Development of a hydrological modelling toolkit to support sustainable development of the Lower Burdekin groundwater system

Conceptualisation of the Lower Burdekin Aquifer

June 2012

Department of Science, Information Technology, Innovation and the Arts

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June 2012

Preface

Through the Raising National Water Standards Program, the National Water Commission (NWC) provided funding to the former Queensland Department of Environment and Resource Management (DERM) to develop a groundwater modelling toolkit for the aquifers of the Lower Burdekin floodplain. The project is titled "Development of a Lower Burdekin Numerical Groundwater Flow and Solute Transport Model". The project was managed by the Queensland Hydrology Unit of the Environment and Resource Sciences section of the Department.

Prior to completion of the project, the Queensland Hydrology Unit became part of the newly formed Department of Science, Information Technology, Innovation and the Arts (DSITIA). Where relevant, all previous references to DERM have been changed to DSITIA.

This report is part of a series of eleven technical reports produced for the project. The overarching title of all departmentally-produced reports is "Development of a hydrological modelling toolkit to support sustainable development of the Lower Burdekin groundwater system." The full list of reports produced for this project are:

1. Review of modelling methods
2. Conceptualisation of the Lower Burdekin aquifer
3. Groundwater flow modelling of the Lower Burdekin aquifer
4. Instructional solute transport model of the Lower Burdekin aquifer
5. A re-evaluation of groundwater discharge from the Burdekin floodplain aquifers using geochemical tracers
6. Quantification of evapotranspiration in a groundwater dependent ecosystem
7. Geochemical assessment and reactive transport modelling of nitrogen dynamics in the Lower Burdekin coastal plain aquifer
8. Predictive uncertainty of the Lower Burdekin groundwater flow model
9. MODFLOW local grid refinement for the Lower Burdekin aquifer
10. Hydroecology of the Lower Burdekin River alluvial aquifer and associated groundwater dependent ecosystems
11. Pesticides in groundwater in the Lower Burdekin floodplain

All reports were produced by DSITIA, with the exception of:

- Report #5 which was authored by the National Centre for Groundwater Research and Training, Flinders University, Adelaide; and
- Reports #10 and #11 which were completed in March 2012 as DERM reports.

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Executive Summary

A National Water Commission (NWC) project has been initiated to develop an integrated and holistic package of modelling tools to support the decision making process for water management in the Lower Burdekin. The proposed enhancements will promote the level of integration of natural and anthropogenic processes by providing a single modelling framework for data synthesis, informing data acquisition strategies and improving the reliability of model predictions. The outputs of the project, the 'toolkit', will comprise an amalgam of models. These models will incorporate unsaturated zone flow, groundwater flow and solute transport processes to simulate the response of groundwater levels and volumetric flow to a range of recharge and discharge conditions.

The terms of reference propose that the model area will comprise the alluvial aquifers of the coastal Haughton-Burdekin system between Mt Elliott and the Mt Inkerman area. The model area includes areas occupied by the North and South Burdekin Water Board areas and the Burdekin Haughton Water Supply Scheme area.

A preliminary element of model development involves the conceptual understanding of how the groundwater system works. This report details the conceptualisation of the Lower Burdekin groundwater flow system. Data for the conceptualisation process is mostly derived from borehole data held and maintained by the Department. The purpose of the conceptual model is to:

- identify the upper, lower and lateral extents of the flow system,
- define their hydraulic properties,
- identify recharge processes,
- assess the relationships between groundwater and surface water and other parts of the flow system, and
- define the components of the water balance.

This report also provides detail on all data including previous studies and reports, hydrological and hydrogeological framework of the Plan area, water balance for all the main components of the system, and a recommendation of an appropriate approach to the proposed modelling of the aquifer system.

Based on the results of water balance calculations, the following conclusions were made:

- The temporal groundwater storage in Lower Burdekin aquifer derived from the recorded groundwater levels matched well with that calculated based on the individual components of water balance;
- Recharge from rainfall and leaching from irrigation application makes up the majority of the inflow to the aquifer. Seepage from channels and recharge from rivers are also important; Abstraction for irrigation is the largest component of the total outflow;
- During the period from 1981 to 1987, outflow is generally in excess of inflow, so the aquifer loses water. From 1988 to 1991, the outflow is generally less than inflow, so the aquifer gains water. The aquifer is being depleted again in the period 1991 to 1996, but it recovers after 1996 until 2000. After 2000, the aquifer is again in shortage with drier climatic conditions prevailing.

Components of the conceptualisation process that link/feed into the groundwater flow model as key inputs are as follows:

- The modelling software MODFLOW2000, will be used to model groundwater flow;
- The model will have high complexity and comprise 3 layers, the upper layer being the main yielding aquifer where the majority of extractions occur;
- The second layer is the secondary aquifer that has been incorporated to represent the knowledge of a permeability contrast in the BHWSS area as indicated by regional personnel;
- The third layer represents the fractured/weathered bedrock zone above the hydraulic base to account for one possible source of saline water. There is virtually no extraction of water from this layer;
- A model grid of 350m x 350m will be used;
- Based on stratigraphic and test pumping response assessments, the upper portions of the aquifer are typically unconfined or semi-confined, with some confining conditions. It is recommended that the upper layer will be modelled as confined and unconfined and the lower two layers will be modelled as confined;
- Calibration of the groundwater flow model should be undertaken using historical groundwater levels from the departmental monitoring network. Only bores with elevation details that match the LiDAR DEM (within 1m difference) should be used in the calibration. Also, all bores selected for calibration and contouring should have a continuity of record and data integrity suitable for calibration purposes;
- Hydraulic conductivities calculated from test pumping analyses will be used as initial values in the calibration. Parameter estimation software, PEST-ASP (Doherty 2002) will be used for optimisation.
- Boundary conditions will comprise fixed head boundaries along ocean boundaries, time varying fixed head boundaries along water courses, time variant flux boundaries along the south-eastern part of southern boundary and no-flow boundaries at geological boundaries.
- Groundwater pumping within most of the BHWSS area is metered, and model inputs for this extraction will be derived from metered usage data. Non-metered bores within the model domain are generally stock and domestic purpose bores, and a nominal usage of 1ML/year will be applied. Groundwater pumping outside the metered area will be estimated based on APSIM-computed irrigation demand.

1 Introduction

The Lower Burdekin floodplain is a nationally significant agriculture area that is dependent on a combination of surface water and groundwater for irrigation and other uses. Production is dominated by irrigated sugarcane, and furrow irrigation systems are used to produce most of the 80,000 hectares of sugarcane grown each year. The gross value of irrigated agriculture in the wider Burdekin catchment was estimated in 2003 at $450 million (Beare et al. 2003).

The Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) is developing a groundwater modelling toolkit to support the decision making process for water management in the Lower Burdekin. The toolkit will be designed to provide a framework from which various environmental resource management scenarios can be modelled.

This project is funded by the National Water Commission (NWC) under the Raising National Water Standards Program. The NWC identified six key issues relevant to the sustainable management of the Lower Burdekin groundwater system, which will form the rationale for the development of the toolkit:

- Rising water tables
- Declining groundwater quality
- Increased discharge of poor quality groundwater to the environment
- Seawater intrusion
- Future impacts of land and water use
- Climate change

To support the development of the modelling toolkit, it is necessary to undertake preliminary hydrogeological assessments to build a conceptual model of the system being modelled. This conceptualisation involves a process of data collation, analysis and interpretation to identify the physical characteristics and groundwater dynamics of the main aquifers. This information is synthesised into a format that can be used to feed data into the numerical models and constrain the key parameters that govern groundwater movement and quality.

This report presents a conceptualisation of the Lower Burdekin aquifers by detailing the source and volume of available hydrogeological data, analysis of data (including known data gaps), interpretations of the groundwater system processes, identification of the components of the water balance, and recommendations of the most appropriate approach to the proposed modelling.

1.1 Objectives

The modelling toolkit aims to construct, calibrate, test and report unsaturated zone, groundwater flow and solute transport models for the Lower Burdekin. By providing a strong understanding of the major features and behaviour of the system, the proposed 'hydrological modelling toolkit' will: (i) support the extension of the water resource planning process to groundwater; (ii) inform generalised on-farm and off-farm water management and use; and (iii) improve understanding of the groundwater-related risks to the Great Barrier Reef lagoon.

The proposed integrated modelling toolkit will be used specifically to:

- support development of the groundwater amendment to the Water Resource Plan, to assess the sustainable groundwater extraction regime for the natural system, and assess potential impacts on groundwater-dependent ecosystems (GDEs);
- support decision making in relation to the management of rising groundwater levels by testing the impacts on regional groundwater and salinity resulting from changes in irrigation practice, reduced channel and drain leakage and increased use of groundwater beyond the natural yield of the system;
- support decision making concerning the management of the water table in relation to the impact on water quality from changes in irrigation practices and water sources, by assessing changes of the salt content in groundwater;
- support decision making about the management of the water table by providing a greater understanding of the processes associated with seawater intrusion and the capability to simulate potential future inland movement of the seawater ‘wedge’ under different management scenarios;
- support decision making in relation to the management of the Reef environment by improving understanding of the salt/nutrient/pesticide discharge from groundwater to the marine environment;
- support decision making in relation to the management of coastal wetlands, including Ramsar sites, by improving understanding of the salt/nutrient/pesticide discharge from groundwater to the coastal wetland environment and potential inland movement of the seawater ‘wedge’;
- support decision making concerning the management of future land and water use, by ensuring that the likely impacts of future water and land use scenarios on the health of the Lower Burdekin groundwater system and connected ecosystems are understood; and
- support the development of the North Queensland Regional Water Supply Strategy by enabling an assessment of the volume of groundwater available in the area of rising groundwater that could be released for use elsewhere in the system through substitution to help meet emerging water supply needs and/or as a contingent source should surface water become depleted.

The outputs of the project, the ‘toolkit’, will comprise an amalgam of models (Figure 1-1). These models will incorporate unsaturated (vadose) zone flow and solute transport, and groundwater flow processes to simulate the response of groundwater levels and volumetric flow to a range of recharge and discharge conditions. The models will also simulate the movement of solutes within the groundwater system to the adjacent ecosystems. The solute transport models will include seawater intrusion and nutrient transport capabilities.

A series of one-dimensional unsaturated (vadose) zone flow and solute transport models representing the major hydrogeological response units are then to be constructed for estimation of aquifer recharge, historical irrigation demand and simulation of solute/nutrient flux to the water table. Such models will have the functionality to incorporate generalised farm-management practices as well as a variety of climatic conditions. A process of upscaling will be required to link such outputs with the associated regional-scale groundwater flow model.

Groundwater models will be constructed to simulate groundwater flow regime, estimate spatial and temporal change in groundwater levels and provide for the spatial variation in hydraulic parameters and aquifer processes at a scale needed to achieve model objectives.

An instructional conservative density-dependant solute transport model that is dynamically-linked to the simulated groundwater flow regime will also be developed. This will provide estimates of salt concentrations in the region, information on the movement of the saltwater interface in response to various management options and estimates of salt loads to receptors like rivers and oceans.

A smaller scale reactive transport model will also be developed to understand geochemical processes occurring near coastal and riparian zones that control nutrient (e.g., nitrates) discharges to wetlands, oceans, rivers and creeks.

The hydrological modelling toolkit will have multiple uses. The groundwater flow models will provide estimates of the aquifer water level response and model uncertainty to:

- various demand on water use patterns;
- various artificial recharge facilities;
- changes to the overall water balance as a result of climate modelling; and
- other surface water impoundments overlying the alluvial aquifers.

Simulated water levels can also be used, by inference, to estimate the flows needed to support groundwater-dependant ecosystems (GDEs). Additionally, aquifer water levels and volumes will assist in identifying water allocation security objectives.

The impact of groundwater management options (including the volume of water intercepted from streamflow, both regulated and unregulated) on surface water environmental flows or baseflow river stage can also be determined from such simulated outputs.

Instructional conservative solute transport model can be used to estimate the impacts of various management options and climate change on:

- the movement of saltwater interface of interest; and
- salt discharges to receptors like rivers and oceans.

Small scale reactive transport model can be used to assess the impacts of various geochemical and hydrologic conditions of coastal and riparian zone groundwater systems on:

- nutrient (e.g., nitrates) discharges to water bodies at specific locations and spatial and temporal variation of nutrient concentration at specific areas.

In addition to the model capabilities previously described, there are a number of additional features which can be integrated into the subsurface flow and transport models of the Lower Burdekin area. Decisions regarding the inclusion of these features will be made during the course of the project as system knowledge is accumulated. These potential features include:

- the ability to develop future data acquisition strategies to reduce the propensity for model predictive error associated with key model outcome;
- optional inclusion of finer model resolution in areas which would benefit from more detailed representation of the hydrostratigraphy, spatial distribution of recharge, extraction, solute/nutrient migration etc; such a model will be referred to as a “parent-child” model; and
- provisions for an operational management module to test the appropriateness of operational management rules for extractions grouped by management zone (hydrogeological response units) or usage type, in a generalised and user-friendly form.

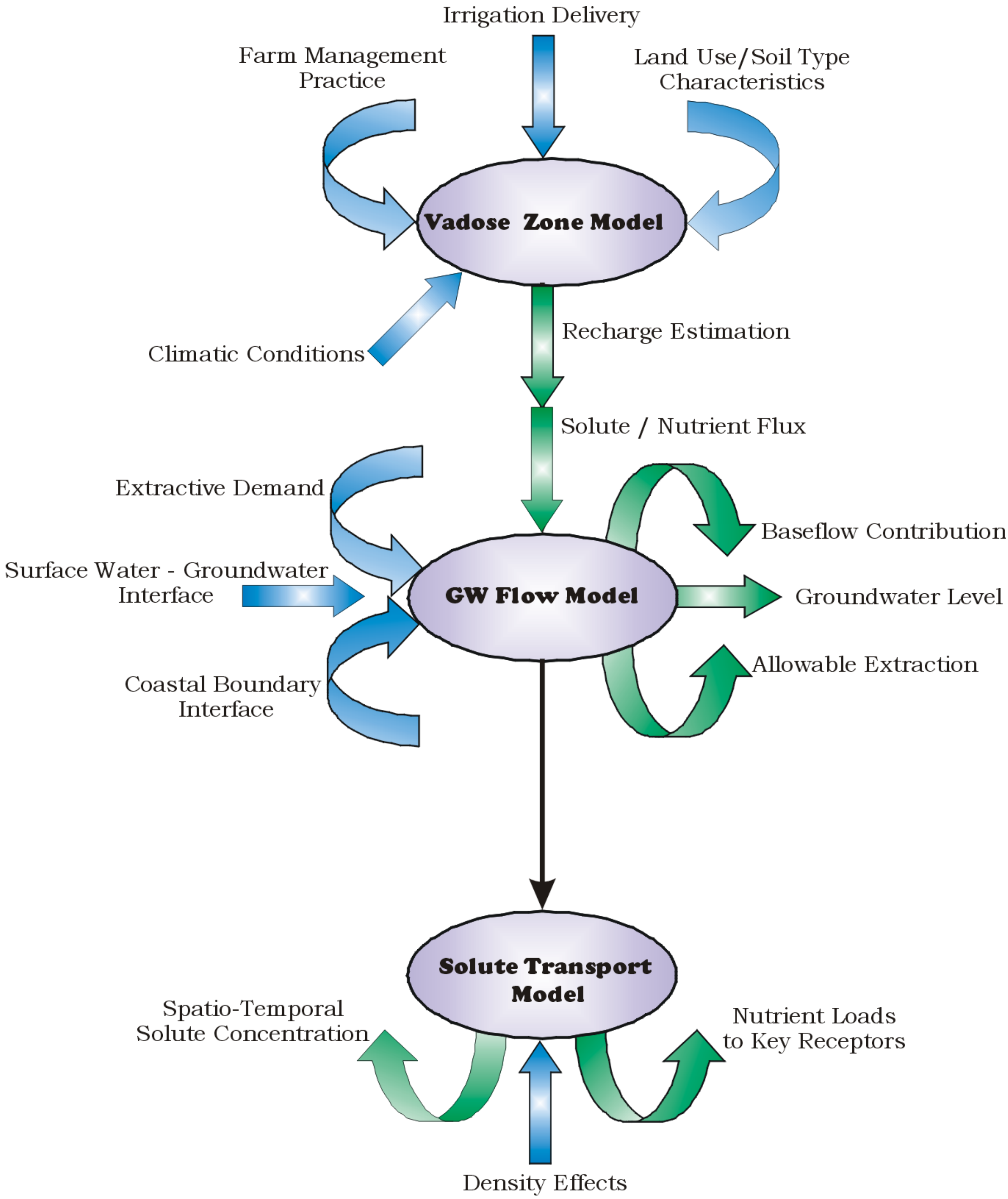


Figure 1-1 Key features of the Lower Burdekin hydrological modelling toolkit. The linkages between the vadose zone, groundwater flow and solute transport models are shown, as well as the key input and output requirements (shown in blue and green respectively).

Objectives of the Conceptualisation Report

A qualitative conceptualisation and quantitative characterisation of a system is necessary to develop an understanding of the important aspects of the system and the hydrological processes that control or impact the system (Kolm et al. 1996, Middlemis, Merrick & and Ross 2000). This conceptualisation report aims to support the development of the groundwater modelling toolkit of the Lower Burdekin by:

- defining the aquifer extent and geometry, including layer depths and thicknesses;
- establishing the physical characteristics of the area that influence the movement of water through the system, such as soils, geology, climatic conditions, land use, topography, and drainage.
- assembling all relevant hydrologic data, such as rainfall and water use;
- collating aquifer hydraulic properties;
- assessing the relationship between groundwater and surface water;
- establishing the condition and trend of water quality parameters;
- identifying recharge processes and estimating deep drainage;
- defining and quantifying the key components of the water balance; and
- providing recommendations for the most appropriate modelling approach.

2 Study area

The Lower Burdekin aquifer system is located on the north-eastern coast of Queensland, approximately 90 kilometres south of the city of Townsville, and covers approximately 2500km^2. There are 5 main towns located within the study area: Ayr, Home Hill, Clare, Brandon and Giru. Three main river systems drain the area (Burdekin River, Haughton River and Barratta Creek) with numerous other tributaries, distributaries and coastal channels. The area is bounded by the Coral Sea to the east and by Bowling Green Bay to the north. To the west, the Mount Elliott complex rises sharply from the Burdekin floodplains forming the western aquifer boundary. To the south, the Stokes Ranges and Mt Woodhouse form more gentle sloping hills and mountains that form the southern boundary. Within the study area, a number of isolated hills and mountains such as Mt Kelly and Mt Inkerman punctuate the main aquifers. A thinning of the alluvial aquifers in the Dingo Park area and the coastal boundary southeast of Mt Inkerman have been delineated with arbitrary boundaries to complete the main study area (Figure 2-1).

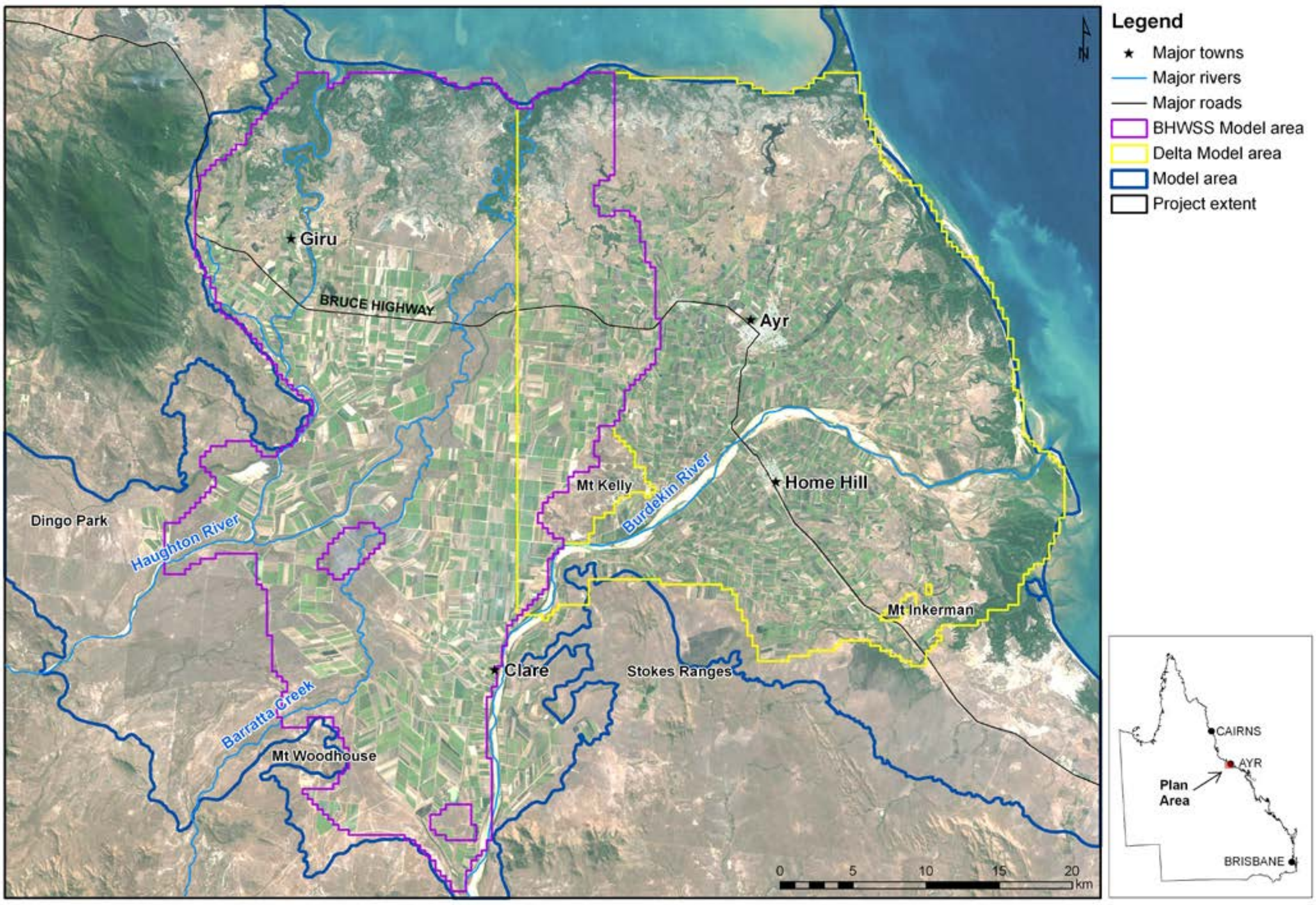


Figure 2-1 Location plan of the Lower Burdekin (dark blue). The previously proposed BHWSS model area is shown in purple, and the Burdekin river Delta areas shown in yellow.

2.1 Review of Previous Studies

The current study area covers an area that encompasses the two main groundwater use areas: the Burdekin Haughton Water Supply Scheme (BHWSS) to the west, and the Burdekin River Delta to the east (Figure 2-1). These areas have been subject to prior investigations by the Department, and are therefore merged as a single study area with additional areas of significance added, particularly in the western and southern regions.

The first production of commercial sugar in the Burdekin Delta began on the north side of the river in 1883 (Arunakumaren, McMahon & Bajracharya 2001). By the end of the nineteenth century, extraction of groundwater from the sandy aquifers of the Delta for irrigation water supplies had become widespread (O'Shea 1985). During an extended drought in 1930-35, groundwater levels fell below sea level (Arunakumaren, McMahon & Bajracharya 2001). To decrease the risk of seawater intrusion resulting from falling groundwater levels, the north and south Burdekin water boards were set up to manage an artificial recharge scheme in 1965 (O'Shea 1985). The scheme involved pumping water from the Burdekin River during times of flow into natural and artificial recharge channels and pits for seepage into the underlying sediments (O'Shea 1985).

Development of irrigated agriculture in the BHWSS commenced with the soldier resettlement scheme at Clare in 1949 (Petheram, Charlesworth & Bristow 2006). River water was used to irrigate tobacco crops until the farms were converted to sugarcane in 1964 (Petheram, Charlesworth & Bristow 2006). Irrigation of sugarcane was then expanded to Mona Park, where groundwater was used for irrigation, in 1965 (Petheram, Charlesworth & Bristow 2006). Further expansion of irrigated agriculture in the BHWSS occurred after the establishment of the Burdekin Falls Dam in 1987 and the construction of surface water supply channels.

The expansion of development in the BHWSS prompted a whole series of investigations focusing primarily on the soils and hydrogeology of the area. Soil surveys were conducted to assess the suitability of the local soils for irrigation purposes. The soils of the BHWSS were found to differ from those being irrigated in the Burdekin Delta (Donnollan 1991). Soil sodicity was found to be the primary limitation to irrigation development in the BHWSS (Day, Loi & Christianos 1992) and a semi confining surficial clay layer was found to be present throughout most of the BHWSS (KBR 2002, Australian Groundwater Consultants 1982, Evans 1987, Evans 1988).

In the 1980s and 1990s, concern was expressed about salinity outbreaks in the BHWSS area. Saline seeps were observed on the right bank of the Burdekin River adjacent to the sections of the BHWSS areas planned for further irrigation development. These saline seeps were found to occur at break of slope positions between upland and alluvial areas formed over granodiorite (Shaw et al. 1982, Shaw et al. 1984). As a result of the difficulties in managing salinity on the right bank, release of farms on the left bank was progressed more quickly than farms on the right bank (QWRC 1985).

In recent studies, concern has been raised about rising groundwater levels in the BHWSS. Rising groundwater levels have been occurring since the 1980’s in parts of the BHWSS (Petheram, Charlesworth & Bristow 2006, KBR 2002, PPK 2002). A number of strategies are currently being considered to manage rising groundwater levels in the area, including increased groundwater extractions for irrigation and/or disposal.

A number of groundwater models have already been developed for different parts of the Lower Burdekin which may be of value for the construction of the current Lower Burdekin groundwater flow model. The extent and purpose of these models is briefly summarised here:

- Volker, R. E. (1977) "Numerical Modelling of an aquifer system with intermittent recharge" Australian Water Resources Council Technical Paper No. 25.

  The purpose of this model of the Burdekin Delta was to assist in management of water resources and to evaluate and improve efficiency of the artificial recharge scheme. The model took into account the groundwater – seawater interface near the coastline and simulated the groundwater system under natural and artificial recharge conditions. The groundwater system was modelled as an unconfined aquifer.

- Australian Groundwater Consultants (1983) "Assessment of Groundwater Resources of the Mona Park / Barratta Creek Area, Stage 2".

  A study was commissioned by the Queensland Water Resources Commission into the groundwater resources of the Mona Park / Barratta Creek area. A two dimensional finite difference model was produced to determine the effect of proposed additional groundwater extractions to the North of Mona Park and to estimate the volume of additional groundwater that could be extracted on a long term basis. Historical recharge and groundwater extraction data was used to calibrate a model which included several groundwater extraction options.

- Doherty, J. (1997) "Processes Affecting Salinity of Groundwater Entering the Southern Burdekin Water Board Area"

  A one dimensional sectional model of a section of the SBWB area was produced to determine the impacts of irrigation south of the SBWB on groundwater salinity entering the SBWB. The modelling demonstrated that the instigation of a conjunctive use irrigation regime would prevent water table rises but it would also lead to a deterioration of water quality entering the board areas. More sophisticated modelling work was recommended to examine the impacts of different irrigation management strategies in greater detail.

- Hillier, J. R. (1998b) "Burdekin River Irrigation Area, Groundwater Modelling Report: Development and Application"

  A MODFLOW model was developed of the Burdekin River Irrigation Area bounded by the Burdekin River and the Haughton River. The objective of the study was to investigate groundwater supplies and to develop a computer based model which could be used to simulate groundwater conditions in the area subject to a land resumption claim at the Cox properties. The area was divided into 21 recharge zones which represent unique combinations of land use, soil type and top clay thickness.

- Merrick, N. P. (1998) "Burdekin Groundwater Modelling Study"

  A MODFLOW model was developed to assess the volume of groundwater that could be extracted for irrigation of sugar cane on the Cox properties. The BHWSS aquifer was modelled as a single layer, bounded by Bowling Green Bay to the north and by rock outcrops to the south and west. The model was calibrated for the period from 1971 to 1988, before the development of the BHWSS. Fluxes from creeks and rivers were found to be the most important source of recharge. The most critical system parameters were found to be groundwater usage and stream conductance.

- Arunakumaren, et al. (2001). "Water Management in the Lower Burdekin: The Burdekin Delta Groundwater Model" Phase 1-4.

  The aim of this project was to develop a groundwater management model to simulate the behaviour of the groundwater system underlying the Burdekin Delta area. A MODFLOW model was used to evaluate a range of water management strategies including maintenance of artificial recharge works, provision of irrigation water to farms and water use on farms. The model was also used to identify areas at risk from environmental degradation (seawater intrusion, rising water tables etc.), improve water management, study water availability in relation to potential farm expansion and to ensure that the principles of ecologically sustainable development are met.

- Narayan, K. A., D. Hartmann, et al. (2004). "Modelling the Effects of Val-Bird Weir Height on Water Tables along the Haughton River (Burdekin Haughton Water Supply System)" CSIRO Land and Water Client Report for Burdekin Dry Tropics Board, CSIRO Land and Water.

  In order to maintain regular water supply for irrigation, the Val-Bird Weir was built in 1983 on the Haughton River as part of the Burdekin Haughton Water Supply Scheme. This has lead to a rise in the water table and potential threat of salinisation of surrounding lands in the region. A MODFLOW model was developed to simulate the impacts of lowering the Val-Bird Weir height by 1 and 2 metres on the elevation of the water table.

- Narayan, K. A., C. Schleeberger, et al. (2007). "Modelling seawater intrusion in the Burdekin Delta Irrigation Area, North Queensland, Australia." Agricultural Water Management 89: 217-228.

  This paper describes the results of seawater intrusion modelling in the Burdekin Delta using a 2D vertical cross-section using the SUTRA code. The modelling was used to define the current and potential extent of seawater intrusion under various pumping and recharge conditions. Modelling results showed that seawater intrusion is far more sensitive to pumping rates and recharge than aquifer properties such as hydraulic conductivity. The effects of tidal fluctuations on groundwater levels are limited to areas very close to the coast.

In addition to the models that have already been developed, two conceptual reports have also been produced fairly recently to provide a framework for the further groundwater model development. The scope and outcomes of these reports will be briefly outlined here.

- Halliburton KBR (2002). "Hydrogeological Conceptualisation: Haughton-Burdekin BRIA Area" Prepared for the Department of Natural Resources and Mines.

  The purpose of this study was to provide the hydrological and hydrogeological framework for the groundwater flow and saltwater intrusion models. The groundwater flow model was considered to be the appropriate approach for addressing groundwater management issues including rising groundwater levels and seawater intrusion. This report includes a brief review of previous studies and a compilation of the datasets required to construct a groundwater flow model. These datasets include surface topography, rainfall, evaporation, surface drainage features, soil properties and aquifer properties.

- Klohn Crippen Berger (2008). “Lower Burdekin Groundwater Modelling, Hydrostratigraphic Assessment”

  This study examined available stratigraphic data from drill logs, hydrogeological cross-sections and downhole geophysical data to aid in the construction of hydro-stratigraphic layers for groundwater modelling. At a regional scale, the results from downhole geophysics work did not significantly alter the previous interpretations. The recent CRC LEME geophysics investigations did not provide the basis for assessing the lateral continuity of sands and clays within the alluvial materials. The general approach suggested for modelling the Lower Burdekin is as a semi-confined alluvial aquifer overlaying a weathered and fractured basement layer. There was anecdotal evidence of a vertical permeability contrast in the Jardine-Selkirk and Horseshoe Lagoon areas. To test the impact of this permeability contrast in these areas, the suggested approach was to create an additional hydro-stratigraphic layer at a position of 75% of the depth of the alluvial sequence.

2.2 Data Availability

The conceptualisation of the Lower Burdekin aquifers is built around a combination of historical records, previous reports, and data collected specifically as part of this project. This data is processed into a form that enables interpretation of the key characteristics of the groundwater system. Table 2-1 presents a summary of the key sources of data from which the interpretations within this report have been made.

Table 2-1 Data availability table of primary and secondary sources of data used in this project

System Characteristic	Extractions/Applicable Data Format	Primary Data Source	Secondary Data Sources
Surface Water			
Stream Water Levels	Text file or graph format	Hydstra Database	DERM - Townsville
Stream Flow Rates	Text file or graph format	Hydstra Database	DERM - Townsville
Surface Water Use	Historical Records	SunWater, NBWB, SBWB, DERM Townsville	
Surface Water Quality	Gauging Station records or spot gauge	Hydstra Database	DERM - Townsville
Channel Seepage	Lumped parameter models		GHD Report
Artificial Recharge	Recorded Data	NBWB, SBWB	
Ground Water			
Monitoring Bore Water Levels	Text file format extracted and processed from GWDB	Groundwater Database (GWDB)	Groundwater Database (GWDB)
Aquifer Geometry	Registration Details, Strata logs, Elevation Details, Casing Information	Groundwater Database (GWDB)	KBR 2004; KCBL, 2008; McMahon, 2004;
Geology - Geophysics Data	Geophysics Data	Departmental internal reports	
Pumping Metered Use Data	Text file data, lumped parameter models	WERD / WMS Database	DERM - Townsville
Hydraulic Conductivity - Pump Test Records	Registration Details, Strata logs, Elevation Details, Pump Test Results data	Groundwater Database (GWDB)	Departmental internal report
Groundwater Water Quality	Water Analysis Results	Groundwater Database (GWDB)	
EC, Salinity Data	Water Analysis Results, Field Quality Results, Multiple Conductivity Results	Groundwater Database (GWDB)	
Land Use and Vegetation Cover			
Historical Land Use Data	Burdekin Land Use Maps		
Climate			
Rainfall	Patched Point Rainfall Dataset	BOM SILO	
Evaporation	Pan Evaporation Data Drill	BOM SILO	BSES
Soil Data			
Soils Classification	Soil Maps	DERM - Spatial Information Group	
Soils Data	Text file format	DERM SALI Database	DERM - Spatial Information Group
Topography			
Digital Elevation Model (DEM)	DEM, LIDAR .las tiles, ASCII xyz data	DERM Spatial Information	Geosciences Australia, GWDB

3 Physical Characterisation

This section highlights the key surface features that influence the groundwater system in general, and how these features are to be transferred into the numerical groundwater model.

3.1 Topography

The area of the Lower Burdekin subject to modelling mainly comprises the widespread floodplains extending from the upland extent of the main irrigation areas of the BHWSS and Water Boards areas through to the coastlines of Bowling Green Bay (to the north) and the Coral Sea (to the east). Within the flooplain, there are a few notable outcrops of bedrock material that punctuate the surrounding the alluvial sediments. These outcrops form steep rocky hills, and include Mt Inkerman (214m), Mt Kelly (189m), and numerous smaller hills close to the margins of the study area. Along the southern and western margins of the study area, the topography rises towards the mountain systems associated with Mt Elliot, Mt Woodhouse and the Stokes Ranges.

The floodplains are essentially flat to slightly undulating as dominated by the alluvial plains associated with the Burdekin River, Haughton River, Barratta Creek system, Sheepstation Creek, Plantation Creek, the Anabranch, and numerous other creeks. The coastal fringes of the area are characterised by low-lying tidal flats with some modern and relict dune systems along the eastern shoreline.

Digital Elevation Model (DEM)

The topography of the Lower Burdekin floodplains has usually been represented by historical topographic mapping data or, in more recent years, by Digital Elevation Models (DEMs) such as NASA's Shuttle Radar Topography Mission (SRTM) which carries a horizontal resolution of 3 arc-seconds (approximately 90m). The disadvantage of using satellite-borne DEMs in low-lying areas is the inherent vertical inaccuracies, with absolute errors in the order of metres. This can be particularly prevalent in areas where dense reflective crops (e.g. sugarcane) can present a source of error. In addition, the resolution of satellite DEMs can present high residual differences when compared against surveyed points on the ground, especially in areas where changes in topography occur (e.g. elevated river banks and hills).

A more accurate DEM can be produced from airborne laser altimetry data obtained via Light Detection And Ranging (LiDAR) technology. LiDAR has been used extensively for accurate surveying and mapping of large areas, and has the advantage of being calibrated against permanent survey marks on the ground. It is reported that 68% of the area surveyed will have a vertical accuracy of +/- 0.15m in clear and open areas. A large part of the Lower Burdekin floodplain has already been mapped by the "Queensland High Resolution Coastal DEM" project (see Figure 3-1). The remainder of the area, mostly in the western and southern parts, was mapped by LiDAR as part of this project and stitched with the existing datasets to form a complete DEM.

The LiDAR DEM is required to establish an accurate reference level for the uppermost level of the aquifers, calculate the thickness of any unconfined aquifers, and to relate measured water level depths to a common datum. The final DEM for this project was constructed using the following data sources:

- LiDAR Data in ASPRS LAS format v1.1 - 1km x 1km tiles.
- Bare Earth DEM with 1 metre resolution in ASCII XYZ format and ASCII GRID (not binary) format - 1km x 1km tiles.

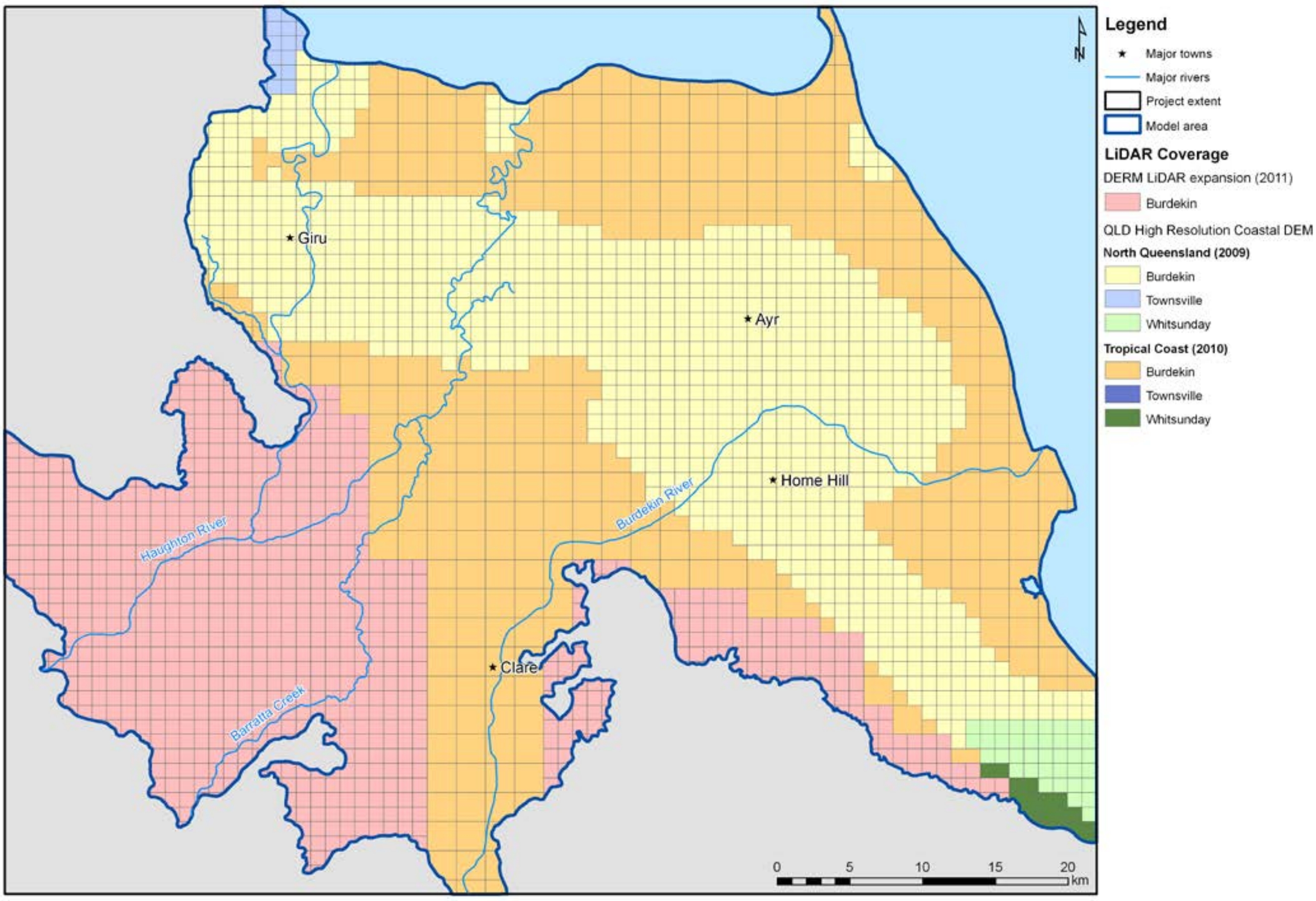


Figure 3-1 Burdekin LiDAR coverage extent including the 2011 Burdekin LiDAR expansion sub-project area that has now been completed as part of this project.

This data was then processed into cartographic contours at an interval of 0.25m and supplied in either 1km x 1km or 2km x 2km tiles. The final DEM is presented in Figure 3-2.

The LiDAR dataset was compared against surveyed bore elevations from GWDB to validate the on-ground vertical accuracy of the LiDAR dataset at relevant point locations. For comparison, the SRTM DEM was also assessed to observe the difference between DEM datasets. ‘Box and whisker’ plots were used to demonstrate the variation in elevation residuals between each DEM and all surveyed bore data. The range of data, average value and the range of the overall bulk of data for both DEMs is shown against bores that have been surveyed in AHD (Figure 3-3). Each of the LiDAR dataset plots show that both are largely centred around 0m difference with 75% of values within less than +/-1 metre of average residual, with outliers that range from +20m to -12m AHD. The SRTM dataset is typically around - 3m difference below surveyed heights, with 75% of data within about 2m of average. It is clear from this comparison that the LiDAR DEM offers superior accuracy when compared to the SRTM DEM.

However, it is still evident that some surveyed bores have a significantly high residual when compared against the LiDAR DEM (up to +20m and -12m). The reasons for this discrepancy are unknown, but observations of the spatial distribution of these bores suggest that they may have been originally surveyed against benchmarks that were not consistent with AHD. This discrepancy is very important for the calibration process as all bores with significantly different bore elevations to the DEM will cause major differences in water levels at those locations if included in the calibration. It is recommended that only bores with accurate natural surface elevations (when compared to the LiDAR DEM) be selected for calibration of the numerical model.

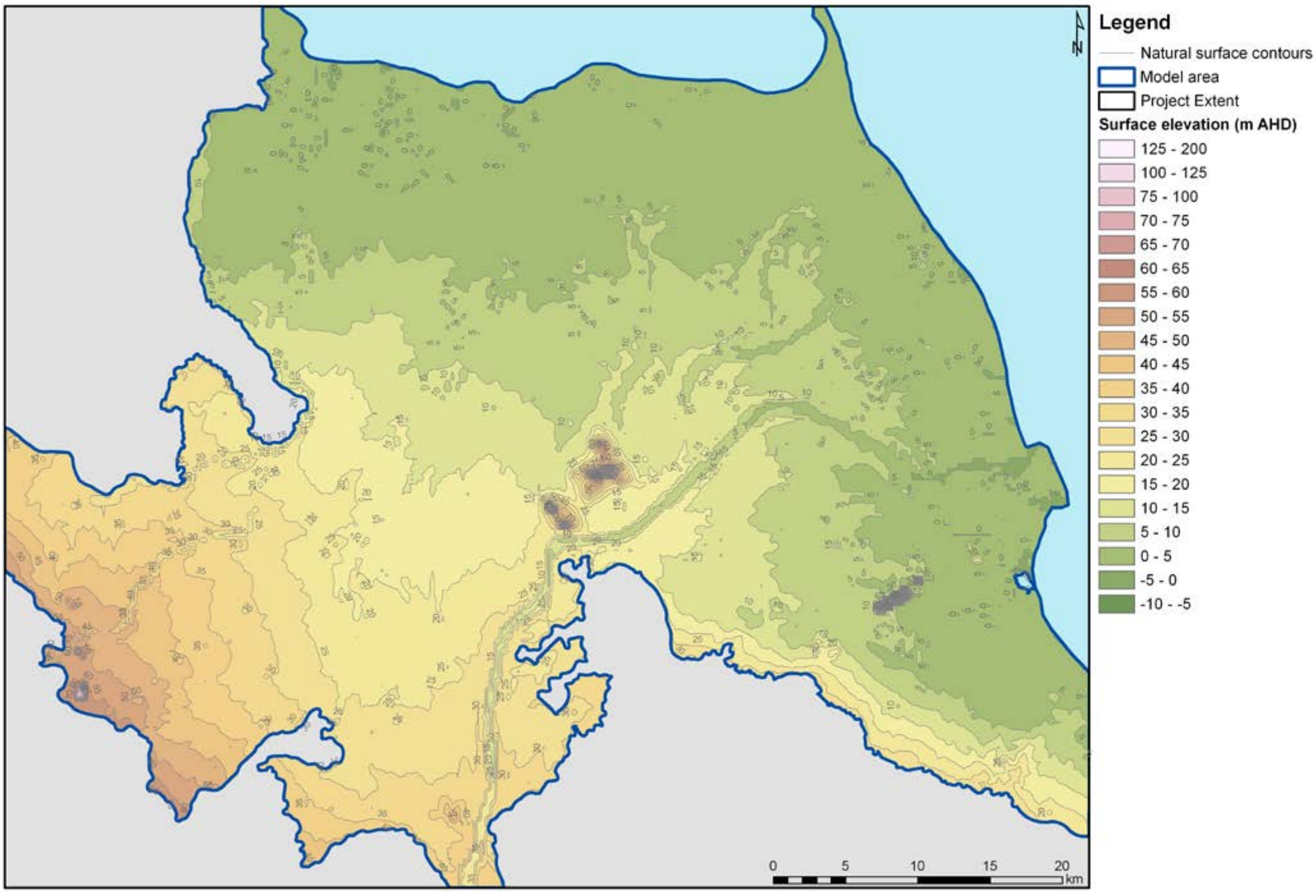


Figure 3-2 Burdekin Digital Elevation Model (DEM) constructed from processed LiDAR data (elevation in metres AHD)

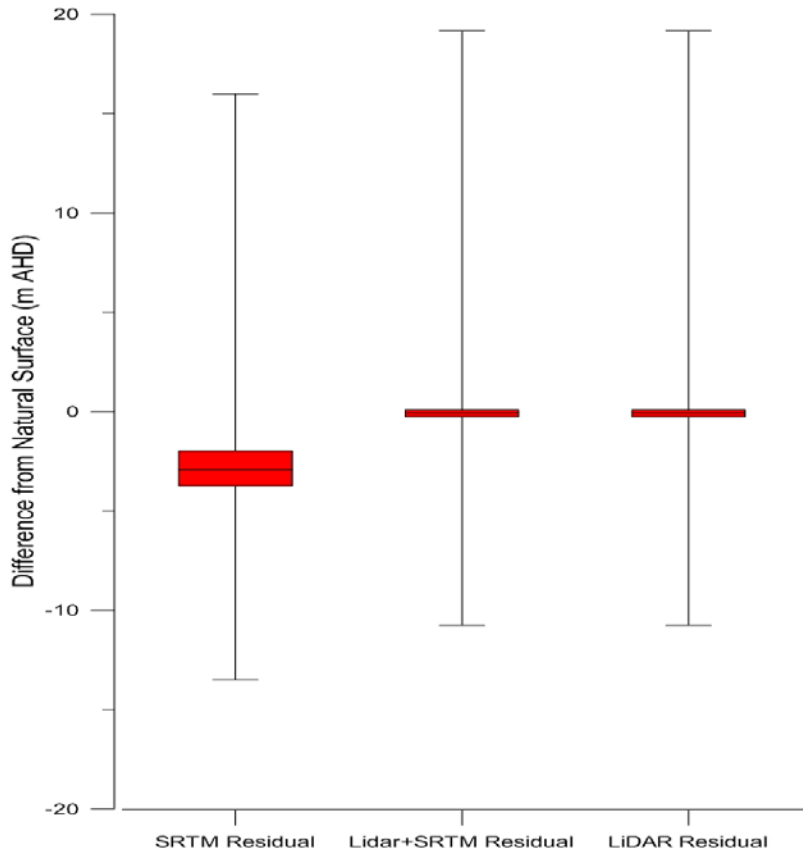


Figure 3-3 'Box and whisker' plot comparisons of SRTM, LiDAR and combined LiDAR & SRTM residuals versus surveyed bore height elevations in m AHD (from GWDB). The red box represents the 75th percentile of data points, with each 'whisker' representing the full range of differences.

