NSW Office of Water

Characterisation of hydrogeochemistry and risks to groundwater quality

Impact of groundwater pumping on groundwater quality:

National Water Commission - Raising National Water Standards Programme

December 2011

B2098_2114803A

PARSONS BRINCKERHOFF

Characterisation of Hydrogeochemistry and Risks to Groundwater Quality

December 2011

NSW Office of Water

Australian Government
National Water Commission

NSW Government
Department of Primary Industries
Office of Water

Acknowledgement

This project was funded by the Australian Government through the National Water Commission's Raising National Water Standards Program and the NSW Office of Water.

PARSONS BRINCKERHOFF

Parsons Brinckerhoff Australia Pty Limited
ABN 80 078 004 798

Level 27, Ernst & Young Centre
680 George Street
Sydney NSW 2000
GPO Box 5394
Sydney NSW 2001
Australia
Telephone *+61 2 9272 5100*
Facsimile *+61 2 9272 5101*
Email *sydney@pb.com.au*

Certified to ISO 9001, ISO 14001, AS/NZS 4801
A+ GRI Rating: Sustainability Report 2010

Revision	Details	Date	Amended By
0	Draft report for NSW Office of Water review	22 November 2011	WM, SB, SS, LR
C	Final report	9 December 2011	WM, SB, LR

Author: ...Wendy McLean, Stuart Brown, Sarah Scarff, Louisa Rochford

Signed: ....L. M. Rochford

Reviewer: ....Dr Stuart Brown

Signed: ....SH Brown

Approved by: ....Liz Webb

Signed: ....

Date: ....9 December 2011

Distribution: ....NSW Office of Water (2), Parsons Brinckerhoff (1)

Contents

Page number

List of tables

Page number

List of figures

Appendices

Glossary

Acidity	Base neutralising capacity.
Alkalinity	Acid neutralising capacity.
Alluvium	Unconsolidated sediments (clays, sands, gravels and other materials) deposited by flowing water. Deposits can be made by streams on river beds, floodplains, and alluvial fans.
Alluvial aquifer	Groundwater stored within unconsolidated alluvial sediments. Shallow alluvial aquifers are generally unconfined.
Ammonia	A compound of nitrogen and hydrogen (NH_3) that is a common by-product of animal waste and landfills but is also found naturally in reduced environments. Ammonia readily converts to nitrate in soils and streams.
Anion	An ion with a negative charge — usually non-metal ions when disassociated and dissolved in water.
Aquatic ecosystem	The stream channel, lake or estuary bed, water, and (or) biotic communities and the habitat features that occur therein.
Aquifer	Rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit economic quantities of water.
Aquifer properties	The characteristics of an aquifer that determine its hydraulic behaviour and its response to abstraction.
Aquifer, confined	An aquifer that is overlain by low permeability strata. The hydraulic conductivity of the confining bed is significantly lower than that of the aquifer.
Aquifer, semi-confined	An aquifer overlain by a low-permeability layer that permits water to slowly flow through it. During pumping, recharge to the aquifer can occur across the confining layer — also known as a leaky artesian or leaky confined aquifer.
Aquifer, unconfined	Also known as a water table or phreatic aquifer. An aquifer in which there are no confining beds between the zone of saturation and the surface. The water table is the upper boundary of an unconfined aquifer.
Australian height datum (AHD)	The reference point (very close to mean sea level) for all elevation measurements, and used for correlating depths of aquifers and water levels in bores.

Baseline sampling	A period of regular water quality and water level measurements that are carried out over a period long enough to determine the natural variability in groundwater conditions.
Beneficial use	Beneficial use is a legislated process that assists in the management and protection of water. Communities decide how a particular water body should be used by choosing a beneficial use category.
Boundary	A lateral discontinuity or change in the aquifer resulting in a significant change in hydraulic conductivity, storativity or recharge.
Carbonate	A salt or ester of carbonic acid containing the ion CO_3^{2-}.
Cainozoic	Is the most recent geological era and covers the period from 65.5 million years ago to the present.
Cation	An ion with a positive charge — usually metal ions when disassociated and dissolved in water.
Concentration	The amount or mass of a substance present in a given volume or mass of sample, usually expressed as microgram per litre (water sample) or micrograms per kilogram (sediment sample).
Confining layer	A body of relatively impermeable material that is stratigraphically adjacent to one or more aquifers — it may lie above or below the aquifer.
Contamination	Contamination is the presence of an unwanted compound in soil, water, chemical or other mixture.
Detection limit	The concentration below which a particular analytical method cannot determine, with a high degree of certainty, a concentration.
Deuterium (^2H)	Also called heavy hydrogen, a stable isotope of hydrogen with a natural abundance of one atom in 6,500 of hydrogen. The nucleus of deuterium, called a deuteron, contains one proton and one neutron, where a normal hydrogen nucleus has just one proton.
Discharge	The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.
Discharge area	An area in which there are upward or lateral components of flow in an aquifer.

Dissolution	Process of dissolving a substance into a liquid. If the saturation index is less than zero, the mineral is undersaturated with respect to the solution and the mineral might dissolve.
Drawdown	A lowering of the water table in an unconfined aquifer or the pressure surface of a confined aquifer caused by pumping of groundwater from bores and wells.
Electrical conductivity (EC)	A measure of a fluid's ability to conduct an electrical current and is an estimation of the total ions dissolved. It is often used as a measure of water salinity.
Environmental isotopes	Also known as stable isotopes, they act as 'groundwater signatures' and can be used as natural groundwater tracers.
Fluvial	Pertaining to a river or stream.
Global Meteoric Water Line (GMWL)	A line that defines the relationship between oxygen-18 (^{18}O) and deuterium (^{2}H) in fresh surface waters and precipitation from a number of global reference sites.
Groundwater	The water contained in interconnected pores located below the water table in an unconfined aquifer or located at depth in a confined aquifer.
Groundwater dependent ecosystems (GDEs)	Groundwater dependent ecosystems are communities of plants, animals and other organisms whose extent and life processes are dependent on groundwater.
Groundwater flow	The movement of water through openings in sediment and rock within the zone of saturation.
Groundwater flow system	A regional aquifer or aquifers within the same geological unit that are likely to have similar recharge, flow, yield and water quality attributes.
Holocene	The Holocene is a geological epoch which began approximately 12,000 years ago.
Hydraulic conductivity	The rate at which water of a specified density and kinematic viscosity can move through a permeable medium (notionally equivalent to the permeability of an aquifer to fresh water).
Hydraulic gradient	The change in total hydraulic head with a change in distance in a given direction.
Hydraulic head	Is a specific measurement of water pressure or total energy per unit weight above a datum, usually measured as a water surface elevation, expressed in units of length. In an aquifer, it can be calculated from the depth to water in a monitoring

	bore. The hydraulic head can be used to determine a hydraulic gradient between two or more points.
Hydrochemistry	Chemical characterisation of water (both surface water and groundwater).
Hydrogeology	The study of the interrelationships of geologic materials and processes with water, especially groundwater.
Hydrology	The study of the occurrence, distribution, and chemistry of all surface waters.
Infiltration	The flow of water downward from the land surface into and through the upper soil layers.
Ion	An ion is an atom or molecule where the total number of electrons is not equal to the total number of protons, giving it a net positive or negative electrical charge.
Isotope	One of multiple forms of an element that has a different number of neutrons than other atoms of that element. Some elements have isotopes that are unstable or radioactive, while others have 'stable isotopes'.
Local meteoric water line (LMWL)	A line that defines the local relationship between oxygen-18 (^{18}O) and deuterium (^{2}H) in fresh surface waters and precipitation. In this report the LMWL used is for coastal Sydney.
Major ions	Constituents commonly present in concentrations exceeding 10 milligram per litre. Dissolved cations generally are calcium, magnesium, sodium, and potassium; the major anions are sulphate, chloride, fluoride, nitrate, and those contributing to alkalinity, most generally assumed to be bicarbonate and carbonate.
Metalloid	Metalloid refers to a subset of elements, which are neither metals nor non-metals, as they contain characteristics of both. Boron, silicon, germanium, arsenic, antimony, tellurium and polonium are generally classified as metalloids.
Microsiemens per centimetre (µS/cm)	A measure of water salinity commonly referred to as EC (see also electrical conductivity). Most commonly measured in the field with calibrated field meters.
Miocene	A geological epoch extending from 23.03 to 5.33 million years ago.
Monitoring bore	A non-pumping bore, is generally of small diameter that is used to measure the elevation of the water table and/or water quality. Bores generally have a short well screen against a

	single aquifer through which water can enter.
Oxidising conditions	Conditions in which a species loses electrons and is present in oxidised form.
Oxygen-18 (^{18}O)	A natural, stable isotope of oxygen and one of the environmental isotopes. It makes up about 0.2% of all naturally-occurring oxygen on Earth.
Palaeovalley	Evidence of ancient subterranean valleys and rivers.
Permeability	The property or capacity of a porous rock, sediment, clay or soil to transmit a fluid. It is a measure of the relative ease of fluid flow under unequal pressure. The hydraulic conductivity is the permeability of a material for water at the prevailing temperature.
Permeable material	Material that permits water to move through it at perceptible rates under the hydraulic gradients normally present.
pH	Potential of Hydrogen; the logarithm of the reciprocal of hydrogen-ion concentration in gram atoms per litre; provides a measure on a scale from 0 to 14 of the acidity or alkalinity of a solution (where 7 is neutral, greater than 7 is alkaline and less than 7 is acidic).
Pleistocene	The Pleistocene is the geological epoch from 2,588,000 to 12,000 years ago.
Pliocene	The Pliocene is the geological epoch that extends from 5.332 million to 2.588 million years ago.
Precipitation	(1) in meteorology and hydrology, rain, snow and other forms of water falling from the sky (2) the formation of a suspension of an insoluble compound by mixing two solutions. Positive values of saturation index (SI) indicate supersaturation and the tendency of the water to precipitate that mineral.
Quaternary	The most recent geological period extending from approximately 2.5 million years ago to the present day.
Quality assurance	Evaluation of quality-control data to allow quantitative determination of the quality of chemical data collected during a study. Techniques used to collect, process, and analyse water samples are evaluated.
Recharge	The process which replenishes groundwater, usually by rainfall infiltrating from the ground surface to the water table and by river water reaching the water table or exposed aquifers. The addition of water to an aquifer.

Recharge area	A geographic area that directly receives infiltrated water from surface and in which there are downward components of hydraulic head in the aquifer. Recharge generally moves downward from the water table into the deeper parts of an aquifer then moves laterally and vertically to recharge other parts of the aquifer or deeper aquifer zones.
Recovery	The difference between the observed water level during the recovery period after cessation of pumping and the water level measured immediately before pumping stopped.
Redox potential (ORP or Eh)	The redox potential is a measure (in volts) of the affinity of a substance for electrons — its electronegativity — compared with hydrogen (which is set at 0). Substances more strongly electronegative than (i.e. capable of oxidising) hydrogen have positive redox potentials. Substances less electronegative than (i.e. capable of reducing) hydrogen have negative redox potentials. Also known as oxidation-reduction potential and Eh.
Redox reaction	Redox reactions, or oxidation-reduction reactions, are a family of reactions that are concerned with the transfer of electrons between species, and are mediated by bacterial catalysis. Reduction and oxidation processes exert an important control on the distribution of species like O_2, Fe^{2+}, H_2S and CH_4 etc. in groundwater.
Reducing conditions	Conditions in which a species gains electrons and is present in reduced form.
Salinity	The concentration of dissolved salts in water, usually expressed in EC units or milligrams of total dissolved solids per litre (mg/L TDS). The conversion factor of 0.6 mg/L TDS = 1 EC unit is commonly used as an approximation of salinity.
Saturated zone	The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric pressure. The water table is the top of the saturated zone in an unconfined aquifer.
Screen	A type of bore lining or casing of special construction, with apertures designed to permit the flow of water into a bore while preventing the entry of aquifer or filter pack material.
Shale	A laminated sediment in which the constituent particles are predominantly of clay size.
Sodium adsorption ratio (SAR)	SAR is the ratio of sodium to calcium and magnesium in relation to known effects on soil used to measure the suitability of water for use in agricultural irrigation.

Specific storage	Relating to the volume of water that is released from an aquifer following a unit change in the hydraulic head. Specific storage normally relates to confined aquifers.
Stable isotope	Stable isotopes are not radioactive, and do not decay over time. For example, most nitrogen atoms have 14 neutrons, while a very small percentage of naturally-occurring nitrogen atoms have 15 neutrons. The ^{15}N atoms are referred to as stable isotopes.
Storativity	The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to specific yield.
Stratigraphy	The depositional order of sedimentary rocks in layers.
Surface water-groundwater interaction	This occurs in two ways: (1) streams gain water from groundwater through the streambed when the elevation of the water table adjacent to the streambed is greater than the water level in the stream; and (2) streams lose water to groundwater through streambeds when the elevation of the water table is lower than the water level in the stream.
Total dissolved solids (TDS)	A measure of the salinity of water, usually expressed in milligrams per litre (mg/L). See also EC.
Toxicity	The degree to which a substance is able to damage an animal or plant life form.
Trace element	An element found in only minor amounts (concentrations less than 10 milligram per litre) in water or sediment; includes heavy metals arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc.
Transmissivity	The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.
Trigger value	Trigger values are conservative water quality assessment levels based mainly on statistical distributions. They are concentrations of key indicators, above or below, which there is a risk of adverse biological or environmental effects.
Turbidity	Reduced clarity of surface water because of suspended particles, usually sediment.

Unsaturated zone	That part of an aquifer between the land surface and water table. It includes the root zone, intermediate zone and capillary fringe.
Water quality	Term used to describe the chemical, physical, and biological characteristics of water, usually in respect to its suitability for a particular purpose.
Water quality data	Chemical, biological, and physical measurements or observations of the characteristics of surface and ground waters, atmospheric deposition, potable water, treated effluents, and waste water and of the immediate environment in which the water exists.
Water sharing plan	A water sharing plan is a legal document prepared under the *Water Management Act 2000*. Water sharing plans establish rules for sharing water between water users and the environmental needs of the river or groundwater system.
Water table	The surface in an unconfined aquifer or confining bed at which the pore water pressure is atmospheric. It can be measured by installing shallow bores extending a few metres into the zone of saturation and then measuring the water level in those bores.

List of abbreviations

ADWG	Australian Drinking Water Guidelines
ANZECC	Australian and New Zealand Environment Conservation Council
BoM	Bureau of Meteorology
EC	Electrical conductivity
GDE	Groundwater dependent ecosystem
NOW	NSW Office of Water
NSW	New South Wales
SAR	Sodium adsorption ratio
TDS	Total dissolved solids

List of units

°C	degrees Celsius
Km	kilometres
L/s	litres per second
m	metres
mAHD	metres Australian height datum
m bgl	metres below ground level
m^2/day	square metres per day
µS/cm	microSiemens per centimetre
mg/L	milligrams per litre
‰	permil

Executive summary

Project objective

As a result of drought and climate change, surface water availability and reliability in some parts of the Murray-Darling Basin are declining and groundwater is being pumped in increasing quantities as an alternative water source. As pumping can lead to water moving within and across aquifers, it can cause deteriorating groundwater quality either through changing salinity or chemical composition.

The NSW Office of Water (NOW) commissioned Parsons Brinckerhoff to characterise the hydrogeochemistry and investigate the risks posed by groundwater pumping on groundwater quality in six alluvial groundwater systems so that a risk assessment of potential groundwater quality impacts could be developed for future Water Sharing Plans (WSPs).

Methodology

NOW sampled and analysed groundwater between September 2009 and February 2011 in six of the large alluvial groundwater systems in inland NSW: Upper Namoi Groundwater Management Area (GMA) Zone 3; Lower Namoi GMA, Lower Macquarie GMA; Lower Lachlan GMA; Lower Murray GMA; and Lower Murrumbidgee GMA.

This data, combined with NOW’s corporate database, was assessed for data quality and then analysed and interpreted using methods, including:

- Aqueous speciation modelling and major ion assessment to characterise the hydrogeochemistry.
- Comparison of stable isotopes results to rainfall values to assess groundwater provenance, recharge and inter-aquifer mixing.
- Mann Kendall analysis to identify trends.
- Comparison to water quality guidelines to assess changes in beneficial use.
- Salt flux modelling in the Lower Murrumbidgee.

Sampling program and data quality review

A comprehensive water quality data set was collected for most catchments, although none of the catchments was monitored for the full 18 months and the number of bores sampled during monitoring events varied. The Lower Macquarie GMA had the least number of monitoring rounds (eight), and in two rounds only one bore was sampled.

The data quality review indicated that ionic balances and field duplicate results were generally acceptable. Data quality issues that were identified included:

- The TRITON database was sometimes inaccurate when compared with laboratory reports.
- An inadequate number of field blanks and field duplicates were collected.
- Field blanks and field duplicates were not labelled correctly.

- The water used in field blanks was not analysed before fieldwork, and with the exception of field blanks in the Lower Macquarie, more than half the field blanks had analyte concentrations an order of magnitude above detection limits.

The data quality issues identified may be the result of a range of issues, including poor database entry protocols, poor field techniques (such as groundwater sampling, sample handling and transport techniques) or poor laboratory analytical techniques (such as cross-contamination via laboratory equipment or inadequate calibration of instruments).

Characterisation of hydrogeochemistry and risks to groundwater quality

Upper Namoi GMA Zone 3

The Upper Namoi GMA Zone 3 has two major hydrogeological units: the shallow Narrabri Formation and the deep Gunnedah Formation. Groundwater from these aquifers is used to irrigate crops (mainly cotton) as well as stock and domestic purposes.

Groundwater was sampled and analysed in 13 rounds during the study period at three bores in the Narrabri Formation and 17 bores in the Gunnedah Formation. The results indicated that:

- Groundwater levels have declined by 4 to 10 m since the mid-1970s.
- The Gunnedah Formation is typically less saline than the overlying Narrabri Formation.
- Major ion chemistry in the Narrabri Formation is dominated by sodium and chloride. Major ion chemistry in the Gunnedah Formation varies with location, reflecting the laterally discontinuous nature of the aquifer with discrete zones of differing salinity and water type.
- Groundwater within the Narrabri Formation is suitable for stock only. Groundwater within the Gunnedah Formation close to the Namoi River is suitable for drinking water based on EC; however, treatment may be required for manganese.
- The beneficial use of groundwater has deteriorated at some bores in the Narrabri Formation (no longer suitable for stock) and Gunnedah Formation (from irrigation to stock) since monitoring began.
- Three Gunnedah Formation bores in the north-east of Zone 3 showed a long-term increasing trend in salinity, which is attributed to either vertical leakage of saline water from the upper to lower aquifer where aquitards are thin or absent, or to leakage of saline water from clay aquitards where pumping has resulted in depressurisation.
- As well as mixing of waters between aquifers, there are other geochemical processes occurring, including ion exchange, weathering of silicate minerals and clays and dissolution and precipitation of minerals such as carbonates and gypsum.
- A change in water type has occurred in some Gunnedah Formation bores where salinity is increasing.

Lower Namoi GMA

The Lower Namoi GMA has three major hydrogeological units: the upper Narrabri Formation, the middle Gunnedah Formation and the lower Cubbaroo Formation. Groundwater from these aquifers is used to irrigate crops (mainly cotton), as well as stock and domestic purposes.

Groundwater was sampled and analysed in 13 rounds during the study period at five bores in the Narrabri Formation, 12 bores in the Gunnedah Formation and five bores in the Cubbaroo Formation, centred around Cryon. The results indicated that:

- Groundwater levels have declined by 1.5 to 4 m since the late 1970s.
- The Gunnedah and Cubbaroo formations are typically less saline than the overlying Narrabri Formation.
- Major ion chemistry in all aquifers is dominated by sodium and chloride.
- Groundwater within the Narrabri Formation is suitable for stock only. Groundwater within the Gunnedah and Cubbaroo formations is suitable for stock; high sodium concentrations limit it being used to irrigate cotton.
- The beneficial use of groundwater has deteriorated at some bores in the Narrabri Formation (no longer suitable for stock), Gunnedah Formation (no longer suitable for some crops including cotton) and Cubbaroo Formation (no longer suitable for some crops including cotton) since monitoring began.
- Four Gunnedah Formation bores showed a long-term increasing trend in salinity, which is attributed to vertical leakage of saline water from the upper aquifer and saline intrusion of pore waters. One Narrabri Formation bore and one Cubbaroo Formation bore also showed a long-term increasing trend in salinity.
- As well as mixing of waters between aquifers, there are other geochemical processes occurring, including ion exchange, reverse ion exchange, and dissolution and precipitation of minerals, such as carbonates and gypsum.
- There were no long-term changes in water type identified.

Lower Macquarie GMA

The Lower Macquarie GMA has three major alluvial hydrogeological units: the upper Narrabri Formation, the middle Gunnedah Formation and the lower Cubbaroo Formation. Groundwater from these aquifers is used to irrigate crops (mainly cotton), as well as stock and domestic purposes. Some groundwater used within the GMA for stock and domestic purposes is sourced from the underlying sandstone aquifers of the Great Artesian Basin.

Groundwater was sampled and analysed in eight rounds during the study period at four bores in the Gunnedah Formation and three bores in the Cubbaroo Formation. The results indicated that:

- Groundwater levels increased between the early 1970s and mid-1990s and have since declined. The Cubbaroo Formation is typically more saline than the overlying Gunnedah Formation.
- Major ion chemistry in both aquifers is dominated by sodium, magnesium and chloride, with monitoring locations with lower salinities also dominated by bicarbonate.
- Groundwater in the south east is suitable for drinking water based on EC; however, groundwater from the Cubbaroo Formation may require treatment for manganese. Groundwater in the south-west is suitable for irrigation.
- Inadequate data was available for analysis of long-term trends in salinity and beneficial use classification. One Cubbaroo Formation bore showed a long-term increasing trend in salinity;

however, the cause cannot be conclusively determined as the Gunnedah Formation is not monitored at this location.

- There were no long-term changes in water type identified.

Lower Lachlan GMA

The Lower Lachlan GMA has three major hydrogeological units: the upper Shepparton Formation, the middle Calivil Formation and the lower Renmark Group. Groundwater from these aquifers is used to irrigate crops (including rice and cereals) as well as stock and domestic purposes.

Groundwater was sampled and analysed in 16 rounds during the study period at 21 bores in the Calivil Formation, nine bores in the Renmark Group and three bores in both the Calivil Formation and Renmark Group. The results indicated that:

- Groundwater levels have generally declined by 2 to 10 m since the mid-1990s when large-scale irrigation development began.
- Groundwater in the Calivil Formation and Renmark Group is fresh.
- Major ion chemistry of groundwater in the Calivil Formation ranges between two end members: a fresh end member characterised by Na-Mg-HCO3-Cl type water and a more saline end member characterised by Na-Mg-Cl-type water. Major ion chemistry in the Renmark Group is dominated by sodium, chloride and bicarbonate.
- Groundwater within the Calivil Formation and Renmark Group is suitable for drinking.
- There has been no change in the beneficial use classification since monitoring began.
- No significant long-term increasing trends in salinity were identified in Calivil bores. Inadequate data was available to analyse long-term trends in salinity in the Renmark Group.
- Water types in the Calivil Formation have evolved to reflect an increase in the relative proportions of magnesium and chloride. There were no changes in water type identified in the Renmark Group.

Lower Murray GMA

The Lower Murray GMA has three major hydrogeological units: the upper Shepparton Formation, the middle Calivil Formation and the lower Renmark Group. Groundwater from these aquifers is used to irrigate crops (including rice and cereals), as well as stock and domestic purposes.

Groundwater was sampled and analysed in 16 rounds during the study period at four bores in the Shepparton Formation, 13 bores in the Calivil Formation, nine bores in the Renmark Group, one bore in both the Shepparton and Calivil formations and one bore in both the Calivil Formation and Renmark Group. The results indicated that:

- Groundwater levels have declined by 5 to 15 m since the mid-1990s.
- Salinity ranges from fresh to saline, with groundwater in the Renmark Group generally more saline than the upper aquifers.
- Major ion chemistry is dominated by sodium, magnesium and chloride, with lower salinity groundwater in the Shepparton and Calivil formations also dominated by bicarbonate.

- Groundwater in the Shepparton Formation and the southern and eastern parts of the Calivil Formation is suitable for drinking water based on EC, but may require treatment for manganese. Groundwater in other parts of the Calivil Formation and the Renmark Group is suitable for irrigation.

- There has been deterioration in drinking water quality in the Shepparton and Calivil formations since monitoring began and groundwater is no longer suitable for rice at some bores in the Renmark Group.

- Four Shepparton Formation bores showed a long-term increasing trend in salinity, which is attributed to leakage from clay aquitards as the aquifer becomes depressurised or dissolution of salts. Five Calivil Formation and three Renmark Group bores in the south of the catchment between Deniliquin and Tocumwal showed a long-term increasing trend in salinity. The increasing trends in salinity are attributed to a range of processes, reflecting the heterogeneity of the formations and complex aquifer interactions.

- With increases in salinity, water types have evolved to reflect an increase in the relative proportions of magnesium and chloride.

Lower Murrumbidgee GMA

The Lower Murrumbidgee GMA has three major hydrogeological units: the upper Shepparton Formation, the middle Calivil Formation and the lower Renmark Group. Groundwater from these aquifers is used for stock and domestic purposes as well as to irrigate crops (including rice and cereals) in two major irrigation areas: the Murrumbidgee Irrigation Area (MIA) and the Colleambally Irrigation Area (CIA).

Groundwater was sampled and analysed in 15 rounds during the study period at six bores in the Shepparton Formation, 11 bores in the Calivil Formation, 22 bores in the Renmark Group, two bores in both the Calivil Formation and Renmark Group and one bore in all three formations. The results indicated that:

- Groundwater levels showed an increasing trend from the late 1980s to early 1990s. Since the mid-1990s, when extraction of groundwater increased, groundwater levels have declined by 3 to 10 m.

- Salinity ranges from fresh to saline, with groundwater in the upper Shepparton Formation generally more saline than the lower aquifers. Groundwater in the Calivil Formation and Renmark Group was freshest in the eastern part of the catchment close to the Murrumbidgee River.

- Major ion chemistry in the Shepparton and Calivil formations is variable with groundwater plotting between two end members: a fresh end member characterised by Na-HCO_3-Cl or Na-HCO_3-type water and a more saline end member characterised by Na-Mg-Cl-type water. Major ion chemistry in the Renmark Group is dominated by sodium, chloride and bicarbonate.

- Groundwater in the Calivil Formation and Renmark Group east of Hay is suitable for drinking water based on EC, but may require treatment for manganese. Groundwater in the Calivil Formation and the Renmark Group west of Hay is suitable for irrigation.

- The beneficial use of groundwater has deteriorated at one bore in the Calivil Formation (no longer suitable for irrigation at one bore in the MIA) since monitoring began.

- No significant long-term trends in salinity were identified in Shepparton Formation bores. Two Calivil Formation bores and one Renmark Group bore within the irrigation areas east of Hay showed a long-term increasing trend in salinity, which is attributed to leakage from overlying formations.

- With increases in salinity, water types have evolved to reflect an increase in the relative proportions of magnesium and chloride.

Summary of results

Catchment	Aquifer	Long-term EC range (median) uS/cm	Beneficial use (based on EC and SAR)	Change in beneficial use to date	Trends
Upper Namoi GMA Zone 3	Narrabri	365 – 23,400 (4,600)	Stock	No longer suitable for some stock at some bores	No significant trends
	Gunnedah	657 – 14,270 (1,230)	Drinking water^ (close to Namoi River), some irrigation* (remaining area)	Change from irrigation to stock at some bores	Increasing EC and a change in water type in the north-east
Lower Namoi GMA	Narrabri	5,270 – 29,700 (14,400)	Stock	No longer suitable for some stock at some bores	No significant trends
	Gunnedah	746 – 28,900 (3,125)	Some irrigation*	No longer suitable for cotton at some bores	Increasing EC at some bores
	Cubbaroo	1,347 – 4,090 (1,930)	Some irrigation*	No longer suitable for cotton at some bores	No significant trends
Lower Macquarie GMA	Gunnedah	978 – 2,260 (1,970)	Drinking water (south-east), irrigation (south-west)	Change in beneficial use could not be assessed due to limited data	Trends could not be analysed due to limited data
	Cubbaroo	456 – 1,350 (860)	Drinking water^ (south-east), irrigation (south-west)		
Lower Lachlan GMA	Calivil	271 – 1,795 (665)	Drinking water	No	No significant trends
	Renmark	456 – 1,350 (860)	Drinking water	No	
Lower Murray GMA	Shepparton	307 – 10,500 (474)	Drinking water^	Some deterioration in drinking water quality, no longer suitable for rice at some bores	Increasing EC and a change in water type at bores in the south (between Deniliquin and Tocumwal)
	Calivil	418 – 20,100 (534)	Drinking water^ (south and east), irrigation (north)		
	Renmark	833 – 20,600 (1,679)	Irrigation	No longer suitable for rice at some bores	
Lower Murrumbidgee GMA	Shepparton	428 – 32,800 (4,010)	Variable	No	No significant trends
	Calivil	369 – 8,930 (758)	Drinking water^ (east of Hay), irrigation (west of Hay)	No longer suitable for irrigation at one bore within MIA (east of Hay)	Increasing EC at some bores within irrigation areas (east of Hay)
	Renmark	322 – 5,500 (635)	Drinking water^ (east of Hay), irrigation (west of Hay)	No	

* SAR needs to be considered, groundwater suitable for irrigation of some crops
^ Treatment for manganese or other analytes may be required

Using numerical modelling to predict groundwater quality change

The use of numerical modelling to estimate groundwater quality change under planned groundwater management scenarios was investigated for the Lower Murrumbidgee catchment. A methodology was developed whereby groundwater flux estimates from the NOW numerical model were combined with groundwater quality estimates from the 2009–2011 monitoring period to estimate the net salt fluxes and trends in average salinity for each aquifer unit at key monitoring locations.

As proof of concept, trends in water quality (as approximated by total dissolved solids) were calculated for five model cell locations where sufficient data were available to estimate the water quality in each of the three aquifers. Trends in groundwater quality were predicted for the 2009–2020 period covered by the numerical model. The results indicated the following:

- The calculated water quality trends in the lower (Calivil Formation and Renmark Group) aquifers imply there is potential for water quality to transgress the drinking water beneficial use category in at least one location within the ten-year WSP period, and perhaps at other locations over longer time frames.
- Groundwater quality may improve over time in the more saline upper aquifer (model layer 1; Shepparton Formation) because of the relatively high modelled flux of irrigation water recharge. Other locations and aquifers show more subtle trends that are unlikely to be detectable above natural variations over a ten-year WSP period, but may be important over longer periods.
- In many cases, the observed groundwater total dissolved solids concentration at representative monitoring bores over the 2009–2011 monitoring period shows significant scatter about the predicted trend line with either no apparent trend or one that diverges from the predicted trend. This suggests that local scale aquifer properties and multiple hydrogeochemical processes control water quality over the short to medium term (seasonal/yearly) and that many more years of data would be required to demonstrate a statistical trend of the magnitudes predicted.

Key findings and recommendations

Data quality

Key finding – None of the catchments were monitored for the full 18 months and the number of bores sampled during monitoring events varied. These data gaps affected the ability to assess water quality trends and identify risks to groundwater quality. The data collected from the Lower Macquarie catchment was inadequate to assess trends and identify risks.

> *Recommendation 1* – Where a groundwater quality monitoring program is established for a catchment, it should be implemented as planned. This will ensure adequate data is collected to assess trends and identify risks to groundwater quality.
>
> *Recommendation 2* – Install dedicated sampling equipment (micropurge pumps) and water level loggers in monitoring bores, particularly those located in high risk areas. This will improve adherence to planned groundwater monitoring programs and increase the quantity and quality of data collected.
>
> *Recommendation 3* – Conduct baseline groundwater quality monitoring in the Lower Macquarie catchment to assess water quality trends and risks to groundwater quality (refer to the table below for details).

Baseline groundwater quality monitoring program for the Lower Macquarie	
Frequency	Monthly
Duration	18 months
Parameters	Groundwater level, major ions, metals, nutrients, stable isotopes
Bores	Monitoring bores and production bores
Number of locations	Minimum of five (5) in each aquifer, preferably at nested locations
Location	Close to main irrigation areas
Aquifers	Narrabri, Gunnedah and Cubbaroo formations

Key finding – The data quality review identified a number of issues with the accuracy of the data in the TRITON database and the sampling techniques used during the 2009–2011 groundwater monitoring program.

> *Recommendation 4* – Review database entry and database management processes to identify areas for improvement.
>
> *Recommendation 5* – Hold a workshop to train (or provide revision for) staff monitoring groundwater to ensure appropriate groundwater sampling, sample handling and sample transport techniques are used as per Parsons Brinckerhoff (2009).
>
> *Recommendation 6* – Regularly audit groundwater monitoring programs. This may include auditing field staff during monitoring or reviewing field notes and laboratory analytical reports. Frequent auditing of groundwater monitoring programs will ensure early detection of issues and improve the quality of data collected.

Early detection of risks to beneficial use

Key finding – The results indicate that changes in beneficial use have occurred at bores in the Upper Namoi, Lower Namoi, Lower Murray and Lower Murrumbidgee since monitoring began. The results also indicate there are increasing trends in salinity at bores in all catchments (except the Lower Macquarie where there was insufficient data for analysis).

> *Recommendation 7* – Monitor groundwater level and quality quarterly in moderate to high risk aquifers and annually in low risk aquifers so as to detect deterioration in beneficial use early (refer to Table 11-2). Moderate to high risk aquifers are defined as aquifers at risk of deterioration in beneficial use. Low risk aquifers are defined as aquifers of low beneficial use and/or aquifers at low risk of deterioration in beneficial use.

Key finding – The results indicate that major ion chemistry is well correlated with salinity in all six catchments.

> *Recommendation 8* – Use EC and SAR as key indicators of deterioration in beneficial use (refer to the table below) and develop catchment-specific triggers for EC and SAR against which monitoring results can be compared. The actions to be taken when triggers are exceeded would be developed as part of the WSP process. One of the actions should be to instigate a more comprehensive monitoring program to better define trends and understand the processes leading to changes in groundwater quality (refer to the table below).

	Groundwater monitoring strategy for moderate to high risk aquifers*	Groundwater monitoring strategy for low risk aquifers^
Standard program	Quarterly – Groundwater level, EC and SAR Annual – Major ions, metals, nutrients	Annual - Groundwater level, EC and SAR
Enhanced program where triggers exceeded	Monthly - Groundwater level, EC and SAR Quarterly – Major ions, metals, nutrients	Quarterly – Groundwater level, EC and SAR Annual - Major ions, metals, nutrients
Bores	Monitoring bores (no production bores)	Monitoring bores (no production bores)
Number of locations	Minimum of five in each aquifer to be monitored, preferably at nested locations	Minimum of five in each aquifer to be monitored, preferably at nested locations
Location and aquifers	• Upper Namoi Zone 3 – Gunnedah • Lower Namoi around Cryon – Gunnedah and Cubbaroo • Lower Murray – Shepparton, Calivil and Renmark • Lower Murrumbidgee MIA and CIA – Shepparton, Calivil, Renmark	• Upper Namoi Zone 3 – Narrabri • Lower Namoi around Cryon – Narrabri • Lower Lachlan – Calivil and Renmark • Lower Murrumbidgee outside the MIA and CIA – Shepparton, Calivil, Renmark

* Moderate to high risk aquifers include aquifers at risk of changes in beneficial use, for example due to increasing trends in salinity

^ Low risk aquifers include aquifers of low beneficial use and aquifers at low risk of deterioration in beneficial use

Key finding – The results indicate that water quality hotspots, where groundwater quality is deteriorating, exist within aquifer systems. Water quality hotspots may form due to the heterogeneity of aquifer stratigraphy; complex physical and chemical aquifer interactions; seasonality of pumping regimes; variation in the local intensity of groundwater extraction; and/or climatic variability.

> *Recommendation 9* – The bores selected for monitoring networks should include bores targeting water quality hotspots, as well as bores outside water quality hotspots, so that the spatial patterns of hotspot trends within the context of the broader catchment can be explored. The current study identified water quality hotspots at the bores in the table below based on long-term trends in water quality.

Catchment	Aquifer	Locations identified as water quality hotspots
Upper Namoi	Narrabri Formation	None
	Gunnedah Formation	GW036038, GW036166, GW036213
Lower Namoi	Narrabri Formation	GW036040
	Gunnedah Formation	GW036314, GW036320, GW036340, GW036364
	Cubbaroo Formation	GW036398, GW036406
Lower Macquarie	Gunnedah Formation	Inadequate data
	Cubbaroo Formation	GW030215, otherwise inadequate data
Lower Lachlan	Calivil Formation	None
	Renmark Group	Inadequate data
Lower Murray	Shepparton Formation	GW036283, GW036876, GW036587, GW036743
	Calivil Formation	GW036283, GW036584, GW036585, GW036586, GW036588
	Renmark Group	GW036587, GW036743, GW036744
Lower Murrumbidgee	Shepparton Formation	None
	Calivil Formation	GW036358, GW036773
	Renmark Group	GW036358

Key finding – The scope of this study was defined by the aquifers and bores selected by the NSW Office of Water and, as such, the recommended monitoring program is focused on these areas. It is recognised that risks to groundwater quality may occur in other parts of the aquifers studied and in other groundwater systems across the state.

> *Recommendation 10* – Make a statewide review of groundwater quality in aquifer systems across the state at regular intervals to ensure that ongoing groundwater monitoring programs target the aquifer systems at highest risk of deterioration in groundwater quality. These reviews may be similar to 'key sites' annual programs.

Understanding processes driving changes in groundwater quality

Key finding – The results indicate that within aquifer systems there is substantial variability in groundwater chemistry and that changes in groundwater chemistry have occurred since monitoring began. However, the processes leading to these changes could not be conclusively determined as some end members were not monitored.

> *Recommendation 11* – Monitoring of end members, including surface water, irrigation water, pore water from aquitards, shallow aquifers, adjacent aquifers and underlying bedrock aquifers should be undertaken in future monitoring programs to better characterise and understand the hydrogeochemical processes leading to changes in water quality.

Key finding – The results indicate that increasing trends in salinity in productive aquifers are due to leakage of saline groundwater from shallow aquifers at some locations. Leakage of saline groundwater from shallow aquifers occurs where productive aquifers are depressurised and aquitards are thin or absent.

> *Recommendation 12* – Delineate the extent and continuity, and investigate the thickness and permeability, of clay aquitards underlying shallow saline aquifers, particularly where they overlie fresh aquifers. This will improve understanding of where risks to groundwater quality exist.

Key finding – The results indicate that increasing trends in salinity in productive aquifers may be due to leakage of saline pore waters from clay aquitards at some locations. Leakage of saline pore waters from aquitards may occur due to aquifer depressurisation.

> *Recommendation 13* – Undertake a research program to improve understanding of the physical and chemical properties of aquitards and associated pore waters. This might involve collecting core samples for laboratory testing, installing monitoring bores in aquitards, and mapping aquitards using geophysics and numerical modelling.

Predicting future changes in groundwater quality using numerical modelling

Key finding – The modelling trial indicated that, despite a number of limitations on local scales, mass balance approaches provide a means to assess potential trends in water quality on a subregional scale, based on calibrated groundwater fluxes and estimates of existing salinity distributions from monitoring data.

> *Recommendation 14* – When the catchment numerical model is run as part of the WSP review process carry out a mass flux analysis step, similar to the approach used in this study, to identify areas that are at risk of deteriorating water quality under the assumed abstraction rates of the proposed WSP..

Key finding – Analysis of solute fluxes is only possible where there are adequate estimates of groundwater quality from monitoring in all adjacent aquifers at each location. In the Lower Murrumbidgee, modelling could only be undertaken at five locations due to limitations in the existing monitoring network.

> *Recommendation 15* – Augment the existing groundwater monitoring network by installing piezometers in non-productive aquifers next to existing piezometers that are screened within productive aquifers.

Key finding – To model local groundwater quality trends more effectively using hydrogeochemical process-based models, it is necessary to improve our conceptual understanding of groundwater flow and reactive transport mechanisms that operate on those local scales.

> *Recommendation 16* – Undertake a research program to improve understanding of solute transport and salinisation mechanisms in high-risk areas. In addition to the scope under Recommendation 12, the research could include the use of isotopic dating and tracer techniques to place constraints on groundwater residence times, groundwater fluxes and the origin of solutes.

Limitations

The findings of this study are limited by the available data, including the geographical spread and target aquifers of the selected bores, the frequency of sampling, the historical data provided and the quality of the field and analytical data. Nevertheless, this study has provided a strong foundation for understanding risks posed by groundwater pumping on groundwater quality. Additional data collected would improve the assessment of risks to groundwater quality.

1. Introduction

1.1 Project background

Parsons Brinckerhoff has been commissioned by the NSW Office of Water to characterise the hydrogeochemistry and investigate the risks posed by groundwater pumping on groundwater quality in six of the large alluvial aquifers in inland NSW. The project is funded by the National Water Commission's Raising National Water Standards Program, which is aimed at projects to improve Australia's national capacity to measure, monitor and manage our water resources.

As a result of drought and climate change, surface water availability and reliability in some parts of the Murray-Darling Basin is declining and groundwater is being pumped in increasing quantities as an alternative water source. Because pumping can lead to water moving within and across aquifers, it can cause deteriorating groundwater quality either through changing salinity or chemical composition.

The NSW Office of Water conducted a groundwater sampling and analysis program between September 2009 and February 2011. This data, combined with the NSW Office of Water's corporate database, is required to be analysed and interpreted to extend current hydrogeochemical knowledge and to investigate groundwater quality risks posed by groundwater pumping. This interpretation will enable a risk assessment of potential groundwater quality impacts to be developed for future Water Sharing Plans. The NSW Office of Water also requires the provision of advice on how numerical modelling can be used to predict groundwater quality change under planned groundwater management scenarios.

This report collates and documents the chemical and isotopic data collected by NSW Office of Water and provides an assessment of groundwater quality in the six alluvial catchments, including the potential for groundwater pumping to cause a decline in groundwater quality. The report also provides an appraisal of numerical modelling methodologies for assessing water quality changes and risks in the Lower Murrumbidgee Groundwater Management Area (GMA), and preliminary results from the selected numerical modelling method.

