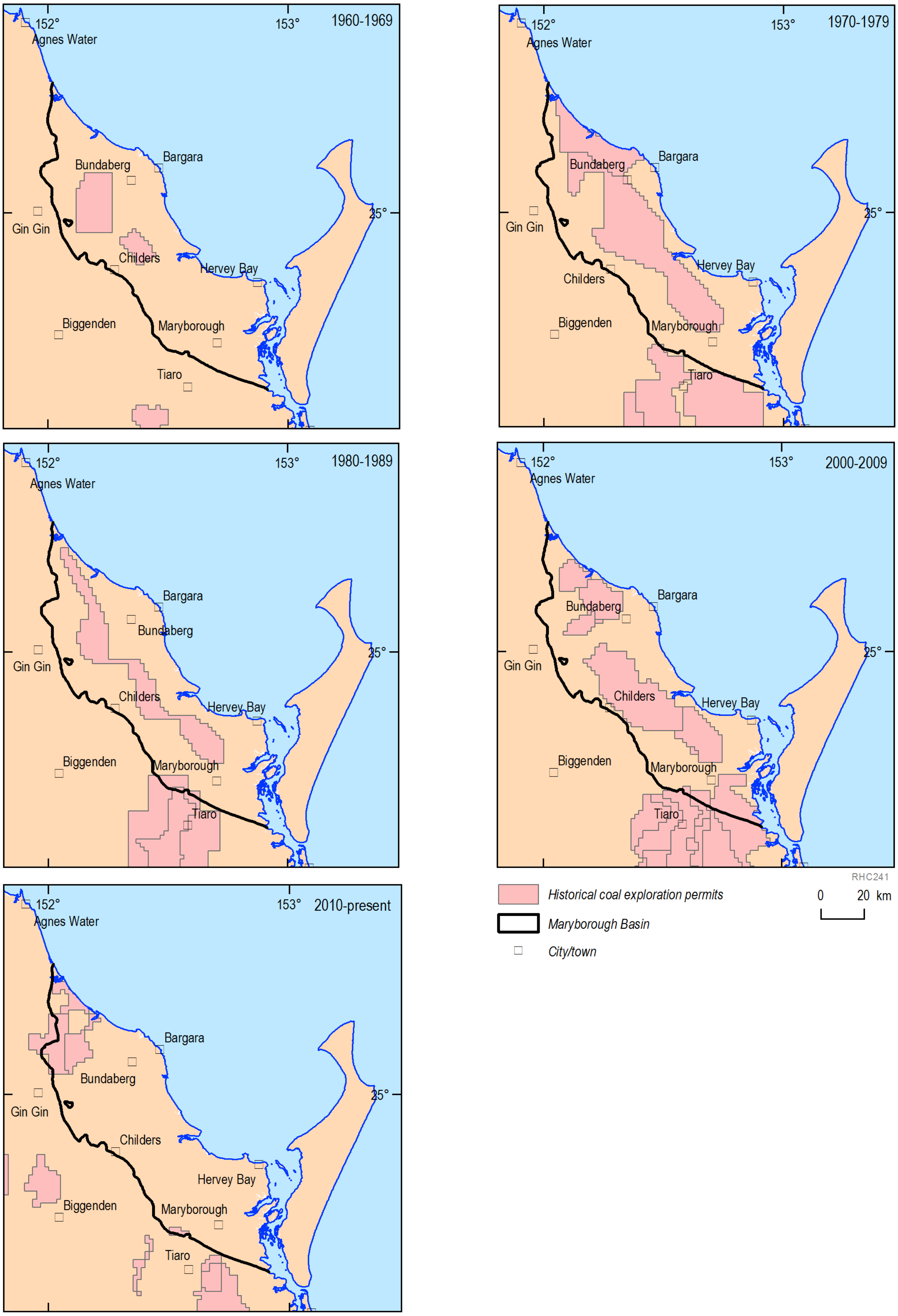

Figure 5.2 Historic coal tenement coverage of the Maryborough Basin.

Table 5.4 Deep exploration wells drilled in the Maryborough Basin.

Well name	Year drilled	Depth (m)	Main finding	Reference
Elliot River-1	1920s	180	Petroleum not found.	Records no longer available
LSD No. 1 Well – Cherwell	1954	2978	Conventional gas exploration – unsuccessful.	Siller (1955)
LSD No. 2 Well - Susan River	1955	2460	Conventional gas exploration – unsuccessful.	Siller (1956)
Gregory River-1	1966	3152	Conventional gas exploration – small flow (estimated 150 to 200 Mcfd)	Shell Development (Aust) Pty Ltd (1968)
Gregory River-2	1981	3310	Conventional gas exploration – flow rates too low to be economic	Derrington (1981)
Burrum-1	2007	438	Exploration for coal and coal seam gas. Plugged and abandoned.	Enter and Grant (2007a)
Burrum-2	2007	535	Exploration for coal and coal seam gas. Plugged and abandoned.	Enter and Grant (2007b)

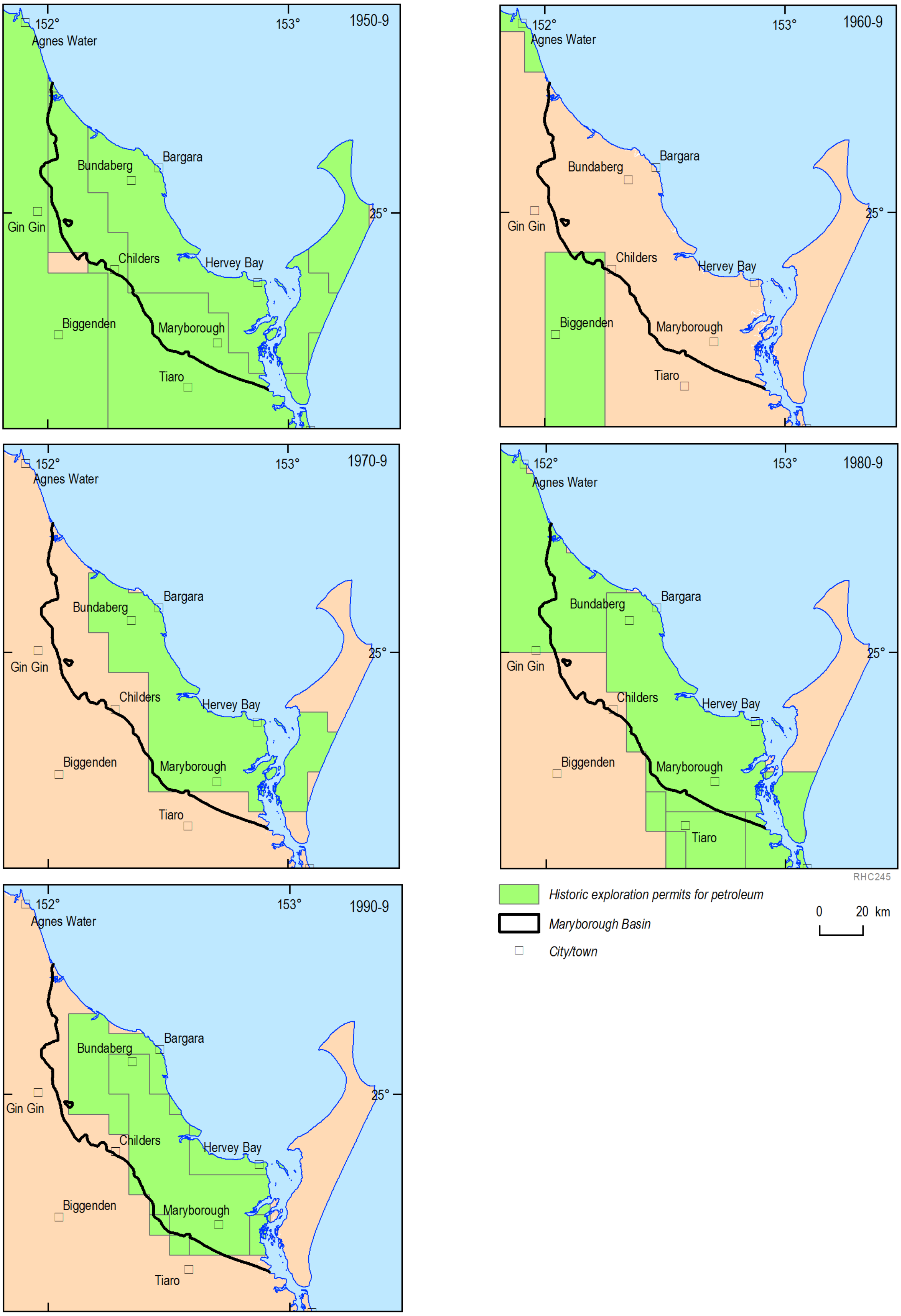

Figure 5.3 Historic petroleum tenement coverage of the Maryborough Basin.

5.4 Current exploration and development focus

There is no current coal or petroleum (including gas) extraction within the Maryborough Basin. The basin contains two tenements for application for a mining lease to extract coal from near the town of Aldershot by Colton Coal Pty Ltd. The Colton mineral deposit consists of thermal coal and is a 76 Mt resource.

The Colton Coal Mine project proposes open-cut mining of an estimated 1.2 Mt of Run of Mine coal per annum by open cut methods, with a predicted production figure of 0.5 Mt of coal for export. The project's production life is anticipated to be 8 to 10 years (AARC 2011).

There are 12 tenements with application status for coal exploration, and 12 tenements have been granted approval for coal exploration (Figure 5.4).

Three petroleum exploration tenements currently exist within the basin (Figure 5.5). Table 5.5 contains details of the current tenements, their status and the principal holder for tenements that lie within, or partially within, the basin. The companies operating at the time this report was written include: Birmanie Nominees Pty Ltd, Booyan Coal Pty Ltd, Cliffs Australia Coal Pty Ltd, Colton Coal Pty Ltd, Fairway Coal Pty Ltd, Gen Resources Pty Ltd, Great White Nominees Pty Ltd, Howard Burrum Pty Ltd, Jindal Steel and Power (Australia) Pty Ltd, Magellan Petroleum (Eastern) Pty Ltd, Shenhuo International Group Pty Ltd, Sierra Coal Pty Ltd, Taroom Coal Pty Ltd, Tiaro Coal Ltd, Tiaro Energy Corporation Pty Ltd and Waratah Coal Pty Ltd.

Table 5.5 Mining and exploration (coal and petroleum) tenements wholly or partially within the Maryborough Basin.

Tenement type	Status	Date lodged	Tenure number	Principal holder
Mining lease	Application	29-Jan-10	50273	Colton Coal Pty Ltd
Mining lease	Application	29-Jan-10	50274	Colton Coal Pty Ltd
Coal exploration permit	Application	25-Aug-10	2195	Birmanie Nominees Pty Ltd
Coal exploration permit	Application	29-Jun-11	2631	Great White Nominees Pty Ltd
Coal exploration permit	Application	2-Jun-11	2597	Howard Burrum Pty Ltd
Coal exploration permit	Application	12-May-11	2532	Howard Burrum Pty Ltd
Coal exploration permit	Application	12-May-11	2533	Howard Burrum Pty Ltd
Coal exploration permit	Application	1-Nov-10	2263	Shenhuo International Group Pty Ltd
Coal exploration permit	Application	1-Apr-08	1265	Taroom Coal Pty Ltd
Coal exploration permit	Application	1-Apr-08	1264	Tiaro Energy Corporation Pty Ltd
Coal exploration permit	Application	1-Apr-08	1269	Tiaro Energy Corporation Pty Ltd
Coal exploration permit	Application	29-Apr-11	2511	Tiaro Energy Corporation Pty Ltd
Coal exploration permit	Application	29-Apr-11	2513	Tiaro Energy Corporation Pty Ltd
Coal exploration permit	Application	1-Apr-08	1266	Waratah Coal Pty Ltd
Coal exploration permit	Granted	18-May-05	969	Booyan Coal Pty Ltd
Coal exploration permit	Granted	24-Jul-08	1523	Cliffs Australia Coal Pty Ltd
Coal exploration permit	Granted	17-Nov-04	923	Colton Coal Pty Ltd
Coal exploration permit	Granted	20-Sep-06	1082	Colton Coal Pty Ltd

Tenement type	Status	Date lodged	Tenure number	Principal holder
Coal exploration permit	Granted	1-Apr-08	1268	Fairway Coal Pty Ltd
Coal exploration permit	Granted	25-Aug-10	2194	Gen Resources Pty Ltd
Coal exploration permit	Granted	25-Aug-10	2196	Gen Resources Pty Ltd
Coal exploration permit	Granted	1-Nov-10	2250	Jindal Steel and Power (Australia) Pty Ltd
Coal exploration permit	Granted	30-Nov-09	2003	Sierra Coal Pty Ltd
Coal exploration permit	Granted	7-Aug-09	1872	Sierra Coal Pty Ltd
Coal exploration permit	Granted	4-Aug-08	1540	Tiaro Coal Ltd
Coal exploration permit	Granted	14-Oct-08	1618	Tiaro Energy Corporation Pty Ltd
Petroleum exploration permit	Granted	7-Nov-94	613	Magellan Petroleum (Eastern) Pty Ltd
Petroleum exploration permit	Granted	10-Mar-99	674	Magellan Petroleum (Eastern) Pty Ltd
Petroleum exploration permit	Granted	28-Feb-03	733	Magellan Petroleum (Eastern) Pty Ltd

Tenements current as of July 2013 (but may change in the future). Gas exploration is categorised as a petroleum tenement.

Figure 5.4 Coal exploration tenements in the Maryborough Basin.

Tenement data current as of June (2013), but may alter in the future

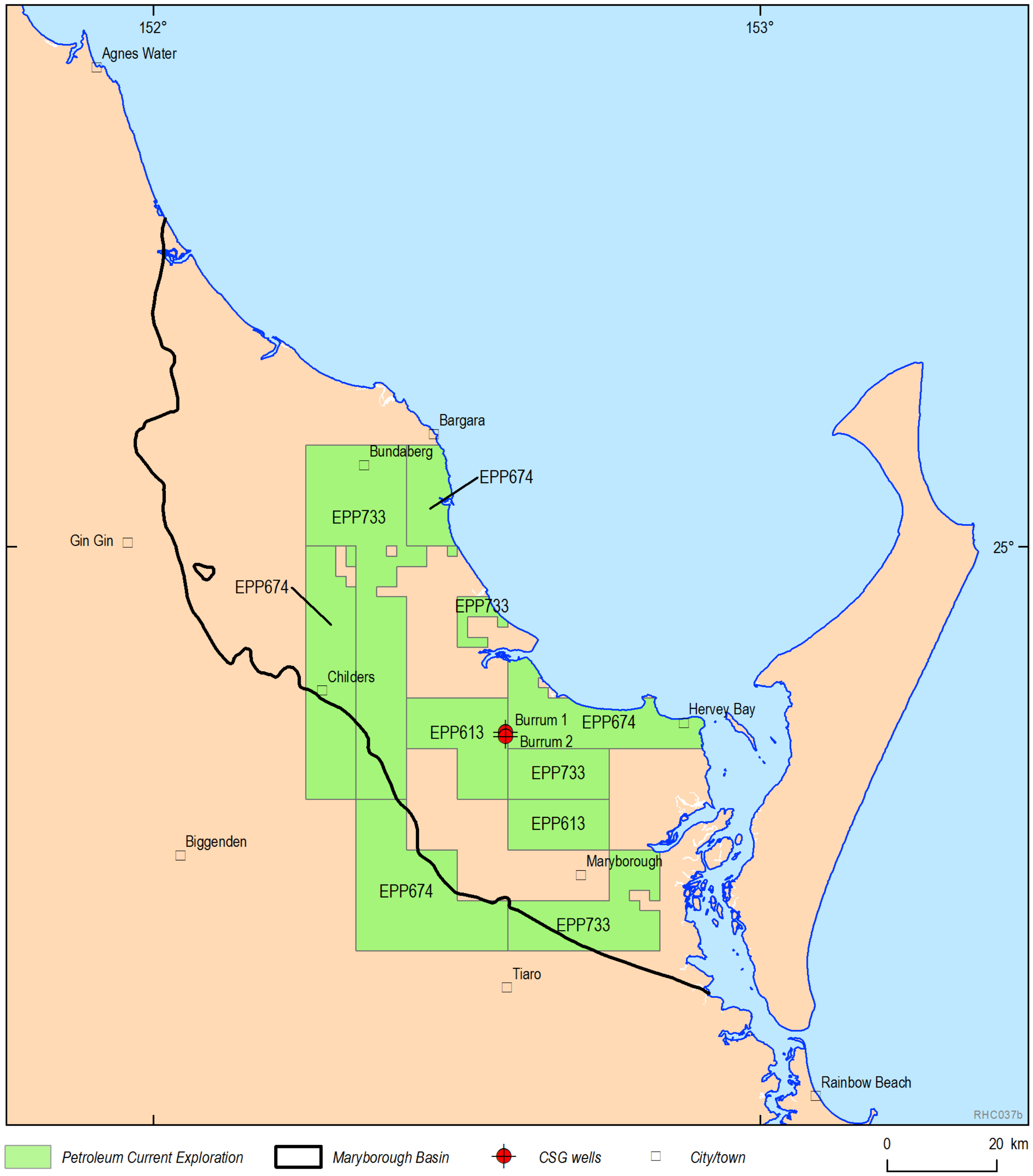

Figure 5.5 Petroleum exploration tenements in the Maryborough Basin.

Tenement data current as of June (2013), but may alter in the future

5.5 Other economic resources

5.5.1 Conventional gas

The oldest potential source rocks in the Maryborough Basin are found in the lower part of the Myrtle Creek Sandstone, which is the lower-most unit of the basin within the Duckinwilla Group. The overlying Tiaro Coal Measures are also considered to have the potential to act as a hydrocarbon source rock. However, both potential source rocks are currently over-matured for liquid hydrocarbons and instead lie within the dry gas window. Conventional oil is thus not a viable resource for the basin (Stephenson and Burch 2004).

The oldest potential reservoir unit within the basin is the Myrtle Creek Sandstone. However, this unit is likely to have low porosity and permeability. Permeability of approximately 30% has been observed at outcrop within this formation, but is considered to be a surface weathering feature and unlikely to translate to other parts of the formation at depth (Swift 2001; Stephenson and Burch 2004). The seal on this unit, where present, would be provided by intraformational shales. Trap integrity is considered to be an issue for gas accumulation, due to deformation during the Late Cretaceous.

The most viable conventional hydrocarbon reservoir in the basin is the Gregory Sandstone Member of the Maryborough Formation (Swift 2001; Stephenson and Burch 2004). This target was drilled (Swift 2001) and was found to flow gas at a rate of up to 200 million cubic feet (Mcf) per day. Formation porosity averages 6%, but 10 to 12% porosity occur in some areas. However, matrix permeability is low and fractures are the most likely conduits for flowing gas (Shell Development (Aust) Pty Ltd 1968; Stephenson and Burch 2004). There is also minor reservoir potential in the Upper Sandy Member of the Maryborough Formation (Swift 2001; Stephenson and Burch 2004).

5.5.2 Shale gas

No information was found regarding historical shale gas exploration in the Maryborough Basin. However, a national assessment of shale gas potential identified the Cherwell Mudstone Member of the Maryborough Formation as a prospective target (MBA Petroleum Consultants 2010). Subsequently, the Maryborough Basin was identified by an international assessment (Kuuskraa, Stevens et al. 2011) to be one of three prospective shale gas target basins in Australia, targeting the Cherwell Mudstone and Goodwood Mudstone members of the Maryborough Formation. Approximately 4,000 km^2 of the basin is potentially prospective for shale gas. The remainder is either too deep or without any data to constrain its capacity (Table 5.6).