3.2 Surface Drainage

The Burdekin River drains an area of 129 500 km^2 and has the largest mean annual runoff of any river on the east coast of Queensland but experiences extreme variability that is both highly seasonal and erratic (Fielding & Alexander, 1996). More than 90% of the annual discharge as measured at three gauging stations (Charters Towers, Clare, Home Hill) occurs consistently between January and April (Fielding & Alexander, 1996).

The major water courses in the Lower Burdekin (Figure 3-4) are the Burdekin River, the Haughton River, Barratta Creek and their tributaries including Oaky Creek, Lagoon Creek, Woodhouse Creek, Clay Creek, Major Creek, Plantation Creek, Sheepstation Creek and Ironbark Creek (KBR 2002). In addition many minor estuarine channels exist within the tidal zones.

Associated with irrigation development of the BHWSS, there has been construction of extensive surface water infrastructure including water storages, pumping stations and irrigation water supply channels. The Burdekin Falls Dam operates in conjunction with the additional water storage infrastructure of Clare Weir and Gorge Weir on the Burdekin River, and Val Bird and Giru weirs on the Haughton River at Giru. Pumping stations are located on the Burdekin River at Clare Weir, to divert water to the Haughton, Elliot and Barratta Main Channels. Channels have been developed on both sides of the Burdekin River and each section is served by major pump stations located on Clare Weir. The pump stations divert water into main channels on each bank of the river and then to customers by a system of distribution channels. The Tom

Fenwick Pump Station services the Haughton and Barratta Main Channels. Associated with the channel reticulation system are two balancing storages, one located in the south east area of the Mulgrave Section to serve the Barratta Main Channel and one located on the boundary of the study area in the central western area of the Haughton Section (KBR 2002).

An artificial recharge scheme exists within the Burdekin Delta. This scheme involves the pumping of Burdekin River water into recharge channels and pits to promote infiltration into the sandy aquifers. The most distinctive channels are Plantation Creek, Sheepstation Creek, Kalamia Creek, and Groper Creek. The location of recharge channels in the Delta is shown in Figure 3-4.

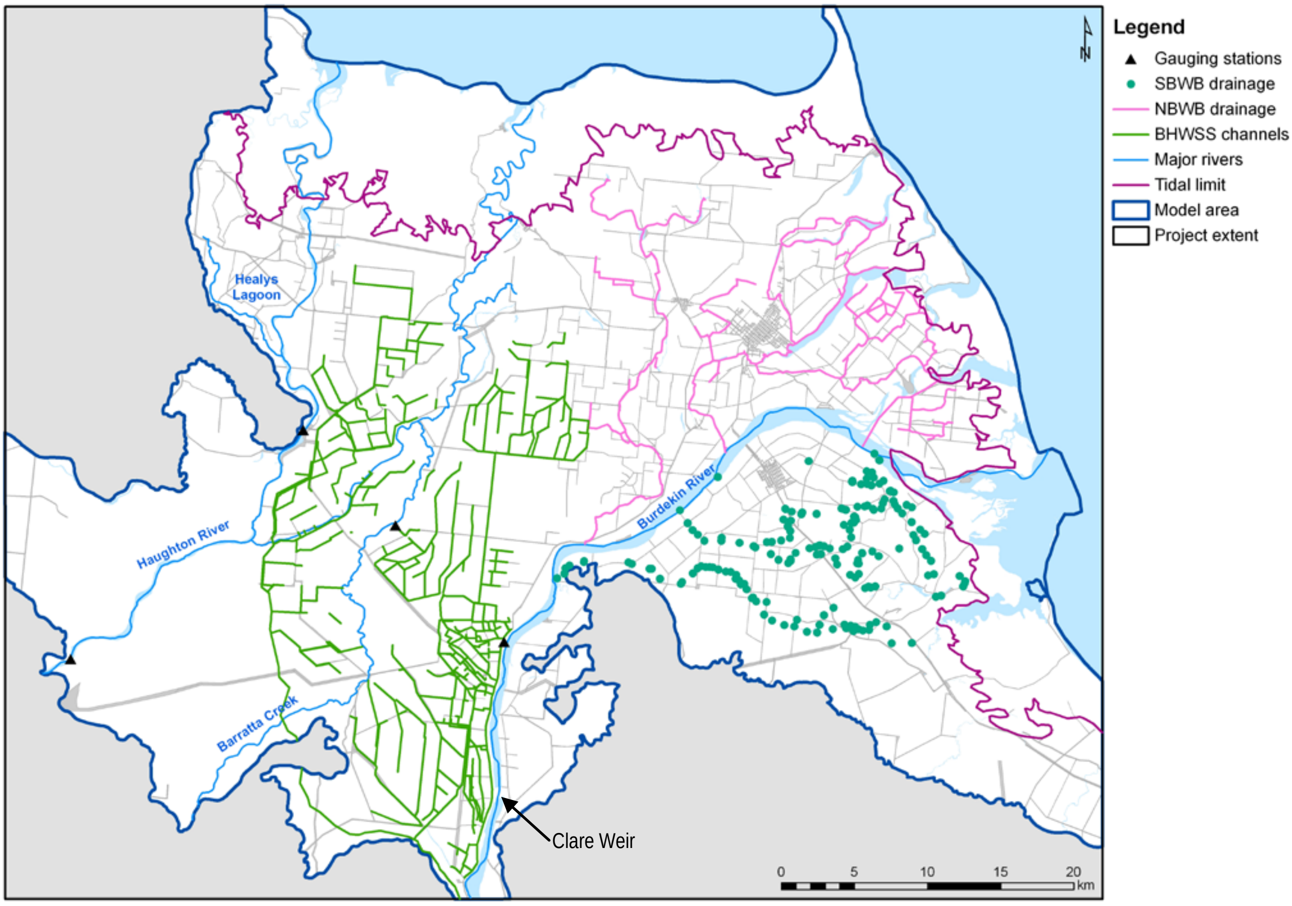


Figure 3-4 Lower Burdekin Surface Water Features

3.3 Regional Geology

Regionally, the Lower Burdekin comprises a basement of mainly granitic rocks of Lower Permian to Upper Carboniferous age with some sandstones and volcanics (Figure 3-5). These are visible as mountains, hills, and rock outcrops, often exposed in sections of the main channels. The basement rocks are generally similar to the rocks of the surrounding hills. Strata logs of bores intersecting these rocks show that they commonly have up to 10 metres of weathering profile, with some evidence of fracturing.

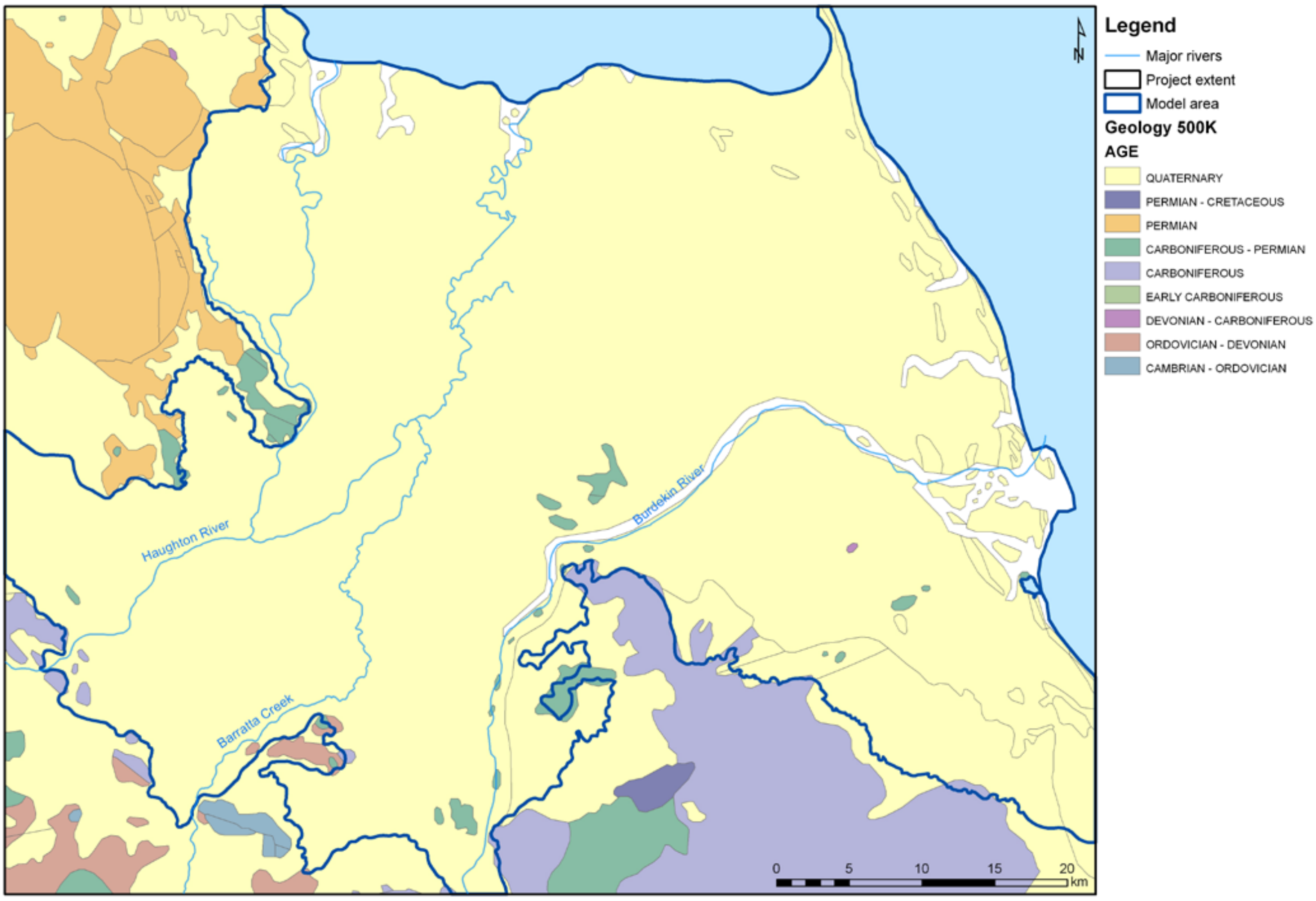


Figure 3-5 Lower Burdekin Geology Map

The Lower Burdekin floodplains comprise Quaternary sequences of alluvial and deltaic sediments that have formed progressively by the combined accumulation of river sediment and the coastal deposition of marine sediment. The floodplains within the study area can be considered to comprise both 'active' and 'inactive' depositional areas. The Burdekin River Delta is essentially an 'active' area with the current main river channel progressively accumulating sediment from fluvial deposition and flooding throughout the Holocene period to the present. The BHWSS area, currently drained by the Haughton and Barratta systems, is relatively 'inactive' with only minor flooding contributing to sediment deposition in recent times. Consequently, the two areas have differing surface geomorphological features. The delta area is predominantly covered in preserved and undulating, "scroll" topography of abandoned and active channel courses, levees and floodplains (Hopley 1970, McMahon 2004, Fielding, Trueman & Alexander 2005). The BHWSS area is notable absent of this undulating topography and is characteristically flat and dominated by a surface layer of thick floodplain silts and muds.

The sediments comprise a combination of layered gravel, sand, silt, clay and mud deposited throughout the formation of the delta by the actions of fluvial, tidal, and wave processes. The stratigraphic sequences are typically indicative of deltaic systems (Fielding, Trueman & Alexander 2006) and more specifically as a fan delta system (Clark 2004). The accompanying report by (Klohn Crippen Berger 2008) compares the difference between fan and conventional deltas in relation to their characteristic stratigraphy.

3.4 Soils

The soils in the lower Burdekin have been mapped at various scales since 1953. In a soil and agricultural potential study by Hubble & Thompson (1953), six topographic forms were separated on the basis of geological and geomorphological differences. Following this, a number of low intensity soil surveys were performed at the 1:100,000 scale (Thompson 1977, Thompson 1990, Reid & Baker 1984). In these soil surveys, the soils were grouped into soil profile classes based on similarity of profile attributes and contiguity of similar profiles in the landscape. These were assigned to one of seven landscape units (topographic forms) (Thompson & Reid 1982). The topographic forms identified were as follows:

- local alluvial-colluvial plains
- major river flood plains
- lacustrine plains of local alluvia, relict local alluvial plains
- dissected uplands on acid intrusives
- dissected uplands on intermediate intrusives
- miscellaneous alluvial deposits
- undulating basalt lands

The soil classification uses a name code system as follows. Each soil profile class (e.g. 3Uga) contains a number indentifying the topographic form, two letters giving the dominant subdivision with a primary profile from Northcote (1979) and a third letter to identify the individual soil profile class.

Prior to the release of land in the BHWSS area for irrigation development, high intensity soil surveys have been conducted at the 1:25,000 scale. These surveys were conducted sequentially for each of the subsections of the BHWSS, starting with the Mulgrave subsection. The reports that accompany these surveys provide information regarding the suitability of the land for irrigation (Day 1994, Donnollan, McClurg & Tucker 1986, Donnollan 1994, Loi, Christianos & McClurg 1994, Loi&McClurg 1994, McClurg, Tucker & Donnollan 1988, McClurg 1995). Some of the limitations to development that were noted include sodicity, flooding, erosion and the presence of rock outcrops

As a result of the complexity of soil and landscape classifications used in the BHWSS, a report was produced that combined all the soil types into four broad soil groups, based on similar properties and management requirements (Donnollan 1991). The soil groups devised were cracking clays, sodic duplex soils, non sodic duplex soils and gradational and uniform non-cracking soils. Out of these four soil groups, the dominant soils in the BHWSS are cracking clays and duplex soils, occupying over three quarters of the area.

Cracking clays are those soils which contain more than 35% clay throughout the profile and crack when dry and swell when wet. The phenomena of swelling and shrinking are related to the nature of the clay minerals. The “cracking clay” classification includes the Barratta soil series. The texture of the A horizon typically ranges from light to medium clay and the texture of the B horizon ranges from medium to heavy clay.

Duplex soils are those soils which have a distinct change in texture from the A horizon to the B horizon. Sodic soils have exchangeable sodium percentages (ESPs) greater than 6 in some part of the profile. The duplex soils are divided into subdivisions based on the colour of the B horizon. Common colours in the BHWSS are yellow-grey, brown and red. “Sodic duplex soils” include the Dowie and Oakey soil series.

The textures of the A horizon typically vary from sandy loam to clay loam. The textures of the B horizon vary from light to medium clay.

Soils in the Burdekin Delta have been not been investigated to the same level of detail as those in the BHWSS. The most detailed soils survey for the Burdekin Delta was conducted at a medium intensity (1:50,000) scale in 2000 to provide information for groundwater model development and irrigation practice guidelines. The soils were typically described as having a uniform texture profile, with the texture ranging from fine (clay) to coarse (sand). Outside of the irrigation areas, only broad-scale mapping from the ASRIS soils coverage database (http://www.asris.csiro.au) is available.

Soils were grouped based on the texture profiles e.g. uniform, duplex or gradational for a range of textures. This enabled a consistent classification across the Lower Burdekin incorporating the soils types identified in previous soil surveys (Figure 3-6). Available soil data for particle size analysis, water holding capacity and chemical properties was then collated for each of the soil groups in the Lower Burdekin. This data was sourced from the Soil and Land Information (SALI) database.

Table 3-1 shows the average particle size analysis and 15 bar moisture content data for each of the 8 soil groups identified.

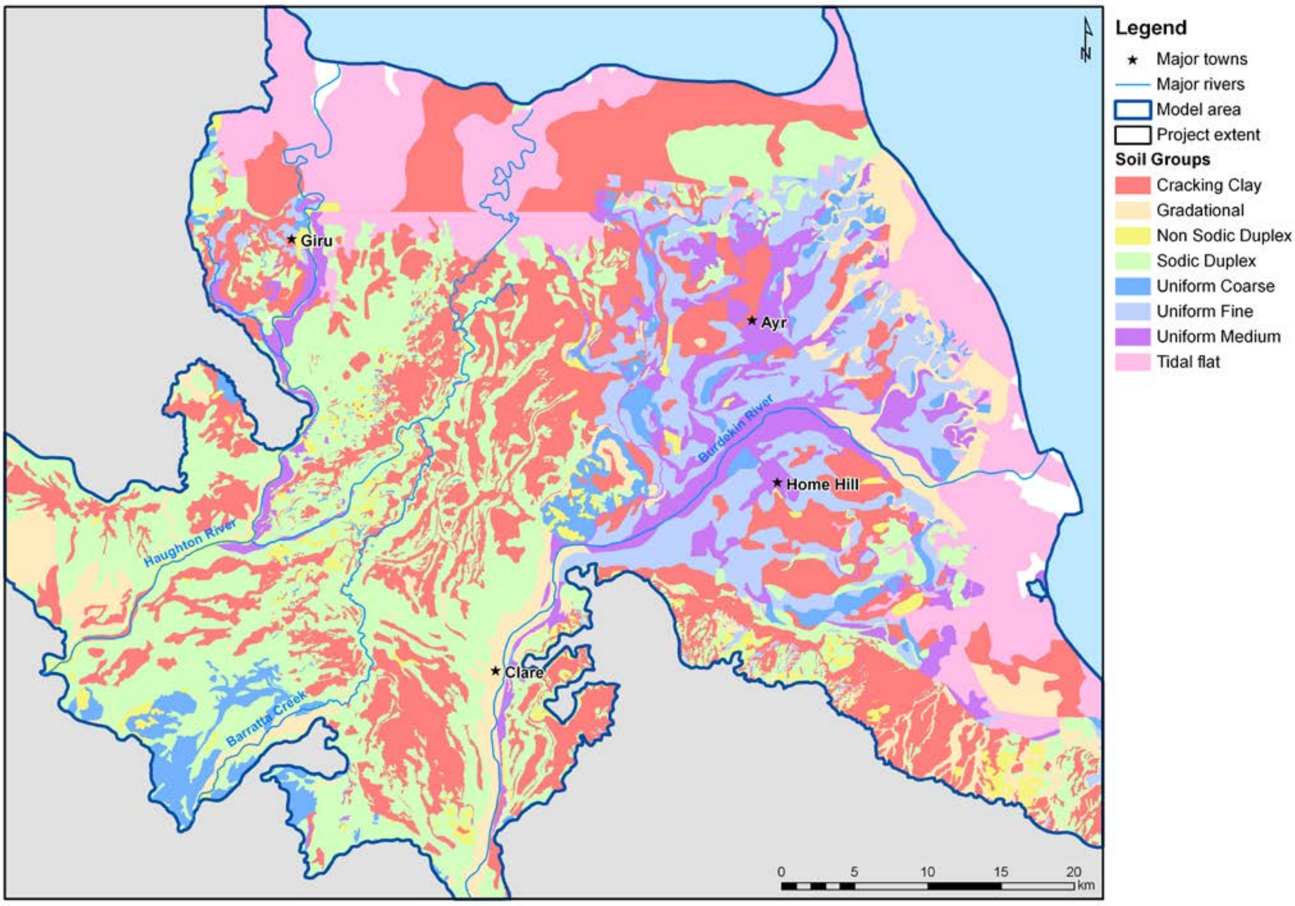


Figure 3-6 Lower Burdekin soil classification

Table 3-1 Soil particle size analysis and soil moisture content for the Lower Burdekin

Soil Group	UPPER DEPTH	LOWER DEPTH	Clay %	Coarse Sand %	Fine Sand %	Sand %	Silt %	15bar
Cracking Clay	0	0.1	45	7	26	33	23	16
	0.2	0.3	53	6	21	28	21	19
	0.5	0.6	54	6	20	26	21	19
	0.8	0.9	53	6	21	27	21	19
	1.1	1.2	53	4	21	25	22	19
	1.4	1.5	42	10	26	36	22	17
Gradational	0	0.1	10	60	24	85	6	3
	0.2	0.3	6	56	30	86	7	3
	0.5	0.6	9	56	27	83	6	9
	0.8	0.9	14	55	24	79	5	6
	1.4	1.5	23	54	12	66	6	8
Non Sodic Duplex	0	0.1	14	30	49	80	10	5
	0.2	0.3	18	31	45	75	9	5
	0.5	0.6	35	24	36	59	8	11
	0.8	0.9	29	31	37	68	5	10
	1.4	1.5	15	11	66	77	8	7
Sodic Duplex	0	0.1	20	19	42	61	21	8
	0.2	0.3	36	15	33	48	18	19
	0.5	0.6	42	13	29	42	17	15
	0.8	0.9	40	13	31	44	18	15
	1.1	1.2	33	9	40	49	18	14
	1.4	1.5	31	6	41	47	21	13
Uniform Coarse	0	0.1	6	66	24	89	7	4
	0.2	0.3	6	63	26	89	6	3
	0.5	0.6	7	56	33	89	6	3
	0.8	0.9	9	50	36	86	6	4
Uniform Fine	0	0.1	23	12	46	58	21	11
	0.2	0.3	22	12	46	58	21	11
	0.5	0.6	23	8	49	57	22	13
	0.8	0.9	24	7	51	59	18	12
Uniform Medium	0	0.1	15	17	53	70	17	9
	0.2	0.3	18	15	51	66	17	9
	0.5	0.6	25	12	48	60	17	11
	0.8	0.9	18	34	37	71	10	9
	1.4	1.5	18	16	50	66	16	9
Tidal Flat	0	0.1	30	13	38	51	20	16
	0.2	0.3	37	11	37	49	17	19
	0.5	0.6	30	13	44	57	15	16
	0.8	0.9	27	14	46	61	14	15
	1.1	1.2	22	20	49	69	9	12
	1.4	1.5	16	29	46	75	9	10

3.5 Land Use

Land use maps for Burdekin are available for the years 1988, 1991, 1994, 1999, 2000 and 2001. The maps consist of 33 land use classifications (refer to Table 3-2). The previously classified land uses were grouped into the following seven broad land uses for modelling purposes.

Table 3-2 Land use classification with land use index

Previous Classification	Index	New Classification
Airports/aerodromes	5	Urban
Aquaculture	7	Water (Rivers/Reservoirs/channels etc.)
Biodiversity	4	Natural Vegetation/Grass Lands
Commercial services	5	Urban
Grazing natural vegetation	4	Natural Vegetation/Grass Lands
Habitat/species management area	4	Natural Vegetation/Grass Lands
Irrigated sugar	1	Sugarcane
Irrigated tree fruits	3	Tree Fruits (Mangoes)
Irrigated vegetables & herbs	2	Small Crops (Vegetables and herbs)
Manufacturing and industrial	5	Urban
Marsh/weland - production	6	Coastal Wetland/Wetlands
Marsh/wetland - conservation	6	Coastal Wetland/Wetlands
National park	6	Coastal Wetland/Wetlands
Natural feature protection	4	Natural Vegetation/Grass Lands
Other conserved area	4	Natural Vegetation/Grass Lands
Public services	5	Urban
Quarries	4	Natural Vegetation/Grass Lands
Railways	4	Natural Vegetation/Grass Lands
Recreation & culture	5	Urban
Remnant native cover	4	Natural Vegetation/Grass Lands
Research facilities	1	Sugarcane
River – intensive use	7	Water (Rivers/Reservoirs/channels etc.)
River - production	7	Water (Rivers/Reservoirs/channels etc.)
Roads	5	Urban
Rural residential	5	Urban
Shade houses	2	Small Crops (Vegetables and herbs)
Supply channel/aqueduct	7	Water (Rivers/Reservoirs/channels etc.)
Urban residential	5	Urban
Water storage and treatment	7	Water (Rivers/Reservoirs/channels etc.)

Table 3-3 shows the areas of different land uses as a percentage of total area (274,400 ha) in the years 1988, 1991, 1994, 1999, 2000 and 2001. The years 1999 and 2000 virtually have the same land use distribution.

Table 3-3 Land use in different years as a percentage

Index	Areas as % of the total area (274,400 ha) in the year					
	1988	1991	1994	1999	2000	2001
1	23.2	25.7	30.2	36.6	36.6	36.7
2	0.3	0.3	0.3	0.3	0.3	0.3
3	0.6	0.6	0.7	0.7	0.7	0.7
4	53.8	51.3	46.8	40.7	40.7	41.0
5	0.9	0.8	0.9	0.9	0.9	0.7
6	18.8	18.8	18.7	18.3	18.3	18.2
7	2.4	2.5	2.5	2.5	2.5	2.3
Total	100.0	100.0	100.0	100.0	100.0	100.0

The majority of the areas in the Lower Burdekin are categorised as natural vegetation and sugarcane cultivation (Figure 3-7). Small crops and tree fruits cover only about 1% of the area. The change in land use coverage is displayed in Figure 3-7 for 1988, 1991, 1994 and 2001. The largest change observed is for sugarcane, which has expanded to cover large parts of the BHWSS area as well as the Delta. About 18% of the total area is wetlands.

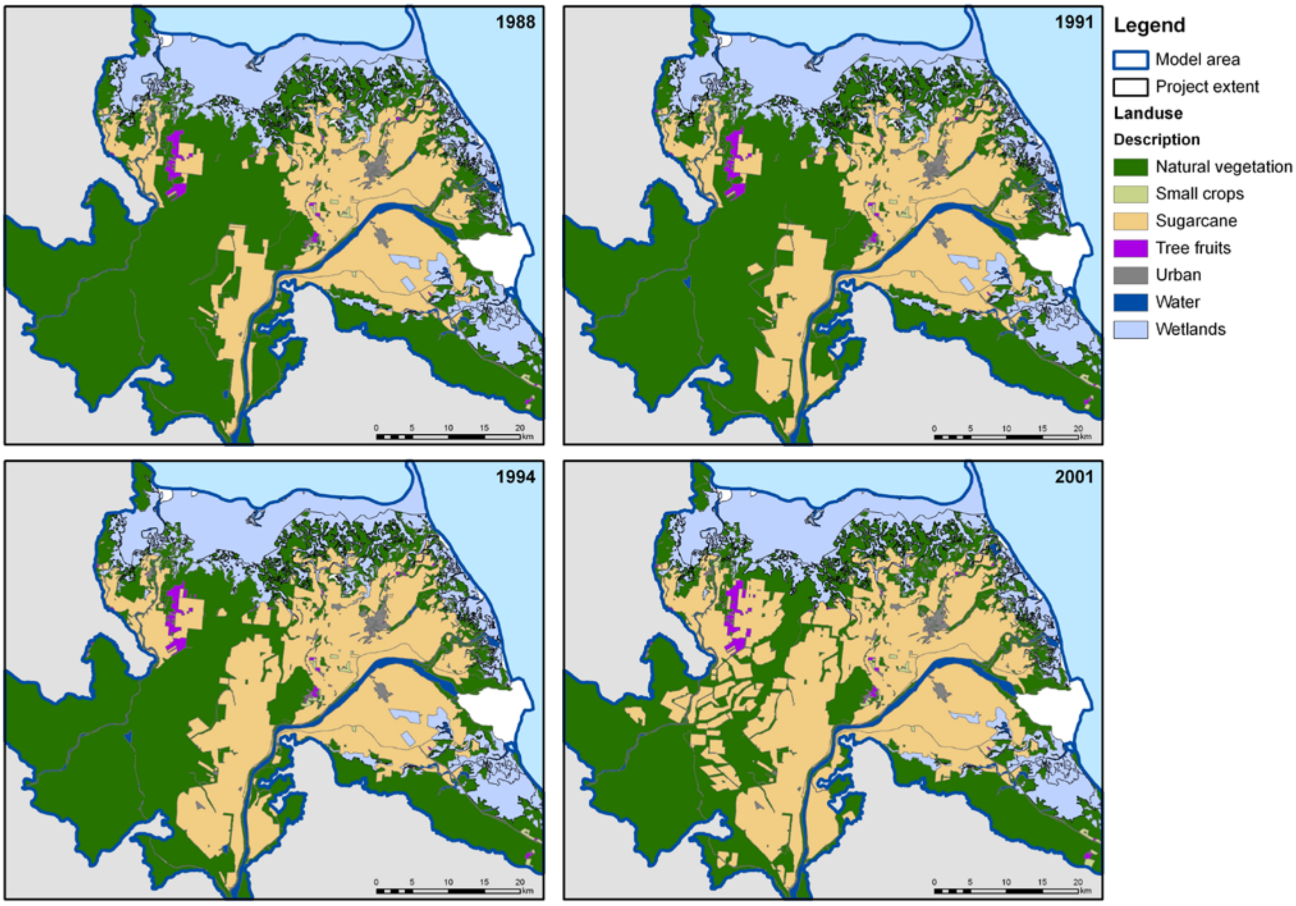


Figure 3-7 Land use coverage for 1988, 1991, 1994 and 2001

3.6 Wetlands

The Bowling Green Bay wetlands along the northern most extent of the model area are classified as a wetland of international significance under the Ramsar convention, (Figure 3-8). In addition, many of the wetlands throughout the area have been classified as having national importance and have been included in the National Directory of Important Wetlands (Environment Australia 2001). These wetlands are also shown in Figure 3-8.

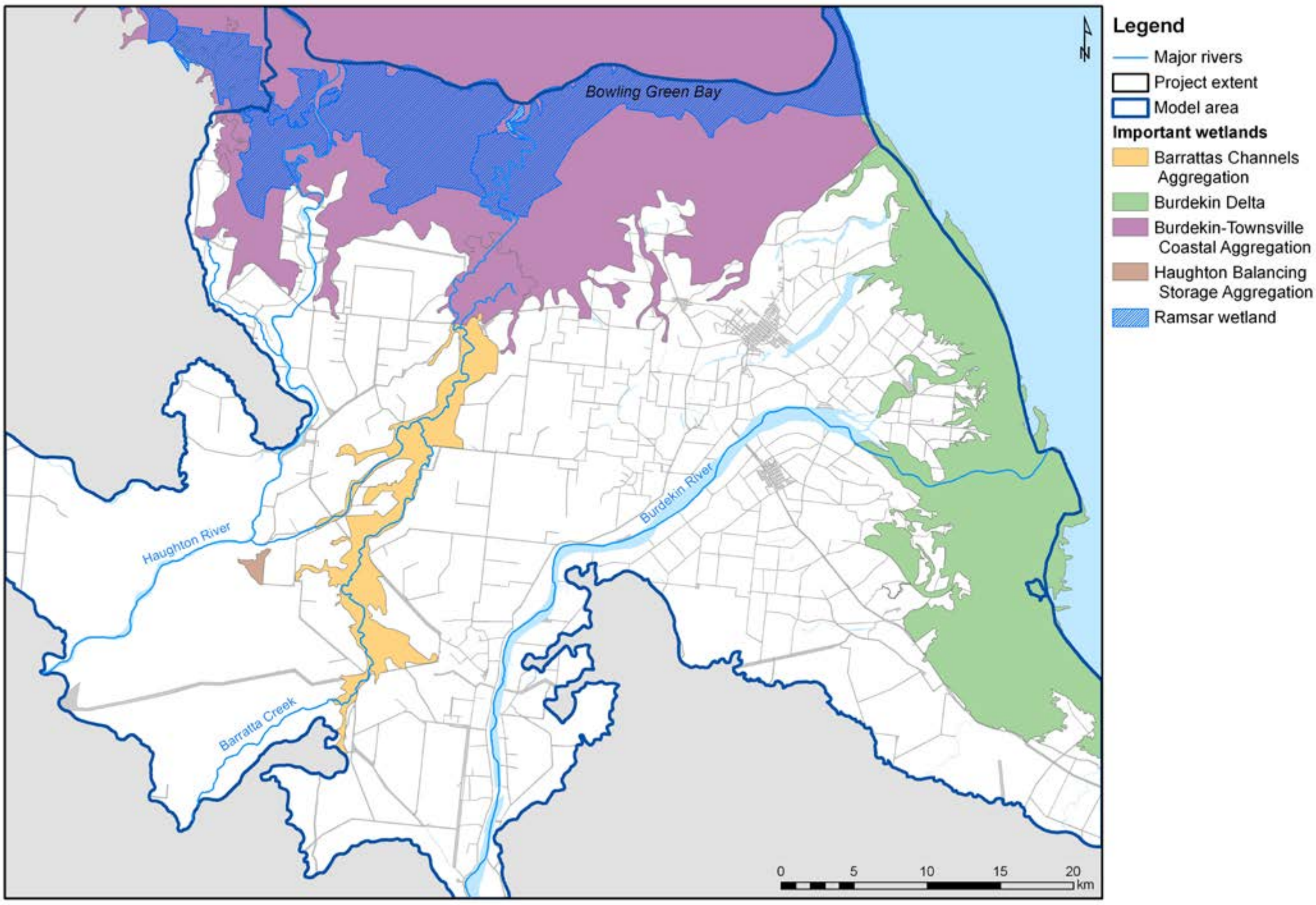


Figure 3-8 Nationally important wetlands in the Lower Burdekin, including Bowling Green Bay, a RAMSAR wetland

Recently, under the Queensland Wetlands Programme, wetlands have been classified and mapped at a scale of 1: 100 000 or greater (EPA 2005). This mapping, for the lower Burdekin, was based on 2005 Landsat imagery. Wetland classifications are based on five major wetland systems as recognised in the scientific literature (Cowardin et al. 1979). These systems are Marine, Estuarine, Riverine, Lacustrine and Palustrine. While Marine and Estuarine systems are typically affected by tidal salinity, the other wetland systems are not. Marine systems consist of the open ocean overlying the continental shelf. Estuarine wetlands are typically comprised of mangroves, salt flats and estuaries and include deepwater tidal habitats and adjacent tidal wetlands. Along the coastlines there is normally appreciable dilution of seawater within the Estuarine wetlands (Cowardin et al. 1979). Riverine, Lacustrine, and Palustrine wetlands are the wetland systems that are associated with rivers, lakes (and topographic depressions or damned river channels), and vegetated non-tidal swamps, respectively.

While the majority of the wetlands in the Lower Burdekin are Estuarine wetlands near the coastline, all of the five major wetland systems are present (Figure 3-9). Some of these wetlands are present within the irrigation areas, adjacent to sugarcane farms and water storage infrastructure (Figure 3-9).

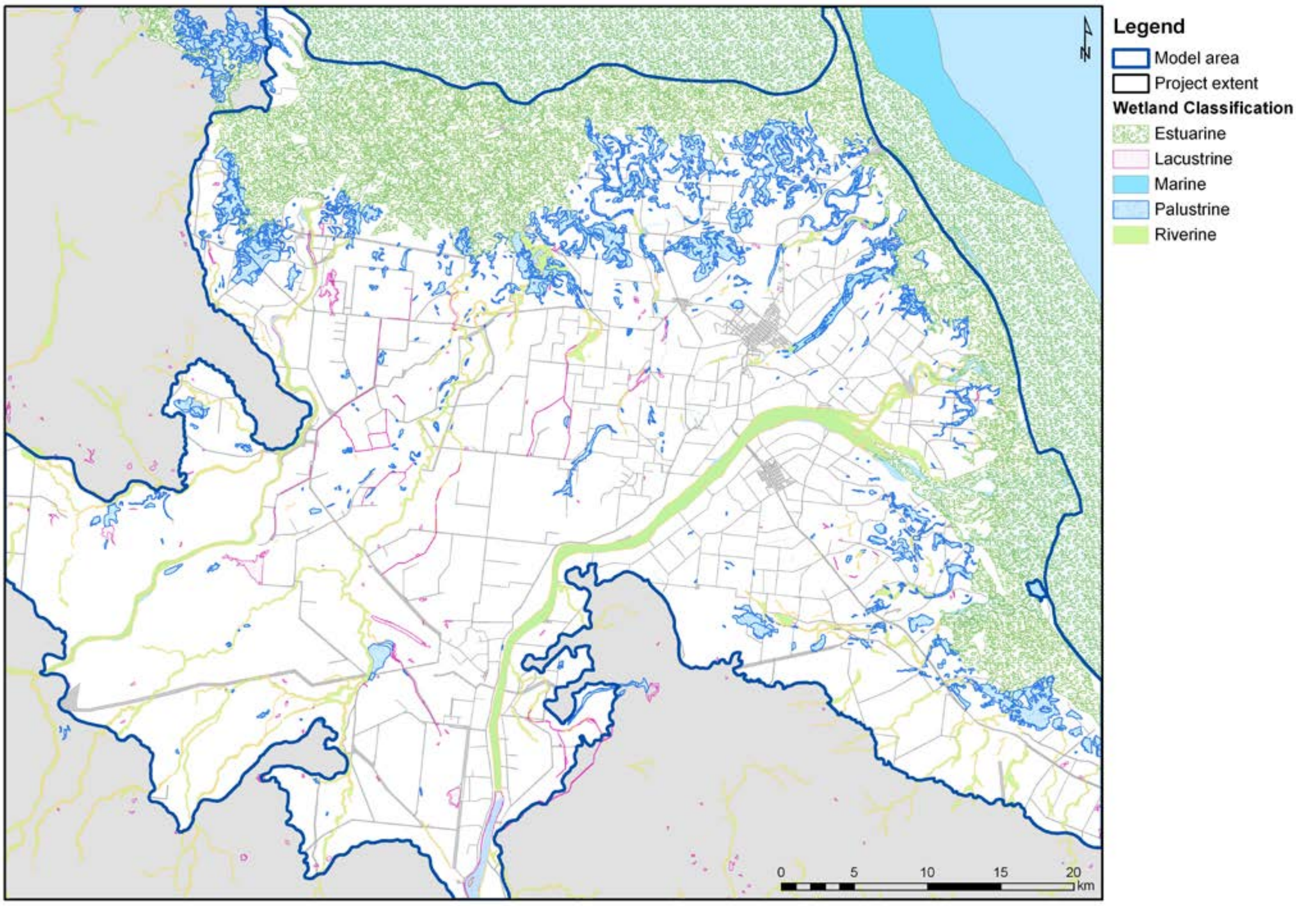


Figure 3-9 Wetland types in the Lower Burdekin

4 Climate

4.1 Rainfall

Rainfall data is needed for estimating the irrigation demand and the recharge to aquifer. There are a number of rainfall stations in and around the Lower Burdekin Area, but no single station has a complete long term record of data. A complete record of rainfall is essential to estimate recharge and irrigation demand through APSIM, therefore the rainfall from the stations presented here is sourced from the patched point dataset from the BOM Silo "patched point" dataset (www.bom.gov.au/silo), in which, the actual record of rainfall and evaporation is kept in the dataset with the gaps between actual records of rainfall and evaporation filled with interpolated data.

Figure 4-1 presents the location of the rainfall stations along with the mean annual rainfall (shown in brackets) for the rainfall stations in the Burdekin Groundwater Model area for the period from July 1890 to June 2006 (based on patched datasets from Silo). Rainfall contours are constructed for the model area using rainfall data obtained from the BOM Silo "data drill" system (interpolated rainfall values to a 5 by 5 km grid cell in the model area).

Figure 4-1 Rainfall stations, mean annual rainfall (mm) and rainfall contours (50mm) in the study area

Table 4-1 presents the average monthly rainfall over the year for each station for the period from July 1890 to June 2006. All the stations show similar monthly rainfall variation across the study area.

Table 4-1 Rainfall monthly distribution pattern for each rainfall station (mm)

Month	Station Number							
	33001	33002	33020	33033	33035	33069	33073	33122
Jan	252	244	239	223	254	302	222	228
Feb	259	250	229	216	253	270	201	196
Mar	170	163	152	138	176	187	146	135
Apr	60	58	54	49	66	64	47	47
May	36	34	33	33	39	38	32	30
Jun	31	30	29	28	31	30	29	27
Jul	18	18	16	16	18	23	18	18
Aug	15	15	14	14	16	19	17	14
Sep	19	18	17	14	17	18	14	14
Oct	24	25	24	24	27	27	21	20
Nov	43	42	39	37	45	51	44	39
Dec	112	105	103	101	111	123	103	94
Total	1039	1003	948	893	1054	1151	893	861

Based on the eight rainfall stations shown in Table 4-1 the cumulative residual mean curve has been constructed (refer to Figure 4-2 for the period from 1980 to 2010. During this time, there is an overall trend of below-average rainfall resulting in a general decline in cumulative residual rainfall. The main exceptions are for periods of above-average rainfall between 1990 and 1992, and between 2000 and 2002.

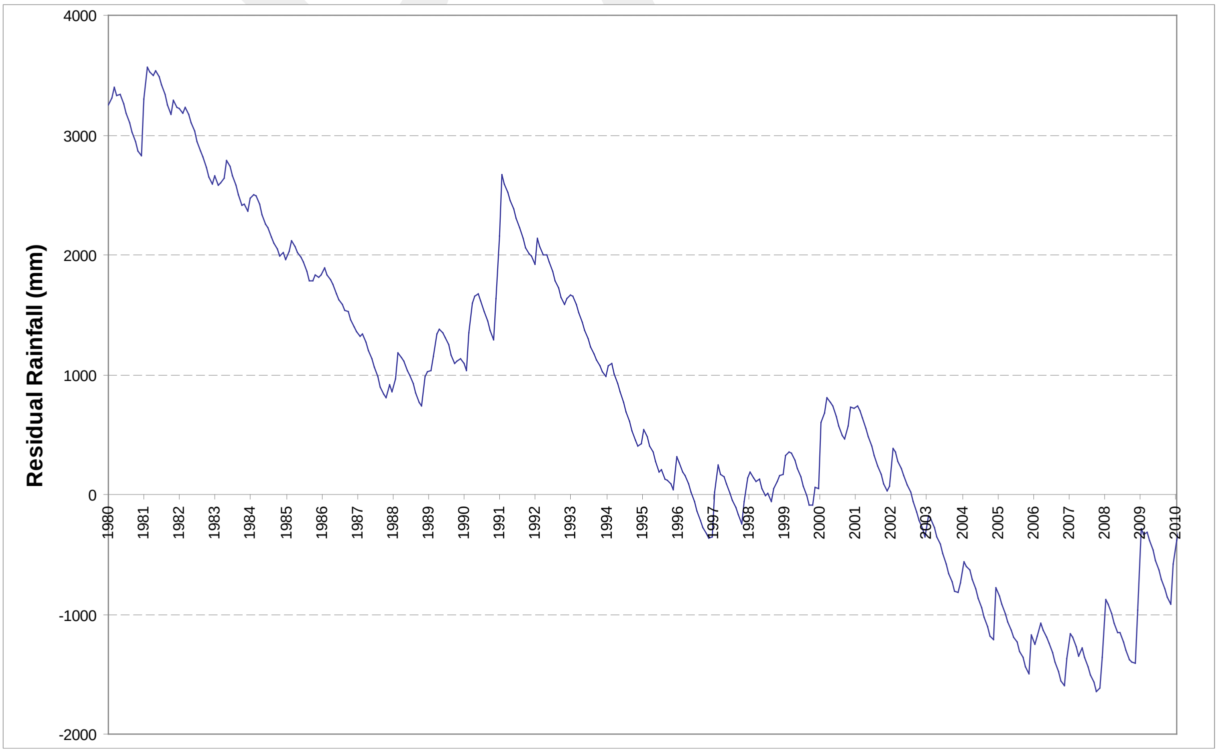


Figure 4-2 Cumulative residual mean rainfall (based on average from the 8 rainfall stations in the model area).

To consider the spatial variation in rainfall across the study area, the total region is divided into four rainfall zones based on the 1000mm contour line and a north-south line that approximates the boundary between the BHWSS and the delta regions (Figure 4-3). One rainfall station has been selected as representative for each area (33001 zone 1, 33069 zone 2, 33073 zone 3 and 33033 zone 4). These stations are used for each zone as they have the longest records compared to surrounding stations.