1.2 Project objectives

The broad objective of this project is to improve the current knowledge on the influence of groundwater use on groundwater quality to enable a risk assessment of potential groundwater quality impacts to be developed for future Water Sharing Plans.

More specifically the objectives of this project were to::

- Provide a characterisation of groundwater quality with consideration of its beneficial use and identify hydrogeochemical processes in six catchments (Figure 1-1):
    - Upper Namoi GMA Zone 3, Breeza area
    - Lower Namoi GMA centred around Cryon
    - Lower Macquarie GMA

  - Lower Lachlan GMA
  - Lower Murray GMA
  - Lower Murrumbidgee GMA.
- Improve understanding of the risk of groundwater quality change to groundwater resources.
- Provide an improved understanding of the processes of groundwater quality change for decision making on water resource allocations.
- Provide estimates of the level of risk to groundwater quality change in other GMAs in NSW.
- Develop NSW Office of Water's capital and intellectual capacity to monitor, evaluate, report and advise on groundwater quality matters as they relate to groundwater resource management.

1.3 Project scope

PB has undertaken the following scope of works, as specified in NSW Office of Water's tender brief:

- Receipt and handling of hydrogeochemical data. Acquisition of groundwater level, flow and rock mineralogy information/data as needed.
- Characterisation of the study areas including a description of topology and surface water hydrology (and chemistry), climate, land use, and hydrogeological conceptualisation.
- Review of the sampling and analysis program; its effectiveness, quality and recommendations for any required changes.
- Statement of the quality of the hydrogeochemical data by reviewing ion balances, and blank and duplicate results.
- Characterisation of the nature of the groundwater chemistry; examining the source of solutes and the hydrogeological processes which affect its composition and variability with space and time. This may include the following:
  - Use of graphics, cross-sections, and maps to effectively represent the nature of the groundwater chemistry and to allow for the easy identification of spatial and temporal trends.
  - Ion ratio assessment to determine the extent of water-rock interaction.
  - Reaction path hydrogeochemical modelling.
  - Trend analysis.

- Examine the water quality results against water quality guidelines, targets and beneficial use classes. Identify any hazards observed in certain determinant concentrations or ion imbalances.
- Examine the influence of groundwater extraction on water quality processes using a variety of techniques in all six study areas, and using numerical groundwater flow modelling in the Lower Murrumbidgee study area only.
- Assessment and statement of risks to groundwater quality, its causes and recommendations for addressing those risks. This shall include advice relating to moving towards an ability to predict water quality change given a small range.
- Undertake a review of how numerical modelling can be used to estimate groundwater quality change under planned groundwater management scenarios, namely:
    - What technologies are techniques are available for predicting groundwater salinity/quality changes?
    - Can NOW's current MODFLOW models be readily coupled with solute transport and/or particle tracking techniques to allow salinity prediction?
    - What data would be needed to allow groundwater quality predictions?
- Use numerical groundwater flow modelling in the Lower Murrumbidgee study area only to analyse salt fluxes by coupling net fluxes (water balance) for each cell screened by a project monitoring (or pumping) bore for the 2009 to 2020 period with EC data.
- Recommendations for future water quality monitoring and studies.

1.4 Report structure

This document provides a comprehensive technical report on the hydrogeochemistry and water quality risks posed by groundwater pumping on groundwater quality in six of the large alluvial aquifers in inland NSW. This report collates chemistry data (field parameters, major ions, trace metals and other analytes) and stable isotope data (oxygen-18 and deuterium) collected during the 2009–2011 sampling program, historical water quality data, historical and current water level data, climate data from the six alluvial catchments and provides an assessment of the chemical composition of groundwater and the risks to water quality posed by pumping. The structure of the report is as follows:

- **Section 1**: provides an introduction to the project, and project scope and objectives.
- **Section 2:** presents the methodology used to undertake hydrogeochemical interpretation, trend assessment and numerical modelling (Lower Murrumbidgee only).
- **Section 3:** discusses the sampling and analysis program, and provides a review of laboratory QA/QC data.
- **Section 4:** presents a climatic and hydrogeological characterisation of the Upper Namoi GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 5:** presents a climatic and hydrogeological characterisation of the Lower Namoi GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 6:** presents a climatic and hydrogeological characterisation of the Lower Macquarie GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 7:** presents a climatic and hydrogeological characterisation of the Lower Lachlan GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 8:** presents a climatic and hydrogeological characterisation of the Lower Murray GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 9:** presents a climatic and hydrogeological characterisation of the Lower Murrumbidgee GMA, characterisation of groundwater chemistry, trend assessment and analysis of risks to groundwater quality, and recommendations for future water quality monitoring and studies.

- **Section 10:** presents the results of the numerical modelling trial and recommendations for future modelling.

- **Section 11:** presents the key findings of the current study and recommendations for future monitoring and investigation.

2. Methodology

2.1 Background information on field and laboratory program

2.1.1 Study locations and bore selection

The project is focussed on areas of major groundwater extraction in the Murray-Darling Basin of NSW. Six areas of investigation have been selected where groundwater of marginal quality occurs near either fresh surface or groundwater resources. Study areas selected for study include:

- Lower Namoi GMA (Cryon)
- Upper Namoi GMA, Zone 3 (Breeza)
- Lower Macquarie GMA (Narromine)
- Lower Lachlan GMA (Hillston)
- Lower Murrumbidgee GMA (Hay)
- Lower Murray GMA (Deniliquin)

Groundwater sampling bores were selected from each GMA by the NSW Office of Water (NOW) regional hydrogeologists. NOW monitoring bores and private extraction bores were selected. Monitoring bores were selected with consideration of a number of requirements including:

- Monitoring bores should be in an area covered by an existing groundwater flow model or have sufficient data to develop one easily.
- Monitoring bores should be in an area with either a local scale (about 10–20 km) or a regional scale (about 50–100 km).
- The targeted groundwater should have significant natural water quality variation, and/or be where aquifers of differing quality are or may be induced to interact under pumping stress.
- Approximately 30 monitoring bores and 10 production bores should be identified for each study area.
- The monitoring bores should be less than 2 km from a production bore.
- The coverage of bores should be sufficient to characterize the aquifer.
- The site should be able to be sampled over 5 day duration (approximately).

2.1.2 Determinant selection

Parsons Brinckerhoff was commissioned by the NOW in 2009 (PB 2009) to scope the components of this projects groundwater sampling program and provide advice on the chemical analyses required to meet the project objectives. The factors considered included the relevance of chemical constituents to the issues being investigated, the acceptable precision and the cost of collection and analysis.

A broad suite of constituents were chosen including major ions, trace metals, nutrients and stable isotopes (NOW 2011).

2.1.3 Sampling strategy

Parsons Brinckerhoff designed a detailed sampling strategy for the NOW, to ensure sample representativeness and sample integrity in the program. The strategy included: decontamination and bore purging techniques, instrument calibration, sample bottle selection, preservation methods and QA/QC processes (PB 2009). All NOW staff involved in field sampling activities undertook hands-on training by Parsons Brinckerhoff.

The sampling program was carried out by NOW personnel. Water level measurements were recorded prior to purging and sampling. Monitoring bores were purged and sampled using one of three methods:

- Grundfos MP1 submersible pump
- A specially designed low flow pump, a micro-purge™ system
- Bailer

Monitoring bores were purged prior to sampling to remove any stagnant water within the bore, allowing a representative groundwater sample from the aquifer to be collected. Purging usually involved the removal of a minimum of two to three bore volumes from the monitoring bore.

The physical parameters of the pumped groundwater were measured during purging to indicate the presence of natural groundwater suitable for sampling and analysis. The following physical parameters of the water were measured using a calibrated water quality meter:

- Electrical Conductivity (EC) – µS/cm
- Temperature – ^{o}C
- pH - pH units
- Oxidation/reduction potential (ORP) – mV (selected monitoring rounds only)

Readings of field parameters were recorded after stabilisation. Samples were collected in plastic bottles and filtered through 0.45 µm cellulose acetate membrane filters for metals and cations samples. Samples for metals were preserved with nitric acid (HNO_3) to a pH less than 2. Samples were kept chilled from the time of sampling to the time of analysis.

2.1.4 Laboratory analysis

Groundwater and surface water samples were sent to the NOW Laboratory at Arncliffe, Sydney, for chemical analysis, and to CSIRO Land and Water Isotope Laboratory, Adelaide, South Australia for stable isotope analysis. A small batch of samples was also sent to the UNSW's Manly Vale Water Laboratory for stable isotope analysis. The analytical suite is listed in Table 2-1.

Table 2-1 Analytical suite

Analyte	Method	Limit of Reporting (LOR)
Water quality parameters (field)		
pH	Field meter	0.01 pH unit
Conductivity (compensated to 25°C)	Field meter	1 µS/cm
Temperature	Field meter	0.1ºC
Redox potential	Field meter	0.1 mV
Water quality parameters (lab)		
pH	pH probe	0.01 pH unit
Electrical conductivity	EC probe	1 µS/cm
Total dissolved solids	Details not provided by lab	5 mg/L
Major elements (soluble)		
Calcium	ICP-AES Lab	1 mg/L
Magnesium	ICP-AES Lab	1 mg/L
Potassium	ICP-AES Lab	1 mg/L
Sodium	ICP-AES Lab	1 mg/L
Sulphate	IC Lab	1 mg/L
Chloride	Mohrs Method Lab	1 mg/L
Silica (reactive)	Determined from Silicon (ICP-AES Lab)	0.1 mg/L
Alkalinity		
Carbonate as CO_3	PC titrator – lab	0.1 mg/L
Bicarbonate as HCO_3	PC titrator – lab	1 mg/L
Measured alkalinity as $CaCO_3$	PC titrator – lab	1 mg/L
Nutrients		
Oxidised nitrogen as N	Colorimetry – Lab	
Nitrate as N	Colorimetry – Lab	0.1 mg/L
Ammonia as N	Colorimetry – Lab	0.01 mg/L
Total Nitrogen as N	Colorimetry – Lab	0.1 mg/L
Phosphorus – Reactive	Discrete analyser – Lab	0.001 mg/L
Phosphorus – Total P	Discrete analyser – Lab	0.001 mg/L
Iron		
Iron – total	ICPMS Lab	
Iron – ferrous	Colorimetric	0.05 mg/L
Trace elements		

Analyte	Method	Limit of Reporting (LOR)
Aluminium (Soluble and Total)	ICPMS Lab	0.01 mg/L
Boron (Soluble and Total)	ICPMS Lab	0.1 mg/L
Bromide	IC Lab	0.1 mg/L
Copper (soluble and total)	ICPMS Lab	0.001 mg/L
Fluoride	IC Lab	0.1 mg/L
Iron (soluble and total)	ICPMS Lab	0.05 mg/L
Lead (soluble and total)	ICPMS Lab	0.002 mg/L
Lithium	ICPMS Lab	0.1 mg/L
Manganese (soluble and total)	ICPMS Lab	0.001 mg/L
Nickel (soluble and total)	ICPMS Lab	0.002 mg/L
Strontium	ICPMS Lab	0.001 mg/L
Zinc (soluble and total)	ICPMS Lab	0.005 mg/L (soluble); 0.01 mg/L (total)
Isotopes		
Oxygen-18	Stable isotope gas ratio Mass spectrometer	0.1‰
Deuterium	Stable isotope gas ratio mass spectrometer	0.01‰

2.1.5 QA/QC procedures

Quality control samples are important for a sampling program as they indicate the quality of the sampling procedure and allow reliable conclusions to be drawn. The QA/QC process included the use of blanks and duplicates. Blanks include Trip Blanks which are supplied by the laboratory. The container is opened in the field for a similar period of time as is required to take sample and is an indicator of contamination introduced during sampling. Filtration blanks are collected by passing distilled water through the filter in the field and provides an assessment of contamination during filtration.

The collection of duplicate samples provides information about the quality of the repeatability of laboratory analytical procedures or sampling precision. Collecting a duplicate sample involves the collection and analysis of a blind separate sample from the same sample locality (AS/NZS 5667:1.1998).

Comparison of the duplicate sample with the primary sample can be undertaken by using the relative percentage difference (RPD) of the two values. This provides the difference between the two values as a percentage. The RPD of the two values, x_1 and x_2, is calculated by dividing the absolute difference by the average value of the same two values as shown in the following equation:

$$Relative\ Percent\ Difference\ (RPD) = \frac{Result\ No.1 - Result\ No.2}{Mean\ of\ Result\ No.1 + Result\ No.2}\ x\ 100$$

2.2 Review of sampling program and data quality

Prior to data analysis each catchment's data set was assessed for data reliability. The ionic balance of each sample was determined using the following equation:

Ionic balance = (sum of cations + sum of anions)/(sum of cations – sum of anions) x100

where cations and anions are expressed as meq/L.

The cations used in the equation included sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}); and the anions included chloride (Cl^-), bicarbonate (HCO_3^-), carbonate (CO_3^-) and sulphate (SO_4^{2-}). Samples with an ionic balance of greater than 10% were not included in the data analysis.

2.3 Characterisation of study areas

The six study areas were characterised in terms of topography, surface hydrology, climate, land use, geology and hydrogeology. Information on these topics for each catchment was sourced from a variety of reference documents including NOW groundwater status reports, technical reports by scientific agencies such as CSIRO, research papers, doctorates of philosophy and climate information from the Bureau of Meteorology (BoM).

Climate information for each study area included rainfall data from two BoM monitoring stations, typically located on opposite sides of each catchment. Long-term cumulative rainfall and monthly rainfall for 2009, 2010, 2011 and average monthly rainfall were plotted.

Long-term cumulative rainfall residual plots are formulated by subtracting the average monthly rainfall from the actual rainfall and then accumulating these residuals over the assessment period. Periods where the cumulative rainfall residual slopes downward correspond to below average rainfall. The steepness of the cumulative residual line reflects the relative magnitude of the departure from average conditions

2.4 Characterisation of groundwater chemistry

Groundwater chemistry was characterised for each of the six study areas by analysis of the chemistry results and interpretation of hydrogeochemical processes. Groundwater chemistry results were analysed through the development of water quality report cards for each monitoring location and stable isotope results were plotted against global and local (where available) meteoric water lines. The processes in each study area were interpreted through the development of major ion/chloride versus chloride graphs, aqueous speciation modelling and ion exchange graphs.

Water quality report cards

A water quality 'report card' has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report card contains the following:

- Piper diagram – The Piper diagram (Piper 1944) displays the relative concentrations of the major cations and anions on two separate tri-linear plots, together with a central quadrilateral field where the points from the two tri-linear plots are projected to show the overall chemical character of the water. Piper diagrams can also be used to show situations where groundwater samples fall on trend lines between key water quality groupings. Such mixing lines will suggest the process of mixing of groundwaters between different aquifers.

- Wilcox diagram – The Wilcox diagram (Wilcox 1948) was devised as a diagram for classifying irrigation waters in terms of salinity and sodicity hazards. The salinity hazard has been divided into four categories on the basis of conductivity while sodium has been divided into four categories based on the probable extent of its adsorption by soil from the water and the rate at which adsorption will occur if the water is applied.

Each report card provides an assessment of water type and documents any change in major ion chemistry during the study period (2009–2011), and EC and water level over the entire length of monitoring (including historical data). An assessment of the salinity and sodicity hazard and beneficial use classification is also included. Water quality report cards for each GMA are provided in Appendices B to G.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for a subset of samples from five out of the six catchments. Stable isotopes were not analysed for the Lower Macquarie catchment.

Stable isotopes in water, ^{18}O and ^{2}H, are affected by meteorological processes that provide a characteristic fingerprint of their origin. This fingerprint is fundamental to investigating the provenance of groundwater. Stable isotopes are used routinely in groundwater investigations and can provide information not only on groundwater provenance, but also recharge, inter-aquifer mixing, water-rock interaction and origin of salinity.

As the concentrations are very small, isotope results are reported as a ratio between one isotope to another (for example $^{18}O/^{16}O$) in the sample and the standard. Conventionally, the ratio is always reported as the heavier isotope to the lighter element. Delta, δ represents the difference between the sample and standard, and is reported in units of per mil, ‰ (parts per thousand). The isotopic composition of a species is defined by the following equation:

$$\delta(‰) = \frac{R_{sample} - R_{standard}}{R_{standard}} \text{x}1000$$

where R is the isotopic ratio given by the number of atoms for the two isotopes.

The two most common stable isotopes of oxygen are ^{18}O and ^{16}O, which have a terrestrial abundance of 0.204% and 99.796%, respectively. Oxygen isotope compositions are commonly reported relative to an agreed sample of ocean water, the international standard referred to as the Standard Mean Ocean Water (SMOW).

$$\delta^{18}O = \frac{\left(^{18}O/^{16}O\right)_{sample}}{\left(^{18}O/^{16}O\right)_{reference}} x1000‰\ VSMOW$$

Hydrogen also has two stable isotopes, ^{1}H and ^{2}H (deuterium) with relative natural abundance percentages of 99.984% and 0.015%, respectively. Thus the delta values for deuterium expressed as permil are:

$$\delta^2 H = \frac{\left({}^2H/{}^1H\right)_{sample}}{\left({}^2H/{}^1H\right)_{reference}} x1000‰\ VSMOW$$

Most of the world's precipitation originates from the evaporation of seawater. As a result, the oxygen-18 and deuterium composition of precipitation throughout the world are linearly correlated and distributed along the global meteoric water line (GMWL) ($\delta^2H = 8.13\delta^{18}O + 10.8$) (Rozanski et al. 1993) and provides a useful benchmark against which regional or local waters can be compared and their isotopic composition interpreted. Local meteoric water lines (LMWL) can be established from isotopic analysis of local precipitation events, and for this study LMWL were sourced from several references for comparison to groundwater samples in each catchment.

Stable isotopes were analysed by CSIRO Land and Water Isotope Laboratory in Adelaide, South Australia, and the University of New South Wales Water Research Laboratory at Manly Vale, NSW.

Stable isotopes results for each catchment were compared to rainfall values and where information was available, to surface water to assess groundwater provenance, recharge and inter-aquifer mixing. Since δ^2H and $\delta^{18}O$ are conservative tracers, the mixing ratio may be deduced if the isotopic signatures of end members are known (Clark and Fritz, 1997).

Major ion/chloride versus chloride plots

Major ion/chloride versus chloride plots can be used to identify whether changes in groundwater chemistry are associate with: mixing of waters with different ion/chloride ratios, water-rock interactions and/or evapotranspiration. Chloride is typically assumed to be a conservative ion in groundwater systems, not participating in geochemical reactions and remaining in the system. Evapotranspiration of the initial water with low Chloride concentration would therefore be expected to result in a horizontal line on major ion/chloride versus chloride plot.

Major ion/chloride versus chloride plots were developed for sodium, potassium, calcium, magnesium, bicarbonate and sulphate ions in AquaChem v 5.1. Groundwater samples were compared with the relevant seawater ratios for each ion, to identify processes affecting ion/chloride ratios.

Aqueous speciation modelling

Aqueous speciation modelling computes the degree of saturation of an aqueous solution with respect to various minerals and also other thermodynamic properties including the molalities and activities of aqueous species. Speciation modelling was performed using the computer modelling code PHREEQC 2.4.2 (Parkhurst and Appelo 1999). The program uses ion association models to calculate thermodynamic properties of aqueous solutions. The ionic strength is computed from:

$$I = ½\Sigma mizi^2$$

where mi and zi are the molality and charge, respectively, of the *ith* ion. The ionic strength is then used to calculate the activity of each ion according to the WATEQ4F Debye Huckel equation (Parkhurst and Appelo 1999).

Following on from the speciation calculation the ion activity product (IAP) can be compared to the solubility product (Ksp) to test for mineral saturation. The saturation index, SI, is computed for each mineral in the database from:

$$SI = log\frac{IAP}{Ksp}$$

If the saturation index is less than zero, the mineral is undersaturated with respect to the solution and the mineral might dissolve. Conversely, positive values of SI indicate supersaturation and the tendency of the water to precipitate that mineral. A value of SI that equals zero indicates apparent equilibrium, a balance between the thermodynamic forces of precipitation and dissolution.

Thermodynamic parameters including ion activities, dissolved inorganic carbon (DIC), total alkalinity, log pCO_2, and saturation indices of carbonate minerals, iron and manganese oxides and oxyhydroxides were chosen as selected output.

Saturation indices were calculated for each catchment based on the known or likely anticipated mineralogy of aquifer sediments. Saturation indices were calculated to determine the likely precipitation and dissolution processes affecting the geochemical evolution in these groundwater systems.

Ion exchange graphs

Ion exchange graphs, where Ca+Mg is plotted versus SO_4+HCO_3 with a 1:1 dissolution line, were developed in AquaChem v 5.1. Groundwater samples were assessed based on their location on the plot and their relation to the 1:1 dissolution line. Groundwater samples that plot below the 1:1 dissolution line indicate depleted calcium + magnesium values with respect to bicarbonate + sulphate and may indicate ion exchange processes. Samples that plot above the dissolution line may indicate reverse ion exchange processes.

Mixing

Ion/Cl graphs, Piper diagrams and stable isotope graphs were analysed to identify potential groundwater end members and mixing between aquifers. Mixing calculations were undertaken where possible for monitoring bores that were identified as having a long term increasing salinity trend.

Binary mixing calculations were undertaken taken using conservative tracers of either Cl or ^{18}O, according to the equation:

$$[Cl_F] = (1-X)[Cl_I] + (X)[Cl_A]$$

Where X is the volumetric proportion of the second end member in the final solution and [Cl] is the dissolved Cl^- concentrations in each end member.

2.5 Analysis of risks to groundwater quality

2.5.1 Beneficial use

The NSW Government has recognised the need for ecologically sustainable management of the State's groundwater resources. This can be achieved through implementation of the State Groundwater Policy Framework Document (DLWC 1997) and its component policies, including the Groundwater Quality Protection Policy (DLWC 1998). One of the management principles of the Groundwater Quality Protection Policy that ensures that the Policy objectives will be achieved is that "all groundwater systems should be managed such that their most sensitive identified beneficial use (or environmental value) is maintained".

The NSW Groundwater Quality Protection Policy provides a framework for sustainable management of groundwater quality through adopting a beneficial use classification system that will be the basis for setting all water quality objectives for all groundwater systems in NSW (DLWC 1998).

Beneficial uses can include:

- Ecosystem protection
- Recreation and aesthetics
- Agricultural water (irrigation, livestock drinking water)
- Raw water for drinking water supply
- Industrial water.

Water quality criteria are available for each beneficial use defined in the Water Sharing Plans in the Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000) and the Australian Drinking Water Guidelines 2011 (NHMRC 2011). Each beneficial use has a unique set of water quality criteria. The term "Water Quality Criteria" refers to a list of the critical concentrations of contaminants in water that must not be exceeded if a given beneficial use is to be sustained (DLWC 1998).

Water Sharing Plans for the six studied groundwater management areas were used in assessing beneficial use of the relevant aquifers:

- *Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources 2003*
- *Water Sharing Plan for the Lower Macquarie Groundwater Sources 2003*
- *Water Sharing Plan for the Lower Lachlan Groundwater Sources 2003*
- *Water Sharing Plan for the Lower Murray Groundwater Source*
- *Water Sharing Plan for the Lower Murrumbidgee Groundwater Sources 2003*

In particular, the water quality objectives and water quality management sections of each plan are used in the corresponding GMA sections of this report. Beneficial use was defined differently within each of the water sharing plans as follows:

- Upper and Lower Namoi WSP – 'The beneficial uses of this groundwater source are raw water for drinking, and irrigation, based on beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996. It is not recommended that the water from this groundwater source be consumed without prior treatment. Land use activities may have polluted the groundwater in some areas.'
- Lower Macquarie – 'The EC limits adopted for this Plan for the beneficial use categories are as follows:

  (a) 800 EC for Raw Drinking Supplies Class; and

  (b) 1,500 EC for Agricultural Water Class.'
- Lower Lachlan – 'The EC limits adopted for this Plan for the beneficial use categories are as follows:

  (a) 800 EC for Raw Drinking Supplies Class; and

  (b) 1,500 EC for Agricultural Water Class.'
- Lower Murray – 'Local access rules may be applied if the aquifer baseline salinity exceeds 650 EC and there is an increase in salinity over a three year period of either 20% or more, or 500 EC or more.'
- Lower Murrumbidgee – 'The beneficial uses of these groundwater sources, based on the beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996, are

  (a) ecosystem protection and agricultural water for the Shallow Groundwater Source, and

  (b) raw water for drinking, ecosystem protection and agricultural.'

Each Water Sharing Plan states that 'water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class'. Therefore as part of this study, the current beneficial use for each aquifer in each catchment has been assessed, and where historical data is available, compared to the historical beneficial use. Areas where there has been a deterioration in water quality leading to a change in beneficial use have been highlighted.

National Health and Medical Research Council guidelines for drinking water have recently been updated in October 2011; therefore, water quality results herein are compared to the current guidelines. Water quality data for all catchments has also be compared to the Australian and New Zealand Environment Conservation Council (ANZECC) (2000), Australian and New Zealand Guidelines for Fresh and Marine Water Quality – Chapter 4 Primary Industries to assess suitability of groundwater for beneficial uses of irrigation and stock water supply.

One of the main indicators to define water quality for each beneficial use is salinity. The salinity thresholds for each beneficial use are given in Table 2-2.

Table 2-2 Salinity criteria for key beneficial use

Beneficial use		TDS (mg/L)	EC (µS/cm)[3]	Comment
Livestock[1]	3,000–19,400	5,000–10,000	7,460–14,925	Loss of production and decline in health of beef cattle
		4,000–7,000	5,970–10,450	Loss of production and decline in health of dairy cattle
		10,000–13,000	14,925–19,400	Loss of production and decline in health of sheep
		6,000–7,000	8,955–10,450	Loss of production and decline in health of horses
		6,000–8,000	8,955–11,940	Loss of production and decline in health of pigs
		3,000–4,000	4,478–5,970	Loss of production and decline in health of poultry
Irrigation[1]	1,500–8,000	5,160	7,700	Unsuitable for cotton irrigation
		1,000	1,500	If used on early season cotton, final yields could be diminished
		4,020	6,000	Unsuitable for wheat irrigation
		5,360	8,000	Unsuitable for barley irrigation
		4,555	6,800	Unsuitable for sorghum
		3,350	5,000	Unsuitable for soybeans
		1,140	1,700	Unsuitable for oranges
		2,010	3,000	Unsuitable for rice
		1,140	1,700	Unsuitable for corn
		1,005	1,500	Unsuitable for grapes
		2,145	3,200	Unsuitable for peaches
		1,540	2,300	Unsuitable for tomatoes
		1,875	2,800	Unsuitable for broccoli
Drinking water[2]	0–1,800	<600	900	Good quality drinking water
		600–900	900–1,350	Fair quality drinking water
		900–1,200	1,350–1,800	Poor quality drinking water
		>1,200	>1,800	Unacceptable quality

[1] From Australian and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC 2000), Chapter 4 Primary Industries; [2] From Australian Drinking Water Guidelines 2011;
[3] EC values calculated form TDS concentration using the equation: EC (µS/cm) x 0.67 = TDS (mg/L)

However, salinity is not the only indicator required to assess beneficial use, other major water quality criterion are required to be assessed. The NHMRC (2011) guidelines for drinking water and the ANZECC (2000) guidelines for irrigation and livestock are discussed in the following sections.

2.5.1.1 Drinking water

The Australian Drinking Water Guidelines (NHMRC 2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the current program are provided in Table 7-2. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary.

Table 2-3 Australian Drinking Water Guideline (2011) values

Analyte	Health guideline value	Aesthetic guideline value	Comments
pH (pH units)		6.5–8.5	While extreme pH values (<4 and >11) may adversely affect health, there is insufficient data to set a health guideline value.
Total dissolved solids (mg/L)		600	Based on taste: <600 mg/L is good quality 600–900 mg/L is fair quality 900–1,200 mg/L is poor quality >1,200 mg/L is unacceptable
Calcium (mg/L)			
Magnesium (mg/L)			
Sodium (mg/L)		180	
Potassium (mg/L)			
Chloride (mg/L)	a	250	
Sulphate (mg/L)	500	250	
Bicarbonate (mg/L)			
Silica (mg/L)		80	
Fluoride (mg/L)	1.5		
Aluminium (mg/L)	b	0.2	
Boron (mg/L)	4		
Bromide (mg/L)			
Copper (mg/L)	2	1	
Iron (mg/L)	b	0.3	
Manganese (mg/L)	0.5	0.1	
Strontium (mg/L)			
Zinc (mg/L)	b	3	Taste problems >3 mg/L
Nitrate (as nitrate) (mg/L)	50		Guideline value will protect bottle-fed infants less than three months from methaemoglobinaemia. Adults and children over three months can safely drink water with up to 100 mg/L nitrate.
Ammonia (as NH_3) (mg/l)	b	0.5	
Total Nitrogen as N (mg/L)			

Analyte	Health guideline value	Aesthetic guideline value	Comments
Total Phosphorus (mg/L)			
Reactive phosphorus (mg/L)			

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

2.5.1.2 Irrigation

To assess the quality of water for irrigation it is necessary to consider salinity, SAR, and toxicity of specific ions such as boron, sulphate, chloride and sodium. A classification scheme was devised by Wilcox (1948) for classifying irrigation waters based on salinity (EC) and sodium (SAR). The SAR is indicative of excessive sodium that may result in nutrient competition and ion sensitivity in plants and soil sodification. This ratio is defined by the following equation:

$$SAR = Na^{+} \div \sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}$$

In the Wilcox diagram, the salinity hazard has been divided into four categories on the basis of conductivity while sodium has been divided into four categories based on the probable extent of its adsorption by soil from the water and the rate at which adsorption will occur if the water is applied. An explanation of the categories is provided in Table 2-4.

Table 2-4 Salinity Hazard categories

TDS	EC (μS/cm)	Class	Remarks
<200	<250	C1	Low salinity water – can be used for most irrigation with most crops on most soils with little likelihood that a salinity problem will develop. Some leaching is required but this occurs under normal irrigation practices except in soils of extremely low permeability.
200–250	250–750	C2	Medium salinity water – can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most instances without special practices for salinity control.
500–1,500	750–2,250	C3	High salinity water – cannot be used on soils with restricted drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.
1,500–3,000	2,250–5,000	C4	Very high salinity water – is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. The soil must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching and very salt tolerant crops should be used.

Table 2-5 Sodium Hazard categories

SAR	Class	Remarks
0–10	S1	Low sodium water can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium sensitive crops such as stonefruit trees and avocado may accumulate injurious concentrations of sodium.
10–18	S2	Medium sodium water will present an appreciable sodium hazard in fine textured soils having a high cation exchange capacity, especially under low leaching conditions, unless gypsum is present in the soil.
18–26	S3	High sodium water may produce harmful levels of exchangeable sodium in most soils and will require special soil management – good drainage, high leaching and organic matter additions.
>26	S4	Very high sodium water is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the dissolving of calcium from the soil or the use of gypsum or other additives may make the use of these waters feasible.

It is also necessary to assess the sensitivity of specific crops to salinity, sodium and other specific ions including chloride and boron. At certain levels specific ions become toxic to plants by limiting the water availability to plants. The most commonly recognised toxic ions of irrigation water are chloride, sodium and boron. Boron is a constituent of all natural waters and is essential to plant growth in relatively small amounts. It is exceedingly toxic at concentrations only slightly above optimum. Boron is often present at toxic levels in saline soils. The ANZECC (2000) guidelines (Chapter 4 Primary Industry) provide a guideline value of 0.5 mg/L the long-term trigger value (LTV) in irrigation water (use up to 100 years).

Chloride is toxic because it is highly mobile in the soil-plant system and is readily adsorbed by plants because of its high solubility. It is accumulated in plant foliage and severe toxicity results in defoliation. The ANZECC (2000) guideline values for chloride are given in Tables 2-6 and 2-7.

Table 2-6 Chloride and sodium concentrations (mg/L) causing foliar injury in crops of varying sensitivity

Sensitive <175 (chloride) <115 (sodium)	Moderately sensitive 175–350 (chloride) 115–230 (sodium)	Moderately tolerant 350–700 (chloride) 230–460 (sodium)	Tolerant >700 (chloride) >460 (sodium)
Almond Apricot Citrus Plum Grape	Pepper Potato Tomato	Barley Maize Cucumber Lucerne Safflower Sorghum	Cauliflower Cotton Sugar beet Sunflower

Table 2-7 Risks of increasing cadmium concentrations in drops due to chloride in irrigation waters

Irrigation water chloride concentration (mg/L)	Risk of increasing crop cadmium concentrations
0–350	Low
350–750	Medium
>750	High

Sodium toxicity is difficult to recognise and most field crops can tolerate a much higher concentration of sodium in their foliage. However, in sensitive crops, sodium toxicity can result in leaf burn and defoliation. Trigger values for sodium in irrigation water are provided in Table 2-6.

2.5.1.3 Stock

One of the main indicators to define water quality for stock is salinity. The salinity thresholds for the different types of stock, as per the ANZECC (2000) guidelines (Chapter 4 Primary Industry) are presented in Table 2.2. For livestock, if TDS concentration is greater than 2,400 mg/L, the water should also be analysed for concentrations of specific ions, as presented in Table 2-8.

Table 2-8 ANZECC (2000) Guidelines – Chapter 4 Primary Industries

Analyte	Guideline value
Calcium (mg/L)	<1,000
Magnesium (mg/L)	<2,000
Sulphate (mg/L)	<1,000
Fluoride (mg/L)	2
Aluminium (mg/L)	5*
Boron (mg/L)	5*
Copper (mg/L)	0.4–5*
Iron (mg/L)	Not sufficiently toxic
Manganese (mg/L)	Not sufficiently toxic
Zinc (mg/L)	20
Nitrate (as nitrate) (mg/L)	<1,500

*Recommended water quality trigger values (low risk) for heavy metals and metalloids in livestock drinking water.

2.5.2 Trends

A detailed analysis of groundwater quality and groundwater level trends was undertaken to determine seasonal or long term trends in water quality (primarily EC) related to pumping (and possibly climatic conditions). Changes in salinity for the study period (September 2009 - 2011) and for long-term data (where available) were assessed using:

- Mann Kendall analysis – The Mann Kendall test is a parametric statistical test that can be used to show whether concentrations of a particular analyte in a monitoring well are increasing, decreasing or stable.
- Rates of change in salinity, determined by gradients of line of best fit for plotted data, and expressed as a change in EC µS/cm per year for long-term data, and as a change in EC µS/cm per month for the study period (September 2009–January 2011).
- Percentage changes between first and last EC values.

A risk to groundwater quality was perceived where short-term and long trends showed an increasing salinity (EC) trend, where there had been a change in beneficial use, or where there had been a change in water type.

2.6 Numerical groundwater modelling

Development of a method for predicting potential trends in groundwater quality from groundwater fluxes derived from the Lower Murrumbidgee MODFLOW model is part of the project scope. Details of the modelling methodology are therefore presented in Section 10.

3. Review of sampling program and data quality

3.1 Review of sampling and analysis program

3.1.1 Sampling program

Two sets of water quality data have been combined for the current study; those collected and analysed specifically for the project from September 2009 to early 2011, and those acquired from 1971 to late 2009. The Lower Murrumbidgee catchment also includes additional data from Timms (2001) and Bell (2007) and NSW Office of Water microfiche data ranging between 1973 and 1986. The number of samples for each dataset is summarised in Table 3.1 and the complete data set is available electronically in Appendix A (CD).

Table 3-1 Summary of NSW Office of Water data

Catchment	No. bores	No. project sampling rounds	Project samples	Total samples	Date range
Upper Namoi	24	13	170	259	Nov 99 – Jan 11
Lower Namoi	22	13	221	1,395	Feb 93 – Jan 11
Lower Macquarie	7	8	26	54	Jan 03 – Sep 10
Lower Lachlan	34	16	229	403	Aug 00 – Feb 11
Lower Murray	43	16	308	1,828	Mar 73 – Jan 11
Lower Murrumbidgee	42	15	323	405	Jul 03 – Dec 10

Monthly sampling was to be undertaken in each catchment for the duration of the project (18 months). None of the catchments were monitored for the full 18 months (Table 3-1).

The Lower Macquarie catchment had the least sampling rounds for the project, with only eight rounds. The first round (September 2009) monitored all seven groundwater bores, and two sampling rounds (April and July 2010) only monitored one groundwater bore each.

The following catchments had one sampling round where only one groundwater bore was monitored:

- The Upper Namoi catchment in July 2010.
- The Lower Namoi catchment in November 2010.
- The Lower Lachlan catchment in January 2011.

The Lower Murray catchment typically had at least 19 groundwater bores monitored per sampling round. The lowest number of groundwater bores monitored was eight in the January 2010 round.

The Lower Murrumbidgee catchment had approximately 20 groundwater bores monitored per sampling round. The lowest number of groundwater bores monitored was seven in the 7 October 2010 round.

Field parameters

Field parameters including pH, electrical conductivity, oxidation reduction potential and temperature were not recorded on several occasions in all the catchments. The sample numbers for each parameter are provided in the statistics tables for each catchment in the following Sections: 4.2, 5.2, 6.2, 7.2, 8.2 and 9.2.

Electrical conductivity (EC) was measured in the laboratory for each sample. Laboratory EC values have primarily been used in this study for data consistency and a comprehensive data set. Laboratory EC for some samples in the Lower Murrumbidgee catchment varied from calculated values (calculated from major ion concentrations) and EC values recorded in the field. It was determined that on several occasions the laboratory EC was incorrect for Lower Murrumbidgee samples. On these occasions the field EC was used.

3.1.2 Analysis program

Prior to data analysis each catchment's data set was assessed for data reliability by calculating the ionic balance. Samples with an ionic balance of greater than 10% were not included in the data analysis.

A total of 24 samples were excluded from further major ion analysis because of unacceptable charge balances. This equates to 0.6% of the total sample set and is considered to be a good result for a sampling program of this size. A summary of the data sets and ionic balances are presented in Table 3.2 and samples excluded from further analysis for each catchment are presented in Table 3.3.

Table 3-2 Summary of ionic balance assessment

Catchment	No. bores	No. samples	Ionic balance % (range)	No. samples excluded
Upper Namoi	24	259	-23.91 – 21.43	5
Lower Namoi	22	1395	-40.4 – 21.7	6
Lower Macquarie	7	54	-6.79 – 4.45	0
Lower Lachlan	34	403	-34.62 – 43.66	8
Lower Murray	43	1828	-10.17 – 6.32	1
Lower Murrumbidgee	42	405	-39.35 – 99.23	4

Table 3-3 Samples excluded from further analysis based on ionic balance

Catchment	Bore ID	Sample date
Upper Namoi	▪ GW036038_3 ▪ GW036213_2 ▪ GW902011_1 ▪ GW030431_2 ▪ GW030431_1	▪ 12/11/2009 ▪ 12/11/2009 ▪ 13/11/2009 ▪ 11/01/2010 ▪ 28/10/2010
Lower Namoi	▪ GW036364_1 ▪ GW036314_3 ▪ GW036340_3 ▪ GW036364_2 ▪ GW036364_3 ▪ GW036320_1	▪ 17/08/2000 ▪ 7/10/2009 ▪ 20/04/2010 ▪ 5/07/2010 ▪ 5/07/2010 ▪ 6/07/2010
Lower Macquarie	▪ None	▪ None
Lower Lachlan	▪ GW030405_2 ▪ GW090085_4 ▪ GW090085_5 ▪ GW036304_1 ▪ GW030406_1 ▪ GW030173_3 ▪ GW090085_5 ▪ GW030406_1	▪ 6/04/2010 ▪ 14/04/2010 ▪ 14/04/2010 ▪ 15/04/2010 ▪ 15/04/2010 ▪ 9/11/2010 ▪ 17/11/2010 ▪ 7/12/2010
Lower Murray	▪ GW036743_2	▪ 23/05/2008
Lower Murrumbidgee	▪ GW036275_1 ▪ GW030323_1 ▪ GW041011_2 ▪ GW273040_2	▪ 31/07/1979 ▪ 16/12/1986 ▪ 24/09/2009 ▪ 23/11/2010

3.2 QA/QC of laboratory data

It was recommended in the ‘Scope of works for hydrogeochemical sampling program – selected NSW sites’ by Parsons Brinckerhoff (2009) that one set of field blanks be taken per field trip (one trip blank and one filtration blank) and that one duplicate be taken for every 20 samples collected. In Sections 3.2.1 and 3.2.2 the field blanks and duplicates collected as part of this study are discussed respectively.

3.2.1 Field blanks

Over the study period (from September 2009 to February 2011) a total of 52 field blanks (including trip and filtration blanks) were collected from the catchments. The recommended frequency of trip and filtration blanks is one of each per trip (Parsons Brinckerhoff 2009). As there were 81 sampling rounds during the study period, an inadequate number of field blanks were collected (a total of 162 field blanks should have been collected).

Field blanks were not labelled with the type of field blank (trip or filtration blank). Furthermore, field blanks were typically not labelled with the catchment they were sampled in, with the exception of eight samples (seven from the Lower Macquarie and one from the Lower Murrumbidgee). All blank samples were analysed for the analytical suite provided in Table 2-1, excluding isotopes, except for the seven blank samples identified from the Lower Macquarie, which were only analysed for five out of the 36 analytes.

Analytical results for all blank samples are provided in Appendix B. Laboratory analysis of water used for blank samples was not conducted prior to the sample being taken in the field. As no initial chemical analysis is available for comparison with the blank samples, it has been assumed that deionised water was used for the field blanks as per the Parsons Brinckerhoff (2009) methodology, and as such the blank results have been compared to the laboratory detection limit for each analyte. Results that are greater than an order of magnitude above the laboratory detection limit for each analyte (excluding sodium which is detected in the majority of the blank samples) have been highlighted.