Table 5.6 Summary of characteristics of the Cherwell Mudstone Member Shale Play.

Environment	Marginal marine
Lithotype	Mudstone/sandstone
Petroleum system	Proven
Depth range	1500 to 5000 m
Thickness (gross)	220 m
Area of play	3171 km^2
Average expected porosity (%)	Unknown
Total organic carbon wt.	0.7 to 1.2 (3 samples)
Kerogen type	Type II and III
Maturity Ro%	> 1.2 %
Geothermal gradient	2.5 °C/100 m
Overpressure	Indicated in places
Gas analyses	Available
Well HC indicators	Gregory River 1 and 2
Market	Gladstone LNG
Prospective resource estimate	2.687 trillion cubic feet (Tcf)

Source: after MBA Petroleum Consultants (2010)

6 Hydrogeology and groundwater systems

6.1 Hydrostratigraphy

The sedimentary successions that occur in the Maryborough Basin were variably deposited in fluvial, deltaic and lacustrine environments, and were influenced by several marine transgressions. The basin stratigraphic sequence consists of heterogeneous layers of sands, shales, silts and minor coal. Many layers are not continuous and occur as lenses. As a result, hydrostratigraphic units are largely heterogeneous. Lithological variation will affect aquifers' properties and their capacity to store and transmit groundwater, which will vary laterally and with depth. In some cases, a range of hydraulic properties can be attributed to a single aquifer.

Intraformational shales and muds are common in many of the aquifers, and these rocks have significantly lower hydraulic conductivity than sand units. Currently, the hydrostratigraphic framework for the basin only includes one aquitard, which may also act as an aquifer at local scales. All units contained in the basin have previously demonstrated the capacity to yield reasonable quantities of fresh to slightly saline groundwater (Laycock 1969). However, it is also likely that there are sections within most aquifers that confine or constrict hydrogeologic flow. Further work is required to characterise the presence and location of such aquitards.

Knowledge of the hydrostratigraphy of the Maryborough Basin has been largely derived from the few previous groundwater studies, coupled with new hydrogeologic analysis based on information outlined in the previous chapters. In the Maryborough Basin, all previous major groundwater investigations have focused solely on the upper 100 m stratigraphic section, due to the presence of good quality and yields of groundwater available at these depths, mainly from the Elliott Aquifer (e.g. Laycock 1969; Laycock 1975; Moser 2004; Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) 2010; AustralAsian Resource Consultants (AARC) 2011). These previous investigations have also focused on local-scale issues. There were no regional-scale hydrogeological assessments of the Maryborough Basin available in the literature at the outset of this study.

The development of a basin-scale hydrostratigraphic framework for the Maryborough Basin was an important objective of this project. The new analytical work classified seven main aquifer units in the basin, listed below from youngest at top to oldest at base (Figure 6.1). These contain varying quantities and qualities of groundwater, and different depths and spatial distribution.

1. Quaternary Coastal Aquifer
2. Quaternary Alluvial Aquifer
3. Quaternary Basalt Aquifer
4. Elliott Aquifer
5. Burrum Aquifer
6. Grahams Creek Aquifer
7. Duckinwilla Aquifer.

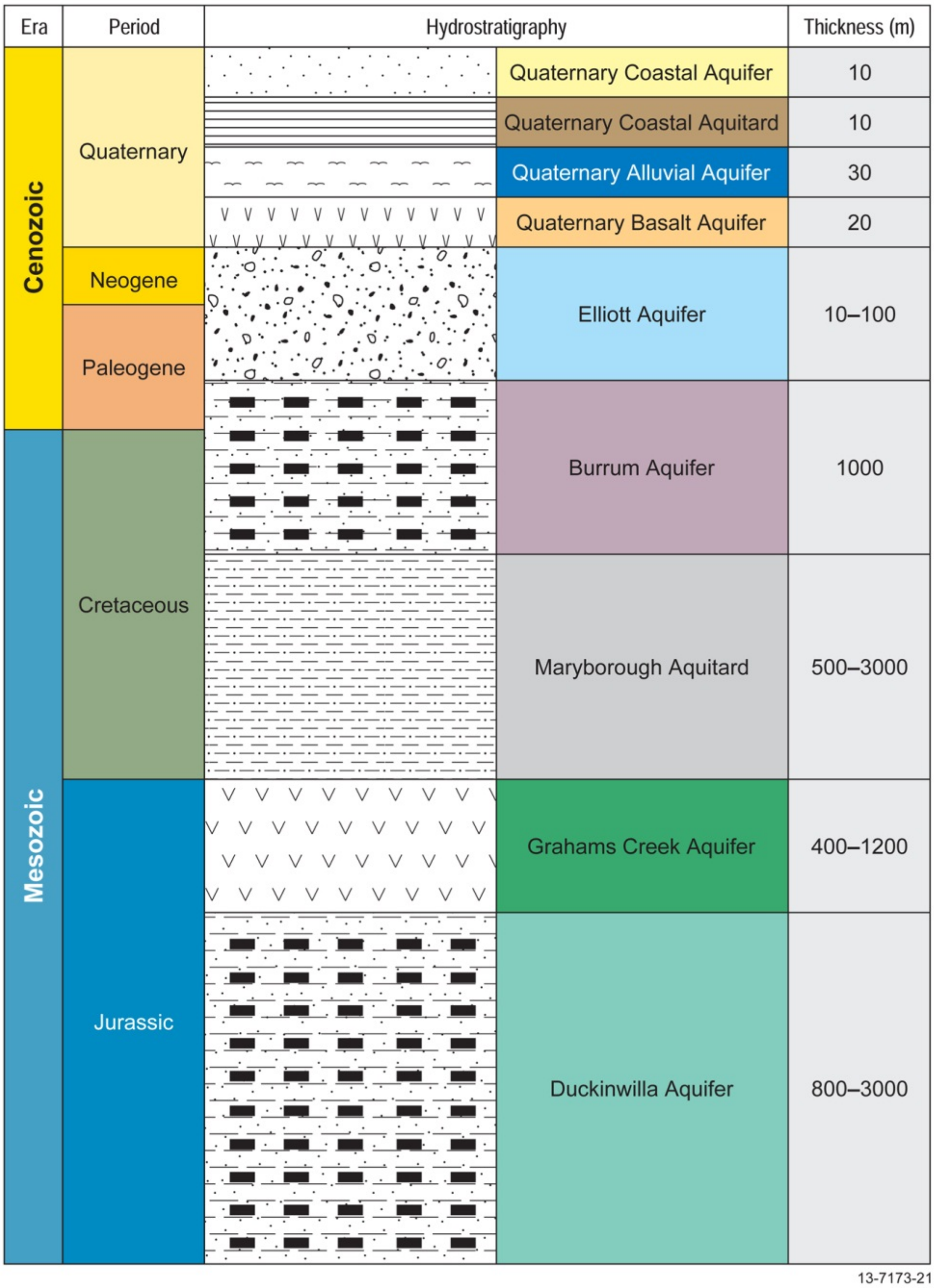

Figure 6.1 Hydrostratigraphy of the Maryborough Basin.

Source: based on research for this study

6.1.1 Quaternary Coastal Aquifer

The Quaternary Coastal Aquifer does not include Holocene (or current) beach sand deposits. Although fresh groundwater can be intersected in modern beach sand (Laycock 1969), for the purpose of this report, the Quaternary Coastal Aquifer includes deposits greater than Holocene age (i.e. Pleistocene, Pliocene and Miocene). The Coastal Sand Dunes Aquifer consists predominantly of unconsolidated quartz sand. Compaction and cementation of the sediments has occurred to some degree but porosity and permeability are both high to very high. The aquifer has a discrete, linear distribution along the coastline (reflecting its depositional setting) and comprises of a series of dunes of varying age. Older dunes occur further away from the coast than younger dunes. The older dunes are more compacted, have a higher percentage of organic material, and are therefore likely to have lower porosity and permeability.

6.1.1.1 Fraser Island

Fraser Island is mostly a Quaternary Coastal Aquifer, and of greater thickness than the Quaternary Coastal Aquifer system onshore. However, Fraser Island has a different hydrogeological setting than the onshore basin. Fraser Island is composed predominantly of coastal plains on the west coast; Pleistocene dunes in the centre; and Holocene dunes along the eastern side. The dunefields, which form most of the island, have been built as a series of overlapping parabolic sand dunes reaching elevations up to 244 m above sea level. They extend below sea level to -40 mAHD in the south and to -100 mAHD at Sandy Cape (Grimes 1992). The surface water systems and the hydrogeology of Fraser Island differ considerably to the onshore Maryborough Basin. The island contains a series of dune lakes with freshwater. The two types of dune lakes are groundwater lakes and perched surface water lakes. Groundwater lakes occur where the land surface extends below the water table and perched lakes have formed atop a less permeable surface such as organic material, iron oxides or fine clay (Grimes 1992) (Figure 6.2).

This report focuses predominantly on the onshore Maryborough Basin and does not include further discussion of Fraser Island groundwater resources, due to the absence of coal or coal seam gas exploration on the island. Additionally, the World Heritage Listing and National Park status of Fraser Island suggests that exploration is unlikely to be approved and therefore the threat from coal and coal seam gas development on the island is considered low.

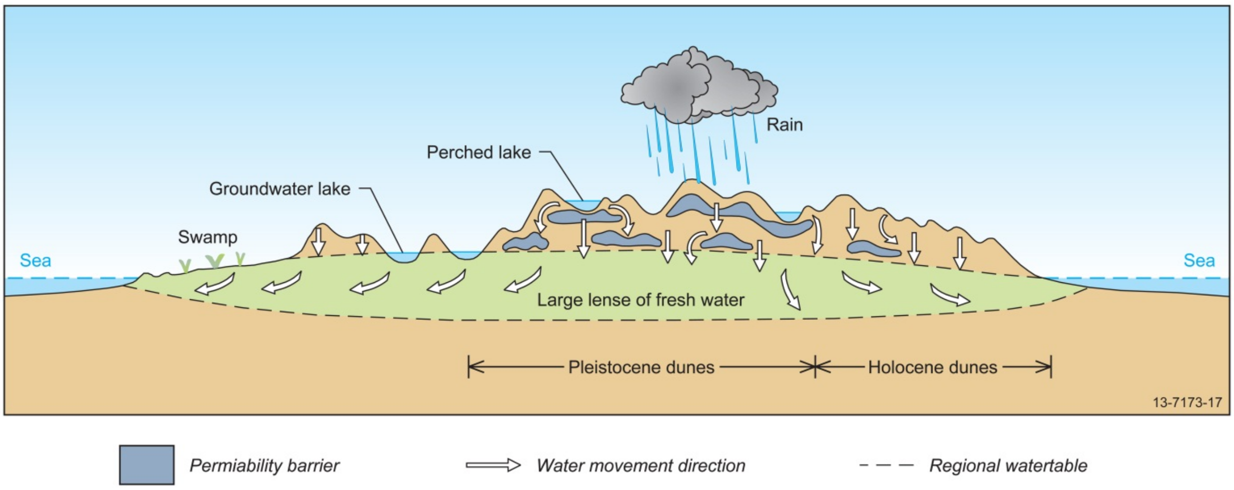

Figure 6.2 Schematic diagram of groundwater systems on Fraser Island.

Source: adapted from Grimes (1992)

6.1.2 Quaternary Alluvial Aquifer

Quaternary unconsolidated sediments are associated predominantly with the Kolan, Burnett, Elliott and Mary rivers. The aquifer predominantly consists of unconsolidated sands and silts deposited in channels. They are not continuous and occur as lenses incised into older rock formations.

6.1.3 Quaternary Basalt Aquifer

There are numerous Quaternary basalt aquifers within the Maryborough Basin; the presence, location and distribution of each aquifer has not been fully determined. Basalt aquifers are less extensive than sedimentary aquifers but can form productive aquifers at a local scale. Groundwater occurs in fractures and vesicular openings (Laycock 1969). The hydraulic conductivity of basaltic aquifers is thus highly variable and mainly depends on the connectivity and spacing of fractures. Weathering of both the fractures and the geological contacts between lava flows is likely to also affect hydraulic conductivity.

6.1.4 Elliott Aquifer

The Elliott Aquifer is the most highly utilised aquifer in the Maryborough Basin. It comprises semi-consolidated to unconsolidated quartzose sandstone, conglomerate, siltstone, mudstone and shale. The formation has extensive duricrust development (Moser 2004). There is some contention in the naming of the Elliott Aquifer. Laycock (1969) suggested that the Elliott Aquifer forms only a thin veneer of sediments across the basin with low groundwater potential and attributes high groundwater productivity to another Cenozoic alluvial unit. This report classifies all Cenozoic alluvium to the Elliott Formation, based mainly on Cranfield (1994) because most recent reporting is consistent with the work of Cranfield (1994), as well as many of the bore records provided by DNRM (2012). The result of hydraulic testing of the Elliott Aquifer is shown in Table 6.1 and hydraulic properties are discussed further in Section 6.3.1.

Table 6.1 Hydraulic properties of the Elliott Formation Aquifer and the Fairymead Beds Aquifer.

	Elliott Aquifer	Fairymead Beds Aquifer
Number of tests	149	25
Average aquifer inflow zone thickness (m)	6.0	8.3
Average transmissivity (m^3/day)	1630	1274
Average hydraulic conductivity (m/day)	290	234
Average test pumping rate (L/s)	17.7	19.7
Minimum test pumping rate (L/s)	0.4	2.5
Maximum test pumping rate (L/s)	50.5	45.0

Source: after Moser (2004)

The aquifer varies in thickness spatially and generally thickens towards the coast. In some parts of the basin it is thin and above the watertable and therefore has little groundwater potential. The aquifer is heterogeneous and has extensive lateral variability in sediment type and facies distribution. Productive groundwater zones of coarse-grained sands are commonly hydraulically isolated among finer-grained clays and silts (Moser 2004). Areas of high hydraulic conductivity within the Elliott Aquifer are commonly associated with paleochannels. The exact dimensions and locations of paleochannels within the basin have not been mapped. They are generally estimated to be 5 to 15 m thick.

A minor aquifer underlies the Elliott Aquifer in the Bundaberg area only (within the ‘Bundaberg Trough’) and is known as the Fairymead Beds Aquifer. This is also of Cenozoic age and comprises unconsolidated sands, gravels and clays. This aquifer is considered to be particularly susceptible to seawater intrusion (Moser 2004). It is semi-confined to confined and separated from the Elliott Aquifer by the Gooburrum Clay Aquitard. The Gooburrum Clay Aquitard is not regionally extensive and contains an upper sandy section that provides an important aquifer unit in hydraulic conductivity with the overlying Elliott Aquifer (Moser 2004).

In the south of the basin, there are some beds known as the Takura Beds, which are colluvium layers deposited at the base of basalt ridges. These beds are coarse-grained and form local aquifers and have been included here within the hydrostratigraphic classification of the Elliott Aquifer.

6.1.5 Burrum Aquifer

The Burrum Aquifer is a highly heterogeneous unit and contains different types of discrete aquifers. The main two are: fractured rock aquifers within shale and coal seams; and confined sandstone aquifers that occur between shales and coals (which act as intervening aquitards). The lithology of a typical bore within the Burrum Aquifer is shown in Table 6.2.

Table 6.2 Representative lithology of the Burrum Aquifer as recorded in the Burrum-2 well.

From depth (m)	To depth (m)	Lithology	Hydrostratigraphy
0	9	Soil	Elliott Aquifer
9	30	Mudstone	Burrum Aquifer
30	94.92	Sandstone minor siltstone	
94.92	142.87	Sandstone minor siltstone and coal	
142.87	154.46	Coal with minor shale	
154.46	181.61	Sandstone with minor siltstone	
181.61	242.42	Coal with minor shale	
242.42	258.2	Sandstone with minor siltstone	
258.2	269.53	Coal with minor shale	
269.53	410	Sandstone with minor siltstone and coal	
410	419	Coal Seam (B2)	
419	518	Sandstone with minor siltstone	
518	545	Siltstone with minor sandstone	

Source: after Enter and Grant (2007b)

Due to paucity of data and limited correlation between lithological logs, no discrete aquifer units have yet been mapped. Instead the Burrum Aquifer is referred to as a single aquifer on a regional scale for the purpose of this report. Hydraulic parameters therefore differ significantly within the aquifer. Surface exposure of the Burrum Aquifer is poor, due to the superficial cover of the Elliott Formation (Cranfield 1994; AustralAsian Resource Consultants (AARC) 2011). The aquifer is confined to semi-confined and is locally confined to synclinal structures within the basin. The aquifer and the coal measures have been best explored in the Burrum Syncline.

Groundwater occurs within each rock type within the coal measures, including the coal, sandstone, mudstone and claystone layers. The aquifer is considered to be confined to semi-confined and, in some parts of the formation, there is an upwards vertical hydraulic gradient from the Burrum Aquifer into the overlying Elliott Aquifer. However, in some areas there is a downward hydraulic gradient (AARC 2011).

The Burrum Aquifer is highly heterogeneous and there is a wide range of hydraulic conductivity values spanning four orders of magnitude. The aquifer has inter-granular primary porosity from pore space and secondary porosity associated with fractures, bedding planes and coal cleats (AARC, 2011; AGE, 2010). The median permeability for the aquifer was calculated to be 0.36 m/d based on falling head test analyses from bores with varying rock types. The variability of the aquifer's hydraulic properties is shown in Table 6.3.

Table 6.3 Hydraulic conductivity of rock types in the Burrum Aquifer.

Bore ID	Gravel Pack Zone (mBGL)	Test zone geology	Hydraulic conductivity	
			m/s	m/d
NMB-026	27.0 to 48.0	Fine-grained sandstone	1.6×10^{-7}	0.014
NMB-029	25.5 to 44.3	Fine-grained sandstone with minor coal	5.3×10^{-4}	45.7
NMB-043	29.5 to 49.5	Clay, sandstone and mudstone	6.9×10^{-7}	0.059
NMB-044	17.0 to 25.0	Sandstone	7.3×10^{-6}	0.627
NMB-045	40.0 to 60.0	Claystone (with coal seams)	4.2×10^{-6}	0.363
NMB-046	6.5 to 12.0	Clay and coal	5.1×10^{-8}	0.004
NMB-047	35.5 to 64.0	Claystone (with coal seams)	6.4×10^{-6}	0.553
NMB-048	24.5 to 32.0	Sandstone, mudstone and claystone with coal	5.5×10^{-7}	0.048
NMB-050	38.0 to 54.0	Clay and coal	3.5×10^{-5}	3.033
NMB-051	29.7 to 37.0	Coal and clay	7.0×10^{-5}	6.074
NMB-052	12.0 to 22.0	Clay and sandstone	1.9×10^{-6}	0.164

Source: from AARC (2011)

A 24 hour pumping test was used to measure the hydraulic properties of the Burrum Aquifer over a broad area (AGE, 2010; AARC 2011). The results from this testing is shown in Table 6.4.

Table 6.4 Hydraulic properties of the Burrum Aquifer derived from test pumping data.

Bore ID	Maximum Drawdown (mbTOC*)	Transmissivity (m^2/d)	Hydraulic conductivity (m/d)	Storage coefficient	Method of analysis
NMB-049	14.73	3.78×10^{-4}	0.65		Cooper-Jacob
		5.28×10^{-4}	0.91		Theis Recovery
NMB-050	9.17	4.04×10^{-4}	0.7	3.49×10^{-4}	Cooper-Jacob
		6.0×10^{-4}	1.04		Theis Recovery

** mbTOC = m below top of casing*
Source: after AARC (2011)

6.1.6 Maryborough Aquitard

The Maryborough Aquitard forms one of the most extensive units in the Maryborough Basin (Laycock 1969). Although considered as a regional aquitard, groundwater is extracted locally in some areas from fractures and joints. The lithology of the formation is predominantly siltstone and mudstone. The Cherwell Mudstone Member is particularly recognised as a seal unit in a conventional petroleum system (Stephenson and Burch 2004). No data on the aquifer parameters were available for compilation in this report.