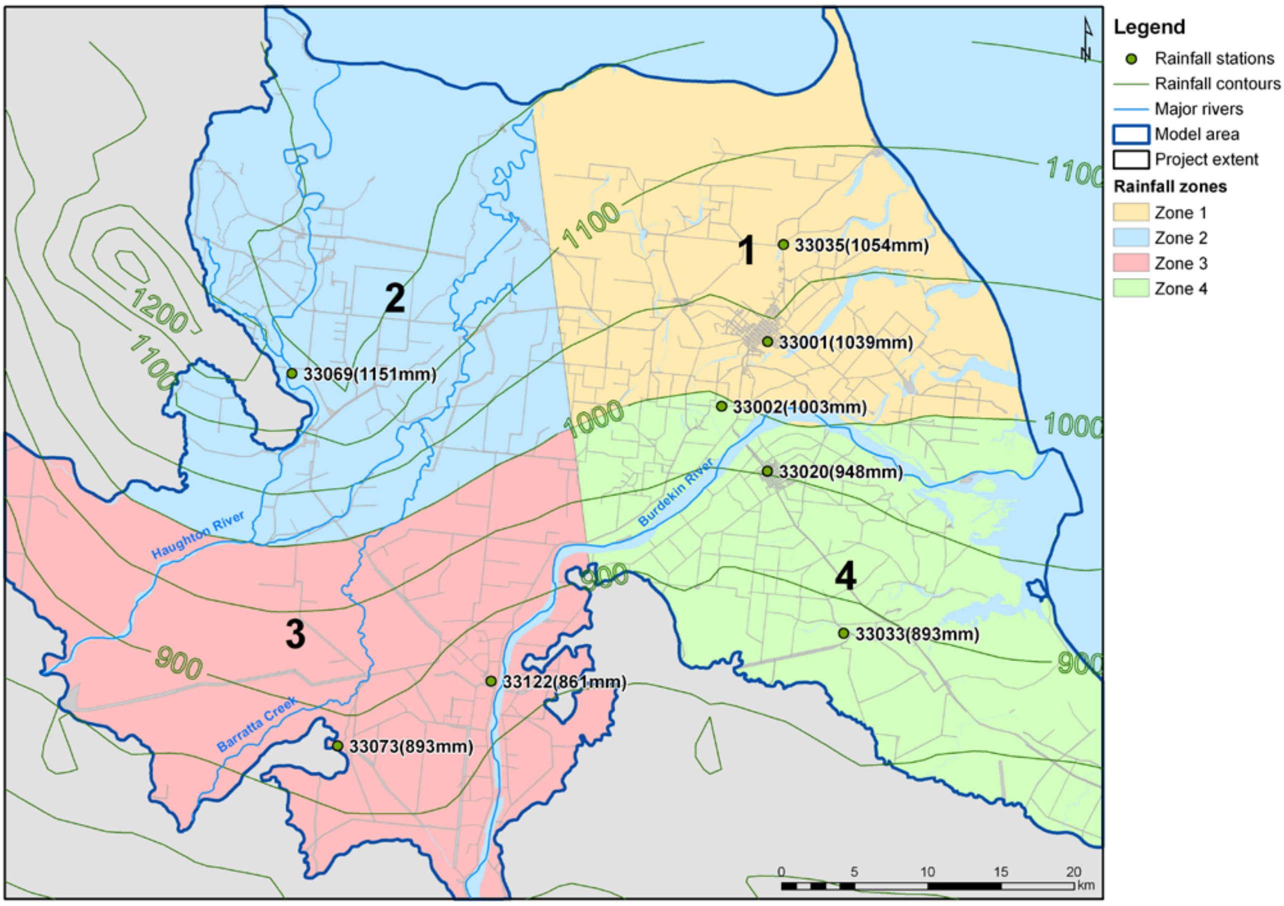


Figure 4-3 Rainfall zones 1-4

4.2 Evaporation

Evaporation stations located within or near the study area are listed in Table 4-2 and locations are shown in Figure 4-4. The Townsville Aero, Millaroo DPI and Guthalungra Qld Salt stations are outside of the study area. The Ayr DPI Research Station is the only pan evaporation station within the study area that has a relatively long record (42 years). The recording of evaporation data for this station started at 1958 and completed at 2000 with some gaps. Based on calendar years having complete records, the mean annual pan evaporation is 2057 mm with maximum 2315 mm and minimum 1829 mm.

Table 4-2 Mean, minimum and maximum annual pan evaporation for evaporation stations near the model area

Name of Station (& Station Number)	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Number of full years of daily recording	Date range for measurements	Annual PAN evaporation (mm)		
						Mean	Min	Max
Townsville Aero (32040)	19.2478	146.767	7.5	34	18/07/1969 - 31/05/2004	2601.13	2169.9	3236.4
Ayr DPI Research Station (33002)	19.6169	147.376	12	26	01/01/1958 - 29/09/2000	2056.97	1828.9	2315.2
Kalamia Estate (33035)	19.5244	147.416	6.1		01/02/1996 - 30/11/1998			
Guthalun-gra QLD Salt (33079)	19.8667	147.817	4.3	2	01/01/1965 - 30/12/1966	2077.52	2045.75	2109.29
Millaroo DPI (33090)	20.0464	147.274	45.4	19	01/01/1965 - 30/06/1993	1778.32	1675.57	1963.9

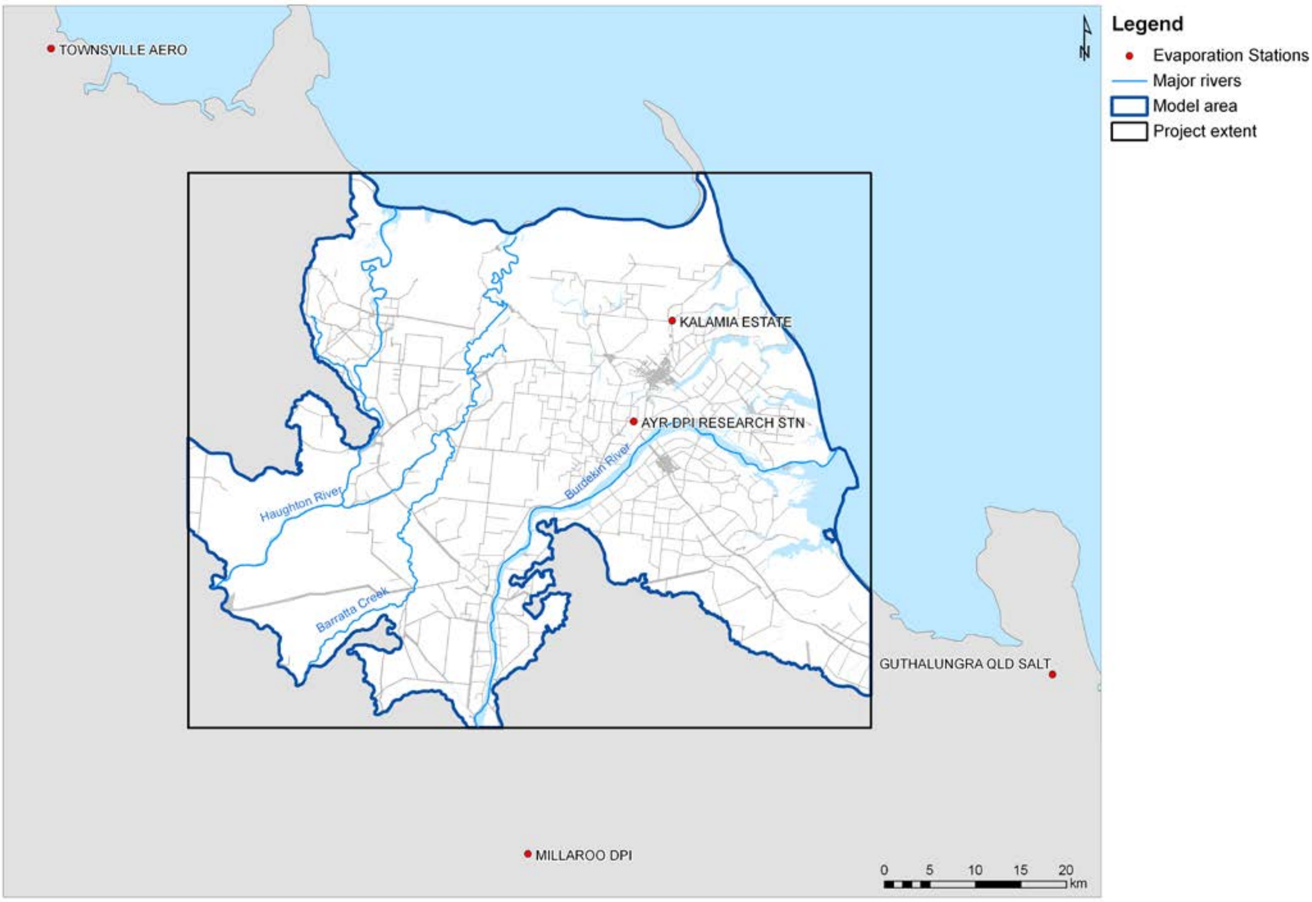


Figure 4-4 Stations with pan evaporation records near the model area

The contours of mean pan evaporation for the period from July 1890 to June 2006 is generated using the pan evaporation data drill obtained from the BOM Silo "data drill" system at 5km distance for the study area and shown in Figure 4-5. Since the evaporation in the study area does not vary as much as rainfall in the study area, and more importantly, Ayr DPI Research Station is the only site which has measured evaporation rates, the patched point dataset of evaporation for the Ayr DPI Research Station is applied to the whole study area.

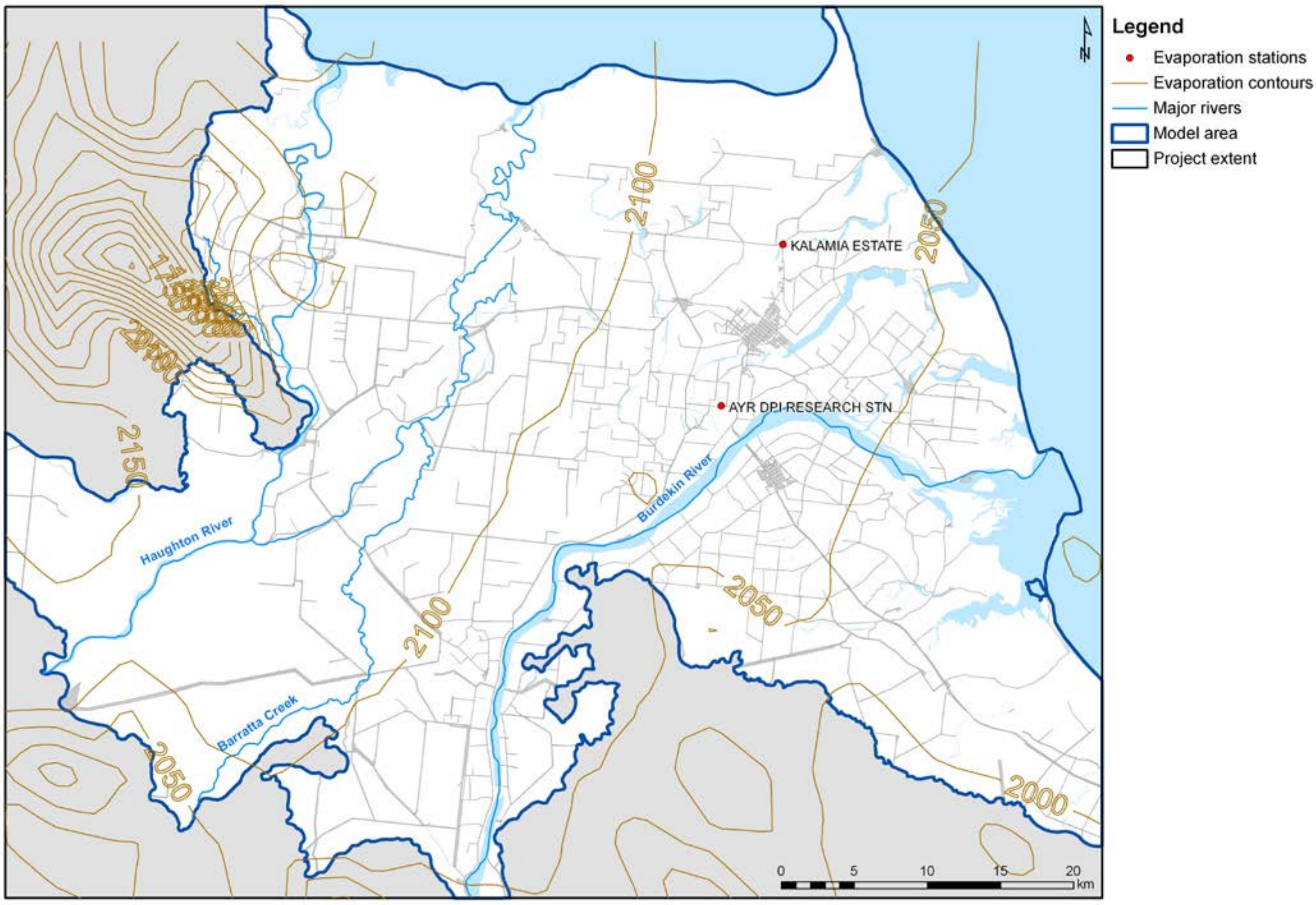


Figure 4-5 Evaporation contours (50mm) in the study area based on the period from July 1980 to June 2006

4.3 Evapotranspiration from Groundwater Dependant Ecosystems

Groundwater dependant ecosystems (GDEs) can include terrestrial vegetation, wetland communities, river base flow systems, aquifers, terrestrial fauna and estuarine and near-shore marine environments (Cook et al. 2006). The degree of dependence of GDEs on groundwater can range from ecosystems being entirely dependant to ecosystems which may only use groundwater opportunistically (Hatton&Evans 1997).

In this section, water uptake by terrestrial and estuarine vegetation is considered and groundwater evapotranspiration (EVT) rates from the wooded areas in the Lower Burdekin are estimated. A methodology to estimate regional EVT rates is presented below with results. This was used to provide input into the overall water balance for this conceptualisation report (presented in section 10). In addition to this methodology, a field program was initiated (as part of this project) to further refine EVT estimations for local conditions. The purpose of the investigation was to provide EVT estimations from local conditions for input into the current groundwater flow model, and to continue to revise these estimations for future modelling. The monitoring project was run concurrently with the model development and due to overlapping timeframes the results of this project were not able to be applied in the water balance calculations as this task preceded the collection of a suitable dataset. For this reason, an initial estimate was approximated for this purpose however the results of the monitoring project were later used in the flow model. The EVT monitoring project is planned to continue to allow for the extension of the dataset and improvement of future EVT estimates.

Initial EVT Estimation (for Water Balance calculations)

Previous studies have determined that groundwater use is likely to be a function of depth to groundwater, maximum rooting depth for individual species, rooting distribution and soil water reserves (O' Grady et al. 2006). Detailed information was not available on rooting depth and distribution and soil water reserves so estimates were made based on groundwater table depths and vegetation density (using foliage projective cover maps). A similar method was used by Groeneveld (2007) where EVT was estimated using vegetation indexes extracted from Landsat images and weather data.

An approach for considering the effects of EVT in a catchment based on depth to groundwater is suggested by Evans (2007). The typical groundwater EVT ranges suggested were between 10-100 mm/year when the ground water table is 2-5m from the ground surface and between 100-1000 mm/year when the water table is within 0-2m from ground surface (Evans 2007). This approach assumes that when the water table is > 10 metres below the surface, EVT of groundwater is negligible.

In Figure 4-6, the depth to groundwater from ground surface is shown for March 1983 and March 1991 (blue colours for greater than 5 meters below ground surface and red/brown colours for within 5 m AHD of ground surface). In 1991, there was a large flood and the figure shows the larger area where the water table is close to the ground surface. The water table is generally shallowest in the coastal area and in the Delta area.

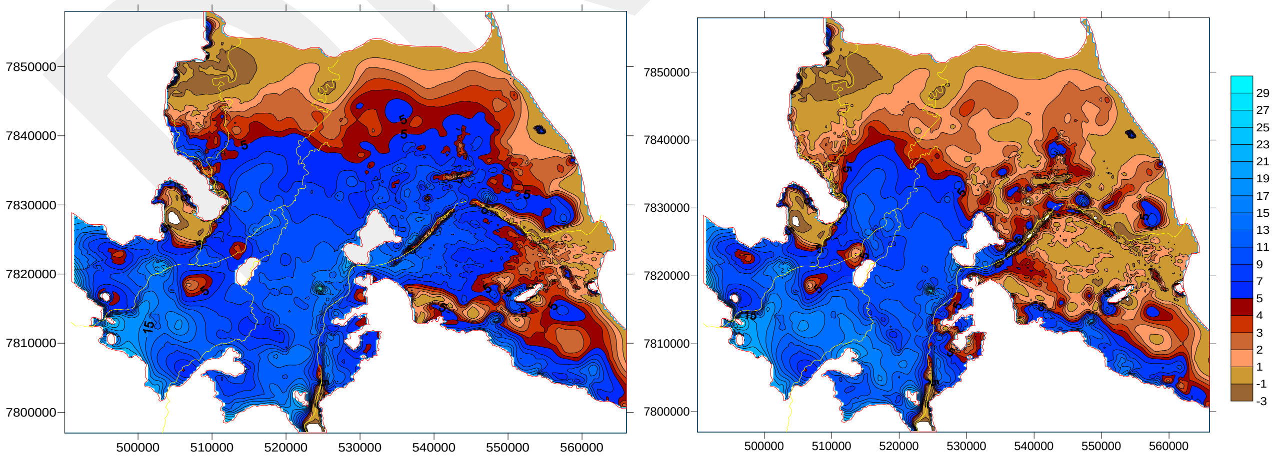


Figure 4-6 Comparison of water levels from ground surface (DEM subtracted from water levels in m AHD) from March 1983 and 1991

In Figure 4-7, the Foliage Projective Cover (FPC) maps for the model area for 2001 is displayed. The light-coloured areas are non-wooded and the darker shades of green represent the foliage cover in the 1-100%

range. The densely wooded areas are concentrated along the coastal zone where estuarine wetlands are present and along Barratta Creek.

Based on the March 1991 groundwater levels, the area where the water table was within 0-5m of ground surface was defined to capture the maximum likely area for groundwater EVT (Figure 4-8). The wooded areas (based on the FPC map) and the areas with shallow water tables were used to estimate annual EVT. The influence of estuarine wetlands (including mangrove areas) on EVT was considered by separating the area where estuarine wetlands are present, as depicted in Figure 4-8.

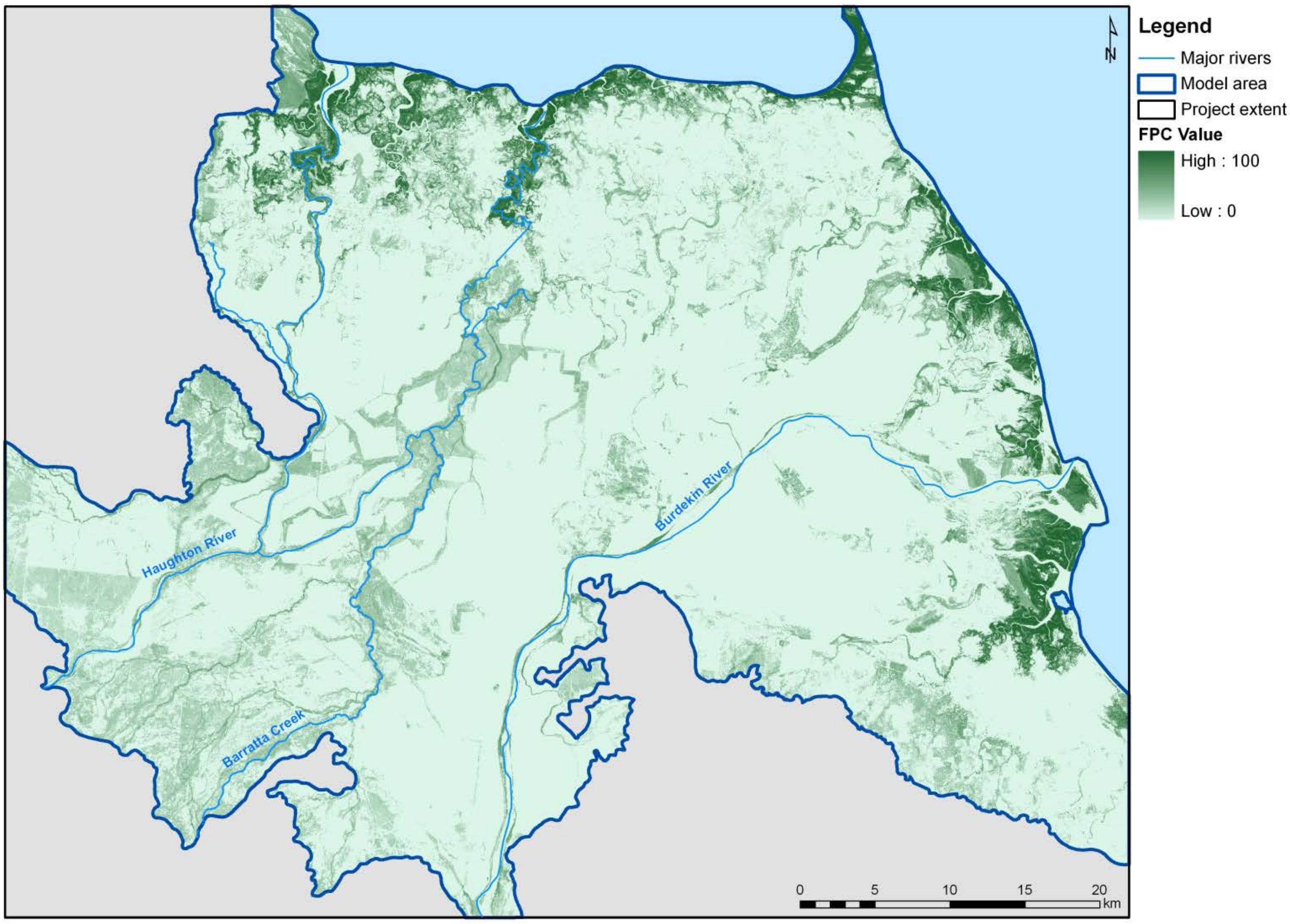


Figure 4-7 Foliage Projective Cover (FPC) map, showing wooded vegetation in the 0-100% range in green

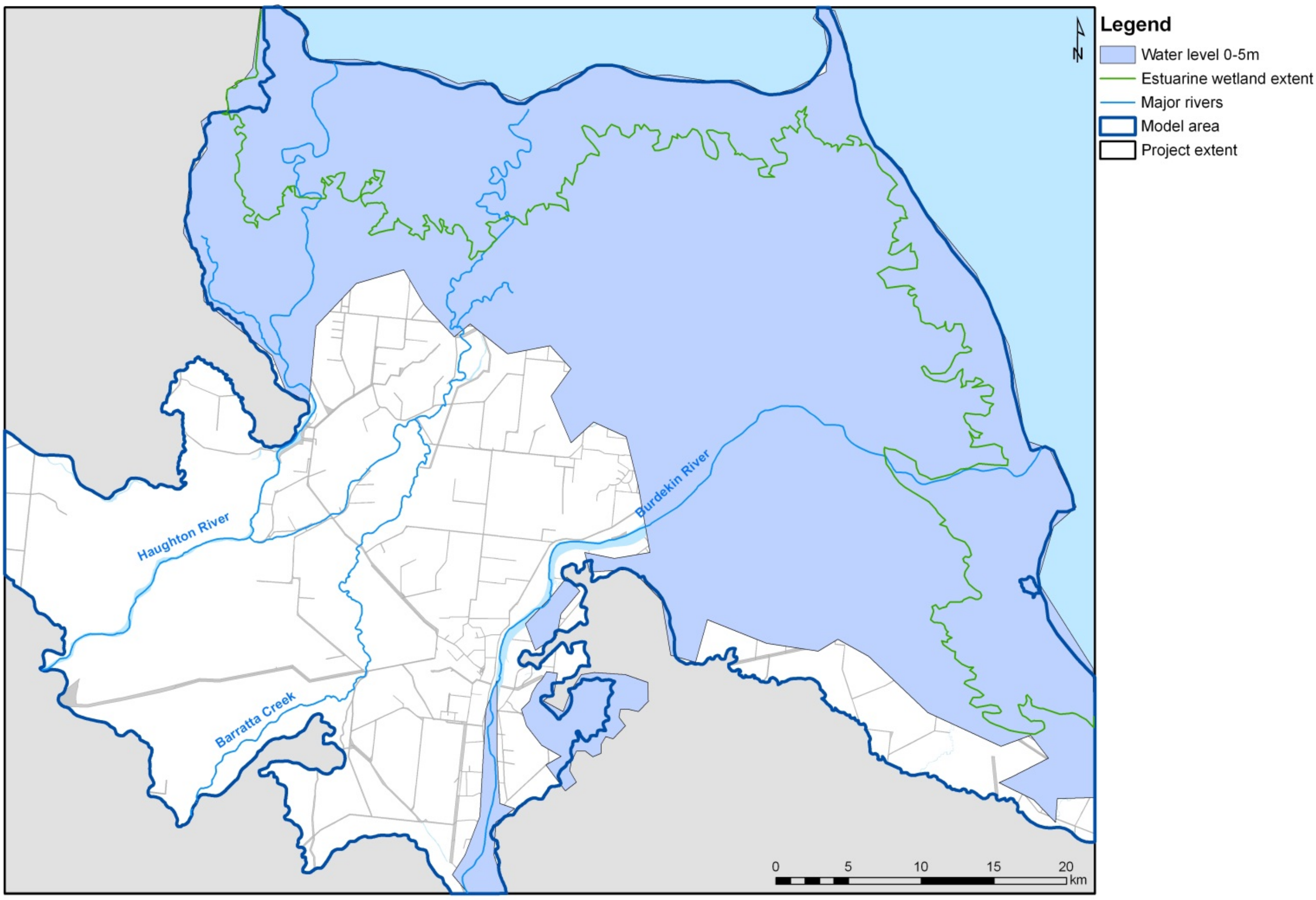


Figure 4-8 Areas where water table was within 0 to 5 m from ground surface is marked in blue. Green line marks the estuarine wetlands extent.

Estimations of yearly evapotranspiration (EVT) have been carried out for 7 different scenarios.

1. Wooded (2-100% FPC), entire model area
2. Heavily wooded (50-100% FPC), entire model area
3. Heavily wooded (50-100% FPC), entire model area, excluding the estuarine wetlands
4. Wooded (2-100% FPC), water tables within 0-5m of ground surface
5. Wooded (2-100% FPC), water table within 0-5m of ground surface, excluding the estuarine wetlands
6. Heavily wooded (50-100% FPC), water table within 0-5 m of ground surface
7. Heavily wooded (50-100% FPC), water table within 0-5 m of ground surface, excluding the estuarine wetlands

An estimated EVT range of 10 to 100 mm/year was used for vegetated areas where the water table is < 5 metres below the surface. The scenarios that take into account the vegetation cover and the depth to groundwater (i.e. scenarios 4-7) are expected to be the most realistic. The results for each scenario are presented in Table 4-3.

Table 4-3 Estimated EVT under different scenarios

	Units	Scenario						
		1	2	3	4	5	6	7
Water Table	m	All	All	All	0-5m	0-5m	0-5m	0-5m
Estuarine Wetlands Included?	-	Yes	Yes	No	Yes	No	Yes	No
FPC	%	2-100	50-100	50-100	2-100	2-100	50-100	50-100
Area	Km^2	839	158	30	450	219	128	21
EVT Min (10mm/y)	ML/Year	8391	1578	295	4502	2189	1283	215
EVT Max (100mm/y)	ML/Year	83907	15781	2950	45017	21893	12831	2145

The model area covers 2760 km2 so the proportions of the area that are wooded or heavily wooded are 30% and 6% respectively. The estuarine wetlands near the coast are the main contributor to the calculated EVT values as most of the wooded vegetation occurs in this area. For example, the EVT values calculated for wooded vegetation and water tables within 5 m of the surface, with estuarine wetlands included range from 4500-45000 ML/year. For the scenario where estuarine wetlands are not included, the EVT values calculated for wooded vegetation and water tables within 5 m of the surface range from 2200-22000 ML/year. However, all of these estimates are based on the assumption that the wooded vegetation present is groundwater dependant. The actual EVT rates would depend on characteristics of the species presents and on dynamic local hydrology variables (e.g. rainfall, evaporation, groundwater levels, river water levels and soil moisture levels).

Revised EVT estimates from monitoring (for Groundwater Flow Model)

Until now there has been a limited understanding of the vegetative losses from groundwater in the Lower Burdekin. Evapotranspiration from groundwater has been measured at sites in the Pioneer Valley catchment for the purposes of identifying GDE condition and processes but no measurements of this type have been made in the Lower Burdekin. Therefore, a research project was initiated in order to determine a location specific evapotranspiration rate from groundwater dependent ecosystems within the Lower Burdekin floodplain. This was accomplished through the undertaking of a significant monitoring project at Inkerman in the Lower Burdekin and resulted in a comprehensive dataset which could be utilised to determine a reliable estimate of groundwater discharge via evaporative fluxes for implementation into the EVT package of the groundwater flow model. The methodology and results of this project are outlined in the accompanying report Quantification of evapotranspiration in a groundwater dependent ecosystem (Corbett & Reading, 2012).

For a given transect of riparian vegetation extending from a baseflow (gaining) stream to an adjacent floodplain, water use for the dominant species was measured using sap flow meters against monitored soil water response, groundwater levels and climatic conditions over a 5 month period. Monitoring is still ongoing and if possible, longer term measurement across a number of years to pick up slower cycles as well as diurnal and seasonal trends would be beneficial. The overall aim was to establish the expected rates of groundwater uptake for dominant vegetation species on a seasonal climatic basis, as well as understanding the degree of dependence on groundwater.

The determination of EVT rates within the Lower Burdekin were ultimately fed into the groundwater flow model. This means that rather than utilising a simple literature value, it can be confidently assumed that the rate of discharge from the aquifer via EVT is based on specific rates measured within the region. Therefore an increase in data confidence and as a result model confidence is obtained. This means that any future work undertaken with the groundwater flow model will ultimately benefit from this research project.

In order to determine a transpiration rate which was applicable to the Lower Burdekin as a whole, the data collected for the representative trees at Inkerman had to be up-scaled to provide a model-wide estimate for the predominant native vegetation type within the project area. Previous studies have used the “quantiles of total” method (or similar approaches) whereby sap flow is measured in a number of selected trees encompassing a range of sizes representative of the stand. This was the approach taken in this study with each monitored tree chosen to represent approximately the same fraction of the selected stand parameter – in this case basal area and leaf area. The parameter must be easily measurable at both the individual tree and stand level. Through mapping of foliage projective cover and the work of Specht (1989) this was made possible.

It must be noted that due to the project’s time constraints and concurrent development of the groundwater flow model and EVT monitoring, only the results from 5 months of EVT monitoring could be applied to the groundwater model. As further modelling is progressed beyond this project, EVT rates can be updated as further monitoring data becomes available.

In order to utilise the measured rates the average basal area of the monitored Eucalypts was determined. The mean basal area of $0.073m^2$ was used in conjunction with the approximate basal area per hectare ($8m^2$) to calculate the equivalent number of trees per hectare. It was calculated that an average of 110 Eucalypts per hectare could be expected for the typical native vegetation type within the Lower Burdekin. This figure was then used in combination with the measured EVT rates from the individual trees to determine an average flux per hectare.

An estimate of the total evapotranspiration from Eucalypts was made using the average leaf area index (LAI) of the region to determine a total basal area per hectare which was then used in conjunction with measured evapotranspiration values. The value estimated for Eucalypt woodland is 4965L/ha per day or 181mm/year. The estimate for the evapotranspiration of riparian vegetation is 6654L/ha per day or 243mm/year. As riparian vegetation could not be distinguished from other vegetation with available mapping, the estimated value of 181 mm/year is used in the model.

5 Hydrogeological characterisation

5.1 Hydrogeology

The aquifers of the Burdekin River Delta comprise a complex assortment of deltaic/ fluvial sediments interbedded with marine / littoral deposits overlying bedrock comprising mostly granitic rocks (McMahon 2004). The dominant processes responsible for the construction of the Holocene delta are related to major runoff events, while waves only modify the shoreline deposits (Fielding, Trueman & Alexander 2006). The vertical sequences and stacking patterns of the Burdekin Delta are dissimilar to those widely regarded as typical of deltaic successions, and they show an internal complexity that is generally under-appreciated (Fielding, Trueman & Alexander 2006).

The Holocene Burdekin River delta was constructed as a series of discrete lobes, formed as the river changed course (Fielding, Trueman & Alexander 2006). The deposits from older former river courses, including the earliest mapped Holocene deposits in the BHWSS area, are typically found deeper in the stratigraphic profile whereas the more recent deposits, including those in the active Delta area, are closer to the surface. These deposits from the former courses of the Burdekin River were mapped by Fielding et al (2006) and dissect the majority of the area to be modelled. In addition, significant channel deposits have also been mapped in the Mulgrave area to the south of areas mapped by Fielding et al (2006). Hence these Holocene deposits dominate the aquifers in the model area.

The Holocene sediments are separated from the underlying Pleistocene sediments by a layer of firm, semi-consolidated and oxidised sediments (McMahon 2004). However it is difficult to map this surface over the whole region as groundwater bore logs typically do not allow clear discrimination between Pleistocene strata and Holocene sediments (Fielding, Trueman & Alexander 2006).

While the complexity of this hydrogeological system is recognised, the individual layers have been previously found to be interconnected and behave hydraulically as one aquifer unit (KBR 2002, Klohn Crippen Berger 2008). Previous models of the Delta and BHWSS areas have therefore used one layer to model the system (Arunakumaren, McMahon & Bajracharya 2001, Doherty 1997, Hillier 1998b, Merrick 1998). A major exception to the single layer classification is in the BHWSS region where an extensive surficial clay layer forms a semi-confining unit to the underlying sand aquifers (Australian Groundwater Consultants 1982, Evans 1998).

By comparison to the sediments, it is typically assumed that the bedrock has very low permeability and is not a major hydrogeologic unit in the region (Hillier 1998b). However, the granite basement that underlies the sedimentary deposits is often weathered or fractured (Hillier 1998b, Hopley 1970, McMahon 2004), and in the southern portion of the study area many bores are screened within the bedrock, indicating some level of groundwater permeability. As the fractured basement formations can play a significant role in groundwater flow, storage, and quality (Klohn Crippen Berger 2008), it is important to incorporate the fractured bedrock into the groundwater flow model as a separate hydrogeological unit.

The final challenge in using one layer to represent the groundwater flow system is the incorporation of local vertical permeability contrasts towards the northern extent of the model area. An example is a shallow sand body which has been delineated in the Giru area in previous stratigraphic assessments (KBR 2002). In addition to anecdotal evidence of permeability decreases with depth in parts of the alluvial aquifer in the

Jardine-Selkirk and Horseshoe Lagoon areas, a previous hydrogeological and modelling study (Australian Groundwater Consultants 1982) defines a clay layer splitting the aquifer in two based on the interpretation of strata logs in this area. However, the presence of this feature can not be confirmed by stratigraphic records or groundwater level behaviour.

Four main hydrogeological units were mapped forming the basis for three conceptual aquifer layers. The deepest layer is the fractured/weathered bedrock zone which is underlain by fresh impermeable bedrock. Directly overlying the basement are the main alluvial sediments that span the Lower Burdekin floodplain. Across the majority of the area, these alluvial sediments can be segregated into a lower unit of pre-Pleistocene age and an upper sequence of younger Holocene sediments. These sedimentary units demonstrate differences in vertical connectivity throughout the Lower Burdekin. The distinction between the upper and lower alluvial units has been mapped as an intermediate mid-alluvial surface. Finally, a clay layer overlies the alluvial aquifer for most of the BHWSS area, and acts essentially as a confining to semi-confining unit. These layers are depicted in Figure 5-1.

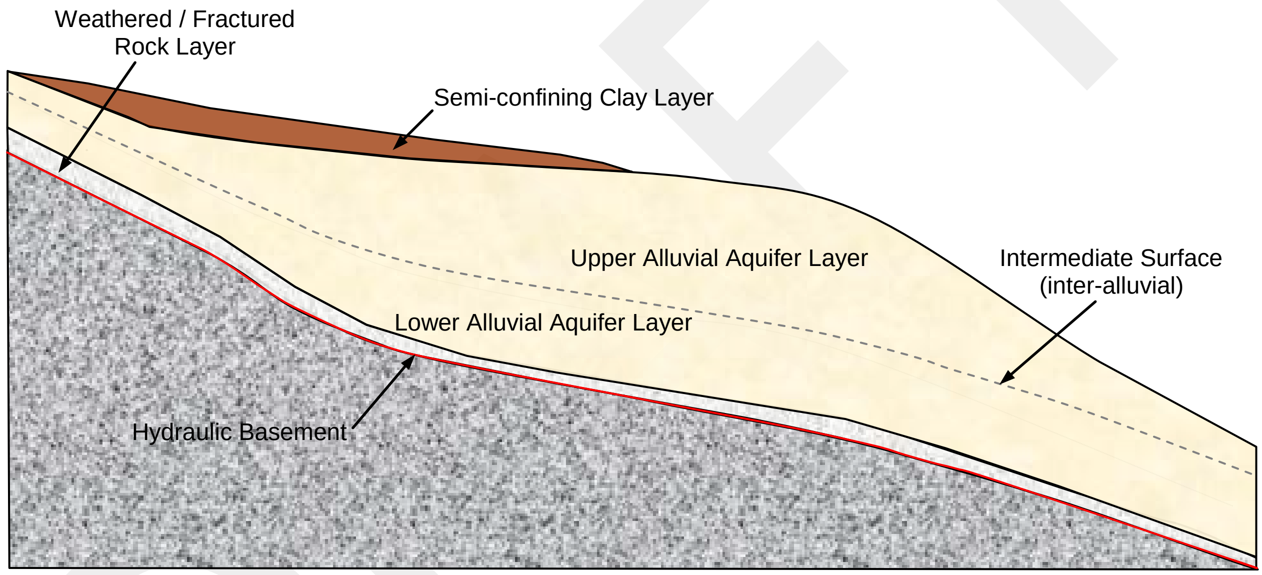


Figure 5-1 Schematic representation of the main hydrogeological layers of the Lower Burdekin aquifer

5.2 Top of Alluvial Aquifer

There are two primary features that define the top of aquifer for the Lower Burdekin area:

- Natural surface where the aquifer is essentially unconfined (no surficial clay layer); and
- Base of surficial clay layer (where semi-confining to confining conditions exist).

The surficial clay layer is restricted to the western part of the study area in the BHWSS region. This clay extends to a maximum thickness of 23 m, but typically averages about 4 m thickness. Fragmented subsurface clay also occurs to a lesser degree in the Delta area to the east, and usually at depth, starting from about 7 m below surface. These sediments are more likely to relate to marine transgressions associated with mangrove mud sequences. These layers have experienced a different depositional history to the surficial clay layer and are frequently discontinuous in section. As a result, these layers considered a lateral extension of the surficial clay layer observed in the BHWSS.

A clay thickness map was generated to show the extent and depth of the surficial clay layer in the BHWSS area (Figure 5-2). The base of this layer represents part of the "Top of Alluvial Aquifer", connecting to the natural surface in the Delta region. The surficial clay layer was mapped from observation of strata logs from GWDB, and as such the transition from natural surface to surficial clay necessitated the use of control points to map the surface across the entire Lower Burdekin region into a final "Top of Alluvial Aquifer" layer (Figure 5-3).

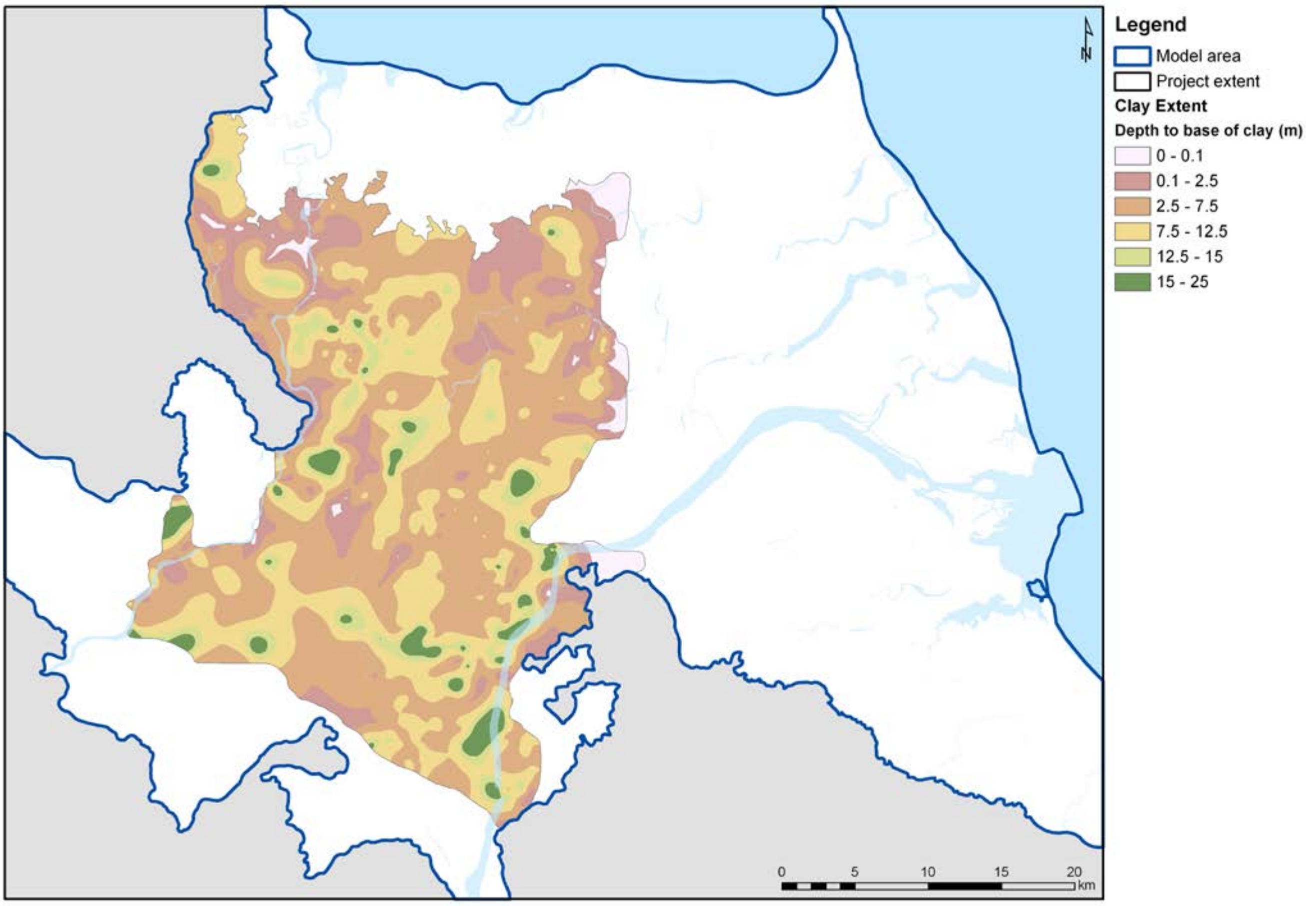


Figure 5-2 Spatial distribution and total thickness of the surficial clay unit

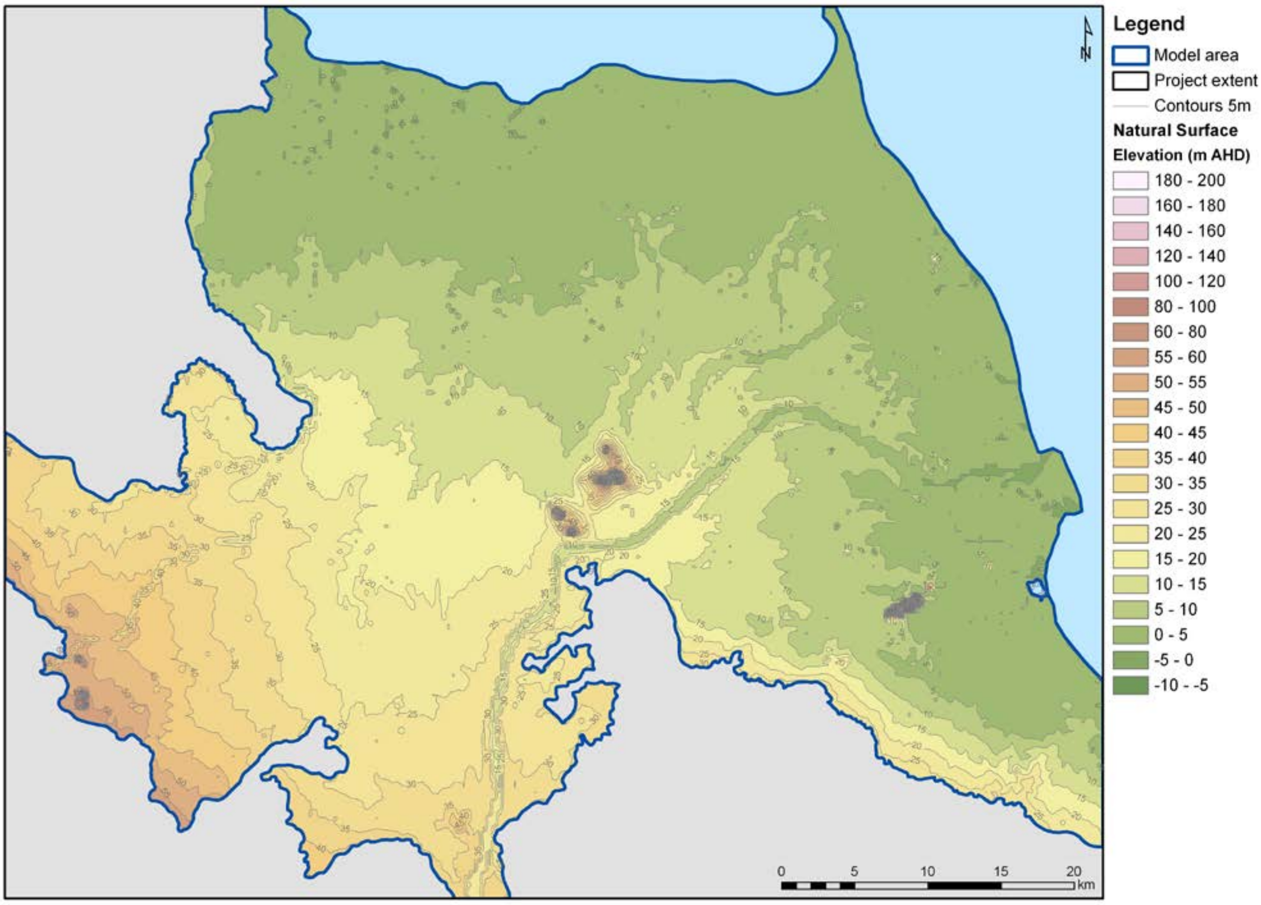


Figure 5-3 Elevation of the top of the alluvial aquifer (m AHD)

5.3 Alluvial Aquifer

The Lower Burdekin alluvium can be defined as having upper and lower alluvial sediments that differ in hydraulic conductivity but are still likely to be vertically interconnected. These alluvial layers, are typically described as being characteristic of cleaner fresher water in the upper-alluvial and dirtier more saline/brackish waters in the lower-alluvial. To differentiate between the two, an inter-alluvial surface, Figure 5-4, was constructed through the use of strata log information, consultant reports [KBR, 2002; *Klohn Crippen Berger*, 2008], research studies (Fielding, Trueman & Alexander 2006) and local expert knowledge established through consultation. A strategy was required that allowed this inter-alluvial aquifer surface to be interpreted and defined on a physical basis. Information relating to the Holocene/Pleistocene sediment separation was utilised to justify and inform the establishment of this surface. However, It was previously noted that the correlation of intermediate sediments is impractical at a regional scale due to lateral discontinuity throughout the Lower Burdekin aquifer system [*Klohn Crippen Berger*, 2008]. As a result the Holocene/Pleistocene sediments have only been used as a starting point for mapping a regional inter-alluvial aquifer surface.