Excluding the seven samples from the Lower Macquarie catchment, half of the blank samples (22 out of 44) had analytical concentrations an order of magnitude greater than the detection limit (excluding sodium concentrations). This is considered to be a poor result. The reasons for the poor field blank results could include:

- The water used for the field blanks may have contained background concentrations of the analytes tested (i.e. deionised water was not used).
- Trip blanks may have been subject to cross contamination (i.e. poor sample handling and transport techniques).
- Filtration equipment may have been contaminated (i.e. poor sampling technique).
- Laboratory analytical methods may have cross contaminated the blank samples via the laboratory equipment (i.e. poor laboratory technique).
- Laboratory analytical methods may be inaccurate (i.e. inadequate calibration of laboratory instruments).

3.2.2 Field duplicates

In total 31 field duplicate samples were collected and able to be identified in the study period (from September 2009 to February 2011). A further 18 field duplicate samples were analysed, however the data was unusable, as the sampling location was unknown. A summary of the number of samples and field duplicates collected over the study period in each catchment is presented in Table 3-4. The recommended frequency of field duplicates is 1 per 20 samples (Parsons Brinckerhoff 2009). On this basis, the number of field duplicates that could be assessed for all catchments was inadequate.

Table 3-4 Catchment QA/QC details for the study period

Catchment	No. samples	No. duplicates*
Upper Namoi	170	7
Lower Namoi	221	6
Lower Macquarie	26	0
Lower Lachlan	229	6
Lower Murray	308	3
Lower Murrumbidgee	323	9

Note: *duplicates with identified locations

Comparison of the duplicate samples with the primary sample was undertaken using the relative percentage difference (RPD) of the two values (See Section 2.1.5). The RPD for each measured analyte for the duplicate samples is presented in Appendix B.

Each duplicate sample had analytes with an RPD of greater than 20% when compared with the primary sample. The majority of high RPDs were for analytes with low concentrations, near the detection limit, where a difference of one unit, results in a relatively high percentage difference. The duplicate results are considered to be acceptable, and indicate that appropriate sampling techniques have been used when collecting duplicate samples and laboratory analysis was precise.

4. Upper Namoi GMA Zone 3

4.1 Characterisation of the study area

The Upper Namoi GMA is divided into zones on the basis of hydrogeology. This report focuses on hydrogeological information from Zone 3 Mooki Valley – Breeza to Gunnedah (Figure 4-1).

The Upper Namoi Zone 3 catchment is located in north-western New South Wales, extending from Gunnedah in the north-west to Breeza in the south. The Upper Namoi Zone 3 catchment is separated from ‘Zone 8’ to the south by the narrowing of the alluvial valley at Breeza, and the Gunnedah-Tamworth Road forms the northern boundary (DLWC 2000).

4.1.1 Topography and surface hydrology

The Upper Namoi GMA catchment extends from Narrabri in the north to just south of Pine Ridge in the south (DIPNR 2004). The catchment primarily covers areas around the dominant surface hydrology; the Namoi and Mooki Rivers and Cox’s Creek. Elevations range from over 1,000 m in the south, near the Liverpool Ranges, to approximately 200 m on the alluvial floodplains of the catchment (Green et al. 2011).

The Namoi River flows in a westerly direction from its headwaters in the Great Dividing Range. The main tributary of the Namoi River is the Peel River which joins the Namoi River east of Gunnedah. The Mooki River and Cox’s Creek are tributaries of the Namoi River, joining the Namoi River just upstream of Gunnedah and Boggabri respectively.

Two dams are located just east of the Upper Namoi GMA catchment Split Rock Dam and Keepit Dam, which regulate flow in the Namoi catchment. Keepit Dam is located on the Namoi River upstream of the Peel River confluence. Split Rock Dam is located on the Manilla River, a tributary of the Namoi River. The Manilla River joins the Namoi River upstream of Keepit Dam.

The Upper Namoi Zone 3 catchment area covers the alluvial plain of the Lower Mooki Valley. The alluvial plain is level to gently sloping and typically has an elevation less than 300 m (Lavitt 1999). The dominant feature of the Zone 3 catchment area is the Mooki River which runs northwards through the catchment from Breeza to Gunnedah. The Mooki River is a tributary of the Namoi River, joining the Namoi River just north of Gunnedah.

4.1.2 Climate

The Upper Namoi GMA is semi-arid and experiences similar climatic conditions throughout the GMA, with average annual rainfalls of 646 mm at Narrabri (BoM station 54120 Narrabri West Bowling Club) in the north and 590 mm at Pine Ridge (BoM station 55037 Mooki Springs) in the south of the GMA.

The closest BoM stations to the study area (Zone 3) are stations 55014 Curlewis (Post Office) and 55065 Breeza (The Park), which have long term average annual rainfalls of 582 mm and 642 mm, respectively. Long term average monthly rainfall and average monthly rainfall for the current study period (2009–2011) for these two BoM stations is shown on Figures 4-2 and 4-3. Historically, almost 50% of rainfall occurs from November to February.

During the study period, monthly rainfall was typically below average for 2009 and above average for the more than 50% of months in 2010, with the exception of January and April to June. Monthly rainfall was below average in early 2011. Daily rainfall for Curlewis over the monitoring period is shown on the hydrographs in Appendix C.

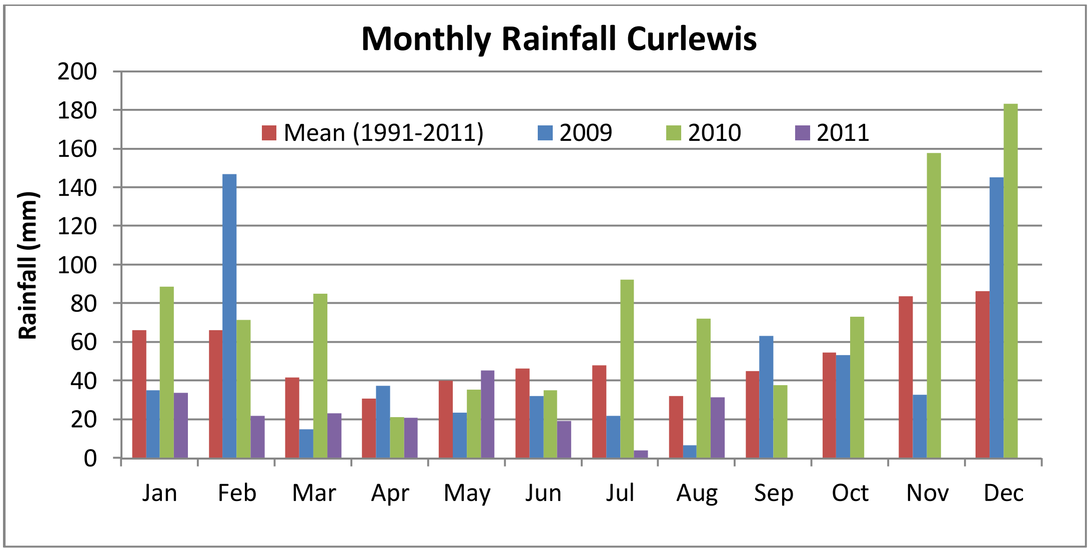


Figure 4-2 Average monthly rainfall, BoM station 055014, Curlewis

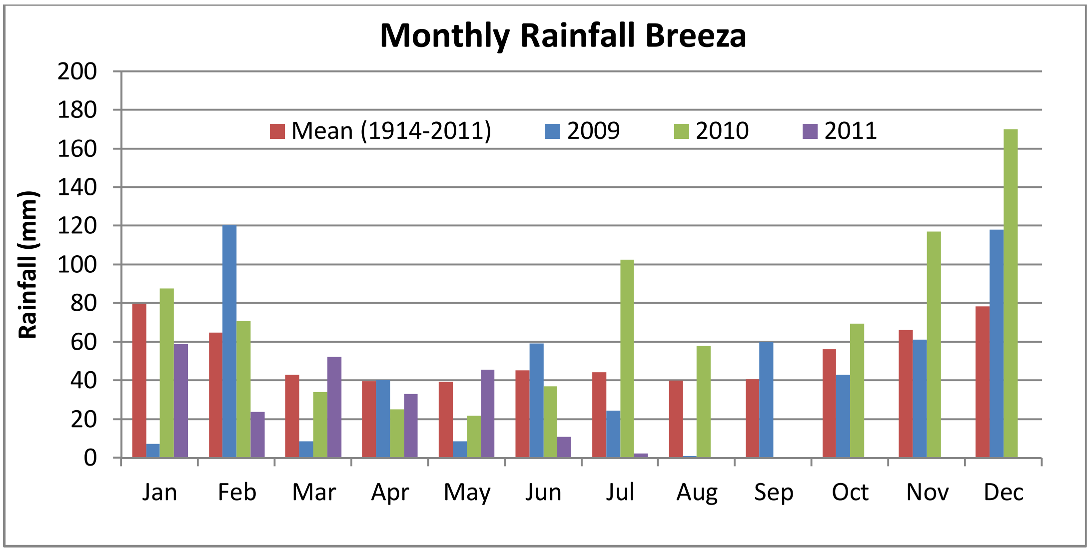


Figure 4-3 Average monthly rainfall, BoM station 055065, Breeza

The long-term cumulative rainfall (Definition and method of calculation discussed in Section 2.3) residual for Breeza and Curlewis are shown on Figure 4-4. The cumulative residual rainfall in Figure 4-4 shows the periods of above average rainfall: 1966–1978, 1986–1991, 1995–1999 and 2006–2010.

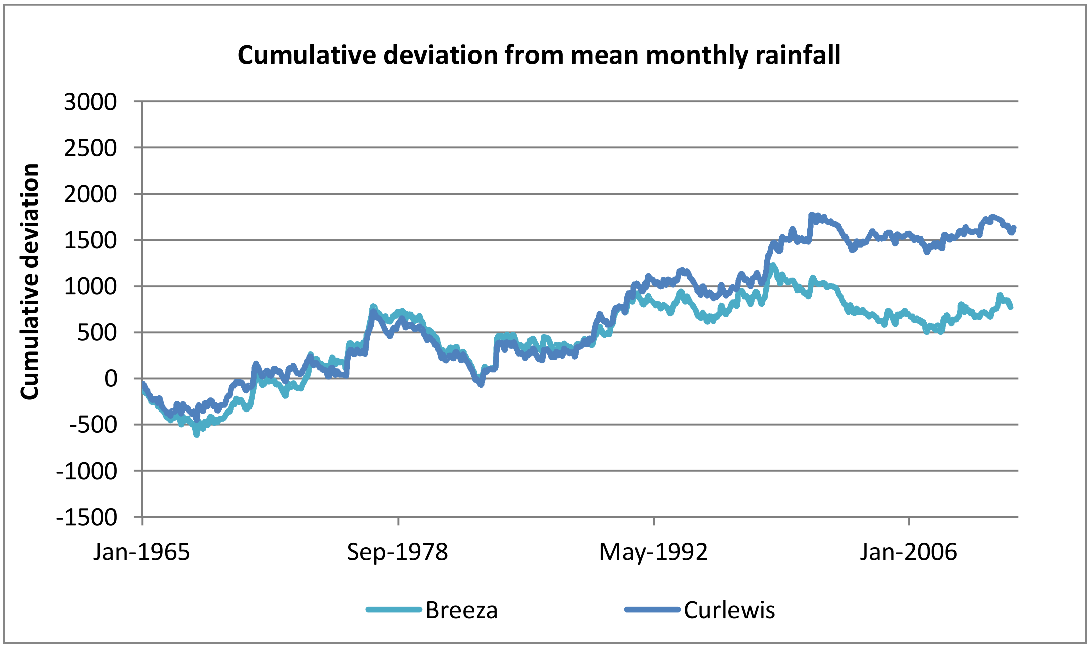


Figure 4-4 Cumulative deviation from mean monthly rainfall, Breeza and Curlewis (1965–2011)

4.1.3 Land use

Land use overlying the Upper Namoi GMA is dominated by sheep and cattle grazing. Wheat, cotton and other broad acre crops are grown along the alluvial floodplains (Green et al. 2011). The irrigated cropping areas are primarily used for cotton production (Green et al. 2011).

In the Zone 3 Mooki River catchment the alluvial floodplains are used for dryland and irrigated cropping in summer (cotton, sunflowers, sorghum and corn) and winter (wheat, canola and barley) (NCMA 2011). The foot slopes of the alluvial floodplains are used for dryland cropping and steeper slopes are used for cattle grazing (NCMA 2011).

4.1.4 Hydrogeology

The Upper Namoi Valley alluvial aquifer system is made up of unconsolidated sediments up to 170 m deep associated with the Namoi and Mooki Rivers and Cox’s Creek (DLWC 2000). The alluvial sediments consist of sand, gravel and clay, with thickness typically controlled by bedrock topography (CSIRO 2007). Palaeochannels represent the deepest parts of the alluvial aquifer (DIPNR 2004). The coarseness of the palaeochannel sediments allows for high groundwater extraction rates (DLWC 2000).

In the Zone 3 Mooki Valley catchment the palaeochannel of the Namoi River runs south from Carroll, turning west before joining the Mooki River palaeochannel (DIPNR 2004). The Mooki River palaeochannel runs approximately parallel to the current course of the Mooki River between Breeza and just north of Gunnedah (DIPNR 2004).

The Upper Namoi GMA has two major layers or hydrostratigraphic units, which have been classified as the following (Williams 1997):

- Narrabri Formation (shallow aquifer) – Quaternary fluviatile unit consisting dominantly of clay with minor sand and gravel. Ranging in thickness from 10 – 40 m.
- Gunnedah Formation (deep aquifer) - Pliocene fluvio-lacustrine that consists of moderately well sorted sand and gravels interbedded with predominantly brown to yellow clays. Generally occurring between 40 to 90 m depth (CSIRO 2007).

The Narrabri Formation conformably overlies the Gunnedah Formation. The high clay content of the Narrabri Formation allows this formation to be exploited as a secondary aquifer yielding small quantities of fresh to saline groundwater.

Recharge to the alluvial aquifer system in the Upper Namoi occurs via several mechanisms including: direct rainfall recharge, irrigation, river leakage, leakage from overbank flooding, inflow from surrounding aquifers and hill slope ‘run-on’ from outcropping bedrock at the aquifer margins (CSIRO 2007). The Gunnedah Formation is typically recharged via infiltration from the overlying Narrabri Formation (CSIRO 2007).

Regional groundwater flows in the Upper Namoi are from east to west, however, the groundwater flow systems within aquifers are generally local to intermediate in scale (CSIRO 2007).

Specifically in the Zone 3 area of the Upper Namoi GMA, the main areas of recharge are located on the alluvial fans and foot slopes bordering the catchment, particularly on the eastern slopes (Lavitt 1999). Other significant sources of recharge in the Zone 3 area include infiltration of irrigation and flood waters on the alluvial plains and groundwater inflow from fractured bedrock into the alluvium (Lavitt 1999).

Groundwater gradients in the Zone 3 area indicate flow from the foot slopes towards the Mooki River in the centre of the catchment and in a north to north-westerly direction (Lavitt, 1999). However, groundwater from the Namoi River alluvium (north of Zone 3) is likely recharging the Mooki River alluvium, resulting in the convergence of groundwater in the centre of the Zone 3 area (Lavitt, 1999). No potentiometric data is available prior to groundwater abstraction commenced in the area. The influence of abstraction on the local groundwater flow regime, particularly near the boundary of the Mooki River and Namoi River alluvium, is uncertain (Lavitt, 1999).

Irrigation development commenced in the early 1960’s in the Upper Namoi Catchment. The drought years of 1992–1993 to 1994–1995 and 2001–2002 to 2003–2004 had a significant impact on groundwater levels, when irrigation extractions increased to nearly twice the average recharge rate (DIPNR 2004). Groundwater levels in the Upper Namoi GMA have been declining since the 1970s (DLWC 2000). Within the Zone 3 study area irrigation commenced in the 1970s (DIPNR 2004) and the earliest groundwater monitoring in the area commenced in 1978.

Areas of clay dominated alluvium act as hydraulic barriers in the Zone 3 area influencing groundwater levels and chemistry. Water level trends show more significant declines for the area north of Breeza, where significant clay deposits are found, in comparison with the area south of Breeza, outside the Zone 3 area (Lavitt 1999).

Hydrograph data for the Zone 3 monitoring bores is shown on Figure 4-5 and a brief summary of groundwater level trends is given in Table 4-1.

Table 4-1 Hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long term hydrogeological conditions
GW030430_1	16.7 – 19.8	NF	Water levels are available from 1973. Pipe 1 shows a dampened water level response indicating there is limited connection between the Narrabri Formation and the underlying formations at this location. Seasonal drawdowns are evident at all pipes (up to 13 m at Pipe 4). Since monitoring commenced the total recovery decline is ~9 m.
GW030430_2	36.5 – 39.6	GF	
GW030430_3	53.3 – 56.3	GF	
GW030430_4	72.5 – 79.2	GF	
GW030431_1	20 – 21	NF	Water levels are available from 1974. Water levels in Pipes 1, 2 and 3 show similar behaviour indicating a hydraulic connection. Since commencement of monitoring, there have been several reversals of the vertical hydraulic gradient between Pipes 2 and 3. Seasonal drawdowns are evident at all pipes (up to 7.5 m). Since monitoring commenced the total recovery decline is ~7.5 m.
GW030431_2	54.3 – 57.3	GF	
GW030431_3	81.7 – 84.7	GF	
GW036038_1	20.4 – 24.7	NF	Water levels are available from 1974. Water levels in Pipes 1, 2 and 3 show similar behaviour indicating a hydraulic connection. Seasonal drawdowns are evident at all pipes (up to 5 m). Pipe 1 shows minimal drawdown between 1995-97 and 2002-10. Since monitoring began the total recovery decline is ~10 m.
GW036038_2	42.1 – 43.1	GF	
GW036038_3	74.7 – 75.6	GF	
GW036150_1	64.6 – 67.7	GF	Water levels are available from 1977. Large seasonal drawdowns are evident at Pipe 1 (up to 24 m). Since monitoring commenced the total recovery decline is ~9 m.
GW036151_1	39.6 – 42.7	NF	Water levels are available from 1977. Pipe 1 shows a dampened water level response indicating there is a limited connection between the Narrabri Formation and deeper aquifer at this location. When monitoring commenced the pressure head of the deeper aquifer was ~0.6 m above that of the shallow aquifer. Since development there has been a reversal of the vertical hydraulic gradient. Large seasonal drawdowns are evident at Pipe 2 (up to 17 m). Since development the total recovery decline is ~10 m for Pipe 2 and ~6 m for Pipe 1.
GW036151_2	86 – 88.1	GF	
GW036166_1	45.7 – 48.7	GF	Water levels are available from 1977. Water levels in Pipes 1, 2 and 3 show similar behaviour indicating a hydraulic connection. Large seasonal drawdowns are evident at all pipes (up to 23 m). Since monitoring commenced the total recovery decline is ~7.5 m.
GW036166_2	77.4 – 80.4	GF	
GW036166_3	95.7 – 98.7	GF	
GW036213_1	18.9 – 21.9	NF	Water levels are available from 1977. Pipe 1 shows a dampened water level response indicating there is a limited connection between the Narrabri Formation and deeper aquifers at this location. Seasonal drawdowns are evident at Pipes 2 and 3 (up to 14 m). Since monitoring commenced the total recovery decline at Pipes 2 and 3 is ~4 m.
GW036213_2	38.1 – 41.1	GF	
GW036213_3	55.2 – 58.2	GF	
GW036231_1	24.4 – 27.4	NF	Water levels are available from 1977. Pipes 1 and 2 have an overall increasing trend from commencement of monitoring, ~8 m and ~4 m respectively.
GW036231_2	64 – 66.4	GF	

Note: NF-Narrabri Formation, GF-Gunnedah Formation.

4.2 Characterisation of groundwater chemistry

Groundwater sampling was undertaken in 13 sampling rounds during the study period (November 2009 to January 2011). Twenty-two monitoring bores were sampled during the study period, with four located in the Narrabri Formation and 17 located in the Gunnedah Formation

4.2.1 Results

Groundwater chemistry statistics are summarised in Tables 4-2 and 4-3 for the Narrabri and Gunnedah formations respectively. The results are presented on a cross-section (Figure 4-6). The location of the cross-section is shown on Figure 4-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 4-7, 4-8 and 4-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix C.

A Piper diagram presenting major ion results for the Narrabri and Gunnedah formations is presented in Figure 4-10.

Stable isotope data (^{18}O and ^{2}H) was collected for several monitoring rounds and is presented in Figures 4-11 and 4-12.

Table 4-2 Upper Namoi Narrabri Formation statistics, Nov 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	26	26	3900	16000	8289	8350	4053
EC (lab)	µS/cm	26	26	5930	18510	10992	11750	4428
pH (field)	pH unit	25	25	6.79	7.42	7.18	7.25	0.18
Eh	mV	3	3	140.3	75.2	102.4	91.8	33.8
K	mg/L	26	26	1	6	3	3	2
Na	mg/L	26	26	900	3900	2131	2300	1122
Ca	mg/L	26	26	140	550	355	360	116
Mg	mg/L	26	26	76	510	302	430	184
Cl	mg/L	26	26	1800	4000	3015	3400	839
SO_4	mg/L	26	26	16	5700	2128.5	2300	2165
Alkalinity ($CaCO_3$)	mg/L	26	26	180	540	309	190	166
CO_3	mg/L	26	0	Not calculated				
HCO_3	mg/L	26	26	210	660	376	230	202
Si	mg/L	26	26	7.6	30.0	16.9	16.0	6.6
F	mg/L	26	24	<0.1	1.10	0.42	0.40	0.23
Al (soluble)	mg/L	26	18	<0.01	2.500	0.136	0.025	0.486
B (soluble)	mg/L	26	25	<0.1	1.40	0.54	0.40	0.43
Br (soluble)	mg/L	26	26	8.5	17.0	12.3	12.0	2.7
Cu (soluble)	mg/L	26	8	<0.01	0.020	0.011	0.005	0.005
Mn (soluble)	mg/L	26	21	<0.002	0.230	0.0117	0.0020	0.0446
Pb (soluble)	mg/L	5	1	<0.02	0.04	0.02	0.01	0.01
Sr (soluble)	mg/L	26	26	5.4	14.0	9.3	9.2	2.6
Zn (soluble)	mg/L	26	19	<0.005	0.082	0.0192	0.0100	0.0202
Mn (total)	mg/L	26	23	<0.002	0.390	0.050	0.017	0.090
Ni (total)	mg/L	26	4	<0.01	0.023	0.011	0.005	0.005
Zn (total)	mg/L	26	22	<0.01	1.400	0.101	0.030	0.269
Al (total)	mg/L	25	25	0.06	20.00	2.68	0.71	4.91
B (total)	mg/L	26	26	0.10	1.50	0.45	0.30	0.30
Cu (total)	mg/L	26	12	<0.005	0.340	0.0215	0.0025	0.0656
Fe (total)	mg/L	26	21	<0.05	14.00	1.725	0.310	3.378
Pb (total)	mg/L	26	7	<0.02	0.05	0.03	0.01	0.02
N_2	mg/L	26	26	0.18	6.00	1.96	1.20	2.00
NH_3	mg/L	26	6	<0.01	0.020	0.011	0.005	0.005
NO_3	mg/L	16	16	0.50	5.80	2.74	1.35	2.19
PO_4	mg/L	26	26	0.005	0.117	0.036	0.013	0.038
Total P	mg/L	26	26	0.011	0.160	0.077	0.071	0.052

Note: SD – standard deviation

Table 4-3 Upper Namoi Gunnedah Formation statistics, Nov 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	141	141	400	10000	2272	680	2808
EC (lab)	µS/cm	141	141	673	14270	3231	1140	3674
pH (field)	pH unit	133	133	5.81	7.95	7.18	7.29	0.57
Eh	mV	13	13	182.1	-244.9	85.8	109.4	112.4
K	mg/L	141	141	1	5	2	2	1
Na	mg/L	141	141	80	2600	580	160	734
Ca	mg/L	141	141	19	460	107	64	104
Mg	mg/L	141	141	8	480	83	23	112
Cl	mg/L	141	141	24	3700	610	130	846
SO_4	mg/L	141	140	0.25	5100	645.8	63	1198.
Alkalinity (CaCO3)	mg/L	141	141	150	530	338	320	92
CO_3	mg/L	141	5	0.5	5.6	1.1	0.5	0.6
HCO_3	mg/L	141	141	190	640	412	390	112
Si	mg/L	141	141	7.8	41.0	17.2	15.0	8.9
F	mg/L	141	126	<0.1	1.20	0.39	0.24	0.31
Al (soluble)	mg/L	141	66	<0.01	0.090	0.016	0.005	0.012
B (soluble)	mg/L	141	78	<0.1	1.70	0.28	0.10	0.37
Br (soluble)	mg/L	141	131	<0.2	15.0	2.3	0.5	3.1
Cu (soluble)	mg/L	141	12	<0.01	0.020	0.010	0.005	0.003
Mn (soluble)	mg/L	141	82	<0.00	1.500	0.065	0.002	0.195
Pb (soluble)	mg/L	4	0	Not calculated				
Sr (soluble)	mg/L	141	141	0.42	12.00	2.24	0.87	2.48
Zn (soluble)	mg/L	141	120	<0.00	0.1400	0.028	0.0170	0.027
Mn (total)	mg/L	141	89	<0.00	1.500	0.069	0.003	0.201
Ni (total)	mg/L	141	2	<0.01	0.022	0.010	0.005	0.002
Zn (total)	mg/L	141	128	<0.01	1.900	0.079	0.030	0.247
Al (total)	mg/L	141	80	<0.05	2.400	0.212	0.060	0.399
B (total)	mg/L	141	85	<0.1	1.90	0.28	0.10	0.35
Cu (total)	mg/L	141	22	<0.00	0.0400	0.005	0.0025	0.004
Fe (total)	mg/L	141	55	<0.05	3.600	0.198	0.025	0.446
Pb (total)	mg/L	141	4	<0.02	0.03	0.02	0.01	0.002
N_2	mg/L	141	127	<0.05	11	1.16	0.29	1.95
NH_3	mg/L	141	46	<0.01	0.100	0.014	0.005	0.012
NO_3	mg/L	38	38	0.30	12.00	3.42	2.95	2.61
PO_4	mg/L	141	141	0.008	0.487	0.077	0.028	0.116
Total P	mg/L	141	141	0.008	0.503	0.106	0.048	0.129

Note: SD – standard deviation

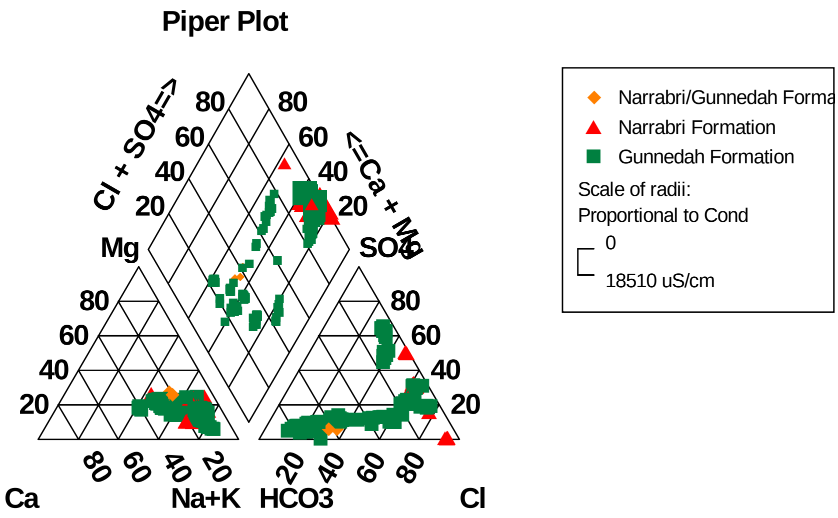


Figure 4-10 Piper diagram for the Upper Namoi Zone 3 Catchment during the study period

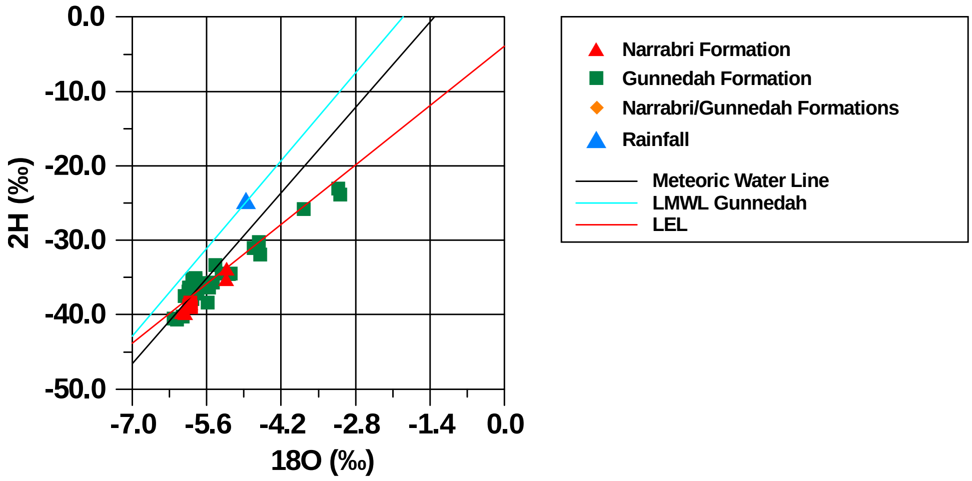


Figure 4-11 Oxygen-18 versus deuterium for groundwater samples from the Upper Namoi Zone 3

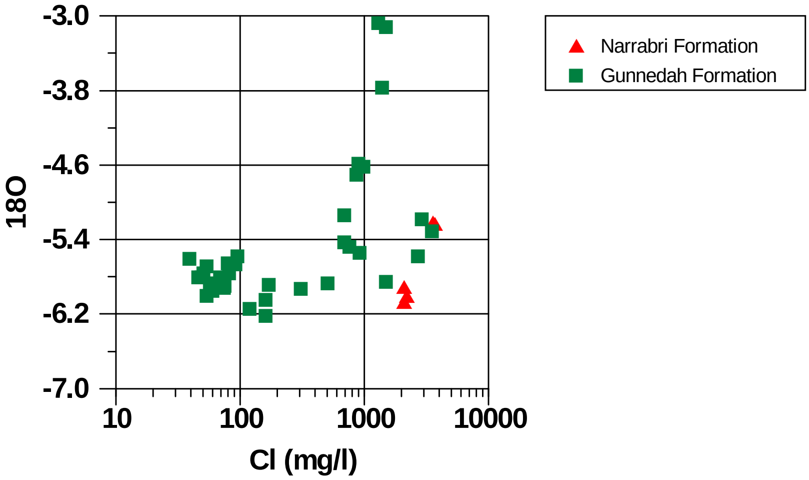


Figure 4-12 Oxygen-18 versus chloride for groundwater samples from the Upper Namoi Zone 3

4.2.1.1 Narrabri Formation

Water quality parameters

Groundwater salinity in the Narrabri Formation in the Zone 3 area is saline, ranging from 5,930 µS/cm (GW036231_1) to 18,510 µS/cm (GW036151_1) (Figure 4-8).

The pH conditions of the Narrabri Formation ranged from near neutral (6.79) to slightly alkaline (7.42). Near neutral pH conditions are typical in aquifers where silicate or chemical weathering is buffering against acidification.

Major and minor ions

Major ion chemistry in the Narrabri Formation was dominated by sodium and chloride in the Zone 3 area. Magnesium, calcium and sulphate were also dominant at some monitoring locations. Calcium was typically dominant in the less saline waters and sodium-magnesium chloride dominant waters were associated with the higher salinity waters in the Narrabri Formation. Lavitt (1999) found higher salinity waters were more associated with sodium-chloride type waters in the Narrabri Formation, with the coarser alluvium dominated by calcium-magnesium bicarbonate. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix C.

Dissolved silicon concentrations in the Narrabri Formation ranged from 7.6 mg/L to 30 mg/L, with an average concentration of 17 mg/L. Weathering of aluminosilicate minerals is a common process in silicate-rich alluvial aquifer systems, and elevated silica concentrations are typical of these systems. Most silicate weathering takes place in the soil zone and unsaturated zone where infiltrating recharge charged with atmospheric CO_2 drives dissolution reactions (Appelo and Postma 1996).

Bromide was detected in all samples, concentrations ranged from 8.5 mg/L to 17 mg/L. The highest concentrations were associated with the highest salinities.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Dissolved boron was detected in 97% of samples, concentrations ranged from below the laboratory limit of reporting (LOR) (0.1 mg/L) to 1.4 mg/L. Total boron was detected in all samples, concentrations ranged from 0.1 mg/L to 1.5 mg/L.

Only total iron was analysed in the Upper Namoi. Total iron was detected in 81% of samples from the Narrabri Formation. Concentrations ranged up to 14 mg/L.

Dissolved and total manganese were detected in the majority of samples. Maximum dissolved and total manganese concentrations were 0.23 mg/L and 0.39 mg/L, respectively. Iron and manganese were well correlated ($r^2 = 0.9$).

Dissolved zinc was detected in 73% of samples, ranging from the LOR to 0.082 mg/L. Total zinc was detected in 85% of samples, ranging from the LOR (0.01 mg/L) to 1.4 mg/L.

Strontium was detected at all monitored bores. Strontium concentrations are elevated, ranging from 5.4 mg/L to 14 mg/L and correlate well with high salinity. Strontium is likely to be associated with Aeolian salts entrained in clays in the alluvial deposits, as well as rainfall accession and carbonate minerals.

Trace metal concentrations are believed to be naturally occurring and are mainly derived from clay minerals and metal oxides and hydroxides.

Nutrients

Total nitrogen concentrations typically represented the nitrate concentration in the system. Nitrate was analysed for 62% of samples and was detected in all samples analysed. Nitrate concentrations ranged from 0.5 mg/L to 5.8 mg/L. Nitrate can be derived from natural sources such as soil degradation or from agricultural sources such as nitrogen based fertilisers.

Total phosphorus concentrations were recorded at all Narrabri Formation monitoring bores, with concentrations ranging from 0.011 mg/L to 0.16 mg/L. Phosphorus in groundwater can be derived from natural processes such as decay of organic matter, and weathering of rocks, and it can also be derived in agricultural areas from animal manure and fertilisers.

Isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for groundwater samples collected in January, June and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^{2}H = 8.41\delta^{18}O + 15.99$) (Timms and Acworth 2002) on Figure 4-11. The Local Meteoric Water Line for the area was based on 17 samples collected between March 1998 and January 2001 (Timms and Acworth 2002). The LMWL is parallel to, but slightly offset to the left of the GMWL. Only 5 groundwater samples from the Narrabri Formation were analysed for stable isotopes. Stable isotope values for the shallow aquifer ranged from -6.07‰ to -5.22‰ for $\delta^{18}O$, and -39.8‰ to -33.8‰ for $\delta^{2}H$. Groundwater samples from the shallow aquifer plotted on or to the right of the GMWL.

4.2.1.2 Gunnedah Formation

Water quality parameters

Salinity (EC) in the Gunnedah Formation is typically less saline than the overlying Narrabri Formation in the Zone 3 area, ranging from fresh (673 µS/cm at GW036038_3) to saline (14,270 µS/cm at GW030431_2) (Figure 4-8). The salinity of the Gunnedah Formation has been recognised as significantly less saline than the overlying Narrabri Formation (DIPNR, 2004), although, groundwater abstraction has resulted in the deterioration of the Gunnedah Formation quality, likely due to the leakage from the overlying Narrabri Formation (Lavitt 1999).

Field pH measurements were recorded for 94% of samples from the Gunnedah Formation. The pH conditions of the Gunnedah Formation ranged from slightly acidic (5.81) to slightly alkaline (7.95). The pH is slightly more variable in the Gunnedah Formation compared with the overlying Narrabri Formation.

Major and minor ions

Major ion chemistry in the Gunnedah Formation varied with location, as the Gunnedah Formation is not laterally continuous, with discrete zones of differing salinity and water type. Locations with higher salinities were dominated by sodium and chloride and occasionally sulphate and magnesium. Locations where salinity was lower showed a dominance of sodium and bicarbonate and occasionally calcium, magnesium and chloride. Water types for each monitoring location are presented in piper plots in the report cards in Appendix C.

Dissolved silicon concentrations in the Gunnedah Formation ranged from 7.8 mg/L to 41 mg/L, with an average concentration of 17.2 mg/L.

Bromide was typically detected in the Gunnedah Formation, concentrations ranged from 0.2 mg/L to 15 mg/L. The highest concentrations were associated with the highest salinities.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Dissolved boron was detected in 55% of samples, with concentrations ranging between the LOR (0.1 mg/L) and 1.7 mg/L. Boron was well correlated with salinity, with the highest concentrations occurring in monitoring bores that had a higher clay content.

Only total iron was analysed in the Upper Namoi. Total iron was detected in 39% of samples from the Gunnedah Formation. Concentrations ranged up to 3.6 mg/L.

Dissolved and total manganese were detected in the majority of samples (58% and 63% respectively). Maximum dissolved and total manganese concentrations were 1.5 mg/L. Iron and manganese concentrations were not as well correlated as the Narrabri Formation (r^2=0.64).

Dissolved zinc was detected in 85% of samples, ranging from the LOR (0.01 mg/L) to 0.14 mg/L. Total zinc was detected in 91% of samples, ranging from the LOR (0.01 mg/L) to 1.9 mg/L.

Strontium was detected at all monitored bores, with concentrations ranging from 0.42 mg/L to 12 mg/L. The highest strontium concentrations were associated with high salinities.

Nutrients

Total nitrogen was detected in 90% of samples in the Gunnedah Formation. Total nitrogen concentrations ranged up to 11 mg/L. Nitrate was only analysed for 27% of samples and detected in all samples analysed. Nitrate concentrations ranged from 0.3 mg/L to 12 mg/L.

Total phosphorus concentrations were recorded at all Gunnedah Formation monitoring bores. Total phosphorus concentrations ranged from 0.008 mg/L to 0.503 mg/L but were typically below 0.1 mg/L.

Isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for groundwater samples collected in January, June and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^{2}H = 8.41\delta^{18}O + 15.99$) (Timms and Acworth 2002) on Figure 4-11.

For the Gunnedah Formation, 40 samples were analysed for stable isotopes. Stable isotope values for the deep aquifer ranged from -6.22‰ to -3.08‰ for $\delta^{18}O$, and -40.7‰ to -23.1‰ for $\delta^{2}H$. A number of samples collected form monitoring bores located on a groundwater flowpath running parallel to the Mooki River plotted on or to the left of the GMWL, while samples located in the north-eastern part of the study area plotted to the right of the GMWL.

4.2.2 Processes

4.2.2.1 Narrabri Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes for groundwater in the Narrabri Formation in Zone 3 (Figure 4-13). Sulphate/chloride ratios were high at some monitoring locations (GW036151_1), indicating the addition of sulphate to the system. No clear trends were identified for the ratios of potassium, bicarbonate, magnesium, sodium and calcium, to chloride, indicating several processes that change the ion ratios may be occurring. These processes could include mixing of waters with different ion/chloride ratios and/or water-rock interactions, or ions gained or removed by precipitation, ion exchange or reduction processes.

A detailed description of processes occurring in the Mooki River catchment is provided by Lavitt (1999). In summary the hydrogeochemical character of the alluvial system is ultimately controlled by water/regolith interactions in the recharge zone and influenced by water/alluvial interaction along flow paths and the addition of CO_2, de-gassing from a mantle source (Lavitt 1999).

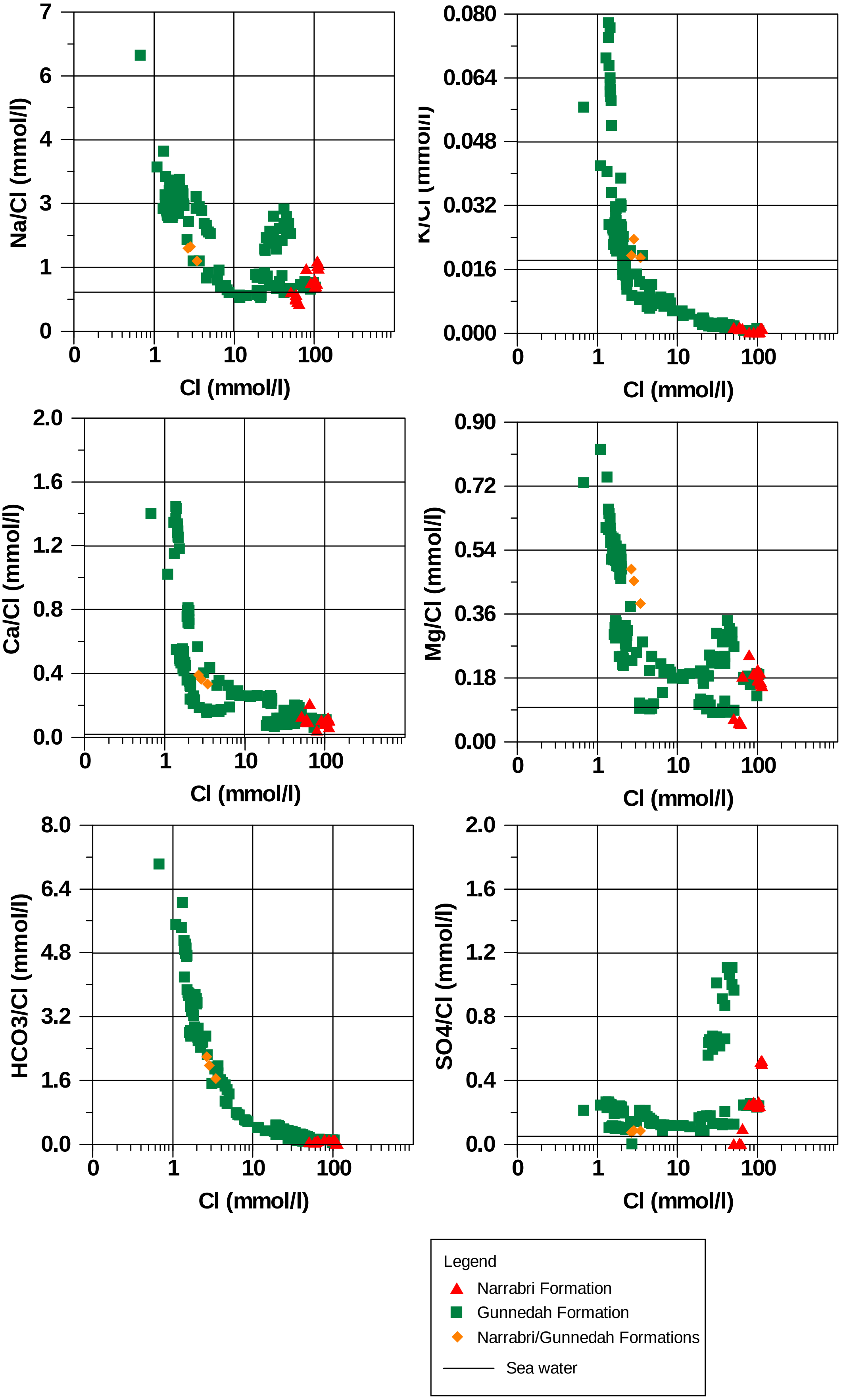


Figure 4-13 Ion/chloride versus chloride graphs for the Upper Namoi Zone 3

Saturation indices for the Narrabri Formation in Zone 3 are plotted in Figure 4-14. The groundwater of the Narrabri Formation in Zone 3 is typically saturated with respect to calcite, dolomite, quartz and montmorillonite. Gypsum and anhydrite are under-saturated in this system.