6.1.7 Grahams Creek Aquifer

The Grahams Creek Aquifer is a volcanic unit comprising of acidic volcanic rocks such as andesite, andesitic tuff and dacite. The aquifer is massive and dense and groundwater occurrence is predominantly in fractures and in the shallow weathered zone (near-surface) at the basin margin. Small supplies of groundwater can be expected from the Grahams Creek Aquifer and water quality is generally suitable for stock or domestic use (Laycock 1969). No data on the aquifer parameters were available for compilation in this report.

6.1.8 Duckinwilla Aquifer

The Tiaro Coal Measures and the Myrtle Creek Sandstone together form one hydrostratigraphic unit known as the Duckinwilla Aquifer. This aquifer has only limited surface exposure along the basin’s western margin and is the oldest hydrostratigraphic unit. There are likely to be high-permeability sections of the Duckinwilla Aquifer that store and transmit higher quantities of groundwater, e.g., in faults and structurally deformed zones. For the purpose of this report, the aquifer is regionally identified only and finer-scale investigations are required to further subdivide the aquifer based on variable parameter values. Within the aquifer, there is a progressive deterioration of water quality and increasing salinity with depth, and effective permeability of the aquifer is expected to be low overall (Laycock 1969). No data on the aquifer parameters were available for compilation in this report.

6.2 Groundwater system characterisation

6.2.1 Flow systems

A hydrogeology map was created for this study to show the spatial variability of the hydrostratigraphic units across the basin (Figure 6.3). There are many different mechanisms for creating hydrogeological maps and different features that can be depicted, depending on the mapping purpose (Struckmeier and Margat 1995). The hydrogeology map of the Maryborough Basin was created to display the watertable aquifer. It shows that across most of the basin, the Elliott Aquifer is widespread. This is a relatively thin regional aquifer across the basin, although it is thicker and more dominant in the north of the basin than in the south (Figure 6.4).

Another important features to note from the hydrogeology map is the considerable variation in the aquifer system along the coast of the basin compared to the basin flanks in the west. In the west, older geological units occur nearer to the surface, and younger geological units are not as common. The Grahams Creek Aquifer, Maryborough Aquitard and the Duckinwilla Aquifer are thus important in the western part of the basin. This contrasts to the eastern margin of the basin, where Quaternary alluvial, deltaic and dune sand deposits form locally-significant aquifers that are not present in the west. Cenozoic basalts are also more common in the east, and these may form locally significant fractured rock aquifers. The distribution of basalt aquifers is controlled by the location of basaltic vents, which allowed extrusion of basalt during the Cenozoic. Vents likely formed along pre-existing fault structures, and hence there is a spatial association of faulting and the location of Quaternary Basalt Aquifers. Locally significant basalt aquifers also occur on the western basin margin, but are less common.

Structural folding and deformation is more pronounced in the southern parts of the basin, due to the tectonic stress regime imposed during basin inversion in the Late Mesozoic to Early Cenozoic (as shown by comparison of cross-sections A to A’ and B to B’ in Figure 6.4). The Elliott Aquifer is also thicker in the north. This will affect the hydrogeology and groundwater flow of the system. The combination of a relatively thick Elliott Aquifer sequence, and the overlying Quaternary Alluvial Aquifer associated with the Burnett River, forms an important hydrogeological system that is used to sustain irrigation for sugar cane in the northern basin area. There is also a major Quaternary Basalt Aquifer south-east of the Burnett River mouth. Groundwater flow in the Cenozoic Basalt Aquifer (largely through fractures) will differ from flow in the adjacent alluvial aquifers (largely through pore space).

Along the coastline, there are several areas of Dune Sand Aquifers. These are shallow linear features that have relatively high porosity and permeability (formed mainly of poorly consolidated quartz sands). There are two systems of dunes, an older, Pleistocene system further from the coast, and younger Holocene dunes adjacent to the coastline. Both types of aquifers are expected to receive rapid recharge infiltration from surface inflow. However, as the Pleistocene dune systems are more indurated, compacted and vegetated than their younger counterparts, they will likely have slightly lower recharge rates and greater volumes of run-off. Dune sands form local groundwater flow systems.

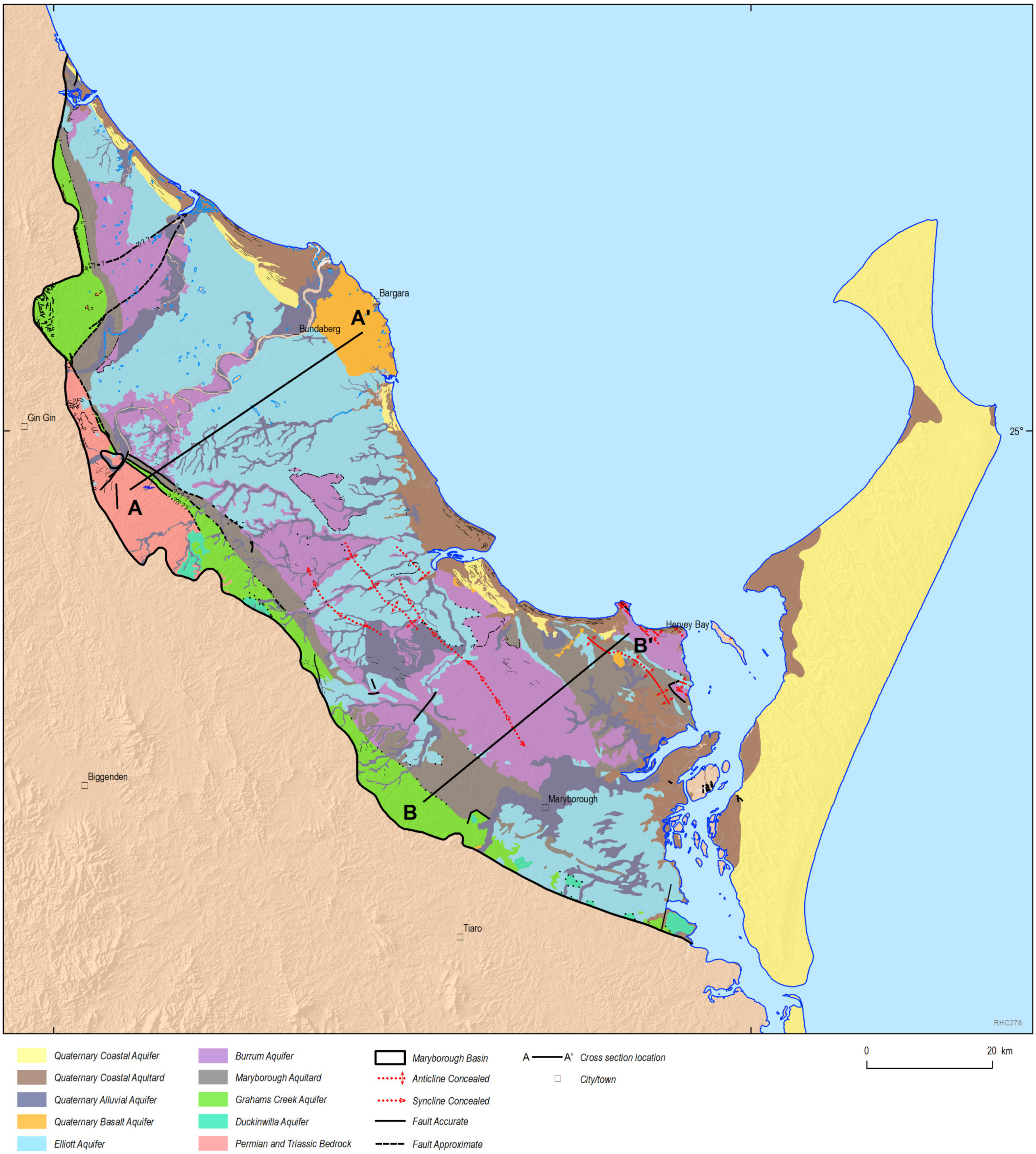

Figure 6.3 Map of superficial aquifers in the Maryborough Basin.

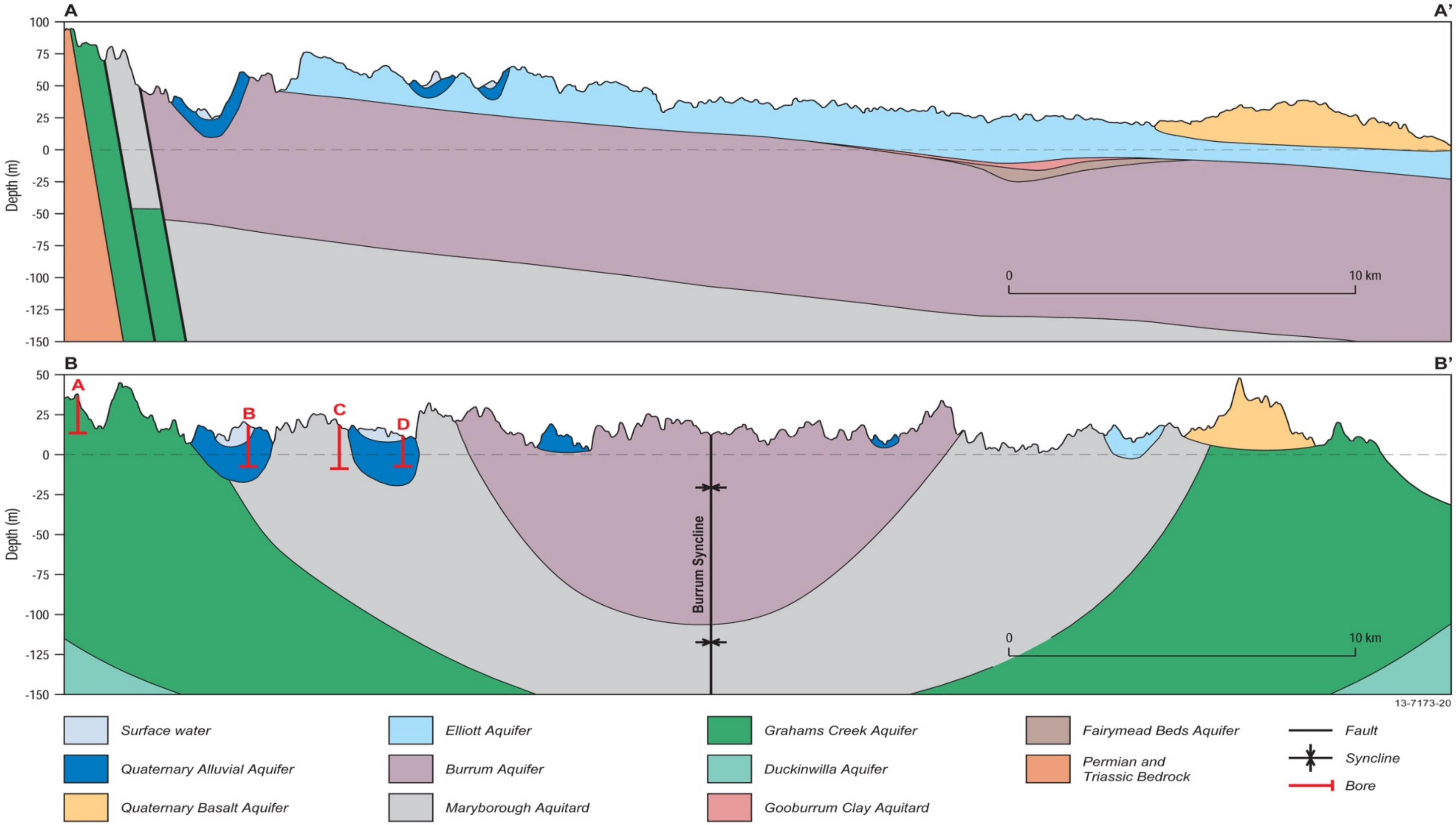

Figure 6.4 Hydrogeological cross sections A to A' and B to B' for the Maryborough Basin.

Faults are distributed throughout the basin and may significantly influence groundwater recharge into, and flow within, the various Mesozoic aquifer systems. Large faults are particularly common on the western margin of the basin, e.g., the Electra Fault System separates the Maryborough Basin from the Gympie Block in the west. Deep groundwater recharge to the Mesozoic sedimentary aquifers is likely to occur along the western margin faults where these units either outcrop or occur closer to the surface. The role of faults in recharge (Section 6.3.2) and connectivity (Section 6.3.3) is discussed later in this chapter.

6.2.2 Watertable contours

In a groundwater system, the watertable is also known as the phreatic surface, and it is defined as the level at which water pressure equals the atmospheric pressure. It is the boundary surface separating the saturated zone (the unconfined watertable aquifer) from the overlying unsaturated zone (where pore spaces are not always fully saturated).

The mapped watertable contours were derived from a limited dataset and thus the final product is an indication of groundwater gradients in a dynamic system, which in reality will vary with time. The regional gradients of groundwater flow can be determined from measuring standing water levels in bores or piezometers and converting to relative levels. To assess horizontal groundwater gradients in the Maryborough Basin, relative water level data from the Healthy Headwaters dataset (Department of Natural Resources and Mines 2012) were mapped and interpolated, and contoured for hydraulic head. In undeveloped areas, the contours were represented as subdued reflections of the topography. Previously, watertable mapping had been undertaken by three studies at a local scale (Laycock 1969; Moser 2004; AustralAsian Resource Consultants (AARC) 2011). These datasets were assessed in conjunction with the Healthy Headwaters dataset to create basin-wide contouring. The spatial distribution of the data points and the previous watertable mapping that were extrapolated to form basin-wide watertable contours are shown in Appendix C (Figure 47). In general, the Healthy Headwaters data correlated well with the previous studies, which improved the level of confidence in the quality of the data available.

Using watertable data from various sources has several limitations though, including:

- Absence of adequate data points to have confidence in extrapolating across areas with poor datasets
- The upper aquifer is assumed to be a hydraulically continuous unit across the basin, whereas its properties may vary due to lithological changes in different units
- Not all of the standing water level measurements used in this study could be definitively attributed to particular hydrogeological units
- Data was not quality-checked and assured and there are no details related to the quality of the data collection methods
- Water level data from many different years was assessed simultaneously for this study, and therefore does not differentiate between steady state and transient gradients at different temporal scales. Transient conditions can lead to substantial variation in water levels, such as from prevailing climatic conditions, irrigation loading and groundwater extractions.

Despite these limitations, the data provided broad spatial coverage, enabling an unprecedented assessment of groundwater regional gradients across the basin. Contours of the potentiometric surface of the phreatic aquifer in the Maryborough Basin are shown in Figure 6.5. The contours have been created for the uppermost aquifer (which is not consistent across the basin), which is generally either the Elliott Aquifer or the Burrum Aquifer. Groundwater regional gradients are broadly from west to the east and are strongly related to the distribution of surface water catchments in the basin. Hydraulic head is greater along and adjacent to river channels in the eastern parts of the basin, where the topographic gradient is relatively flat, suggesting that groundwater recharge via surface water inflow is a significant mechanism in these areas.

Flow between surface and groundwater occurs from areas of high hydraulic head to areas of low hydraulic head. Groundwater divides can be seen on the map; they occur mainly at elevated topographic divides that are likely also to act as surface water divides. The rate of flow between surface water and groundwater systems will depend on the level of surface water–groundwater connectivity. A more comprehensive assessment of connectivity (including new field studies) between surface water and groundwater systems would prove useful to better understand the degree, magnitude and direction of flow.

Basin-scale recharge occurs mainly along the western basin margins, and groundwater systems flow regionally eastwards towards the coast. Steep gradients in the contours can be seen along the western margin, whereas along the coastline the gradient is shallower and flow rates are relatively slower. If there is no significant flux of groundwater being discharged along the coastline, seawater intrusion could become a problem in parts of the basin. The Elliott Aquifer was previously identified as having a high current and future vulnerability to seawater intrusion, and seawater intrusion has been an issue in the Bundaberg area in the past (Ivkovic et al., 2012).

There are insufficient data available to produce a potentiometric map for any of the deeper (confined) aquifers of the Maryborough Basin. The overall regional flow path of groundwater in all aquifers is expected to be similar to that of the watertable, i.e., groundwater recharge into the deeper aquifers occurs along the western basin margin and flows from west to east, discharging along the coast. However, local- to intermediate-scale variations in the overall regional flow system are likely, potentially associated with areas of recharge (such as in the areas immediately underlying surface water catchments); areas of increased hydraulic conductivity (such as in paleochannels); or where there is decreased hydraulic conductivity (e.g., higher proportion of clays and fine-grained sediments in the stratigraphy). Discharge via groundwater extractions and areas of intense groundwater development, such as in the area around Bundaberg, will also impact groundwater gradients. Variation in thickness of each unit will also affect groundwater flow.

In addition to regional flow systems, there are also likely to be many local-scale groundwater flow systems operating in the basin. Non-continuous geological units, such as basalts and dune sands form important local aquifers. This research has shown that further work is required to characterise the dynamics of local-scale flow systems across the Maryborough Basin.

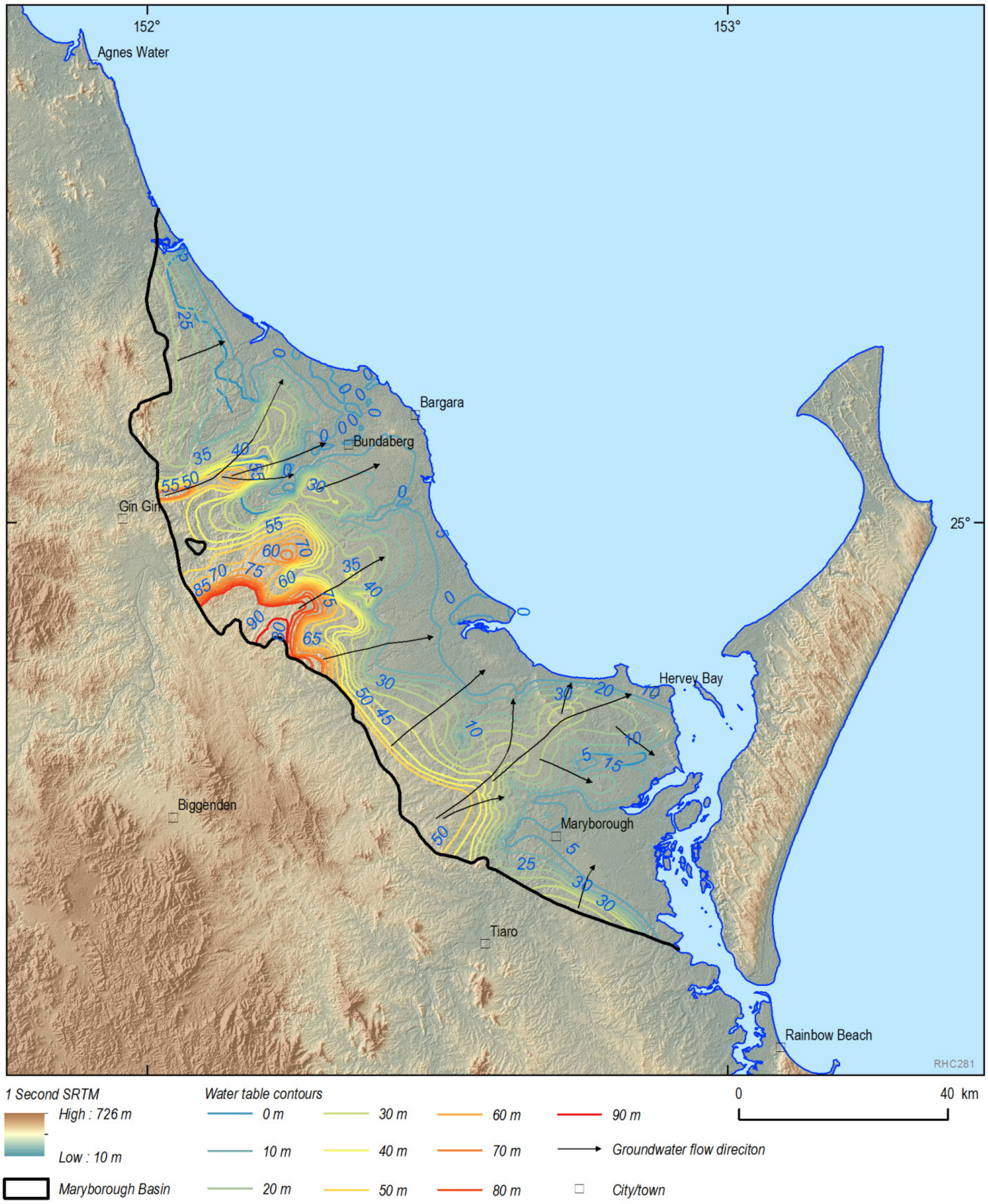

Figure 6.5 Regional watertable contours and direction of groundwater flow in the upper aquifer of the Maryborough Basin. Contour units are metres relative to the Australian Height Datum (mAHD)

6.2.3 Groundwater hydrochemistry

A detailed chemical analysis of groundwater compositions was out of scope for this project, although preliminary interpretation of groundwater chemistry data has nevertheless been conducted. Some chemical data is available for groundwater from the Healthy Headwaters (Department of Natural Resources and Mines 2012) dataset. In addition, information about the composition of groundwater was extracted from several of the local groundwater studies (previously mentioned).