This inter-alluvial surface has also been created to allow for the modelling of vertical variations in hydraulic conductivity, in the Jardine-Selkirk and Horseshoe Lagoon areas where anecdotal evidence indicates less permeable sediments at approximately 30m depth. The purpose of this surface is to test the impact of varying permeability with depth in areas where this surface forms a clear separation in the upper and lower alluvial aquifers. Outside of these areas, where the upper and lower portions of the aquifer are interconnected, hydraulic properties can be allocated such that they remain vertically homogeneous.

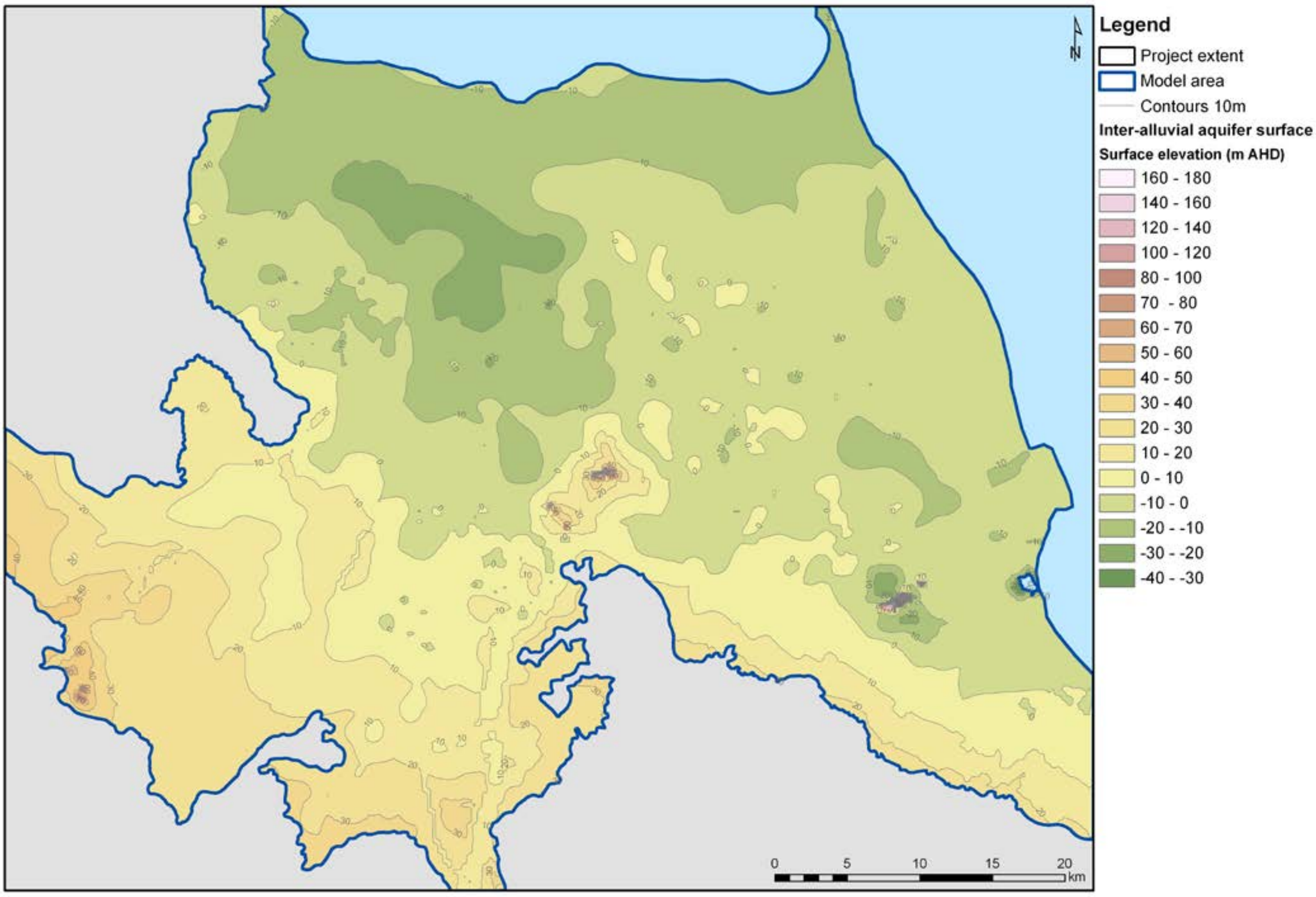


Figure 5-4 Elevation of the Inter-alluvial aquifer surface (m AHD)

5.4 Upper-Alluvial Aquifer

The upper-alluvial aquifer lies below the “Top of Alluvial Aquifer” and immediately above the inter-alluvial surface developed from the previously discussed rationale. Alluvial geometry for both the upper and lower alluvial aquifer layers was interpreted from all available strata log information in the Lower Burdekin area and newly constructed cross sections including any previous work in the area [KBR, 2002; *McMahon, 2004*; *Klohn Crippen Berger, 2008*].

This layer represents the alluvium throughout the Lower Burdekin that is typically tapped for irrigation water purposes by local property owners and irrigators. While this is generally where the fresher water of the aquifer is located, this is not however always the case in all areas of the Burdekin.

5.5 Lower-Alluvial Aquifer

The lower-alluvial aquifer lies directly above the fractured bedrock and below the inter-alluvial aquifer surface. The lateral and vertical extent of this aquifer has been defined using the same information as the upper-alluvial aquifer layer. In cases where monitoring bores do not extend fully to basement or strata log information is insufficient for determining aquifer thickness, some assumptions were made in order to determine the depth of the base of alluvium.

For bores that do not extend to the fractured zone, the bedrock level of adjacent and nearby bores are used to infer an appropriate bedrock level below the full drill depth. Control points were used at these bore locations to ensure that contouring levels remained at appropriate depths below the final depth recorded in the strata log. This resulted in a number of bores being removed from the contouring of aquifer thickness due to possible errors or inconsistencies with surrounding bores. In areas where bedrock outcrops are present, due to the lack of boreholes, control points were also used to best represent aquifer and fractured zone thickness at these locations (e.g. Mt Kelly, Mt Inkerman and Charlie's Hill etc.). A contour map of the base of the alluvial aquifer (i.e. top of bedrock) is presented in Figure 5-5.

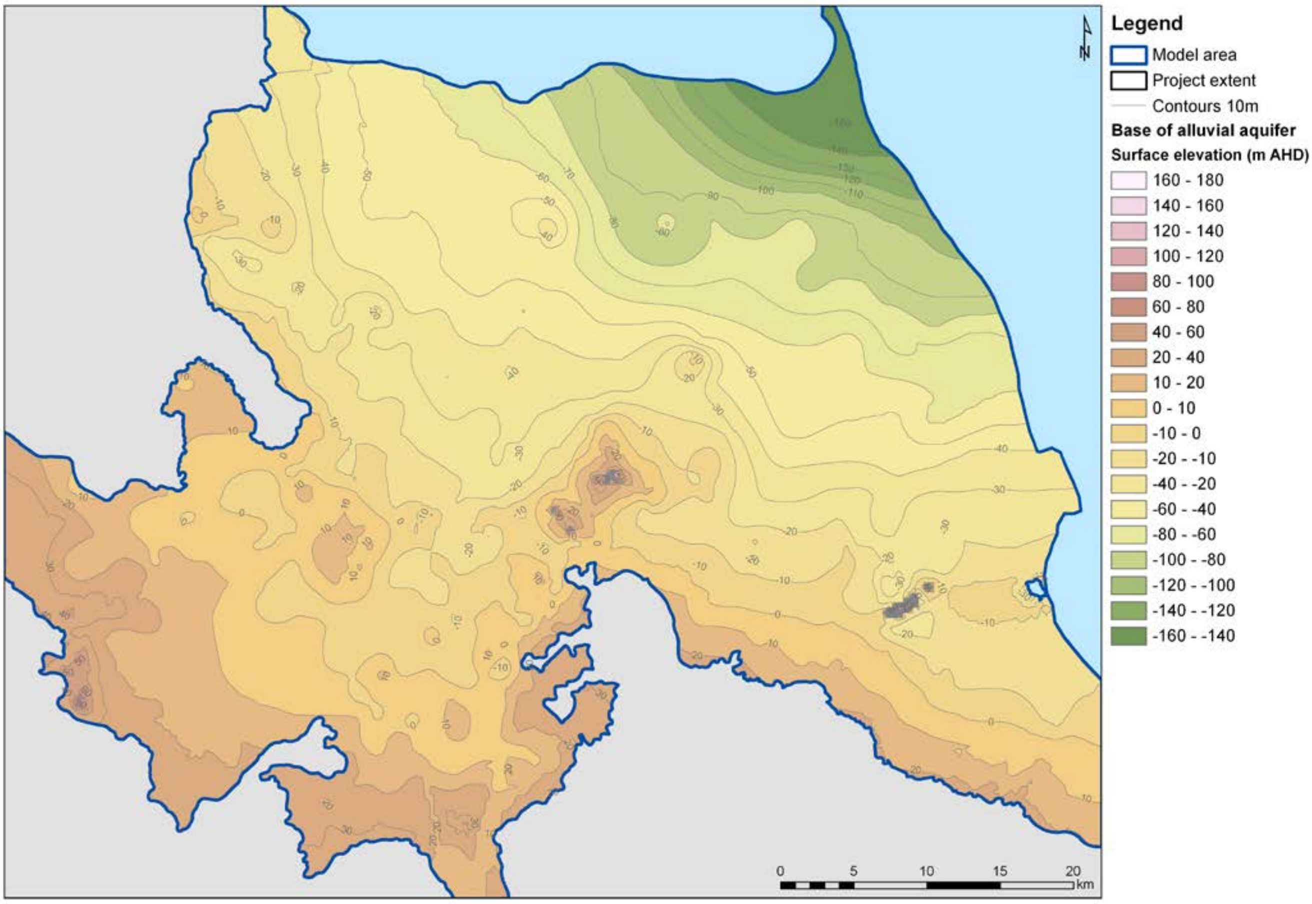


Figure 5-5 Base of the alluvial aquifer (m AHD)

5.6 Weathered / Fractured Bedrock

The underlying bedrock typically comprises granitic rocks similar to those exposed at the surface at places like Mt Kelly and Mt Inkerman. Strata log records show that the top of the bedrock is often fractured and/or weathered and numerous monitoring bores have been screened within this zone, indicating at least some level of notable transmissivity. Similarities in hydraulic head trends suggest that there is hydraulic connection between the lower alluvium and fractured bedrock. Figure 5-7, Figure 5-8 and Figure 5-9 show comparisons for bores screened in both the alluvial aquifer and the fractured/weathered bedrock zones. The similarities in water level movement between the layers supports the notion that both layers respond to changes in pressure reasonably equally, indicating interconnectivity. The locations of the bores which provided water levels for these hydrographs can be seen in Figure 5-6. Therefore a fractured bedrock layer has been included to allow provision for movement of groundwater between the weathered/fractured basement rocks and the alluvium.

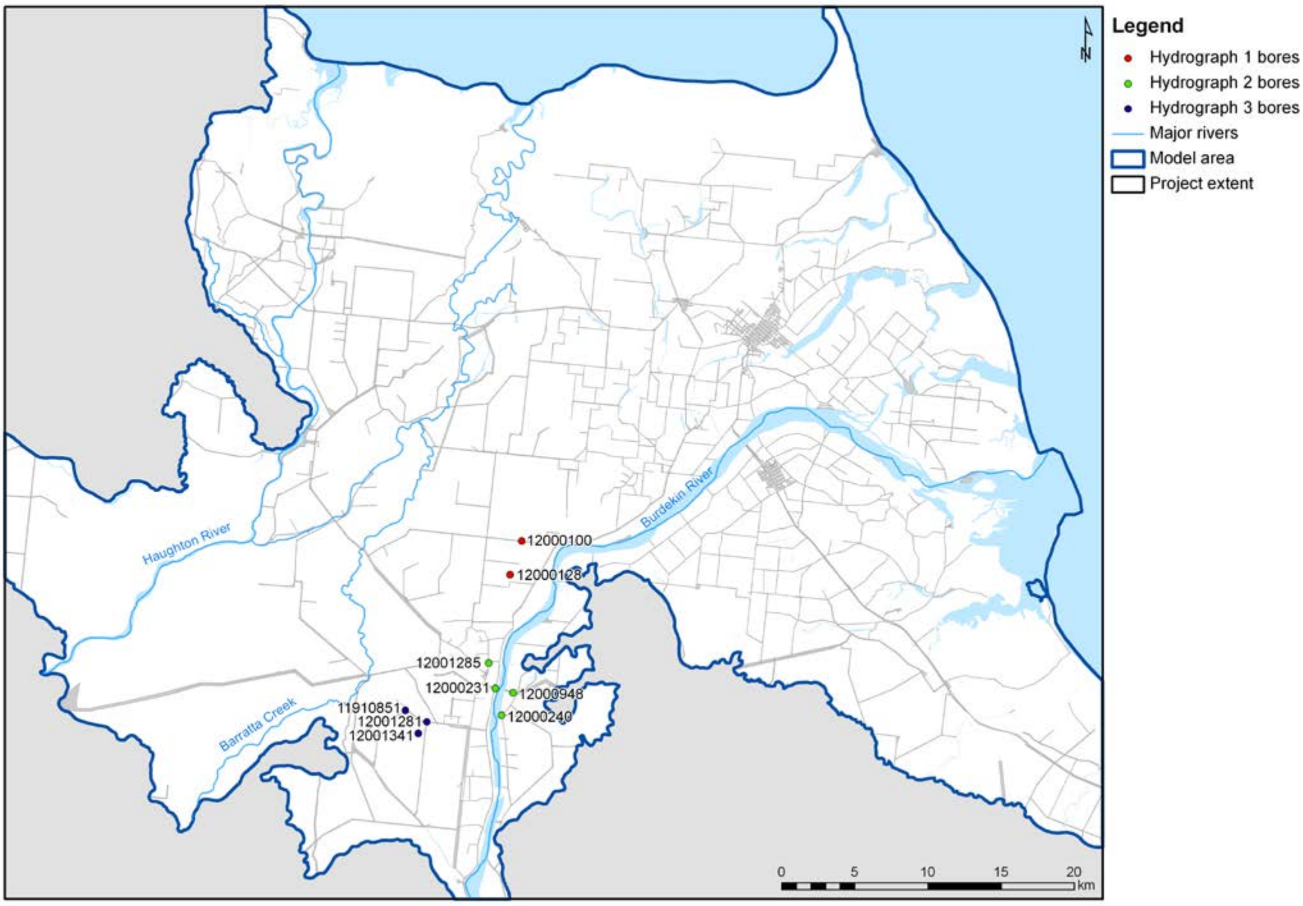


Figure 5-6 Location map for all bores that make up the hydrographs 1-3 in the following figures

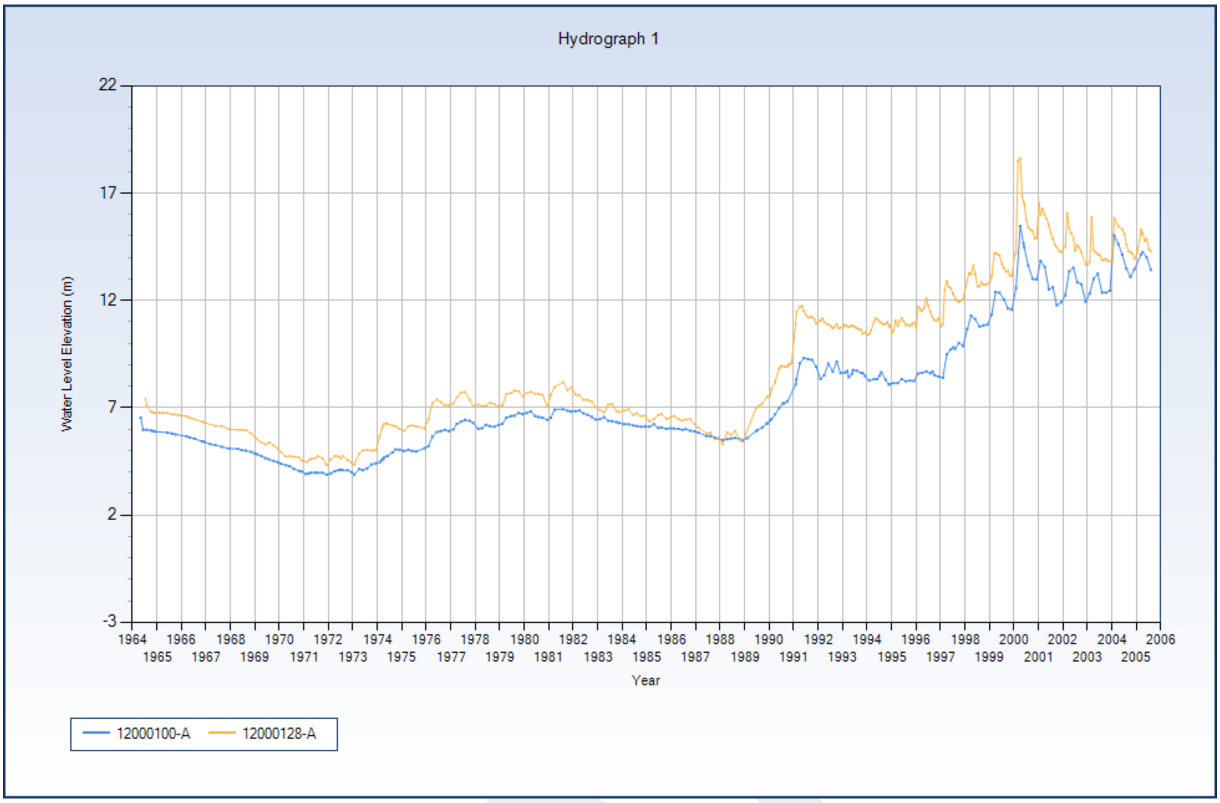


Figure 5-7 Groundwater hydrograph of RN12000100 and RN1200128. RN12000128 is screened in the fractured/weathered bedrock zone, while RN12000100 is screened in the alluvium.

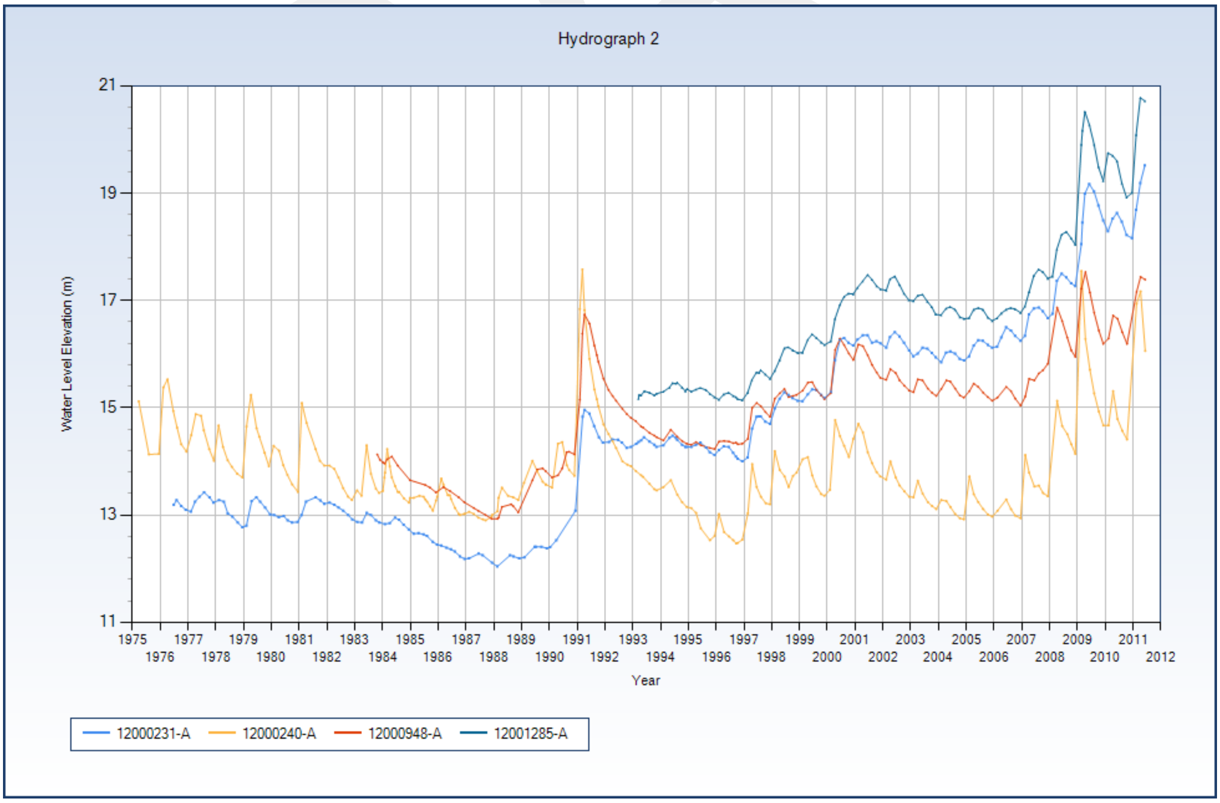


Figure 5-8 Groundwater hydrograph of RN12000231, RN12000240, RN12000948 and RN12001285. RN12000240, RN12000948 and RN12001285 all have observed screen locations within the fractured bedrock zone. RN12000231 is screened in the alluvial aquifer at a nearby location.

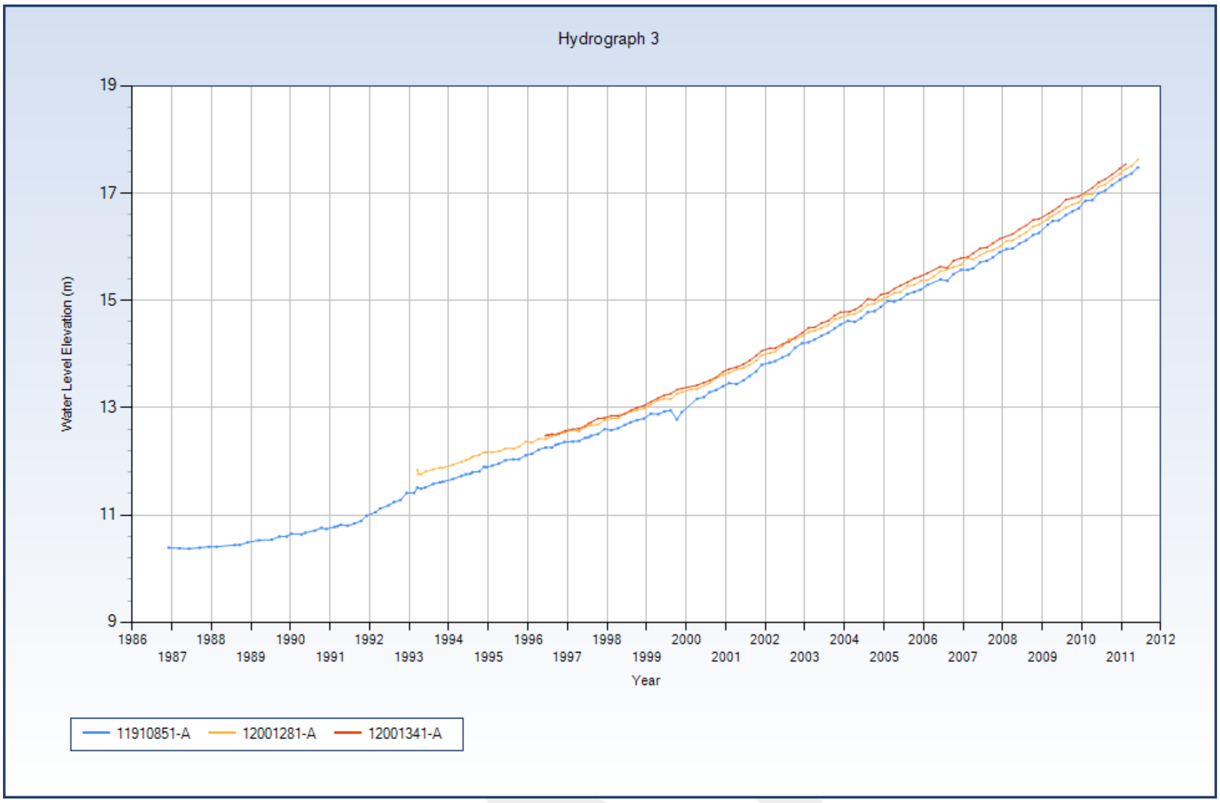


Figure 5-9 Groundwater hydrograph of RN11910851, RN12001281 and RN12001341. RN 12001341 and RN11910851 are screened in the fractured/weathered zone while RN12001341 has a s creen location in the alluvium.

Figure 5-10 shows a spatial representation of all bores, both private and monitoring, that provided strata log information to inform the surface contouring of the fractured/weathered bedrock zone and hydraulic basement. A total of 470 strata logs were used to map the thickness of the fractured bedrock layer. This layer ranges in thickness from 0 to 20m, averaging 6.5m. However, not all bores presented here fully penetrate the weathered/fractured bedrock through to fresh underlying bedrock, restricting the ability to measure the thickness of that layer at those points. To assign a nominal thickness of weathered/fractured bedrock to those bores, the average thickness calculated from all fully-penetrating bores (6.5m) was assigned to the partially penetrating bores. Figure 5-11 shows the distribution of fractured/weathered bedrock thickness for all fully penetrating bores that reach the hydraulic basement. The average thickness of the fractured/weathered zone is 6.5 metres. This thickness was assigned to bores that penetrate the fractured zone, but do not reach fresh bedrock.

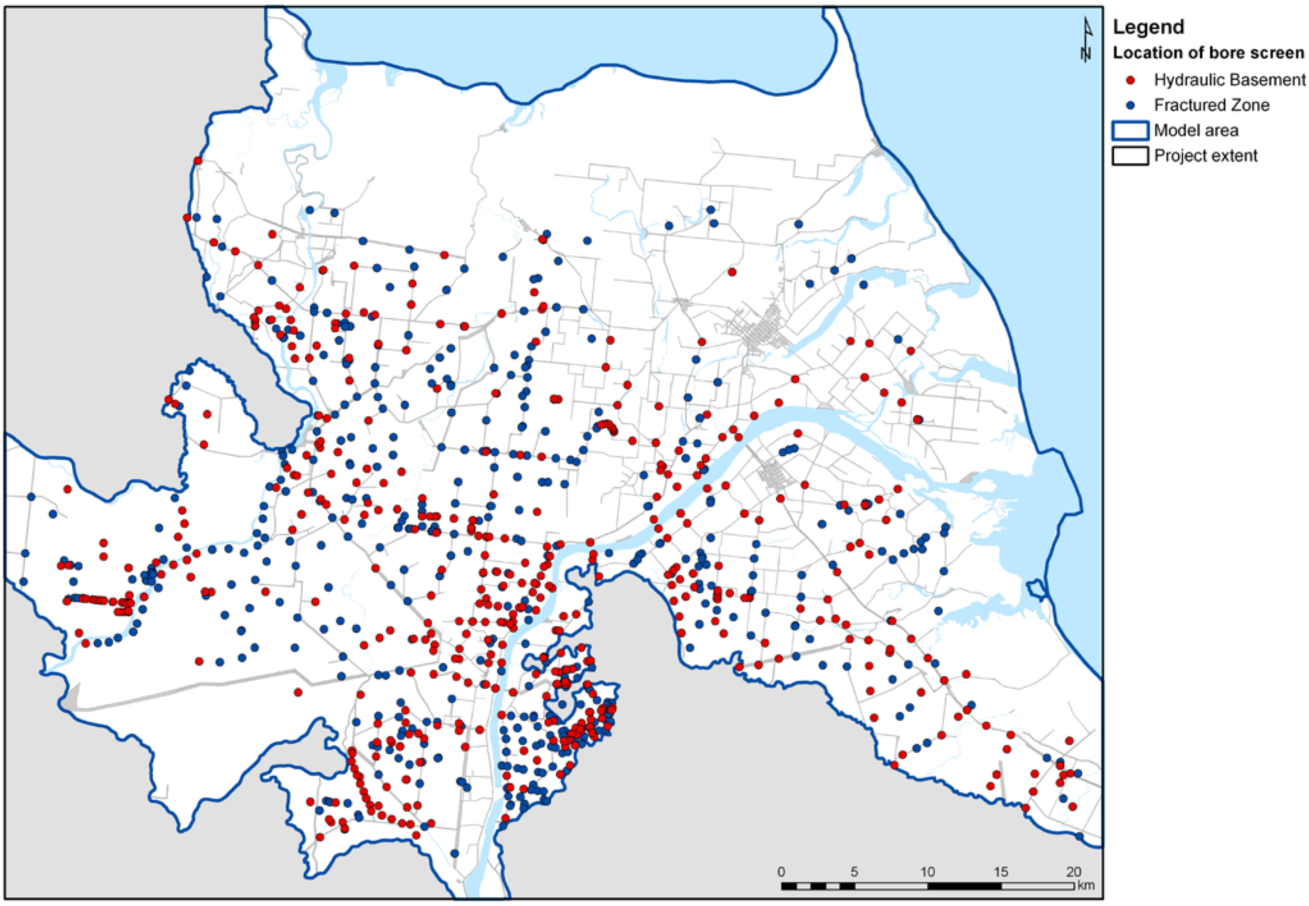


Figure 5-10 Bores in the Lower Burdekin region classified based on screen location. Screened within the fractured/weathered zone of the alluvial aquifer or drilled through the full extent of this zone into the hydraulic basement.

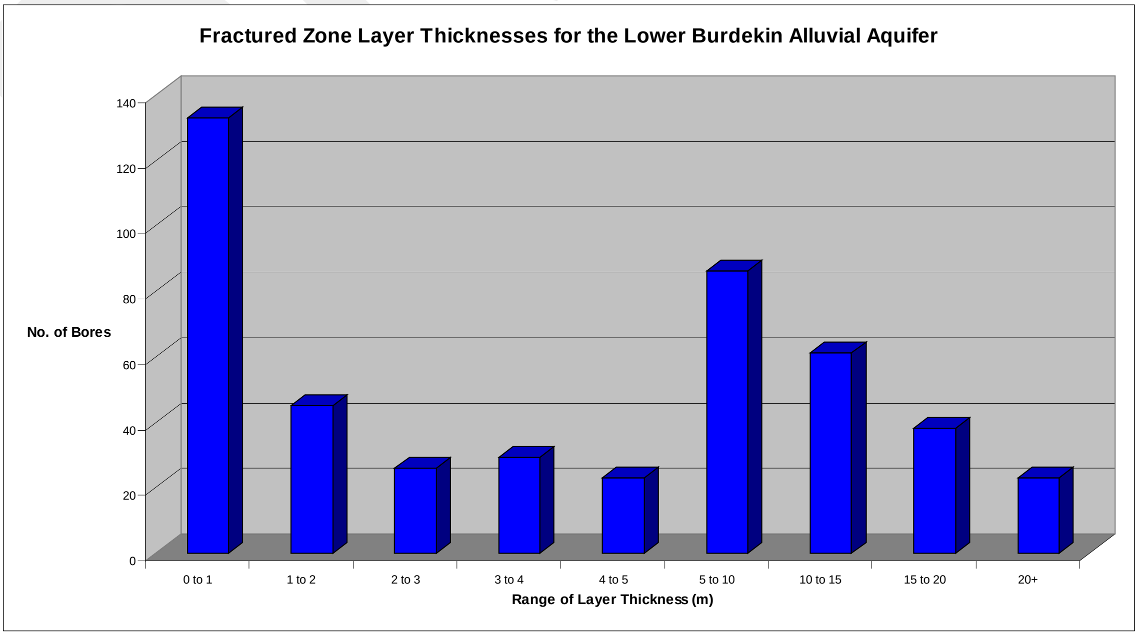


Figure 5-11 Calculated fractured zone layer thickness for a ~470 bore data set

The final hydraulic basement surface was created by merging calculated and estimated depth data consisting of bores that achieve a depth with evidence of basement bedrock and bores that penetrate the weathered zone but trigger the application of this average thickness assumption (Figure 5-12).

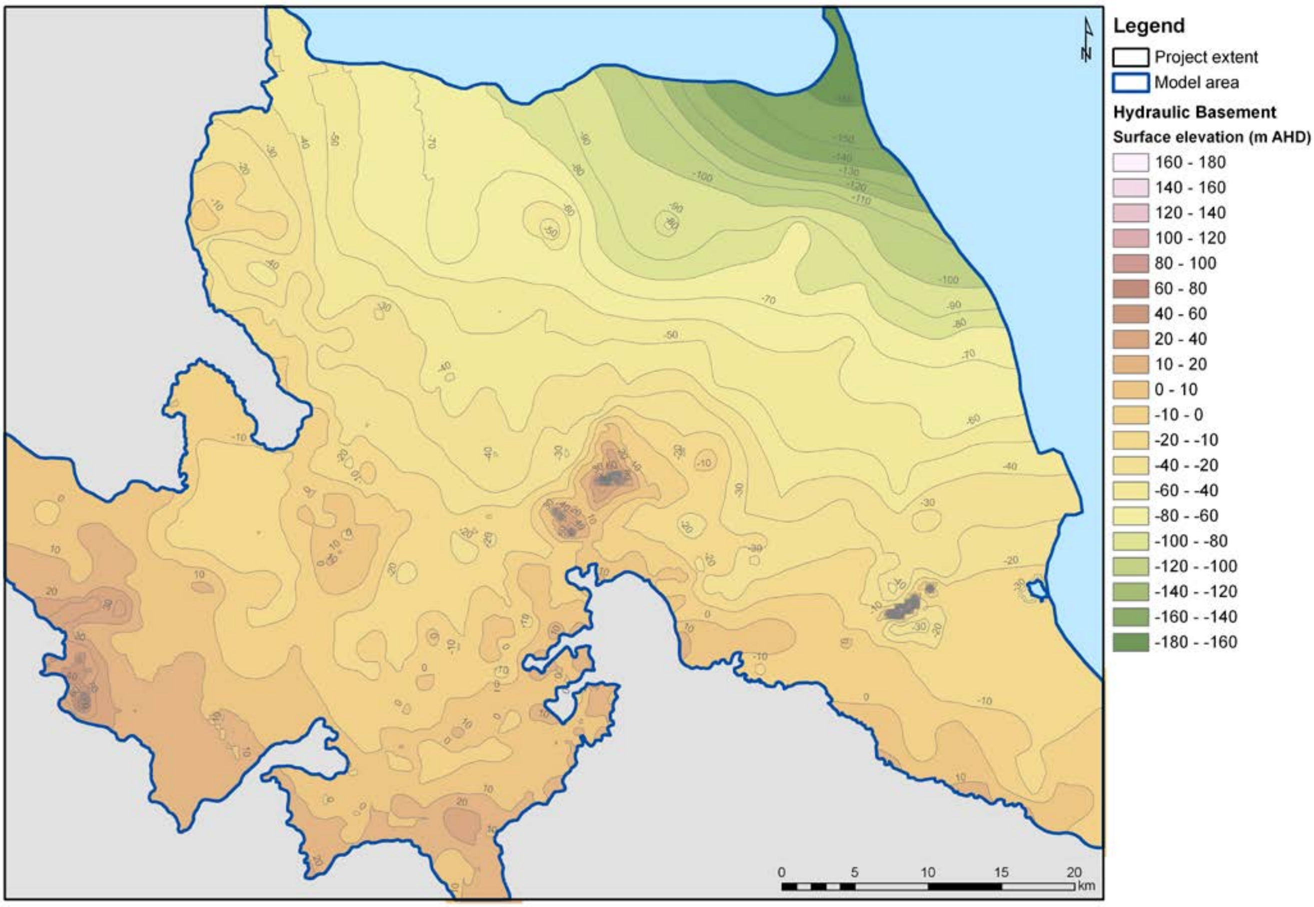


Figure 5-12 Hydraulic basement (m AHD)

5.7 Cross-Sections and Aquifer Geometry

A series of twenty-nine cross sections spanning the extent of the region were constructed to develop geological representations and an understanding of the regional aquifer geometry (Appendix A). Strata log information was extracted from the GWDB for a number of bores throughout the region in order to establish surface contours that define the complete aquifer geometry of the model area. As described in the above descriptions of each conceptual layer, there were significant characteristics of each layer that had to be reflected in the final aquifer geometry for the region. This was achieved by following a defined interpretation strategy for each layer based on borehole strata logs, casing information and earlier geological interpretations [eg. KBR, 2002; *McMahon, 2004*; *Klohn Crippen Berger, 2008*]. These strategies were employed in order to construct all three conceptual layers in all cross sections and then expanded to include all remaining bores in the aquifer geometry for the whole model area.

Assumptions and Limitations

- In some cases interpretation of strata logs can become challenging due to a lack of clear information provided by drillers ie. “clayey sand white”, “sandy clay with gravel”, “sandy clayey silt” etc.
- When this type of description appears in a strata log, the base word within the description is taken as being the most true, for example in the above three descriptions, the base words provided are sand, clay and silt respectively.
- The basis for interpretation of all layers was identification of the most highly permeable sediments, ie. Ranging from highest to lowest: gravel, sand, silt, clay (assumed to be essentially impermeable).
- Where unclear descriptions such as “clay with coarse–grained sand/gravel”. the sediment is mostly clay but may have been assumed to have some aquifer properties due to the presence of coarse-grained sand or gravel.
- If strata log information is incomplete or lacking detailed sediment description, the data was excluded from contouring of surfaces.
- Where monitoring bores are screened wholly or partially within the fractured bedrock, the base of the screen is taken as the minimum depth at which the fresh bedrock could exist. This is to allow for some acceptance of local and departmental drillers knowledge of where to place a screen to ensure it will yield water.

Upper-Alluvial Aquifer Layer

The top of the upper-alluvial aquifer layer is interpreted to include the base of the surficial clay in the BHWSS area and unconfined by the natural land surface in the Delta region. The base is the Inter-Alluvial Aquifer Surface. In order to identify the most accurate depth at which the alluvium began, the following strategy was employed throughout the development of all cross sections:

- The top of the upper-alluvial aquifer layer is defined as either:
    - Where the aquifer is unconfined, the natural surface (eg. Delta)
    - Where the aquifer is confined or semi-confined the base of the overlying clay (eg. BHWSS)
- The most reasonable interpretation of the main aquifer body was based on identifying strata described as being mainly “Sand” and coarse-grained materials such as “gravel” or “pebbles”.
- If interpreted aquifer material was found to be surrounded by clay, depending on extent and thickness, another interpretation of the main aquifer body may have been made.

Inter-Alluvial Aquifer Surface

Much of the Lower Burdekin has been locally known to comprise an upper more transmissive aquifer overlying an older less-transmissive aquifer. The distinction between the two is likely to be the transition between older sediments associated with pre-Pleistocene deposition to younger loose Holocene sediments. However, identifying the surface between the two in strata records is not always clear. The physical basis for separation of these sediments was important so that the upper and lower aquifer layer could be maintained across the whole model domain. It was this model requirement that lead to the following interpretive approach being undertaken.

With regards to groundwater flow, the upper and lower aquifer layers form the most significant saturated zone components of the Lower Burdekin aquifer system. Knowledge of the Pleistocene sediments, alongside previous efforts at mapping the Holocene [*Hopley 1970; Fielding et al., 2006*], provided the starting point for this inter-alluvial aquifer surface in some areas. In locations further away from the coastline where evidence of this Holocene base was less prevalent, a more interpretive approach was taken in identifying an appropriate inter-alluvial aquifer surface. Changes in texture, permeability and sediment colour identified from strata log information became key factors in constructing an intermediate surface. Initially, in areas where significant clay layers were found to be present, this change in sediment permeability was utilised as a separation between upper and lower alluvium. In situations that arise where there is no clear clay layer separation, local driller knowledge, screen location and changes in sediment texture were incorporated to this surface development process. The strategy defined for interpretation of this significant surface has been provided as follows:

- The Pleistocene surface has previously been identified as "hard or tight red-brown clays" that underlie transgressive marine sediments such as "mangrove muds" or "blue marine clays" and range in colour from yellow to red or light brown [*McMahon, 2004*]. Often these oxidised clays and sands are described by drillers as being "Mottled" or "Indurated".
- These descriptors formed the basis for interpretation of this Pleistocene surface alongside previous work done in the area [*Hopley 1970; Fielding et al., 2006*; *McMahon, 2004*].
- The next step in the development of this inter-alluvial aquifer surface was to identify areas where significant clay layers are evident within the alluvium, this could be done by identifying clays within the strata logs and establishing an interpretation that provides evidence that the clay can be extended across the distance between two boreholes.
- At times, this is not possible and this method was excluded and differences in textural change were used to establish an interpretation for this surface.
- In areas where the Pleistocene surface is not evident and there is no obvious inter-alluvial clay separation, textural change was incorporated. An example of this could be where sediments progress from "coarse-grained sands" to "fine-grained sands" or "Claybound gravel".
- In some areas throughout the model domain, there is no significant evidence of a vertical textural change. For mapping purposes, a boundary between the upper and lower alluvial layer is arbitrarily assigned based on surrounding bore data. When this occurs, it has to be assumed that there is connectivity between the Upper and Lower alluvial aquifers and as a result, this situation will be dealt with in the numerical calculations performed in the groundwater flow model.

Lower-Alluvial Aquifer Layer

The following strategy was used for interpreting the base of the Lower-Alluvial Aquifer Layer from strata log information:

- The base of alluvium is usually where sediments lie atop weathered or fractured bedrock (usually granite).
- In the GWDB the bedrock was usually described as "Weathered rock", "Decomposed rock/granite/diorite", "Fractured rock/granite/diorite/granodiorite" and other granitic type materials described as "Mica, Andesite, Leucogranite, Adamellite, bedrock and Microdiorite".
- In some cases, strata log details may fail to distinguish highly weathered bedrock from basal sediments (eg. Very clayey sand may refer to alluvium or highly weathered granite). In these cases, evidence from surrounding bores was used to support interpretations.
- Where the drilled depth was insufficient to reach the base of the alluvium, the alluvial basement surface was checked to ensure that the interpolated basement remains below the last drill description of these bores (ie. The deepest point reached in drilling).

- Where the strata log ends on bedrock with no mention of weathered or fractured zone, the alluvial base is taken as the top of hydraulic basement.
- In the BHWSS, there exists a surficial clay layer which can extend from surface to fractured/weathered bedrock in some areas. Where this is observed, a clear “pinch” point or discontinuity of the alluvial aquifer occurs, the “top of aquifer” and inter-alluvial aquifer surface are continued at a minimum thickness between the base of the clay and the fractured/weathered bedrock.

Fractured/Weathered Zone Layer

The process and assumptions for creating the fractured bedrock layer are outlined below:

- Only bores that record some form of contact between alluvium and fractured basement rock are used to determine the depth to top of this weathered zone layer.
- The hydraulic basement is defined as occurring at the depth where the hard or fresh rock is first recorded (usually granite, but may include descriptions such as “hard rock” or “bedrock”).
- For bores, both private and monitoring, that only partially penetrate the hydraulic basement, the average thickness of the fractured/weathered zone across the whole area is added to the last recorded depth of weathered/fractured material.
- In some instances, where bores at depth are progressing from “very weathered” to “moderately weathered” to “slightly weathered” or described as “becoming fresher” this assumption may not have been applied and the hydraulic basement taken as the base of the borehole.

5.8 Aquifer Hydraulic Properties

Available pumping test data were analysed to assess the distribution of aquifer characteristics such as hydraulic conductivity, transmissivity and storage coefficients.

Hydraulic Conductivity

The hydraulic conductivity of the main aquifers in the area has been estimated from the transmissivity values measured in pump tests. As there is not enough information to determine the saturated aquifer thickness for the pump tests, the total aquifer thickness was used to calculate the hydraulic conductivity. The pump test results for 52 bores were used to calculate hydraulic conductivity. The hydraulic conductivities for the majority of these bores (32 bores) were less than 100 m/day, 18 bores had hydraulic conductivities between 100 and 300 m/day and only 3 bores had hydraulic conductivities greater than 300 m/day (Figure 5-13). The highest hydraulic conductivity values occurred north of Clare (Figure 5-14) with no apparent pattern for the hydraulic conductivities in the rest of the model area.

The pump test results shown here correspond to aquifer materials that are primarily sands and gravels. These materials are expected to have higher hydraulic conductivities than some of the other alluvial materials present in the Lower Burdekin, for example, silts and clays. The hydraulic conductivities shown in (Figure 5-13 and Figure 5-14) are within the published ranges of values for well sorted sands and gravels (Fetter 2001).