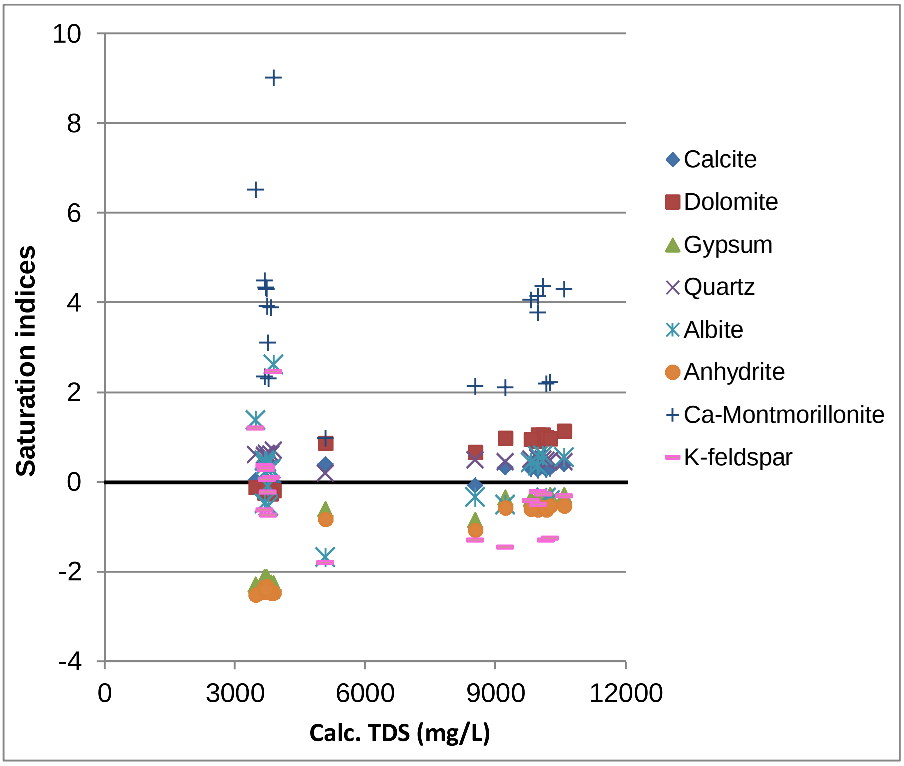


Figure 4-14 Saturation indices versus TDS for the Narrabri Formation

Ion exchange

Figure 4-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Groundwater in the Narrabri Formation in Zone 3 is likely undergoing ion exchange, as the majority of samples are plotted below the dissolution line. Ion exchange is a particularly important process within dynamic aquifer systems where the flow and mixing of groundwater of different composition triggers ion exchange, which acts a buffer in non-steady state systems such as the heavily pumped Upper Namoi aquifer system.

However, a number of samples from monitoring bores which had high salinity plot above the 1:1 line, indicating that reverse ion may be occurring. Lavitt (1999) found that considerable pressure gradients caused by long-term abstraction has resulted in pressure readjustments within the clay dominated system, and the movement of saline pore fluids into the aquifer. He found that reverse ion exchange, resulting in a relative enrichment in Ca^{2+} and Mg^{2+} and depletion of Na^{+} in solution, was associated with this intrusion of saline pore water into aquifers. The amount of reverse ion exchange that can occur will depend on the amount of calcium within the clay. Once all the calcium is removed, reverse ion exchange will cease, and groundwater will have evolved to $CaCl_2$ type water.

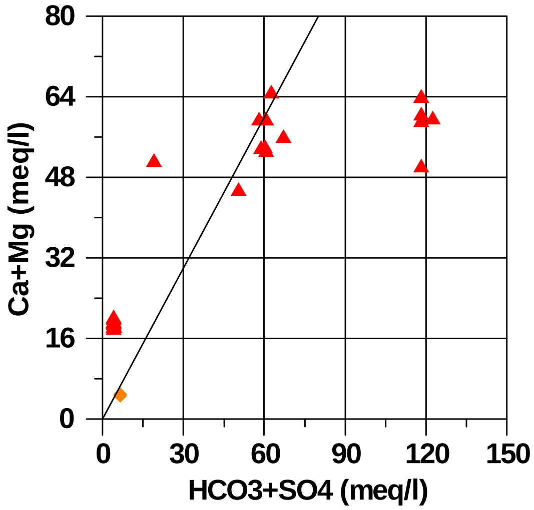


Figure 4-15 Calcium + magnesium versus bicarbonate + sulphate in the Narrabri Formation

Stable isotopes

Only 5 groundwater samples from two monitoring bores (GW030431_1 and GW036231_1) were analysed for stable isotopes from the Narrabri Formation. These groundwater samples had similar isotopic signatures to samples from the Gunnedah Formation suggesting thorough mixing within the alluvial aquifer system. At GW030431_1 vertical hydraulic gradients indicate an upward flux from the deep to shallow aquifers; hence mixing of different groundwaters has resulted in the homogenisation of stable isotope values at this location in the catchment. At GW036231_1, the shallow and deep aquifers are also hydraulically connected.

4.2.2.2 Gunnedah Formation

Major ion/chloride ratios were plotted versus chloride to determine hydrogeochemical processes for groundwater in the Gunnedah Formation (Figure 4-13). Linear horizontal relationships indicate only evapotranspiration is affecting the ionic relationships. Sodium, magnesium, calcium, potassium and bicarbonate showed curved trends with high ion/chloride ratios, indicating ions have been gained or removed from the system. This could occur through mixing of waters with different ion/chloride ratios and/or water-rock interactions, or ions gained or removed by precipitation, ion exchange or reduction processes. Some locations had high sulphate/chloride ratios, although no clear trend was identified.

A detailed description of processes occurring in the Mooki River catchment is provided by Lavitt (1999). As the Gunnedah Formation contains constricting clay layers of variable connectivity, a varied hydrogeochemical signature is present, with clay dominated areas enriched in soluble salt ions relative to the gravel rich groundwater (Lavitt 1999).

Saturation indices for the Gunnedah Formation in Zone 3 are plotted in Figure 4-16. The groundwater of the Gunnedah Formation in Zone 3 is typically saturated with respect to quartz and montmorillonite. Calcite, dolomite, gypsum and anhydrite are under-saturated in this system at low salinities; however, as salinities increase they approach saturation.

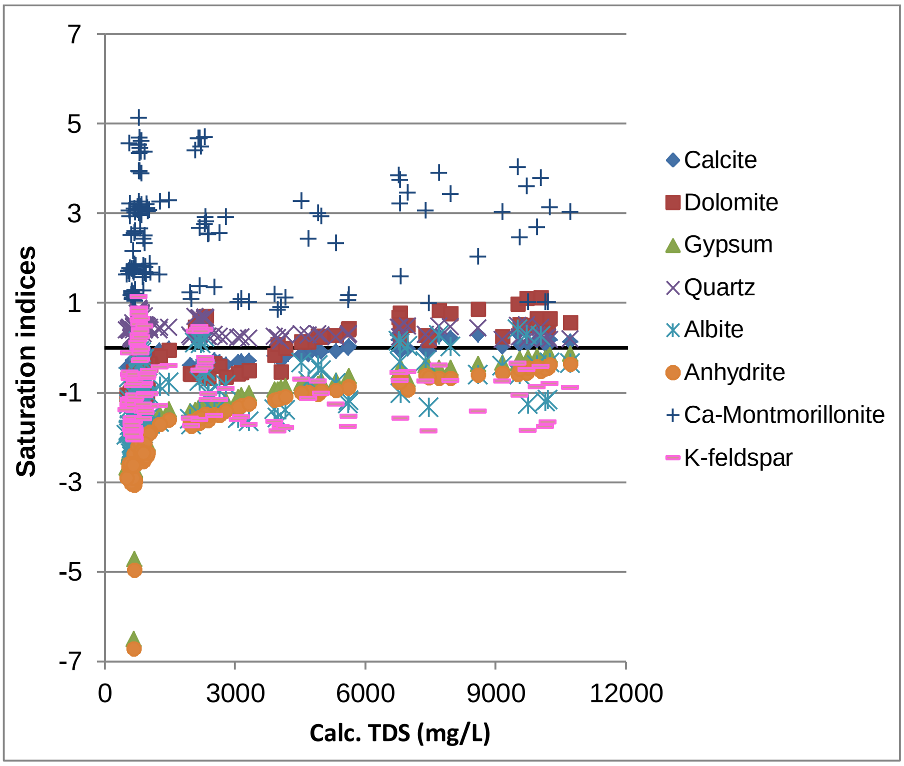


Figure 4-16 Saturation indices versus TDS for the Gunnedah Formation

Ion exchange

Figure 4-17 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The majority of samples from the Gunnedah Formation in Zone 3 are plotted below the dissolution line, indicating groundwater in the Gunnedah Formation is likely undergoing ion exchange. Lavitt (1999) found a typical trend along flow paths was an increase in sodium with respect to calcium and magnesium. However, similarly to the Narrabri Formation, reverse ion exchange is likely occurring in monitoring bores where groundwater salinity has shown an increasing trend.

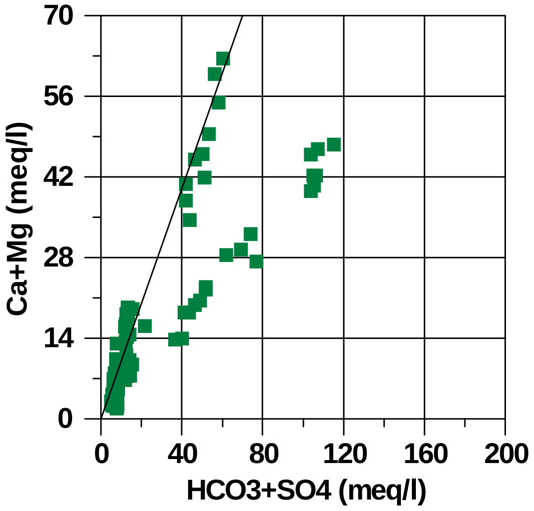


Figure 4-17 **Calcium + magnesium versus bicarbonate + sulphate in the Gunnedah Formation**

Stable isotopes

A number of samples from the Gunnedah Formation plot to left of the LMWL, and show a relative depletion of δ^2H. These samples were collected from monitoring bores located on the S-N flow path running parallel to the Mooki River, and have values that are more depleted than the amount weighted average rainfall values for the area (δ^{18}O=-4.86‰ and δ^2H=-24.7‰). These depleted signatures indicate either modern recharge during wetter periods, or recharge during paleoclimatic conditions that were wetter and cooler. Lavitt (1999) investigated the link between stable isotope signatures and groundwater ages in the Mooki Catchment, using radiocarbon ages reported by Coram (1999). Lavitt (1999) concluded that based on a literature search of climatic conditions across south-eastern Australia, wetter cooler climatic conditions existed between 1,000 years and 3,000 years ago. He found that groundwater samples with depleted isotopic compositions in the Mooki catchment corresponded to radiocarbon dates (uncorrected) of 1,000 to 2,500 years old, supporting the theory of groundwater recharge during cooler, wetter palaeoclimatic conditions.

A number of samples have enriched isotopic signatures (plotting to the right of the LMWL and GMWL), which could be indicative of a number of processes including recharge under hotter, drier climatic conditions, evaporative enrichment, or mixing with groundwater or surface water with an enriched isotopic signature. No surface water samples were collected for chemical or isotopic analysis during the study period (2009–2011); however surface water samples have been collected from various sections of the Namoi River near Gunnedah and between Boggabri and Narrabri between 2002 and 2007 (Andersen et al. 2008). The majority of these samples plot on a line referred to by Andersen et al (2008) as the Local Evaporation Line (LEL: $\delta^2H = 5.7\delta^{18}O - 3.91$). Groundwater samples from the current program are compared to the LEL on Figure 4-11. The enriched groundwater samples located in the north-eastern part of Zone 3 plotted along this LEL, suggesting recharge by surface water; however, without end member composition for this catchment, it cannot be determined conclusively.

Looking at a plot of $\delta^{18}O$ versus Cl^- (Figure 4-12), the majority of samples show no relationship between $\delta^{18}O$ enrichment and salinity, indicating that increasing salt concentrations in the majority of samples is not related to evaporative concentration of salts, rather a number of other processes are at play. The samples that plot along the LEL show an $\delta^{18}O$ enrichment with increasing Cl^- concentration, suggesting that evaporation or perhaps mixing with a groundwater or surface water end member with an enriched isotopic signature. Further investigation of end members is required to confirm this.

4.2.3 Beneficial use

The risk to groundwater in Zone 3 of the Upper Namoi GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered ‘at risk’.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Upper Namoi.

The *Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources 2003* defines seven objectives; including an objective relating to water quality, ‘protect the structural integrity of the aquifers and groundwater quality, by ensuring groundwater extraction does not result in any aquifer compaction, aquitard compaction, land subsidence or change in the beneficial use of the aquifer’. To meet this objective, water quality management is detailed in the Plan:

> ‘38 Water quality management
>
> (1) The beneficial uses of this groundwater source are raw water for drinking, and irrigation, based on beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996. It is not recommended that the water from this groundwater source be consumed without prior treatment. Land use activities may have polluted the groundwater in some areas.
>
> (2) Water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class.’

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 4-4. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in Zone 3 of the Upper Namoi GMA. SAR is also well correlated with salinity, and therefore both SAR and EC are considered as good indicators to assess changes in beneficial use.

Table 4-4 Correlation analysis of parameters used to assess salinity and sodicity hazards

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.939	0.943	0.982	0.854
TDS		1	0.967	0.938	0.961
Na^+			1	0.93	0.895
Cl^-				1	0.847
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Upper Namoi GMA, Zone 3.

4.2.3.1 Narrabri Formation

Based on salinity (EC) only, groundwater within the Narrabri Formation was generally suitable for stock only. There was one exception, GW036231_1 located near the Namoi River, which had a lower salinity (average EC 6,316 µS/cm) and was suitable for irrigation.

The Australian Drinking Water Guidelines (NHMRC 2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances in the Narrabri Formation are provided in Table 4-5. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. From Table 4-5, it is clear that groundwater in the Narrabri Formation is not suitable for drinking water supply, not only in terms of salinity but also specific analytes including sodium, chloride and sulphate, manganese and fluoride.

Table 4-5 ADWG (2011) values and percentage of samples above guideline values, Narrabri Formation (N=27) Zone 3 Upper Namoi GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		0
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		100
Potassium (mg/L)				
Chloride (mg/L)	a	250		100
Sulphate (mg/L)	500	250	63	63
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		15	
Aluminium (mg/L)	b	0.2		7
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Manganese (mg/L)	0.5	0.1	0	4
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

Salinity and sodium irrigation hazards for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix C. Using the Wilcox classification (see Section 2.5.3), groundwater from the Narrabri Formation was classified as having a very high salinity, and is generally not suitable for irrigation. Sodium adsorption ratios (SARs) ranged from 8 to 33 (average 20), and 73% of samples (n=19) were classified as having a medium to high sodium hazard. Looking specifically at the ANZECC (2000) guidelines for Na+ concentrations that can cause foliar injury to cotton (>460 mg/L), all samples (n=26) from the Narrabri Formation were above this value. All chloride samples (n=26) were also above the ANZECC (2000) for Cl- concentrations that can cause foliar injury to cotton (>700 mg/L). All samples (n=26) were below the threshold value for boron toxicity for cotton (6–10 mg/L) (Maas 1990).

One of the main indicators to define water quality for stock is salinity. The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), groundwater from the Narrabri Formation is suitable for stock watering.

For livestock, if TDS concentration is greater than 2,400 mg/L, the water should also be analysed to concentrations of specific ions. Based on the guideline values (Table 2-8), 59% of samples (n=16) from the Narrabri Formation exceeded guideline values for sulphate. All other values were below the guidelines for major ions, metals and nitrate.

4.2.3.2 Gunnedah Formation

Gunnedah Formation monitoring bores located close to the Mooki River had low enough salinities to make groundwater suitable for drinking water. At monitoring bore GW036166, EC decreased with depth within the Gunnedah Formation, and the beneficial use category improved from stock in Pipe 1 to irrigation in Pipe 2 and drinking water in Pipe 3.

The number of groundwater samples from the Gunnedah Formation in Zone 3 of the Upper Namoi GMA above health and aesthetic guideline values is shown in Table 4-6. Some parts of the Gunnedah Formation, particular in those areas close to the Namoi River, groundwater is suitable for drinking water based on EC but would probably require treatment for metals such as manganese.

Table 4-6 ADWG (2011) values and percentage of samples above guideline values, Gunnedah Formation (N=45) Zone 3 Upper Namoi GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		15
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		47
Potassium (mg/L)				
Chloride (mg/L)	a	250		41
Sulphate (mg/L)	500	250	24	31
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		18	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	12
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

Note: a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

Salinity and sodium irrigation hazards for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix C. Using the Wilcox classification (see Section 2.5.3), groundwater within the Gunnedah Formation generally had a lower salinity classification than the overlying Narrabri Formation, and 75% of samples (n=93) had a medium to high salinity hazard rating based on the Wilcox classification. Sodium adsorption ratios (SARs) for the Gunnedah Formation range from 2 to 25, with an average of 9. 68% of samples (n=98) were classified as having a low sodium hazard. The remaining 32% of samples (n=46) had a medium to high sodium hazard. Looking at the specific toxicity of Na^+ and Cl^- to cotton, 70% of samples (n=101) and 66% of samples (n=66) were above Na^+ and Cl^- concentrations, respectively, that can cause foliar injury to cotton. All samples (n=144) were below the threshold value for boron toxicity for cotton (6-10 mg/L) (Maas 1990).

One of the main indicators to define water quality for stock is salinity. The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), groundwater from the Gunnedah Formation is suitable for stock watering.

Based on the guideline values (Table 2-8), 22% of samples from the Gunnedah Formation (n=32) exceeded guideline values for sulphate. All other values were below the guidelines for major ions, metals and nitrate.

4.2.4 Trends

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2. The results of these analyses are presented in Tables 4-7 and 4-8 for the Narrabri and Gunnedah formations respectively.

4.2.4.1 Narrabri Formation

Study period trends

During the study period (October 2009–January 2011) salinity increased at two out of three monitoring locations in the Narrabri Formation. Increasing trends in sulphate were identified at both locations with increasing salinity trends. The increasing salinity trend identified at GW030431_1 appears to be associated with an increasing water level. Water types remained similar over the monitoring period except at GW036231_1, where calcium dominance fluctuated.

Long term trends

Only three monitoring bores (with more than one sample) in the Narrabri Formation were monitored as part of the current study. These bores had historical water quality data dating back to 1994/95.

Only one of these monitoring bores, GW036151_1, showed a decreasing salinity (EC) trend which was associated with a decrease in Ca^{2+}, Mg^{2+}, Na^{+} and Cl^{-}. However, SO_4^{2-} and HCO_3^{-} showed an increasing trend, and the water-type has changed from Na-Cl-SO_4 type to Na-SO_4-Cl type.

Beneficial use trends

Based on salinity (EC) only, groundwater within the Narrabri Formation was generally suitable for stock only. However, increasing salinity (EC) at some monitoring bores meant that groundwater was not suitable for some stock.

Table 4-7 Short- and long-term trends, Narrabri Formation, Zone 3 Upper Namoi GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW030431_1	9	Increase	11,500	14,580	245	27	15	-	-	-	-	-	-
GW036038_1	1	ID	ID	ID	ID	ID	3	ID	ID	ID	ID	ID	-
GW036151_1	6	-	-	-	-	-	15	Decrease	23,400 (07/02)	18,510	-735	-21	Na-Cl-SO4 to Na-SO4-Cl
GW036231_1	10	Increase	6,110	6,650	55	9	12	-	-				-
GW038144_1	3	ID	ID	ID	ID	ID	3	ND	ND	ND	ND	ND	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; – No trend or change; (mm/yy) Date of initial sampling

4.2.4.2 Gunnedah Formation

Study period trends

Salinity increased at six out of fourteen monitoring locations in the Gunnedah Formation during the study period (October 2009–January 2011). Where an increase in salinity and major ions was determined, no change in water type was identified, except at GW036213_3, where chloride became dominant in late 2010.

The increasing salinity trend identified at GW030431_2 is similar to the overlying Narrabri Formation at the same location (GW030431_1) and appears to be associated with an increasing water level.

Several monitoring locations in the Upper Namoi have more than one pipe screened in the Gunnedah Formation and at some locations these pipes have differing salinity and water type, indicating disconnected zones in the aquifer. The clay dominated alluvium present in the Zone 3 area is likely responsible for ‘sealing’ areas of the aquifer.

Long term trends

Three monitoring bores within the Gunnedah Formation showed a long term increasing salinity (EC) trend.

At GW036038_3, increasing salinity is related to an increase in chloride, and the chemical composition has evolved from Na-Mg-HCO_3 type water to Na-Mg-HCO_3-Cl type water. At this location, the upper and lower aquifers are hydraulically connected and reversals of vertical hydraulic gradient have occurred on numerous occasions since 1993 (see Figure 4-5). Therefore downward leakage of poorer quality water (average EC 1,418 µS/cm) is likely to be attributing to increasing salinity at this location. Based on simple mixing calculations, the current observed groundwater chemistry is consistent with a mix of 20% Narrabri Formation and 80% Gunnedah Formation.

At GW036166_1, increasing salinity is associated with increasing concentrations of Na^+, K^+, Ca^{2+}, Mg^{2+} and HCO_3^-. The upper aquifer is not monitored at this location, so although large seasonal drawdowns occur in the Gunnedah Formation at this location, there is no information to assess hydraulic connectivity between the Narrabri and Gunnedah formations at this location and to determine if leakage of poorer quality groundwater from the upper aquifer is occurring.

At GW036213_2, increasing salinity is associated with a general increase in the concentrations of all major ions. Groundwater water has evolved from Na-Ca-Cl-HCO_3 in the early part of the decade to Na-Ca-Mg-Cl-HCO_3 type water in 2010/11. At this location, given that Pipe 1 shows a dampened water level response indicating there is a limited connection between the Narrabri Formation and deeper aquifers at this location, it is more likely that the increase in salinity is associated with mobilisation of salts from clay layers within the Gunnedah Formation. Given that reverse ion exchange appears to be occurring in this monitoring bore based on the relative concentrations for Ca^{2+} + Mg^{2+}, compared to HCO_3^- + SO_4^{2-} (Figure 4-17) as salinity increases, it is more likely that intrusion of saline pore fluids from clay aquitards surrounding the aquifer is causing the increase in salinity. These findings are consistent with Lavitt (1999) who found that considerable pressure gradients caused by persistent abstraction has resulted pressure readjustments within the clay dominated system, and the movement of saline pore fluids into the aquifer. At GW036213_3, large seasonal pressure gradients occur, with changes of up to 14 m in one irrigation season. Long term, the total recovery decline has been approximately 4 m.

Beneficial use trends

At some locations there was a change in the current beneficial use for the historical use, with a change in classification from irrigation to stock watering at some monitoring bores.

4.2.5 Risks to groundwater quality

Risk factors to groundwater quality within the Upper Namoi GMA Zone 3 include rate of groundwater extraction resulting in aquifer depressurisation and in some instances reversal of hydraulic gradients, and the presence/mobilisation of salts from salt stores such as clay aquitards. Other factors include variability in rainfall and recharge, and in some parts irrigation intensity and timing.

Groundwater quality within the Narrabri Formation is generally saline. Although data are limited for the Narrabri Formation (only five bores were monitored for this study) the results do highlight specific areas or ‘hotspots’ where groundwater quality is at risk. No long-term increasing salinity trends were observed in the upper aquifer; however, two monitoring bores were identified as having short-term increasing salinity trends (GW030431_1 and GW036231_1). The risk to water quality is greatest at monitoring bore GW030431_1, located in the central part of Zone 3, where salinity (EC) increased by 27% within the last two years. The increasing salinity at this monitoring bore means that groundwater at this location is no longer suitable for some stock.

Groundwater quality within the Gunnedah Formation is generally of better quality (lower salinity) than the overlying Narrabri Formation. However, results of trend analysis indicate that water quality is at risk from increasing salinity at a number of locations. Long term increasing salinity trends have been detected at monitoring bores GW036038_3, GW036166_1 and GW036213_2. Long term salinity changes are greatest at GW036166_1 and GW036213_2, where EC has increased by 129% and 152%, respectively. Both monitoring bores are located in the north-eastern part of Zone 3, and the long term EC changes have resulted in the beneficial use being degraded. Short-term increasing trends were observed at these 3 monitoring bores, as well as GW030431_2, GW036150_1, GW036213_3 and GW036231_2, with the greatest short-term increase occurring at GW036150_1 (505%). Short-term increases in EC have resulted in the beneficial use being degraded at a number of monitoring bores in the northern part of Zone 3.

The increasing salinity in the Gunnedah Formation can be attributed to either vertical leakage of saline water from the upper to lower aquifer where aquitards are thin or absent, or to leakage of saline water from clay aquitards where pumping has resulted in depressurisation. The results of Mann-Kendall trend analysis highlight areas at risk, particularly in the northern part of the catchment. Future monitoring needs to be focused in these areas.

Table 4-8 Short- and long-term trends, Gunnedah Formation, Zone 3 Upper Namoi GMA

	Short-term trends 2009–2011						Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030430_2	12	-	-	-	-	-	14	-	-	-	-	-	-
GW030430_3	11	-	-	-	-	-	12	-	-	-	-	-	-
GW030431_2	9	Increase	9,070	14,270	465	57	14	-	-	-	-	-	-
GW030431_3	12	-	-	-	-	-	18	-	-	-	-	-	Ca-Na-HCO3 to Na-Ca-HCO3
GW036038_2	11	-	-	-	-	-	13	-	-	-	-	-	Na-Ca-HCO3-Cl to Na-Ca-Mg-Cl-HCO3
GW036038_3	10	-	-	-	-	-	11	Increase	657 (12/95)	711	5	8	-
GW036150_1	8	Increase	2,180	13,250	505	508	11	-	-	-	-	-	Na-Cl to Na-Cl-SO4
GW036151_2	6	-	-	-	-	-	14	-	-	-	-	-	-
GW036166_1	10	Increase	7,490	12,600	280	68	12	Increase	5,500 (09/95)	12,600	270	129	Na-Cl-SO4 to Na-SO4-Cl
GW036166_2	10	-	-	-	-	-	11	-	-	-	-	-	Na-Cl-SO4 to Na-SO4-Cl
GW036166_3	9	-	-	-	-	-	11	-	-	-	-	-	-
GW036213_2	9	Increase	2,440	3,230	50	32	18	Increase	1,280 (07/02)	3,230	125	152	Ca-Mg-HCO3-Cl to Na-Ca-Mg-Cl-HCO3
GW036213_3	11	Increase	945	1,002	5	6	21	-	-	-	-	-	-
GW036231_2	10	Increase	1,060	1,277	20	20	12	-	-	-	-	-	-
GW053439_1	1	ID	ID	ID	ID	ID	1	ND	ND	ND	ND	ND	ID
GW060216_1	1	ID	ID	ID	ID	ID	1	ND	ND	ND	ND	ND	ID
GW902011_1	N	ND	ND	ND	ND	ND	1	ID	ID	ID	ID	ID	ID

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

5. Lower Namoi GMA

5.1 Characterisation of the study area

The Lower Namoi GMA is located in north-western New South Wales, extending from Narrabri in the east to Walgett in the west (Figure 5-1). It is a broad infill fan comprising unconsolidated deposits of Cenozoic alluvium covering approximately 7,600 km^2.

5.1.1 Topography and surface hydrology

Within the Lower Namoi GMA, the most prominent topographic feature in the catchment is the Nandewar Range lying on the eastern border reaching 1,508 m above mean Australian sea level at Mt Kaputar. Elevation declines from 220 m at Narrabri to approximately 130 m at the western extremity of the catchment on the alluvial plains near Walgett. Apart from the Nandewar Ranges, the topography to the west of Narrabri is dominated by gently sloping plains of which more than 80% have slopes less than 3% and can be classified as almost entirely flat land. Minor variations in elevation do occur in the catchment and are associated with prior stream formations and river terracing. Land to the south and southwest of the catchment gradually rises to approximately 400 m along the catchment boundary on the dissected sandstone of the Pilliga Plateau.

The Namoi River flows in a westerly direction from its headwaters in the Great Dividing Range where it originates as the McDonald River. The main tributary of the Namoi River is the Peel River which joins the Namoi River near Gunnedah. Other major tributaries include the Manilla River which flows into Split Rock Dam, Coxs Creek and the Mooki and Cockburn rivers which join the Namoi upstream of Boggabri. The Namoi River then flows westerly across the western plains and joins the Barwon River near Walgett. The main effluents of the Namoi River are Pian Creek, Gunidgera Creek and Drildool Creek which all depart from the right bank of the river near the town of Wee Waa. These creeks all re-enter the Namoi River at various points downstream. Gunidgera Creek re-joins upstream of the township of Pilliga and Pian Creek rejoins 16 km upstream of the Namoi-Barwon confluence.

Three dams regulate flow in the Namoi catchment. Keepit Dam on the Namoi River upstream of the Peel River confluence was constructed in 1960 and has a storage capacity of 423 GL ML. Split Rock Dam on the Manilla River was constructed in 1988 and has a maximum storage capacity of 397 GL. Chaffey Dam on the Peel River upstream of Tamworth was constructed in 1979 and has a maximum storage capacity of 62 GL. Additionally a series of weirs regulate flow downstream of Keepit Dam at Mollee and Gunidgera.

5.1.2 Climate

The Lower Namoi GMA is semi-arid and experiences an east-west climatic gradient, with average annual rainfall decreasing from 646 mm at Narrabri in the east of the GMA (BoM station 54120 Narrabri West Bowling Club) to 483.1 mm at Walgett in the west of the GMA (BoM station 52026 Walgett Council Depot).

The closest BoM stations to the study area are stations 52001 Burren Junction (Hastings St) and station 52003 Cryon (Koothney), which have long term average annual rainfalls of 506.4

mm and 497.4 mm, respectively. Long term average monthly rainfall and monthly rainfall for the current study period (2009–2011) for these two BoM stations is shown on Figures 5-2 and 5-3.

Historically, almost 50% of rainfall occurs from November to February. During the study period, monthly rainfall was typically below average for 2009 and above average in 2010, with the exception of January and April to June. Monthly rainfall was below average in the early part of 2011. Daily rainfall for the monitoring period is shown on the hydrographs in Appendix D.

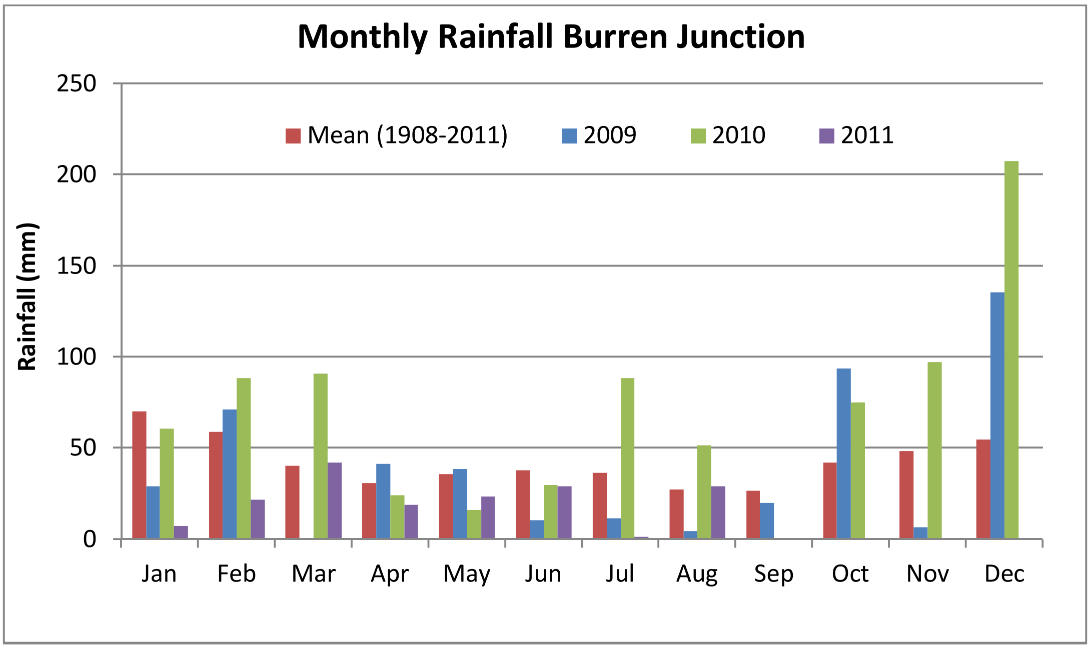


Figure 5-2 Average monthly rainfall, BoM station 52001 Burren Junction (Hastings St)

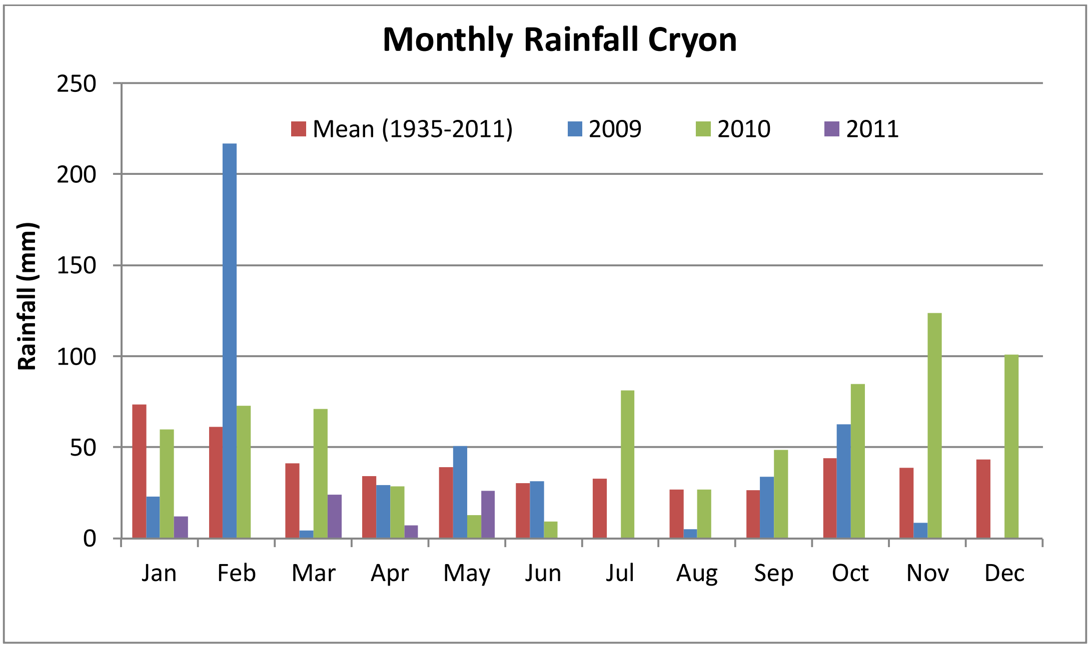


Figure 5-3 Average monthly rainfall, BoM station 52003 Cryon (Koothney)

The long-term cumulative rainfall residual for Burren Junction and Cryon are shown on Figure 5-4. As seen in Figure 5-4, the periods of 1965–1971, 1978–1983, 1991–1997 and 2000–2007 saw decreasing rainfall. From 2007–2010, rainfall has tended to be above long term averages.

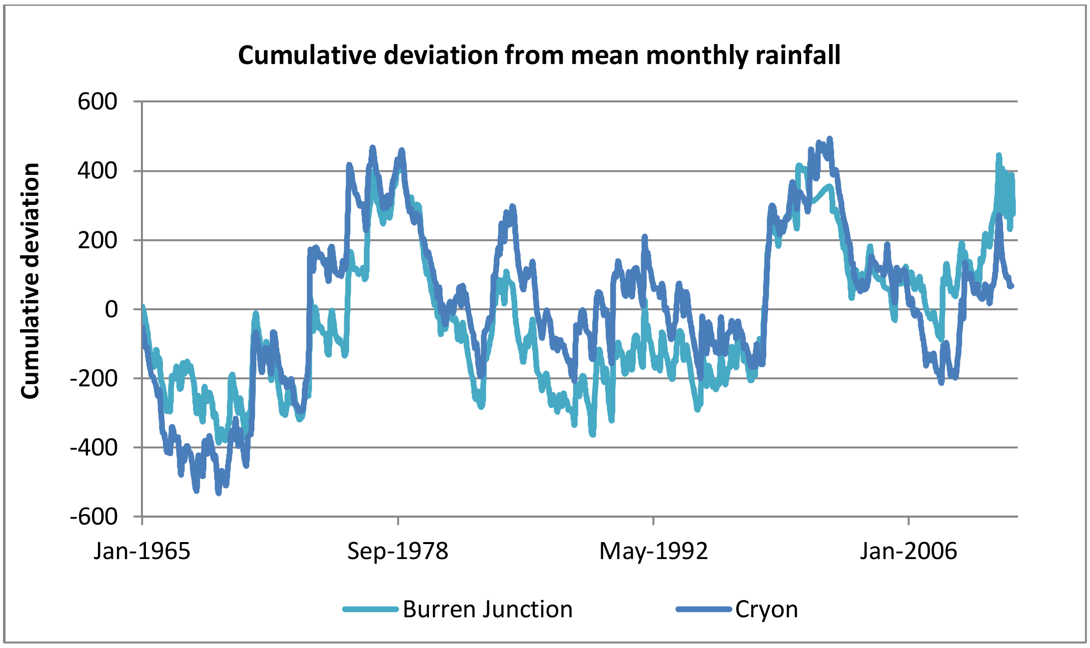


Figure 5-4 **Cumulative deviation from mean monthly rainfall, Burren Junction and Cryon (1965–2011)**

5.1.3 Land use

Land use overlying the Lower Namoi GMA comprises irrigated cropping, grazing, dryland cropping and horticulture. Cotton is the primary crop grown in the eastern part of the GMA, centred on the towns of Wee Waa and Narrabri. Other crops grown include soybeans, sunflowers, barley, sorghum, and wheat. In the west of the GMA, dryland agriculture still predominates with sheep and wheat the main agricultural resources.

5.1.4 Hydrogeology

The Lower Namoi GMA has three major layers or hydrostratigraphic units, which have been classified as the following (Williams 1986):

- Narrabri Formation (upper aquifer) – Quaternary fluviatile unit consisting dominantly of brown clay with minor sand and gravel with sporadic calcareous and ferruginous nodules.
- Gunnedah Formation (middle aquifer) – Pliocene fluvio-lacustrine that consists of moderately well sorted sand and gravels interbedded with predominantly brown to yellow clays.
- Cubbaroo Formation (lower aquifer) – Mid-Miocene fluviatile unit that consists of quartz sand and gravel supported by a clay matrix with minor carbonaceous stringers.

The Narrabri Formation conformably overlies the Gunnedah Formation and ranges in thickness from 10–40 m. The high clay content of the Narrabri Formation results in this formation being exploited as a secondary aquifer yielding small quantities of fresh to saline groundwater. Transmissivities are less than 200 m^2/day (Barrett et al. 2006). The Gunnedah Formation overlies the Cubbaroo Formation and is generally less than 40 m thick (Barrett et al. 2006). The Cubbaroo Formation is up to 50 m thick and is confined to the main paleochannel that runs north-northwest of the present river course. The Gunnedah Formation overlies the Cubbaroo Formation and has transmissivities ranging from 200 to 800 m^2/day (Barrett et al. 2006).

Regionally, groundwater gradients indicate flow in a north westerly to westerly direction away from the Namoi River. The groundwater system is mainly recharged in the eastern part of the catchment from the Namoi River and tributaries and diffuse recharge is believed to occur during major flooding events. In the western part of the catchment, an unsaturated zone develops where the watertable falls below streams and infiltration of surface water to the underlying aquifer takes place through an unsaturated zone. At the far western edge of the GMA, watertables are closer to the surface and conditions become saturated again (CSIRO 2007). Other contributions come from diffuse infiltration of rainfall, leakage from GAB, inflow from the neighbouring catchments to the southeast and northwest and on-farm water losses. Groundwater salinity increases away from the main recharge areas in the eastern part of the GMA, increasing from the mean Namoi River EC value of 560 µS/cm to over 30,000 µS/cm in the upper aquifer (Barrett et al. 2006).

Generally in the eastern part of the catchment there is downward movement of groundwater from the Narrabri to the Gunnedah Formation and vertical hydraulic gradients are reversed at the western margin of the GMA. However, in areas of heavy abstraction there has been some reversal of vertical hydraulic gradients.

In general, groundwater levels in the Lower Namoi GMA have been declining since the late 1960s/early 1970s. Water levels stabilised or recovered during a period of reduced extraction during 1996–2001; however, since 2001 water levels have continued to decline due to the onset of drought and drawdown has reached up to 40% of the saturated thickness in large areas of the GMA. During pumping up to 60% of the saturated thickness is being drawn down in some areas (Smithson 2009).