Groundwater chemistry was determined for groundwater in the vicinity of the town of Maryborough (south Maryborough Basin) within the Quaternary Coastal Aquifer (a); Quaternary Alluvial Aquifer (b); Quaternary Basalt Aquifer (c); Elliott Aquifer (d); Burrum Aquifer (e); and Grahams Creek Aquifer (f) by Laycock (1969) (see Figure 6.6). The overall chemical character of groundwater for each aquifer type is shown on the Piper diagrams in Figure 6.6, highlighting the balance between the major anions and cations. These enable the visualisation of differing water types between different sites and support an understanding of the variability in ratios of ions between different samples. Overall, the dominant anion in the basin is chloride and the most common cation is sodium (typical of many groundwater systems in Australia). Potassium concentrations are minimal in all measurements (Laycock 1969).

The groundwater within the Elliott Aquifer, Burrum Aquifer, the Quaternary Basalt Aquifer and the Grahams Creek Aquifer has broadly similar chemical compositions. The dominant anion is chloride, and bicarbonate is also relatively dominant, with sodium the main cation. There is a range in type and the water quality is heterogeneous, which may be because they have a range of lithologies and there are likely to be zones within each aquifer with slightly different compositions (groundwater mixing). Groundwater within the Quaternary Coastal Aquifer and the Quaternary Alluvial Aquifer has slightly different signatures than water hosted in the older geological units. The Quaternary Coastal Aquifer has a greater proportion of calcium and bicarbonate, instead of sodium and chloride. This may suggest that the dune sands aquifer comprises of calcium-carbonate rich sediments rather than purely quartz sand. The Quaternary Alluvial Aquifer has a chemically distinct groundwater type with a more narrow range than the other aquifers. It also is highly dominated by sodium-chloride-type water. The water may be largely derived from inflow of surface water.

A map of pH in the basin is shown in Figure 6.7. Groundwater with high, moderate and low pH occurs across the basin, and there is a relatively uniform distribution of acidic, neutral and basic groundwater with no obvious spatial trends. Waters of different pH may be due to variations in the lithology of the aquifer or may result from differences in residence times of water and chemical changes (e.g., water-rock interactions, evapotranspiration etc.) that occur as water flows through the groundwater system. It may also be due to the impact of fertiliser on the chemistry of the groundwater. Variations in pH can also occur because of the method of analysis. pH can either be measured in the field or in the laboratory, and this may cause slight variations in the reported result. No data quality checks were able to be undertaken for this project due to limitations in the data and the overall time constraints.

A map of electrical conductivity (EC) of groundwater in the basin is shown in Figure 6.8. Higher values of EC indicate water of elevated salinity. Figure 6.8 shows that water in the Bundaberg area is generally fresh (low EC). In areas downstream, near the confluence with the ocean, salinity is higher. Groundwater extractions in the Bundaberg area from the Elliott Aquifer in the tidal sections of the Burnett and Elliott Rivers has caused inflow from the rivers and (to a lesser extent) seawater into the aquifers (Moser 2004). This may be the cause of higher salinity water adjacent the coastline and hosted by the Quaternary Alluvial Aquifers. Higher salinity groundwater also occurs along the western basin margin. Groundwater salinity is generally greater in the south of the basin than in the north. This is likely because aquifers in these areas are less permeable than the alluvial Elliott Aquifer associated with the Burnett River in the Bundaberg area. Higher permeability sediments may recharge more rapidly and will be better flushed with fresh recharge waters, resulting in generally lower salinities.

6.2.4 Groundwater models

The purpose of this section is to discuss specific groundwater models that currently exist for the Maryborough Basin, as the design and results of these may be able to be drawn upon for future groundwater assessments. Most previous groundwater modelling of the Maryborough Basin exists in the Bundaberg area, where models have been developed as a water management tool to support the sugar cane industry and to help minimise seawater intrusion. The only known modelling in the south of the basin was done to provide information related to a proposed coal mine development (Colton Coal Mine). There is no modelling to date for the entire basin extent. Each existing model focuses on the shallow aquifer unit, the Elliott Aquifer and the Burrum Aquifer and there are no models that have included groundwater flow system interactions with the deeper Mesozoic aquifers/aquitards.

Groundwater modelling in the Bundaberg area was first undertaken in 1981 for the area south of the Elliott River. Since then, there has been an expansion and improvement in modelling as a water management tool. The largest and most recent of these models was developed by Moser (2004), intended for use in conjunction with other tools and as a basis for assessment of proposed amendments to the Burnett Basin Water Resource Plan and Resource Operations Plan. The two-layer model (developed with MODFLOW) has been used to manage the Elliott Aquifer in the Bundaberg area. The MODFLOW model was later adapted to the MODHMS code to provide a specific seawater intrusion model for the Elliott Aquifer in the Bundaberg area (Bajracharya, Moser et al. 2006).

AGE (2010) developed a numerical model for Northern Energy Corporation Limited (NEC). NEC proposed to develop an open-cut coal mine north of Maryborough and, to gain approval, an Environmental Management Plan was required. The groundwater model was developed based on a data review and field investigation. The field investigation included the installation of monitoring bores, permeability tests and water quality analyses. Falling head and pumping tests were conducted to determine hydraulic parameters used in the model.

Numerical simulation of the Colton groundwater flow was conducted using MODFLOW SURFACT code Version3. After the steady state and transient model were calibrated to the available data, predictive scenario modelling was run. The objectives of the predictive numerical modelling were to: estimate groundwater inflow into the coal mine; predict the zone of influence from dewatering and the level and rate of drawdown at specific locations; identify areas where groundwater resources may be impacted by the mine; and to predict the impact of dewatering on groundwater discharge and how it affects other groundwater users. Overall, the modelling found that the proposed mine would reduce groundwater levels up to 3 km away from the proposed open cut pit. However, based on this modelling, there are no registered bores expected to be affected (as they fall outside of the zone of influence); and that *“as the wetlands are not likely to be a groundwater discharge zone, they will not be impacted by mine dewatering”*.

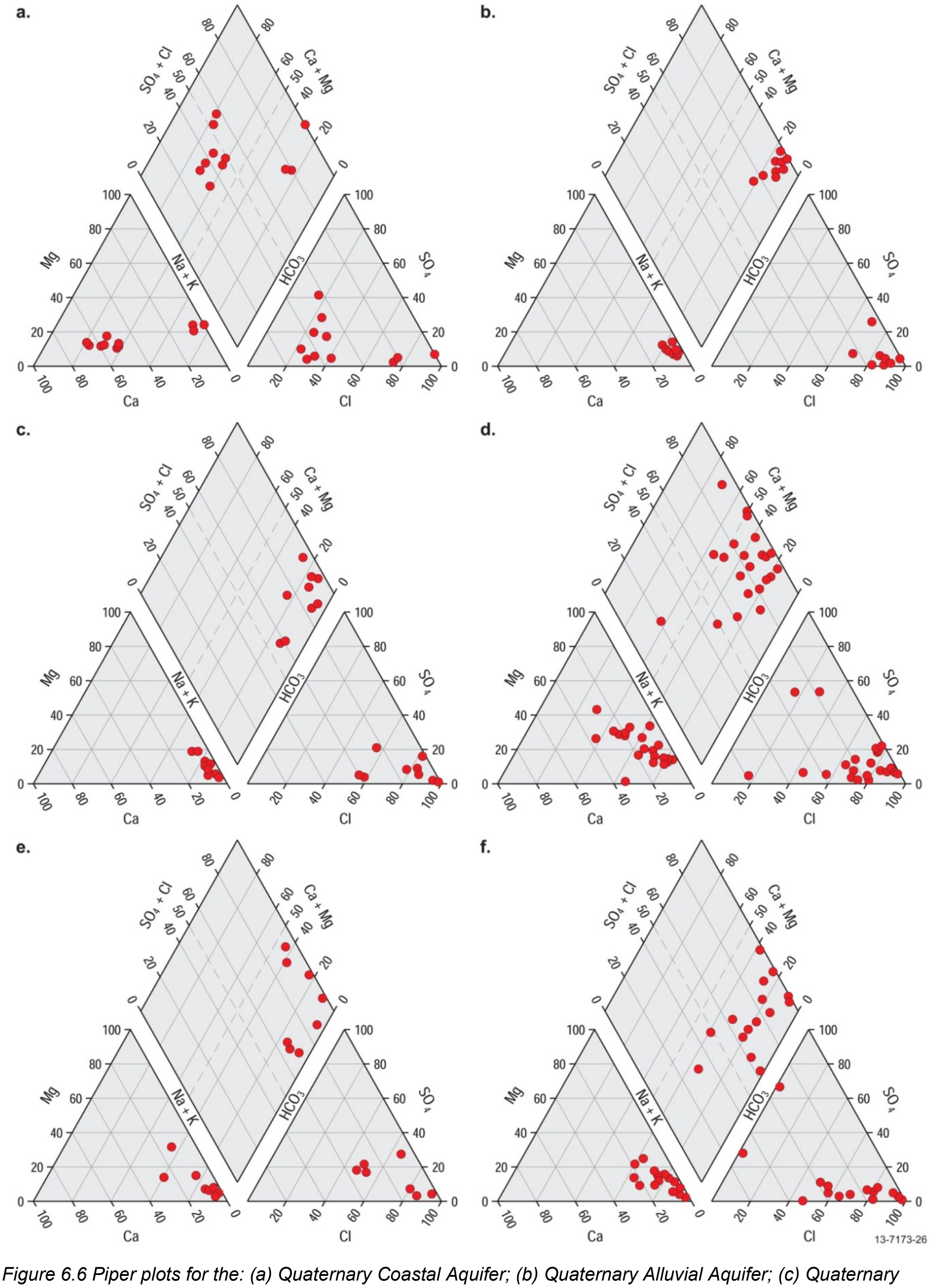

Figure 6.6 Piper plots for the: (a) Quaternary Coastal Aquifer; (b) Quaternary Alluvial Aquifer; (c) Quaternary Basalt Aquifer; (d) Elliott Aquifer; (e) Burrum Aquifer; and (f) Grahams Creek Aquifer.

Source: adapted from Laycock (1969)

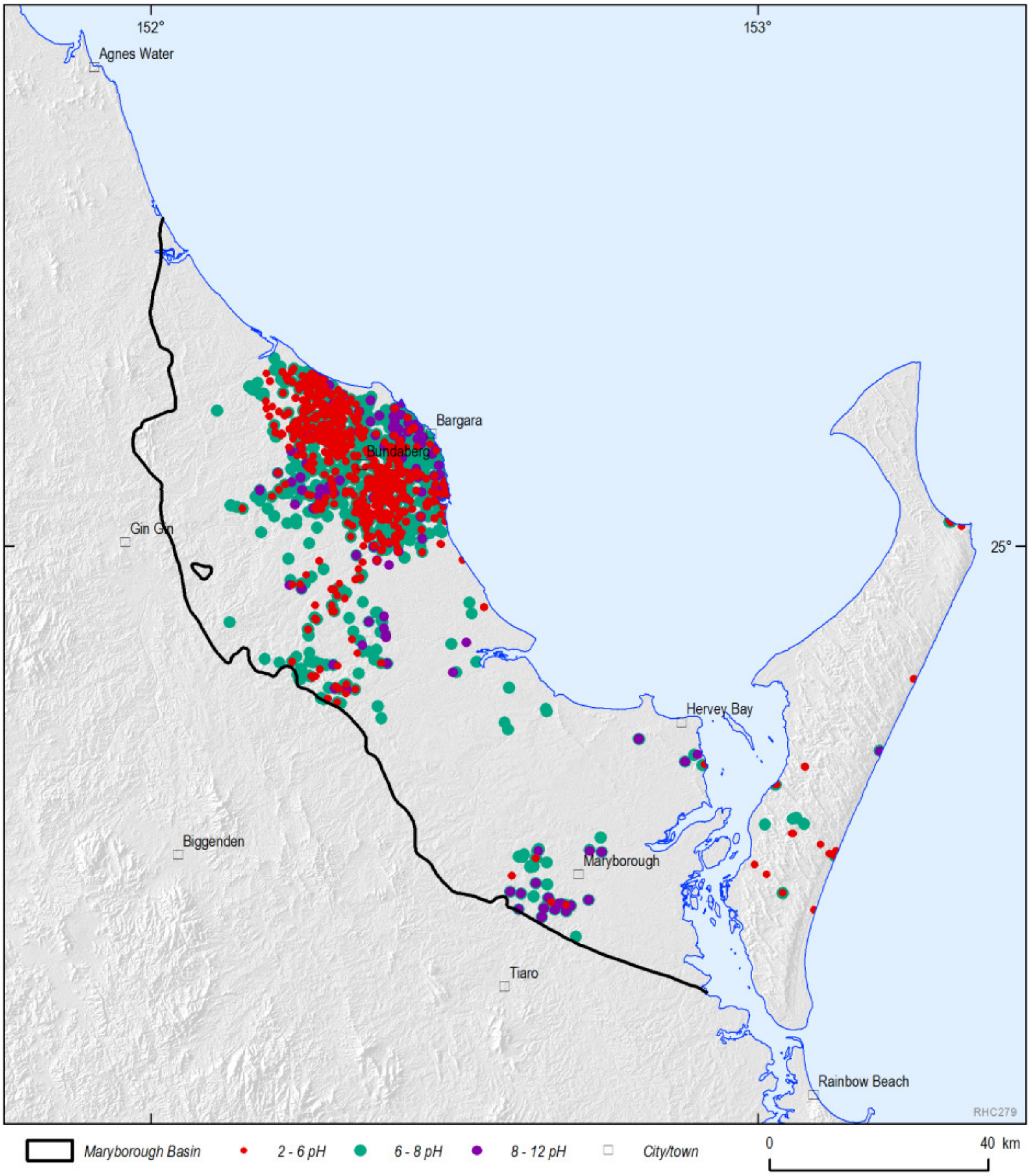

Figure 6.7 Groundwater pH in the Maryborough Basin.

Data shown here combined for all source aquifers

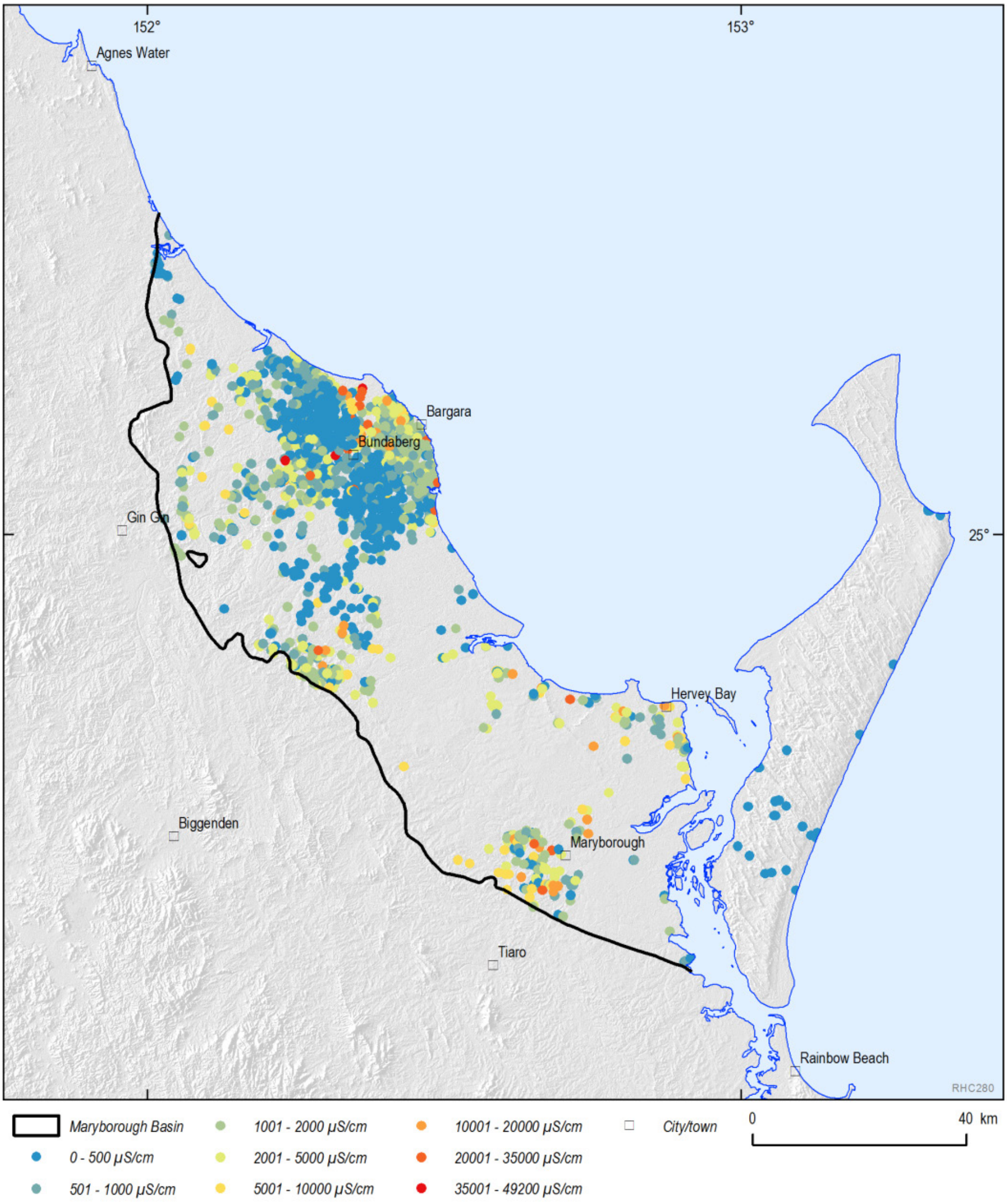

Figure 6.8 Electrical conductivity data for groundwater in the Maryborough Basin.