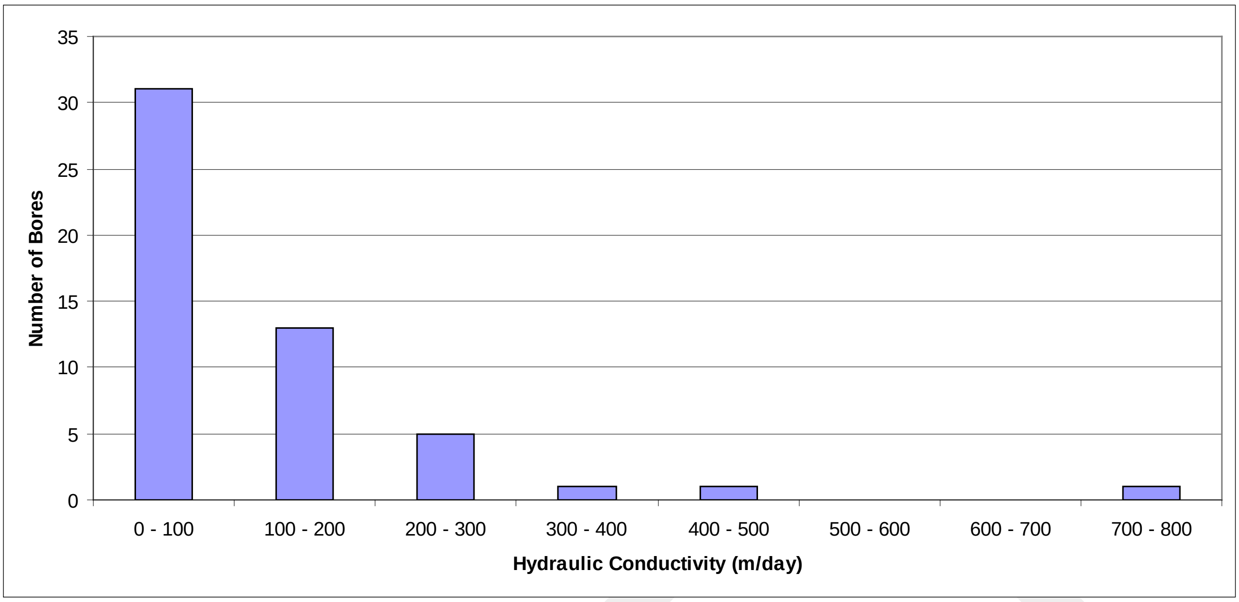


Figure 5-13 Hydraulic conductivity ranges from pump test results

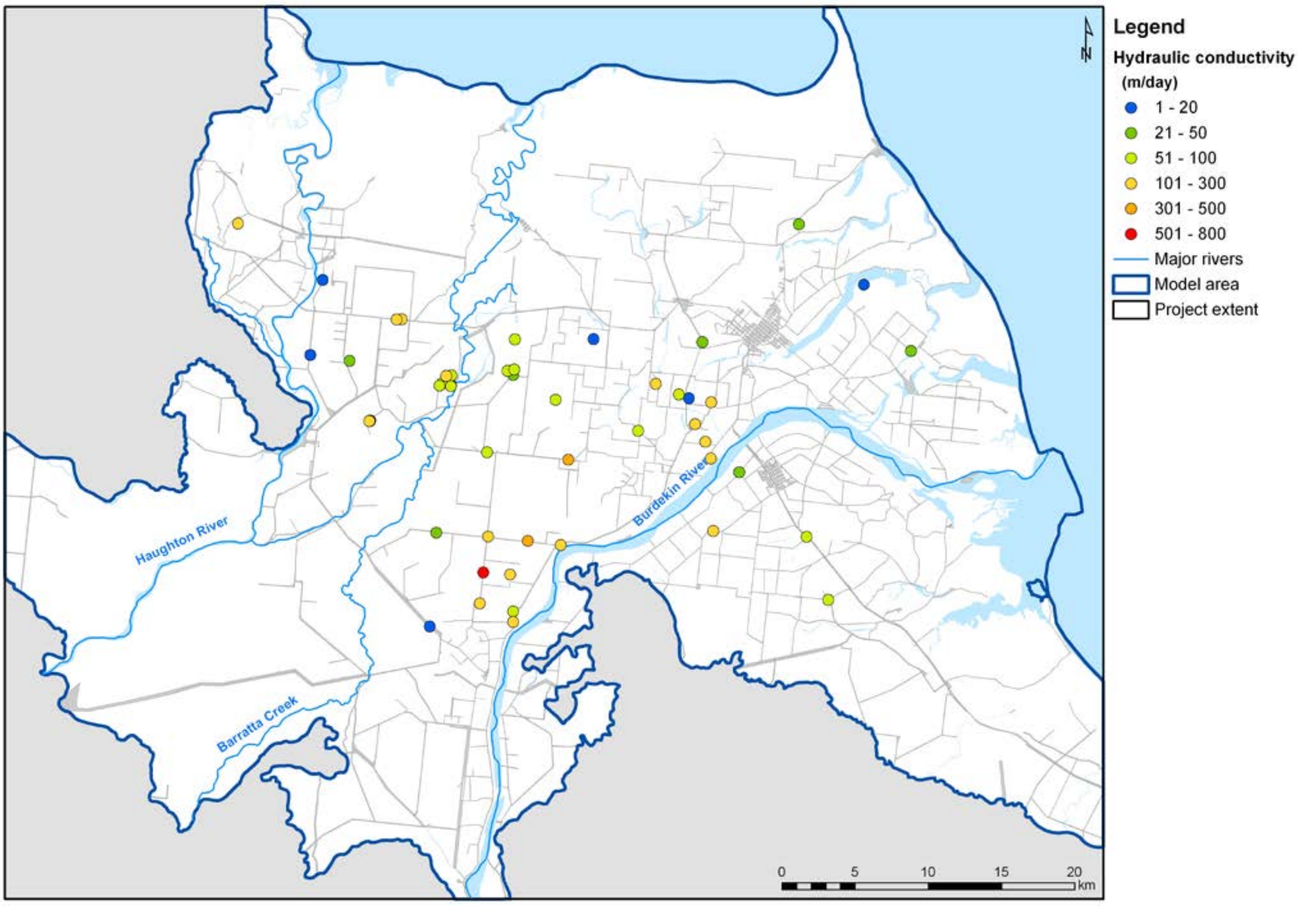


Figure 5-14 Estimated hydraulic conductivity for bores in the model area

There are some limitations with using pump test data to estimate hydraulic conductivity for a regional groundwater flow model. Pump tests are often conducted within the higher yielding aquifer materials. This bias for higher yielding locations may result in an overestimation of regional hydraulic conductivity. To calculate hydraulic conductivity, the total aquifer thickness was used as the saturated thickness was not known. This may lead to an underestimation of hydraulic conductivity at the locations where pump tests were conducted.

The final distribution of hydraulic conductivity values will be estimated by model calibration. The initial range of estimated values will be used as a guide in the optimisation process for which optimisation software, PEST-ASP, will be used.

Storage Coefficient

The departmental groundwater database holds records in the pump test data table for 52 bores. However, storage coefficient and specific yield values are only provided for very few bores. Therefore storage coefficient and specific yield values will be estimated by model calibration. The initial values will be based on values derived from textural information of aquifer materials.

5.9 Groundwater Flow

Groundwater Observation Data

There are about 1675 monitoring bores drilled in the model area. The first water level was measured in 1931 for a single bore near Ayr. From 1942 another 26 bores located around Home Hill started recording water levels. Since 1949, observations of groundwater levels have been gradually extended to other areas of Lower Burdekin. Table 5-1 shows the number of observation bores for each period from 1931-2006.

Table 5-1 Number of observation bores and records from 1931-2006 (excluding dry observations)

Period	No of Bores	No of records
1931-1939	1	99
1940-1949	38	3399
1950-1959	77	3580
1960-1969	358	12422
1970-1979	632	37937
1980-1989	1048	46476
1990-1999	1282	94232
2000-2006	1133	54697

All bores were classified according to their screen level whether they were tapping alluvial, fractured or weathered bedrock based on the information in the strata logs in the GWDB. This distribution of bores is displayed in Figure 5-15. Bores located near the southern boundary tend to occur within weathered or fractured basement. In the coastal areas there are very few bores and in south western corner only few bores are available.

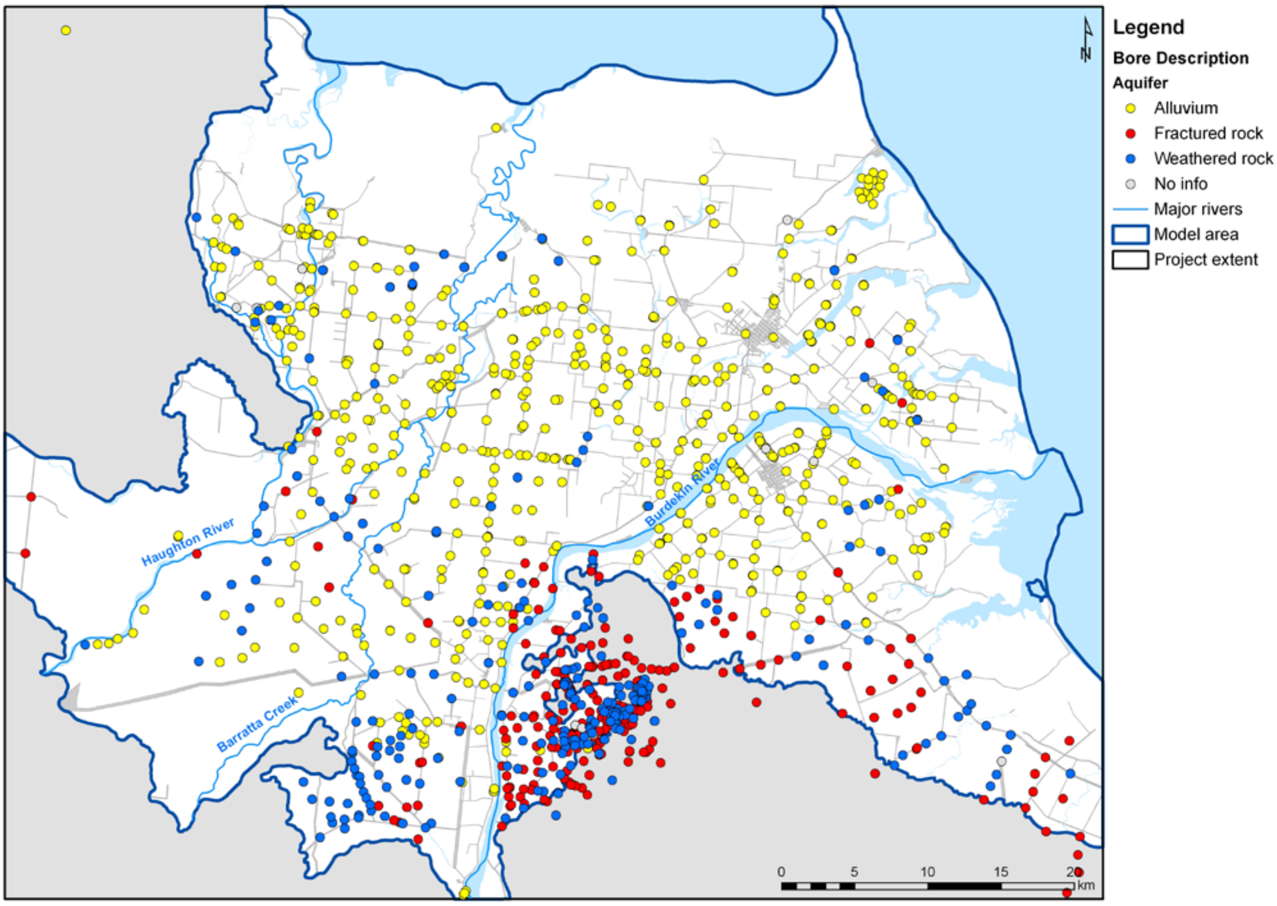


Figure 5-15 Bore classification (aquifer screened in bore)

Groundwater Level Responses

Distinct differences can be seen in the groundwater level responses for the bores assigned to the three main aquifer types, fractured/weathered rock, alluvial confined and alluvial unconfined. The fractured/weathered rocks and confined alluvial aquifers occur mostly in the BHWSS. The groundwater levels in the BHWSS typically show rising trends, particularly since 1990 (Figure 5-16 and Figure 5-17). For the fractured/weathered rocks in the Mulgrave section of the BHWSS, the trends range from fairly stable to gradually rising with seasonal peaks more noticeable in recent years (Figure 5-16). In the Northcote and Mona Park sections of the BHWSS within the confined alluvial aquifer, groundwater levels have generally been rising since 1988 and seasonal peaks can be seen throughout the monitoring record (Figure 5-17). The seasonal fluctuations in water level trends correspond with heavy seasonal rainfall that typically occurs between December and March (Figure 5-18).

In contrast with the groundwater level trends in the BHWSS, the long term trends in the unconfined alluvial aquifer in the Delta show a long term fluctuating trend with significant seasonal variations (Figure 5-19 and Figure 5-20) i.e. there are increases in groundwater levels of up to 5 metres for the unconfined bores in the Delta following a large rainfall event compared with approximately 1 metre for the confined bores in the BHWSS. Furthermore, a number of bores throughout the Lower Burdekin have been classified into hydrological response units that show distinct differences in hydrograph trend. These classifications and location maps can be seen in Appendix B of this report.

Figure 5-16 Groundwater level responses for the fractured/weathered rock aquifers in the Mulgrave section of the BHWSS versus cumulative monthly residual rainfall

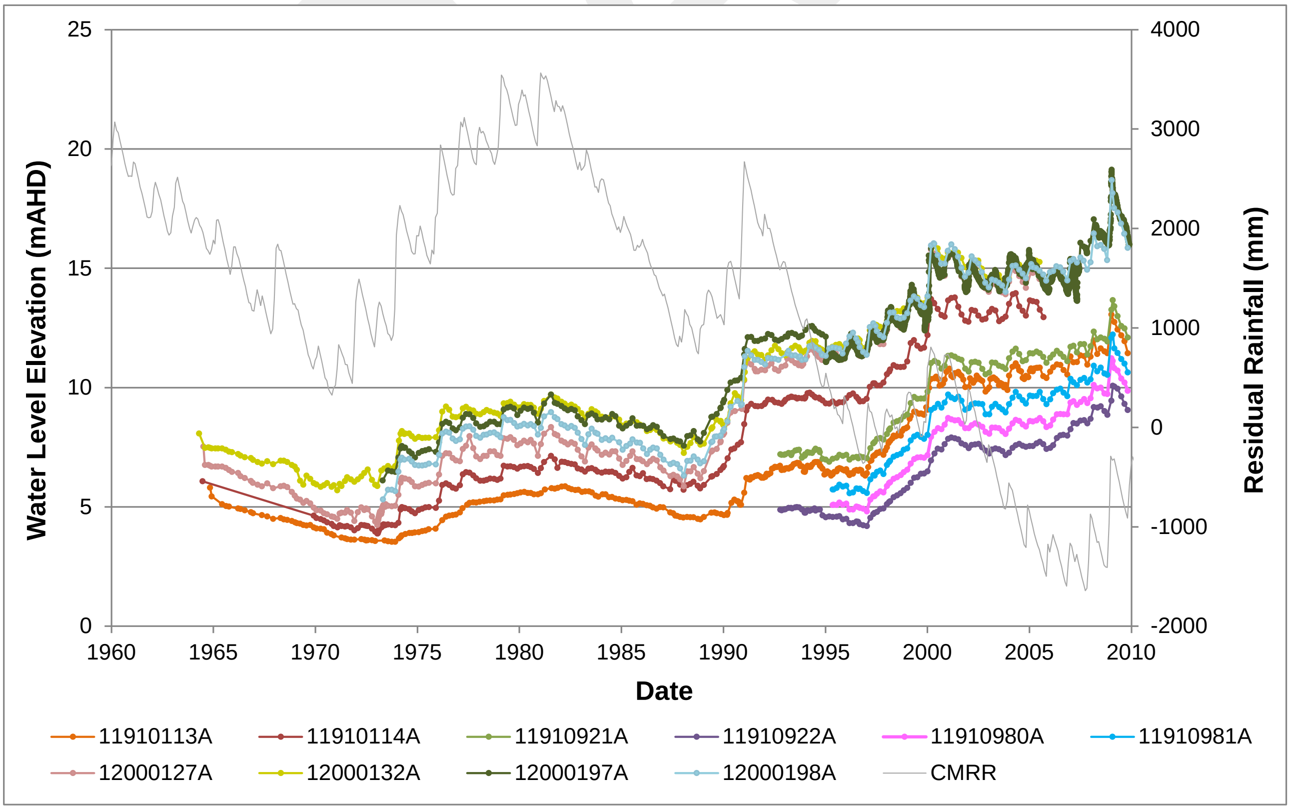


Figure 5-17 Groundwater level responses for the confined alluvial aquifers in the Northcote and Mona Park sections of the BHWSS versus cumulative monthly residual rainfall

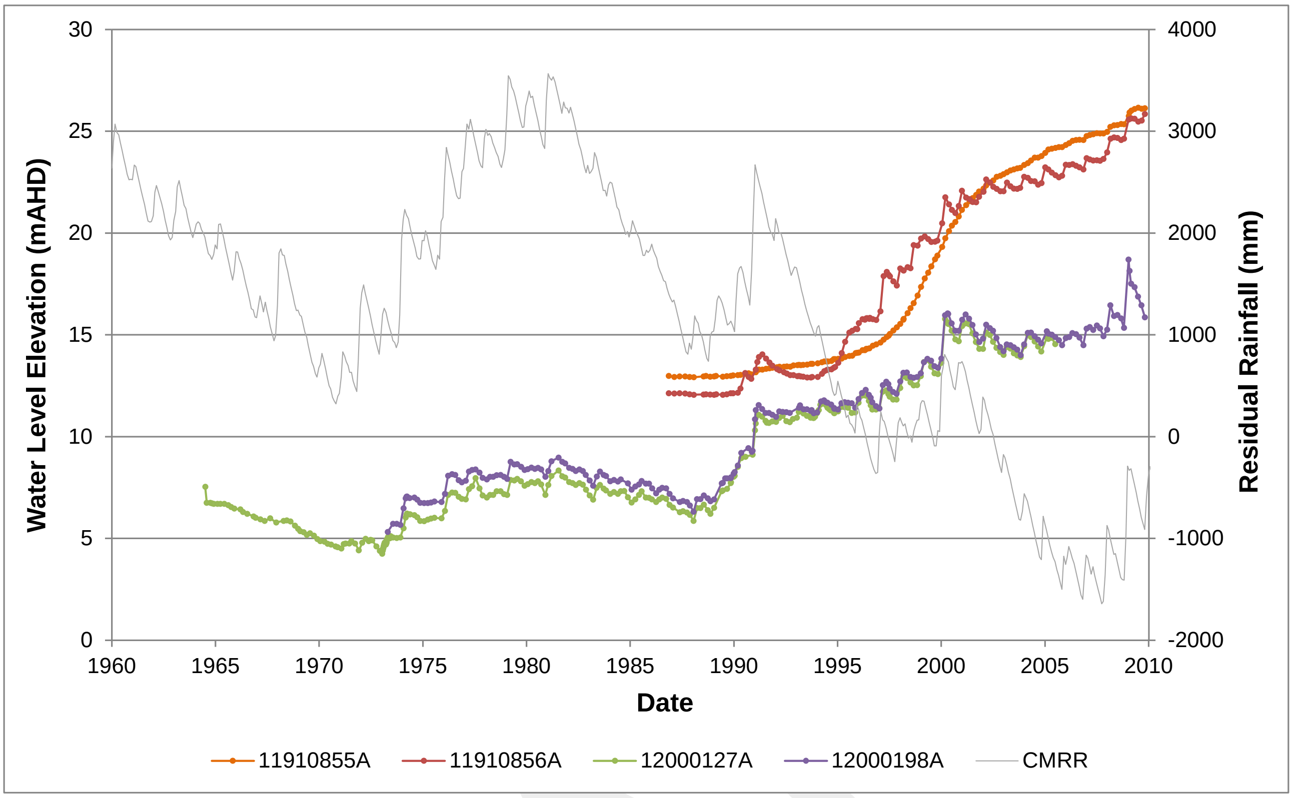


Figure 5-18 Groundwater level responses in the BHWSS versus cumulative monthly residual rainfall

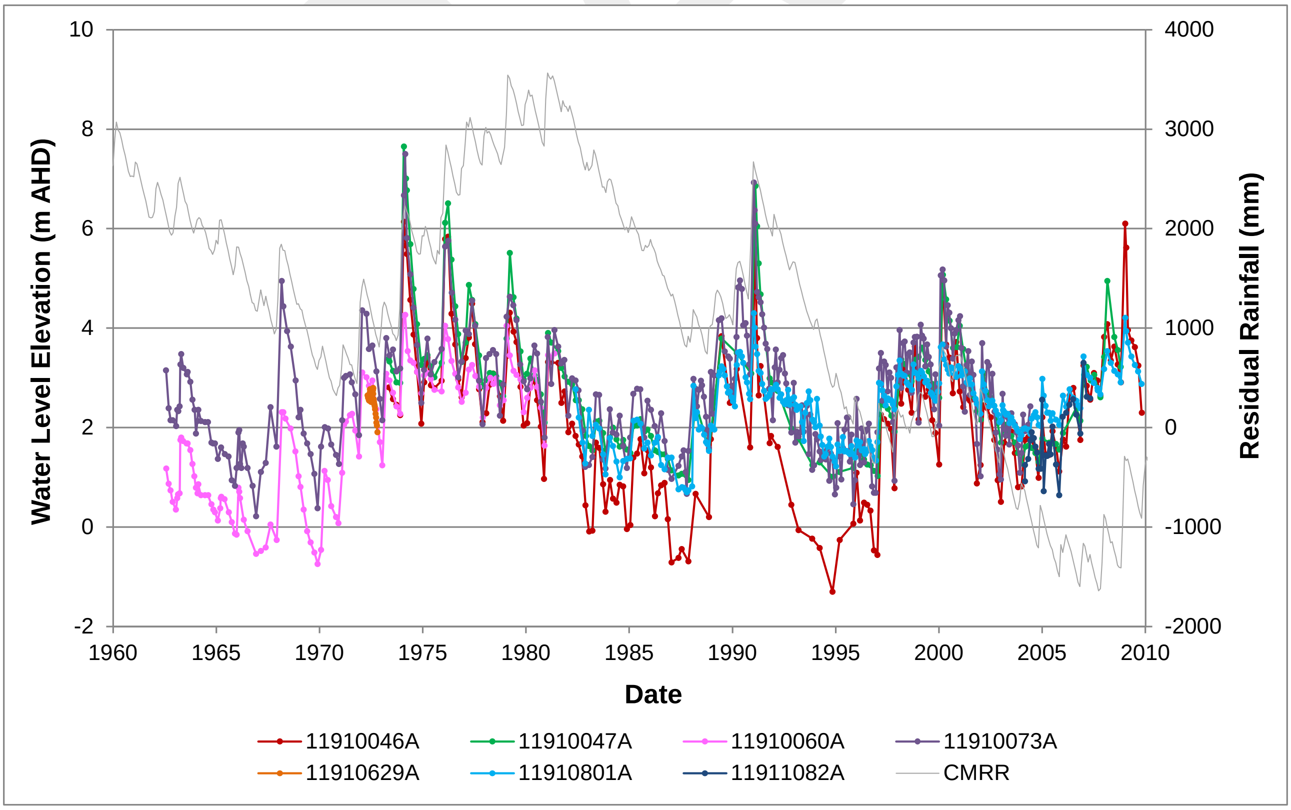


Figure 5-19 Groundwater level responses within the unconfined alluvial aquifer near Ayr in the Delta versus cumulative monthly residual rainfall

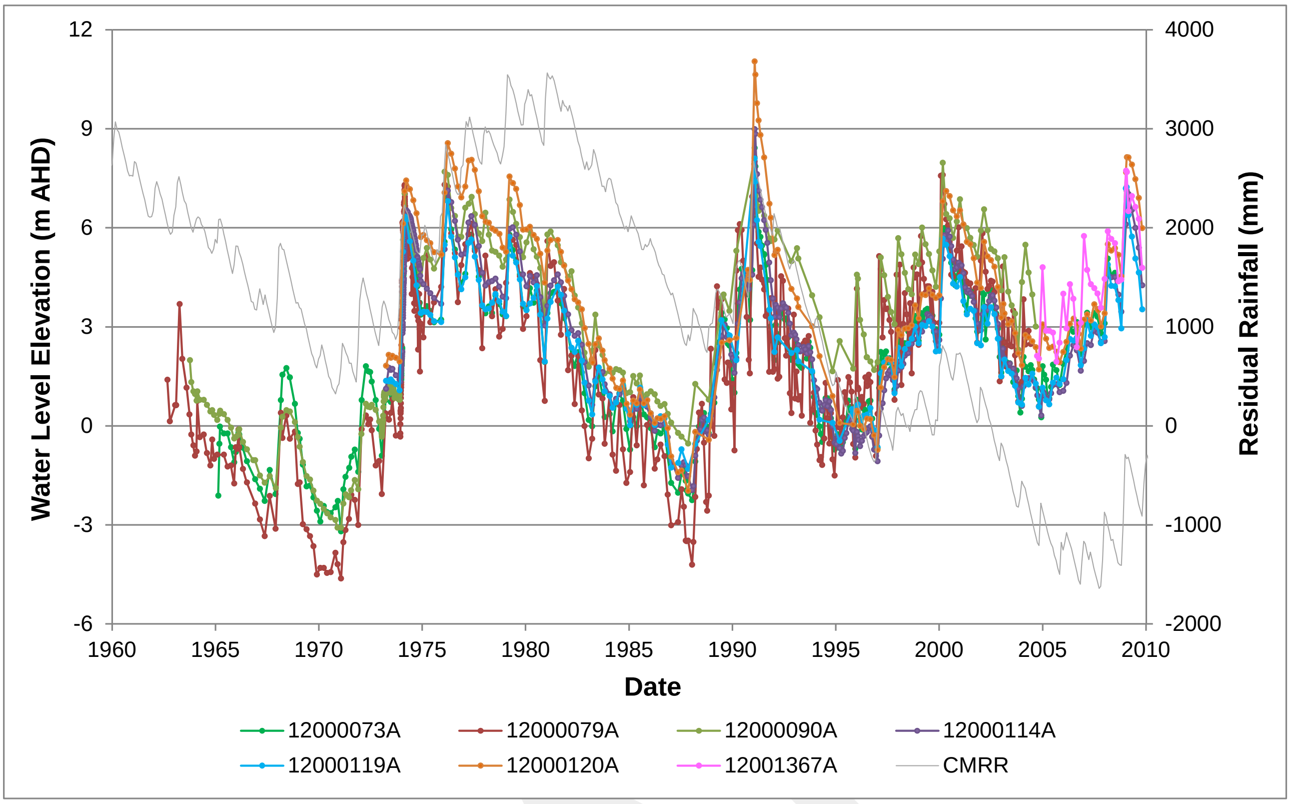


Figure 5-20 Groundwater level responses within the unconfined alluvial aquifer near Home Hill in the Delta versus cumulative monthly residual rainfall

Regional Flow Directions

Monthly water level contours have been generated for from the period 1980-2006. Due to variability of the frequency and distribution of water monitoring data, monthly values were sometimes derived by linear interpolation of data and assigned to the first day the month. Figure 5-21 and Figure 5-22 show water level contours for generally dry conditions and wet conditions, respectively. These examples (dry: August 1996 and January 1997, and wet: February 2001 and June 2006) are included as examples of how groundwater flow directions are affected by different climatic conditions.

In general, groundwater flow is approximately parallel to the course of the main natural watercourses, extending from the upland areas and flowing to the coast in a northerly to northeasterly direction. In the vicinity of the major streams, groundwater flow is locally influenced by the relative height of the groundwater table to the river stage height. During low-flow conditions (Figure 5-21), groundwater tables are lower and recharged by surface water. In low-lying areas near the coast, water tables commonly drop below sea level (0m AHD). During wet conditions (Figure 5-22), groundwater levels are higher then river stage heights (except during periodic floods) and tend to discharge into the rivers. Where groundwater levels remain high, discharge (or baseflow) is potentially sustained.

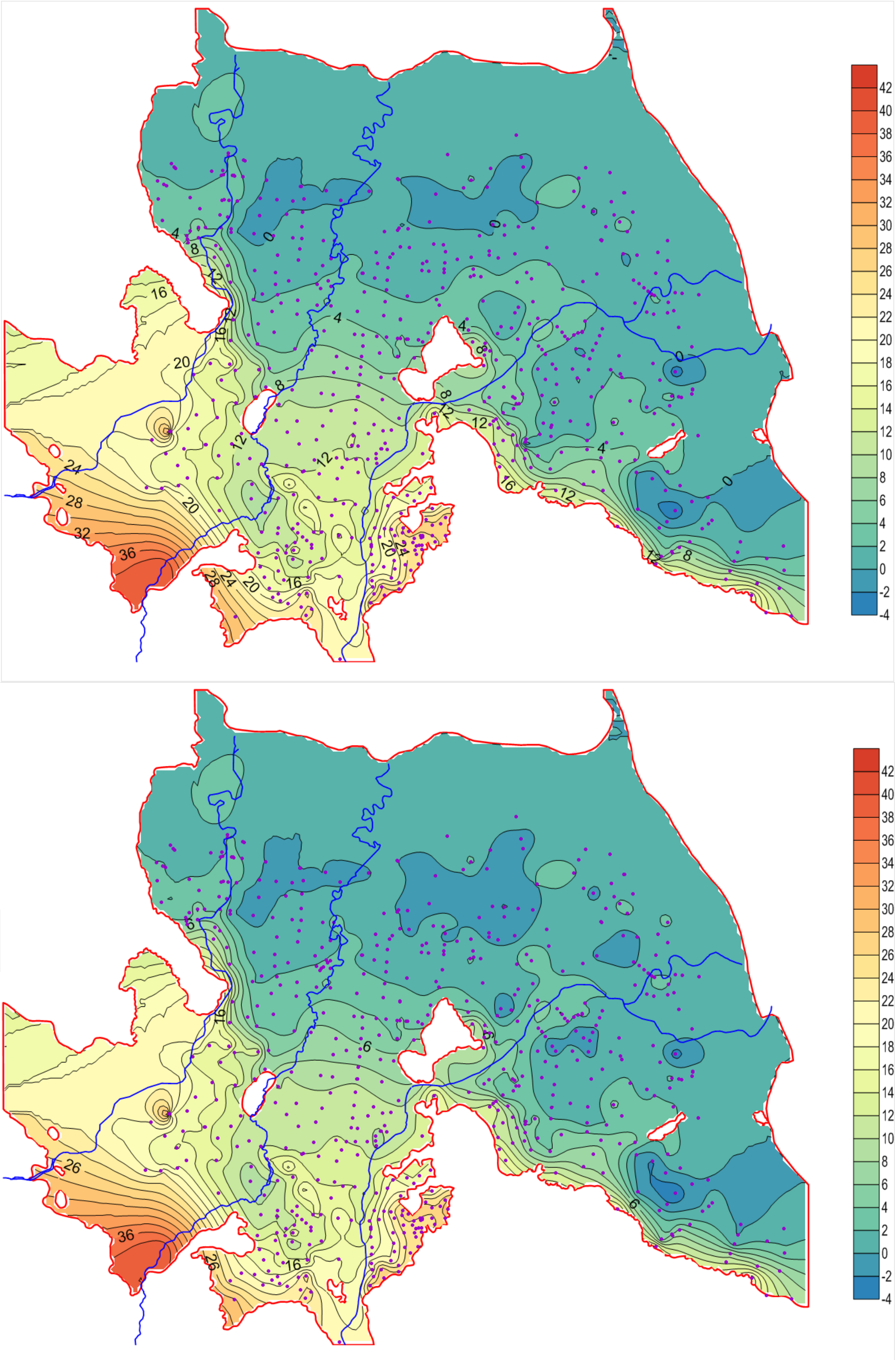


Figure 5-21 Water Level Contour for August 1996 and January 1997 (Low season water levels). Scale represents water level heights in metres AHD.

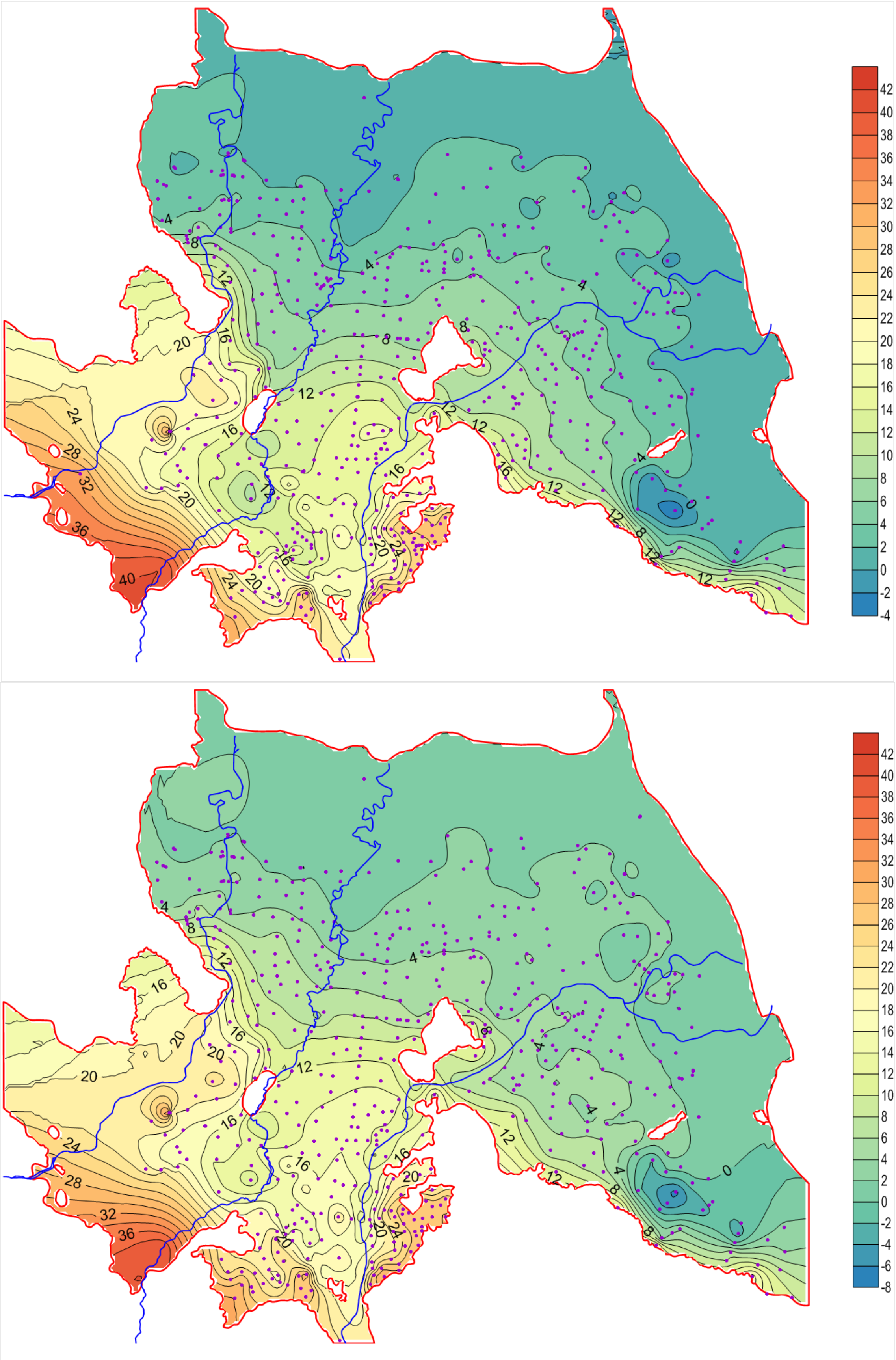


Figure 5-22 Water Level Contour for February 2001 and June 2006 (High season water levels). Scale represents water level heights in metres AHD.

5.10 Boundary Flow

South Eastern Boundary

In the Burdekin Delta Groundwater model developed by NR&M (Arunakumaren, McMahon & Bajracharya 2001), a no flow boundary was applied to the southern boundary of the Delta area. In the CSIRO model (Narayan et al. 2003), the southern boundary was simulated as a time varying boundary. The analysis of groundwater levels around this area indicated that there was groundwater flow across the boundary.

In this section the groundwater flow across the South Eastern part of the southern boundary (shown in Figure 5-25) is estimated on a monthly basis. The boundary flows were not estimated for other parts of the model boundary due to the lack of observed water levels or the fact that the groundwater contours are perpendicular to the boundary implying little or no flow across the boundary.

It is assumed that groundwater flow in the study area obeys Darcy's law:

$$Q = -K \frac{dh}{dl} A \qquad \text{Equation 1}$$

where, K is hydraulic conductivity of the saturated aquifer, dh/dl is the hydraulic gradient, dh is the difference of groundwater level between two points (Points P1 and P2 in Figure 5-23), dl is the distance between the two points, A is the cross-sectional area of flow (height of saturated aquifer and width) and Q is the groundwater discharge.

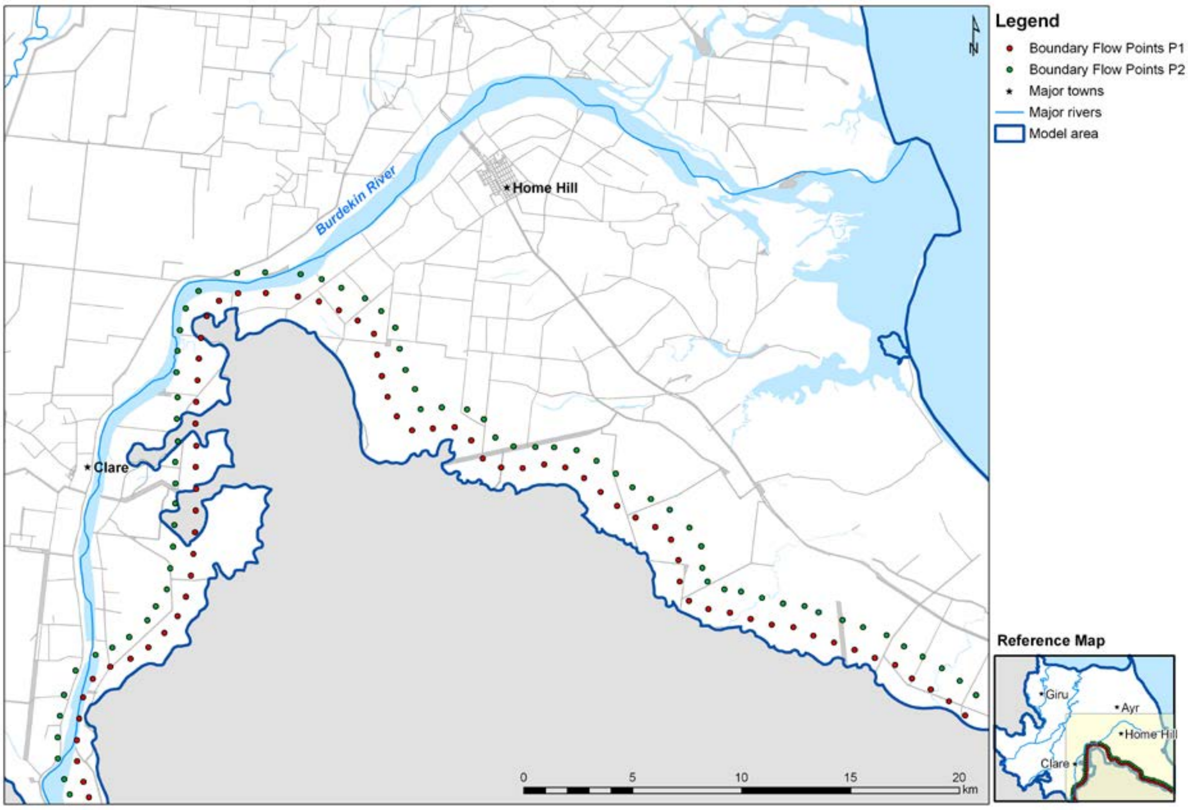


Figure 5-23 Location of boundary flow points P1 and P2 used to calculate the difference in head and the water table height

Most bores in the area around the South East Boundary are placed in fractured/weathered rocks. However, there are no bores with recorded transmissivity in this area. Therefore, alternative approaches have to be sought for the estimation of hydraulic conductivity of weathered and fractured bedrock associated with this area.

In the model developed by NR&M (Arunakumaren, McMahon & Bajracharya 2001), the calibrated hydraulic conductivity was 0.1 to 100 m/day for this boundary area. In the CSIRO model (Narayan et al. 2003), 100 m/day was used. The hydraulic conductivity of 5 m/day is used in the calculation here considering that the aquifer in this section mainly consists of weathered and fractured bedrock. The estimated volume of boundary flow is shown in Figure 5-24.

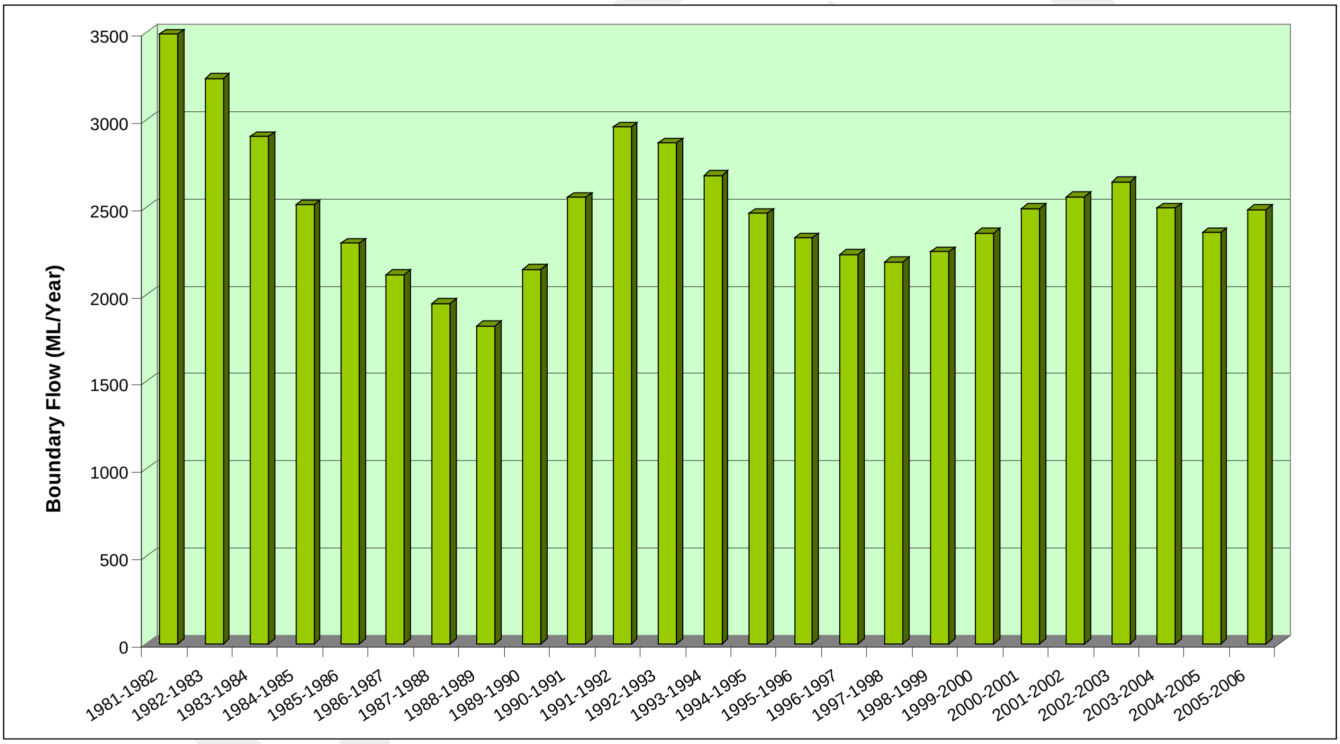


Figure 5-24 Estimated boundary flow

The annual average inflow across the boundary is 2494 ML for the period from July 1981 to June 2006.

Coastal Boundary

The Burdekin groundwater model has coastal boundaries to the North (Bowling Green Bay) and to the East (the Coral Sea). Groundwater level contours demonstrate that the regional flow in the area is towards the ocean.

Coastal discharge Q (m^3/d) was estimated for the area shown in Figure 5-25 (the line labelled discharge points) using the following relationship:

$$Q = \sum Khwi \qquad \text{Equation 2}$$

where

K = Hydraulic Conductivity (m/d)

h = Water depth at the section (m)

w = Width of the section (m)

i = Groundwater surface gradient

Electrical conductivity (EC) data have demonstrated that groundwater in the coastal area is saline. Equivalent fresh water heads were used to calculate coastal discharge (see section following section, “Density-corrected water levels”).

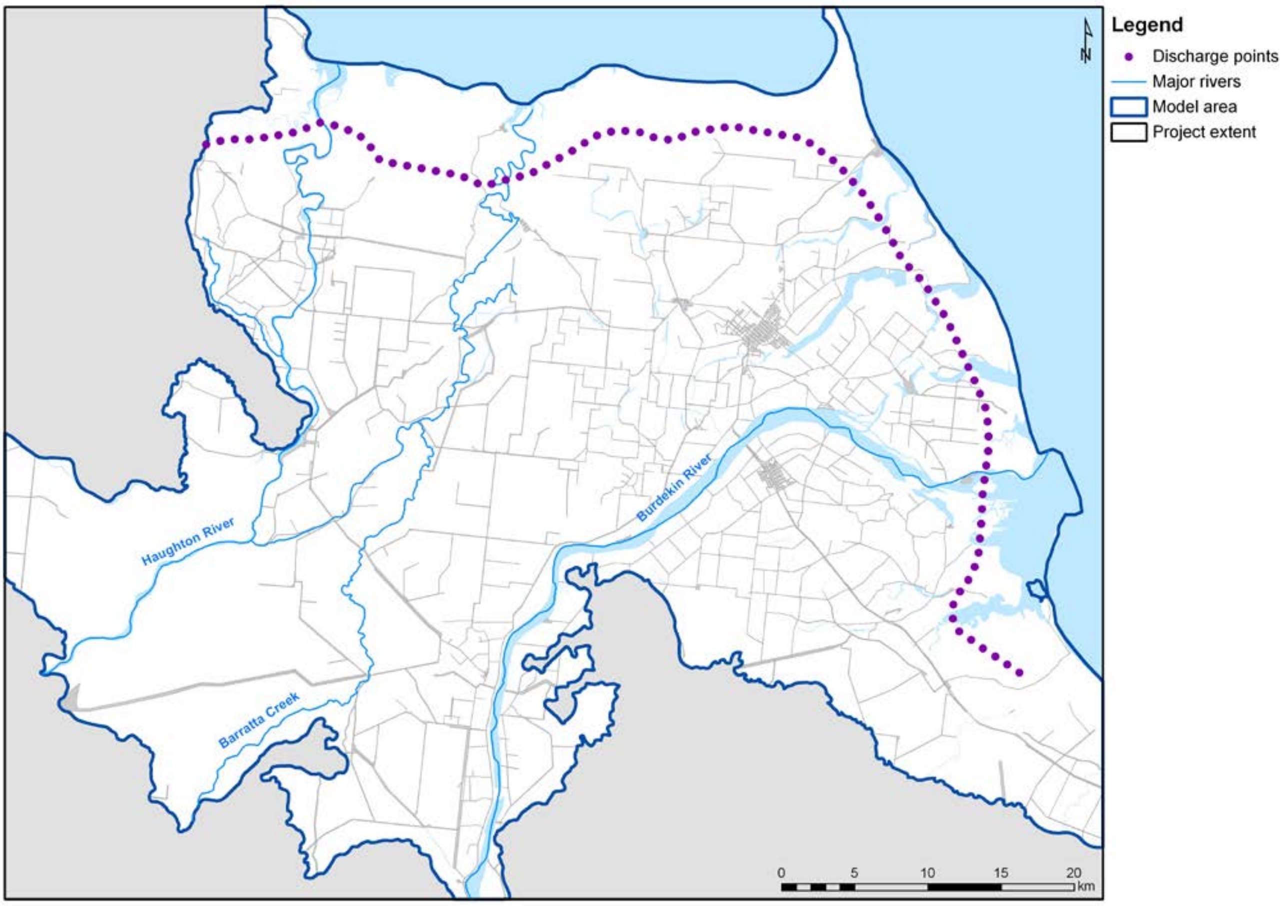


Figure 5-25 Location of coastal discharge points

Density-Corrected Water Levels

To calculate groundwater discharge through the coastal interface, groundwater levels are required to be adjusted to account for density due to saline groundwater.