Within the current study area centred on Cryon the development of groundwater commenced in the 1980/81 water year (Barrett 2006). The earliest groundwater monitoring in the area commenced in 1978. Hydrograph data for these monitoring bores is shown on Figure 5-5 and a brief summary of groundwater level trends is given in Table 5-1.

Table 5-1 Hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long term hydrogeological conditions
GW036280_1	31.9–34.4	NF	Pipe 1 shows a dampened water level response indicating there is only a limited connection between the Narrabri Formation and deeper aquifers at this location. Water levels in Pipe 3 show large seasonal fluctuations (up to 37 m) and since monitoring commenced the total recovery decline is ~3 m.
GW036280_3	101.0–107.0	CF	
GW036314_1	29.0–30.0	NF	Pipe 1 shows a dampened water level response indicating there is only a limited connection between
GW036314_2	51.0–54.0	GF	

Bore No.	Slotted interval (mbgl)	Aquifer	Long term hydrogeological conditions
GW036314_3	60.0–64.0	GF	the Narrabri Formation and deeper aquifers at this location. Water levels in Pipe 2 and Pipe 3 show similar water level behaviour indicating a hydraulic connection. Prior to development, the pressure head of the deeper aquifer was ~0.2 m above that of the shallow aquifer. Since development there has been a reversal of the vertical hydraulic gradient. Large seasonal drawdowns are evident in Pipes 2 and 3, and since development the total recovery decline is ~1.5 m.
GW036320_1	35.0–38.0	NF	Pipe 1 shows a dampened water level response indicating there is only a limited connection between the Narrabri Formation and deeper aquifers at this location. Pipe 2 and Pipe 3 show similar water level behaviour indicating a hydraulic connection. Prior to development, the pressure head of the deeper aquifer was ~0.3 m above that of the shallow aquifer. Since development there has been a reversal of the vertical hydraulic gradient. Large seasonal drawdowns are evident in Pipes 2 and 3, and since development the total recovery decline is ~3 m.
GW036320_2	54.3–55.5	GF	
GW036320_3	64.5–68.8	GF	
GW036340_1	37.0–40.0	NF	Water levels in all three pipes are similar, showing that the three aquifers are hydraulically connected at this location. Seasonal water level variations up to ~7m are evident in all three pipes and the long term recovery decline is ~3 m
GW036340_2	82.0–88.0	GF	
GW036340_3	105.0–107.0	CF	
GW036364_1	34.0–38.0	GF	Pipe 1 shows a dampened water level response indicating there is only a limited connection between the Narrabri Formation and deeper aquifers at this location. All three pipes show seasonal drawdowns, with the greatest drawdowns occurring in Pipe 3 (10 m). Long term recovery drawdowns in Pipe 3 are ~4 m.
GW036364_2	82.0-88.0	GF	
GW036364_3	105.0–117.0	CF	
GW036377_1	29.0–33.0	NF	Since monitoring commenced there has been a reversal of vertical hydraulic gradients at this location, with current water levels in Pipe 1 ~0.75 m above Pipe 2. Pipe 1 shows a dampened water level response indicating there is only a limited connection between the Narrabri Formation and Gunnedah Formation at this location. Seasonal drawdowns of up to ~7 m occur in Pipe 2.
GW036377_2	73.0–81.0	GF	
GW036398_1	73.1–79.2	GF	Water levels in Pipe 1 and Pipe 2 are very similar

Bore No.	Slotted interval (mbgl)	Aquifer	Long term hydrogeological conditions
GW036398_2	109.7–115.8	CF	showing that the two deep aquifers are hydraulically connected at these locations. Large seasonal drawdowns are evident (up to 33 m) and occasional seasonal reversals of hydraulic gradient occur. Long term recovery declines in both pipes is ~2.5 m.
GW036406_1	57.9–64.0	GF	Water levels only show small seasonal fluctuations and show no real declining trend. Water levels in Pipe 1 are higher than Pipe 2, showing a downward vertical hydraulic gradient.
GW036406_2	106.6–112.7	CF	

Note: NF-Narrabri Formation, GF-Gunnedah formation, CF-Cubbaroo Formation.

5.2 Characterisation of groundwater chemistry (2009-2011)

Groundwater sampling was undertaken in 13 sampling rounds during the study period (October 2009 to January 2011). 22 monitoring bores were sampled during the study period, with 5 located in the Narrabri Formation, 12 located in the Gunnedah Formation and 5 located in the Cubbaroo Formation.

As the study area for the Lower Namoi is centred on the Cryon area, groundwater chemistry trends geographically across the catchment cannot be determined. Groundwater chemistry interpretation is for the Cryon area only and no assumptions can be made on changes with chemistry along the flow paths in the Lower Namoi GMA.

5.2.1 Results

Groundwater chemistry statistics are summarised in Tables 5-2, 5-3 and 5-4 for the Narrabri, Gunnedah and Cubbaroo formations respectively. The results are presented on a cross-section (Figure 5-6). The location of the cross-section is shown on Figure 5-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 5-7, 5-8 and 5-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix D.

A Piper diagram presenting results for the Narrabri, Gunnedah and Cubbaroo formations is presented in Figure 5-10.

Stable isotope data (^{18}O and ^{2}H) was collected for several monitoring rounds and is presented in Figures 5-11 and 5-12.

Table 5-2 Lower Namoi Narrabri Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	50	50	3800	22000	10286	9200	4810
EC (lab)	µS/cm	50	50	6460	29500	14148	1270	5508
pH (field)	pH unit	44	44	6.79	7.71	7.30	7.28	0.26
K	mg/L	50	50	2.0	7.5	4.6	4.5	1.3
Na	mg/L	50	50	1100	6300	2922	2650	1344
Ca	mg/L	50	50	74	730	291	255	180
Mg	mg/L	50	50	83	950	357	320	230
Cl	mg/L	50	50	1600	10000	4766	4650	2379
SO_4	mg/L	50	50	240	3400	1498	990	998
Alkalinity ($CaCO_3$)	mg/L	50	50	180	410	261	240	82
CO_3	mg/L	50	7	0.5	16.0	1.6	0.5	3.3
HCO_3	mg/L	50	50	200	500	317	290	101
Si	mg/L	50	50	4.8	15.0	10.1	10.0	1.6
F	mg/L	50	29	<0.1	1.40	0.25	0.17	0.28
Al (soluble)	mg/L	50	43	<0.01	1.600	0.061	0.025	0.223
B (soluble)	mg/L	50	49	<0.1	1.00	0.37	0.30	0.26
Br (soluble)	mg/L	50	50	5.1	40.0	17.4	14.5	9.3
Cu (soluble)	mg/L	50	19	<0.01	1.000	0.123	0.005	0.257
Mn (soluble)	mg/L	50	38	<0.002	0.170	0.014	0.003	0.034
Pb (soluble)	mg/L	8	1	<0.1	0.08	0.02	0.01	0.02
Sr (soluble)	mg/L	50	50	2.7	27.0	10.4	8.5	6.6
Zn (soluble)	mg/L	50	48	<0.005	2.000	0.095	0.046	0.282
Mn (total)	mg/L	50	50	0.002	0.380	0.046	0.011	0.083
Ni (total)	mg/L	50	15	<0.01	0.042	0.009	0.005	0.007
Zn (total)	mg/L	50	50	0.011	0.360	0.074	0.065	0.063
Al (total)	mg/L	50	47	<0.05	15.000	2.157	0.300	3.637
B (total)	mg/L	50	49	<0.1	1.00	0.35	0.20	0.23
Cu (total)	mg/L	50	34	<0.005	2.000	0.174	0.009	0.454
Fe (total)	mg/L	50	42	<0.05	17.000	2.041	0.270	3.744
Pb (total)	mg/L	50	9	<0.1	0.06	0.01	0.01	0.01
N_2	mg/L	50	50	0.13	6.60	1.22	0.34	1.90
NH_3	mg/L	50	20	<0.01	0.560	0.035	0.005	0.086
NO_3	mg/L	10	10	1.10	6.10	3.94	4.30	1.60
PO_4	mg/L	50	49	<0.005	0.281	0.019	0.013	0.038
Total P	mg/L	50	50	0.006	0.358	0.060	0.022	0.088

Note: SD – standard deviation

Table 5-3 Lower Namoi Gunnedah Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	124	124	460	11000	2776	1900	2491
EC (lab)	µS/cm	124	124	746	16600	4511	3325	3595
pH (field)	pH unit	110	110	6.99	7.82	7.42	7.44	0.24
K	mg/L	124	124	0.7	7.2	2.5	2.1	1.4
Na	mg/L	124	124	100	3100	854	615	720
Ca	mg/L	124	124	5	310	68	37	78
Mg	mg/L	124	124	4	380	74	39	95
Cl	mg/L	124	124	110	5500	1314	840	1354
SO_4	mg/L	124	124	40	1100	262	170	253
Alkalinity ($CaCO_3$)	mg/L	124	124	62	260	214	220	32
CO_3	mg/L	124	19	0.5	15.0	1.6	0.5	3.3
HCO_3	mg/L	124	124	75	320	259	270	40
Si	mg/L	124	124	4.7	33.0	16.4	14.0	6.3
F	mg/L	124	74	<0.1	0.74	0.12	0.11	0.08
Al (soluble)	mg/L	124	35	<0.01	0.080	0.010	0.005	0.012
B (soluble)	mg/L	124	24	<0.1	0.30	0.07	0.05	0.05
Br (soluble)	mg/L	124	123	<0.2	23.0	4.7	2.9	5.0
Cu (soluble)	mg/L	124	6	<0.01	0.390	0.008	0.005	0.035
Mn (soluble)	mg/L	124	87	<0.002	0.320	0.041	0.004	0.072
Pb (soluble)	mg/L	6	0	Not calculated				
Sr (soluble)	mg/L	124	124	0.15	12.00	2.20	1.20	2.88
Zn (soluble)	mg/L	124	111	<0.005	0.130	0.032	0.017	0.031
Mn (total)	mg/L	124	100	<0.002	0.330	0.043	0.007	0.071
Ni (total)	mg/L	124	9	<0.01	0.021	0.006	0.005	0.002
Zn (total)	mg/L	124	112	<0.01	0.690	0.042	0.020	0.067
Al (total)	mg/L	124	61	<0.05	2.400	0.136	0.025	0.318
B (total)	mg/L	124	32	<0.1	0.3	0.074	0.05	0.0515
Cu (total)	mg/L	124	17	<0.005	1.000	0.012	0.003	0.090
Fe (total)	mg/L	124	64	<0.05	2.100	0.131	0.050	0.288
Pb (total)	mg/L	124	6	<0.1	0.034	0.010	0.01	0.0033
N_2	mg/L	124	107	<0.05	0.530	0.140	0.120	0.094
NH_3	mg/L	124	33	<0.01	0.190	0.012	0.005	0.021
NO_3	mg/L	1	1	Not calculated				
PO_4	mg/L	124	122	<0.005	0.378	0.084	0.044	0.096
Total P	mg/L	124	124	0.007	0.376	0.099	0.063	0.093

Note: SD – standard deviation

Table 5-4 Lower Namoi Cubbaroo Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	47	47	520	6500	2123	1600	1851
EC (lab)	µS/cm	47	47	890	10700	3439	2600	2846
pH (field)	pH unit	39	39	6.71	7.70	7.29	7.39	0.28
K	mg/L	47	47	0.9	5.0	2.4	2.2	1.1
Na	mg/L	47	47	200	1800	668	530	498
Ca	mg/L	47	47	3	200	47	30	60
Mg	mg/L	47	47	2	240	50	19	76
Cl	mg/L	47	47	97	3100	877	670	893
SO_4	mg/L	47	47	10	1000	287	200	291
Alkalinity ($CaCO_3$)	mg/L	47	47	210	290	243	250	28
CO_3	mg/L	47	5	0.5	16.0	1.7	0.5	3.7
HCO_3	mg/L	47	47	230	350	295	290	35
Si	mg/L	47	47	9.4	18.0	12.6	12.0	2.0
F	mg/L	47	41	<0.1	0.37	0.21	0.18	0.10
Al (soluble)	mg/L	47	10	<0.01	0.030	0.008	0.005	0.007
B (soluble)	mg/L	47	15	<0.1	0.20	0.07	0.05	0.04
Br (soluble)	mg/L	47	47	0.3	12.0	3.1	2.3	3.2
Cu (soluble)	mg/L	47	2	<0.01	0.020	0.006	0.005	0.003
Mn (soluble)	mg/L	47	42	<0.002	0.180	0.069	0.056	0.059
Pb (soluble)	mg/L	2	0	Not calculated				
Sr (soluble)	mg/L	47	47	0.095	6.200	1.436	0.880	1.895
Zn (soluble)	mg/L	47	39	<0.005	0.130	0.032	0.014	0.035
Mn (total)	mg/L	47	43	<0.002	0.180	0.071	0.060	0.060
Ni (total)	mg/L	47	3	<0.01	0.011	0.005	0.005	0.001
Zn (total)	mg/L	47	41	<0.01	0.260	0.047	0.020	0.051
Al (total)	mg/L	47	22	<0.05	0.250	0.062	0.025	0.056
B (total)	mg/L	47	24	<0.1	0.20	0.09	0.10	0.05
Cu (total)	mg/L	47	5	<0.005	0.060	0.005	0.003	0.010
Fe (total)	mg/L	47	41	<0.05	1.900	0.469	0.170	0.585
Pb (total)	mg/L	47	2	<0.1	0.03	0.01	0.01	0.00
N_2	mg/L	47	46	<0.05	1.100	0.323	0.230	0.257
NH_3	mg/L	47	37	<0.01	0.380	0.144	0.110	0.126
NO_3	mg/L	2	2	0.80	0.90	0.85	0.00	0.07
PO_4	mg/L	46	46	0.015	0.750	0.266	0.259	0.239
Total P	mg/L	47	47	0.040	1.260	0.310	0.304	0.254

Note: SD – standard deviation

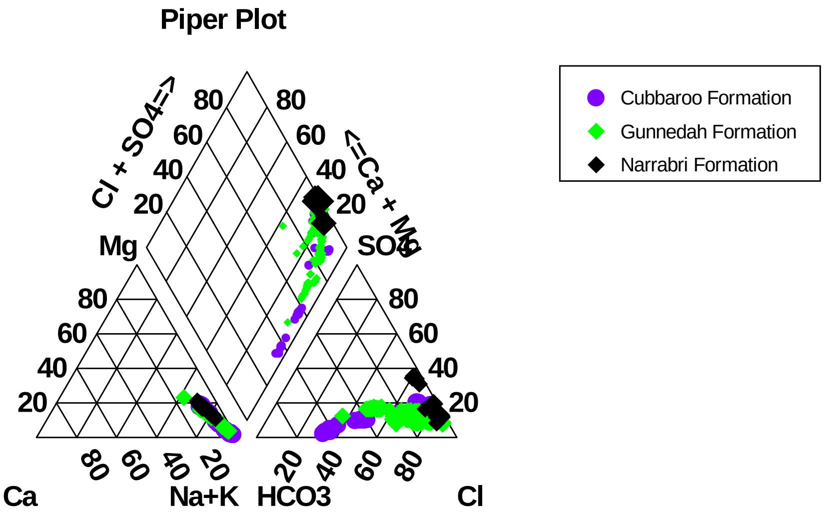


Figure 5-10 **Piper diagram for the Narrabri and Gunnedah formations during the study period**

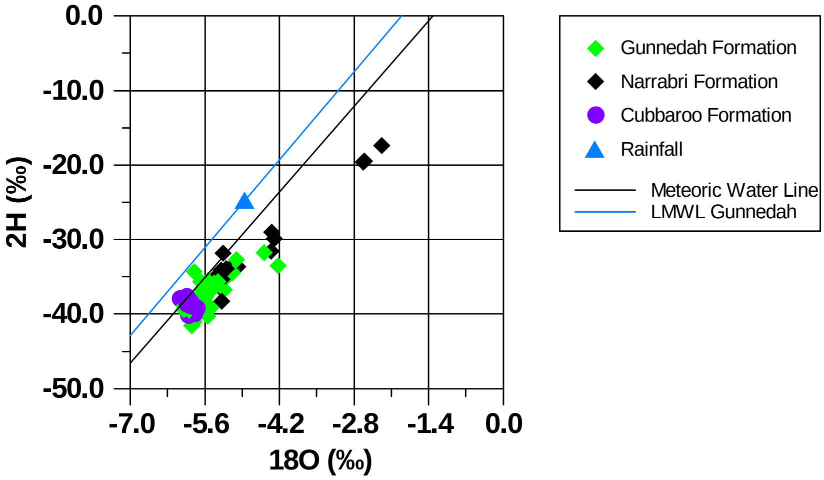


Figure 5-11 **Oxygen-18 versus deuterium for groundwater samples from the Lower Namoi (Cryon)**

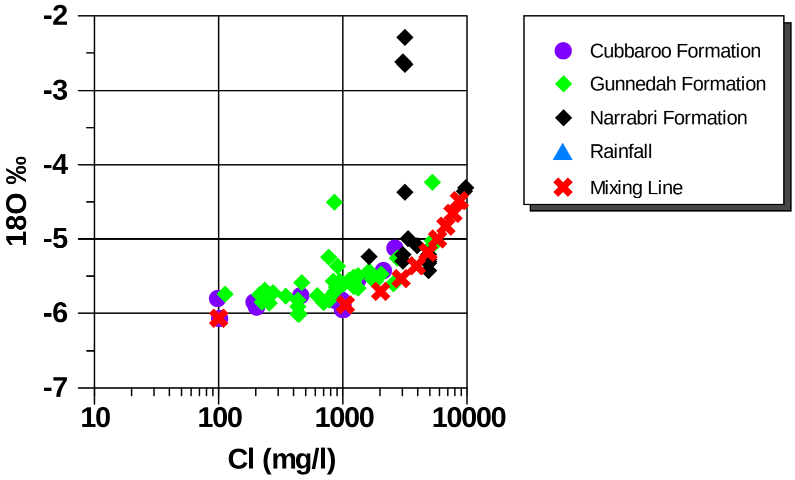


Figure 5-12 Oxygen-18 versus chloride for groundwater samples from the Lower Namoi (Cryon)

5.2.1.1 Narrabri Formation

Water quality parameters

Groundwater salinity in the Narrabri Formation in the Cryon area is saline, ranging from 6,460 µS/cm (GW036340_1) to 29,550 µS/cm (GW036314_1) (Figure 5-8).

The pH conditions of the Narrabri Formation ranged from near neutral (6.79) to slightly alkaline (7.71). Near neutral pH conditions are typical in aquifers where silicate or chemical weathering is buffering against acidification.

Major and minor ions

Major ion chemistry in the Narrabri Formation was dominated by sodium and chloride in the Cryon area. Two monitoring locations (GW036280_1 and GW036314_1) were dominated by sulphate on at least one occasion. GW036314_1 was also dominated by magnesium in 30% of sampling rounds. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix D.

Dissolved silicon concentrations in the Narrabri Formation ranged from 4.8 mg/L to 15 mg/L, with an average concentration of 10 mg/L.

Bromide was detected in all samples, concentrations ranged from 5 mg/L to 40 mg/L. The highest concentrations were associated with the highest salinities.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Dissolved and total boron concentrations were detected in 98% of samples. Dissolved and total boron concentrations were similar ranging from the LOR (<0.1 mg/L) to 1 mg/L.

Only total iron was analysed in the Lower Namoi. Total iron was detected in 84% of samples from the Narrabri Formation. Concentrations ranged up to 17 mg/L.

Dissolved and total manganese were detected in the majority of samples. Maximum dissolved and total manganese concentrations were relatively low (0.17 and 0.38 mg/L respectively).

Strontium was detected in all samples, ranging from 2.7 mg/L to 27 mg/L. A correlation between strontium and salinity was determined.

Nutrients

Total nitrogen and total phosphorus concentrations were recorded at all Narrabri Formation monitoring bores. Total nitrogen concentrations were typically below 1 mg/L. Total phosphorus concentrations were typically (84%) below 0.1 mg/L.

Nitrate was only analysed for 20% of samples and was only analysed at GW036280_1. Nitrate concentrations at GW036280_1 ranged from 1.1 mg/L to 6.1 mg/L. Nitrate can be derived from natural sources such as soil degradation or from anthropogenic sources such as nitrogen based fertiliser application.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for groundwater samples collected in November/December 2009 and January, July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^{2}H = 8.41\delta^{18}O + 15.99$) (Timms and Acworth 2002) on Figure 5-11.

Fourteen groundwater samples from the Narrabri Formation for analysed for stable isotopes. Stable isotope values for the shallow aquifer ranged from -5.43‰ to -2.29‰ for $\delta^{18}O$, and -38.3‰ to -17.4‰ for $\delta^{2}H$, and samples plotted to the right of the LMWL and GMWL.

5.2.1.2 Gunnedah Formation

Water quality parameters

Groundwater salinity in the Gunnedah Formation in the Cryon area ranges from fresh, 746 µS/cm (GW036406_1) to saline, 16,600 µS/cm (GW036364_1) (Figure 5-8). Groundwater salinity is typically fresher in the Gunnedah Formation in comparison with the overlying Narrabri Formation.

The pH conditions of the Gunnedah Formation were similar to the Narrabri Formation and ranged from near neutral (6.99) to slightly alkaline (7.82).

Major and minor ions

Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix D. Major ion chemistry for all samples from the Gunnedah Formation is compared to groundwater from the Narrabri and Cubbaroo formations. Major ion proportions for groundwater samples collected form monitoring bores within the Gunnedah Formation show a constrained trend, reflecting mixing between a fresh $NaHCO_3$-Cl type groundwater with more saline Na-Cl type groundwater.

Dissolved silicon concentrations in the Gunnedah Formation ranged from 5 mg/L to 33 mg/L, with an average concentration of 16 mg/L, and were generally higher than the Narrabri Formation.

Bromide was detected in 99% of samples, concentrations ranged from <0.2 mg/L to 23 mg/L.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Namoi. Total iron was detected in 52% of samples ranging from 0.05 mg/L up to 2.1 mg/L. Low iron concentrations within the Gunnedah formation suggests that iron is mainly retained within sediments as ferrihydrite and iron oxides and hydroxides.

Dissolved and total manganese were detected in the majority of samples. Dissolved and total manganese concentrations were similar and relatively low, maximum concentrations were 0.32 mg/L and 0.33 mg/L respectively.

Dissolved and total zinc was detected in 90% of samples. Dissolved zinc ranged from <0.005 mg/L to 0.13 mg/L. Total zinc ranged from <0.01 mg/L to 0.69 mg/L.

Strontium was detected in all samples, ranging from 0.15 mg/L to 12 mg/L, with the highest concentrations associated with high salinities. McLean (20030 determined form strontium isotope analysis that elevated strontium concentrations were associated with the dissolution of salts entrained in clays.

Nutrients

Total nitrogen was recorded in 86% of samples. Total nitrogen concentrations ranged from <0.05 mg/L to 0.53 mg/L. Ammonia was detected in 27% of samples and ranged from 0.01 mg/L to 0.19 mg/L. Nitrate was only analysed for 1 out of 124 samples. Nitrate was only analysed at GW036314_2 (0.3 mg/L) in March 2010.

Total phosphorus concentrations were recorded at all Gunnedah Formation monitoring bores and ranged from 0.007 mg/L to 0.376 mg/L. Total phosphorus concentrations were typically (69%) below 0.1 mg/L.

Isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for groundwater samples collected in November/December 2009 and January, July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^{2}H = 8.41\delta^{18}O + 15.99$) (Timms and Acworth 2002) on Figure 5-11.

Forty-one samples from the Gunnedah Formation were analysed for stable isotopes. Stable isotope values for the shallow aquifer ranged from -6.01‰ to -4.21‰ for $\delta^{18}O$, and -41.6‰ to -31.8‰ for $\delta^{2}H$, and samples plotted on or slightly to the right of the GMWL.

5.2.1.3 Cubbaroo Formation

Water quality parameters

Groundwater salinity in the Cubbaroo Formation in the Cryon area ranges from fresh (890 µS/cm at GW036364_3) to saline (10,700 µS/cm at GW036280_3) (Figure 5-8). Groundwater salinity in the Cubbaroo Formation is generally better quality than the overlying Gunnedah Formation.

The pH conditions of the Cubbaroo Formation were similar to the overlying Gunnedah and Narrabri formations and ranged from near neutral (6.71) to slightly alkaline (7.70).

Major and minor ions

Major ion chemistry in the Cubbaroo Formation was typically dominated by sodium and chloride in the Cryon area. At the three monitored locations with the lowest salinity (GW036364_3, GW036398_2 and GW965760_1) bicarbonate was also dominant. Sulphate was also dominant at one monitoring location (GW036406_2). Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix D.

Dissolved silicon concentrations in the Cubbaroo Formation ranged from 9 mg/L to 18 mg/L, with an average concentration of 13 mg/L.

Bromide was detected in all samples, concentrations ranged from 0.3 mg/L to 12 mg/L.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Namoi. Total iron was detected in 87% of samples ranging from the LOR (0.05 mg/)L up to 1.9 mg/L.

Dissolved and total manganese were detected in the majority of samples. Dissolved and total manganese concentrations were similar and relatively low, maximum concentrations were both 0.18 mg/L.

Dissolved and total zinc were detected in 83% and 87% of samples respectively. Dissolved zinc ranged from <0.005 mg/L to 0.13 mg/L. Total zinc ranged from <0.01 mg/L to 0.26 mg/L.

Strontium was detected at all monitored bores, ranging from 0.095 mg/L to 6.2 mg/L, with the highest concentrations associated with high salinities.

Nutrients

Total nitrogen was recorded in 98% of samples. Total nitrogen concentrations ranged up to 1.1 mg/L. Ammonia was detected in 79% of samples and ranged from 0.02 mg/L to 0.38 mg/L. Nitrate was only analysed at one monitoring location (GW0362804_3) on two occasions, March (0.8 mg/L) and June (0.9 mg/L) 2010.

Total phosphorus concentrations were recorded at all Cubbaroo Formation monitoring bores and ranged from 0.04 mg/L to 1.26 mg/L (GW036364_3). Total phosphorus concentrations were higher in the Cubbaroo Formation than the two overlying formations (Gunnedah and Narrabri) and appear to be increasing with depth. Phosphorus in groundwater can be derived from natural processes such as the decay of organic matter or weathering processes, or agricultural sources such as fertilisers or animal manure.

Isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for groundwater samples collected in November/December 2009 and January, July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^{2}H = 8.41\delta^{18}O + 15.99$) (Timms and Acworth 2002) on Figure 5-11.

Stable isotope values for the deep aquifer ranged from -6.07‰ to -5.13‰ for $\delta^{18}O$, and -40.6‰ to -34.1‰ for $\delta^{2}H$. Samples from the Cubbaroo Formation (n=15) generally show the most depleted signatures and plot in a cluster close to the GMWL. The exception is GW036280_3 which has slightly more enriched signatures than the rest of the samples from the Cubbaroo Formation.

5.2.2 Processes

5.2.2.1 Narrabri Formation

Dissolution and precipitation

Major ion/chloride ratios are plotted versus chloride concentration to determine hydrogeochemical processes for groundwater in the Narrabri Formation (Figure 5-13). Sodium/chloride ratios were high at some monitoring locations (GW036280_1), indicating the addition of sodium to the system. No clear trends were identified for magnesium, sulphate and calcium to chloride ratios, indicating several processes affecting ion ratios may be occurring.

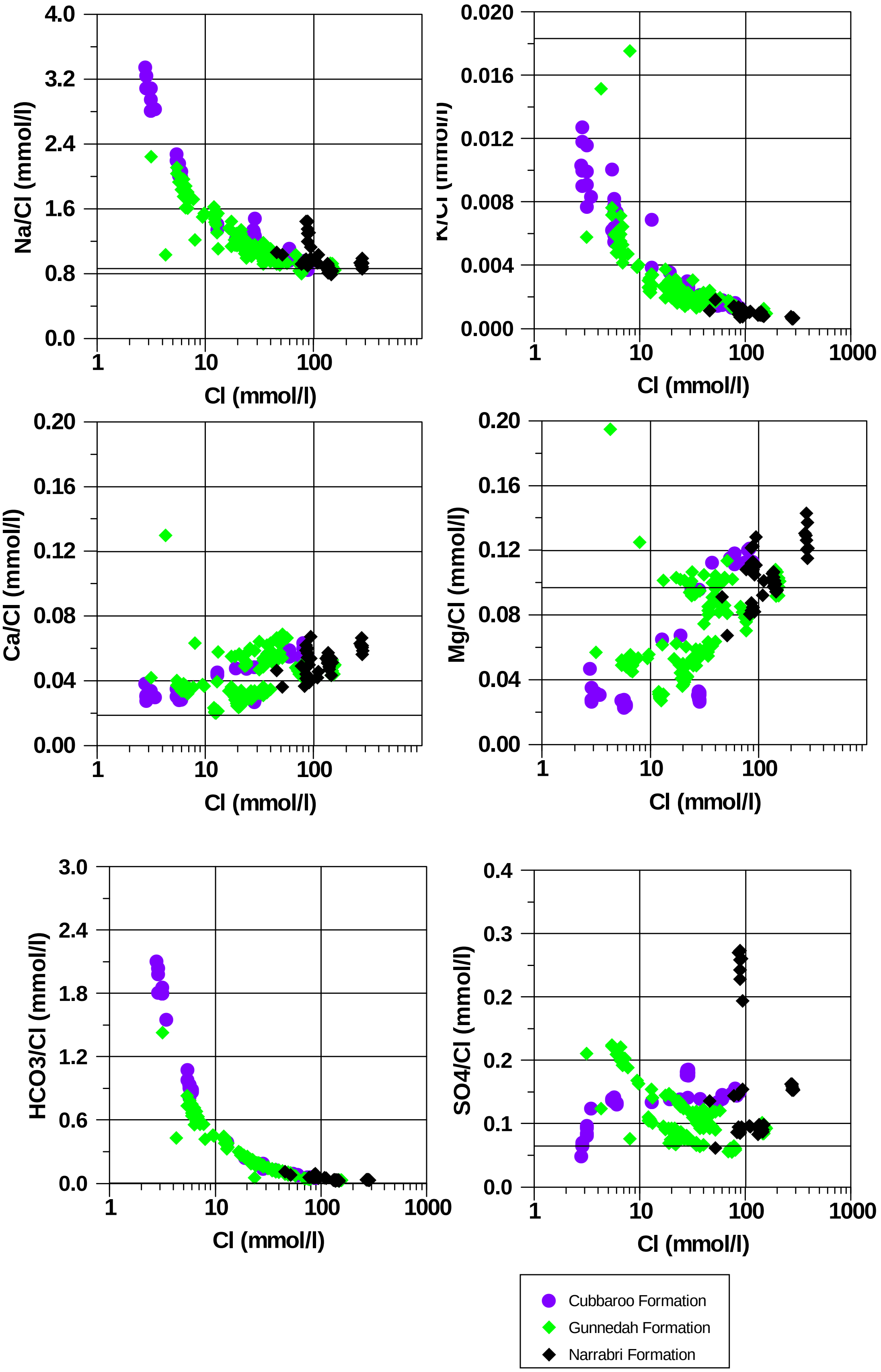


Figure 5-13 Ion/chloride versus chloride graphs for the Lower Namoi Catchment

Saturation indices for the Narrabri Formation are plotted in Figure 5-14. Lower salinity groundwater is under-saturated with respect to calcite and dolomite but becomes saturated with increasing salinity. With respect to gypsum and anhydrite this system does not become over-saturated. Montmorillonite typically is saturated in this system.

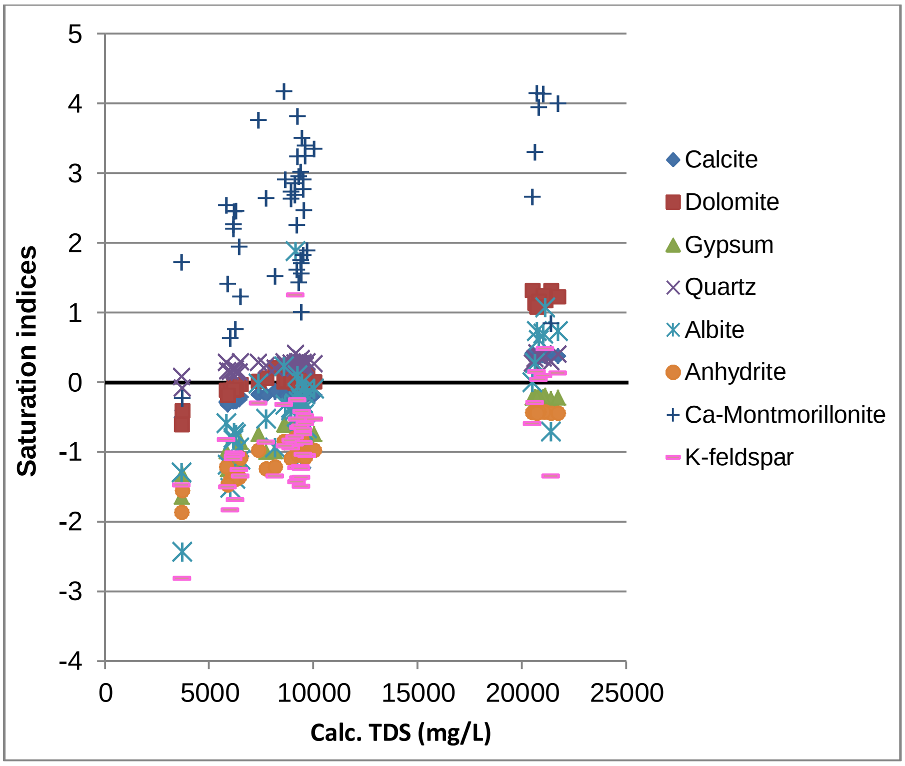


Figure 5-14 Saturation indices versus TDS for the Narrabri Formation

Ion exchange

Figure 5-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Groundwater in the Narrabri Formation is likely undergoing reverse ion exchange, as there is an excess of calcium and magnesium, resulting in the majority of samples plotting above the dissolution line. McLean (2003) identified that reverse ion exchange was an important geochemical process occurring in both the Narrabri and Gunnedah formations in the western part of the Lower Namoi GMA. Reverse ion exchange requires clay with exchangeable Ca^{2+} and Mg^{2+} (usually montmorillonite) and a flowing water of higher Na^{+} concentration relative to the clay matrix to drive the reaction as the system equilibrates. Williams (1986) identified that the percentage of clay in the Pleistocene and Pliocene sediments increases in the west as this distal section of the alluvial fan and the clay facies changes from kaolinite dominant to montmorillonite dominant.

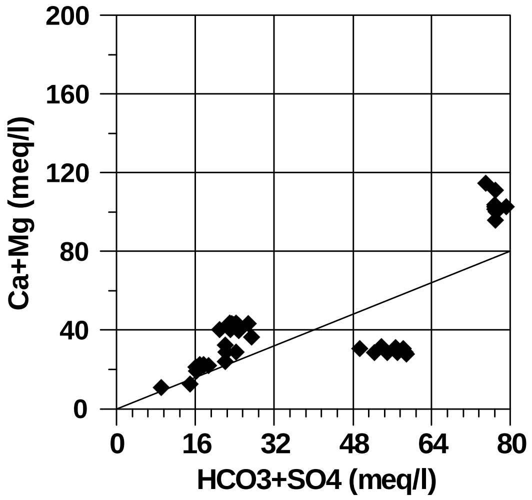


Figure 5-15 Calcium + magnesium versus bicarbonate + sulphate in the Narrabri Formation

Stable isotopes

Samples from the Narrabri Formation generally plotted closely to samples from the Gunnedah Formation, indicating the system is well mixed. There were two exceptions; samples from GW038280_1 from November and December 2009 were much more enriched than other samples from this monitoring bore and the other Narrabri Formation monitoring bores, suggesting that perhaps evaporation was occurring. However, since this monitoring bore is screened from 31.9 to 34.4 m bgl and water level was approximately 29 m bgl during this time, evaporative enrichment is discounted as possibility for isotopic enrichment.

5.2.2.2 Gunnedah Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 5-13). Major ion ratios showed curved trends on ion/chloride plots suggesting mixing between fresh and saline end member sis occurring, as well as other geochemical processes.

Saturation indices for the Gunnedah Formation are plotted in Figure 5-16. Lower salinity groundwater in the Gunnedah Formation is under-saturated with respect to calcite, dolomite, gypsum and anhydrite, but approaches saturation with increasing salinity. Montmorillonite and quartz are typically over-saturated in this system. McLean (2003) identified while weathering of aluminosilicate minerals was occurring in the eastern part of the catchment (recharge zone), transformation of kaolinite to montmorillonite is occurring in the western part of the catchment, hence groundwaters are over-saturated or are in equilibrium with montmorillonite.

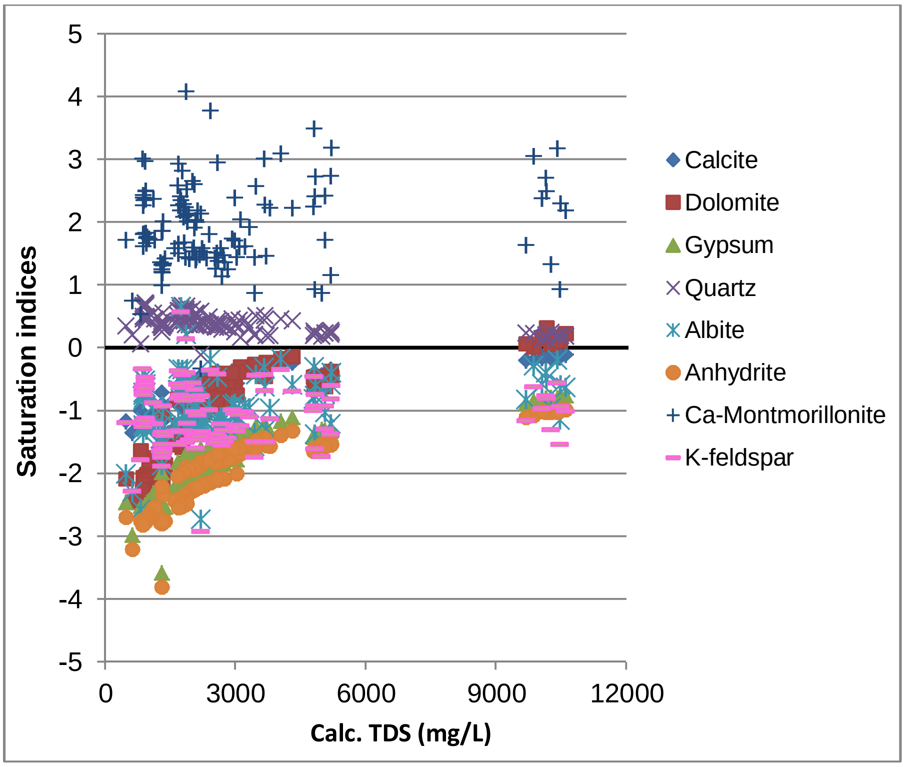


Figure 5-16 **Saturation indices versus TDS for the Gunnedah Formation**

Ion exchange

Figure 5-17 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Groundwater samples from the Gunnedah Formation typically plot below the 1:1 dissolution line and are indicative of ion exchange processes, although three of the monitoring locations plot above the dissolution line: GW036364_1, GW036320_2 and GW036398_1, indicating reverse ion exchange. This process is discussed in detail in Section 5.2.2.1. From Figure 5-17, there is also a distinct trend apparent of increasing Ca^{2+} + Mg^{2+} and SO_4^{2-}+ HCO_3^-, suggesting that mixing between a fresh and saline end member is also occurring.

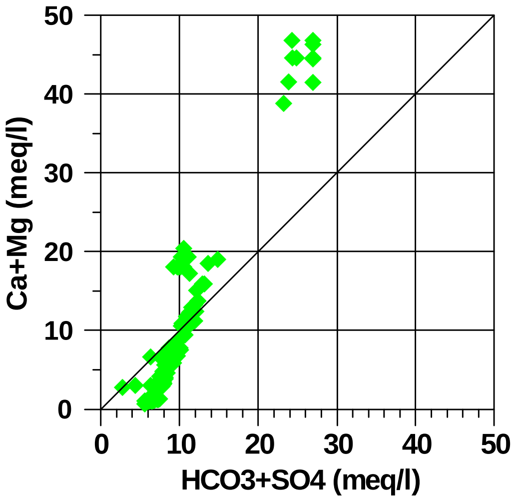


Figure 5-17 Calcium + magnesium versus bicarbonate + sulphate in the Gunnedah Formation

Stable isotopes

Groundwater samples from the Lower Namoi River (Cryon) plot along a regression line with the equation $\delta^2H = 5.8\delta^{18}O - 4.17$. Such a high slope could be attributed to evaporative concentration occurring at the groundwater surface under humidity of ~80% (Clark & Fritz 1997). However, given that samples are beyond the depth of active evaporative processes, and that radiocarbon dating by McLean (2003) indicates that groundwater in the Gunnedah Formation is >20,000 yrs BP in this part of the Lower Namoi, groundwater mixing and recharge under palaeoclimatic conditions is more likely to be responsible for the slope of 5.8, rather than evaporative processes. Figure 5-12 is a plot of $\delta^{18}O$ versus Cl^-, and shows a mixing curve between two groundwater end members; a fresh end member which has a depleted $\delta^{18}O$ signature, and a saline end member which has an enriched $\delta^{18}O$ signature. From 5-12 it is clear that the slope of the groundwater line is a largely a product of mixing between two groundwater end members, with many samples from the Gunnedah Formation falling on the mixing line. Since δ^2H and $\delta^{18}O$ are conservative tracers, the mixing ratio may be deduced if the isotopic signatures of end members are known (Clark and Fritz 1997). On this basis the isotopic signature of these mixed waters can be accounted for by about 10 to 40% enriched groundwater and 60–90% depleted groundwater.

5.2.2.3 Cubbaroo Formation

Dissolution and precipitation

Major ion/chloride ratios are plotted versus chloride concentration to determine hydrogeochemical processes (Figure 5-13). Na/Cl ratios show curved trends on ion/chloride plots suggesting mixing between fresh and saline end members is occurring, however, other ion/Cl ratios show a broader range of values and no specific trend, indicating other geochemical processes are occurring.