Data shown here combined for all source aquifers

6.2.5 Groundwater extraction, management and use

In the Maryborough Basin, there are currently two groundwater management units (GMU): the Bundaberg GMU and the Fraser Island GMU. The Bundaberg GMU is currently being re-classified and extended further east to include a larger portion of the Elliott Aquifer. The new area is known as the Coastal Burnett Groundwater Management Area and the reclassification will enable more efficient conjunctive water use management (Department of Environment and Resource Management 2010).

Groundwater Management Units (GMU) of the Maryborough Basin defined by the Australian Water Resources Audit of 2005 (National Water Commission 2005) are shown in Figure 6.9 and information about water use from the GMUs in Table 6.5. Most of the basin is not covered by a GMU. There are 6,093 bores in the Bundaberg GMU, 46 bores within the Fraser Island GMU and 2869 bores within the unmanaged area (Bureau of Meteorology, 2013b). There are approximately 9000 registered bores within the Maryborough Basin. Of these bores, 95 are less than 5 metres deep; 2,519 are 5 to 20 m; 4,607 are 20 to 50 m; 432 are 50 to 100 m; and 23 bores are greater than 100 m deep. The remaining 1,282 bores do not have depth information attributed (Bureau of Meteorology, 2013b).

Out of the 2,988 bores that have aquifer information attributed, 901 bores (30.2%) are in the Quaternary Sand Aquifer, 112 bores (3.7%) are in the Quaternary Alluvial Aquifer; 201 bores (6.7%) are in the Quaternary Basalt Aquifer; 1696 bores (56.8%) are in the Elliott Aquifer (with 28 in the Fairymead Beds); 43 bores (1.4%) are in the Burrum Aquifer; 18 bores are (0.6%) in the Maryborough Aquitard and 17 bores (0.6%) tap the Grahams Creek Aquifer (Figure 6.10).

The Bundaberg GMU is 782 km^2. In this GMU a cap has been placed on groundwater extraction, which includes water extracted for irrigation, urban supply, commercial and industrial use, mining for oil and gas, forestry, and drought supply. The cap does not include water extracted for stock and domestic use, grey-water use, effluent recycling, or aquifer storage and recovery. In the GMU, groundwater and surface water are managed as an integrated water resource. The sustainable yield for the Bundaberg GMU for 2004 to 2005 was 40,000 ML based on simple analytical calculations. The level of development in the GMU relative to sustainable yield is considered to be high and the total groundwater extraction for 2004 to 2005 was 29,023 ML (73% of sustainable yield). In the GMU, entitlements are required for: irrigation, urban supply, commercial/industrial, farm dams, mining for oil and gas, forestry, floodplain harvesting, drought supply, grey-water use, effluent recycling, and aquifer storage and recovery (National Water Commission 2005).

The Fraser Island GMU is 1,662 km^2. A cap has not been placed on surface water use or groundwater extraction in this management area. Surface water and groundwater are not managed as an integrated resource because *“restrictions presently applied are considered to be very conservative”* (National Water Commission 2005). There was no sustainable yield assessed for 2004 to 2005, but the level of development relative to sustainable yield is considered low. Total groundwater extraction for the management unit is unknown. In the GMU, water entitlements are required for: irrigation, urban supply, commercial/industrial, farm dams, mining for oil and gas, forestry, floodplain harvesting, drought supply, grey-water use, effluent recycling, and aquifer storage and recovery (National Water Commission 2005).

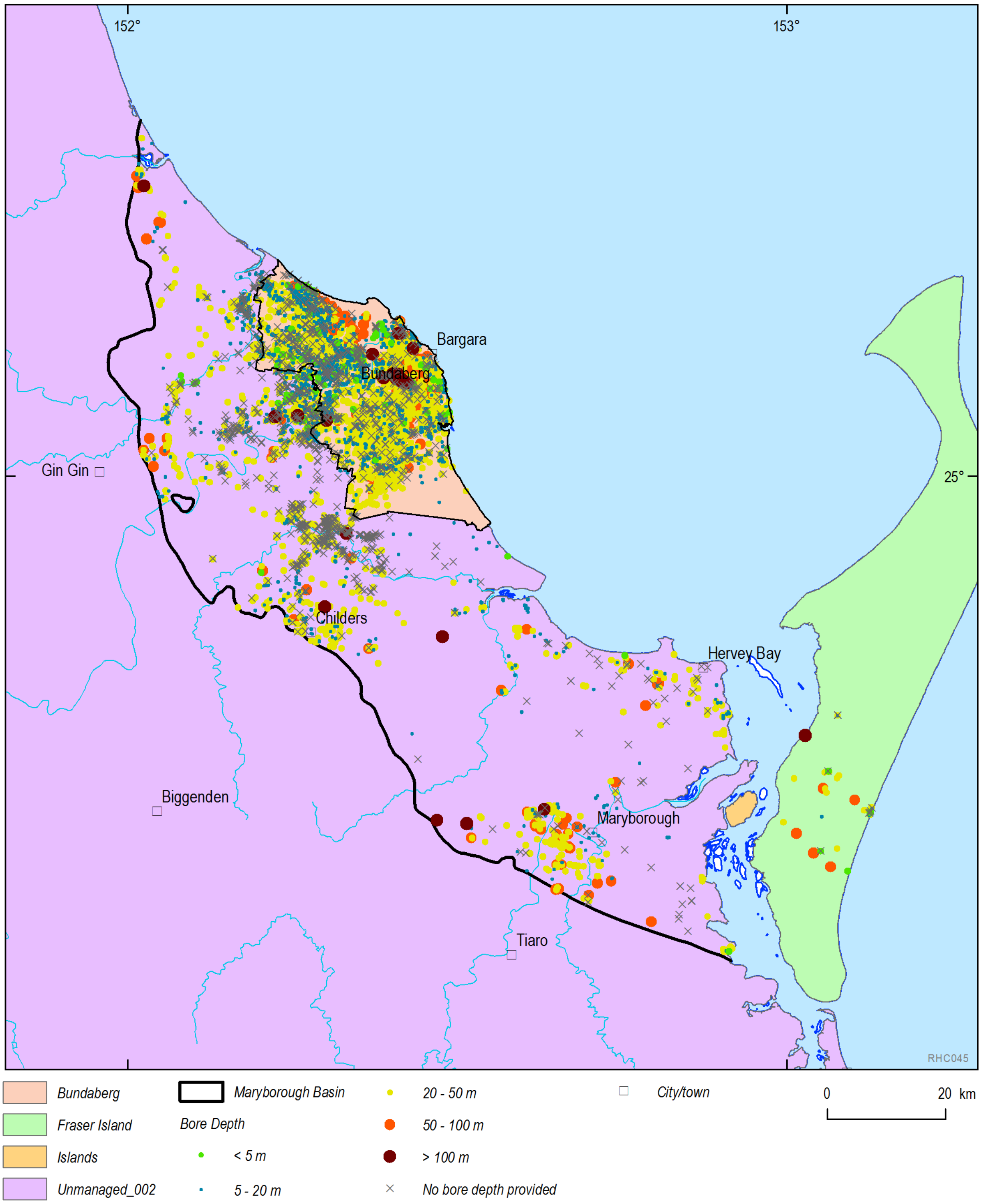

Figure 6.9 Bores and bore depths for groundwater management units within the Maryborough Basin.

Source: Data from Bureau of Meteorology (2013)

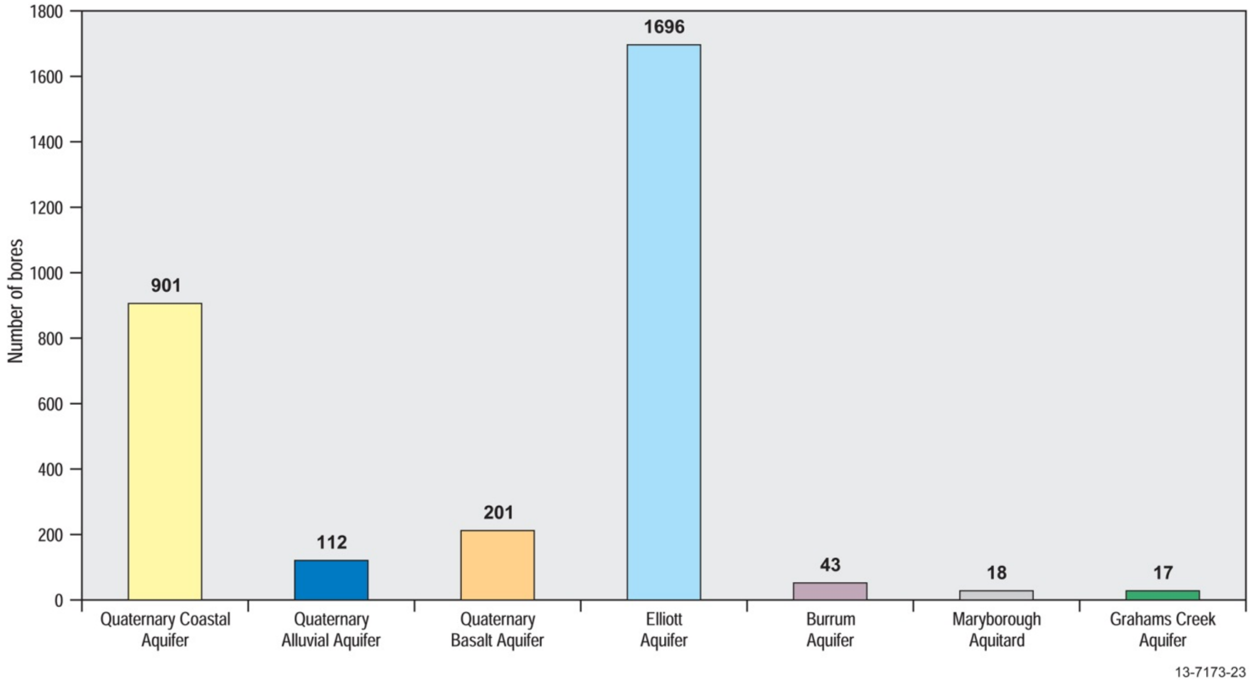

Figure 6.10 Distribution of bores between different aquifers within the Maryborough Basin.

Hydrostratigraphic information is only available for 33% of all bores in the Maryborough Basin

Table 6.5 Groundwater use in the Maryborough Basin.

	Area (km^2)	Sustainable yield (ML)	Total groundwater extraction (ML in 2004/05)	Level of development
Bundaberg Groundwater Management Unit	782	40,000	29,023	High
Fraser Island Groundwater Management Unit	1662	no data	no data	Low

Source: National Water Commission (2005)

6.3 Regional groundwater conceptualisation

The purpose of conceptualising the Maryborough Basin was for it to describe the aspects of the groundwater system that are understood, and to identify significant knowledge gaps to guide future investigations, prior to any future coal and coal seam gas development. For the purpose of this report, the conceptual model is not a predecessor of a numerical model. The particular focus of the conceptual model for the purpose of this report is to:

1. Communicate the scale of the basin and the relationship of major aquifers with coal seams
2. Communicate the variability of aquifer type and thickness within the basin
3. Interpret groundwater flow and major hydrogeological processes of the basin
4. Identify recharge areas and processes
5. Identify discharge areas and processes
6. Approximate the level of connectivity between aquifers and coal seams.

A guiding principle for conceptualising hydrogeological systems is that *'the level of detail within the conceptual model should be chosen, based on the modelling objectives, the availability of quality data, knowledge of the groundwater system of interest, and its complexity'* (Barnett et al., 2012). Although there is no current numerical modelling for the entire basin, the detail is constrained by the availability of quality data, knowledge of the groundwater system, and the inherent geological characteristics.

The regional conceptual model developed for the Maryborough Basin was based on best-available, pre-existing data. As new data may become available in the future, the conceptual model for the basin should be updated appropriately.

6.3.1 Hydraulic properties of aquifers

To develop a conceptual model of a groundwater system, hydraulic properties of each hydrostratigraphic unit are required. The purpose of this section is to best describe the characteristics and hydraulic properties of each aquifer. Definitions of hydraulic parameters are in Table 6.6. Although the hydraulic properties of each unit will vary spatially, a simplified estimation is provided for conceptualisation of the system (Table 6.7).

Table 6.6 Hydraulic parameters used to characterise hydrostratigraphic units.

Hydraulic parameter	Definition
Hydraulic conductivity, K (m/day)	Measure of the ease with which water can be transmitted through a geological material.
Storativity, S	Volume of water that is released per unit of hydraulic head drop per unit surface area due to the compressibility of water and the deformation of the aquifer matrix. In unconfined aquifers, water is gained and released from storage through the filling and draining of the aquifer pores and the storativity is referred to as the specific yield.
Specific storage	Storativity divided by the saturated thickness of a hydrostratigraphic unit.
Specific yield, S_y	The volume of water that is released per unit of watertable drop per unit surface area. This is only applicable in an unconfined aquifer.
Total porosity, n (%)	Volume of pores as a percentage of the total aquifer volume, measuring the maximum amount of water that can be stored in a hydrostratigraphic unit.
Transmissivity, T (m^2/day)	The rate at which water can be transmitted through a unit strip of aquifer, normal to the direction of flow. Product of the hydraulic conductivity and aquifer thickness.

Table 6.7 shows the known hydraulic parameters for the hydrostratigraphic units of the Maryborough Basin. These values are important for understanding and quantifying groundwater flow through the system. Currently, only sporadic data exists for hydraulic properties of the main basin aquifers.

Table 6.7 Estimated hydraulic parameters of hydrogeological units in the Maryborough Basin.

	Horizontal hydraulic conductivity (K_h) (m/day)	Vertical hydraulic conductivity (K_v) (m/day)	Storativity	Specific storage, Ss	Specific yield, S_y	Total porosity, n (%)	Transmissivity (m^2/day)
Quaternary Coastal Aquifer	no data	no data	no data	no data	15 to 32^	35 to 50^	no data
Quaternary Coastal Aquitard	no data	no data	no data	no data	no data	no data	no data
Quaternary Alluvial Aquifer	no data	no data	no data	no data	20 to 35^	25 to 35^	no data
Quaternary Basalt Aquifer	no data	no data	no data	no data	no data	1 to 12 (if weathered at surface likely to be higher, about 30 to 60)*	no data
Elliott Aquifer	290	no data	6×10^{-6} to 6^	no data	5 to14.2*	25 to 35^	1,630
Burrum Aquifer	0.004 to 45.7#	no data	n/a	1×10^{-5} to1 $\times 10^{-4}$ #	0.1 to 5#	25 to 35^	no data
Mary-borough Aquitard	no data	no data	no data	no data	no data	no data	no data
Grahams Creek Aquifer	no data	no data	no data	no data	no data	10 to 50^	no data
Duckinwilla Aquifer	no data	no data	no data	no data	no data	10 to 25^	no data

^ – Estimate, based on lithology, from Fetter (2001)
** – From Moser (2004)*
 # – From Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) (2010)

6.3.2 Recharge and discharge

Recharge in the Maryborough Basin has been suggested to be low, due to the relatively high salinity of the groundwater (AGE 2010). There are no studies that have directly measured recharge values into the aquifers and mechanisms of recharge are also poorly understood. The amount of recharge will vary depending on the spatial location on an aquifer and will also vary between aquifers. Based on available evidence there are likely to be five major recharge mechanisms in the basin which, for some aquifers, may be sourced by inter-aquifer processes:

1. Direct recharge as infiltration of rainfall (into overlying unconsolidated sediments or into outcrop)
2. Irrigation accessions in the intensely irrigated areas
3. Recharge via leakage from losing surface water systems
4. Deeper aquifer recharge via faults and other conduits of groundwater flow
5. Vertical leakage through aquifers.

Firstly, recharge is likely to occur via direct infiltration of rainfall into the superficial aquifer. Recharge rate will be influenced by the amount and intensity of rainfall, the aquifer material at the surface and the land cover. AARC (2011) suggested that recharge via rainfall is most effective during high intensity rainfall events. Flooding will also impact groundwater recharge volumes. This mechanism is suggested in Figure 6.11, which shows groundwater levels in a bore being monitored approximately 5 km from the Burnett River and approximately 10 km south-west of Bundaberg. The bore (RN13600150A) is 17 m deep and it targets the Elliott Aquifer with a screened interval of 9 – 12 m.

The hydrograph shows a strong and rapid correlation between high rainfall events and groundwater levels. However, this data is for one bore only and may not be indicative of conditions for the entire groundwater system. A full study of hydrograph data was not possible within the scope of this project. A review of the spatial distribution of observation bores (and their temporal trends) is an important next step in further progressing the understanding of the groundwater system and data gaps. AARC (2011) undertook a recharge study of the Burrum Coal Measures by installing and monitoring *Diver* pressure transducer logging instruments in response to rainfall events. Overall, they found that the response of water levels to rainfall events was characterised by a small, rapid response followed by a prolonged gradual response. This has been interpreted by AARC as an initial recharge from rainfall through the overlying Elliott Aquifer via preferential flow pathways such as fractures, root channels or soil/rock interfaces. The prolonged gradual response can be attributed to slower groundwater flow through less permeable sediments. It may also be interpreted as a delayed impact from flooding events, recharging as direct rainfall, and gradually being transferred through the groundwater system.

Leakage to groundwater from surface water systems will occur where the stream is a losing stream. This results when the water level of the stream is higher than that of the watertable. There have been no previous studies to quantify surface water–groundwater connectivity at a basin scale. However, a study by Sinclair Knight Merz (2012), assessed groundwater–surface water connectivity and the impact of groundwater extraction on surface water availability across different catchments in Australia. This work found that the Burnett and Burrum river catchments were *very highly connected* in relation to surface water and groundwater; and that the Kolan river catchment is *highly connected* in relation to surface water and groundwater. The amount of recharge will depend on the lithology of the aquifer and the sediment type at the base of the stream. Sediments with greater permeability, such as sand and gravel, enable better connection than those of low permeability, such as silt and clay. Pump testing or hydrochemical studies could be conducted to better understand and quantify the magnitude and direction of surface water–groundwater connectivity in the Maryborough Basin.

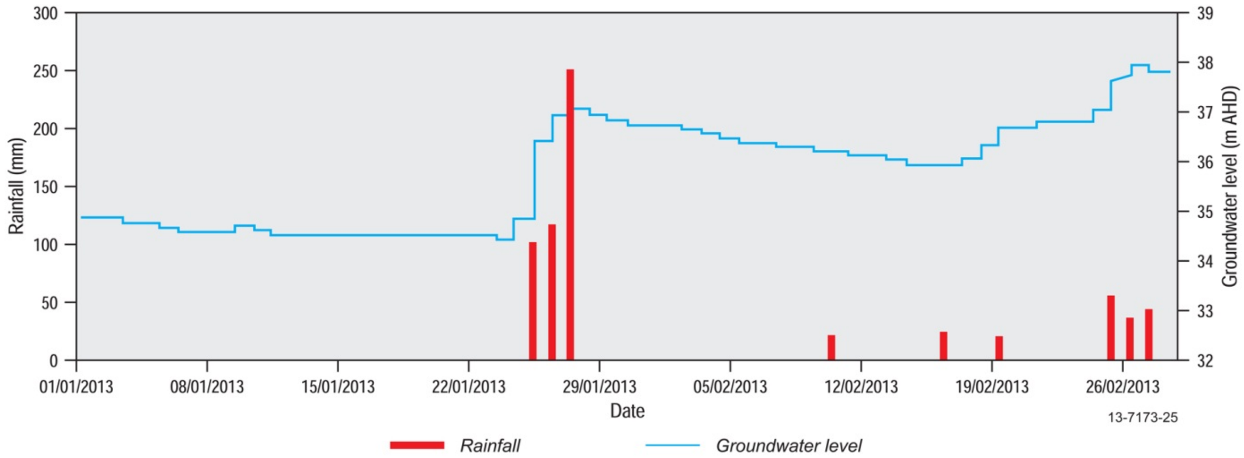

Figure 6.11 Rainfall and groundwater levels during January and February 2013 on an hourly basis for bore RN13600150A at 'Kentucky Bluegrass' adjacent to the Bundaberg River.