Equivalent fresh water head, h_f, is given by:

$$h_f = \frac{\rho}{\rho_f} h - \frac{\rho - \rho_f}{\rho_f} z \qquad \text{Equation 3}$$

h_f = equivalent fresh water head

ρ_f = density of fresh water

ρ = density of sea water

z = elevation of reference point/depth of water

h = saline water head

To convert EC measurements to density, a relationship between total dissolved solids (TDS) and EC was first established. For this, all the EC records of the water samples taken in the Burdekin Project area were plotted against the corresponding TDS (refer Figure 5-26). Figure 5-26 clearly indicates an approximately linear relationship between TDS and EC. Some scatter is observed but generally there is a linear trend up to the concentration of seawater (approximately 35,000mg/L). For saline concentrations in excess of seawater, the relationship tends to scatter and deviate slightly off a linear trend. For the purposes of this project, the relationship between TDS and EC is considered linear. Note that temperature dependence of EC has not been considered here. The linear relationship between TDS and EC is given by:

TDS(mg/l) = EC(μS/cm) *0.7697 Equation 4

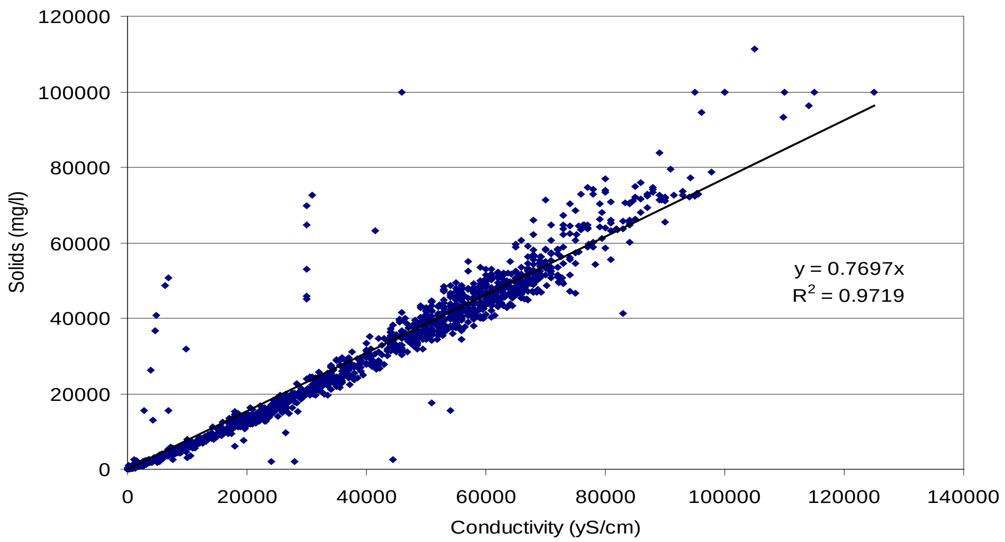


Figure 5-26 Relationship between electrical conductivity (EC) and total dissolved solids (TDS) for Lower Burdekin groundwater

The average density of seawater at the surface of the ocean is 1,025 kg/m^3 with 35,000mg/L of TDS. Fresh water reaches a maximum density of 1,000 kg/m^3 at a temperature of 4°C. Freshwater is defined as water with TDS less than 500mg/L. A linear relationship between density and TDS has been assumed as follows:

Density(kg/m^3) = TDS(g/l)*0.7143 + 1000 (kg/m^3) Equation 5

Combining equations 1 and 2, the density of saline water as a function of electrical conductivity is given by:

Density(kg/m^3) = EC/1000*0.55+1000(kg/m^3) Equation 6

As water levels and salinity are not measured at the same frequency, density corrected water levels have been based on average EC values of each bore. This implies that density used for calculating equivalent fresh water head is not changing over time.

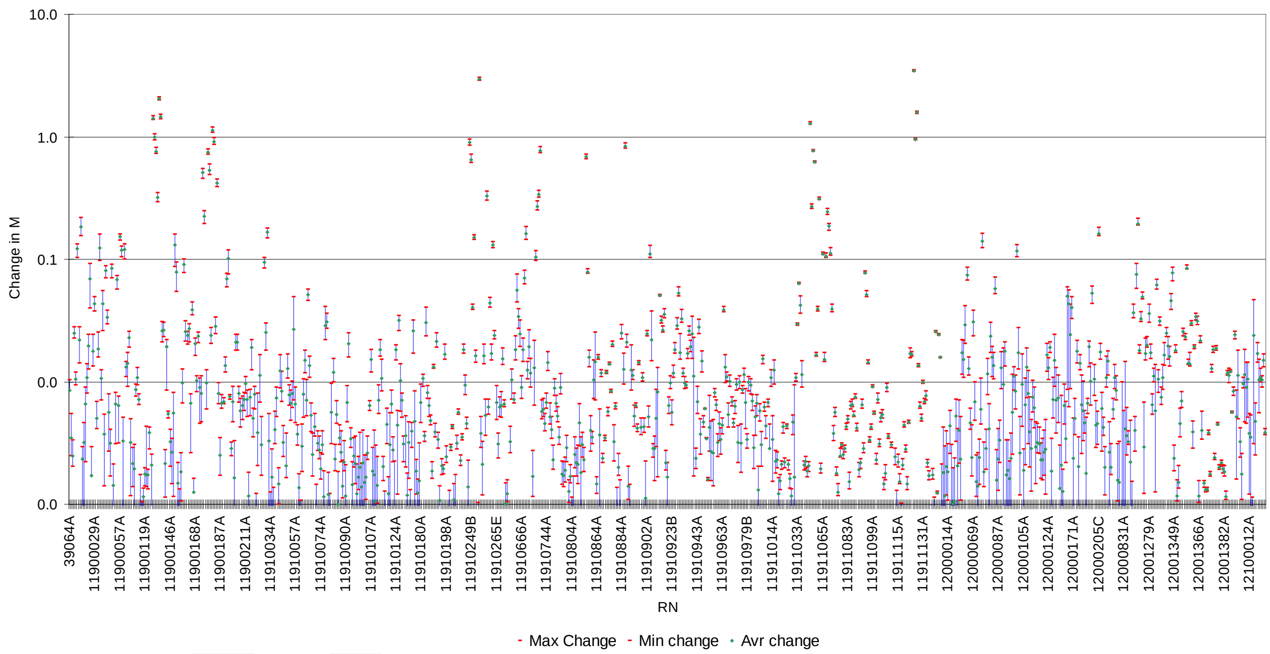


Figure 5-27 Change in water levels when correcting for salinity (based on min, max and average EC values)

A comparison of the change in water levels for minimum, maximum and average EC measurements are shown in Figure 5-27. Most bores are within 0-0.5 m change. 12 bores have been adjusted by more than 1 m. The graph shows that the change between minimum and maximum water level correction is relatively small (the maximum change was 0.17 m). It is therefore reasonable to calculate equivalent fresh water head based on average EC.

Some bores have water level corrections of up to 3.5 m. This is because some of the measured groundwater ECs were much higher than the average seawater salinity (>50,000 µS/cm). According to Fass et al (2007) the isotopic signature of these highly saline waters is not consistent with surface water evaporation, geological or anthropogenic sources. Highly saline water currently exists below mangrove vegetation. It has been postulated that saline waters that were present beneath earlier mangrove communities have sunk through the aquifer due to density effects (Fass et al. 2007).

Results

The discharge across the coastal boundary has been calculated on a monthly basis. At each of the discharge points along the line (discharge points, shown in Figure 5-25), the distance between the water level surface and the basement surface has been calculated. In addition, the maximum water level gradient is calculated at each of the discharge points. A hydraulic conductivity of 150m/d is used to calculate coastal discharge.

Figure 5-28 presents the yearly amount of coastal outflow. The 25-year average annual coastal outflow is estimated at 37395 ML.

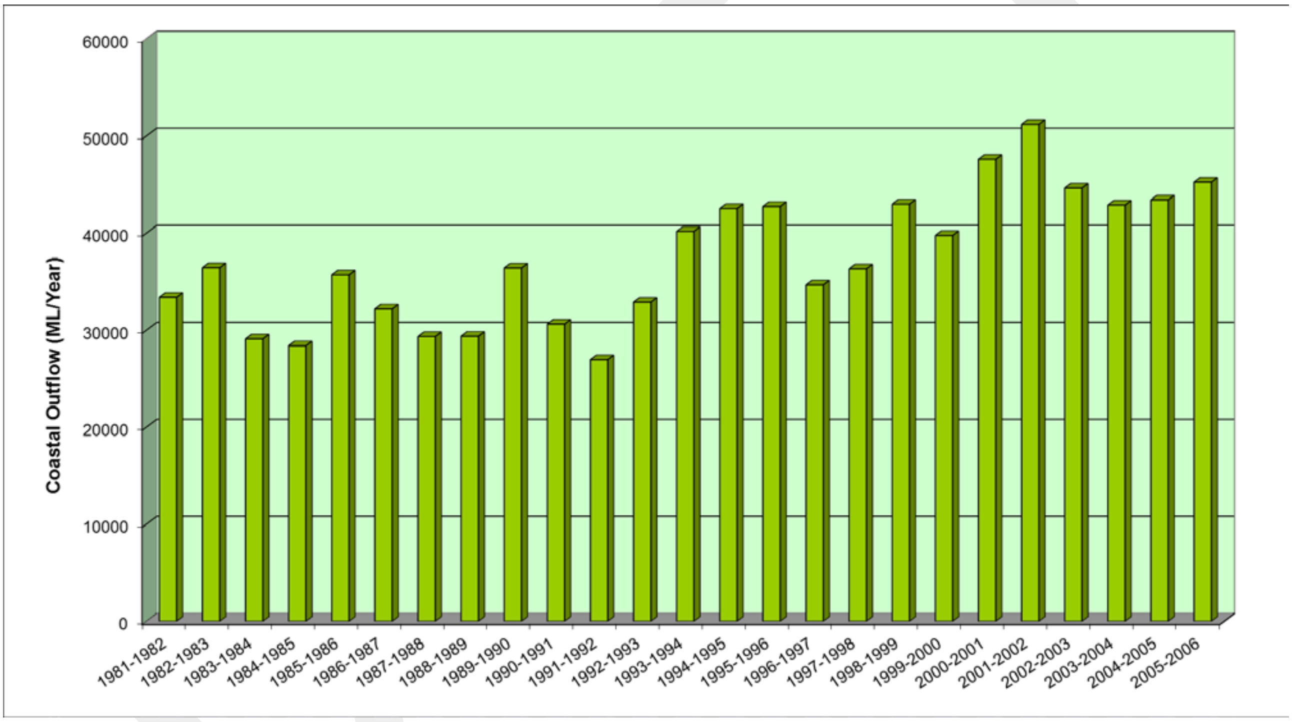


Figure 5-28 Estimated annual coastal outflow

Cook, Stieglitz & Clark (2004) estimated the groundwater discharge to be 50 – 400,000 ML/year into Bowling Green Bay from radon and radium activities. McMahon et al (2002) estimated that the discharge to the Coral Sea to the east of the model area to be in the range of 1,500 to 9,000 ML/year using a hydraulic conductivity of 150m/d.

5.11 Groundwater Quality

Groundwater quality in the Lower Burdekin may be affected by a number of factors including physical and chemical characteristics of aquifer materials, proximity to surface water bodies and proximity to the coast. In addition, groundwater quality is influenced by agricultural activities that lead to enhanced recharge, leaching of fertilisers and enhanced mixing of different salinity waters. There is a strong potential for nitrate accumulation in groundwaters due to applied fertilizers and recycling processes in the Burdekin Delta. In addition, high groundwater salinity concentrations in the Lower Burdekin have been associated with a number of processes including seawater intrusion and secondary salinisation associated with irrigation.

The primary source of groundwater chemistry data for the Lower Burdekin is the Queensland Government's groundwater database (GWDB). The monitoring record is quite variable, with the greatest coverage between 1977 and 2001, followed by fairly limited monitoring since 2001 (Figure 5-29). The number of chemical analyses reached a peak in 1990. Prior to 1960, there are only a few records. Due to the paucity of recent groundwater chemistry data, water analyses from the 1990s are presented in this section.

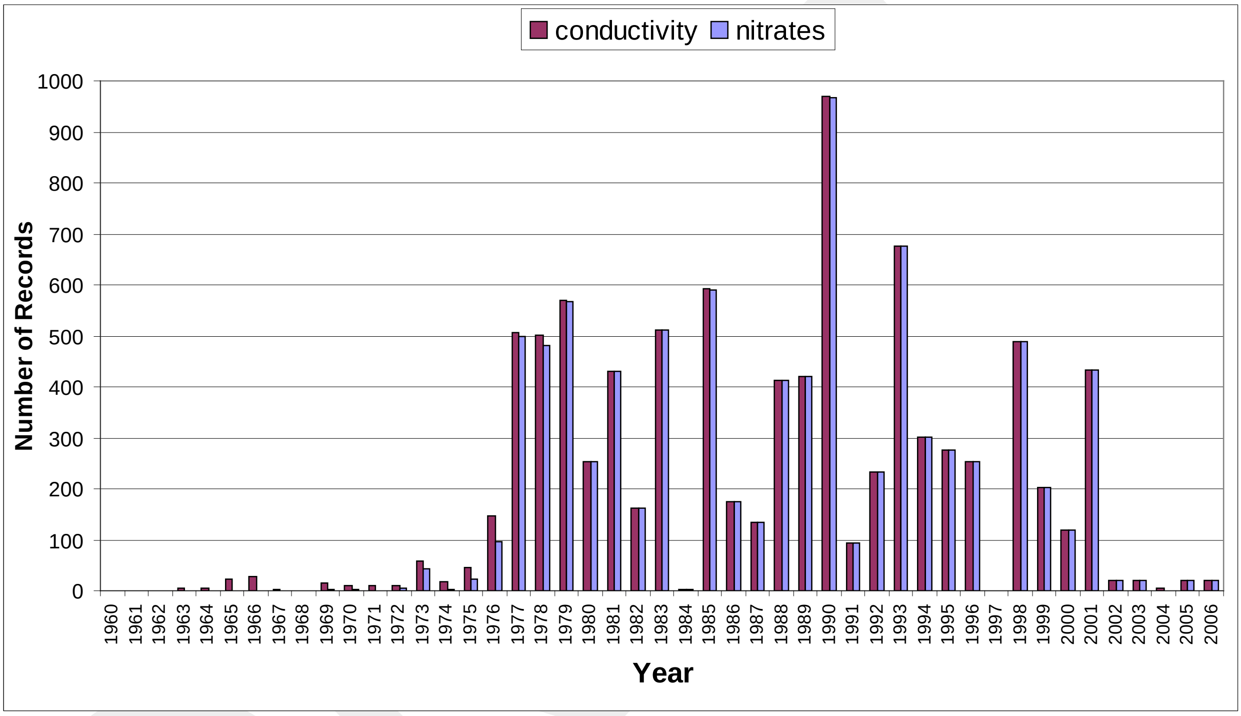


Figure 5-29 Groundwater chemistry data held in the groundwater database

Groundwater Nitrogen

Nitrate is the dominant chemical species of nitrogen in groundwater which may be derived from soil organic material nitrogen, organic and inorganic fertilizers, wastewater irrigation, livestock waste, feedlots, sewerage and atmospheric precipitation. The organic nitrogen compounds and ammonium ions (NH_4^+) are often converted to nitrate (NO_3^-) in the oxygen rich soils. In order for nitrate to leach into aquifer systems, two conditions are required: 1. there must be a source of nitrogen; and 2. there must be sufficient vertical drainage beneath the root zone. The quantity of nitrate that can leach into aquifer systems therefore strongly depends on the magnitude and timing of fertilizer applications, crop growth and groundwater recharge. Mechanisms for controlling nitrate losses to groundwater systems include the use of irrigation scheduling; fertilization based on soil tests and conservation tillage (Power&Schepers 1989).

The major source of nitrate to groundwaters in the Lower Burdekin is applied fertilizers (Biggs et al. 2001, Weier 1999). Farming practices in the region typically involve application of significant amounts of nitrogenous fertilizer (160-220 kg N/(ha year)) (Stewart et al. 2006). High background levels of nitrate have also been detected in irrigation waters used in the Burdekin Delta. Thus, estimates of nitrate loads to aquifer systems must account for the background levels of nitrate in irrigation water in addition to fertilizer application rates (Charlesworth&Bristow 2004).

There have been a number of investigations of agricultural chemicals in groundwater in the Burdekin. High nitrate concentrations in the Home Hill region were identified by Brodie *et al.* (1984), Keating *et al.* (1996) and Weier (1999). Weier (1999) also highlighted the high nitrate concentrations around Clare as an area of concern. Brodie *et al.* (1984) stated that nitrate concentrations were generally found to decrease with increasing depth and observed a steady decline in overall nitrate concentrations during the dry season. Keating *et al*. (1996) highlighted an increasing groundwater nitrate trend for a bore in the Burdekin Delta and attributed this to the impacts of effluent disposal onto nearby caneland. It should be noted that interpretations of temporal variation in nitrate concentration in groundwater need to account for the time lag between fertilizers application to crops and detection in groundwater. Detection of agricultural contaminants at a certain depth or flow path position may reflect contaminants introduced to the aquifer decades prior to sample collection (Bohlke 2002) and kilometres from its source (Appelo&Postma 1999).

The spatial distribution of nitrate concentrations in groundwater has been assessed for the period when the greatest number of groundwater samples were collected and analysed (the 1990s). During this period, the majority of the bores sampled had nitrate concentrations below 10 mg/L (Figure 5-30). Nitrate concentrations greater than 10 mg/L and in some cases up to 100 mg/L were recorded near Clare and Home Hill. Nitrate concentrations greater than 20 mg/L were also detected in groundwater sampled near the tidal limit (Figure 5-30).

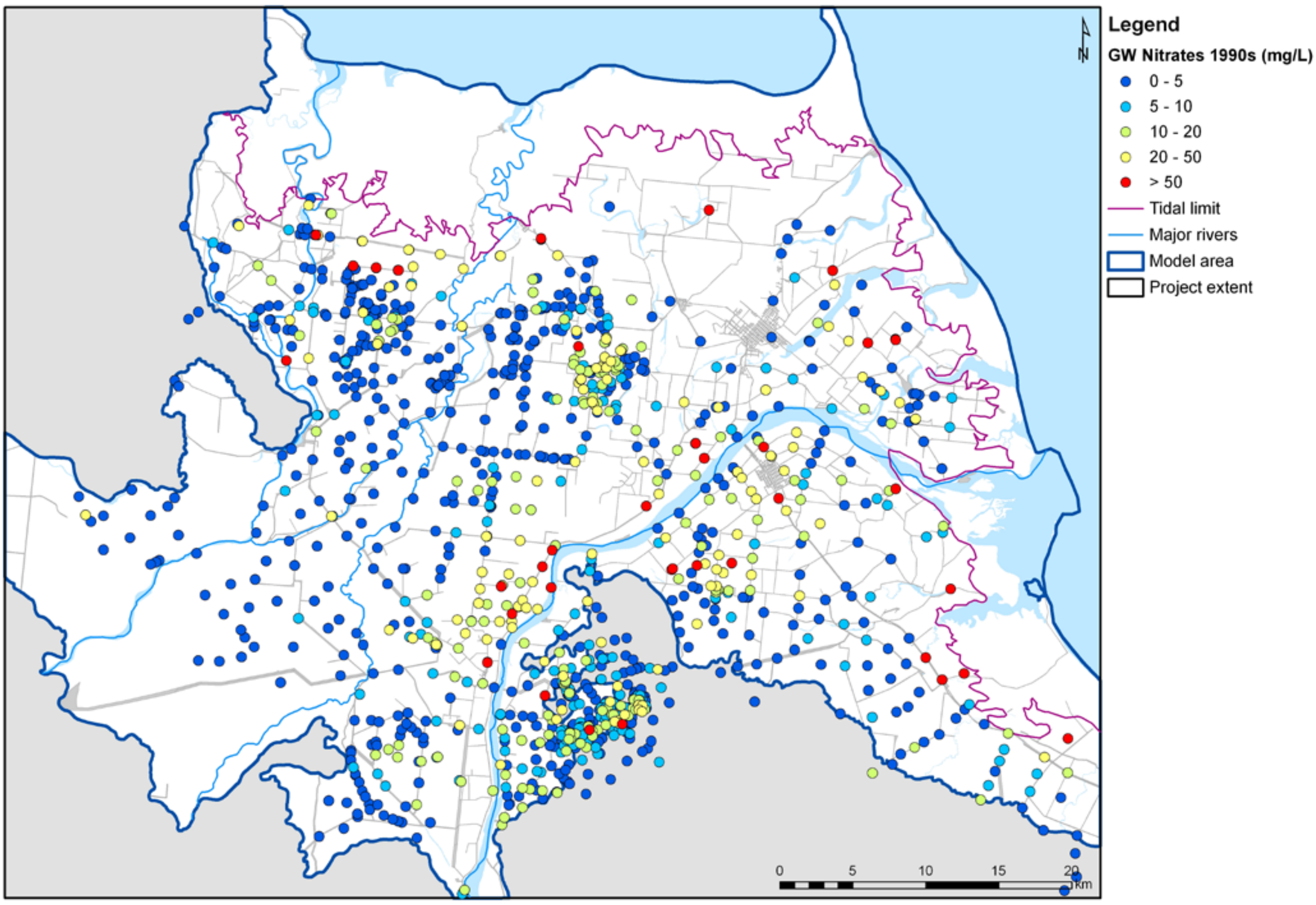


Figure 5-30 Maximum groundwater nitrate concentrations in the 1990s

In order to determine the degree of nitrate contamination beneath sugarcane fields, a three year study was initiated in 1997 with the analysis of 1028 groundwater samples from a number of sugarcane regions in New South Wales and Queensland (Weier 1999). Following the initial sampling and analysis for nitrate in 1997, bores with nitrate concentrations greater than 20 mg/L were resampled 8 times between 1998 and 2000 to determine temporal trends (Biggs et al. 2001, Thorburn et al. 2003). This study concluded that no temporal trends in nitrate concentrations were observed in the Burdekin during the monitoring period. The percentage of groundwater bores that were classified as having rising groundwater nitrate concentration trends was 4% (2 bores out of the 52 sampled). Nitrate concentrations were found to be unrelated to sampling depth or depth to water table.

In 2005 a statistical analysis of the groundwater nitrate and salinity data from the GWDB was conducted by CSIRO (Barnes, Marvanek & Miller 2005), for the period of 1970 – 2003. A key finding was that 21% of the bores assessed exhibited statistically significant increases in nitrate levels over time. Average nitrate concentrations across all bores were found to be increasing, with an average rate of rise in nitrate concentrations of 0.25 mg/L/year.

Recent investigations of nitrate concentrations in Lower Burdekin groundwaters have studied the influence of redox processes (Thayalakumaran, Charlesworth & Bristow 2004, Lenahan&Bristow 2010a, Thayalakumaran et al. 2008). Nitrate attenuation in the Lower Burdekin has been attributed to a combination of denitrification and dissimilatory nitrate reduction to ammonium (DNRA) (Thayalakumaran, Charlesworth & Bristow 2004, Lenahan&Bristow 2010a, Thayalakumaran et al. 2008). The geochemical conditions that promote these two nitrate attenuation reactions include low dissolved oxygen (DO) concentrations, the presence of ferrous iron and availability of dissolved organic carbon (DOC).

It is possible that local high concentrations of nitrate occur due to the occurrence of DO levels above the levels suitable for denitrification (Thayalakumaran et al. 2008), particularly within the coarse grained palaeochannel deposits (Lenahan&Bristow 2010a). High nitrate concentrations have also been found to occur in groundwaters that have been recharged since the 1980s, with nitrate concentrations decreasing with CFC-12 modelled groundwater age (Thayalakumaran et al. 2008). Low nitrate concentrations in bores close to the coast suggest that while nitrate concentrations are high in some areas of the lower Burdekin, much of the nitrate could be attenuated before the groundwater is discharged to the GBR lagoon (Thayalakumaran et al. 2008).

The existence of low nitrate concentrations in groundwater samples with high levels of ammonium suggest that DNRA is also occuring (Thayalakumaran et al. 2008). It has been hypothesized that DNRA is favoured when nitrate is limiting and denitrification is favoured when DOC is limiting (Tiedje 1988). When nitrate is reduced to ammonium, the ammonium ions are often immobilized due to adsorption onto exchange sites (Lenahan&Bristow 2010a). However, in higher salinity waters sodium may out-compete ammonium for the exchange sites of clay minerals. Furthermore, salinisation of aquifer systems may result in the displacement of ammonium ions present on the exchange sites (Slomp&Van Cappellen 2004). Higher salinity environments can limit the ability of microorganisims to denitrify even in the presence of suitable electron donors (Rysgaard et al., Mariangel et al. 2008). The ultimate fate of ammonium in groundwater in the coastal zone of the lower Burdekin is not yet known.

Groundwater Salinity

A statistical analysis of the groundwater salinity data from the GWDB by CSIRO (Barnes, Marvanek & Miller 2005), found that a large proportion of bores (44%) exhibited conductivity levels that were increasing with time for the period of 1970 – 2003. Another key finding was that a large proportion of bores have excessive conductivity levels, greater than 3000 µS/cm. Excessive conductivity levels like this would affect plant growth, therefore groundwater in this category would need to be mixed with surface waters if used for irrigation (Barnes, Marvanek & Miller 2005).

Saline groundwaters in the Lower Burdekin occur due to a range of processes. Naturally occurring saline groundwaters are present in the "saline wedge" associated with the seawater interface (Arunakumaren, McMahon & Bajracharya 2001, Narayan, Schleeberger & Bristow 2007, McMahon, Hillier & Arunakumaren 2001). Higher salinity groundwater encountered further inland may be attributed to upward migration of saline connate waters from marine deposits that underlie the Holocene alluvial aquifer (Lenahan&Bristow 2010b). Solutes within the aquifer system have likely been sourced from rainwater, irrigation waters, unsaturated zone soil water and evaporite minerals, and from mixing with saline groundwaters that reside at depth in some parts of the system.

Seawater intrusion contributes to high groundwater salinity in the coastal parts of the Lower Burdekin (Narayan, Schleeberger & Bristow 2007, McMahon, Arunakumaren & Bajracharya 2002). Previous research relating to coastal groundwater salinity has focussed on modelling seawater intrusion and upconing under different pumping scenarios. The seawater interface has been characterised as extending kilometres inland and being quite dynamic (Narayan, Schleeberger & Bristow 2007, McMahon, Arunakumaren & Bajracharya 2002). Groundwater conductivity within 2 km of the tidal limit ranges from <5000 µS/cm to >50000 µS/cm (Figure 5-31, Figure 5-32 and Figure 5-33).

There are also locations further inland where groundwaters are highly saline (>10,000 µS/cm), including at Leichardt Downs and Mulgrave (Figure 5-31, Figure 5-32 and Figure 5-33). Some of the theories that have been proposed to explain the occurrence of saline groundwaters further inland from the tidal zone include:

- movement of salt from the unsaturated zone into groundwater (Lenahan&Bristow 2010b, Petheram, Bristow & Nelson 2008);
- influxes of salts from bedrock outcrops (Arunakumaren, McMahon & Bajracharya 2001);
- evaporative salinity due to shallow water tables (Arunakumaren, McMahon & Bajracharya 2001);
- upward migration of saline waters trapped in marine deposits up to 30 km inland from the coast (Lenahan&Bristow 2010b), and
- downward movement of saline water trapped beneath mangroves during the early Holocene (Fass et al. 2007).

The study by Fass (2007) concluded that the presence of highly saline groundwaters up to 15 km from the present coastline can be explained by the transpiration of seawater by mangroves when sea levels were 2 to 3 m above modern sea level, followed by the subsequent downward movement of this highly saline water due to density effects. This process results in the stratification of groundwater salinity inland from the coastline and the development of zones of highly saline groundwater at the bottom of the unconfined aquifer.

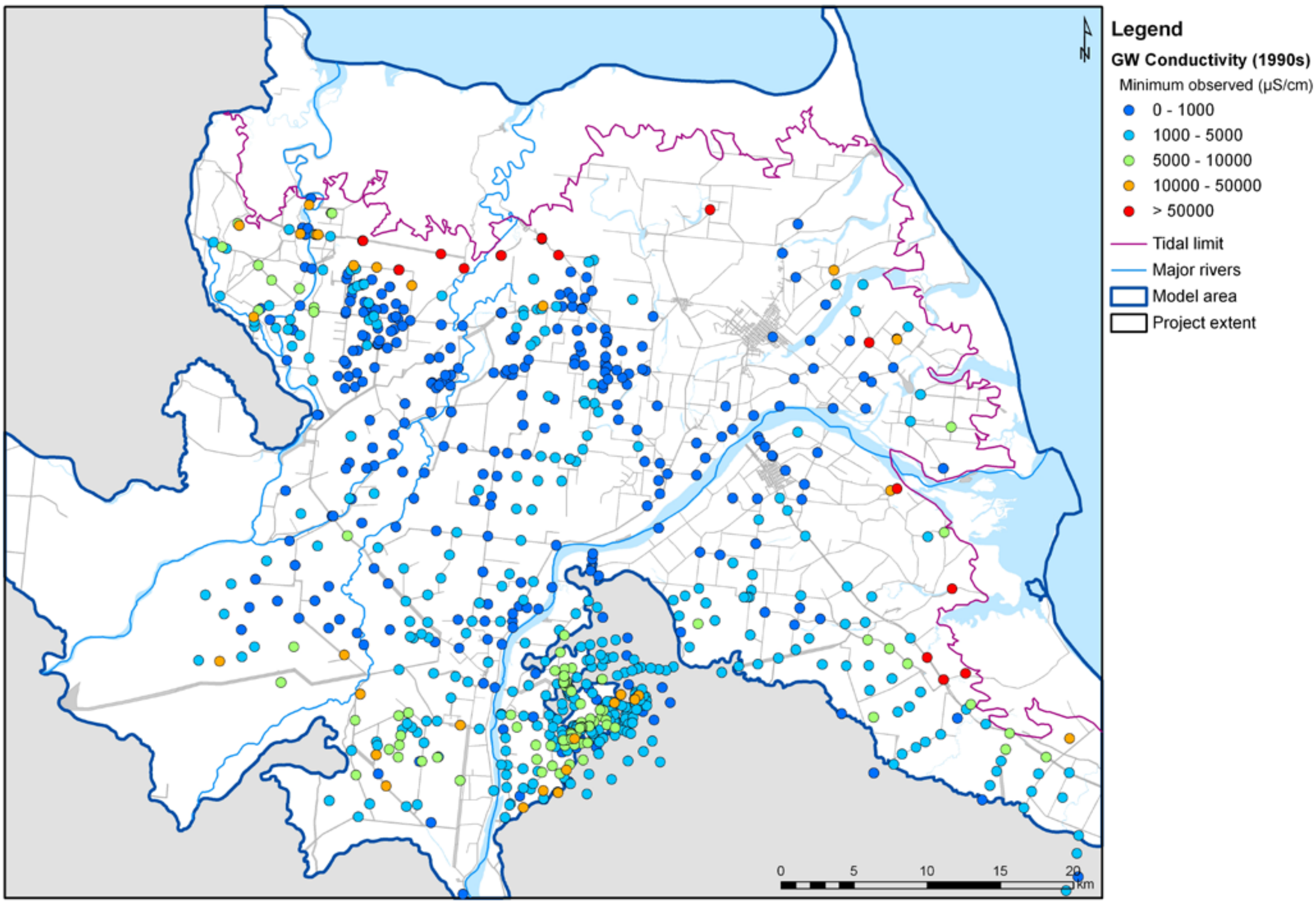


Figure 5-31 Minimum groundwater conductivity in the 1990s

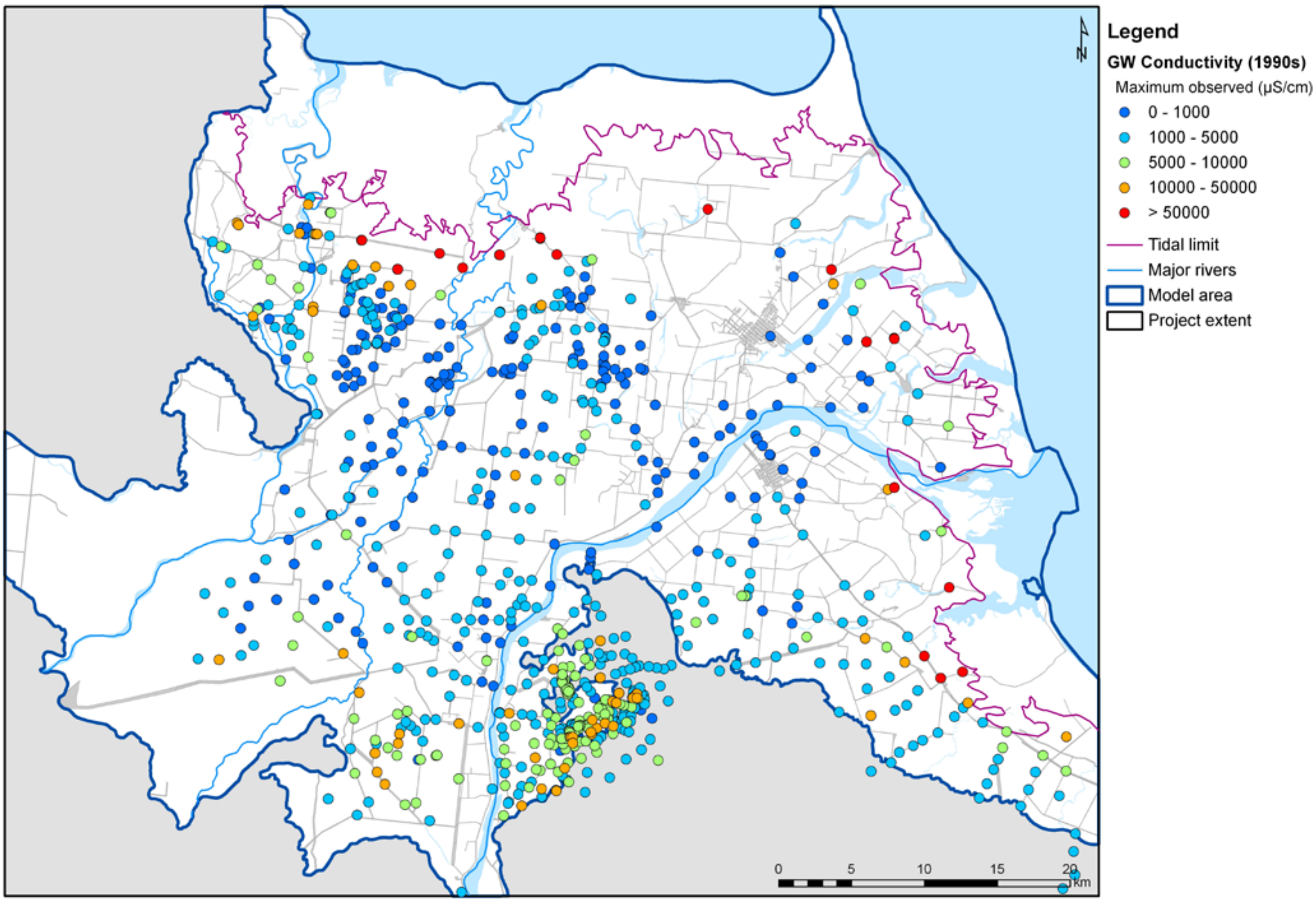


Figure 5-32 Maximum groundwater conductivity in the 1990s

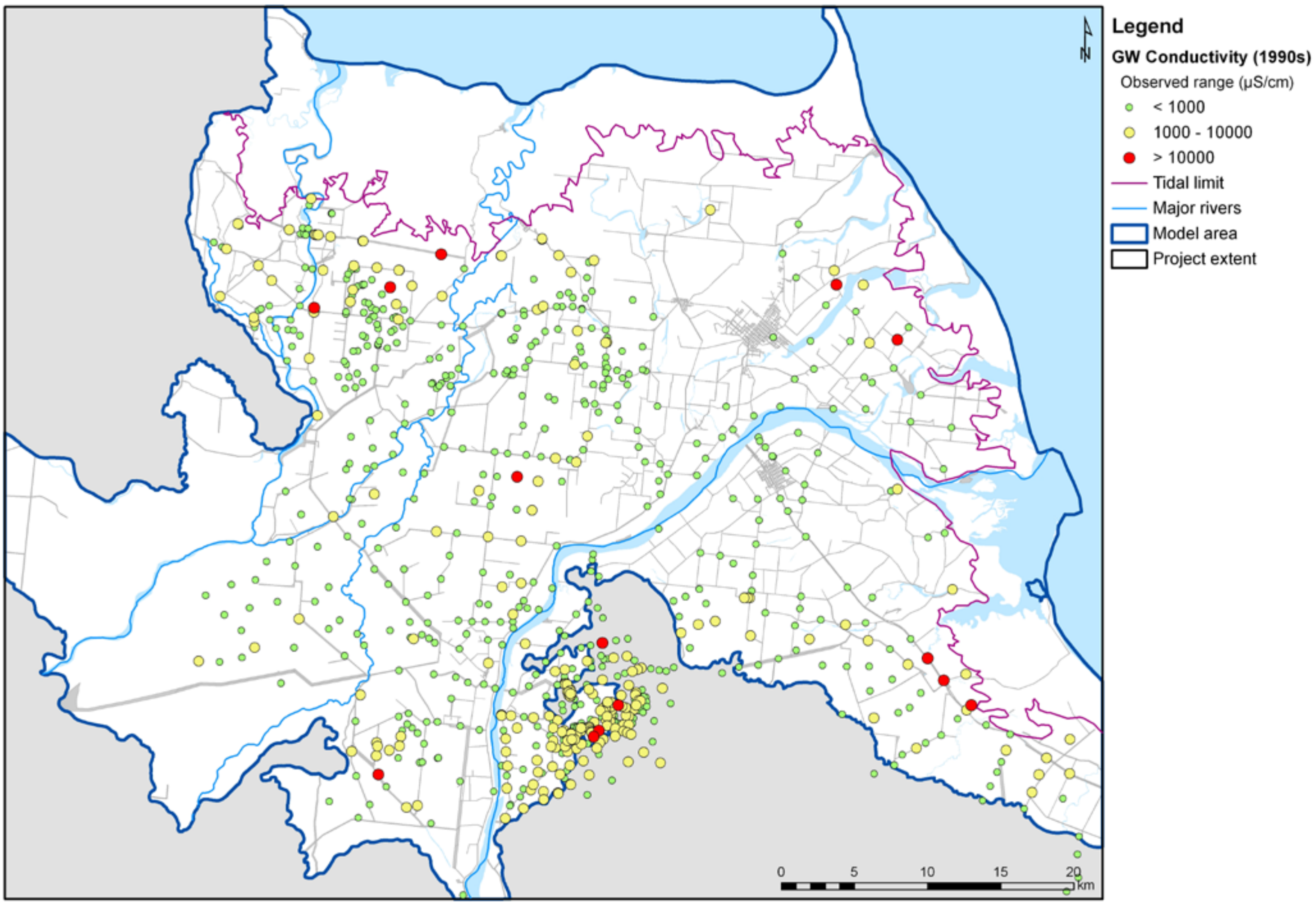


Figure 5-33 Range of recorded conductivity values in the 1990s

Major Ion Chemistry

McNeil (1981) investigated the factors determining ionic distribution in Queensland's alluvial groundwaters and found that in the lower Burdekin, there was a great variability in water types (see Figure 5-34). Two primary causes are suggested for this variability:

1. Because there are many factors contributing to the water composition (including seawater intrusion, mixing with connate saline waters trapped in old deltaic sediments, solute adsorption onto clays and leaching of fertilizers) and
2. Because the aquifer system is not in permanent equilibrium with these factors (McNeil 1981).

Water types were found to range from a group of water types similar to seawater to a group of fresh water types resulting from Burdekin River recharge. Ten major water types were described (McNeil 1981). Variations in water composition were found to occur horizontally as well as laterally.

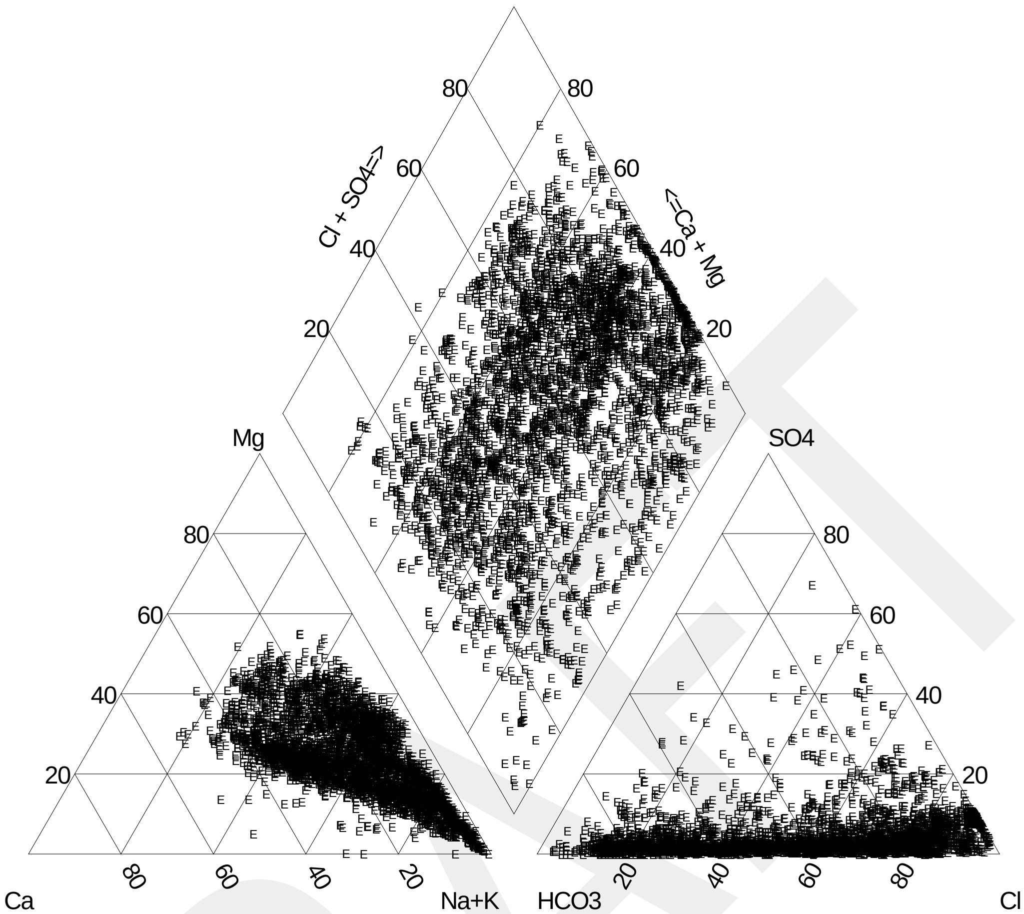


Figure 5-34 Piper diagram showing major ion chemistry of groundwater in the Lower Burdekin (all data)

McMahon (2004) used the relationships between major ions to provide information on the sources of groundwater and the processes that led to their composition. Discrete statistical groups of ionic ratios were discriminated using cumulative frequency distributions. The statistical groups were bounded by critical values that distinguish different chemical processes, referred to as hydrogeochemical indicators. The hydrogeochemical proceses determined were: seawater mixing, evaporative concentration of salts, hydrolysis of Na- feldspar, base exchange reaction, reverse base exchange reaction, fresh HCO_3 type recharge waters, carbonate dissolution, river recharge, oxidation of Fe sulphides, sulphate reduction, flow from sediments (high SO_4 content) and flow from bedrock (low SO_4 content). Seawater mixing processes were identifiable from five different ionic ratios, for example, a Na/Cl ratio of less than 1 (see Figure 5-35).