Saturation indices for the Cubbaroo Formation are plotted in Figure 5-18. Lower salinity groundwater in the Cubbaroo Formation is under-saturated with respect to calcite, dolomite, gypsum and anhydrite, but approaches saturation with increasing salinity. Montmorillonite and quartz are typically saturated in this system.

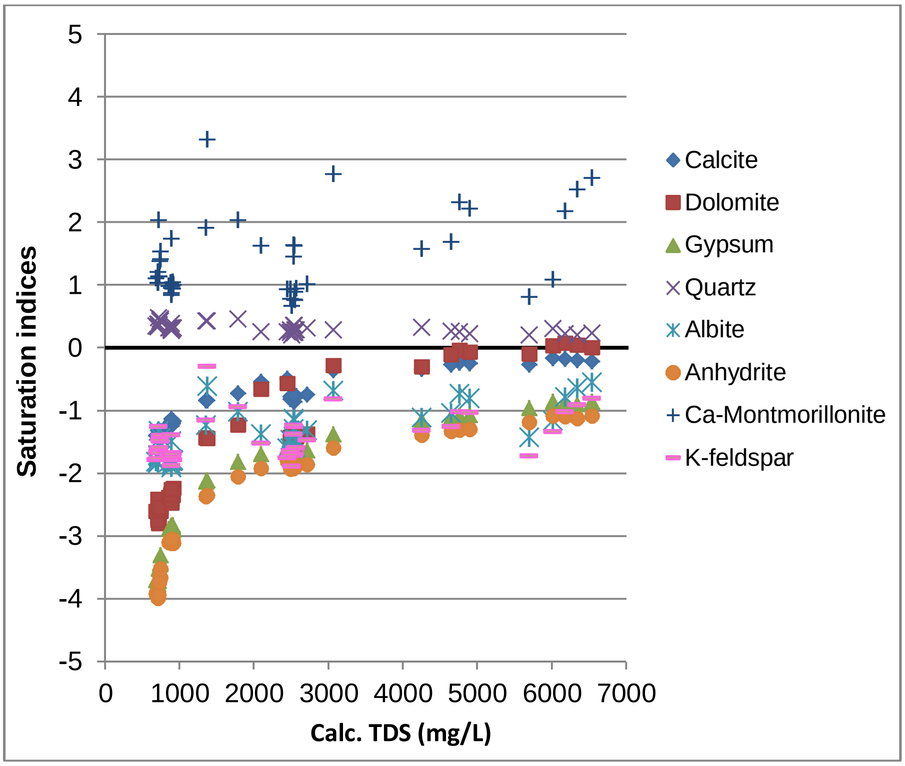


Figure 5-18 **Saturation indices versus TDS for the Cubbaroo Formation**

Ion exchange

Figure 5-19 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Some Cubbaroo Formation samples plot below the dissolution line indicating groundwater is likely undergoing ion exchange, however, other samples plot above the dissolution line indicating reverse ion exchange. As seen in Figure 5-19, there is also a distinct trend apparent of increasing Ca^{2+} + Mg^{2+} and SO_4^{2-}+ HCO_3^-, suggesting that mixing between a fresh and saline end member is also occurring.

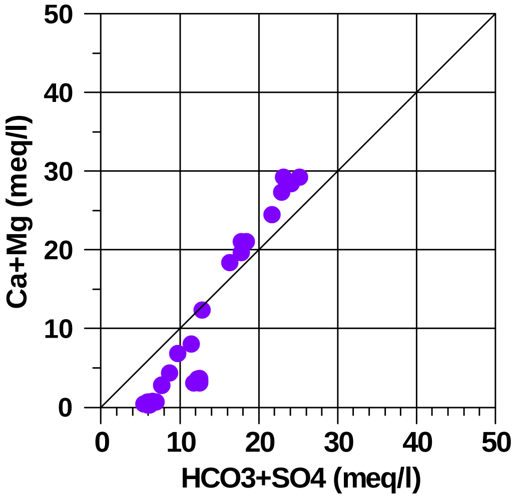


Figure 5-19 Calcium + magnesium versus bicarbonate + sulphate in the Cubbaroo Formation

Stable isotopes

Groundwater samples from the Cubbaroo Formation plot close to the GMWL (Figure 5-11), and plot close to many samples from the Gunnedah Formation indicating the system is well mixed. This is supported by the hydrograph data (Figure 5-5) which shows in the vicinity of Cryon, the Gunnedah and Cubbaroo formations are hydraulically connected.

Figure 5-12 is a plot of $\delta^{18}O$ versus Cl^-, and shows a mixing curve between two groundwater end members; a fresh end member which has a depleted $\delta^{18}O$ signature, and a saline end member which has an enriched $\delta^{18}O$ signature. From 5-12 it is clear that the slope of the groundwater line is a largely a product of mixing between two groundwater end members, with many samples from the Cubbaroo Formation falling on the mixing line. Since δ^2H and $\delta^{18}O$ are conservative tracers, the mixing ratio may be deduced if the isotopic signatures of end members are known. On this basis the isotopic signature of these mixed waters can be accounted for by about 10 to 40% enriched groundwater and 60–90% depleted groundwater.

5.2.3 Beneficial use

The risk to groundwater in the Lower Namoi GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered ‘at risk’.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Lower Namoi.

The *Water Sharing Plan for the Upper and Lower Namoi Groundwater Sources 2003* defines seven objectives; including an objective relating to water quality, ‘protect the structural integrity of the aquifers and groundwater quality, by ensuring groundwater extraction does not result in any aquifer compaction, aquitard compaction, land subsidence or change in the beneficial use of the aquifer’. To meet this objective, water quality management is detailed in the Plan:

> ‘38 Water quality management
>
> (1) The beneficial uses of this groundwater source are raw water for drinking, and irrigation, based on beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996. It is not recommended that the water from this groundwater source be consumed without prior treatment. Land use activities may have polluted the groundwater in some areas.
>
> (2) Water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class.

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 5-5. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in the Lower Namoi GMA (Cryon Section).

Table 5-5 Correlation analysis of parameters used to assess salinity and sodicity hazards

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.987	0.991	0.991	0.546
TDS		1	0.99	0.996	0.606
Na^+			1	0.996	0.546
Cl^-				1	0.564
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Lower Namoi GMA based on a comparison with the ANZECC (2000) guidelines for Primary Industry and the Australian Drinking Water Guidelines (2011).

5.2.3.1 Narrabri Formation

Based on salinity (EC) only, groundwater within the Narrabri Formation was generally suitable for stock only. There was one exception, monitoring GW036314_1 in which the average EC for the monitoring period (2009–2011) was unsuitable even for stock at 24,890 µS/cm. The number of groundwater samples from the Narrabri Formation in the Lower Namoi GMA above health and aesthetic guideline values is shown in Table 5-6. Narrabri Formation groundwater is generally not suitable for drinking water supply, not only in terms of salinity (EC), but also specific analytes including sodium, chloride, sulphate, aluminium, manganese, iron and ammonia.

Table 5-6 ADWG (2011) values and percentage of samples above guideline values, Narrabri Formation (N=50), Lower Namoi GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		0
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		100
Potassium (mg/L)				
Chloride (mg/L)	a	250		100
Sulphate (mg/L)	500	250	96	98
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5			
Aluminium (mg/L)	b	0.2	10	2
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		4
Manganese (mg/L)	0.5	0.1		4
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		2
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

Note: a: No health-based value considered necessary; b: Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix D. Using the Wilcox classification, groundwater from the Narrabri Formation was classified as having a very high salinity, and is generally not suitable for irrigation. Sodium adsorption ratios (SARs) ranged from 19 to 37 (average 27). Using the Wilcox classification, 54% (n=27) of samples had a high sodium hazard, and 46% (n=23) were classified as having a very high sodium hazard. Looking specifically at the ANZECC (2000) guidelines for Na+ concentrations that can cause foliar injury to cotton (>460 mg/L), all samples (n=50) from the Narrabri Formation were above this value. All chloride samples (n=50) were also above the ANZECC (2000) for Cl- concentrations that can cause foliar injury to cotton (>700 mg/L). All samples (n=50) were below the threshold value for boron toxicity for cotton (6–10 mg/L) (Maas, 1990).

For livestock, if TDS concentration is greater than 2,400 mg/L, the water should also be analysed to concentrations of specific ions, as discussed in Chapter 4 primary Industries of the ANZECC (2000) guidelines. Based on the guideline values (Table 2-8), 38% of samples (n=19) from the Narrabri Formation exceeded guideline values for sulphate. All other values were below the guidelines for major ions, metals and nitrate (see Table 2-8).

5.2.3.2 Gunnedah Formation

Groundwater within the Gunnedah Formation was generally suitable for irrigation, with two exceptions (GW36320_2 and GW036364_1). Based on the EC, at these locations groundwater was suitable for stock supply only.

The number of groundwater samples from the Gunnedah Formation in the Lower Namoi GMA above health and aesthetic guideline values is shown in Table 5-7. Gunnedah Formation groundwater is generally not suitable for drinking water supply, not only in terms of salinity (TDS), but also specific analytes including sodium, chloride, sulphate and manganese.

Table 5-7 ADWG (2011) values and percentage of samples above guideline values, Gunnedah Formation (N=124), Lower Namoi GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		0
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		98
Potassium (mg/L)				
Chloride (mg/L)	a	250		85
Sulphate (mg/L)	500	250	9	35
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		0	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4			
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	18
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

Note: a: No health-based value considered necessary; b: Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix D. For the Gunnedah Formation, based on the Wilcox classification, groundwater has a high (10% samples, n=13) to very high (90% samples, n=110) salinity. Sodium adsorption ratios (SARs) range from 4 to 29, with an average of 19. 90% samples (n=112) have a moderate to high SAR hazard. Looking at the specific toxicity of Na+ and Cl- to cotton, 70% of samples (n=87) and 63% of samples (n=78) were above Na+ and Cl- concentrations, respectively, that can cause foliar injury to cotton. All samples (n=50) were below the threshold value for boron toxicity for cotton (6-10 mg/L) (Maas, 1990).

For livestock, if TDS concentration is greater than 2,400 mg/L, the water should also be analysed to concentrations of specific ions, as discussed in Chapter 4 primary Industries of the ANZECC (2000) guidelines. Based on the guideline values (Table 2-8), 4% of samples for the Gunnedah Formation exceeded guideline values for sulphate. All other values were below the guidelines for major ions, metals and nitrate (see Table 2-8).

5.2.3.3 Cubbaroo Formation

Within the Cubbaroo Formation, groundwater was suitable for drinking water or irrigation based on EC.

The number of groundwater samples from the Cubbaroo Formation in the Lower Namoi GMA above health and aesthetic guideline values is shown in Table 5-8. Groundwater in some parts of the Cubbaroo Formation may be suitable for drinking water but would probably require treatment for metals such as manganese. Other areas are not suitable for drinking water supply, not only in terms of salinity, but also specific analytes including sodium, chloride, sulphate and manganese.

Table 5-8 ADWG (2011) values and percentage of samples above guideline values, Cubbaroo Formation (N=47), Lower Namoi GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		0
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		100
Potassium (mg/L)				
Chloride (mg/L)	a	250		55
Sulphate (mg/L)	500	250	19	47
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		0	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4			
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	26
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Reactive phosphorus (mg/L)				

Note: a: No health-based value considered necessary; b: Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix D. Based on EC, groundwater samples from the Cubbaroo Formation are classified as high (49% of samples, n=23) to very high (51% of samples, n=24). Sodium adsorption ratios for samples from the Gunnedah Formation ranged from 14 to 31 (average 22). 77% of samples (n=36) had a moderate to high sodium hazard, and 51% (n=24) had Na^+ concentrations above the ANZECC (2000) guidelines for Na^+ concentrations that can cause foliar injury to cotton (>460 mg/L). All samples (n=47) were below the threshold value for boron toxicity for cotton (6–10 mg/L) (Maas 1990).

5.2.4 Trends

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2. The results of these analyses are presented in Tables 5-9, 5-10 and 5-11 for the Narrabri, Gunnedah and Cubbaroo formations respectively.

Trends in water quality in the Cryon section of the Lower Namoi GMA have also previously been studied by McLean (2003); Barrett et al. (2006) and Timms et al. (2010).

5.2.4.1 Narrabri Formation

Study period trends

Salinity increased at three out of five monitoring locations in the Narrabri Formation during the study period. No clear corresponding increasing trends in major ions were identified at the bores with increasing salinity. Water types remained similar over the monitoring period except at GW036280_1. Water type was $Na\text{-}Cl\text{-}SO_4$ up to June 2010, but from July 2010 water type changed to Na-Cl.

Long-term trends

Of five monitoring bores screened in the upper Narrabri Formation, three showed decreasing salinity (EC) trends, one showed an increasing trend and one showed no trend.

In most cases of decreasing salinity, a decrease in K^+ and HCO_3^- was observed, although in general the changes in major ion concentrations did not cause a significant enough change in the relative proportion on major ions to result in a change of water type.

GW036340_1 was the only monitoring bore to show a long term increasing salinity (EC) trend, and this corresponded to an increasing trend in all major ions except K^+. The historical and current water type for this bore is Na-Cl. The increase in salinity is associated with mobilisation of salts from clay layers within the Narrabri Formation resulting from a reduction in throughflow and decline in water level (~3 m). Based on the relative concentrations for Ca^{2+} + Mg^{2+}, compared to HCO_3^- + SO_4^{2-} (Figure 5-15), reverse ion exchange is likely to be occurring at this location, which is indicative of saline intrusion. In systems such as the Upper and Lower Namoi, the saline intrusion is pore water from clays.

Beneficial use trend

The current beneficial use (based on EC) has not changed class from historical beneficial use, with groundwater generally still classified as suitable for stock watering. However, based on the change in EC, there has been a change within this class, with groundwater no longer suitable for some stock.

Table 5-9 Short- and long-term trends, Narrabri Formation, Lower Namoi GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW036280_1	11	-	-	-	-	-	68	Decrease	13,900 (07/03)	9,260	-660	-33	-
GW036314_1	9	Increase	22,800	29,200	700	22	66	Decrease	29,700 (08/00)	29,200	-100	-2	-
GW036320_1	9	Increase	12,700	14,030	150	10	67	Decrease	14,830 (11/99)	14,030	-150	-5	-
GW036340_1	12	-	-	-	-	-	68	Increase	7,965 (08/00)	9,450	260	19	-
GW036377_1	9	Increase	12,700	15,070	210	19	63	-	-	-	-	-	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

5.2.4.2 Gunnedah Formation

Study period trends

Increasing salinity trends were identified at two (GW036320_2 and GW036364_1) out of six monitoring locations in the Gunnedah Formation during the study period. The increasing salinity at GW036320_2 is not related to an increase in major ions. The increasing salinity at GW036364_1 is associated with an increase in sulphate and may be a result of leakage from the overlying Narrabri Formation, which is typically more saline.

Decreasing trends in salinity were identified at two out of six monitoring locations in the Gunnedah Formation during the study period. The decreasing salinity was associated with decreases in calcium, magnesium and chloride at GW036314_2 and decreases in sodium, calcium, magnesium, chloride and sulphate at GW036398_1. The decrease in salinity at GW036398_1 and GW036314_2 is related to increasing water levels at these locations.

Water types remained similar at each of the monitoring bores over the study period.

Long term trends

Of 10 monitoring bores screened in the Gunnedah Formation, four showed no long term salinity (EC) trend, three showed a decreasing salinity (EC) trend and three showed an increasing salinity (EC) trend.

In the three monitoring bores showing a long term increasing trend in EC (GW036314_2, GW036320_2 and GW036340_2), the EC increase was generally due to an increase in all major ions, and therefore water type at the end of the 2009-2011 monitoring period was the same as at the start of monitoring (Na-Cl). Seasonal variations in major ion concentrations and EC were evident in all 3 of these monitoring bores; however in bores GW036314_2 and GW036320_2 the change in relative percentage of major ions was not significant enough to cause a change in water type. In GW036340_3, during the early years of monitoring (2003-2006) seasonal changes from Na-Cl to Na-HCO_3-Cl occurred due to pumping; however, from 2006 onwards, water has been Na-Cl dominant during both drawdown and recovery periods.

At GW036314_2, hydrograph data indicates that there is only a limited hydraulic connection between the Narrabri and Gunnedah formations. Prior to development, the pressure head of the deeper aquifer was ~0.2 m above that of the shallow aquifer. Since development there has been a reversal of the vertical hydraulic gradient. Large seasonal drawdowns are evident in Pipes 2 and 3, and since development the total recovery decline is ~1.5 m. Leakage from Narrabri Formation (average EC 24,990 µS/cm) may be contributing to the increasing salinity observed in the Gunnedah Formation at GW036314_2; however, mixing calculations indicate the percentage of saline water from the Narrabri Formation is ~2%, and the observed data for GW036314_2 did not linearly on mixing lines, indicating other processes are contributing to increasing salinity. Based on major ion/Cl ratios and saturation indices calculations, ion exchange, and dissolution of carbonates, gypsum and halite may also be occurring.

At GW036320_2, there is also a limited hydraulic connection between the Narrabri and Gunnedah formations. Prior to development, the pressure head of the deeper aquifer was ~0.3 m above that of the shallow aquifer. Since development there has been a reversal of the vertical hydraulic gradient. Large seasonal drawdowns are evident in GW036320_2, and since development the total recovery decline is ~3 m. Based on optimisation of mixing calculations leakage of approximately 15% of groundwater from the shallow aquifer (which currently has an average EC of 13,450 µS/cm) may be contributing to the observed increasing salinity at GW036320_2. However, based on the relative concentrations for Ca^{2+} + Mg^{2+}, compared to HCO_3^- + SO_4^{2-} (Figure 5-17), reverse ion exchange is likely to be occurring at this location, which can be indicative of saline intrusion of pore waters from aquitards surrounding the aquifer.

At GW036340_2, there is a good hydraulic connection between the Narrabri and Gunnedah formations, and vertical leakage of as much as 50% from shallow to deep aquifers is indicated by mixing calculations. At this location salinity in the shallow aquifer has also been increasing, and is currently 6,460 µS/cm. As salinity increases in the Gunnedah aquifer, reverse ion exchange also appears to be occurring.

In the four monitoring bores that showed no trends and the three monitoring bores that showed long term decreasing EC trends, seasonal fluctuations in major ion concentrations did occur. However, these fluctuations did not result in significant changes to the relative proportions of major ions, and therefore water types did not change over time.

Beneficial use trend

The current beneficial use (based on EC) had not changed from historical beneficial class (irrigation); however deterioration of EC at some monitoring bores resulted in a change within the irrigation beneficial use class. The current EC of groundwater makes it unsuitable for irrigation of certain crops, including cotton.

Table 5-10 Short- and long-term trends, Gunnedah Formation, Lower Namoi GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW036314_2	12	Decrease	3,210	2,599	-85	-19	70	Increase	2,560 (11/99)	4,640	128	81	-
GW036314_3	11	-	-	-	-	-	74	-	-	-	-	-	-
GW036320_2	11	Increase	7,640	8,560	80	12	67	Increase	7,570 (08/02)	8,560	40	13	-
GW036320_3	11	-	-	-	-	-	73	Decrease	-	-	-	-	-
GW036340_2	12	-	-	-	-	-	67	Increase	3,600 (08/00)	5,330	260	48	-
GW036340_3	13	-	-	-	-	-	72	-	-	-	-	-	-
GW036364_1	10	Increase	13,900	16,110	250	16	64	Increase	13600 (08/03)	16,110	100	18	-
GW036364_2	11	-					66	-	-	-	-	-	-
GW036377_2	11	-					70	-	-	-	-	-	-
GW036398_1	11	Decrease	5,140	4,290	-140	-17	69	Decrease	7,190 (11/99)	4,290	-210	40	-
GW036406_1	12	-	-	-	-	-	70	-	-	-	-	-	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

5.2.4.3 Cubbaroo Formation

Study period trends

Salinity (EC) increased at one out of five monitoring locations in the Cubbaroo Formation during the study period. No corresponding increasing trends in major ions were identified at GW036406_2, where the increasing salinity trend was determined.

Although a salinity trend was not identified via Mann Kendall analysis at GW036280_3, a trend between salinity and the seasonal fluctuations in water level associated with pumping of groundwater was identified (Appendix D).

Water types remained similar at each of the monitoring bores over the study period.

Long-term trends

In the Cubbaroo Formation, seasonal fluctuations were observed were observed in all five monitoring bores, however only one monitoring bore showed a long term increasing trend (GW036398_2), which was associated with increasing Na+ and Cl- concentrations. Although seasonal fluctuations in major ion concentrations did occur these fluctuations did not result in significant changes to the relative proportions of major ions, and therefore water types did not change over time.

At GW036398, water levels in Pipe 1 (GF) and Pipe 2 (CF) are very similar showing that the two deep aquifers are hydraulically connected at these locations. Large seasonal drawdowns are evident (up to 33 m) and occasional seasonal reversals of hydraulic gradient occur. Long term recovery declines in both pipes are ~2.5 m. It can be inferred that the seasonal reversal of vertical hydraulic gradients is resulting in mixing between higher salinity water from the Gunnedah Formation (average EC 5,138 µS/cm) and Cubbaroo Formation (average EC 1,314 µS/cm), resulting in an increase in salinity in the deeper aquifer.

Beneficial use trends

Within the Cubbaroo Formation, groundwater was suitable for drinking water or irrigation based on EC, and the current beneficial use was comparable to the historical beneficial use classes.

Table 5-11 Short- and long-term trends, Cubbaroo Formation, Lower Namoi GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW036280_3	12	-	-	-	-	-	71	-	-	-	-	-	-
GW036364_3	10	-					71	-	-	-	-	-	-
GW036398_2	11	-	-	-	-	-	71	Increase	1,109 (07/03)	1,293	15	17	-
GW036406_2	11	Increase	3,630	4,110	30	13	74	-	-	-	-	-	Na-Cl to Na-Cl-SO4
GW965760_1	3	ID	ID	ID	ID	ID	7	-	-	-	-	-	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

5.2.5 Risks to groundwater quality

Risk factors to groundwater quality within the Lower Namoi (Cryon section) include rate of groundwater extraction resulting in aquifer depressurisation and in some instances reversal of hydraulic gradients, as well as mobilisation of salts from salt stores such as aquitards. Groundwater levels around Cryon declined by 1.5 to 4.0 m since the late 1970s and the results of this study identify localised areas of declining water quality, particularly within the Gunnedah Formation.

Groundwater quality within the Narrabri Formation around Cryon is saline. Although data are limited for the Narrabri formation (only five bores were monitored), the results highlight a number of ‘hotspots’ where beneficial use of groundwater is at risk of being further degraded. A long term increasing salinity trend is observed at GW036040_1, where a 19% increase in EC occurred over the last 10 years. Short-term trends identify monitoring bores at risk: GW036314_1, GW036320_1 and GW036377_1. EC has increased by 150 to 700% over the last 2 years, and groundwater is no longer suitable for certain stock. These bores should be monitored closely over the short term to assess whether these trends are continuing.

In the Gunnedah Formation, long-term EC increases are observed at monitoring bores GW036314_2, GW036320_2, GW036340_2 and GW036364_1, where EC increases ranged from 40 to 260%. Deterioration of EC at these monitoring bores resulted in a change within the irrigation beneficial use class. The current EC of groundwater makes it unsuitable for irrigation of certain crops, including cotton.

Groundwater within the Cubbaroo Formation is generally of better quality (lower EC) than both the Narrabri and Gunnedah formations, and deterioration of water quality has not been as severe in this aquifer as the overlying aquifers. Over the long term, a low EC is observed at only one monitoring bore (GW036398_2), where EC increased from 1,109 µS/cm to 1,293 µS/cm (19%). Over the short-term monitoring period, an increasing salinity (EC) trend is observed at GW036406_2, where salinity increases from 3,630 µS/cm to 4,110 µS/cm (30% increase).

6. Lower Macquarie GMA

6.1 Characterisation of the study area

The Lower Macquarie GMA catchment area is located in central western New South Wales, extending from Narromine in the east to Nevertire in the west (Figure 6-1).

6.1.1 Topography and surface hydrology

The Lower Macquarie GMA catchment area is dominated by flat alluvial floodplains associated with the Macquarie River. The catchment area is typically less than 250 m elevation.

The Macquarie River headwaters are located in the Great Dividing Range, near Bathurst, at the confluence of the Fish and Campbell Rivers. The Macquarie River flows through the north of the Lower Macquarie GMA in a north-west direction. Approximately 50 km north of Warren and the Lower Macquarie GMA, the Macquarie River joins the system of creeks, wetlands and floodplains, known as the Macquarie Marshes (Dent et al. 2007).

The Bogan River also flows through the south of the Lower Macquarie GMA, travelling north-west through Dandaloo, towards the Macquarie Marshes. The Bogan River flows parallel to the Macquarie River through the catchment area.

A series of cowals, likely abandoned river channels of the Macquarie River, are located between the Bogan and Macquarie Rivers, south of Nevertire (Dent et al. 2007). The Backwater – Boggy Cowal is a system of small depressions, which carries local runoff and the floodwater from the Macquarie River towards Nevertire (Dent et al. 2007).

6.1.2 Climate

The Lower Macquarie GMA is generally semi-arid and experiences similar climatic conditions across the GMA. The average annual rainfall in the west of the GMA at Narromine (BoM station 051037 Alagalah St) is 527.2 mm and the average annual rainfall in the east of the GMA at Dandaloo (BoM station 050018 Kelvin) is 493.9 mm. Long term average monthly rainfall and monthly rainfall for the current study period (2009 – 2011) for these two BoM stations is shown on Figures 6-2 and 6-3.

Historically, the highest monthly rainfall occurs from November to February at Narromine and from December to March at Dandaloo. During the study period, monthly rainfall was below average for 60% of months in 2009 and above average for the majority of months during 2010. Monthly rainfall was typically below average in the early part of 2011. During the study period rainfall was not consistently measured at Dandaloo. Daily rainfall for the monitoring period at Narromine is shown on the hydrographs in Appendix E.

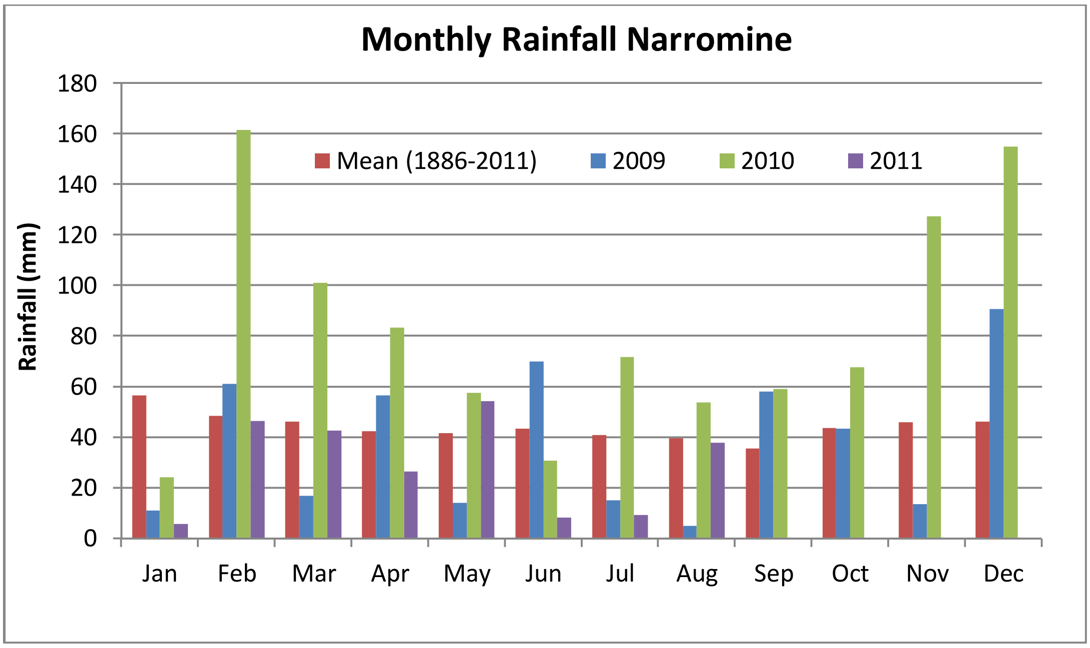


Figure 6-2 Average monthly rainfall, BoM station 051037, Narromine

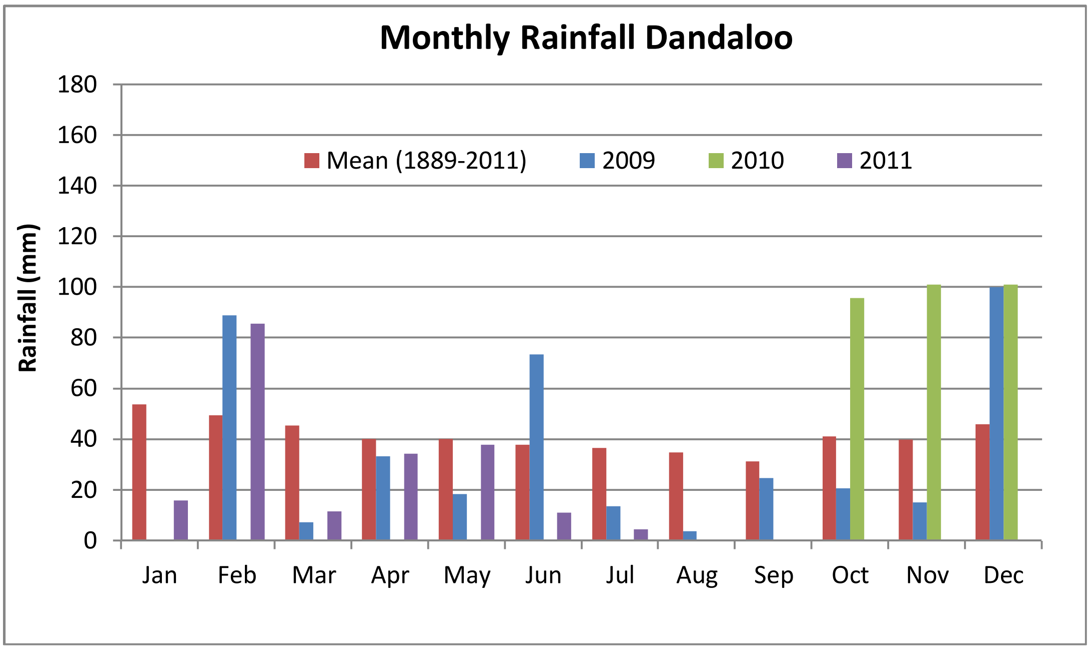


Figure 6-3 Average monthly rainfall, BoM station 050018, Dandaloo

The long-term cumulative rainfall residual for Narromine and Dandaloo are shown on Figure 6-4. The cumulative residual rainfall in Figure 6-4 shows periods of above rainfall at Dandaloo: 1967–1978, 1983–1984, 1987–1993 and 1997–2002, and periods of above average rainfall at Narromine: 1967–1978, 1983–1984, 1997–2001 and 2009–2010.

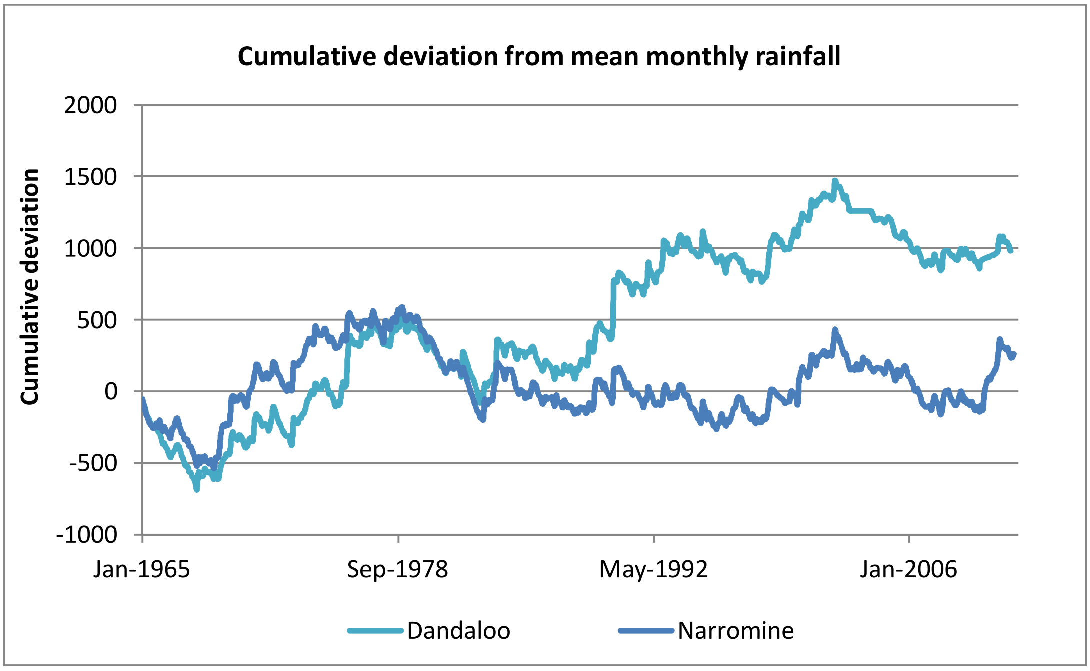


Figure 6-4 Cumulative deviation from mean monthly rainfall, Dandaloo and Narromine (1965–2011)

6.1.3 Land use

Land use overlying the Lower Macquarie GMA comprises both cropping (cotton, wheat, oilseeds, vegetables and pasture) and grazing (wool and beef). Irrigated cotton is the primary summer crop in the Macquarie GMA and is grown mainly along the alluvial floodplains of the Macquarie River, particularly in the Warren – Trangie – Narromine district (Dent et al. 2007).

6.1.4 Hydrogeology

Two distinct aquifer systems are present in the Lower Macquarie catchment (DLWC, 1999):

- Cainozoic alluvial sequence (consisting of the Narrabri, Gunnedah and Cubbaroo formations), varying in thickness from 20 m to 150 m. The deepest and most permeable alluvium is associated with the Backwater Boggy Cowals, the old Macquarie River channel.
- Underlying Mesozoic sandstone aquifers separated by shale and mudstone confining beds, part of the Great Artesian Basin (GAB) sedimentary units (Dent et al. 2007).

Groundwater extraction in the Lower Macquarie GMA is primarily from the unconfined alluvial aquifers, consisting of the Narrabri Formation and the underlying Gunnedah Formation (Lamontagne et al. 2011b) although, some groundwater is currently extracted from the Mesozoic GAB aquifers primarily for domestic and stock purposes (DLWC 1999).

The Narrabri system consists of extensive shallow alluvial fan sediments deposited by creeks draining the nearby highlands. Groundwater is contained in small discontinuous lenses and quality and yield is variable (Dent et al. 2007).

The Gunnedah Formation comprises coarse grained pebbly sands in palaeochannels and an overlying finer sandy unit and does not outcrop in the Macquarie catchment. Groundwater in the Gunnedah system deteriorates in quality towards the west (Dent et al. 2007). Currently there is some difficulty in distinguishing the Gunnedah and Cubbaroo formations.

Regionally groundwater typically flows from east to west. The alluvial aquifer formations are recharged via the Macquarie River and rainfall infiltration (Dent et al. 2007). The Mesozoic GAB aquifers are not influenced by rainfall and some monitoring bores indicate recharge by Macquarie River leakage (DLWC, 1999). The Macquarie River flows have been regulated since the construction of the Burrendong Dam, near Wellington, in 1967 (DLWC 1999). The regulated flows of the Macquarie River have impacted recharge to aquifers hydraulically connected to the River (DLWC 1999).

Irrigation developed in the Macquarie catchment area in 1967, following the construction of Burrendong Dam (Hope 2003) and the operation of irrigation bores in the area commenced in 1968 (DLWC 1999). The alluvial aquifers typically recover steadily following the irrigation season. The Mesozoic GAB aquifers recover slowly following the irrigation season (DLWC 1999). Groundwater levels in the Lower Macquarie typically were increasing up to 1993–1994, and since then have steadily decreased (DLWC 1999).

The monitoring bores studied in this project are located in the alluvium in the south of the Lower Macquarie GMA. A brief summary of groundwater level trends is in Table 6-1. Hydrograph data for these monitoring bores is shown on Figure 6-5.

Table 6-1 Hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long term hydrogeological conditions
GW030211_1	54.9 – 73.2	GF	Water levels are available from 1972. Water levels at Pipe 1 were steadily increasing from 1978 to 1995. Drawdowns are evident at Pipe 1 (up to 5 m) in some years. Since 1995 the total recovery decline is ~3 m.
GW030214_1	64 – 73.2	CF	Water levels are available from 1972. Water levels at Pipe 1 were steadily increasing until 1993. Drawdowns are evident at Pipe 1 (up to 1 m) in some years. Since 1993 the total recovery decline is ~4 m
GW030215_1	70.1 – 100.6	CF	Water levels are available from 1972. Water levels at Pipe 1 were steadily increasing until 1993. Drawdowns are evident at Pipe 1 (up to 8 m) in some years. Since 1993 the total recovery decline is ~4.5 m
GW096000_1	119 – 124	CF	Water levels are available from 1999. Seasonal drawdowns are evident at Pipe 1 (up to 8 m). Since monitoring commenced the total recovery decline is ~2.5 m.
GW096144_1	66 – 72	GF	Water levels are available from 2004. Pipe 1 shows a dampened water level response indicating there a limited connection between the pipes at this location. Pipe 1 levels have decreased from 51 to 56 m bgl. Seasonal drawdowns are evident at Pipe 1 (up to 2 m) and Pipe 2 (up to 15 m). Since monitoring commenced the total recovery decline is ~3 m.
GW096144_2	133 – 139	CF	
GW096147_1	52 – 58	GF	Water levels are available from 2004. Pipe 1 levels have decreased from 50 to 51 m bgl. Seasonal drawdowns are evident at Pipe 2 (up to 6 m). Pipe 2 water levels have recovered in 2010 to match Pipe 1.
GW096147_2	90 – 102	CF	

Note: GF-Gunnedah formation, CF-Cubbaroo Formation.

6.2 Characterisation of groundwater chemistry

Groundwater sampling was undertaken in eight sampling rounds during the study period (October 2009 to January 2011). seven monitoring bores were sampled during the study period, with four located in the Gunnedah Formation and three located in the Cubbaroo Formation.

As the study area for the Lower Macquarie is located in the south of the GMA, east of Dandaloo, groundwater chemistry trends geographically across the catchment cannot be determined. Groundwater chemistry interpretation is for the south of the GMA east of Dandaloo only and no assumptions can be made on changes with chemistry in the north of the GMA or along the flow paths in the Lower Macquarie GMA.

6.2.1 Results

Groundwater chemistry statistics are summarised in Tables 6-2 and 6-3 for the Gunnedah and Cubbaroo formations respectively. The results are presented on a cross-section (Figure 6-6). The location of the cross-section is shown on Figure 6-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 6-7, 6-8 and 6-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix E.

A Piper diagram presenting results for the Gunnedah and Cubbaroo formations is presented in Figure 6-10.