Source: Water level data is from Department of Natural Resources and Mines (2012a) and rainfall data from Bureau of Meteorology (2012)

Recharge into outcrop areas of Mesozoic rocks is likely to be a significant recharge mechanism to the deeper hydrostratigraphic units of the basin (Laycock 1969). This type of recharge occurs mainly along the western margin of the basin. The amount of weathering, fracturing and land cover will influence the volume of recharge in any given area. The intensity and duration of rainfall, and the slope of the outcrop, will also influence recharge rates, i.e., as run-off volumes increase, recharge may decrease.

There is significant faulting in the Maryborough Basin. Faults can either act as barriers or conduits of groundwater flow, depending predominantly on the material that has formed within the zone of deformation associated with the fault. Faults can act as pathways for recharge of water into deeper aquifer units, either from the surface or from upper aquifers into deeper aquifers.

Another mechanism for recharge into aquifers is as leakage of groundwater from adjacent aquifers, either upwards or downwards. This depends on the hydraulic properties of the aquifer and on the potentiometric head of each aquifer. It is also influenced by the nature and continuity of aquitard layers that may separate aquifers. There is presently no information available to understand connectivity between aquifers and the rate of recharge as leakage.

The amount of recharge via infiltration will vary between the different aquifer types in the basin. Where available, the details of recharge for each aquifer have been compiled and are available in Table 6.8.

There are no known estimates of discharge in the Maryborough Basin. Some likely mechanisms of discharge are:

1. Evapotranspiration (ET), which will occur especially where vegetation is dense. ET rates in the south of the basin near the town of Colton were estimated to be 1 mm/day by AGE (2010). Evapotranspiration from the basin is likely to be significant and depends on the land use, which is variable across the basin
2. Groundwater discharge to the sea resulting from out-flow from aquifers
3. Groundwater discharge onshore (such as into wetlands)
4. Surface water discharge to the sea
5. Groundwater extraction
6. Surface water extraction.

Table 6.8 Recharge sources for aquifers in the Maryborough Basin.

Aquifer	Recharge description	Recharge estimate (mm/year)
Quaternary Coastal Aquifer	Recharge into the Coastal Quaternary Aquifer is thought to occur via direct infiltration of rainfall, and potentially from irrigation returns, and is likely to be relatively rapid.	none available
Quaternary Alluvial Aquifer	Vertical infiltration of rainfall and leakage from surface water (as losing streams); there may also be recharge from surrounding aquifers where highly connected. Potentially receives recharge from irrigation returns.	none available
Quaternary Basalt Aquifer	Direct recharge from rainfall likely to be the major recharge mechanism.	none available
Elliott Aquifer	Via direct infiltration of rainfall and also from streamflow as well as from irrigation returns. AGE (2010) obtained an estimate of recharge based on numerical model calibration and based on a comparison of chloride concentrations in rainfall with the concentration in the aquifers.	2[#]
Burrum Aquifer	Recharge is likely to occur into the Burrum Aquifer via infiltration into the Elliott Formation, or via direct infiltration where the aquifer outcrops. It may receive recharge from irrigation returns. Where the land surface is open woodland, a large amount of transpiration and therefore less recharge is expected.	none available
Grahams Creek Aquifer	Recharge via rainfall infiltration at outcrop of western basin margin likely to be the major form of recharge; some recharge could occur as downward leakage but this depends on the integrity of the overlying Maryborough Aquitard.	none available
Duckinwilla Aquifer	Recharge via rainfall infiltration at outcrop at western basin margin likely to be the major form of recharge; some recharge could occur as downward leakage but this is likely to be minimal.	none available

 # – From Australasian Groundwater and Environmental Consultants Pty Ltd (AGE) (2010)

6.3.3 Connectivity between aquifers

Connectivity between the aquifers of the Maryborough Basin's multilayered hydrogeologic system is difficult to explicitly determine. Depending on the hydraulic properties of each aquifer, groundwater may flow downwards, from upper aquifers into lower aquifers; groundwater may also flow upwards from lower aquifers into upper aquifers. The degree of groundwater flow between aquifers depends on the lithology and the composition of any layers that may separate aquifers (aquitards). It also depends on the potentiometric pressure and the hydraulic head of the individual aquifers.

Each aquifer in the Maryborough Basin has a heterogeneous lithology due to variations in the original sedimentary depositional environments. Thus, to simplify the system, each stratigraphic unit is classified as either a predominant aquifer or aquitard. However, at local and intermediate scales, units may contain a mix of sands and clays with varying hydraulic conductivities. An aquifer is defined as a *"saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients"*. An aquitard, however, is a *"less-permeable bed in a stratigraphic sequence…permeable enough to transmit water in quantities that are significant in the study of regional groundwater flow, but their permeability is not sufficient to allow the completion of production wells within them"* (Freeze and Cherry 1979). The Maryborough Formation is the only known continuous aquitard in the Maryborough Basin but there are likely to be many other lower-permeability units within aquifers that act as local aquitards but are currently unknown.

Structural deformation in the basin is likely to enhance connectivity. In areas where there is significant faulting, groundwater may flow along faults between aquifers. Where there is folding, axial planar cleavage may increase connectivity between aquifers. In general, this may be more likely to occur in the south of the basin as this region is geologically more deformed than the north.

Determining the connectivity between aquifers is important to adequately assess the impact that coal mining or coal seam gas may have on groundwater levels for affected aquifers. However, there is currently little to no information available to assist this assessment. Hydrogeological testing is required, including the installation of nested bores to determine estimates of vertical gradients.

6.4 Regional water balance assessment

A regional water balance assessment is useful for natural resource management and water use planning. In the absence of detailed numerical modelling, it can be informed by a conceptual model to determine relative water input and output of the basin. Hydrogeological systems vary significantly both spatially and temporally, and a regional water balance estimate attempts to characterise the hydrogeological conditions in a simplified, steady-state system. Marginal changes to the steady state, such as an increase in groundwater extraction, or increased recharge through a flooding event can be incorporated into the water balance to assess change.

The Maryborough Basin is a multi-layered, folded, faulted and intruded sedimentary aquifer system. It is structurally complex and spatially heterogeneous. There is also limited data coverage to estimate specific values of water input and output. As such, the analysis for this study is a relatively simple first-pass assessment of the regional water balance. With increased data availability, the quantification of parameters in the water balance may potentially improve over time.

To undertake the water balance analysis, a definition of the area and time of the calculations is required (e.g., Paydar et al., 2009). The boundary of the assessment is the boundary of the Maryborough Basin and only includes the onshore part. The base of the Duckinwilla Aquifer provides the base of the conceptual model. The water balance quantitatively assesses the amount of water (inflow) into the system and amount of water out of the system (outflow). This is known as the change in water storage, or ΔS. The mathematical formula for the water balance can be shown as:

$$\text{Inflows} - \text{Outflows} = \Delta S \tag{1}$$

To simplify the water balance calculation and derive the water balance for steady state, the change in storage, ΔS can be assumed to be zero.

A schematic conceptual model diagram is shown in Figure 6.12. This shows the dominant processes occurring in the basin. The water balance for this conceptual model requires a quantitative analysis of inflows and outflows into the system and each value is shown in Table 6.9 and the large discrepancy between the input and output value estimates highlights the large data gaps in the assessment. This should not be assumed to represent actual water balance until further research is conducted to provide more certainty about water fluxes through the system.

Table 6.9 Regional water balance assessment of the Maryborough Basin.

Input description	Input value estimate (ML/year)	Output description	Output value estimate (ML/year)
Precipitation	10 465	(7) Evapotranspiration	(Min = 3321.5, Max = 13 650) 8485.75
Infiltration (recharge to Elliott Aquifer)	18.2	(8) Groundwater discharge to sea	*Unknown*
Surface water inflow	*Unknown*	(9) Groundwater discharge onshore	*Unknown*
Throughflow from outside basin	0	(10) Surface water discharge to sea	*Unknown*
Vertical leakage/down-flow to deep aquifers	*Unknown*	(11) Groundwater extraction	29,023
Upward flow from deep aquifers	*Unknown*	(12) Surface water extraction	277,145
Total (as based on currently incomplete data)	10,483		314,654

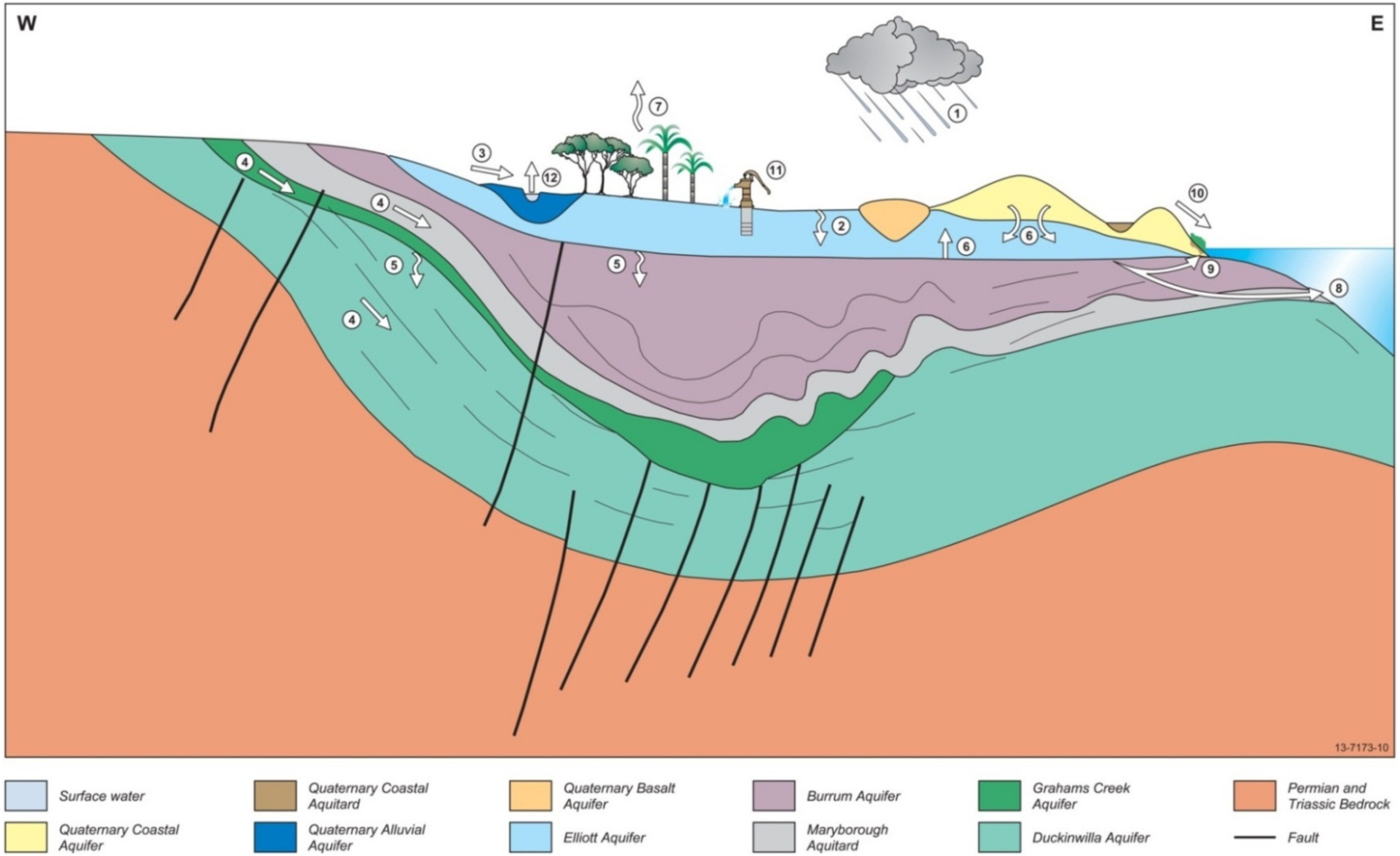

Figure 6.12 Conceptual model for the Maryborough Basin, showing components of the regional water balance.

(1) precipitation; (2) direct recharge from precipitation via infiltration; (3) surface water inflow; (4) groundwater inflow; (5) vertical recharge/leakage from shallower aquifers into deeper aquifers; (6) upflow from deeper aquifers; (7) evapotranspiration; (8) groundwater discharge to the sea; (9) groundwater discharge onshore (such as into a wetland); surface water discharge to the sea; (11) groundwater extraction; and (12) surface water extraction.

Recharge via surface infiltration and leakage from overlying or underlying aquifers is the major inflow into each aquifer. The loss, or outflow, of water includes evapotranspiration, groundwater discharge to the sea, groundwater discharge onshore, surface water discharge to the sea and groundwater extraction. Each component of the water balance is shown in Figure 6.12, and an explanation of derived inflow and outflow values is outlined below:

- Precipitation is approximately 1,100 m/year over the 9,100 km^2 basin (see Table 3.2). This was converted to a volume unit of water (10,465 ML/year).
- The estimate of infiltration was derived from an estimate of 2 mm of recharge across the basin into the uppermost aquifer (AustralAsian Resource Consultants (AARC) 2011). Due to the high rainfall rates (Figure 3.5), infiltration may be greater than this, but the value is incorporated as it is the only known (derived) estimate.
- An accurate estimate of surface water inflow is unavailable for the basin. Although stream-flow data is available from two stations in the basin, it is unknown how much surface water is being introduced from outside the basin margins.
- Throughflow from outside the basin is minimal, as the Mesozoic aquifers are juxtaposed against Gympie Block basement rocks of very low hydraulic conductivity.
- Vertical leakage and down-flow volumes to deeper aquifers are unknown, and therefore the regional water balance is only able to be estimated for the upper (Elliott) aquifer, rather than the entire hydrostratigraphic succession.
- Upward flow from deep aquifers was also unable to be estimated, although it was suggested that there is an upwards hydraulic gradient from the Burrum Aquifer into the Elliott Aquifer in parts (AustralAsian Resource Consultants (AARC) 2011). This is only likely to contribute a relatively small amount of water to the Elliott Aquifer.
- Potential ET was estimated from Bureau of Meteorology (2012) data (see Section 3.3). However, Actual ET varies considerably depending on land use (and vegetation) type, and a more detailed assessment that takes this into consideration is required for further studies.
- In areas of intense agricultural activity, irrigation-derived recharge (for example, via processes such as rootzone drainage and irrigated area losses, is likely to be an important factor to consider in assessing recharge volume estimates. However, there are no data available to address the magnitude of irrigation recharge in the Maryborough Basin.
- No data are available for an estimation of groundwater discharge to sea.
- No data are available for an estimation of groundwater discharge onshore, such as in springs, wetlands and other surface water expressions of groundwater.
- No data are available for an estimation of surface water discharge to the sea.
- Groundwater extraction data is available for the Bundaberg GMU only, so it is likely to be an underestimate of the entire basin groundwater use (National Water Commission 2005).
- Surface water extraction data were obtained from DSEWPaC (2010), see Section 3.5.5 for more information.

Data from hydrogeological and geological investigations has been included in the table, where possible. It can be seen, however, that there were limited data available.

The current totals of input and output water into the system are imprecise and incomplete and no weight should be given to them in regards to water planning. This is because there is not enough information available to provide a more comprehensive and reliable assessment. The water balance still, however, shows the importance for accurate measurement and monitoring of both natural processes (such as streamflow) and anthropogenic use (such as groundwater extraction and irrigation input). It is very useful for highlighting the data gaps, large uncertainties in the estimates, and areas to be targeted in future work. The water balance assessment also relied on key assumptions, including the:

- Elliott Aquifer is continuous over the area
- Rivers are constantly flowing
- Deeper formations outcrop, and provide the main recharge point for deeper aquifers.

Particular exceptions where the water balance may vary from the basin average are:

- Particularly high extraction levels associated with irrigation
- Particularly high Actual ET associated with state forests
- Areas where the Burrum Aquifer has been exposed
- Where (potential) CSG extraction increases extraction from the Burrum Aquifer.

7 Data and knowledge gaps

There are significant data and knowledge gaps that have influenced the degree of certainty that can be placed on the hydrogeological conceptualisation presented here for the Maryborough Basin. This is particularly affected by the lack of previous regional-scale hydrogeological assessments, and the focus of most previous work on the shallower aquifers. There is also spatially limited stratigraphic and geophysical data available that could be used (for this study) to improve definition of key groundwater parameters and processes for much of the basin hydrostratigraphy. Additional data are thus required to undertake a more rigorous and quantitative assessment of the Maryborough Basin’s groundwater system, which would be especially important to better understand any water-related impacts from future coal or CSG developments. Furthermore, additional interpretation of existing data is also required, such as through the analyses of observation bore locations and bore hydrograph trends.

The most important data and knowledge gaps identified from this investigation are:

1. The need for more widespread and detailed information on the thickness, continuity and hydraulic parameters of the main aquifers (and aquitards). There has been only limited hydraulic testing of aquifers to characterise hydraulic properties. In particular, characteristics of the deep aquifers are currently poorly understood.
2. Hydraulic head measurements are sporadic and span many decades, and have not been part of a well-coordinated basin-wide monitoring programme.
3. There are limited bore construction records. These are required to assign hydraulic head values or groundwater chemistry data to specific aquifers. Bores have generally not been drilled and constructed for the specific purpose of groundwater monitoring of targeted aquifers.
4. Limited stream gauging data exists to support base flow analyses, as there are only two gauging stations within the Maryborough Basin.
5. There are no nested groundwater piezometers installed in the basin to understand inter-aquifer connectivity and the magnitude and direction of groundwater flow between aquifers.
6. More information about GDEs in the basin is required. This may include integrated field studies following remote assessment (i.e., using satellite data).
7. There is only limited information on the location, orientation and role of faults and other geological structures, especially their role impact on the regional groundwater systems. Faults can act as both conduits and barriers to groundwater flow, and thus it is important that field-based data is available to improve assessment of structural systems in the basin.
8. The extent, magnitude and focus of submarine groundwater discharge in the offshore basin are unknown. This may impact offshore ecosystems or Fraser Island (and potentially the Great Barrier Reef).
9. There is no regional water quality assessment for the basin. This includes the groundwater concentration of major and minor elements, salinity, alkalinity and pH in different aquifers and surface water bodies. Time-series chemistry data would also be very useful to better understand temporal trends or characteristics.

10. There have been no basin-scale recharge studies to identify volumes and mechanisms of recharge into each aquifer.
11. There are only a few studies within the Maryborough Basin to understand the connectivity between surface water and groundwater systems. None of these consider the regional scale of the basin. This is important for understanding how increased extraction from aquifers will impact surface water flow and vice versa.
12. The distribution of the Burrum Coal Measures is not well-understood across some parts of the basin. The extent of the deeper Tiaro Coal Measures is particularly poorly understood. Currently, the Tiaro Coal Measures are mapped as outcropping on the surface of the basin and have also been identified in shallow drill core. However, recent reclassification of the basin stratigraphy by the GSQ indicates that they the Tiaro Coal Measures are part of the underlying Northern Nambour Basin. This confusion should be resolved to improve the stratigraphic definition of the Maryborough Basin.
13. Water volume estimates required for use in regional water balance assessments are poorly constrained.
14. Evapotranspiration variation across the basin according to land cover type has not been characterised.