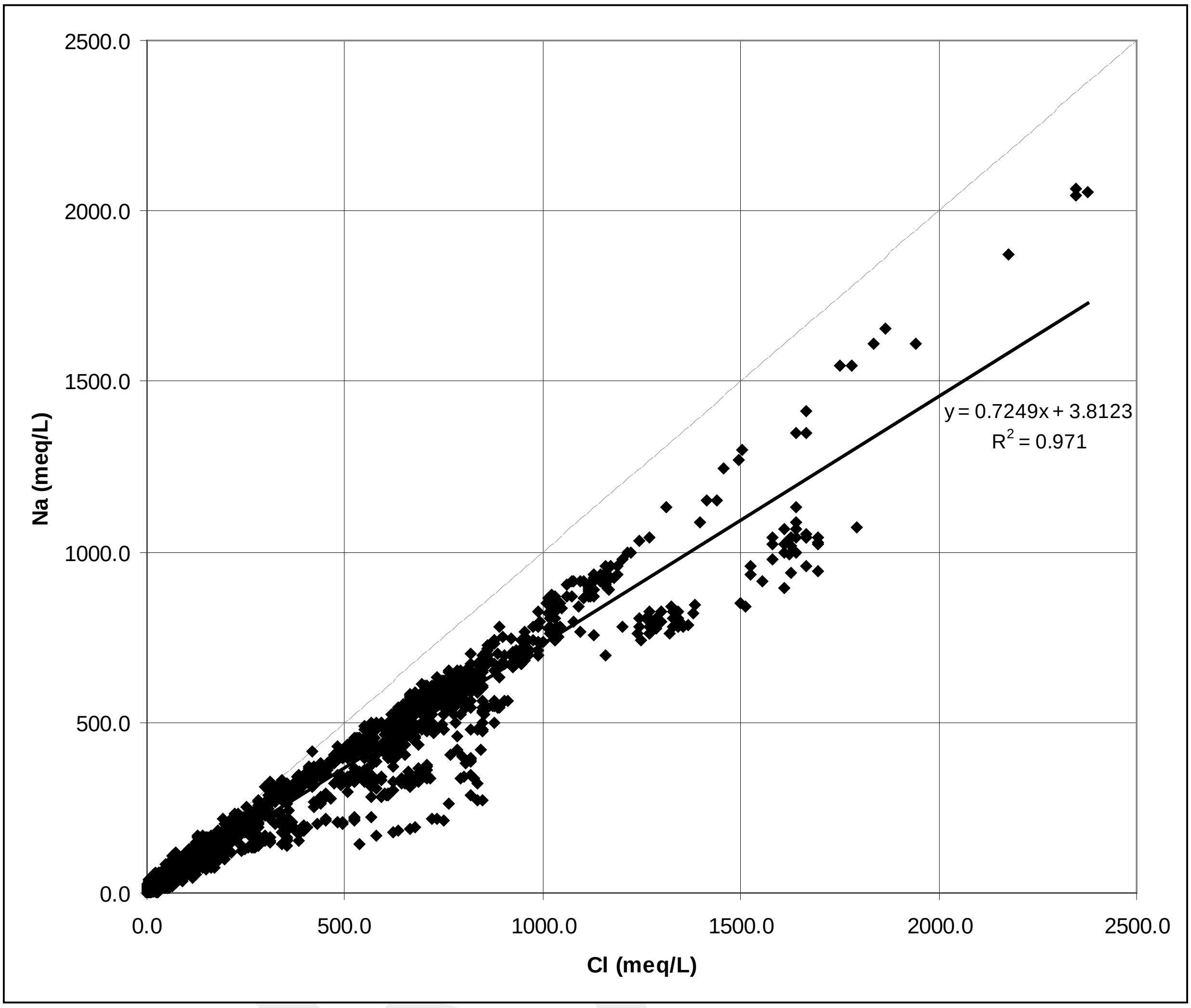


Figure 5-35 Na/Cl ratios for Lower Burdekin groundwaters (all data), the regression line shows that most of the data falls below a Na/Cl ratio of 1 (dotted line).

McMahon (2004) was able to differentiate major ion chemistry between the north and south sections of the Burdekin delta. In the southern part of the delta, the predominance of Mg,Ca-Cl type waters was attributed to mineral hydrolysis and evaporation of groundwater sourced from fractured rock aquifers (granite basement) followed by reverse cation exchange. Whereas in the northern part of the delta, the absence of NaCl type waters maintains groundwater composition towards Na-HCO_3 type due to mineral hydrolysis and base-exchange reactions. Both sides of the delta are recharged by fresh Ca-HCO_3 type waters from the Burdekin River. Water types for the basement rocks were found to range from Na,Mg,Ca-Cl,HCO_3 to Na,Mg-Cl water types. This range of water types has evolved from the mixing of Na-Cl type waters from evaporative concentration of recharge water containing atmospheric salts and Na-HCO_3 type waters from water-aquifer interaction in the weathered zone of exposed granitic bedrock).

More recently, Lenahan (2010b) assessed major ion chemistry for groundwater to determine salinization mechanisms in the lower Burdekin. The groundwater chemistry data was split into groups based on chloride concentrations (<100 mg/L, <500 mg/L and >20,000 mg/L). Comparisons were made with Burdekin River water (Cl<15 mg/L) and Global Seawater (Cl=20,000 mg/L). The chemical composition of Burdekin River water and low-salinity groundwater (Cl<100 mg/L) were found to be characterised by Ca-Na-HCO_3 and Na-Ca-HCO_3 type waters while the composition of saline groundwater (and seawater) was dominated by Na and

Cl. This study assumed that cation exchange and weathering of Na-bearing minerals were relatively insignificant and that the processes controlling Na concentrations were dominated by mixing and/or evapotranspiration. The Na and Cl concentrations of groundwaters of intermediate salinity were attributed to conservative mixing between low salinity groundwaters (derived from irrigation water, river water and rainwater) and saline groundwaters (seawater intrusion and relic seawater deposits). Increases in salinity over time for selected bores in the upper and lower delta plain and alluvial valley were also explained by this conservative mixing and it was concluded that enhanced recharge and intensive groundwater extraction led to mobilization of unsaturated zone solute stores and induced mixing between shallow, low salinity groundwater and deeper more saline waters.

6 Groundwater Management

An important component of the conceptualisation of an aquifer system for the purposes of groundwater flow modelling is an understanding of the current and historical groundwater use patterns. Neither recorded water usage nor entitlement data is available for Delta area. However, both data exist for BHWSS area. This section addresses groundwater management within the BHWSS area for the purposes of constructing a water balance model and characterising hydrographic responses.

6.1 Groundwater Entitlement

The entitlement data were collected from Townsville office. There are 538 bores with entitlements in BHWSS area. They are classified on the basis of their purpose and presented in Table 6-1. Of the 538 bores, 482 bores are irrigation bores with a total entitlement of 58953.1ML, thirteen bores are for industrial water supply with a total entitlement of 336ML. 43 stock watering and domestic supply bores are also included in the entitlement data though more are expected as stock watering and domestic supply bores do not need a licence in the Burdekin catchment.

Table 6-1 Breakdown of pumping bores based on licensed purpose

Purpose	Number of bores	Total Entitlement (ML)
Irrigation		
Agriculture, irrigation	470	58679.7
Domestic supply, irrigation	1	
Industrial, irrigation	1	25
Irrigation, commercial	3	10.4
Irrigation, stock	7	238
Total	*482*	*58953.1*
Stock watering and domestic supply		
Domestic supply	1	2
Domestic supply, stock	1	1.5
Stock watering	41	3.5 (Only 2 bores shown allocation)
Total	*43*	*7*
Industrial water supply		
Amenities	2	238
Commercial	2	7
Industrial	3	9
School	5	75
Test purpose	1	7
Total	*13*	*336*

6.2 Metered Groundwater Use

The record of groundwater pumping in BHWSS area began in 1973 and was limited to a few bores. Since then, the number of bores metered has increased (Table 6-2).

Table 6-2 Number of bores metered for each period in the BHWSS area

Period	No of bores metered
1973-1980	13
1981-1985	134
1986-1990	158
1991-1995	187
1996-2000	277
2001-2006	260

The metered use from individual bores is amalgamated by sub area shown in Figure 6-1.

Figure 6-1 Location of the BHWSS sub areas

Table 6-3 shows the yearly water usage by sub area. Years highlighted in grey only have readings for 2 or 3 of the quarters. The table demonstrates that data are relatively complete for all the sub areas from 1998/1999. There is no metered groundwater pumping for Delta area.

Table 6-3 Yearly metered groundwater usage from 1973-2006 by sub area (ML)

Subarea	1973/ 1974	1974/ 1975	1975/ 1976	1976/ 1977	1977/ 1978	1978/ 1979	1979/ 1980	1980/ 1981	1981/ 1982	1982/ 1983	1983/ 1984
Clare											
Giru									10354	11367	
Haughton											
Horseshoe Lagoon	807	590	793	803	1125	985	1156	801	1408	1130	1659
Jardine									66	76	
Mona Park		34	55	254	463	387	280	220	421	234	395
Mulgrave											57
Northcote				188	228	426	770	569	1219	966	835
Selkirk									163	91	
Total	807	624	848	1245	1817	1798	2205	1590	13632	13866	2946

Table 6-3 continued

Subarea	1984/ 1985	1985/ 1986	1986/ 1987	1987/ 1988	1988/ 1989	1989/ 1990	1990/ 1991	1991/ 1992	1992/ 1993	1993/ 1994	1994/ 1995
Clare											
Giru				12268	6711	17095	15567	18957	23963	23244	17182
Haughton											
Horseshoe Lagoon	1242	1404	2660	2379	2482	4881	9063	10494	12111	96075	3994
Jardine			3	1	94	64	1	59	113	21	32
Mona Park	210	167	272	0	0	0	0	0	0	0	0
Mulgrave	1	0									
Northcote	816	917	1777	739	1003	783	1126	1779	2496	2776	2372
Selkirk			96	91	98	94	263	2360	4090	3578	3629
Total	2269	2488	4749	15838	10388	22917	26019	33649	42773	39226	27209

Table 6-3 continued

Subarea	1995/ 1996	1996/ 1997	1997/ 1998	1998/ 1999	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	2003/ 2004	2004/ 2005	2005 /2006
Clare	115	141	391	1563	2245	1647	1045	2015	1462	2443	1343
Giru	22524	14585	5384	17494	8024	11957	19611	22834	19110	22048	14233
Haughton			100	1163	428	487	444	445	424	386	510
Horseshoe Lagoon	1252	2723	51	11932	2873	5726	5272	8305	9152	7520	3017
Jardine	8	24	1847	8292	8589	12517	12953	14565	14156	16279	6528
Mona Park	0	0	1330	9704	7908	8889	5552	8243	12642	12250	5495
Mulgrave		0	0	64	152	82	194	240	76	200	334
Northcote	1899	2171	1654	10190	9821	13872	13538	13526	19189	18589	8097
Selkirk	1698	3280	238	3323	2320	3522	2529	4779	3558	4715	1576
Total	27496	22924	10995	69725	42359	58697	61109	74952	79769	84430	41134

7 Surface Water Management

7.1 Surface Water Use

7.1.1 BHWSS

In order to better understand the sharing of irrigation demand among surface water and groundwater, the surface water use for the purpose of irrigation is also collected and presented.

Metered surface water usage for the BHWSS was obtained from the following three sources:

- SunWater IROL water use report for the period from January 2001 to March 2006
- Data provided by Townsville office in 2007 for the period from 2001/2002 to 2005/2006
- Data collected in 2004 for the period from 1997/1998 to 2002/2003

In the SunWater IROL water use report, the metered water use is recorded quarterly against the Offtake No. The other two sources present quarterly metered usage by subarea.

Table 7-1 shows the yearly metered surface water usage in BHWSS area.

Table 7-1 Yearly Metered Surface Water Usage in the BHWSS (ML) (Sunwater)

Subarea	1997/ 1998	1998/ 1999	1999/ 2000	2000/ 2001	2001/ 2002	2002/ 2003	2003/ 2004	2004/ 2005	2005/ 2006
Clare	21909	16497	18161	22352	29783	33677	29292	32005	24108
Mulgrave/Woodhouse	34690	26496	23883	27374	40416	46969	40041	42463	34296
Northcote/Mona Park	33560	27867	29124	32382	51213	79915	76004	88460	51365
Jardine	24534	17423	18788	20401	27747	30637	27168	33206	21349
Haughton/Selkirk/ Horseshoelagoon	44649	35533	60386	60974	87562	87012	88295	91539	65820
Leichhardt Downs	12232	8815	9706	11557	21580	26349	21697	22731	15819
Giru Benefited Area	28297	18618	22847	26256	42527	22984	23003	25301	18221
Total	**199871**	**151249**	**182895**	**201296**	**300828**	**327543**	**305500**	**335705**	**230977**

7.1.2 Delta

The Burdekin Delta Recharge Scheme has been operational since 1965. It is a system of recharge pits, diversion channels and creeks. Water is pumped from the Burdekin River to channels and recharge pits.

The North Burdekin Water Board (NBWB) operates 4 pump stations along the Burdekin River and the Anabranch: The Rocks, Plantation Creek PC (No 1 and 2), Rita Island and Roncato pump station.

Water is pumped from the river to Sheep station creek, Kalamia creek and Plantation creek then re-lifted from there at the following channel pumps: Lilliesmere, Pest board, Kilrie Gully, Airdmillan, Lochinvar, McAllister relift, Red Lilly and Klondyke Lilliesmer.

Pumping data from the river pumps have been recorded on monthly basis from 1981-2006 and for pumping from the channels/relift data is recorded only for some months from 1970-2006. In Figure 7-1, the distribution of river and channel pumping from 1981-2006 is shown.

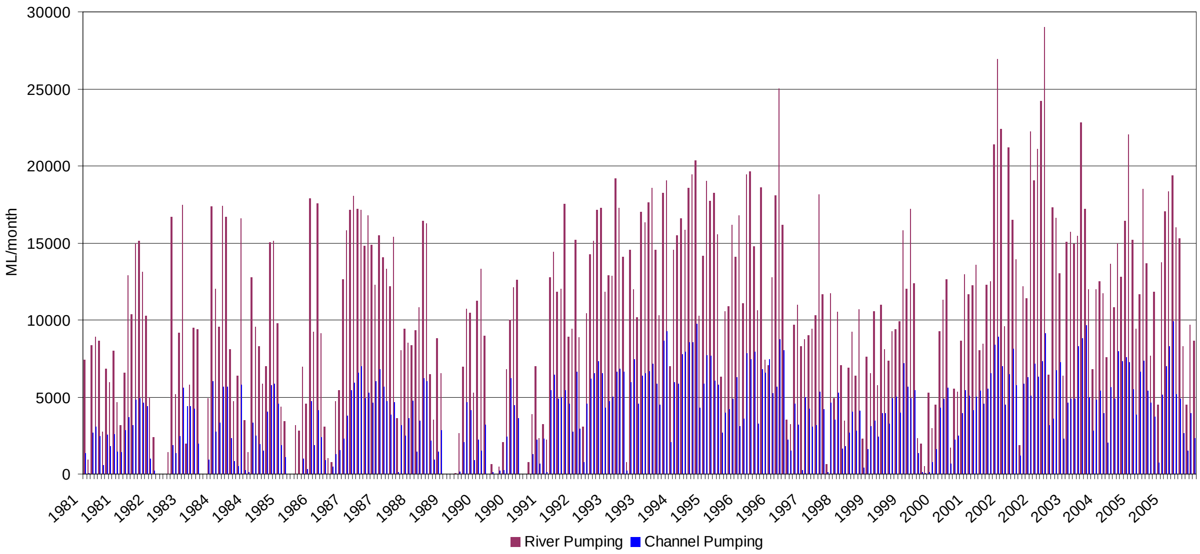


Figure 7-1 Monthly river and channel pumping for NBWB 1981-2006

The South Burdekin Water Board (SBWB) divide the water pumped into:

- Pumped from river
- Pumped from recharge pits
- Pumped by farmers
- In channel replenishment (River-(pits+farmers))

Data is available on a monthly basis from 1981-2007 (distribution in shown in Figure 7-2), where channel pumping = farmer pumping + recharge pits.

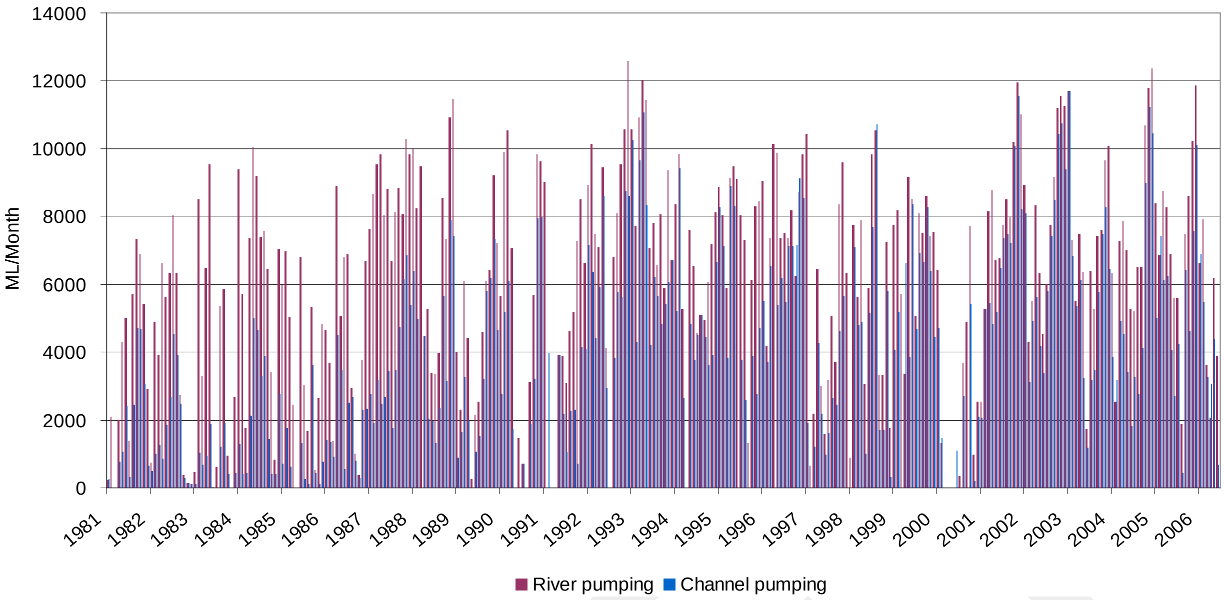


Figure 7-2 Monthly river and channel pumping for SBWB 1981-2006

7.1.2.1 Artificial Recharge

Estimates of artificial recharge through the pits and channels are documented on a monthly basis (subtracting the river pumping and channel pumping to get recharge). The Board's monthly recharge estimates will be used for groundwater replenishment in the groundwater model. The North and South Water Board's monthly pit and channel replenishment (recharge) estimates are shown in Figure 7-3.

For SBWB the artificial recharge is calculated as follows:

Recharge = River pumping + recharge pits – channel pumping

If no channel pumping data are available then recharge is set to the sum of river pumping and pit recharges. In any observation period, if no river pumping is recorded then recharge is set to zero even if pit recharges or channel pumping are recorded. The first option will overestimate the recharge while the second will underestimate it.

For NBWB the artificial recharge is calculated as follows:

Recharge = River pumping – channel pumping

When river pumping is smaller than channel pumping, recharge is set to zero.

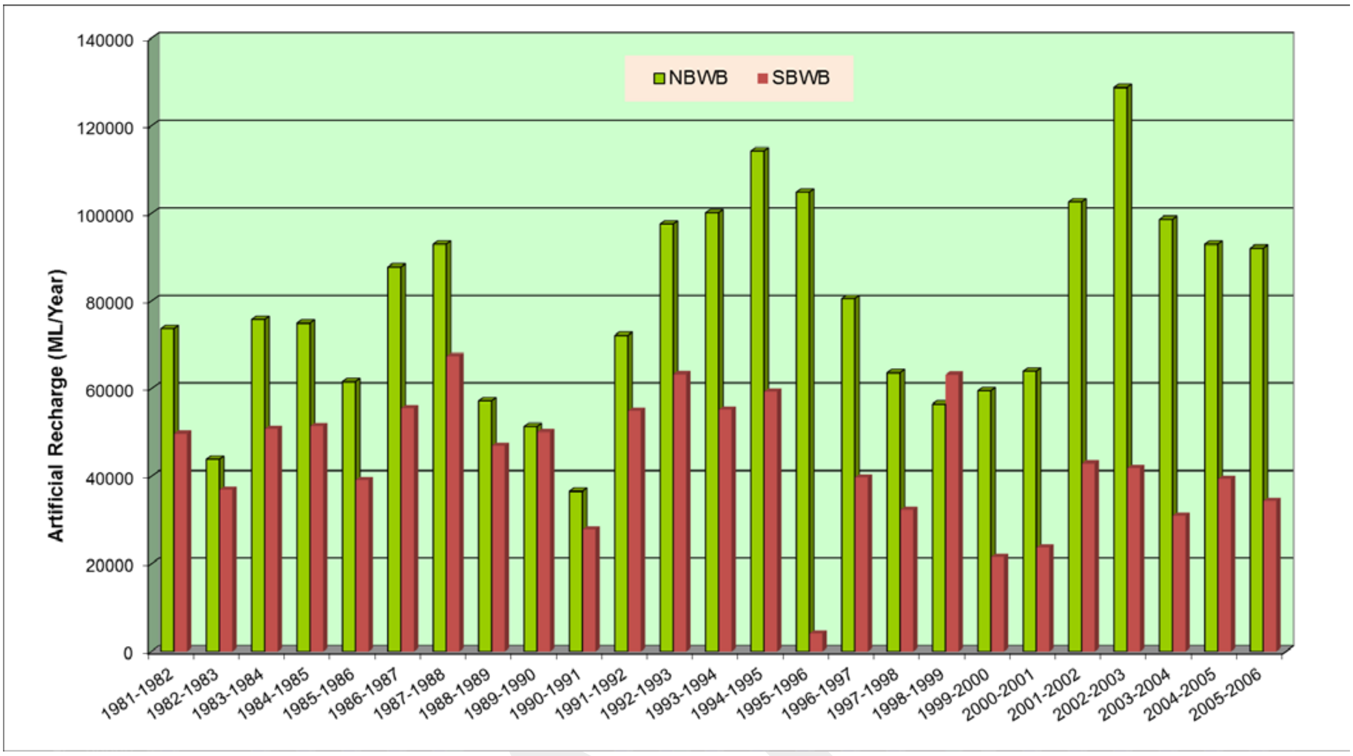


Figure 7-3 Yearly recharge values in Delta area (NBWB and SBWB)

8 Surface water / groundwater interaction

8.1 Previous work

For a given stream reach, differences between the surface water elevation and the head levels in nearby piezometers tapping a hydraulically connected aquifer system may be used to determine the net direction of surface water – groundwater interaction. While estimation of the direction of groundwater – surface water interaction is relatively straightforward in instances where such data are available, what remains problematic is the quantification of the associated flow rate because the hydraulic conductivity of both the aquifer and riverbed sediments which governs this rate of transfer is difficult to characterise on this scale.

In an attempt to address this limitation, a study of groundwater discharge from the Burdekin floodplain aquifer to the Burdekin River, Barratta Creek and Haughton River for the period 2003 – 2004 was undertaken by Cook et al (2004) using radon and radium isotope sampling in conjunction with a steady-state one-dimensional model of radon exchange with surface water flows. This assessment utilised stream discharge data obtained from gauging stations with automatic stage recorders located on the Burdekin River at Clare (Station 120006B), Barratta Creek at Northcote (Station 119101A) and Haughton River at Powerline (Station 119003A), while stream stage heights were obtained from 31 surface water monitoring sites within the departmental database.

Following a comparison of surface water and groundwater hydrographs (within a five kilometre radius of each reach), Cook et al (2004) found that groundwater inflows were generally highest during sampling undertaken in April to May, when groundwater heads were still elevated from the previous wet season, while the stream stage has correspondingly fallen. As groundwater levels decline, the rate of groundwater discharge would correspondingly decrease. When groundwater levels fall below river stage height (or river stage height rises above groundwater levels), groundwater discharge would become reversed and recharge from the river would occur. Estimated mean daily groundwater discharge for specific reaches of the Burdekin River, Barratta Creek and Haughton River are given in Figure 8-1. Sensitivity analyses undertaken by Cook et al (2004) indicated that a -50% to +200% error could be associated with groundwater inflow estimation of the upstream reaches, increasing in the downstream tidal reaches. After due consideration of this, the range of groundwater discharge to surface waters for the entire alluvial floodplain was estimated as 30,000 – 150,000 ML/year.

Table 8-1 Estimated groundwater inflow along given reaches of major watercourses in the Burdekin floodplain aquifer. Reach distances are measured from upstream (chainage 0 km) for the Burdekin River at Clare Weir, Haughton River at Giru Weir and Barratta Creek at the Clare Road crossing.

Watercourse	Reach Chainage (km)	Groundwater Inflow (ML/d)
Burdekin River	0 – 14	22.4
	14 – 31	79.9
	31 – 35	25.2
Haughton River	0 - 17	8.5
	17 – 18	5
	18 – 44	12.3–32.3
Barratta Creek	0 – 12	1.8
	12 – 33	4.6
	33 – 50	23.8

Information on surface water – groundwater interaction could prove invaluable to the numerical flow model in the parameter estimation process, in particular, as a means of reducing model non-uniqueness through incorporation of prior information. By increasing (or "penalising") the value of the objective function (i.e. the sum of squared deviations between model simulated response and observations) in proportion to the extent to which items of prior information are contravened, the stability of the calibration process can be markedly improved. This is most notable in situations where parameters, as determined solely from the current observation dataset, are highly correlated and can produce non-unique parameter estimates because variation in certain parameter combinations may result in little change in the objective function.

One possible means by which this prior information could be incorporated includes the stipulation of ordering relationships for the zonation of riverbed conductance (or perhaps more appropriately the bed hydraulic conductivity) in the MODFLOW river package, which could be accomplished by estimating de-facto parameters which act as proxies for each zone of equivalent conductance (or hydraulic conductivity). These would take the form of a series of ratios of the zonal conductance (or hydraulic conductivity) parameters, which if appropriately defined, ensure that the desired zonal parameter ordering relationships are maintained. Such an approach would need to be guided by site evidence for hydraulic conductivity variation along the stream reaches in conjunction with the groundwater inflow information given above.

Also, the estimated groundwater inflows of Table 8-1 could be included directly as observations in the calibration process, provided appropriate weightings were applied that adequately reflect the inherent uncertainty in these estimates. This would produce a composite objective function that serves to improve estimation of the zonal riverbed conductance (or bed hydraulic conductivity) parameters in particular, through a likely reduction in overall model non-uniqueness.

8.2 Estimation method

In this section the magnitude of interaction between the groundwater system and the streams in the Lower Burdekin Catchment is estimated.

The estimated discharges were calculated for the following three stream sections:

- Lower Burdekin River including Anabranch,
- Haughton River,
- Barratta Creek including Upper Barratta Creek

The interaction between the aquifer and streams is calculated based on monthly groundwater level grid files from 1980-2006 and the location and water levels in the river or creek. If the groundwater level is higher than the river water level, then the river acts as a drain and water is discharged into the river from the aquifer. When the ground water levels are below the river water level, the river acts as a recharge source and water enters into the aquifer. The following equations are used in the estimation:

$Q = C_{riv}\ (h_r\text{-}ha)\quad \text{if } h_a>h_{rb}$ Equation 7

$Q = C_{riv}\ (h_r\text{-}h_{rb})\quad \text{if } h_a<h_{rb}$ Equation 8

Where $C_{riv} = KLW/M$

Where, K = Bed hydraulic conductivity (m/d)

L = Length of river stretch (m)

W = Width of the river (m)

M = Riverbed thickness (m)

h_a = Ground water level (mAHD)

h_r = River water level (mAHD)

h_{rb} = River bed level (mAHD)

C_{riv} = Riverbed conductance

Streamflows

There are a total of three current streamflow gauging stations in the study area for which data are available. Table 8-2 shows details of these three stations and the available period of record.

Table 8-2 Statistics of Recorded Flows at Gauging Stations in the Lower Burdekin Catchment

Stream Gauging Station	Gauge Zero (mAHD)	AMTD (km)	Catchment Area (km^2)	Period of Record	Daily Flow (ML/d)		Monthly Flow (GL/month)	
					Mean	Max	Mean	Max
Burdekin River at Clare (GS120006B)	9.397	39.8	129,876	1/10/1974-Present (14/08/2006)	19,370	2,291,00	594.8	21,234
Haughton River at Powerline (GS119003A)	8.875	32.5	1,773	16/09/1969-Present (30/06/2006)	996	226,700	30.4	960
Barratta Creek at Northcote (GS119 101A)	8.721	51.3	753	9/10/1974-Present (22/08/2006)	372	62,195	11.3	289

Cross sections

MIKE-11 is a one-dimensional branched network model for simulating open channel flow in natural stream systems. The Department commissioned SunWater to provide the hydraulic stream cross sections data for the model area.

A total of 87 hydraulic stream cross sections are available for the model area (28 are located on the Lower Burdekin River including the Anabranch, 19 on the Haughton River, 26 on Barratta Creek including the Upper Barratta Ck, and 14 on Plantation Creek). The locations of these cross sections are shown in Figure 8-1.

The relationship between discharge and water level and that between discharge and width of stream were established by SunWater through the MIKE-11 Model.

Based on the average daily recorded discharge at gauging station, Clare (GS120006B), the mean water level and cross sectional width are estimated for each month at each cross section on Burdekin River and its Anabranch on the basis of the relationship of discharge with water level or cross sectional width of the streams.

The same procedure is also performed for the Haughton River and Barratta Creek but uses the mean monthly flows at the gauging stations GS119003A and GS119101A, respectively and the corresponding cross sectional data on the Haughton River and Barratta Creek.

At this stage, both Sheep station Creek and Plantation Creek are not included in the estimation of surface water and groundwater interaction, as they have been used as channels to receive water pumped from Burdekin River and have been included in the artificial recharge.

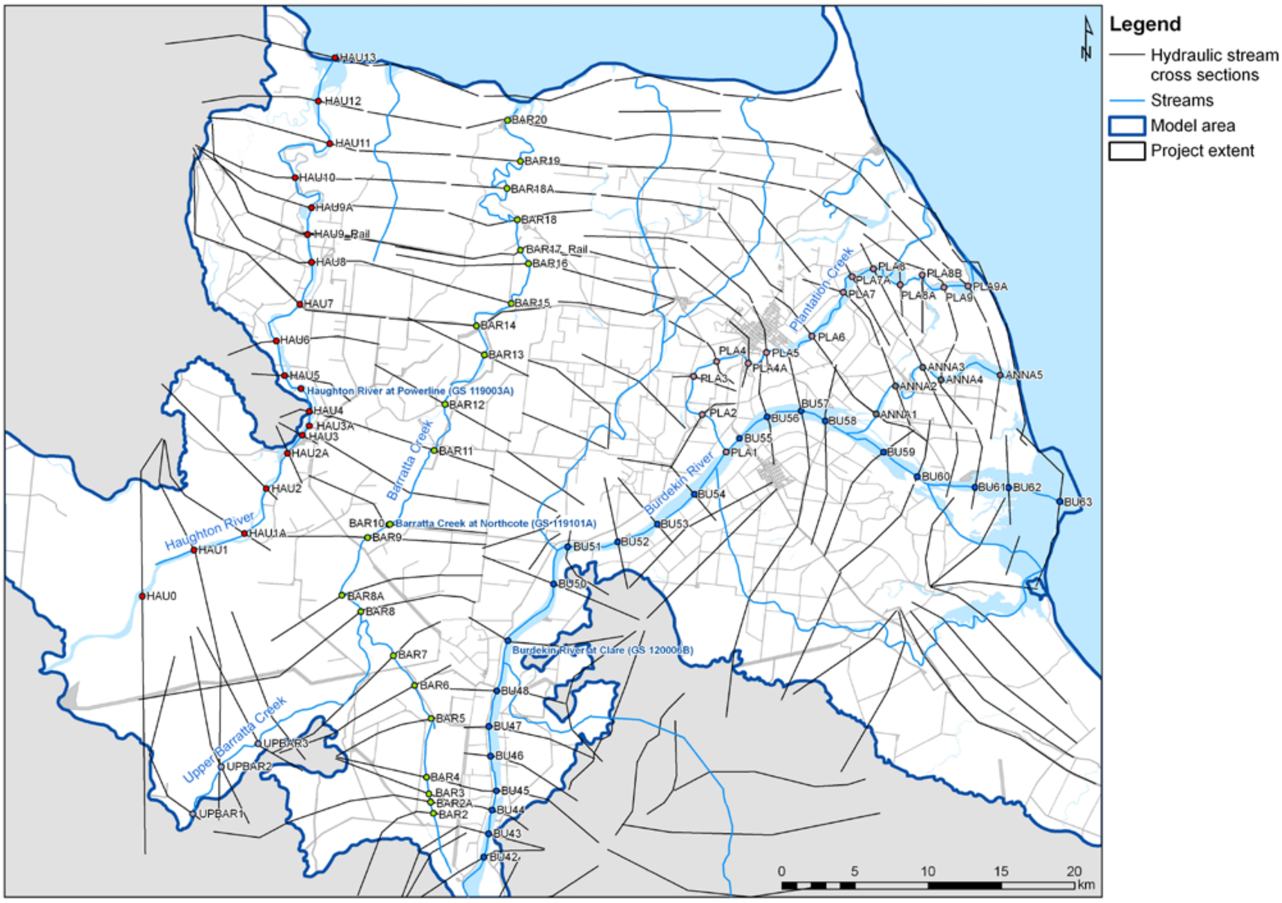


Figure 8-1 Location of Hydraulic Stream Cross Sections in Lower Burdekin

SW/GW Interaction estimates

The calculation has been carried out for the period from July 1980 to June 2006 for the stream sections. The riverbed hydraulic conductivity and thickness were assumed to be 0.01m/d and 5cm, respectively. The river bed level for each location is assumed as the river water level when the flow is zero and is linearly interpolated using Sunwater MIKE-11 cross sections data.

Groundwater levels at the locations of the MIKE-11 cross sections were extracted from the monthly groundwater level contours for the three main channels (Burdekin River, Haughton River and Barratta Creek). This data was then converted to annual river-aquifer flux to or from the aquifer as shown in Figure 8-2.

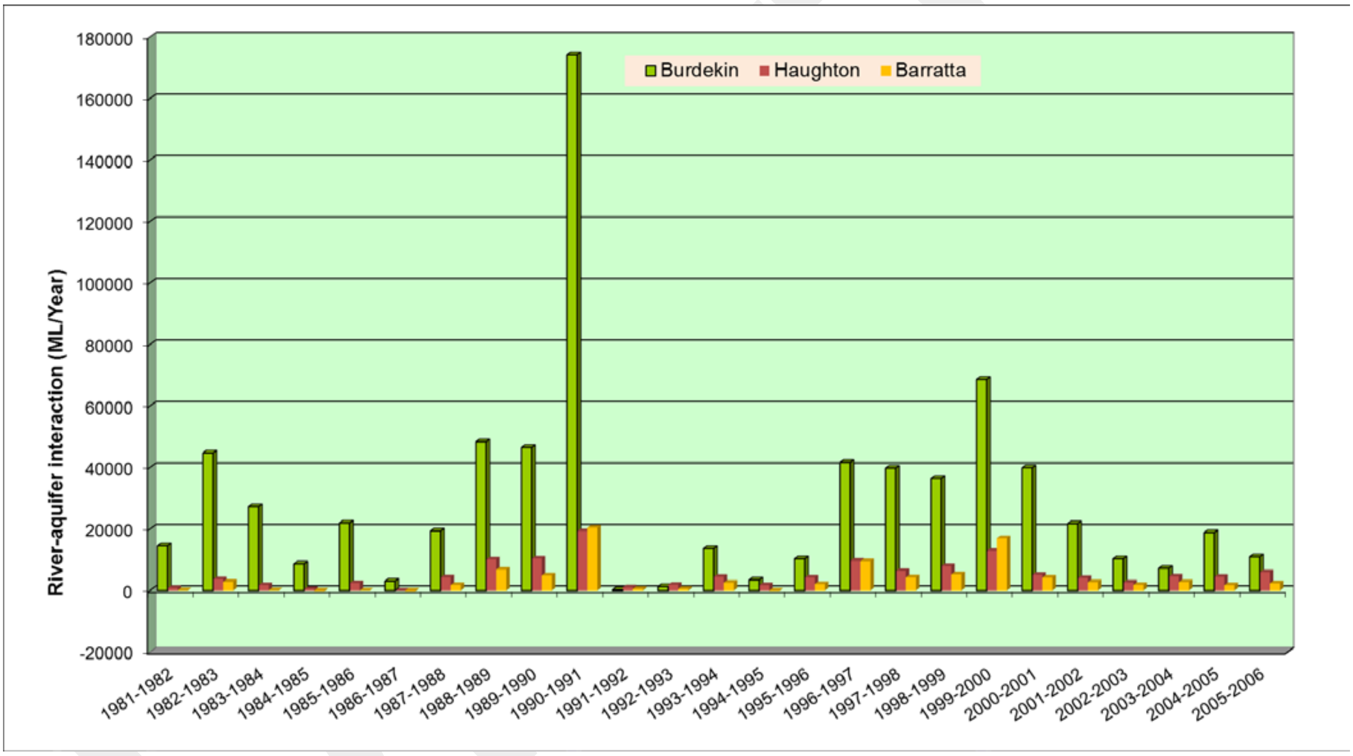


Figure 8-2 Interaction between aquifers and rivers

A positive value indicates recharge from the rivers to the aquifer and a negative value indicates discharge from the aquifer to the rivers. The results show recharge into the aquifer virtually dominates in the Lower Burdekin Catchment.

Flood events have been accounted for in the MIKE-11 model. The much higher value of river widths indicate bank overflows during flood periods. Therefore, recharge presented in the above table also includes those from over bank flows, though calculated on a monthly basis.

The methodology for the assessment of recharge from rivers will require further investigation in future research, as the inherent assumptions place a reasonable level of uncertainty upon the final results. Comparison of these results with past and future river loss assessments should be undertaken and further research undertaken to refine the assessment of river recharge.

9 Recharge estimation

The recharge processes identified in the study area can be grouped into the following categories:

- Recharge from rivers (refer to section 1 on surface water/groundwater interaction) including recharge from overbank flows
- Leaching from irrigation application
- Natural rainfall recharge
- Artificial Recharge that includes pit and channel recharge

Artificial recharge and river recharge have been addressed in sections 7 and 8 respectively. This section focuses on the recharge from natural rainfall and irrigation.

Since the exact volumes of recharge from rainfall and irrigation water cannot be directly measured, it has been estimated using an unsaturated zone model. In this study, APSIM was used with the STRESGEN code to simulate the recharge and crop irrigation demand for the soil types of the Burdekin region.

STRESGEN is a code that converts the one-dimensional depth data (eg. mm of recharge or irrigation demand) from APSIM into volumes. To convert the one dimensional depths resulting from ASPIM into volumes, STRESGEN utilises the areas of each hydrologic response units (HRU) which is a unique combination of soil, crop and rainfall zone.

The recharge from over bank flooding has been included in Section 8. For the overland flooding, the information about the size and location of ponds are currently not available to this study, therefore the resulting recharge is not calculated. It should be included whenever the information is available.

9.1 The APSIM Model

A range of potentially suitable unsaturated zone models were reviewed to determine the most suitable model for this project. The results of this review were included in the “Review of Modelling Methods” milestone report for this project. Through this review process, the APSIM model was selected for this project as it has a number of advantages over alternative models.

APSIM (Agricultural Production Systems sIMulator) was developed by the Agricultural Productions Systems Research Unit (APSRU), a collaborative group made up from CSIRO and Queensland State Government agencies (Keating et al. 2003). APSIM is well suited to the simulation of cropping systems where rainfall is highly variable from year to year as it allows dynamic representation of both crop growth and soil processes, and it is capable of simulating conditional management rules (Verburg&Bond 2003).

APSIM contains modules for simulating specific crops, including sugarcane. This is a significant advantage for the Lower Burdekin modelling toolkit as sugarcane crops are prevalent in the Lower Burdekin. The capability to simulate sugarcane management practices, sugarcane growth, sugarcane water uptake and sugarcane solute uptake is likely to improve predictions of deep drainage and solute transport beneath irrigated sugarcane. APSIM models including the sugarcane module have previously been developed for the Lower Burdekin (Stewart et al. 2006, Thorburn et al. 2009).

APSIM is also a flexible modelling platform. Not only can modules be "plugged-in" or "plugged-out", many of the modules can also be modified by the user. This will allow specific management practices relevant to the Lower Burdekin to be built into the simulations. The model developers can provide support when the model needs to be modified.

The APSIM-SoilWat module has been used to simulate the water balance. In APSIM-SoilWat, separate algorithms are used for saturated or unsaturated water flow. The water characteristics of the soil are specified in terms of the lower limit, drained upper limit and saturated volumetric water contents.

The water balance is calculated on a daily scale by simulating the following processes sequentially:

- runoff
- saturated water flow
- movement of solutes associated with saturated flow
- soil evaporation
- unsaturated water flow
- movement of solutes associated with unsaturated flow
- plant transpiration

Runoff from rainfall is calculated using the USDA-Soil Conservation Service curve number technique. Runoff response curves are used to represent the percentage of rainfall that becomes runoff i.e. 0 to 100%.

Soil evaporation is assumed to take place in two stages. In the first stage, the evaporation rate is at least equal to the potential evaporation rate. In the second stage, the soil water content has decreased below a threshold value and the rate of the supply from the soil is less than potential evaporation.

The parameters required for simulating the water balance in APSIM-SoilWat are shown in Table 9-1. Where measured data was available, this data was used for APSIM inputs. In the absence of measured data, APSIM inputs were estimated based on expert recommendations and literature review. A full list of parameters used and information about the derivation of these parameters is described in detail in Appendix C.

Table 9-1 Type, name and description of parameters used in APSIM-SoilWat models.

Parameter Type	Parameter Name	Parameter Description and Units
Water Content and Saturated Water Flow	KS	Saturated Hydraulic Conductivity (mm/day)
	BD	Bulk Density (g/cm^3)
	AirDry	Soil Water Content resulting from atmospheric drying (mm/mm)
	LL15	Soil Water Content at Lower Limit – 15 bar (mm/mm)
	DUL	Soil Water Content at Drained Upper Limit (mm/mm)
	SAT	Soil Water Content at Saturation (mm/mm)
	SWCON	Drainage Coefficient
Evaporation	SummerCona	Cona = regression coefficient used to calculate evaporation after first stage evaporation has ended (upper limit of water flux to the surface for soil evaporation loss)
	Summer U	U = the amount of cumulative evaporation, since the soil wetting, before soil supply decreases below atmospheric demand (first stage evaporation)
	SummerDate	Date for summer evaporation
	WinterCona	Cona = regression coefficient used to calculate evaporation after first stage evaporation has ended (upper limit of water flux to the surface for soil evaporation loss)
	WinterU	U = the amount of cumulative evaporation, since the soil wetting, before soil supply decreases below atmospheric demand (first stage evaporation)
	WinterDate	Date for winter evaporation
Unsaturated Water Flow	DiffusConst	Diffusivity constant – a constant used to calculate diffusivity
	DiffusSlope	Diffusivity slope – a constant used to calculate diffusivity
Soil Reflectivity	Salb	Soil Albedo
Runoff Curve-Number	CN2Bare	Curve Number under average antecedent rainfall conditions for 0% cover
	CNRed	Minimum curve number
	CNCov	Fraction of 100% cover where Curve Number reaches a minimum

9.2 APSIM modelling approach

APSIM has been used to provide estimates of deep drainage, nitrogen leaching and chloride leaching under a number of soil types, land uses and management practices. APSIM produces 1D outputs that need to be assigned spatially. STRESGEN is used to assign APSIM results based on mapped extents of soil types, land use types and management practices.

The approach which has been applied for APSIM simulations for sugarcane is to use measured data where possible for model inputs and use local information about sugarcane management practices. Workshops were conducted to obtain this local information and come to an agreement on suitable APSIM model inputs for sugarcane management. It was decided that the key parameters that needed to be simulated were: irrigation volume and frequency, fertilizer application rate, irrigation water quality and sugarcane planting and harvesting dates. As 120 year simulations were run and management practices are known to have changed significantly during this time period, the sugarcane management modules were modified to include time-varying management practices. The details of these management practices are contained in Appendix C.

The predominant native vegetation types within the Lower Burdekin are open eucalypt woodland and native grassland. The regions of native vegetation were simulated through the use of the egrandis and bambatsi modules within APSIM. The egrandis and bambatsi pasture modules were "plugged-in" and used in conjunction to undertake the APSIM modelling. Rather than utilising a site specific egrandis sowing density it was recommended that each case was arbitrarily assigned a density of 10 plants per hectare and calibrated to the climax canopy state through the Foliage Projective Cover (FPC) and Leaf Area Index (LAI) output variables (personal communications, Neil Huth 2011).

Work by (Specht&Specht 1989) showed that both the Foliage Projective Cover (FPC%) and Leaf Area Index (LAI) of mature climax evergreen plant communities is related to the evaporative coefficient (k). The annual evaporative power of the atmosphere is directly correlated with horizontal cover (FPC) and the ecomorphological characteristics of Leaf Area and Leaf Specific Area in the sunlit section of the canopy. These attributes affect the Vegetation resistance and ultimately the flux of water trough the ecosystem. For this reason, utilisation of FPC and LAI were used to calibrate the native vegetation simulations.

Foliage Projective Cover is the horizontal cover of the vegetation over the surface area of the ground. APSIM output was compared to values obtained from the Foliage Projective Cover map shown in Figure 4-7 together with literature values (Specht 1983) to ensure the model was providing suitable results. The FPC map was used in conjunction with the soil type map to determine valid FPC ranges for each soil type. The canopy of an evergreen community eventually reaches a climax canopy state or steady-state value of FPC which is correlated to the annual water balance of the ecosystem (Specht 1972, Specht 1981). The FPC of the overstorey follows a linear correlation to the evaporative coefficient. This trend follows the linear regression: Overstorey FPC = 960 k – 6.0 (Specht 1983). This climax canopy state can take approximately 20-30 years to reach and for this reason the simulation was extended to include a 20 year period of "dummy" data to allow the simulated vegetation to reach equilibrium. The FPC output from the 32 soil-met combinations was then compared to these ranges to ensure that the simulations could be trusted as providing relevant deep drainage results.

Leaf Area Index is determined by the leaf number, leaf area and leaf longetivity. (Specht&Specht 1989)) calculated the relationship between Leaf Area Index of the overstorey of mature climax evergreen plant communities and the evaporative Coefficient (k). LAI is dependent on microclimatic conditions such that for a specific FPC a range of LAI values may be observed. The map of isoline values of Evaporative Coefficient for evergreen plant communities throughout Australia provided an Evaporative Coefficient of approximately 0.058 for the Burdekin region. This corresponds to a Leaf Area Index of 0.914 (refer to Figure 3a and 10 of (Specht&Specht 1989). This was used to further validate the reliability of the APSIM results.

The average annual deep drainage was then validated against accepted values for the Burdekin (Ahern&Rosenthal 1988).

9.3 APSIM results

Figure 9-1 presents estimates of yearly recharge in BHWSS and Delta area. The average annual recharge is estimated at approximately 135,300 ML for BHWSS and 767,100 ML for Delta for the period July 1981 to June 2006.