Table 6-2 Lower Macquarie Gunnedah Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	14	14	530	1200	791	640	0.3
EC (lab)	µS/cm	14	14	978	2179	1441	1181	0.3
pH (field)	pH unit	10	10	5.82	7.14	6.43	6.46	0.05
K	mg/L	14	14	4.0	6.8	5.6	6.2	0.2
Na	mg/L	14	14	150	330	218	180	0.3
Ca	mg/L	14	14	21	46	30	29	0.3
Mg	mg/L	14	14	25	57	37	31	0.3
Cl	mg/L	14	14	160	540	308	210	0.5
SO_4	mg/L	14	14	42	100	64	54	0.4
Alkalinity ($CaCO_3$)	mg/L	14	14	160	230	199	200	0.1
CO3	mg/L	14	0	Not calculated				
HCO3	mg/L	14	14	200	280	243	250	0.1
Si	mg/L	14	14	9.9	20.0	16.1	17.5	0.3
F	mg/L	14	14	0.14	0.30	0.22	0.22	0.19
Al (soluble)	mg/L	14	0	Not calculated				
B (soluble)	mg/L	14	3	<0.1	0.10	0.10	0.05	0.30
Br (soluble)	mg/L	14	14	0.6	2.3	1.1	0.8	0.5
Cu (soluble)	mg/L	14	0	Not calculated				
Mn (soluble)	mg/L	14	8	<0.002	0.024	0.005	0.002	1.410
Sr (soluble)	mg/L	14	14	0.35	0.90	0.53	0.47	0.32
Zn (soluble)	mg/L	14	10	<0.005	0.140	0.043	0.041	1.488
Mn (total)	mg/L	14	10	<0.002	0.020	0.007	0.004	1.063
Ni (total)	mg/L	14	0	Not calculated				
Zn (total)	mg/L	14	10	<0.01	0.110	0.049	0.040	1.235
Al (total)	mg/L	14	8	<0.05	0.420	0.124	0.080	1.026
B (total)	mg/L	14	6	<0.1	0.20	0.11	0.05	0.45
Cu (total)	mg/L	14	1	<0.005	0.009	0.005	0.003	0.327
Fe (total)	mg/L	14	10	<0.05	0.970	0.179	0.065	1.148
Pb (total)	mg/L	14	0	Not calculated				
N_2	mg/L	14	14	0.05	0.71	0.20	0.14	0.84
NH_3	mg/L	14	5	<0.01	0.040	0.016	0.005	0.862
PO_4	mg/L	14	14	0.006	0.017	0.010	0.010	0.221
Total P	mg/L	14	13	<0.005	0.027	0.012	0.012	0.586

Note: SD – standard deviation

Table 6-3 Lower Macquarie Cubbaroo Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	12	12	740	2400	1532	1050	0.5
EC (lab)	µS/cm	12	12	1347	4090	2676	1871	0.5
pH (field)	pH unit	9	9	6.39	7.28	6.83	6.78	0.04
K	mg/L	12	12	5.2	11.0	8.3	7.5	0.3
Na	mg/L	12	12	170	650	378	240	0.5
Ca	mg/L	12	12	46	98	70	65	0.3
Mg	mg/L	12	12	32	130	77	53	0.5
Cl	mg/L	12	12	270	1100	691	450	0.6
SO_4	mg/L	12	12	62	250	151	96	0.6
Alkalinity ($CaCO_3$)	mg/L	12	12	180	210	195	190	0.05
CO_3	mg/L	12	0	Not calculated				
HCO_3	mg/L	12	12	220	260	240	240	0.1
Si	mg/L	12	12	8.9	15.0	11.4	12.0	0.2
F	mg/L	12	11	<0.1	0.39	0.18	0.17	0.52
Al (soluble)	mg/L	12	1	<0.01	0.020	0.011	0.005	0.400
B (soluble)	mg/L	12	5	<0.1	0.20	0.11	0.05	0.47
Br (soluble)	mg/L	12	12	1.0	4.2	2.4	1.8	0.5
Cu (soluble)	mg/L	12	0	Not calculated				
Mn (soluble)	mg/L	12	10	<0.002	0.800	0.312	0.044	2.757
Sr (soluble)	mg/L	12	12	0.82	2.00	1.43	1.40	0.29
Zn (soluble)	mg/L	12	8	<0.005	0.240	0.054	0.035	1.672
Mn (total)	mg/L	12	8	<0.002	0.770	0.315	0.050	2.982
Ni (total)	mg/L	12	0	Not calculated				
Zn (total)	mg/L	12	10	<0.01	0.090	0.053	0.060	1.019
Al (total)	mg/L	12	3	<0.05	0.130	0.068	0.025	0.722
B (total)	mg/L	12	5	<0.1	0.10	0.10	0.05	0.36
Cu (total)	mg/L	12	1	<0.005	0.005	0.005	0.003	0.217
Fe (total)	mg/L	12	7	<0.05	11.00	4.647	0.255	2.923
Pb (total)	mg/L	12	0	Not calculated				
N_2	mg/L	12	12	0.06	0.88	0.32	0.27	0.83
NH_3	mg/L	12	10	<0.01	0.580	0.119	0.070	1.603
PO_4	mg/L	12	11	<0.005	0.013	0.010	0.010	0.421
Total P	mg/L	12	11	<0.005	0.035	0.013	0.009	0.668

Note: SD – standard deviation

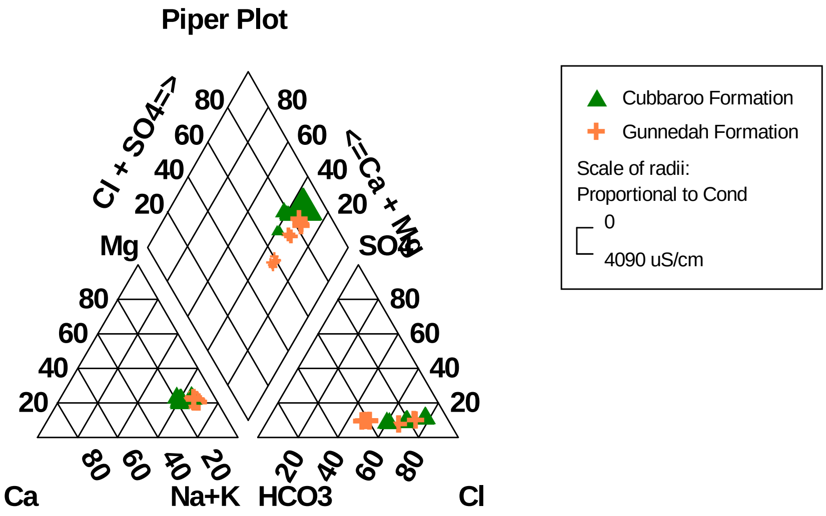


Figure 6-10 Piper diagram for the Lower Macquarie GMA during the study period

6.2.1.1 Gunnedah Formation

Water quality parameters

Salinity in the Gunnedah Formation ranges from fresh, 978 µS/cm (GW030214_1) to brackish, 2,179 µS/cm (GW030211_1) (Figure 6-8). The alluvium in the south of the GMA (where the monitoring bores for this study are located) typically has a higher salinity compared to the north, near to the Macquarie River (DLWC 1999).

Field pH measurements were recorded for 71% of samples from the Gunnedah Formation. The pH conditions of the Gunnedah Formation ranged from slightly acidic (5.82) to near neutral (7.14).

Major and minor ions

Major ion chemistry in the Gunnedah Formation is dominated by sodium, magnesium, chloride and bicarbonate, with only the monitoring locations with lower salinities (<2,000 µS/cm) dominated by bicarbonate. Water types for each monitoring location are presented in piper plots in the report cards in Appendix E and in Figure 6-10. Some mixing between Gunnedah and Cubbaroo formations may be inferred from the Piper diagram in Figure 6-10.

Dissolved silicon concentrations in the Gunnedah Formation ranged from 9.9 mg/L to 20 mg/L, with an average concentration of 16.1 mg/L. Silicon was negatively correlated with salinity, with the freshet groundwater having the highest silicon concentrations. This is because most silicate weathering takes place in the soil zone and unsaturated zone where infiltrating recharge charged with atmospheric CO_2 drives dissolution reactions (Appelo & Postma 1996).

Bromide was detected in all samples and concentrations ranged from 0.6 mg/L to 2.3 mg/L. The highest bromide concentrations were associated with the higher salinities.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Macquarie. Total iron was detected in 71% of samples from the Gunnedah Formation. Concentrations ranged up to 0.97 mg/L.

Dissolved manganese was detected in 57% of samples; with a maximum concentration of 0.024 mg/L. Total manganese was detected in 71% of samples; with a maximum concentration of 0.020 mg/L.

Strontium was detected at all monitored bores, with concentrations ranging from 0.35 mg/L to 0.90 mg/L. Strontium concentrations were well correlated with salinity (r^2=0.95).

Nutrients

Total nitrogen was detected in all samples from the Gunnedah Formation. Total nitrogen concentrations ranged from 0.05 mg/L to 0.71 mg/L. Ammonia was detected in 36% of samples and concentrations ranged from the LOR (0.01 mg/L) to 0.04 mg/L.

Total phosphorus was detected at 93% of samples and reactive phosphorus was detected in all samples. The maximum total phosphorus concentration was 0.027 mg/L and reactive phosphorus concentrations ranged from 0.006 mg/L to 0.017 mg/L. Phosphorus in groundwater can be derived from natural processes such as the decay of organic matter or weathering processes, or agricultural sources such as fertilisers or animal manure.

Stable isotopes

Groundwater samples from the Lower Macquarie GMA were not analysed for stable isotopes during this study.

6.2.1.2 Cubbaroo Formation

Water quality parameters

Groundwater salinity in the Cubbaroo Formation ranges from fresh, 1,347 µS/cm (GW096147_2) to brackish, 4,090 µS/cm (GW030215_1) (Figure 6-8). Groundwater salinity in the Cubbaroo Formation is slightly more saline than the overlying Gunnedah Formation.

The pH conditions of the Cubbaroo Formation were similar to the overlying Gunnedah Formation and ranged from slightly acidic (6.39) to slightly alkaline (7.28).

Major and minor ions

Major ion chemistry in the Cubbaroo Formation was similar to the overlying Gunnedah Formation; dominated by sodium, magnesium and chloride, with monitoring locations with lower salinities (<2,000 µS/cm) also dominated by bicarbonate. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix E.

Dissolved silicon concentrations in the Cubbaroo Formation ranged from 8.9 mg/L to 15 mg/L, with an average concentration of 11.4 mg/L.

Bromide was detected in all samples, concentrations ranged from 1 mg/L to 4.2 mg/L.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Macquarie. Total iron was detected in 47% of samples, ranging from the LOR (0.05 mg/L) up to 11 mg/L.

Dissolved and total manganese were detected in 83% and 67% of samples respectively. Dissolved and total manganese concentrations were similar; with average concentrations of 0.312 mg/L and 0.315 mg/L respectively.

Strontium was detected at all monitored bores, ranging from 0.82 mg/L to 2 mg/L, with the highest concentrations associated with high salinities.

Nutrients

Total nitrogen was detected in all samples and concentrations ranged from 0.06 mg/L to 0.88 mg/L. Ammonia was detected in 83% of samples and ranged from 0.01 mg/L to 0.58 mg/L.

Total and reactive phosphorus were detected in 92% of samples. The maximum total phosphorus concentration was 0.035 mg/L and the maximum reactive phosphorus concentration was 0.013 mg/L.

Stable isotopes

Groundwater samples from the Lower Macquarie GMA were not analysed for stable isotopes during this study.

6.2.2 Processes

6.2.2.1 Gunnedah Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted are chloride concentration to determine hydrogeochemical processes (Figure 6-11). Sodium, magnesium, calcium and bicarbonate showed curved trends with high ion/chloride ratios, indicating mixing between fresh and more saline end members as well other geochemical processes are occurring.

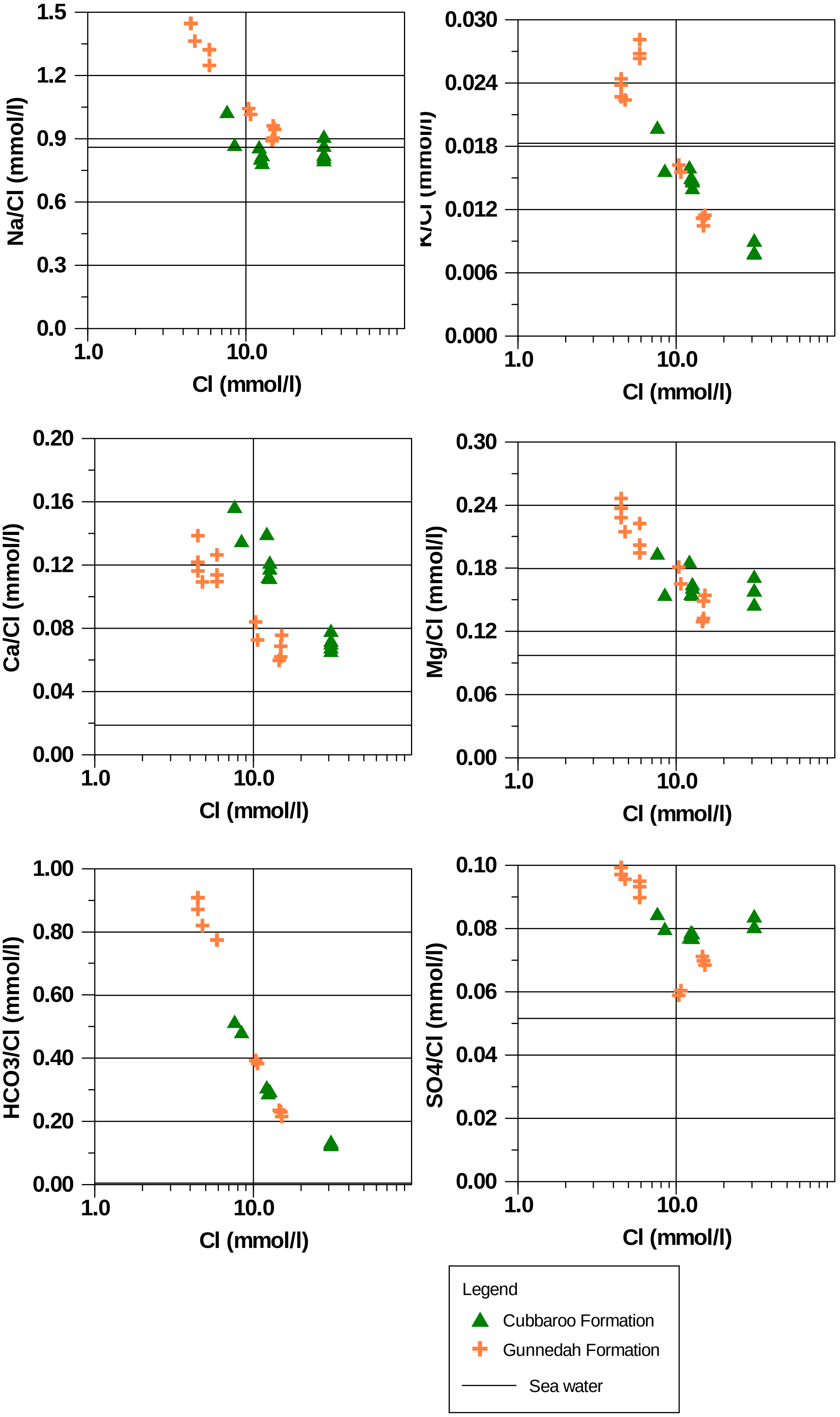


Figure 6-11 Ion/chloride versus chloride graphs for the Lower Macquarie GMA

Saturation indices for the Gunnedah Formation are plotted in Figure 6-12. Groundwater in the Gunnedah Formation is saturated with respect to montmorillonite and quartz. A slight increasing trend of gypsum and anhydrite saturation with increasing salinity was found for the Gunnedah Formation. Groundwaters were all undersaturated with respect to calcite, dolomite and feldspars.

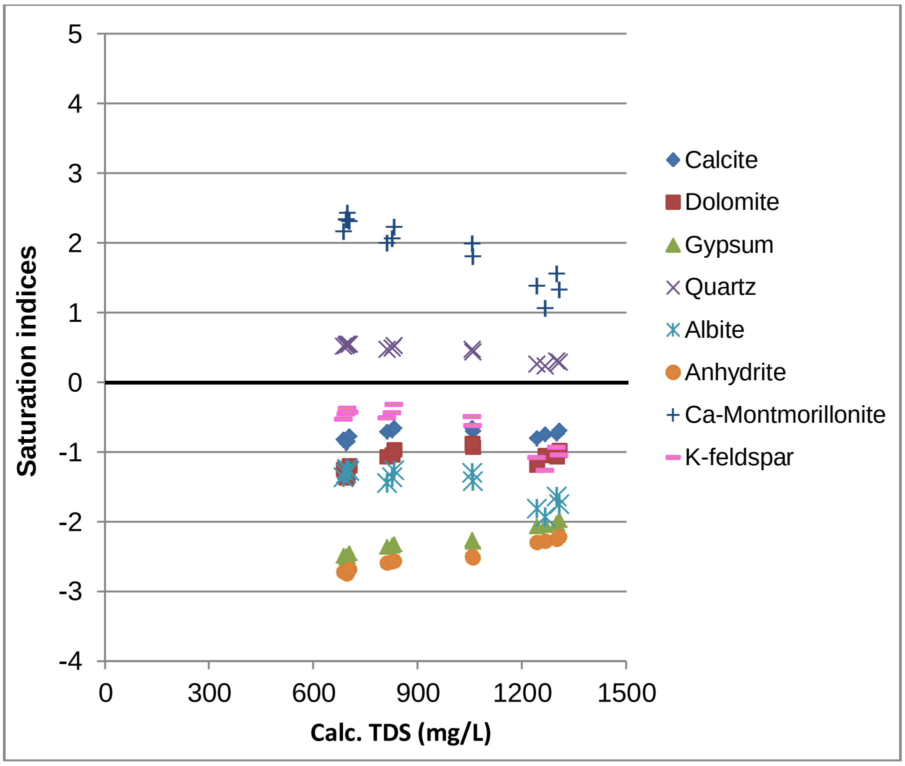


Figure 6-12 Saturation indices versus TDS for the Gunnedah Formation

Ion exchange

Figure 6-13 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Groundwater samples from the Gunnedah Formation plot below the dissolution line indicating ion exchange processes, except the monitoring location GW030211_1, which primarily plots above the line, indicating reverse ion exchange.

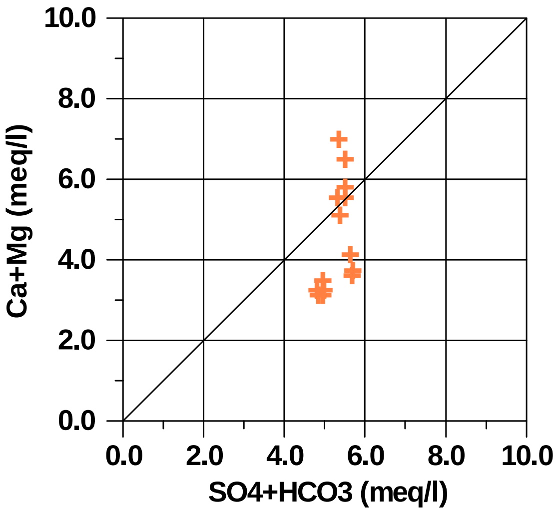


Figure 6-13 **Calcium + magnesium versus bicarbonate + sulphate in the Gunnedah Formation**

Stable isotopes

Groundwater samples from the Lower Macquarie GMA were not analysed for stable isotopes during this study.

6.2.2.2 Cubbaroo Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 6-11). Similarly to the Gunnedah Fromation, Sodium, magnesium, calcium and bicarbonate showed curved trends with high ion/chloride ratios, indicating mixing between fresh and more saline end members as well other geochemical processes is occurring.

Saturation indices for the Cubbaroo Formation are plotted in Figure 6-14. Groundwater in the Cubbaroo Formation is over-saturated with respect to montmorillonite and quartz, but is under-saturated with respect to gypsum, calcite, dolomite and feldspars.

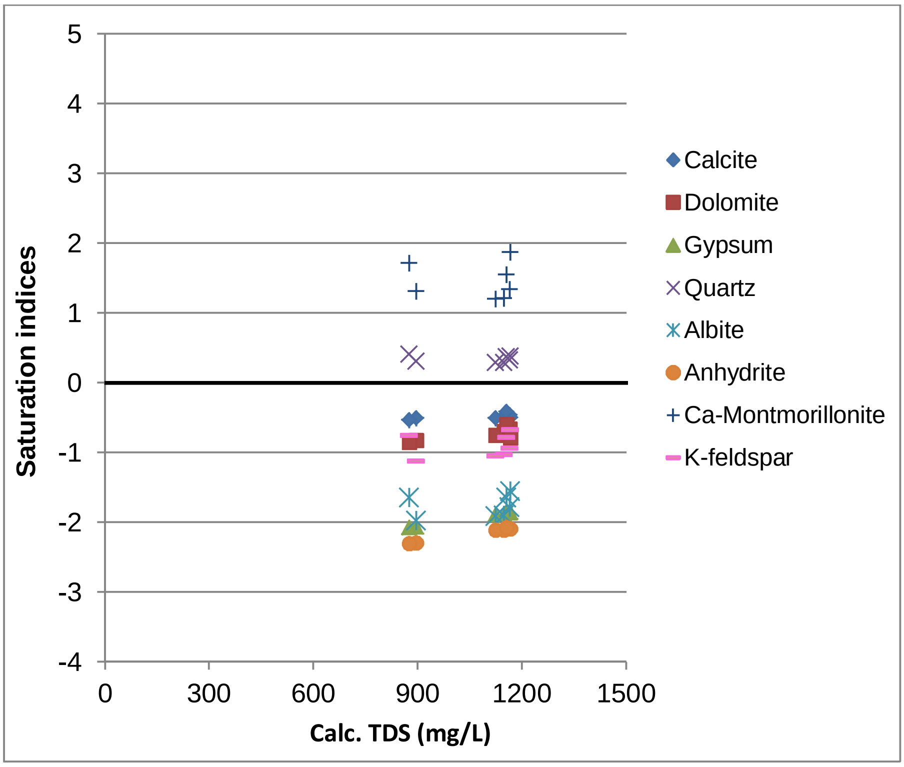


Figure 6-14 **Saturation indices versus TDS for the Cubbaroo Formation**

Ion exchange

Figure 6-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The majority of groundwater samples from the Cubbaroo Formation plot above the dissolution line indicating reverse ion exchange processes.

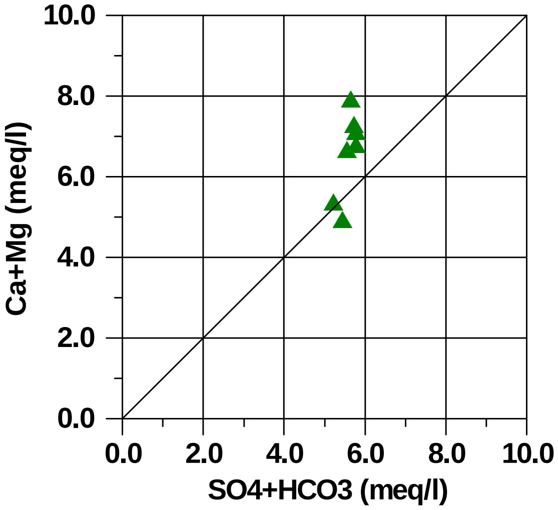


Figure 6-15 **Calcium + magnesium versus bicarbonate + sulphate in the Cubbaroo Formation**

Stable isotopes

Groundwater samples from the Lower Macquarie GMA were not analysed for stable isotopes during this study.

6.2.3 Beneficial use

The risk to groundwater in the Lower Macquarie GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered ‘at risk’.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Lower Macquarie GMA.

The *Water Sharing Plan for the Lower Macquarie Groundwater Sources* defines five objectives; including an objective relating to groundwater quality:

‘(b) optimise or maximise the social outcomes of groundwater management,
N**ote.** Subclause (b) is a social objective. The outcomes of this objective would include: no decline in groundwater quality as a result of extraction; sustainable groundwater source for present and future generations; priority of access for town water supply and basic rights; and social impacts of management changes defined and assessed against the Vision.’

To meet this objective, water quality management is detailed in the Plan:

> ‘38 Water quality management
>
> (1) The beneficial uses of this groundwater source are raw water for drinking, and irrigation, based on beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996. It is not recommended that the water from this groundwater source be consumed without prior treatment. Land use activities may have polluted the groundwater in some areas.
>
> (2) Water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class…
>
> (5) The EC limits adopted for this Plan for the beneficial use categories are as follows:
>
>> (a) 800 EC for Raw Drinking Supplies Class; and
>>
>> (b) 1,500 EC for Agricultural Water Class.’

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 6-4. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in the Lower Macquarie GMA.

Table 6-4 Correlation analysis of parameters used to assess salinity and sodicity hazards, Lower Macquarie GMA

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.951	0.978	0.976	0.82
TDS		1	0.958	0.965	0.913
Na^+			1	0.985	0.848
Cl^-				1	0.836
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Lower Macquarie GMA based on the Australian Drinking Water Guidelines (2011) and ANZECC (2000) guidelines for Primary Industry.

6.2.3.1 Gunnedah Formation

Based on salinity (EC) only, groundwater within the Gunnedah Formation in the south-eastern part of the GMA is suitable for drinking water and irrigation in the south-western part.

Percentages of groundwater samples from the Gunnedah Formation that are above health and aesthetic guideline values for drinking water are shown in Table 6-5. Concentrations of Na^+ and Cl^- were above aesthetic guideline values in some samples.

Table 6-5 ADWG (2011) values and percentage of samples above guideline values, Gunnedah Formation (N=14), Lower Macquarie GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		36
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		43
Potassium (mg/L)				
Chloride (mg/L)	a	250		43
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		0	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	0
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix E. Groundwater from the Gunnedah Formation had low sodium hazards, with SARs ranging from 5 to 8 with an average of 6. Groundwater is generally suitable for irrigation of sensitive to moderately sensitive plants based on ANZECC (2000) guideline values for Na^+ and Cl^- concentrations that can cause foliar injury to plants.

One of the main indicators to define water quality for stock is salinity. The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), all samples from the Gunnedah Formation were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

6.2.3.2 Cubbaroo Formation

Based on salinity (EC) only, groundwater within the Cubbaroo Formation in the south-eastern part of the GMA is suitable for drinking water and irrigation in the south-western part.

Percentages of groundwater samples from the Cubbaroo Formation that are above health and aesthetic guideline values for drinking water are shown in Table 6-6. Concentrations of

Na^+ and Cl^- are above aesthetic guideline values in the majority of samples, and manganese is above both aesthetic and health guideline values in nearly 50% of samples from the Cubbaroo Formation.

Table 6-6 ADWG (2011) values and percentage of samples above guideline values, Cubbaroo Formation (N=12), Lower Macquarie GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		0
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		83
Potassium (mg/L)				
Chloride (mg/L)	a	250		100
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		0	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	42	42
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		8
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix E. Groundwater from both the Cubbaroo Formation had low sodium hazards, with SARs ranging from 5 to 10 with an average of 7. Groundwater is generally suitable for irrigation of sensitive to moderately sensitive plants based on ANZECC (2000) guideline values for Na^+ and Cl^-concentrations that can cause foliar injury to plants.

One of the main indicators to define water quality for stock is salinity. The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), all samples from the Cubbaroo Formation were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

6.2.4 **Trends**

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2. The results of these analyses are presented in Tables 6-7 and 6-8 for the Gunnedah and Cubbaroo formations respectively.

6.2.4.1 Gunnedah Formation

Study period trends

No changes in salinity were identified via Mann Kendall analysis for the study period in the Gunnedah Formation of the Lower Macquarie GMA. Only a limited number of samples were collected from monitoring bores within the Gunnedah Formation, so therefore short-term assessment of trends using Mann Kendall analysis was only possible for two bores (GW030211_1, GW030214_1), where no trends were identified. Water types generally remained consistent for the monitoring period.

Groundwater salinity does appear to increase in the Gunnedah Formation as it flows to the west of the Lower Macquarie GMA.

The response of water quality to a pumping season was investigated by comparing the change in water levels and salinity over the monitoring period (October 2009–January 2011), as shown on the Water Quality Report Cards in Appendix E. Based on the Mann Kendall no short-term trends in salinity (EC) or major ions were detected. This may be related to no seasonal or pumping related drawdowns in groundwater level observed in the Gunnedah Formation for this period.

There was insufficient data to determine if there were any seasonal changes in EC and water type (major ion chemistry) due to pumping.

Long term trends

The long term response of water quality to pumping was investigated by comparing the change in water levels and salinity for the entire data set. Historical water quality data is available from 2003 for two monitoring bores in the Gunnedah Formation, however only one monitoring bore (GW030211_1) had sufficient data for analysis. There was no significant trend identified for GW030211_1.

Beneficial use trends

Based on salinity (EC) only, groundwater within the Gunnedah Formation in the south-eastern part of the GMA is suitable for drinking water and irrigation in the south-western part. The current beneficial use (based on EC) was not compared to historical beneficial use due to the lack of data.

Table 6-7 Short- and long-term trends, Gunnedah Formation, Lower Macquarie GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030211_1	4	-	-	-	-	-	12	-	-	-	-	-	-
GW030214_1	5	-	-	-	-	-	N	ND	ND	ND	ND	ND	ND
GW096144_1	2	ID	ID	ID	ID	ID	3	ID	ID	ID	ID	ID	ID
GW096147_1	2	ID	ID	ID	ID	ID	3	ID	ID	ID	ID	ID	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

6.2.4.2 Cubbaroo Formation

Study period trends

No clear trends in salinity were identified for the study period (2009-2011) in the Cubbaroo Formation of the Lower Macquarie GMA (Table 6-8). Only a limited number of samples were collected from monitoring bores within the Cubbaroo Formation, so therefore short-term assessment of trends using Mann Kendall analysis was only possible for two bores (GW030215_1 and GW096000_1), where no trends were identified. Water types for the Cubbaroo Formation monitoring locations typically remained consistent for the monitoring period.

The response of water quality to a pumping season was investigated by comparing the change in water levels and salinity over the monitoring period (October 2009–January 2011), as shown on the Water Quality Report Cards in Appendix E. There was insufficient data to determine if there were any seasonal changes in EC and water type (major ion chemistry) due to pumping.

There were also no groundwater level drawdowns observed in monitoring locations in the Cubbaroo Formation for this period, except at GW096144_2. GW096144_2 showed groundwater level drawdowns in late 2009 and early 2010, however, groundwater chemistry was not monitored at this location.

Long-term trends

The long-term response of water quality to pumping was investigated by comparing the change in water levels and salinity for the entire data set. Historical water quality data was available from 2003 for the three monitoring bores located in the Cubbaroo Formation; however only two monitoring bores (GW030215_1 and GW096000_1) had sufficient data for analysis. There was no significant trend identified for GW096000_1.

A long-term increasing salinity trend was identified at GW030215_1. The Gunnedah Formation is not monitored at this location; therefore the cause of increasing salinity in the deeper aquifer cannot be conclusively determined.

Beneficial use trends

Based on salinity (EC) only, groundwater within the Cubbaroo Formation in the south-eastern part of the GMA is suitable for drinking water and irrigation in the south-western part. The current beneficial use (based on EC) was not compared to historical beneficial use due to the lack of data.

Table 6-8 Short- and long-term trends, Cubbaroo Formation, Lower Macquarie GMA

Short-term trends 2009–2011							Long–term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030215_1	5	-	-	-	-	-	14	Increase	3,120 (03/04)	4,026	100	29	-
GW096000_1	5	-	-	-	-	-	14	-	-	-	-	-	-
GW096147_2	2	ID	ID	ID	ID	ID	3	ND	ND	ND	ND	ND	ID

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

6.2.5 Risks to groundwater quality

Very limited monitoring data was available to assess long-term trends in salinity and beneficial use in the Gunnedah and Cubbaroo formations. One Cubbaroo Formation monitoring bore showed a long-term increasing trend in salinity, however the cause cannot be conclusively determined as the Gunnedah Formation is not monitored at this location.

An extensive monitoring program needs to be implemented to assess risks to groundwater quality in the Lower Macquarie GMA.

7. Lower Lachlan GMA

7.1 Characterisation of the study area

The Lower Lachlan GMA is located in central-western New South Wales and lies along the Lachlan River between Lake Cargelligo and Oxley in the south-west and beyond Ivanhoe in the north-west. The GMA covers approximately 26,118 km^2 (Figure 7-1). The GMA lies on the on the north-eastern margin of the Riverine Plain of the Murray Geological Basin.

7.1.1 Topography and surface hydrology

Within the Lower Lachlan GMA, the topography is predominantly flat, with a small decreasing gradient form east to west. Groundwater elevations decrease from 169 mAHD at Lake Cargelligo in the east to 144 mAHD at Oxley in the south-west and 85 mAHD at Ivanhoe in the north-west.

The Lachlan River originates in the Great Dividing Range north-west of Lake George near Gunning and flows 1,400 km across western NSW to its junction with the Murrumbidgee River near Oxley. The Lachlan River is a terminal system with little water flowing past the Great Cumbung Swamp at the end of the river under normal climatic conditions. However, during large flood events water does flow through to the Murrumbidgee River. Wyangala Dam is the major water storage and is located upstream of Cowra at the confluence of the Lachlan and Abercrombie rivers. The major tributaries of the Lachlan River include the Abercrombie, Boorowa, Belubula and Crookwell rivers and Willandra Creek. There are numerous weirs along the length of the Lachlan River and offstream storages including Lake Cargelligo and Lake Brewster.

The Lower Lachlan floodplain environment features many wetlands and effluent streams. Between Hillston and Booligal the Merrimajeel and Muggabah creeks flow away from the Lachlan River and from the Booligal Wetlands which are one the most valuable wetland habitats in the catchment. Downstream of Booligal numerous small flood channels dissect the floodplain and feed numerous shallow basins on the western side of the river. Downstream of Oxley the Lachlan River enters the Great Cumbung Swamp which covers around 16,000 ha and is adjacent to the Murrumbidgee River and the Lowbidgee Wetlands.

7.1.2 Climate

Average annual rainfall in the Lower Lachlan GMA varies from 421 mm at Lake Cargelligo in the east to 320 mm at Oxley in the south-west and 304 mm pa at Ivanhoe in the north-west.

The closest BoM stations to the study area are BoM stations 075032 Hillston Airport and station 075044 Merriwagga (The Old School Caravan Park). The long-term average annual rainfall at these two locations is 366.4 mm and 384 mm, respectively. Long-term average monthly rainfall and monthly rainfall for the current study period (2009–2011) for these two BoM stations is shown on Figures 7-2 and 7-3.

Historically, rainfall is fairly uniform throughout the year. During the current study period, monthly rainfall was above the long-term average at in the latter part of 2009 and nearly all months in 2010. Rainfall was also above average in January 2011. The highest monthly rainfall occurred in October 2010. The total annual rainfall at Hillston in 2010 was 820 mm, more than double the long-term average annual rainfall.

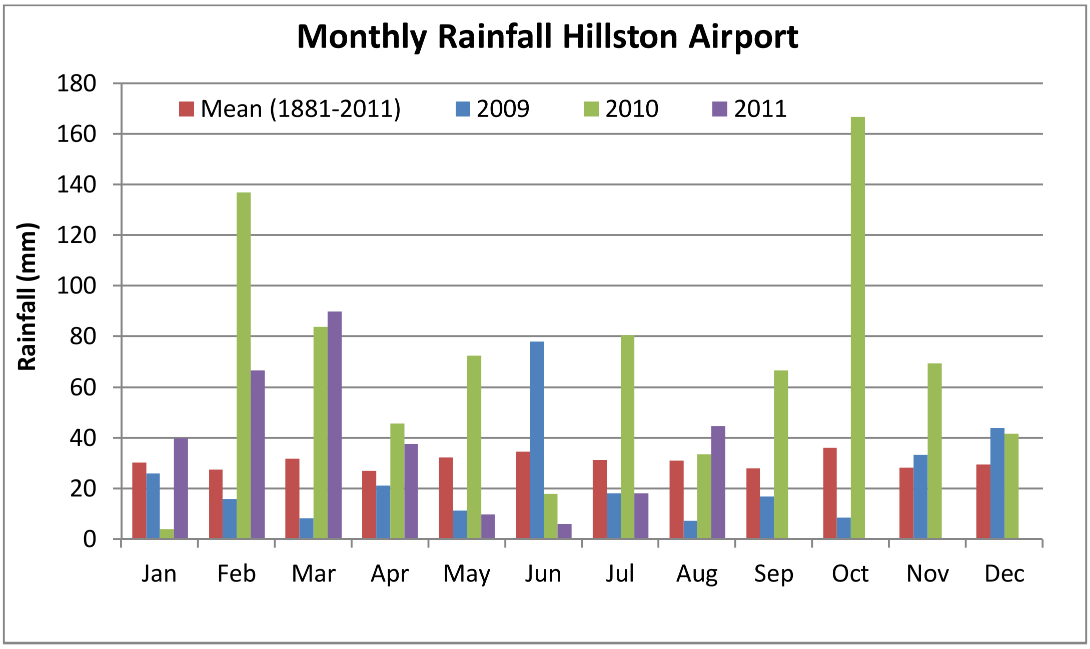


Figure 7-2 **Average monthly rainfall, BoM station 075032 Hillston Airport**

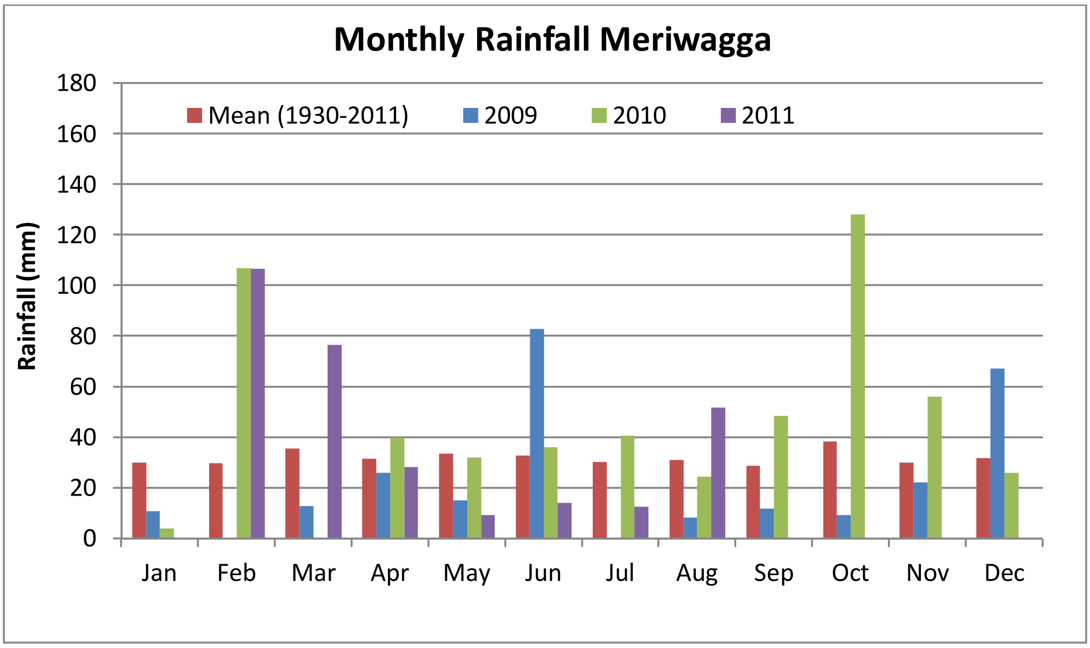


Figure 7-3 **Average monthly rainfall, BoM station 075044 Merriwagga (The Old School Caravan Park)**

The long-term cumulative rainfall residual for Hillston and Merriwagga for the period 1965 to 2011 are shown on Figure 7-4. Rainfall generally showed an above average trend from 1967–2000, and a below average trend from 2000–2009. During the study period (2009–2011), rainfall was above the long-term averages.

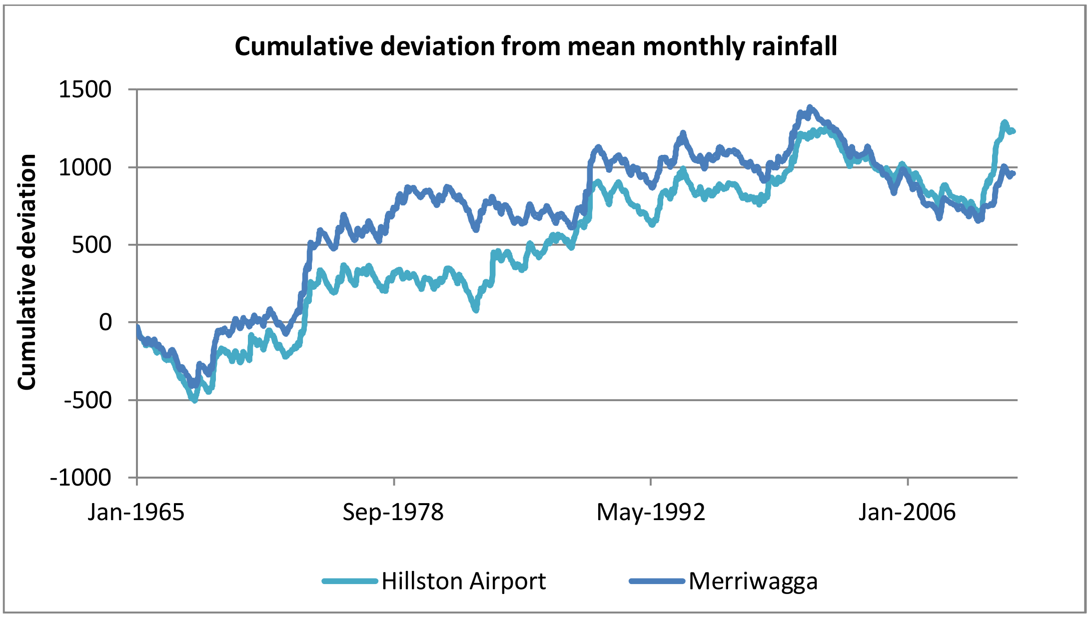


Figure 7-4 Cumulative deviation from mean monthly rainfall, Hillston and Merriwagga (1965 – 2011)

7.1.3 Land use

Land use in the Lower Lachlan GMA is dominated by extensive agriculture with the majority of the catchment used for livestock grazing. Dryland cropping is also undertaken. A range of winter crops are grown, and more recently areas of citrus, cotton, vines and vegetables have been grown near Hillston (NSW Agriculture 2003). Several parcels of land have also been designated for conservation.

7.1.4 Hydrogeology

The Lower Lachlan GMA lies predominantly on the north-eastern margin of the Riverine Plain of the Murray Geological Basin. The aquifers of the GMA are contained within the sediments of the Shepparton Formation, Calivil Formation and Renmark Group:

- Shepparton Formation (upper aquifer) – Late Pliocene to Pleistocene age unit that comprises river and lake deposits of variegated clay and lenses of yellow and brown shoestring sands.
- Calivil Formation (middle aquifer) – Late Miocene and Pliocene unit comprising coarse alluvial channel sands and gravels.
- Renmark Group (lower aquifer) - Palaeocene to Miocene unit comprising alluvial sands and gravels and black clay and peat.

The Shepparton Formation contains the uppermost unconfined aquifer system and is unsaturated in the north and north-west (under the Willandra Creek system) margins of the GMA. In the eastern part of the GMA the Calivil Formation and Renmark Group aquifers are hydraulically connected and form a leaky confined aquifer system. The Shepparton Formation is partially connected to the underlying Calivil Formation. In the western part of the GMA, the Middle Renmark unit separates the Lower Renmark from the overlying Upper

Renmark/Calivil aquifers. The Shepparton Formation is also partially connected to the Calivil in the western part of the GMA. Groundwater is abstracted from all units but predominantly from the two deeper units.

Groundwater salinity increases from the eastern part of the GMA where groundwater salinities in the Shepparton and Calivil formations are similar (TDS <500 mg/L) to the western part of the GMA where salinity in the Shepparton Formation can reach >7,000 mg/L and is higher than the deeper aquifers in which salinity ranges between 1,500 and 7,000 mg/L) (URS 2006).

The principal sources of aquifer recharge are from the Lachlan River and its various anabranches including Willandra Creek, particularly during flood events. Other recharge sources include rainfall and irrigation water. Groundwater flow is generally east to west in all three aquifers; however, small changes in flow direction occur due to recharge from the Lachlan River. In the western margin of the Riverine Plain between Hatfield and Balranald the Iona Ridge forms a barrier to groundwater flow from the Lower Lachlan GMA, and groundwater discharge occurs (Kellett 1989). Groundwater from the Lower Lachlan GMA either discharges vertically upwards or flows more south-westerly towards the Murray River.