8 Conclusions

This project has undertaken an analysis of existing datasets and literature to develop a basin-scale understanding of regional and local groundwater systems. A new hydrostratigraphic framework was developed for the Maryborough Basin, which enables the identification of the main aquifers and confining units. CSG extraction and coal mining activities have also been assessed to understand likely future impacts of these activities on regional groundwater resources.

8.1 Groundwater resource issues

Currently, the major issue for the Maryborough Basin is characterising the size and distribution of aquifers and aquitards. A detailed conceptual model for the Bundaberg area only has previously been conducted and there are only sporadic bore holes with stratigraphic information located in the remainder of the basin. Conceptualisation and groundwater studies previously have focused mainly on the upper 100 m, describing only the Elliott Aquifer and Burrum Aquifer. To manage potential impact of coal and coal seam gas resource issues on groundwater, it is imperative that future conceptualisation of the system also includes deeper stratigraphic units.

The Burrum Coal Measures is a target for coal mining and CSG exploration, but it is also an important aquifer. Extraction of groundwater from the Burrum Coal Measures associated with CSG extraction may impact groundwater levels within the Burrum Aquifer and could result in reduction of supply for users of this groundwater resource.

Over-extraction and pumping is also a potential groundwater issue for the basin. A large amount of groundwater is required to support irrigation requirements, particularly for the sugar cane industry. The Elliott Aquifer is the major aquifer for the basin and is relatively thin thus does not have a high storage capacity. It receives most of its recharge directly during summer months from rainfall infiltration. This makes it particularly susceptible to impacts during periods of low rainfall.

A key issue related to water resources is to develop a better understanding of connectivity between different aquifers. As all aquifers are lithologically heterogeneous, there is likely to be a complex relationship between aquifers and distinct aquitards, which may also translate to complex hydraulic systems and groundwater flow patterns. Potential issues with de-pressuring coal seams are unable to be simply modelled or predicted because of sub-surface variability.

Salinity is a potential issue for groundwater in the basin. Although some of the basin contains reasonably fresh groundwater, areas that are not highly permeable and receive less recharge have greater salinities. Salinisation of groundwater during periods of low recharge or high extraction is possible. This is especially an issue along the highly tidal coastline. Seawater intrusion has already been identified as an issue for parts of the basin and is accelerated along conduits of high permeability, such as paleochannels in the Elliott Aquifer.

High extraction rates that may occur as a result of increased CSG or coal mining in the basin could have an impact on groundwater systems. There is likely to be connectivity between the Burrum Coal Measures and the Elliott Aquifer due to the high number of faults in the basin and the absence of any regional aquitard overlying the Burrum Coal Measures. If large amounts of groundwater are extracted from the Burrum Coal Measures during the extraction of CSG or during dewatering of a coal mine, this could cause a lowering of hydraulic head in the Elliott Aquifer. This may decrease the capacity of stock and domestic bores to extract groundwater in the vicinity of such developments.

There are many GDEs in the Maryborough Basin. Groundwater extraction as a result of CSG or coal mining may decrease the supply of water supporting the ecosystems; potentially impacting native flora and fauna.

Connectivity between groundwater and surface water systems has not been extensively studied. In some parts of the basin, connectivity is likely. This means that decreased hydraulic heads (e.g., of the watertable) due to CSG extraction or coal mining may result in decreased surface water flows. There are significant ecosystems, wetlands, important bird areas and national parks (particularly along the coast) supported by surface water systems which may be influenced by a reduction in surface water flow or fresh water discharge to the coast.

Increased groundwater extraction of groundwater may impact freshwater discharge to the coast. There is currently no known estimate or information about where freshwater is discharging offshore. However, such discharge may have ecological or environmental significance.

The area is environmentally significant. There are numerous national parks, threatened species, DIWA areas, IBAs and the World Heritage Listed Fraser Island. The World Heritage Listed Great Barrier Reef also lies not far from the coastline. The broad coverage of GDE across the basin shows that the native environment strongly relies on groundwater. Thus, any future impacts on groundwater quality and quantity associated with coal or CSG extraction could have significant impacts on the environment.

The Maryborough region also has a high (and growing) population. Many industries in the area rely heavily on water, particularly the sugar cane industry, production forestry, cattle, and tourism. For this reason, any impact on groundwater quality and quality will have significant impacts on the wider community within the basin.

Table 8.1 Summary of current knowledge and key data gaps and uncertainties for the Maryborough Basin groundwater system.

	State of current knowledge and conceptual understanding	Main data gaps and uncertainties
Hydro-stratigraphy	Coarse understanding of hydrostratigraphy exists and the basin is divided into seven aquifers including: Quaternary Coastal Aquifer; Quaternary Alluvial Aquifer; Quaternary Basalt Aquifer; Elliott Aquifer; Burrum Aquifer; Grahams Creek Aquifer; and the Duckinwilla Aquifer. There are two aquitards and these are the Quaternary Coastal Aquitard and the Maryborough Aquitard.	Definition of productive water-bearing zones within hydrostratigraphic units. The hydrostratigraphy of the Burrum Aquifer in particular should be further refined. The Duckinwilla Aquifer may need to be excluded from the hydrostratigraphy (based on the re-classification of the Duckinwilla Group as occurring within the Northern Nambour Basin). If not, it also may need to be divided to differentiate between the Tiaro Coal Measures and the underlying Myrtle Creek Sandstone.
Aquifer properties	Some information exists for the upper Elliott Aquifer and Burrum Aquifer but there is no data for the remaining five aquifers. The Elliott Aquifer has a hydraulic conductivity of ~290 m/day, storativity of 6×10^{-6} to 6 % and specific yield of 5 to14.2 %. The Burrum Aquifer has a hydraulic conductivity of 0.004 to 45.7 m/day, a specific storage of 1×10^{-5} to 1×10^{-4}, and a specific yield of 0.1 to 5%.	Testing of all aquifers is required to improve knowledge of hydraulic parameters.
Conceptual boundaries	The western and northern basin margin is well defined by the Electra Fault System.	A large amount of work is required to characterise the lower boundary of the basin and to distinguish between the Northern Nambour Basin and Maryborough Basin. The offshore extent of the basin is still poorly understood, as is the southern margin.
System stresses	Key stresses include: groundwater extraction from agriculture; potential seawater intrusion at the coastal margin.	Increased extraction as a result of coal and CSG extraction is a potential future stress and the impact of this is unknown. Current groundwater extraction amounts for the entire basin (outside the Bundaberg area) are poorly understood.
Recharge	Recharge predominantly occurs via infiltration of rainfall directly into the uppermost aquifer. Recharge into deeper aquifers occurs at the western basin margins.	Rates and exact mechanisms for recharge are unknown. Recharge via downward leakage is poorly understood.
Hydrodynamic flow	There are likely to be local-scale flow systems operating within the Quaternary Coastal Aquifer; Quaternary Alluvial Aquifer and the Quaternary Basalt Aquifer. Regional flow is likely in the Elliott Aquifer, Burrum Aquifer, Grahams Creek Aquifer and the Duckinwilla Aquifer.	Little is known about hydrodynamic flow, including within and between aquifers.
Discharge	Discharge mechanisms and rates are poorly understood.	Further work is required to define rates and volumes of evapotranspiration (and how it varies across the basin); submarine discharge, and groundwater discharge onshore (including the interaction with GDEs).

8.2 Energy resource issues

Currently, most of the basin is covered by coal or petroleum exploration tenements and there is potential for future coal and CSG extraction. Coal and methane extracted previously from the basin during exploration is relatively shallow and generally of good quality. The location of the basin near infrastructure and export facilities also makes the region a particularly viable economic target.

Previously, the area that has been most extensively explored for coal and CSG is the Burrum Syncline in the south of the Maryborough Basin. The Burrum Coal Measures outcrop here and have been eroded away from anticlinal structures in the basin. Exploration has previously focused on areas where the coal measures outcrop and where small-scale onshore seismic studies have occurred. The Burrum Coal Measures have also been identified in core logs to be underlying the Elliott Formation in the north of the basin; thus, it is possible that exploration may focus more broadly in other areas into the future. The area of the Burrum Syncline is still likely to be a focus of exploration but currently there is no GMU or groundwater management strategy for this area, and thus there is limited information about local extraction volumes and groundwater levels.

Coal and CSG extraction may affect regional groundwater flow systems, particularly in the Burrum Aquifer and the Elliott Aquifer but are less likely to affect local flow systems, such as of the Quaternary Basalt Aquifer and the Quaternary Coastal Aquifer.

The disposal of co-produced and mine dewatering water is potentially an energy resource issue that may arise if future CSG and coal mining developments are progressed in the basin. There are many significant ecosystems, national parks, wetlands, important bird areas and surface water systems that could be affected by an introduction of saline or low-quality water derived from coal seams. Surface water storage of co-produced water is an issue because the basin is commonly affected by flooding and high rainfall that may potentially disrupt uncovered surface storages.

Subsidence in the basin could also become an issue if significant volumes of groundwater are extracted during CSG extraction. Once water is extracted from coal seams, compaction may occur and it is difficult to reintroduce porosity. Consequently, any future developments should also consider establishing adequate monitoring programs to detect subsidence.

9 Potential future work

The regional hydrogeological understanding of the Maryborough Basin is currently at the initial conceptual stage. This report provides a summary of current knowledge and a new hydrostratigraphic framework to be built upon by successive studies. A large amount of data collection and analysis preferably spanning multiple seasons for transient data is required to gain an improved understanding of the Maryborough Basin groundwater systems and determine, with confidence, how they may be impacted by any future coal mining and/or CSG extraction. Potential future work to improve regional understanding of the groundwater systems of the Maryborough Basin are as follows.

Build on and better clarify the hydrostratigraphic framework

This is extremely important to improve understanding of the distribution of aquifers within the stratigraphy. Key aquifer and aquitard characteristics including their depths, thicknesses, spatial variation and hydraulic properties could be investigated. This could initially be conducted by fully digitising all available stratigraphic information, and incorporating the digital outputs into a 3D conceptual model of the basin. New data could be collected through deep drilling and installation of a network of nested monitoring bores across the basin. Aquifer characterisation studies (e.g., pump testing) would improve the understanding of hydrodynamic flow and connectivity. Basin-scale correlation of drill logs would also assist in the identification of additional aquitards and groundwater flow barriers that may not yet be recognised.

Apply geochemical studies to improve groundwater system characterisation

To appreciate the hydrodynamics of the groundwater system (based on an improved hydrostratigraphic framework), geochemical studies could be used to determine the age and flow of groundwater in different aquifers; likely recharge mechanisms; connectivity between aquifers and the integrity of aquitards; surface water–groundwater connectivity; and the quality of the groundwater.

Better characterise basin structure to improve understanding of regional and local flow regimes

Geophysical methods provide a useful tool to understand the structure of a geological basin. Electro-magnetic (EM) methods can be used particularly to identify aquifers and airborne EM (AEM) surveys would provide a basin-scale dataset to improve spatial definition of key formations. AEM studies would be improved by the addition of new seismic studies across the basin, coupled with re-processing of existing seismic data where available. Drilling or existing well logs should be used to correlate and calibrate geophysical surveys. Key questions include: the extent and thickness of the hydrostratigraphic units (using the new regional hydrogeology map as a starting point for aquifer extents); coal seam extent and distribution; depth to the underlying basement and variations in this depth at the regional-scale; characterisation of basin faults and folds; and the distribution of paleochannels across the basin.

Improve groundwater monitoring and assessment

Reliable and regular groundwater monitoring and water balance assessments should be spread further across the entire basin than currently occurs, rather than being focused on only a few areas. The primary area for coal and CSG exploration is not currently within a GMU. Other suggestions to improve groundwater management in the Maryborough Basin include: the development of a basin-scale hydrogeological 3D model; improvement of the current regional water balance (requiring the collection of new data); improvement of the bore monitoring network that includes spatial coverage across the basin and nested piezometers to measure groundwater at varying depths; conjunctive surface water–groundwater management practices; modelling of the cumulative impact of coal mines and CSG operations; and a comprehensive plan to address disposal of co-produced water (should future developments occur).

For effective groundwater management practices, the regional water balance assessment of the basin requires additional data. Particular data required includes: groundwater and surface water extraction estimates across the whole basin; surface water flow data (and a quantification of flow from outside the basin); quantities of water supplied from dams and other water storage facilities; data to improve assessment of ET across the basin; and a detailed recharge study to quantify recharge. A study of hydrographs would help to understand recharge processes and surface water–groundwater connectivity.

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Glossary

AEM. See Airborne Electromagnetic.

AHD. Australian Height Datum.

Airborne Electromagnetics (AEM). A geophysical survey method that measures the electromagnetic properties of a rock. Electric conductivity and magnetic susceptibility are calculated, and because these properties vary depending on the nature of the rock, water saturation, salinity and other parameters, the resultant maps are used for estimation of the nature of underground rock formations, ground water, contamination and other geological and environmental changes.

Airborne radiometrics. See radiometrics.

Alluvial/alluvium. Non-marine sediments deposited by the action of water.

Alluvial terrace. A deposit of alluvial sediment related to an existing river but found at a higher level in the landscape than that presently being deposited. Alluvial terraces indicate former higher levels of river action.

Anticline. An arch shaped fold of originally flat lying sedimentary layers.

Aquiclude. A rock or sediment whose very low hydraulic conductivity makes it almost impermeable to groundwater flow (even though it may be saturated with groundwater). It limits an aquifer, and may form confining strata.

Aquifer. A geological formation, group of formations or part of a formation which is sufficiently porous and permeable to store, and allow the movement of, groundwater. Aquifers may yield quantities of groundwater for consumptive use.

Aquitard. Saturated geological unit that can store large volumes of water but cannot transmit significant quantities of water to production wells. Also can be called a ‘confining bed’.

Artificial recharge. The deliberate recharge of aquifers through pumping water into them via bores or increasing surface water infiltration through pits. Also known as managed aquifer recharge. Artificial recharge in coastal aquifers may be used to slow, contain, or reverse seawater intrusion. See also aquifer storage and recovery, aquifer storage, transport and recovery and managed aquifer recharge

Architecture. The relationship of different geological units to each other in space. For example, regolith architecture, sedimentary architecture etc.

Basalt. A dark volcanic rock rich in iron and magnesium.

Basin. A large depression in the Earth’s crust filled by sedimentary or volcanic rocks.

Basin inversion. The relative uplift of a sedimentary basin to surrounding low lying areas from a variety of tectonic processes.

Basement. Bedrock that underlies the geological materials of interest.

Bed/bedding. Layers/layering of sediments or sedimentary rocks that reflect differences in size, composition or colour of constituent grains.

Bedload. The coarse-grained (sand and gravel) faction of the sediment carried by a river along its bed.

Bedrock. Loose term given to any geological material that underlies the stratum of interest. Bedrock is often composed of crystalline rocks such as granite or metasedimentary rocks.

Bore Yield. The amount of water which can be abstracted from a bore (either by pumping or natural artesian flow) over a specific time interval frame. Bore yields are usually measured in litres per second.

Calcrete. Calcium carbonate ($CaCO_3$) formed in soil or sediments in a semi-arid region under conditions of sparse rainfall and warm temperatures, normally by precipitation of calcium. Calcrete is common in low-lying areas in arid to semi-arid regions, particularly palaeovalleys ('valley calcrete'), and may form aureoles around salt lakes. It is commonly a significant near-surface aquifer in the arid zone.

Carbonate. Refers to CO_3 ions, can be carried in solution in surface water or groundwater and precipitated with Ca, Mg, or Fe ions to form carbonate minerals and rocks.

Catchment. The area of land from which rainwater drains into a river, stream or lake. Catchments are separated from each other by divides or watersheds.

Cemented. The cementation of sedimentary grains by later minerals precipitated from groundwater. Sometimes consolidated is used as an approximate synonym.

Cenozoic. Geological Era extending from 65.5 million years ago to the present.

Clast. A rock fragment or grain resulting from the breakdown of larger rocks.

Clay. Refers to either grain size or mineralogy. (a) An earthy sediment composed of rock or mineral fragments or detrital particles smaller than a very fine silt grain; (b) clay minerals are hydrous aluminium silicates derived largely from feldspars, micas and carbonate by weathering.

Colluvial. Gravity depositional processes found in slope depositional environments forming colluvium.

Colluvium. See colluvial.

Conceptual model. See model.

Confined Aquifer. An aquifer that is overlain and underlain by impervious layers (aquitards), and is not associated with the water table.

Conjunctive Water Use. Coordinated management of surface-water and groundwater resources.

Conglomerate. A sedimentary deposit formed by cementing gravels and cobbles together with minerals precipitated from groundwater.

Consolidated. See *cemented.*

Core/coring. Drilling method that recovers intact samples of subsurface materials.

Delta. A more or less triangular (similar to the Greek letter delta) deposit of sediment built up where a river flows into the sea. Deltas can be river, tide, or wave dominated, depending on which is the most important deposition process acting along the coastline.

DEMs. See *Digital Elevation Models.*

Digital Elevation Models (DEMs). Digital representations of the topography of the earth that are important components of geographic information systems (GIS). DEMs are obtained by many systems, including ground surveying, airborne radar and laser surveys, or from satellite radar.

Discharge (Groundwater). The flow of groundwater to surface water, bores, between aquifers or the sea.

Discharge (Stream). Amount of water flowing in the stream.

Discharge zone. An area in which subsurface water is discharged to the land surface; in the arid zone it is where evaporite minerals (salts) precipitate as the water evaporates to the atmosphere. See also spring.

Distributary. A stream that branches off and flows away from a main stream channel.

Drawdown. Water table lowering.

Duricrust. A hardened layer formed in the regolith by cementation of soil or sediment, generally by minerals rich in iron, sulfate, silica, or carbonate.

Electrical conductivity (EC). The ability of electrical current to pass through a substance. EC is commonly used to estimate the amount of soluble salt in solution. EC measurements can be made with a range of devices on ground and stream water, soils, and soil-paste extracts. Units of electrical conductivity are commonly given in mS/m, dS/m or μS/cm; 100 mS/m = 1 dS/m = 1000 μS/cm. Here, S is the symbol for siemens, and the prefixes d is deci (10^{-1}), c is centi (10^{-2}), m is milli (10^{-3}) and μ is micro (10^{-6}).

Electromagnetic (EM). Comprised of a time-varying electrical and magnetic field. Radio waves are common electromagnetic fields. In geophysics, an electromagnetic system is one which transmits a time-varying primary field to induce eddy currents in the ground, and then measures the secondary field emitted by those eddy currents.

Ephemeral. Watercourses that are active for only a short period of time.

Evapotranspiration. The total water loss from the soil through the combined effects of evaporation and transpiration.

Extensional fault. A normal fault characterised by vertical movement on an inclined plane that vertically thins and horizontally extends portions of the Earth's crust. In normal faults the hanging wall (rock above the fault plane) moves downward relative to the footwall (rock below the fault plane).

Fault. Fracture in a rock body along which displacement has occurred.

Fault Scarp. A break slope in at the earth surface caused by relative uplift along a fault.

Ferricrete. An iron-rich duricrust.

Fracture. Cracks in indurated rocks formed by stress and strain. Fractures along which significant movement has occurred are called faults.

Freshwater lens. A lens-shaped body of less dense fresh water floating on top of denser saline water in an unconfined coastal aquifer. See *Ghyben-Herzberg lens*.

Floodplain. A low-lying area adjacent to a river or stream subject to inundation when that stream floods. Floodplains are often sites of deposition of fine-grained sediments.

Fluvial. River depositional environment.