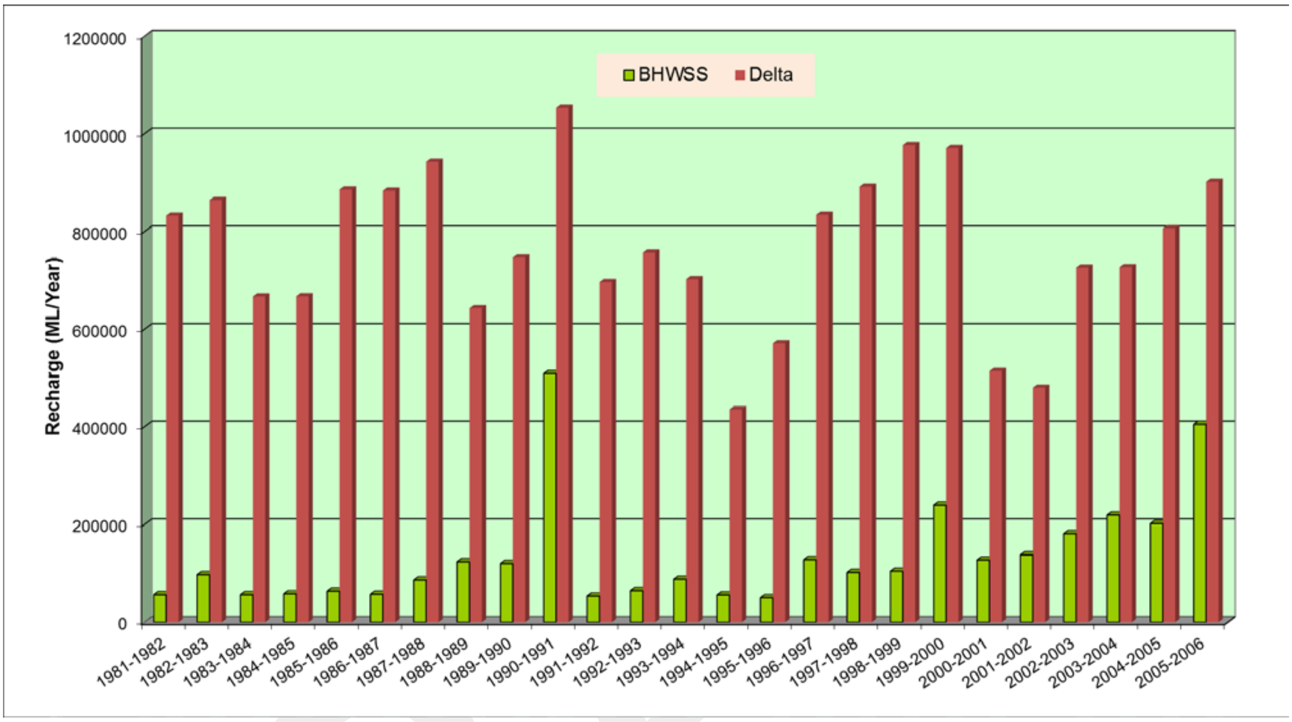


Figure 9-1 Estimated Annual Recharge in BHWSS and Delta Area

A previous study (Hillier 1998b) estimated the average annual rainfall recharge for BHWSS to be 29 mm/year. This study estimates recharge (from both rainfall and irrigation application) at 55 mm/year for the BHWSS area.

For the Delta area, previous studies (Arunakumaren, McMahon & Bajracharya 2001, Volker 1977, Hadgraft, R. G. and Volker, R. E. 1980, Sinclair Knight Merz 1997) estimated the recharge from floods and rainfall to range from 150,00 ML/year to 500,000 ML/year. The irrigation accessions to groundwater were estimated to range from 230,000 ML/year to 650,000 ML/year (Arunakumaren, McMahon & Bajracharya 2001, Sinclair Knight Merz 1997).

10 Water Balance

Climatic conditions, land use and human activities all have impacts on the groundwater flux. In order to study their influence on the aquifer and the subsequent temporal behaviour of the aquifer storage, a groundwater balance calculation is carried out for the Burdekin model area. The main tasks in the water balance include:

- identifying the components contributing to the natural recharge and discharge of the aquifer;
- analysing the human impacts on the aquifer in terms of the abstraction, the artificial recharge, the seepage from irrigation channels and leaching from irrigation application;
- quantifying the interaction between the surface water bodies and the aquifer; and
- estimating historical gain or loss of groundwater using individual water balance components and comparing these gain or loss to the storage change estimated from the observed historical groundwater levels.

Water balance calculations have been carried out for the period commencing from July 1981 and ending June 2006. It covers the study area shown as 'model area' in Figure 2-1:

- The entire alluvial aquifer is included in this study. All the components of inflows and out flows of the aquifer of the Lower Burdekin Catchment have been considered;
- All the sugar cane area and the areas covering other crops are included;
- All the water depletion from the aquifer for irrigation and aquifer replenishment as a result of leaching from irrigation applications are accounted for;
- Almost all of the groundwater abstractions are located in the area;
- In most of the areas, the observation bores are well distributed and the water levels are well recorded allowing more accurate estimation of aquifer water storage;
- All the service area of Burdekin Haughton Water Supply Scheme within lower Burdekin catchment is located within this area. So, leaching from surface water is considered.

The general equation for the water balance is as follows:

Change in Storage = Inflow – outflow

Aquifer inflows include boundary flows, recharge from rainfall and leaching from irrigation application, recharge from rivers, channel and recharge pits whereas aquifer outflows consist of outflows from coastal areas, water abstraction for irrigation, industry and town water use, domestic and stock water use. Outflow also includes discharge from the aquifer to the rivers and evapotranspiration from groundwater dependent ecosystem.

10.1 Estimation of Aquifer Storage

Storage estimation is carried out based on groundwater levels and aquifer thicknesses. The hydraulic basement (base of weathered/fractured bedrock) is used in the calculation.

The groundwater level contours used in the estimation of aquifer storage are constructed using the following data:

- Water levels at each of the observation bores for each month. They are either observed water levels or interpolated values from observed water levels for each month;
- Water levels at rivers and creeks. Ideally the groundwater levels along Burdekin Rivers, Haughton River and Barratta Creek could be determined and used in the generation of groundwater level contours. However, for most of the reaches of these rivers, there is no observation bores monitoring the groundwater levels. The river water levels of these rivers were then used instead.
- Water levels along the coast. Along the coastal boundary, the groundwater levels are assumed as 0.0m

Specific yield is required in the storage estimation. There are few bores with specific yield values ranging from 0.016 to 0.56 in the BHWSS area and from 0.015 to 0.396 in the Delta area. In the study by University of Technology, Sydney (Merrick 1998), the BHWSS aquifer is divided into thirteen zones with specific yields of most zones between 0.10 and 0.16. In the report by Hillier (1998a) the calibrated specific yield in the BHWSS area ranged from 0.01 to 0.187. For the Delta area, the previous conceptual study (Arunakumaren, McMahon & Bajracharya 2001) used a specific yield of 0.15. Considering bore data and data used in the previous studies, a specific yield of 0.2 is used for both BHWSS and Delta area for storage estimation in this water balance assesment. However, final specific yield values will be calibrated in the numerical model.

The storage of the aquifer has been estimated every month for the period July 1981 to June 2006 and later used to compare with the storage calculated from water balance components.

10.2 Components of Water Balance

Inflow to the aquifer of the lower Burdekin catchment consists of:

- Coastal inflow
- Boundary flow
- Recharge from rainfall and leaching from irrigation application
- Recharge from Burdekin River, Haughton River and Barratta Creek
- Leakage from Channels of BHWSS including Clare, Haughton and Elliot Distribution Systems
- Artificial recharge from recharge channels and pits in the Delta area

Outflow from the aquifer consists of:

- Coastal outflow

- Abstraction for irrigation, stock watering, domestic, industrial, and town water supplies
- Discharge to the Burdekin River, Haughton River and Barratta Creek
- Evapotranspiration from groundwater dependent ecosystem

Except for irrigation channel leakages and water abstractions, all the other water balance components have already been addressed in the previous sections. Irrigation channel leakages and groundwater abstractions are discussed below.

Figure 10-1 illustrates how the main components of the water balance of the Lower Burdekin floodplain interact, including both groundwater and surface water processes and their interaction.

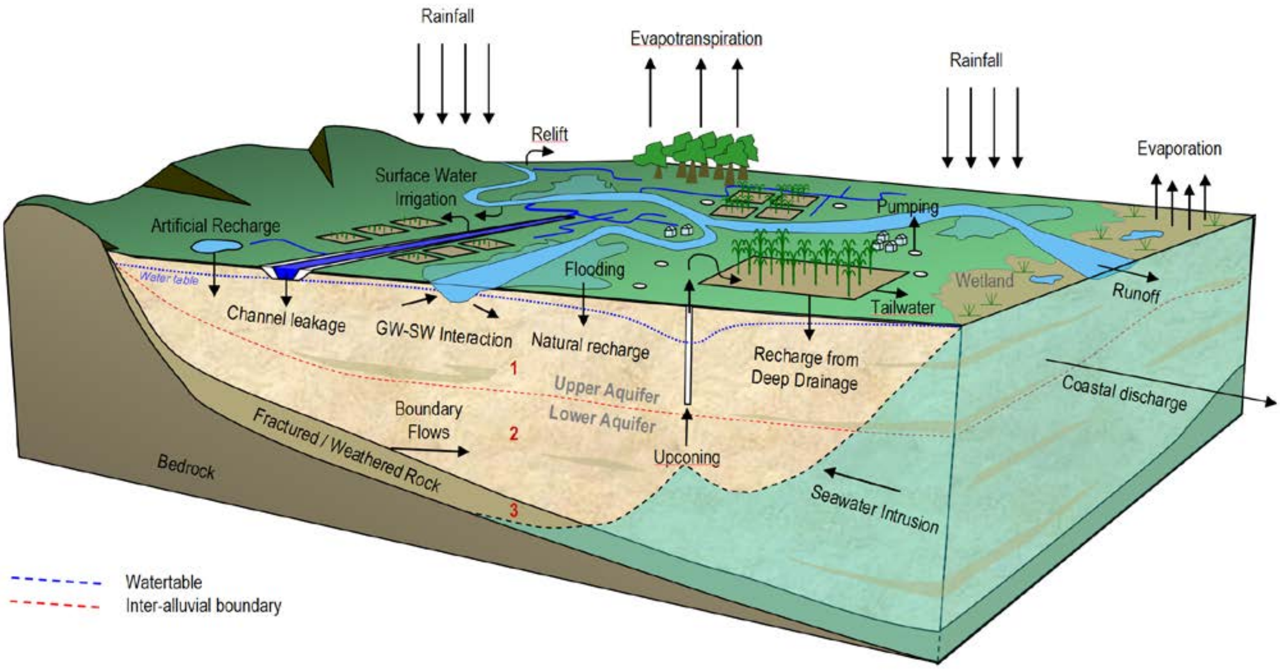


Figure 10-1 Three-dimensional representation of Lower Burdekin water balance components

Leakage from channels of distribution systems

A GHD report estimated that seepage from Haughton, Clare and Elliot distribution systems at 7177 ML/year, 335 ML/year and 1601 ML/year respectively with a total leakage of 9113 ML per year(GHD 2001). Bennett (2012) assumes 2% of surface irrigation water leaking to the aquifer through channel systems (5% for Clare distribution system) and his estimates ranges from 3500 ML/year to 6500ML/year for the period from 2002 to 2010 with an average of 5000ML per year. In this project, the estimates from GHD are used and it is assumed that all leakage replenishes groundwater in the vicinity of the channels.

Groundwater withdrawal for irrigation

Even though the metered groundwater usage is collected for most sub areas in BHWSS area, it is not complete for most of the water balance period. Furthermore, metered groundwater usage is not available for the Leichhardt area. The estimated groundwater withdrawal in the BHWSS is therefore used in the water balance.

The APSIM-SoilWat module for the BHWSS area is used to estimate the total irrigation demand in the area. Both surface and groundwater irrigation has been developed in the model area, therefore the estimated irrigation demand is shared among surface water and groundwater. Surface water irrigation was originally applied by direct pumping from the Burdekin and Haughton Rivers. The rivers were still the principle irrigation source for Clare Irrigation Area in early 1980s (Hillier 1998). With the inception of the development and construction of irrigation channels from 1987, surface water became more prevalent as an irrigation source. In the water balance, 10% to 30% of irrigation demand is assumed to be supplied by groundwater based on the metered usage data of surface water and groundwater available from 1998 to 2006. The rest is assumed to be supplied by surface water.

There is no metered groundwater usage data for irrigation in the Delta area. The estimated groundwater abstraction derived by APSIM modelling is therefore used in the water balance calculation for the Delta area.

The APSIM-SoilWat module for the Delta area is used to estimate the total irrigation demand in the area. The estimated irrigation demand is also shared among surface water and groundwater. There are some parcels purely supplied by surface water. For the area supplied by both surface water and groundwater, in the previous study (Arunakumaren, McMahon & Bajracharya 2001), 60% to 90% of total irrigation demand was supplied by groundwater with the rest from surface water. The same assumption is also adopted in this study.

Figure 10-2 presents estimates of yearly groundwater pumping for irrigation purpose in BHWSS and the Delta area. The average annual pumping is estimated at 58565ML for BHWSS and 921828 over the Delta for the period July 1981 to June 2006.

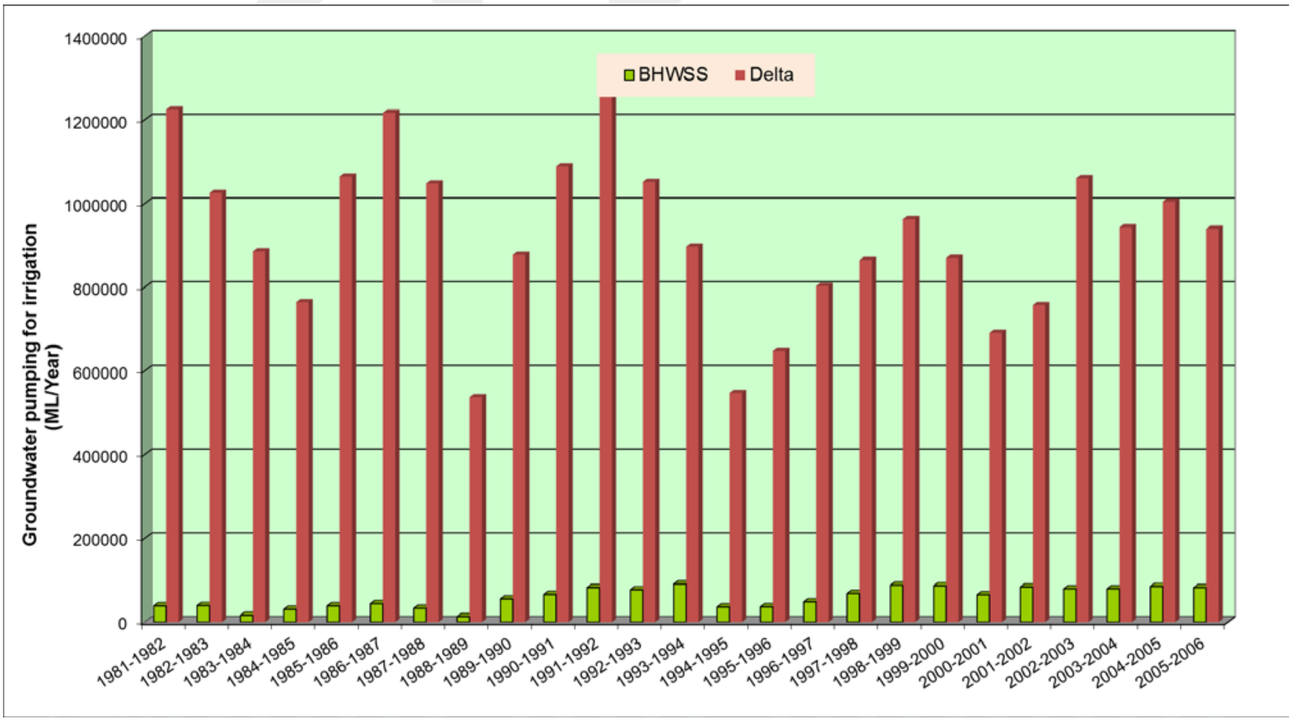


Figure 10-2 Estimated groundwater withdrawal for irrigation in both BHWSS and Delta area (ML/year)

Stock, industrial, commercial and town water supply

Based on the entitlement data of BHWSS area, there are 43 stock water supply bores and 13 industrial and commercial water supply bores with a total entitlement of 343 ML. Since stock and domestic supply bores do not require a licence in the Burdekin catchment, it is expected that stock and domestic bores exist but are not monitored. In the Delta area, information on stock, domestic, industrial or commercial water supply bores are not available.

Since the metered use data are not available for most of these bores, only the entitlement of 343 ML is used in the water balance.

Metered town water supply data is obtained from the Burdekin Shire Council and is presented in Table 10-1.

Table 10-1 Groundwater withdrawal for Town Water Supply (ML/year).

System/Year	Ayr/Brandon	Home Hill	Mt. Kelly	Giru	Total (all towns)
1984-1985	6315	2248			8563
1985-1986	6407	2342			8749
1986-1987	5968	2163			8131
1987-1988	5550	2066			7616
1988-1989	4870	1638			6508
1989-1990	3779	1548			5327
1990-1991	4197	1718			5915
1991-1992	4398	1747			6145
1992-1993	4639	1601	143		6383
1993-1994	4891	1821	110		6822
1994-1995	5501	1834	214		7549
1995-1996	4079	1583	159		5821
1996-1997	5156	1685	128	225	7194
1997-1998	4897	1342	110	250	6599
1998-1999	3969	1032	79	162	5242
1999-2000	4684	1277	86	126	6173
2000-2001	4876	1399	103	125	6503
2001-2002	4396	1305	113	145	5959
2002-2003	4260	1278	132	154	5824
2003-2004	4268	1099	124	132	5623
2004-2005	4286	1103	143	118	5650
2005-2006	3546	902	95	107	4650
2006-2007	3613.5	1068.05	85.35	115.07	4881.97

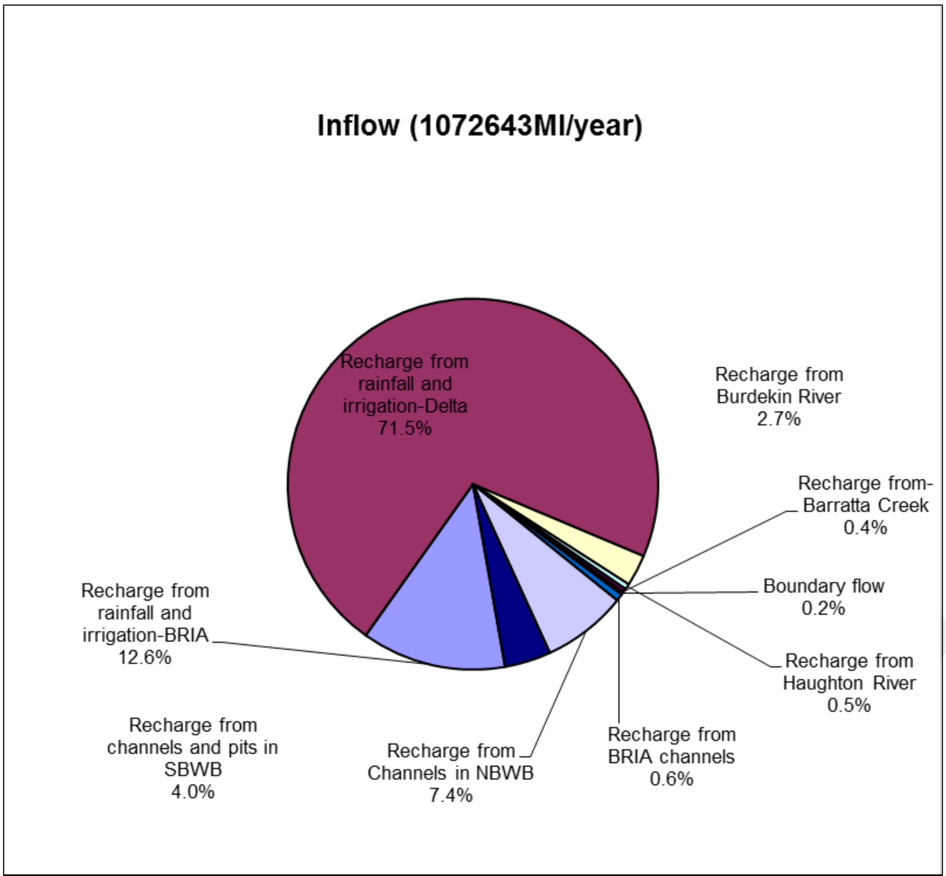
Since data is only available on an annual basis, the values were distributed into monthly pumping by equally distributing this quantity throughout the year for all stock, industrial, commercial and town water supply. For estimates of town water supply prior to 1984/1985, it is assumed that the same pumping volume of 1984/1985 was adopted, and subsequently applied in this water balance.

10.3 Results and Analysis

Table 10-2 and Figure 10-3 summarise the results of water balance.

Table 10-2 Water balance of Lower Burdekin catchment for the period from July 1981 to June 2006

	Details	Average (ML/year)	Maximum (ML/year)	Minimum (ML/year)
Inflow				
1. Recharge from Rainfall and Irrigation	BHWSS	135300	508900	50060
	Delta	767100	1052900	435700
2. Recharge from Rivers	Burdekin River	29340	174200	240
	Haughton River	5240	19330	-30
	Barratta Creek	3760	20470	-260
3. Boundary Flow	-	2500	3350	1920
4. Recharge from Channels and Pits	BHWSS channels	6740	9110	0
	Channels in NBWB	79400	128800	36560
	Channels and pits in SBWB	43310	67430	4130
Subtotal		1072690		
Outflow				
1. Groundwater Withdrawal	Irrigation in BHWSS	58570	90990	13090
	Irrigation in Delta	921800	1271000	537000
	Stock and industrial supply	340	340	340
	Town water supply	6750	8750	4650
2. Coastal Outflow	-	37400	51190	26950
3. Evapotranspiration from GDEs	-	45010	45010	45010
Subtotal		1069870		
Outflow-Inflow		2820		



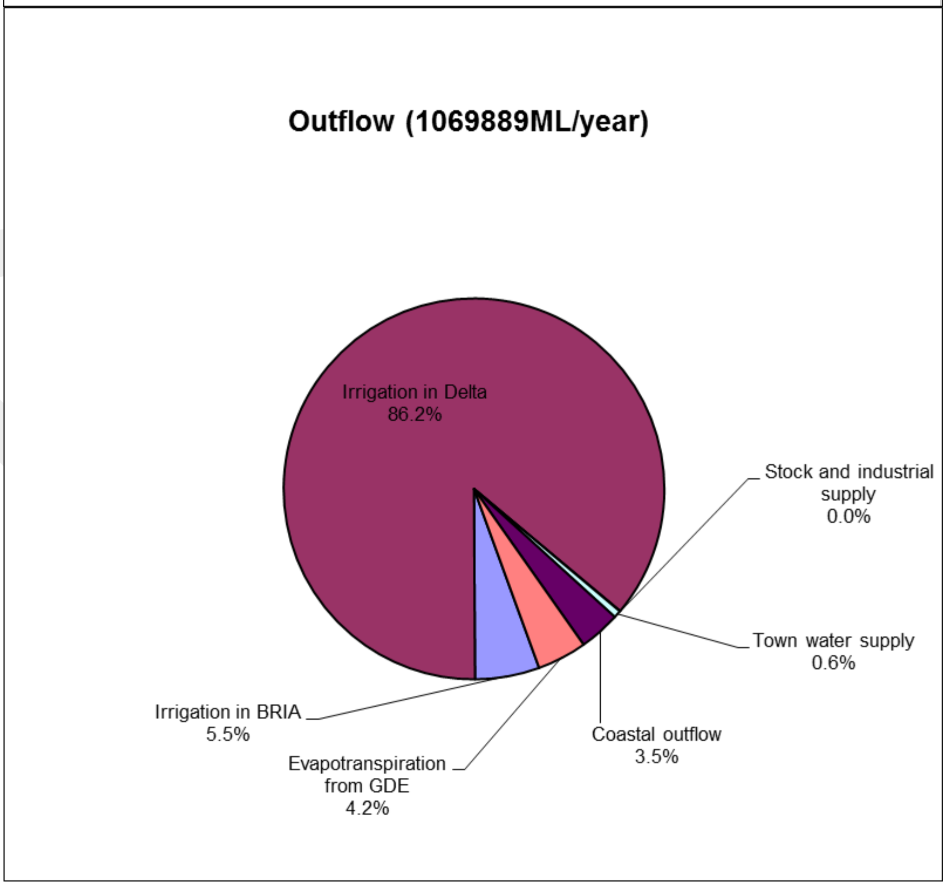


Figure 10-3 Components of Water Balance for the period from 1981 to 2006

The groundwater storage in Lower Burdekin aquifer based on the recorded groundwater levels is compared with that calculated based on the individual components of water balance. The temporal storages from the two methods are pictorially presented in Figure 10-4.

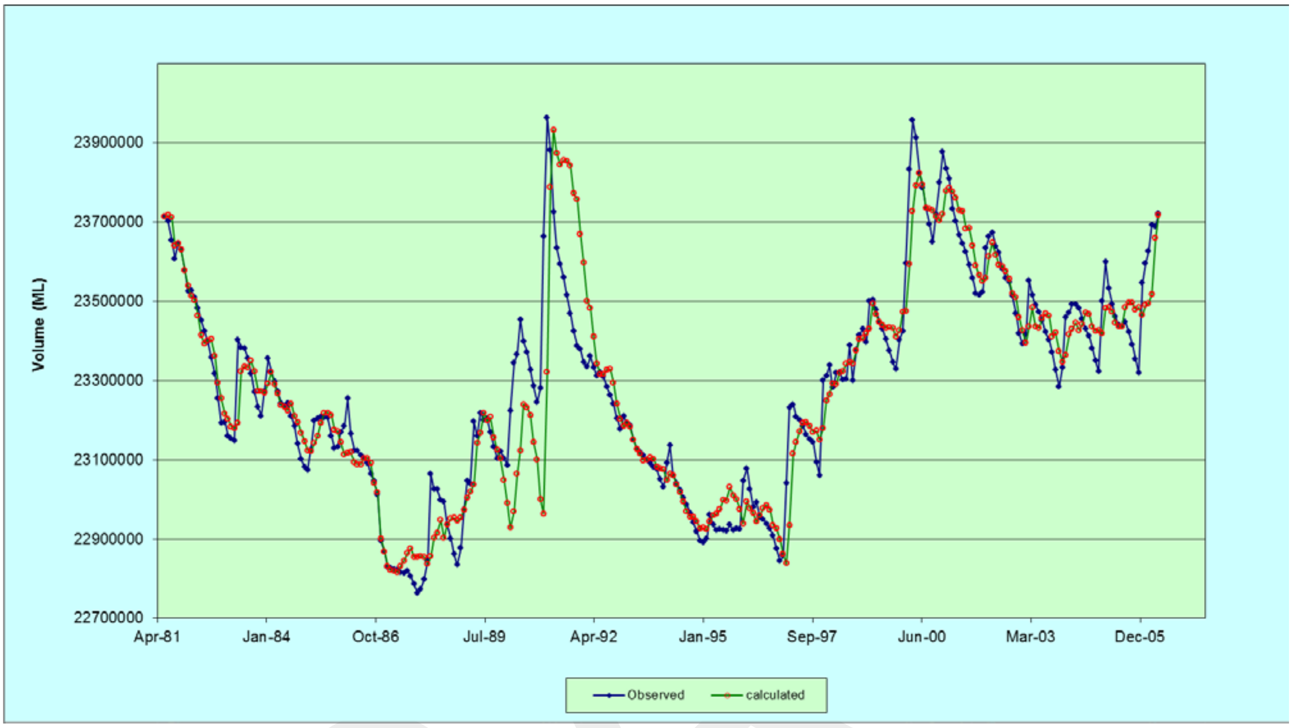


Figure 10-4 Groundwater storage change in Lower Burdekin aquifer

Figure 10-3 and Figure 10-4 have demonstrated the following conclusions:

- The temporal groundwater storage in Lower Burdekin aquifer derived from the recorded groundwater levels match well with that calculated based on the individual components of water balance;
- Recharge from rainfall and leaching from irrigation application makes up the majority of the inflow to the aquifer. Estimates of seepage from channels and recharge from rivers are also significant in both the BHWSS and Delta areas; Abstraction for irrigation is the largest component of the total outflow;
- During the period from 1981 to 1987, outflow is generally in excess of inflow, the aquifer loses water. From 1988 to 1991, the outflow is generally less than inflow, the aquifer gains water. Aquifer is losing water again in the period 1991 to 1996, but it recovers after 1996 until 2000. After 2000, the aquifer is again in shortage with drier climatic conditions prevailing. These trends are generally consistent with the residual mass rainfall curve.

11 Conclusions and Recommendations

The following conclusions and recommendations are a result of an examination of the physical and hydrological characteristics of the Lower Burdekin aquifers. The conceptualisation of the groundwater system serves to support the construction of numerical groundwater flow and solute transport models that can simulate the regional groundwater character and behaviour of the Lower Burdekin system. These models form a 'toolkit' that can be used to support important water resource management decisions.

The following conclusions have been drawn from this assessment of the Lower Burdekin groundwater system:

- A full high-resolution DEM of the Lower Burdekin is now available, and this has been used to represent the topography of the whole area, and forms the top of aquifer surface for the numerical model;
- The Lower Burdekin floodplain comprises an extensive unit of permeable sediments of alluvial and deltaic origin, overlying a mostly granitic bedrock. These sediments form the main aquifers used for irrigation, stock and domestic purposes;
- The alluvial deposits can be segregated into an upper and lower alluvial unit, based on an apparent permeability contrast and previous stratigraphic mapping (e.g. the Pleistocene – Holocene boundary). The boundary between these two layers is not always apparent in strata records, and some interpolation is required to extend the surface across the alluvial area. Examination of hydrographs shows that both layers respond similarly to recharge and discharge stresses. The total alluvial thickness can extend over 100m deep near the coast;
- The weathered and fractured zone of the bedrock is up to 20m thick and can store and transmit groundwater. Therefore, it is recommended that the groundwater flow model comprise 3 layers: upper alluvium, lower alluvium, and weathered/fractured bedrock;
- The Lower Burdekin aquifer flanked to the west and south by exposed bedrock, and to the north and east by the coast. Boundary inflows have been calculated in the southeast section of the Lower Burdekin (Stokes Ranges). Boundary inflows were not calculated for other parts of the study area adjacent to bedrock due to a lack of water table information and the consideration that infows are likely to be negligible in these areas;
- The aquifers underlying the BHWSS and the Delta areas tend to demonstrate varying responses to recharge and discharge events. The cause of this is mostly due to the presence of the surface clay layer over much of the BHWSS area, resulting in semi-confining conditions, compared to the Delta area that is mostly devoid of surface clay and behaves as a highly permeable and unconfined system. Subsurface clay lenses occur throughout the aquifer, creating local variability but are rarely extensive over large areas. Correspondingly, the regional response of the aquifer to recharge events is generally consistent and rapid;
- Rising groundwater tables are accompanied by increases of groundwater discharge to streams;
- Recharge to the groundwater system occurs via direct rainfall infiltration, irrigation deep drainage, artificial recharge, and river recharge. Rainfall and deep drainage recharge estimates were made using an unsaturated zone model (APSIM);
- A water balance assessment of the Lower Burdekin aquifer was made for the period July 1981 – June 2006 with an average inflow of 1,072,643 ML/year and an average outflow of 1,069,889

ML/yr. The net difference between inflow and outflow to the groundwater system each year is variable depending on climatic conditions.

11.1 Numerical Model Development

This conceptualisation of the Lower Burdekin groundwater system forms the basis for setting up the numerical groundwater flow and solute transport models. The conceptualisation attempts to provide the most contemporary alternatives for deriving input datasets and groundwater flow model conditions. A fairly complex alternative but computationally expensive model has been adopted in which a three layer model configuration has been proposed. This approach recognises that groundwater flow model simulations are essentially the average of hydrological interactions which are occurring at a far smaller scale. Model results will be sensitive to the individual inputs to varying degrees and there are significant benefits to model construction, calibration, and use if input dataset provision can be kept as simple as possible.

A review of modelling methods was undertaken as a preliminary phase to the completion of this conceptualisation report. The review proposed the following model codes be used in the development of the modelling toolkit:

- APSIM (unsaturated zone model)
- MODFLOW (groundwater flow model)
- SEAWAT (groundwater solute transport model)
- PHT3D (groundwater reactive solute transport model), with pre-processing support of GWB

The following points highlight the proposed approach for groundwater modelling:

- The model should be modelled as a high-complexity 3-layer model, including: an upper alluvial layer, a lower alluvial layer, and a basal weathered/fractured bedrock layer;
- Calibration of the groundwater flow model should be undertaken using historical groundwater levels from the departmental monitoring network. Only bores with elevation details that match the LiDAR DEM (within 1m difference) should be used in the calibration. Also, all bores selected for calibration and contouring should have a continuity of record and data integrity suitable for calibration purposes;
- The lower alluvial layer demonstrated hydraulic connection with the upper layer, but is incorporated to represent the local knowledge of a permeability contrast;
- The lowermost layer represents the weathered/fractured bedrock to account for the transmission of groundwater from beneath the alluvium. There is very little extraction of groundwater from this layer;
- A model cell size of 350m x 350m is recommended, which will form a model domain of 175 rows and 215 columns, and a total of 23416 active cells. This figure takes into account the size of the area, distribution of monitoring bores, pumping sites, and computation time;
- Despite the absence of groundwater level information within the surface clay in the BHWSS area, it will be included as part of the upper alluvial layer;

- Hydraulic conductivities calculated from test pumping analyses will be used as initial values in the calibration. Parameter estimation software, PEST-ASP (Doherty 2002) will be used for optimisation, given that there is limited pumping test data available;
- Boundary conditions will comprise fixed head boundaries along ocean boundaries, time varying fixed head boundaries along water courses, time variant flux boundaries along the south-eastern part of southern boundary and no-flow boundaries at geological boundaries;
- Sensitivity runs will be conducted with and without density corrections for the coastal fixed head boundary;
- Groundwater / surface water interaction for major watercourses inside the model domain will be simulated by the RIVER package within MODFLOW;
- Groundwater pumping within most of the BHWSS area is metered, and model inputs for this extraction will be derived from metered usage data. Groundwater pumping outside the metered area will be estimated based on APSIM-computed irrigation demand.

11.2 Recommendations for future work

The compilation of the conceptual model for the Lower Burdekin has highlighted a number of data gaps and areas where improvements could be made to current approaches. It is recommended that the following steps are taken:

- There is potential to improve the method used for grouping soil types and deriving soil parameters in order to ensure that the resulting distribution of soil properties is more closely matched with current understanding of soils in the area;
- There is a need to understanding solute transport in the Lower Burdekin, in order to achieve this, additional monitoring and new or refined modelling approaches will be required to build on current datasets and revise future solute transport models;
- Evapotranspiration (ET) by groundwater dependant ecosystems (GDEs) is a major data gap in the Lower Burdekin. There is a need to invest some effort in GDE assessments and field measurements of ET;
- Further investigations into GW-SW interactions would assist model development and calibration. In particular, information on river bed permeability would be useful for this purpose;
- There is an apparent high level of uncertainty with calculations of recharge from rivers. Dedicated investigations into river loss (and gain) calculations will help to reduce the uncertainty.
- A review of groundwater chemistry data and related research for the Lower Burdekin should be undertaken to assess the potential for using groundwater chemistry to support conceptualisation of aquifers and to determine any requirements for additional groundwater chemistry monitoring;
- The inflow of groundwater into the model area, especially from the western boundary, requires investigation;
- Water quality monitoring is currently not adequate for a proper calibration of solute transport modelling, particularly nitrogen and pesticides. The fate of these solutes from aquifer to stream should be investigated across the major channels that drain to the marine environment;
- Investigations into the processes and volumes of tailwater recycling may improve the understanding of the irrigation assessments.

- The use of cumulative frequency distribution curves for key parameters will help to validate their median and exceedance statistics for use in future groundwater models.

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Abbreviations

AHD	Australian Height Datum
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Productions Systems Research Unit
BHWSS	Burdekin-Haughton Water Supply Scheme
BOM	Bureau of Meteorology
BRIA	Burdekin River Irrigation Area (now BHWSS)
BSES	Burdekin Sugar Experiment Station
CFC	Chlorofluorocarbon
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEM	Digital Elevation Model
DERM	Department of Environment and Resource Management
DNRA	Dissimilatory Nitrate and Reduction to Ammonium
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPI	Department of Primary Industries
DSITIA	Department of Science, Information Technology, Innovation and the Arts
EC	Electrical Conductivity
ESP	Exchangeable Sodium Percentage
ET	Evapotranspiration
FPC	Foliage Projective Cover
GBR	Great Barrier Reef
GDE	Groundwater-Dependant Ecosystem
GWB	Geochemist’s Workbench (software)
GWDB	Groundwater Database
HRU	Hydrologic Response Unit
IROL	Interim Resource Operations Licence
LAI	Leaf Area Index
LiDAR	Light Detection and Ranging
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
NBWB	North Burdekin Water Board
NR&M	Department of Natural Resources and Mines (former)
NRW	Department of Natural Resources and Water (former)
NWC	National Water Commission
PEST	Parameter Estimation (software)
PEST-ASP	

SALI	Soil and Land Information (database)
SBWB	South Burdekin Water Board
Silo	
SRTM	Shuttle Radar Topography Mission
STRESGEN	
TDS	Total Dissolved Solids
USDA	United States Department of Agriculture
WERD	Water Entitlement Registration Database
WMS	Water Management System
WRP	Water Resource Plan

Units of Measurement

Mass

mg/L	milligrams per litre

Length

mm	millimetres
mm/yr	millimetres per year
m	metres
m/d	metres per day
km	kilometre

Area

ha	hectare
m^2/d	square metres per day
km^2	square kilometre

Volume

cumec	cubic metres per second
L	litre
L/s	litres per second
mL	millilitre
µL	microlitre
kL	kilolitre (one thousand litres)
kL/d	kilolitres per day
ML	megalitre (one million litres)
ML/d	megalitres per day
ML/yr	megalitres per year
m^3	cubic metre
m^3/d	cubic metres per day
$m^3/m/d$	cubic metres per metre per day

Other

mS/cm	milliSiemens per centimetre
µS/cm	microSiemens per centimetre
%	per cent (parts per hundred)
‰	per mille (parts per thousand)

Glossary

Term	Definition
Administrative hold	This is the mechanism under which specified applications for licences are held unprocessed, other than for registration, for an unspecified, but significant period, pending the completion of a resource assessment, allocation and management planning process. This was a policy-based management tool.
Aerosol salts	Oceanic salts carried as a part of a colloidal system (usually air) by on-shore winds and deposited in coastal environments.
Allocation	An authority to take water under Section 121 or 122 of the Water Act.
Alluvial	Composed of or pertaining to alluvium.
Alluvium	A general term for clay, silt, sand, gravel or similar unconsolidated material deposited during comparatively recent geologic time by a stream or other body of running water.
AMTD	Distance in kilometres from mouth of watercourse.
Anion	A negatively charged ion.
Artificial recharge	The process by which water is injected or infiltrated into an aquifer by the deliberate actions of man.
Aquatic	(Habitats and organisms) that occur in water.
Aquiclude	A geologic formation, group of formations or part of a formation through which virtually no water moves.
Aquifer	A permeable rock formation, group of formations, or part of a formation that stores and transmits sufficient groundwater to yield significant quantities of water to wells, bores and springs.
Aquitard.	A saturated, but poorly permeable bed, formation, or group of formations that does not yield water freely to a bore.
Baseflow	Stream flow coming from groundwater seepage into a stream.
Bedrock/basement	A general term for the rock, usually solid, that underlies soil or other unconsolidated material.
Cainozoic age	Covers the Earth's history for the last 65 million years. Contains Tertiary (65 million to 2 million years ago) and Quaternary (last 2 million years) periods.
Cation	A positively charged ion.
Carboniferous age	The time interval between 360 and 290 million years ago.
Confined aquifer	A confined aquifer is a completely saturated permeable formation of which the upper and lower boundaries are impervious layers.
Connate water	Water that is trapped in the interstices of a sedimentary rock, at the time it was deposited.
Devonian age	The time interval between 410 and 360 million years ago.

Electrical conductivity (EC)	A measure of the ease with which a conducting current can be caused to flow through a material under the influence of an applied electric field. It is the reciprocal of resistivity and is measured in Microsiemens per centimetre (µS/cm).
Ecology	The study of organisms and how they interact with each other and their physical surroundings.
Ecosystems	The sum of everything pertaining to ecology at a location. This includes physical habitats and organisms.
Environmental flow objective	For a water resource plan, means a flow objective for the protection of the health of natural ecosystems for the achievement of ecological outcomes.
Fabri-dam	Rubber air bag inflated to increase weir height and therefore weir holding volume.
Fluviatile	Pertaining to, belonging to, or peculiar to rivers, especially the physical properties of river action.
Fractured rock	A general term for rock which has been deformed to contain cracks, joints, faults, and other breaks by earth movement to form voids. The voids may contain water.
Groundwater-dependent ecosystems	Those ecosystems that derive some or all of their water requirements from groundwater.
Groundwater gradient	The change in static or total head per unit of distance in a given direction. The direction is that which yields a maximum rate of decrease in head.
Groundwater head	Energy contained in a water mass, produced by elevation, pressure or velocity. Usually measured as the standing height or water level that can be supported by the static pressure of the bore.
Habitat	The native environment or kind of place where a given animal or plant naturally lives or grows.
Homogeneous	Pertaining to a substance having identical characteristics everywhere.
Hydrograph	A graphical presentation which shows the water level in a bore as a function of time.
Hydraulic conductivity	The rate at which water can move through a porous medium.
Hydraulic gradient	The rate of change in total head per unit of distance of flow in a given direction.
Heterogeneous	Non-uniform in structure or composition throughout.
Hyporheic zone	The transition zone over which the fluctuations in exchange between surface water and groundwater occur.
Infiltration	The movement of a fluid into a solid substance through pores or cracks; in particular, the movement of water into soil or porous rock.
Interim water allocation	Means an authority to take water managed under an interim resource operations licence that represents a volumetric share of water and any condition attached to the authority.
Intrusive rocks	Igneous rocks formed of magma that consolidates beneath the earth's surface. May be later exposed by weathering.
Intrusives	General term for intrusive rocks.
Ion	An element or compound that has gained or lost an electron.
Lithology	The mineral composition and properties of rocks.

Megalitre	One million litres (1,000 cubic metres or appox. 220,000 gallons).
Mesozoic age	The time interval between 250 and 65 million years ago.
Metamorphosed	Altered by metamorphism, the process which produces structural and mineralogical changes in any type of rock in response to physical and chemical conditions differing from those under which the rocks originally formed.
Metasediments	Sedimentary rocks which have been altered by metamorphism.
Meteoric water	Water derived from the atmosphere, generally in the form of rain or sometimes snow and hail.
Organisms	Living things such as plants, animals and bacteria.
Palaeo-channels	Old or ancient watercourses inferred by the geology.
Permeability	The capacity of a porous material for transmitting a fluid.
Permian period	The time interval at the end of the Palaeozoic age (590 to 250 million years ago) spanning between 290 and 250 million years ago.
pH	The measure of acidity or alkalinity of a solution, Numerically equal to 7 in neutral solutions.
Phreatophytes	Phreatophytes are plants with deep roots that draw water from the water table.
Redox	A chemical reaction in which an atom or molecule loses electrons to another atom or molecule. Also called oxidation-reduction. Oxidation is the loss of electrons; reduction is the gain in electrons.
Riparian	Abuts a watercourse or lake or through which a watercourse flows or a lake is situated.
Resource Operations Plan	Means a statutory plan under the Water Act 2000 that details how the objectives identified in a Water Resource Plan are to be achieved. Where necessary ROP will establish the rules for trading. ROP will address how water use will be managed, how additional water can be allocated and how water infrastructure is to be managed. ROP will also specify practices and responsibilities for monitoring water and aquatic ecosystems.
Riparian zone	Pertaining to banks of a river (usually more broadly defined as the strip of land tens of metres wide along the banks of the stream).
Riverine processes	The processes of a river pertaining to the geomorphology or ecology.
Saltwater intrusion	The movement of saline water into previously fresh groundwater. This most commonly occurs in coastal zones and is usually the result of human activity.
Saturated zone	The zone of an aquifer where the voids in the rock or soil are completely filled with water at a pressure greater than atmospheric. The watertable is the top of the saturated zone in an unconfined aquifer.
Sediment	Particles at the bottom of the water column of rivers and the sea generally derived from soil on land. In the plural, the word refers to all kinds of deposits by water, wind and ice. They may be consolidated or unconsolidated.
Semiconsolidated sediments	Soil or sediments, which have become partially firm due to increased surface load or cementation.
Storativity	The volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head.

Stygofauna	An all-encompassing term for animals that occur in groundwater.
Subartesian water	Water that occurs naturally in, or is artificially introduced into, an aquifer, which if tapped by a bore would not flow naturally to the surface.
Supplemented stream	Stream which in addition to natural flow is augmented by flows from a dam, weir, or irrigation scheme.
Sustainable yield	The amount of groundwater that could be extracted from an aquifer on a sustained basis without causing long-continuing reduction of groundwater quantity, quality, and other undesirable effects such as environmental damage.
Tertiary	The geologic time period from 65 to 2 million years ago.
Transmissivity	A measure of the amount of water that can be transmitted horizontally through a unit width by the full saturated thickness of the aquifer under a hydraulic gradient of 1.
Trilinear diagrams	A graphical presentation, which can show the percentage composition of the major ions in water.
Unconfined aquifer	An aquifer where there are no impermeable barriers (confining layers) between the watertable and the surface. The upper boundary of the saturated zone, the watertable, is at atmospheric pressure.
Unconsolidated sediments	Soil or sediments, which have not been altered, cemented or compacted since their deposition.
Unsaturated zone	The zone between the land surface and the watertable. The pore spaces are partly filled with air and contain water at less than atmospheric pressure. Also known as the vadose zone.
Unsupplemented stream	Stream in which natural flow is not augmented by flows from a dam, weir, or irrigation scheme.
Water allocation	Means an authority granted under the relevant sections of the Water Act 2000.
Water allocation security objective	Means an objective that may be expressed as a performance indicator and is stated in a water resource plan for the protection of the probability of being able to obtain water in accordance with a water allocation.
Water entitlement	A water allocation, interim water allocation or water licence.
Water licence	Means a licence granted under the relevant sections of the Water Act 2000. A water licence is tied to a particular parcel of land.
Water resource plan	Means a plan approved under the relevant sections of the Water Act 2000.
Water service provider	Register under the relevant sections of the Water Act 2000 as a provider for a water service. (For the Pioneer – SunWater, Pioneer Valley Water Board).
Water table	A surface which defines the top of the saturated zone in an unconfined aquifer at which the pressure of the water is equal to that of the atmosphere.

APPENDICES