Fractured Rock Aquifer. Aquifers which store groundwater in the fractures, joints, bedding planes and cavities of the rock mass.

Freshwater lens. A lens-shaped body of less dense fresh water floating on top of denser saline water in an unconfined coastal aquifer. See Ghyben-Herzberg lens.

Gaining Stream. A stream or river-reach into which groundwater flows via the stream bed and/or banks.

Geographical Information Systems (GIS). GIS are computer-based systems for creating, storing, analysing and managing multiple layers of spatial data. These datasets include maps of geology, topography, infrastructure, soils, vegetation, and land use. GIS allow users to create interactive queries to analyse trends and patterns in spatial information.

Geomorphology. The study of landforms.

Geophysics. The study of the Earth by quantitative physical methods, such as magnetics, electromagnetics, gamma ray spectrometry (radiometrics), seismology and gravity.

Gigalitre (GL). 1000 megalitres.

GIS. See Geographical Information Systems.

Granite. A coarse-grained igneous rock consisting mainly of quartz and feldspar.

Graben. A depressed or down-thrown block bounded on at least two sides by faults. See also half graben.

Groundwater. Water stored below ground within the pore spaces or fractures of a rock mass.

Groundwater Management Unit. A hydraulically connected groundwater system that is defined and recognised by State and Territory agencies for management purposes.

Groundwater models. Simulate natural groundwater flow or other groundwater characteristics. Numerical groundwater models compute mathematical equations of the physics of groundwater flow processes.

Head. A measurement of water pressure representing the total energy at the entrance of a piezometer. Usually measured as a water surface elevation. Differences in Head between two or more points can be used to determine hydraulic gradient and direction of groundwater flow. Synonymous with Hydraulic Head.

Holocene. Most recent Geological Epoch extending from 12,000 years ago to the present.

Hydraulic conductivity (K). Hydraulic conductivity is the volume of water flowing through a 1 m^2 cross-sectional area of an aquifer under a hydraulic gradient of 1 m/1 m (100%) in a given time (usually 1 day).

Hydraulic gradient. With regard to an aquifer, the rate of change of hydraulic head per unit of distance of flow at a given point and in a given direction.

Hydraulic head. The hydraulic head (or potentiometric head) is the height of the watertable above a given datum in an unconfined aquifer (representing the zone of saturated aquifer), and is the potential energy in a confined aquifer above a given datum.

Hydrogeology. The study of geological properties of rocks, soils, and sediments as they relate to groundwater movement and storage.

Hydrograph (Bore). Graphical representation showing the variation in time in the groundwater level within a bore.

Hydrostratigraphy. The identification of mappable stratigraphic units on the basis of hydraulic properties (aquifer / aquitard).

Igneous. Applied to one of three main groups of rock types (igneous, metamorphic and sedimentary), to describe those rocks that have crystallised from molten rock (magma). Examples include basalt, dolerite and granite.

Kilolitre (kL). 1000 litres (equivalent to one cubic metre. m^3)

Lacustrine. Depositional environments or sediments associated with lakes.

Lithology. Physical characteristics of a rock or sediment.

Losing Stream. A stream or river reach where the stream bed leaks surface water to an underlying aquifer.

Mafic. Describes dark-coloured igneous rocks that are rich in iron and magnesium.

Megalitre. 1,000,000 litres (ML).

Model. Used in two senses in this report. hydrological models are based on mathematical equations that allow the behaviour of a hydrologic system to be quantitatively predicted; conceptual models are qualitative descriptions of features such as aquifers or coastal landforms.

NRM. Natural Resource Management.

Orogeny, Orogenesis. The forces and events that lead to the deformation of the Earth’s lithosphere (crust and upper mantle) resulting in the formation of mountains.

Paleo-. Prefix meaning old or ancient often now-defunct.

Paleochannels. Former river channels that are recognised in the surface (from aerial or satellite images) or subsurface (typically in *AEM* surveys or drilling).

Permeability. The ability of a material, such as rock or sediment, to allow the passage of a liquid, such as water. Permeable gravel and sand, allow free movement, whereas impermeable clays are barriers.

Piezometer. A bore used specifically to monitor water levels or hydraulic head within an aquifer.

Pleistocene. Geological Epoch extending from 2.5 million to 12 thousand years ago.

Pliocene. Geological Epoch extending from 5.3 to 2.5 million years ago.

Porosity. Open spaces in rocks and sediments that can hold water. *Primary porosity* formed when the sediments were laid down; these spaces may be variably infilled by *cement*, leaving remnant primary porosity. *Secondary porosity* forms through modification of rocks, such as by dissolution of soluble grains, formation of *fractures*, or solution-forming *karst.*

Potentiometric head. See hydraulic head.

Potentiometric surface. A surface which represents the hypothetical level that water under pressure, within a confined aquifer, would rise to if tapped by a bore.

Proterozoic. A geological era that encompasses the time between 2500 and 545 million years ago. The Proterozoic is formally divided into the Paleoproterozoic (2500 to 1600 million years), Mesoproterozoic (1600 to 1000 million years), and Neoproterozoic (1000 to 545 million years).

Porosity. A measure of the water-bearing capacity of an aquifer and water movement depends on both the size and interconnectivity of voids.

Pump Test. A hydrological assessment; undertaken when an aquifer is 'stressed' by pumping or injecting water and noting the water drawdown level over space and time.

Quaternary. Geological Period extending from 2.5 million years ago to the present.

Quartz. A very common mineral consisting of silicon dioxide that commonly occurs in river sands and as the main mineral in sandstones.

Radiometrics. The collection of information of the distribution of naturally occurring uranium, thorium and radioactive potassium from their emitted gamma radiation, usually from an aircraft. Radiometric data is normally plotted as three colour images with a different colour for each element. Radiometric data is typically reviewed as part of a GIS and is very useful in the mapping of soil types and salinity outbreaks and is able to see through vegetation and crops to a large extent. Also known as airborne radiometrics.

Recharge. The process by which water is added to an aquifer.

Regolith. The entire unconsolidated or secondarily re-cemented cover that overlies more coherent bedrock, between fresh rock and fresh air, that has been formed by weathering, erosion, transport and/or deposition of the older material. Includes *weathered* rocks, soils, shallow groundwater and sediments.

Resistivity (ρ). The strength with which the earth or a geological formation resists the flow of electricity, typically the flow induced by the primary field of the electromagnetic transmitter. Normally expressed in ohm-metres, it is the reciprocal of conductivity.

Runoff. Overland flow and steam flow of rainfall not absorbed by the soil.

Salinity ranges. The following ranges are typically used when discussing groundwater salinity. <1000 mg/L TDS = fresh water, 1001 to 10,000 mg/L = brackish water, 10,001 to 35,000 mg/L = saline water, >35,000 mg/L = hypersaline water.

Seawater intrusion. The landward movement of seawater into coastal aquifers, due to natural or human-related changes in groundwater dynamics.

Sedimentary. Pertaining to deposition of sediments and sedimentary process, for example, a sedimentary rock is a rock once composed of sediments such as sand, gravel, silt, etc.

Semi-confined aquifer. An aquifer which is partly overlain and completely underlain by impervious layers.

Shale. A *sedimentary* rock composed of clay particles.

Stratigraphy. The study of how different layers of sediments can be related to each other.

Subduction the downward movement of a tectonic plate under another resulting from the convergence of the two plates. Considered a force in orogenies.

Sustainable yield. The level of groundwater extraction measured over a specified planning timeframe that would, if exceeded, compromise key environmental assets, ecosystem functions or the productive base of the resource associated with the aquifer. Also referred to as the environmentally sustainable level of extraction.

Tectonics. The study of structures in the Earth's crust and the processes that form them, such as earthquakes.

Transpiration. Water given off by plants via pores in the surface tissues. See also evapotranspiration.

Transmissivity (T). The capacity of a rock to transmit water under pressure. Expressed as the volume of water flowing through a cross-sectional area of an aquifer that is 1m x the aquifer thickness under a hydraulic gradient of 100% in a given amount of time (usually 1 day). Transmissivity is equal to the hydraulic conductivity (K) times the aquifer thickness.

Unconfined aquifer. A type of aquifer in which the upper boundary is defined by the water table. Unconfined aquifers are recharged directly from the ground surface.

Unconformity. A *bounding surface* where the rocks below rest at a different angle to those above, for example, where alluvial gravels rest on bedrock.

Unconsolidated. See *uncemented.*

Vertical Infiltration. Downward movement of water from the surface into soil or sediment.

Volcanic. Processes and materials (such as ash and lava) produced by volcanic activity.

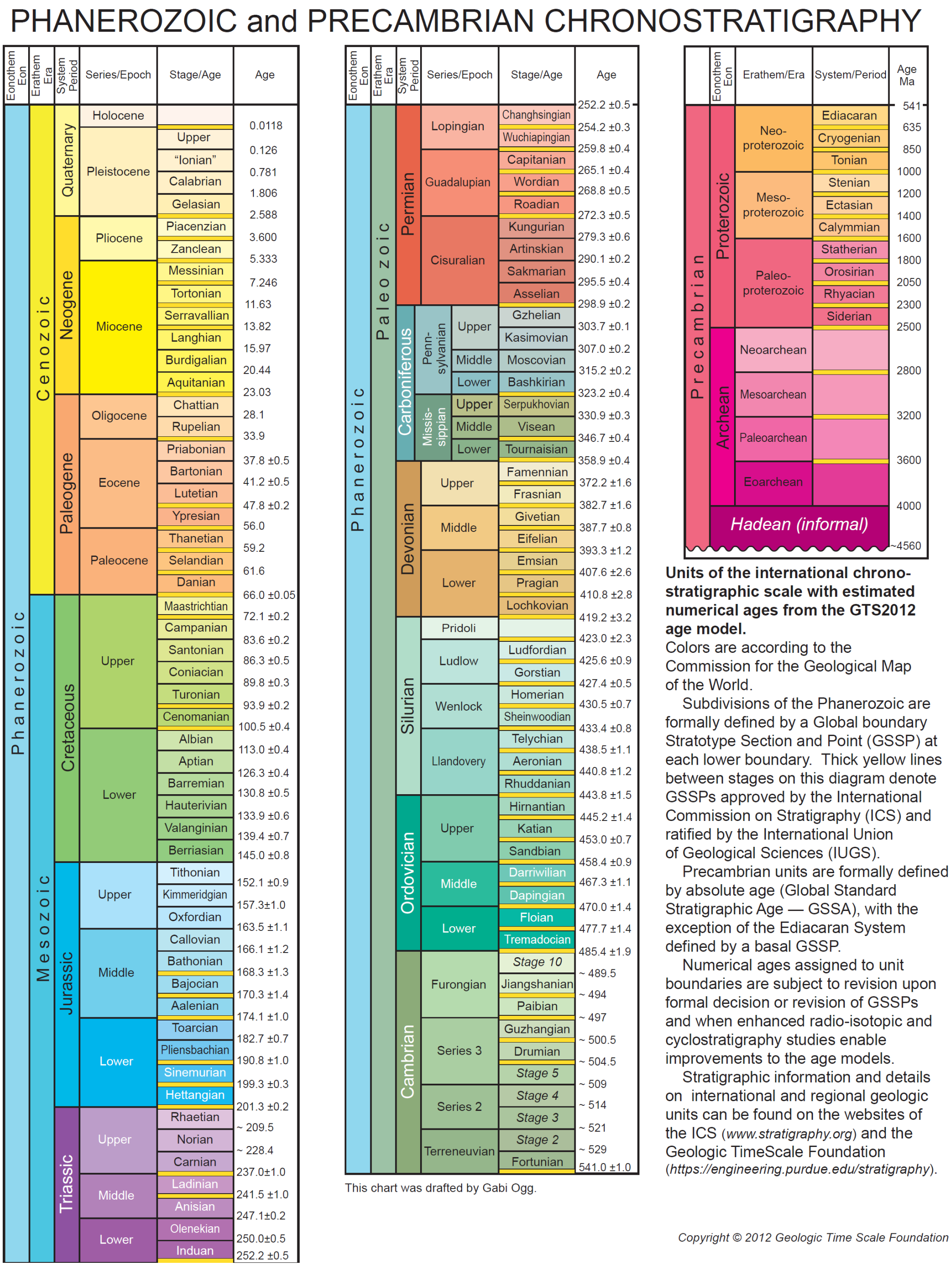
Watertable. The surface below which an unconfined aquifer is saturated with water. See also potentiometric surface.

Weathered/weathering. The physical and chemical changes that a rock undergoes when it is exposed to the atmosphere and shallow groundwater.

Wetlands. Low-lying areas subject to partial or continuous inundation. Also called swamps.

Appendix A Geological timescale

This appendix contains a reproduction of the current Geological Timescale (GTS 2012; Gradstein et al. 2012).



Appendix Figure A.1 Geological Timescale showing the international chronostratigraphic scale (Gradstein et al. 2012)

Appendix B Legislation and policy impacting hydrogeology and management in Queensland

In Queensland, a 'groundwater area' is an area identified in the Water Regulation 2002 to manage groundwater resources in a particular area. They may be referred to as groundwater management areas, management areas, management units or sub-artesian management areas, but all be referred to generically as 'groundwater areas' (Department of Natural Resources and Mines 2013). In these areas, authorisation is required to access groundwater and/or construct works to extract groundwater.

In 1970, the Bundaberg Subartesian Area (BSA) was defined and included arrangements to license and meter all production bores and introduce an announced allocation regime. The Bundaberg Irrigation Scheme was implemented between 1976 and 1992, which provided surface water entitlements intended to replace and supplement existing groundwater entitlements. In 2000, the primary water resource management tool for the Maryborough Basin was introduced, known as the Burnett Water Resource Plan (Burnett WRP). Amendments were made in 2007 and a single, integrated surface water-groundwater resource known as the Coastal Burnett Groundwater Management Area (CBGMA) was the focus of water management. Currently, water resource planning processes occur for the entire CBGMA and are focused on: controlling seawater intrusion; sustainable use of groundwater; and groundwater entitlement specifications (Heidke, Carruthers et al. 2010).

The *Water Act 2000* has influenced water resource planning and management in Queensland significantly. It requires the consideration of sustainable water management and allocation to ensure that Queensland's future water requirements are met. This includes the consideration of water required to protect natural ecosystems.

Water Resource Plans (WRP) detail the social, economic and environmental aims for a catchment. Resource Operation Plans (ROP) are used to define how these aims will be achieved by specifying management, allocation, trading and monitoring rules.

Two key legislations are the primary controls on water resource management in Queensland. These are the *Water Act 2000* and the *Environmental Protection Act 1994* (EP Act). Subordinate legislation includes:

1. *Water Regulation 2002*
2. Water resource plans
3. Resource operation plans
4. *Environmental Protection (Water) Policy 2007* (EPP Water)

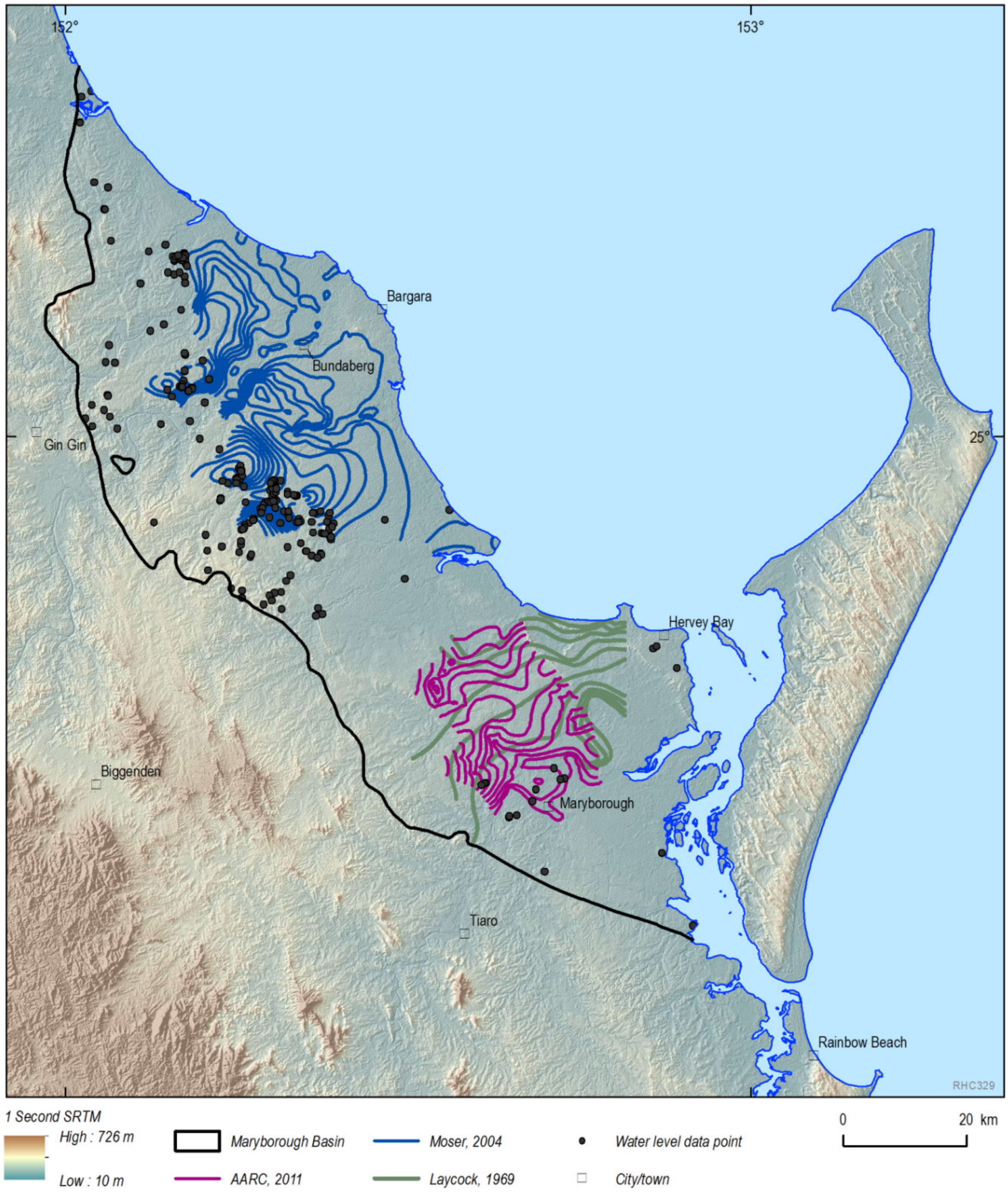
Relevant to the coal seam gas (CSG) industry in Queensland, co-produced CSG water is regulated by several pieces of legislation which, additional to the Water Act and EP Act outlined above, include the:

- *Petroleum and Gas (Production and Safety) Act 2004*
- *State Development and Public Works Organisation Act 1971*
- *Water Supply (Safety and Reliability) Act 2004*

There are specific legislative requirements for managing co-produced CSG water, including salt disposal, and these depend on definition of the co-produced water as either a waste product or a resource under the EP Act. There are requirements under the Water Act to manage groundwater in response to CSG operations (NWC, 2011).

Relevant to coal mines, a licence is required in Queensland for companies to dewater mining operations in areas where groundwater is regulated (NWC, 2011). In some cases there are specific volumetric limits associated with dewatering licences, although it is recognised that such limits can be difficult to accurately determine. General water rights for most mining operations in Queensland are administered under the Water Act.

Appendix C Spatial representation of data input for the formation of the Maryborough Basin watertable contours and flow direction map



Appendix Figure C.1 Data points (Healthy Headwaters Dataset; Department of Natural Resources and Mines, 2012) and previous watertable mapping used as inputs for the formation of watertable contour mapping in the Maryborough Basin