Upstream of Lake Brewster the Lachlan River is direct hydraulic connection with shallow aquifers (connected stream). For the majority of the GMA, the Lachlan River is disconnected from the groundwater systems, that is, there is an unsaturated zone immediately below the river. At the western margin it is possible that groundwater levels are high enough for conditions to become saturated and groundwater and surface water systems connected again. However, this is difficult to establish with any certainty due to the highly ephemeral nature of the river systems at the western margin.

Groundwater extraction in the Lower Lachlan GMA began in the 1860s for town water supply and expanded in the late 1960s. In the early 1990s large-scale development for irrigation commenced. Hydrograph data from monitoring bores in the main extraction area indicate that groundwater levels have declined. Since the Shepparton and Calivil systems are partially connected, where pumping exceeds lateral throughflow, there is potential for more saline groundwater from the Shepparton Formation to leak into the Calivil Formation and cause an increase in salinity. In the western part of the GMA (outside of main pumping area) groundwater levels are rising.

Hydrographs of monitoring bores included in the current study are shown on Figure 7-5 and a brief summary of groundwater level trends is given in Table 7-1.

Table 7-1 Historical and current hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW030106_1	54.3–60.4	CF	GW03016 is located north of Hillston. Both pipes are screened in the Calivil Formation and are hydraulically connected. Water levels show a seasonal response to pumping since the mid-1990s and have decreased ~5 m since this time.
GW030106_2	68.9–73.2	CF	
GW030173_1	31.4–34.4	CF	GW030173 is located just north of Hillston. All three pipes are screened in the Calivil Formation. Since the
GW030173_2	54.9–61.0	CF	

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW030173_3	73.2–76.2	CF	mid-1990s Pipes 2 and 3 have shown seasonal drawdowns, and Pipe 1 has shown a more subdued response to pumping. Water levels in all three pipes have decline ~8 m.
GW030405_1	36.5–41.4	CF	GW030405 is located west of Hillston. In the 1980s and early 1990s water levels in all three pipes were similar and showed a slight rising trend. From 1994, water levels have shown a declining trend with large seasonal drawdowns evident in the Renmark group aquifers. Long-term drawdowns of ~10 m have occurred in the Calivil and Renmark aquifers.
GW030405_2	80.2–84.7	RG	
GW030405_3	121.9–128.1	RG	
GW030406_1	45.7–51.8	CF	GW030406 is located north-west of Hillston. In the 1980s and early 1990s water levels in all three pipes were similar and showed a slight rising trend. From 1994, water levels have shown a declining trend with large seasonal drawdowns evident in the Renmark group aquifers. Long-term drawdowns of ~7 m have occurred in the Calivil and Renmark aquifers.
GW030406_2	100.5–106.0	RG	
GW030406_3	128.0–134.0	RG	
GW036284_1	39.6–42.6	CF	GW036284 is located west of Hillston. Water levels in the Calivil and Renmark aquifer shave shown a slight decreasing trend since early 2000, and declined ~2 m in the last decade.
GW036284_2	167.6–179.8	RG	
GW036304_1	136.5–142.2	RG	GW036304 is located south-west of Hillston and is screened in the Renmark Group. Water levels increased during the late 1990s, but showed a decreasing trend between 2000 and 2006. Water levels have plateaued since 2006 at ~27.2 mbgl.
GW060153_1	37.4-43.5	CF	GW060153 is a pumping bore near Hillston, screened in the Calivil Formation. Water levels show seasonal drawdowns of up to 5 m.
GW090085_3	44.0–54.0	CF	GW090085 is a monitoring located east of Hillston. Hydrograph data indicates that the lower Calivil and Renmark aquifers are hydraulically connected and that groundwater levels have declined ~3 m since monitoring commenced in 2004.
GW090085_4	78.5–84.5	CF	
GW090085_5	134.0–140.0	RG	

Note: RG-Renmark Group, CF-Calivil Formation.

7.2 Characterisation of groundwater chemistry (2009–2011)

Groundwater sampling was undertaken in 16 sampling rounds during the study period (October 2009 to January 2011). 33 monitoring bores were sampled during the study, with nine located in the Renmark Group, 21 located in the Calivil Formation and three located in both Renmark and Calivil formations.

As the study area for the Lower Lachlan is centred on Hillston, groundwater chemistry trends geographically across the catchment cannot be determined. Groundwater chemistry interpretation is for the Hillston area only and no assumptions can be made on chemistry changes along flow paths in the Lower Lachlan GMA.

7.2.1 Results

Groundwater chemistry statistics are summarised in Tables 7-2 and 7-3 for the Calivil Formation and Renmark Group respectively. The results are presented on a cross-section (Figure 7-6). The location of the cross-section is shown on Figure 7-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 7-7, 7-8 and 7-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix F.

A Piper diagram presenting major ion chemistry for groundwater samples from the Calivil Formation and Renmark Group is presented in Figure 7-10.

Stable isotope data (^{18}O and ^{2}H) was collected for several monitoring rounds and is presented in Figures 7-11 and 7-12.

.

Table 7-2 Lower Lachlan Calivil Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	138	138	150	1100	371	305	221
EC (lab)	µS/cm	138	138	305	1791	649	563	362
pH (field)	pH unit	123	123	5.21	8.21	6.48	6.36	0.50
K	mg/L	138	138	2.1	11.0	4.0	3.3	2.2
Na	mg/L	138	138	31	240	92	56	64
Ca	mg/L	138	138	7.5	57.0	16.6	13.0	10.6
Mg	mg/L	138	138	9	67	18	14	11
Cl	mg/L	138	138	21	470	105	76	91
SO_4	mg/L	138	138	10	87	29	20	21
Alkalinity ($CaCO_3$)	mg/L	138	138	76	340	134	110	70
CO_3	mg/L	138	6	0.5	3.1	0.6	0.5	0.4
HCO_3	mg/L	138	138	93	420	163	130	84
Si	mg/L	138	138	5.0	19.0	8.3	8.4	2.4
F	mg/L	138	134	<0.1	2.40	0.50	0.31	0.56
Al (soluble)	mg/L	138	19	<0.01	0.320	0.013	0.005	0.035
B (soluble)	mg/L	138	53	<0.1	0.70	0.14	0.05	0.18
Br (soluble)	mg/L	138	89	<0.2	1.7	0.4	0.3	0.4
Cu (soluble)	mg/L	138	2	<0.01	0.030	0.005	0.005	0.002
Mn (soluble)	mg/L	137	23	<0.002	0.0250	0.001	0.0010	0.002
Ni (soluble)	mg/L	14	3	<0.01	0.021	0.007	0.005	0.005
Sr (soluble)	mg/L	138	138	0.12	1.10	0.28	0.24	0.17
Zn (soluble)	mg/L	138	114	<0.005	0.2400	0.030	0.0130	0.038
Mn (total)	mg/L	138	39	<0.002	0.030	0.002	0.001	0.004
Ni (total)	mg/L	138	14	<0.01	0.180	0.008	0.005	0.017
Zn (total)	mg/L	138	98	<0.01	1.000	0.043	0.020	0.099
Al (total)	mg/L	138	59	<0.05	3.100	0.122	0.025	0.328
B (total)	mg/L	138	52	<0.1	0.80	0.15	0.05	0.18
Cu (total)	mg/L	138	12	<0.005	0.0120	0.002	0.0025	0.001
Fe (total)	mg/L	138	46	<0.05	3.600	0.105	0.025	0.358
Pb (total)	mg/L	138	0	Not calculated				
N_2	mg/L	138	113	<0.05	2.300	0.211	0.090	0.361
NH_3	mg/L	138	18	<0.01	0.040	0.007	0.005	0.005
NO_3	mg/L	3	3	1.1	2.2	1.7	1.8	0.6
PO_4	mg/L	138	138	0.006	0.048	0.021	0.022	0.008
Total P	mg/L	138	138	0.006	0.054	0.025	0.026	0.009

Note: SD – standard deviation

Table 7-3 Lower Lachlan Renmark Group statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	75	75	250	750	528	500	138
EC (lab)	µS/cm	75	75	464	1350	957	906	246
pH (field)	pH unit	71	71	6.02	7.87	6.58	6.55	0.29
K	mg/L	75	75	2.3	5.4	4.0	4.1	0.7
Na	mg/L	75	75	55	230	149	150	47
Ca	mg/L	75	75	10	27	18	18	4
Mg	mg/L	75	75	13	31	21	21	5
Cl	mg/L	75	75	80	290	185	170	70
SO_4	mg/L	75	66	0.25	98	47	42	29
Alkalinity ($CaCO_3$)	mg/L	75	75	89	180	145	140	21
CO_3	mg/L	75	0	Not calculated				
HCO_3	mg/L	75	75	110	220	176	170	26
Si	mg/L	75	75	4.2	10.0	6.0	5.6	1.2
F	mg/L	75	75	<0.1	0.87	0.49	0.49	0.19
Al (soluble)	mg/L	75	8	<0.01	0.120	0.009	0.005	0.018
B (soluble)	mg/L	75	69	<0.1	0.30	0.15	0.10	0.08
Br (soluble)	mg/L	75	74	<0.2	1.2	0.7	0.7	0.3
Cu (soluble)	mg/L	75	2	<0.01	0.040	0.006	0.005	0.004
Mn (soluble)	mg/L	75	71	<0.002	0.100	0.023	0.016	0.019
Ni (soluble)	mg/L	3	1	<0.01	0.010	0.007	0.005	0.003
Sr (soluble)	mg/L	75	75	0.20	0.53	0.34	0.32	0.09
Zn (soluble)	mg/L	75	40	<0.005	0.1100	0.020	0.0060	0.0248
Mn (total)	mg/L	75	70	<0.002	0.100	0.022	0.017	0.018
Ni (total)	mg/L	75	3	<0.01	0.017	0.005	0.005	0.002
Zn (total)	mg/L	75	39	<0.01	0.100	0.025	0.012	0.026
Al (total)	mg/L	75	52	<0.05	0.250	0.084	0.070	0.054
B (total)	mg/L	75	70	<0.1	0.30	0.17	0.20	0.08
Cu (total)	mg/L	75	1	<0.005	0.0083	0.002	0.0025	0.0007
Fe (total)	mg/L	75	64	<0.05	1.600	0.279	0.140	0.353
Pb (total)	mg/L	75	2	0.010	0.033	0.010	0.010	0.003
N_2	mg/L	75	68	<0.05	0.720	0.169	0.140	0.126
NH_3	mg/L	75	60	<0.01	0.210	0.061	0.040	0.056
PO_4	mg/L	75	75	0.010	0.463	0.091	0.040	0.105
Total P	mg/L	75	75	0.019	0.623	0.139	0.066	0.170

Note: SD – standard deviation

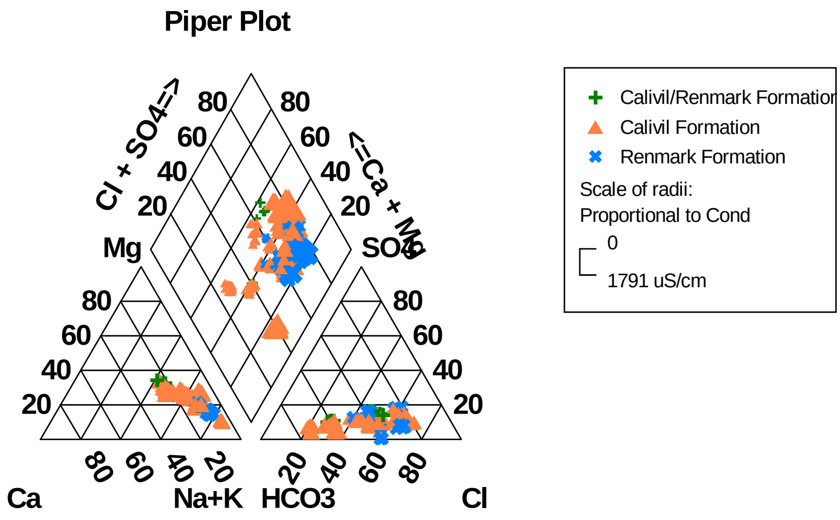


Figure 7-10 Piper diagram for the Lower Lachlan Catchment during the study period

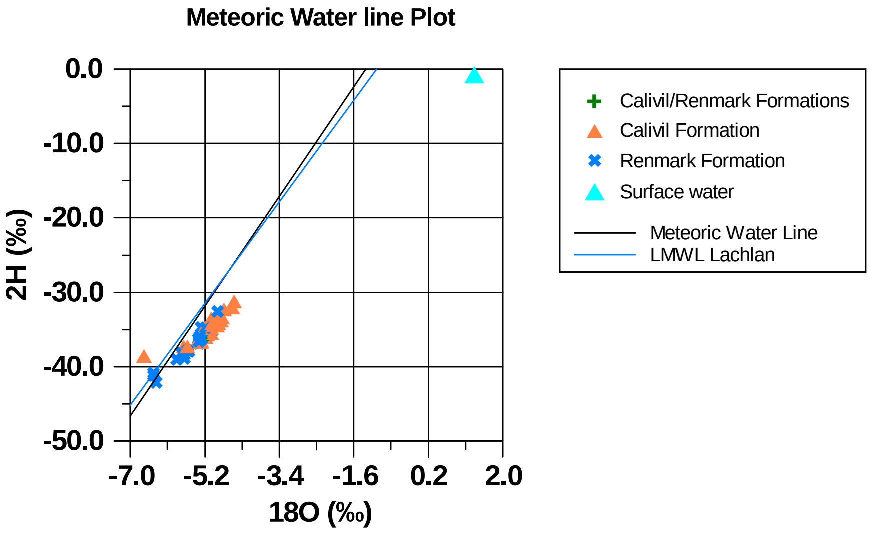


Figure 7-11 Oxygen-18 versus deuterium for groundwater samples from the Lower Lachlan GMA

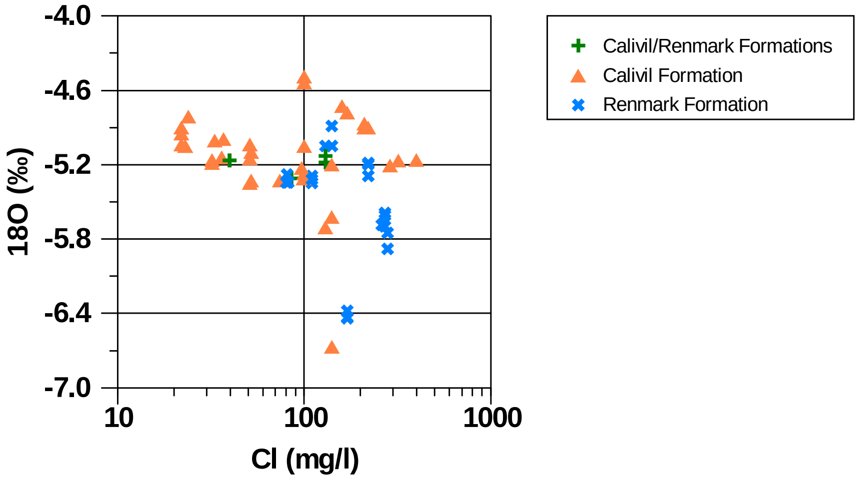


Figure 7-12 Oxygen-18 versus chloride for groundwater samples from the Lower Lachlan GMA

7.2.1.1 Calivil Formation

Water quality parameters

Groundwater salinity within the Calivil Formation is fresh with EC ranging from 138 µS/cm to 1,791 µS/cm (150 mg/L to 1,100 mg/L TDS). The lowest salinity groundwater occurs in monitoring and pumping bores closest to the Lachlan River near Hillston.

The pH values ranged from acidic (pH 5.21) to alkaline (pH 8.21), with average pH conditions slightly acidic (pH 6.48). The lowest pH groundwater generally occurs close to the Lachlan River near Hillston.

Major and minor ions

The average major ion composition for the Calivil Formation is shown on Figure 7-7. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix F.

As seen in Figure 7-7, the major ion composition is variable, with groundwaters plotting between two end members; a fresh (low salinity) end member characterised by Na-Mg-HCO_3-Cl type water (GW030106_1) and a more saline end member characterised by Na-Mg-Cl type water (GW030406_1). Groundwaters plotting between these two end members have major ion compositions that are classified as either mixed cation-HCO_3-Cl or mixed cation-Cl-HCO_3.

Dissolved silicon concentrations ranged from 5 mg/L to 19 mg/L. The highest silicon concentrations occur in bores located close to the Lachlan River at Hillston.

Fluoride concentrations range from detection limit (<0.01 mg/L) to 2.4 mg/L. Fluoride concentrations are well correlated with salinity (r^2=0.77). Bromide concentrations ranged from 0.1 mg/L to 1.7 mg/L, and were well correlated with salinity (r^2=0.92).

Metals and metalloids

Groundwater samples were analysed for dissolved metals and metalloids (aluminium, boron, copper, manganese, strontium and zinc) and total metals (aluminium, boron, copper, iron, lead, manganese, nickel and zinc).

Boron was detected in 38% of samples, with concentrations of up to 0.7 mg/L (dissolved) and 0.8 mg/L (total). Aluminium (total) was detected in 43% of samples with maximum concentrations 3.1 mg/L.

Copper and nickel were detected in few samples (<10%). Lead was not detected in any samples. Zinc was detected in the majority of samples (82%) reaching concentrations of up to 0.24 mg/L (soluble). Manganese (total) was detected in 28% of samples, and reached maximum concentrations of 0.03 mg/L. Total iron was detected in 33% of samples, up to concentrations of 3.6 mg/L.

Strontium was detected in all samples, with concentrations ranging from 0.12 mg/L to 1.10 mg/L. Strontium was well correlated with salinity (r^2=0.86).

Nutrients

Ammonia was only detected in 13% of samples, reaching maximum concentrations of 2.3 mg/L. Nitrate was only analysed and detected in three samples, with concentrations ranging from 1.1 mg/L to 2.2 mg/L. Total and reactive phosphorus were detected in in all groundwater samples, and reached maximum concentrations of 0.054 mg/L and 0.048 mg/L, respectively. These results indicate that nearly all phosphorus in the system is present as orthophosphate which is the most thermodynamically stable species in natural waters.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H), were analysed for groundwater samples collected in December 2009, and January and July 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^2H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^2H = 7.6\delta^{18}O + 8$) (Lamontagne et al 2011) on Figure 7-11.

Forty-one samples were analysed for stable isotopes in the Calivil Formation. Stable isotope values for the shallow aquifer ranged from –6.67‰ to -4.49‰ for $\delta^{18}O$, and -38.6‰ to -31.3‰ for δ^2H and generally plotted to the right of the LMWL and GMWL, showing an evaporative signature.

7.2.1.2 Renmark Group

Water quality parameters

Groundwater salinity within the Renmark Group is fresh with EC ranging from 464 µS/cm to 1,350 µS/cm (250 mg/L to 750 mg/L TDS). The pH values ranged from slightly acidic (pH 6.02) to slightly alkaline (.pH 7.87). The average pH conditions were slightly acidic (pH 6.49).

Major and minor ions

The average major ion composition for the Renmark Group is shown on Figure 7-7. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix F. Groundwater composition showed only small variations with groundwater chemically classified as either Na-Cl-HCO_3, Na-HCO_3-Cl or Na-Mg-Cl-HCO_3 type water.

Dissolved silicon concentrations ranged from 4.2 mg/L to 10.0 mg/L. The highest silicon concentrations occur in bores located close to the Lachlan River at Hillston.

Fluoride concentrations ranged from 0.15 mg/L to 0.85 mg/L, and showed no spatial trend. Bromide concentrations ranged from <0.1 to 1.2 mg/L, and were well correlated with salinity (r^2=0.92).

Metals and metalloids

Groundwater samples were analysed for dissolved metals and metalloids (aluminium, boron, copper, manganese, strontium and zinc) and total metals (aluminium, boron, copper, iron, lead, manganese, nickel and zinc).

Boron was detected in 92% of samples, with concentrations ranging from <0.1 mg/L to 0.3 mg/L. Aluminium (total) was detected in 69% of samples, with maximum concentrations of 0.25 mg/L. Copper, nickel and lead were detected in few samples (<5%).Zinc was detected in 53% of samples, and reached maximum concentrations of 0.11 mg/L (soluble). Manganese was detected in 95% of samples, and maximum concentrations of up to 0.1 mg/L. Total iron concentrations was detected in 85% of samples, and concentrations of up to 1.6 mg/L were detected.

Strontium was detected in all samples, with concentrations ranging from 0.2mg/L to 0.53 mg/L. Strontium was well correlated with salinity (r^2=0.79).

Nutrients

Ammonia was detected in 80% of samples, and concentrations reached up to 0.21 mg/L. Total and reactive phosphorus were detected in in all groundwater samples, and reached maximum concentrations of 0.623 mg/L and 0.463 mg/L, respectively. These results indicate that nearly all phosphorus in the system is present as orthophosphate which is the most thermodynamically stable species in natural waters. Higher concentrations may be related to peat and lignite layers that are common throughout the Renmark Group.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H), were analysed for groundwater samples collected in December 2009, and January and July 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^2H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Gunnedah ($\delta^2H = 7.6\delta^{18}O + 8$) (Lamontagne et al 2011) on Figure 7-11.

Twenty-one samples from the Renmark Group were analysed for stable isotopes. Stable isotope values for the shallow aquifer ranged from –6.44‰ to -4.89‰ for $\delta^{18}O$, and -42.1‰ to -32.6‰ for δ^2H. The majority of samples plotted to the right of the LMWL and GMWL, showing an enriched stable isotope signature. One exception was the deep monitoring bore GW090085_5 located near Hillston. Stable isotope values from this monitoring bore plotted on the GMWL and were the most depleted values monitored during the current study.

7.2.2 Processes

7.2.2.1 Calivil Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 7-13). Calcium, magnesium, potassium and bicarbonate showed curved ion/Cl trends, suggesting mixing between a fresh and higher salinity end member. Na/Cl ratios are more scattered, with the majority of samples plotting above the Na/Cl seawater line. Higher salinity samples plotted along a straight line (seawater line) with increasing salinity indicating that dissolution of salts or evaporative concentration are the major processes increasing salinity. A number of samples plotted below the Na/Cl seawater indicating a process such as reverse ion exchange may be removing Na.

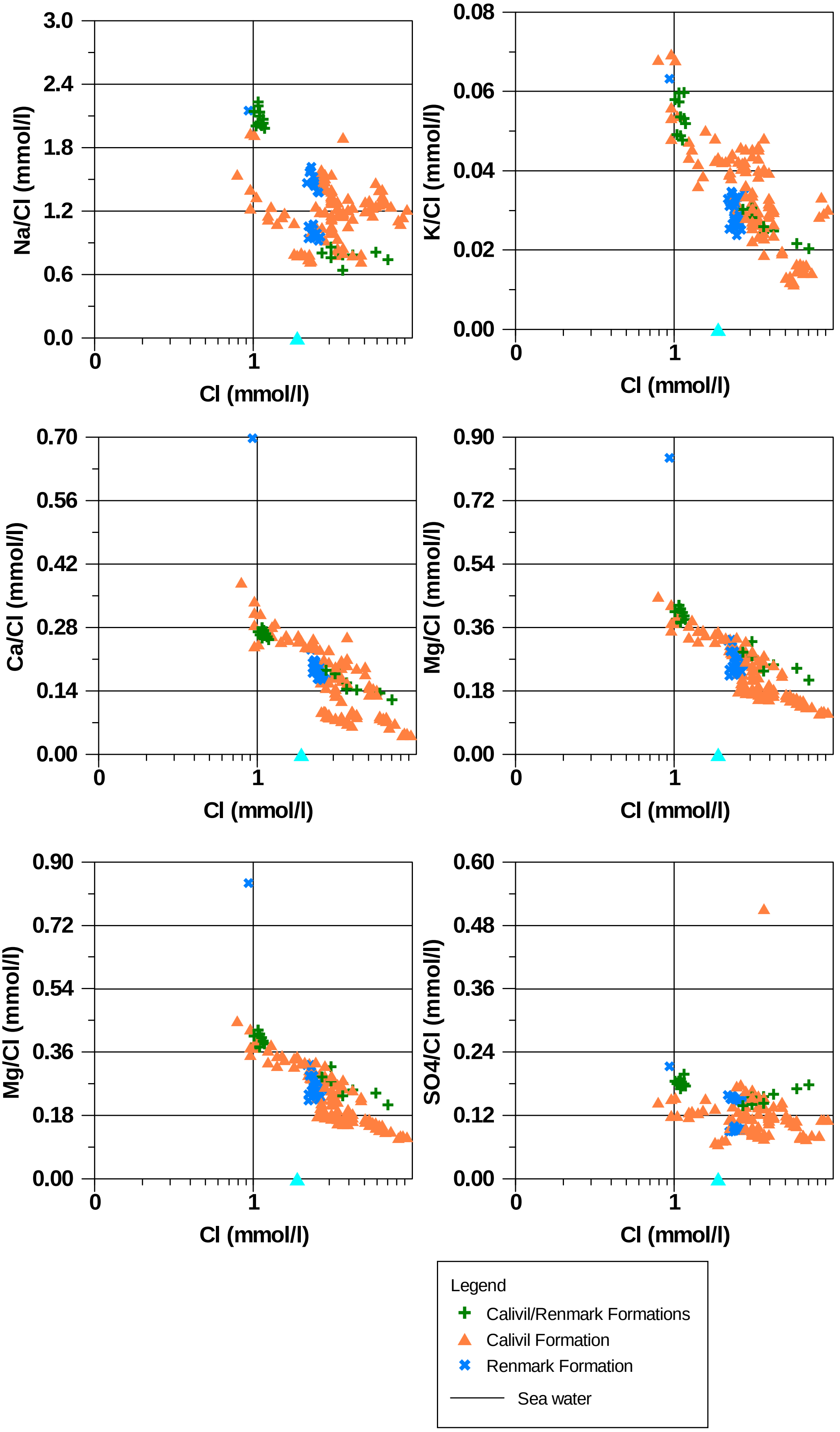


Figure 7-13 Ion/chloride versus chloride graphs for the Lower Lachlan GMA

Saturation indices for the Calivil Formation are plotted in Figure 7-14. Saturation indices predict if samples are supersaturated, under-saturated or in equilibrium with respect to the mineral phase. In general groundwater in the Calivil Formation is under-saturated with respect to calcite, gypsum, dolomite and anhydrite.

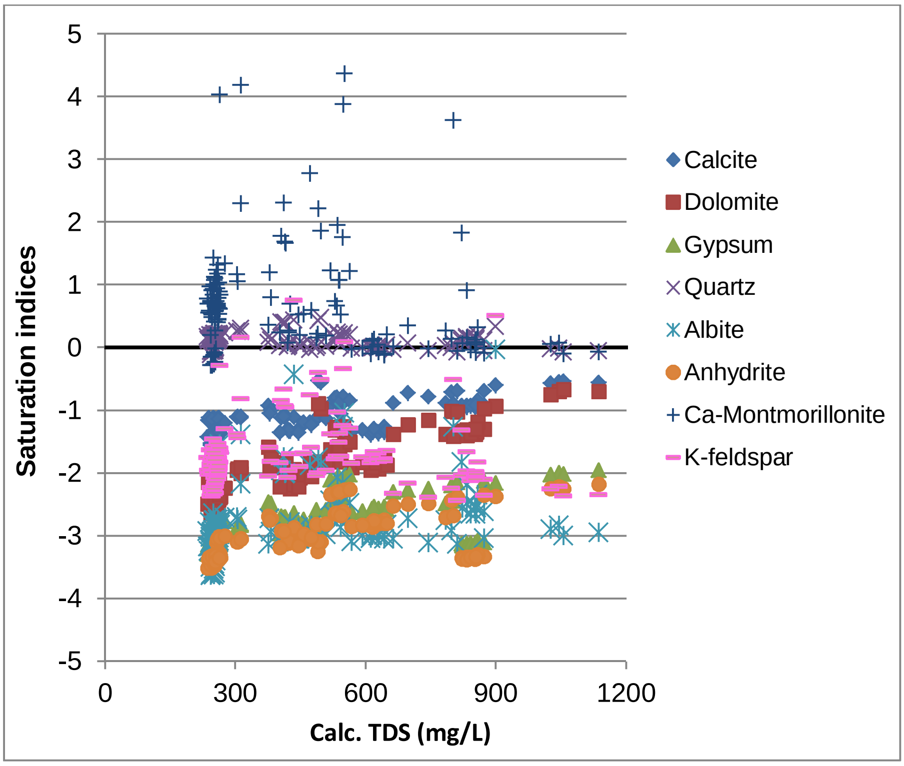


Figure 7-14 **Saturation indices versus TDS for the Calivil Formation**

Ion exchange

Figure 7-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. Groundwater samples generally plot below the 1:1 line, indicating that ion exchange may be occurring. A few higher salinity samples and samples from some pumping bores plot above the 1:1 line, indicating reverse ion exchange may be occurring. These bores have Na/Cl below the seawater line.

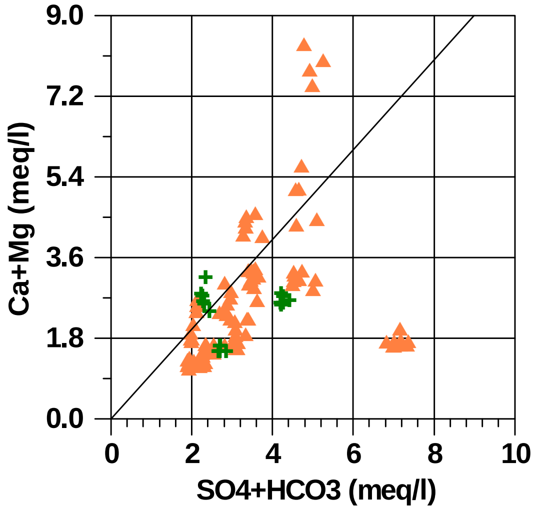


Figure 7-15 Calcium + magnesium versus bicarbonate + sulphate in the Calivil Formation

Stable isotopes

Deep groundwater samples from near Hillston plot on the LMWL and GMWL. This depleted signature is consistent with winter rainfall in the Murray-Darling Basin (Lamontagne et al. 2011). All other groundwater samples plot along an evaporation line with surface water. The evaporation line has the equation $\delta^2H = 5.16\delta^{18}O + -8.5$, which is consistent with the findings of Lamontagne et al. (2011). These authors concluded isotopic enrichment in most groundwater samples is consistent with some infiltration from upstream reservoir releases, which are isotopically enriched in comparison to winter rainfall.

Looking at Figure 7-11 and Figure 7-12 which shows $\delta^{18}O$ versus Cl, there is some clear overlap in the isotopic signatures of groundwater from the Calivil Formation and Renmark Group, supporting the hydrogeological and chemical data which indicates some mixing occurring between these two aquifers. However, without clear defined end members, the proportion of mixing was not determined.

7.2.2.2 Renmark Group

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 7-13). Linear relationships would indicate only evapotranspiration is affecting the ionic relationships. Calcium, magnesium, potassium and bicarbonate showed curved ion/Cl trends, suggesting mixing between a fresh and higher salinity end member. Na/Cl ratios are more scattered, however all samples plot above the Na/Cl seawater line.

Saturation indices for the Renmark Group are plotted in Figure 7-16. Saturation indices predict if samples are supersaturated, under-saturated or in equilibrium with respect to the mineral phase. Similarly to groundwater from the Calivil Formation, groundwater from the Renmark group is under-saturated with respect to calcite, dolomite, gypsum and anhydrite.

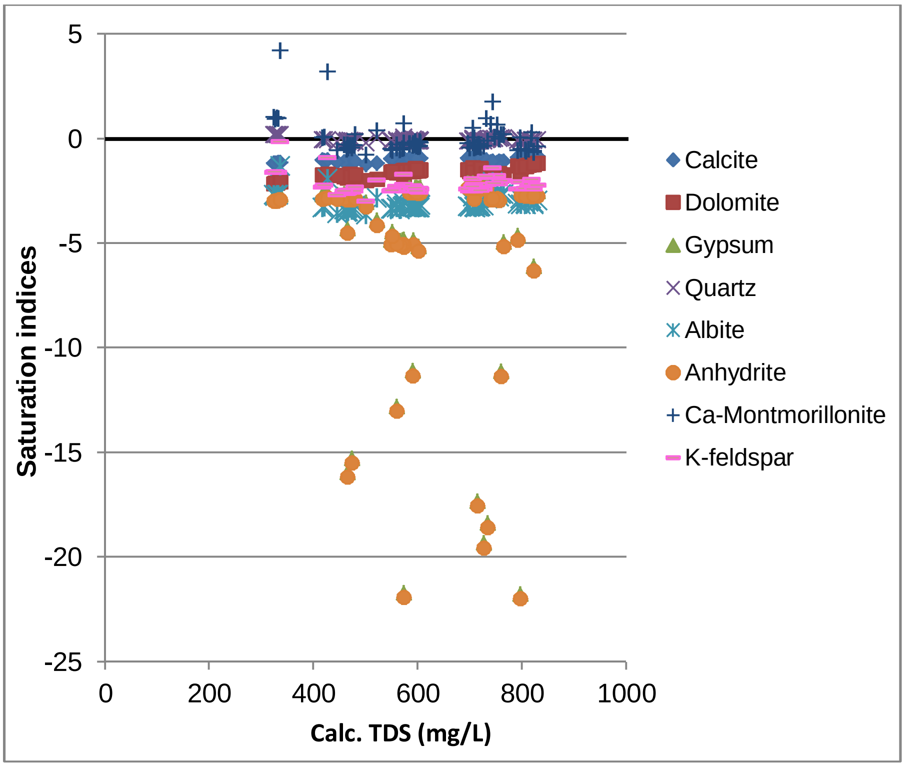


Figure 7-16 **Saturation indices versus TDS for the Renmark Group**

Ion exchange

Figure 7-17 shows the relationship between calcium + magnesium and bicarbonate + sulphate. All groundwater samples plot below the 1:1 line, indicating that ion exchange may be occurring.

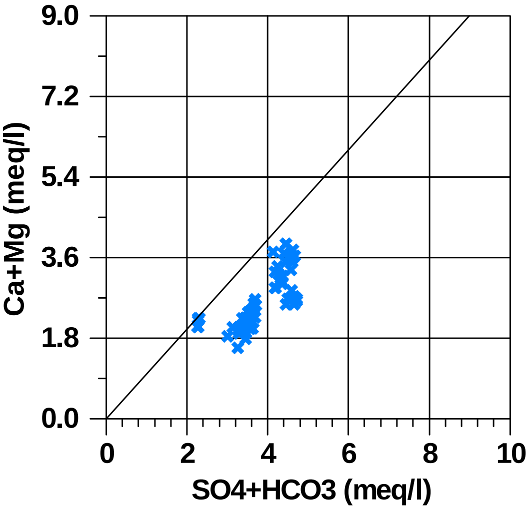


Figure 7-17 **Calcium + magnesium versus bicarbonate + sulphate in the Renmark Group**

Stable isotopes

As discussed in Section 7.2.2.1 there is some clear overlap in the isotopic signatures of groundwater from the Calivil Formation and Renmark Group, supporting the hydrogeological and chemical data which indicates some mixing occurring between these two aquifers. However, without clear defined end members, the proportion of mixing was not determined.

7.2.3 Beneficial use

The risk to groundwater in the Lower Lachlan GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered ‘at risk’.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Lower Lachlan GMA.

The *Water Sharing Plan for the Lower Lachlan Groundwater Sources* defines four objectives; including an objective relating to groundwater quality:

> ‘(b) determine resource access and clarify reliability for groundwater users,
>
> **Note.** The expected outcomes of this objective are that: groundwater usage does not exceed the extraction limit; the rate of extraction does not induce detrimental changes to water quality; groundwater users have a clear understanding of resource access and reliability; sustainable economic benefits will be maximised; more flexible and efficient use of water will be facilitated; and, there will be equitable access to the groundwater source within the extraction limit.’

To meet this objective, water quality management is detailed in the Plan:

> ‘38 Water quality management
>
> (1) The beneficial uses of this groundwater source based on the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2000, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996, are raw water for drinking supplies, and agriculture water.
>
> (2) Water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class…
>
> (5) The EC limits adopted for this Plan for the beneficial use categories are as follows:
>
> > (a) 800 EC for Raw Drinking Supplies Class; and
> >
> > (b) 1,500 EC for Agricultural Water Class.’

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 7-4. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in the Lower Macquarie GMA.

Table 7-4 Correlation analysis of parameters used to assess salinity and sodicity hazards, Lower Lachlan GMA

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.956	0.971	0.965	0.864
TDS		1	0.917	0.963	0.948
Na^+			1	0.921	0.83
Cl^-				1	0.867
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Lower Lachlan GMA based on the Australian Drinking Water Guidelines (2011) and ANZECC (2000) guidelines for Primary Industry.

7.2.3.1 Calivil Formation

Based on EC groundwater from the Calivil Formation is generally suitable for drinking water. However, other analytes need to be considered in the assessment of groundwater for drinking water purposes. Percentages of groundwater samples from the Calivil Formation that are above health and aesthetic guideline values for drinking water are shown in Table 7-5.

Table 7-5 ADWG (2011) values and percentage of samples above guideline values, Calivil Formation (N=127) Lower Lachlan GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		67
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		13
Potassium (mg/L)				
Chloride (mg/L)	a	250		6
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		16	
Aluminium (mg/L)	b	0.2		1
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	0
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix F. Groundwater from the Calivil Formation had low sodium hazards, with SARs ranging from 2 to 10, with an average of 4. Groundwater is generally suitable for irrigation of sensitive to moderately sensitive plants based on ANZECC (2000) guideline values for Na$^+$ and Cl$^-$concentrations that can cause foliar injury to plants.

The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), all samples from the Calivil Formation were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

7.2.3.2 Renmark Group

Based on EC, groundwater from the Renmark Group is suitable for drinking water. However, other analytes need to be considered in the assessment of groundwater for drinking water purposes. Percentages of groundwater samples from the Renmark Group that are above health and aesthetic guideline values for drinking water are shown in Table 7-6. Groundwater in the Renmark Group exceeds pH, sodium and chloride in some samples.

Table 7-6 ADWG (2011) values and percentage of samples above guideline values, Renmark Group (N=73) Lower Lachlan GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		44
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		24
Potassium (mg/L)				
Chloride (mg/L)	a	250		24
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		18	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	0
Strontium (mg/L)				

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix F.

Groundwater from the Renmark Group had low sodium hazards, with SARs ranging from 2 to 8, with an average of 6. Groundwater is generally suitable for irrigation of sensitive to moderately sensitive plants based on ANZECC (2000) guideline values for Na^+ and Cl^- concentrations that can cause foliar injury to plants.

The salinity thresholds for the different types of stock are presented in Table 2-2. Based on salinity (EC), all samples from the Renmark Group were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

7.2.4 Trends

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2.The results of these analyses are presented in Tables 7-8 and 7-7 for the Calivil Formation and Renmark Group respectively.

7.2.4.1 Calivil Formation

Study period trends

During the study period, increasing salinity trends were observed in 6 of the 25 bores monitored in the Calivil or Calivil/Renmark aquifers (5 sites). All bores were located west of Hillston. Although slight changes in the relative proportions of major ions were observed, the water type did not change for any bores showing an increasing salinity trend. Two of the bores showing an increasing trend were pumping bores. At two out of the three other sites, seasonal changes in vertical gradients occurred during the monitoring period, resulting in mixing between water from the upper aquifer which had a higher salinity, with groundwater from deeper aquifers with lower salinity.

Long-term trends

Five of the bores monitored in the Calivil and Calivil/Renmark that had sufficient data to assess a long term trends showed increasing salinity (EC) trends. Four of these bores were pumping bores, with no water level data available. Therefore it is not possible to determine if the observed trends in water quality are related to a hydrogeological process.

One monitoring bore, GW030106_2, located north of Hillston, showed a long-term increasing salinity trend based on historical data dating back to 2000. At this location the overlying

Shepparton Formation is not monitored so it is unclear whether leakage from this aquifer is resulting in increasing salinity in the Calivil aquifer.

Beneficial use trends

The current beneficial use of groundwater from the Calivil Formation is comparable to historical beneficial use (drinking water).

Table 7-7 Short- and long-term trends, Calivil Formation, Lower Lachlan GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW030106_1	12	-	-	-	-	-	13	-	-	-	-	-	-
GW030106_2	14	Increase	339	355	2	5	15	Increase	321 (08/00)	355	5	11	-
GW030173_1	2	ID					ND	ND	ND	ND	ND	ND	ND
GW030173_2	12	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW030173_3	11	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW030405_1	12	Increase	1050	1,120	6	7	ND	ND	ND	ND	ND	ND	ND
GW030406_1	9	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW036284_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ND
GW042633_1	7	-	-	-	-	-	19	Increase	415 (11/02)	921	40	122	Na-Mg-Ca-HCO3-Cl to Na-Mg-Ca-Cl-HCO3
GW059167_1	6	-	-	-	-	-	19	-	-	-	-	-	-
GW060153_1	4	-	-	-	-	-	17	-	-	-	-	-	-
GW064785_1	4	-	-	-	-	-	13	-	-	-	-	-	-
GW090085_3	11	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW090085_4	10	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW700674_1	2	ID	ID	ID	ID	ID	13	-	-	-	-	-	-
GW700925_1	5	Increase	615	702	6	14	17	Increase	619 (11/02)	702	8	13	-
GW701062_1	1	ID	ID	ID	ID	ID	8	-	-	-	-	-	-

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW701089_1	0	ID	ID	ID	ID	ID	4	Decrease	1,550 (01/03)	1,220	-350	21	-
GW701101_1	5	-	-	-	-	-	18	-	-	-	-	-	Na-Cl-HCO3 to Na-Mg-Cl-HCO3
GW701507_1	5	-	-	-	-	-	16	Increase	271 (10/03)	419	10	55	-
GW701620_1	4	-	-	-	-	-	16	-	-	-	-	-	Na-Cl-HCO3 to Na-Mg-Cl-HCO3
GW702975_1	3	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ND
GW700971_1*	6	-	822	874	12	6	ND	ND	ND	ND	ND	ND	ND
GW059244_1*	6	-	-	-	-	-	17	Increase	394 (11/02)	413	5	5	-
GW702263_1*	5	-	-	-	-	-	13	Decrease	1,080 (11/05)	566	-315	-48	Na-Mg-Cl-SO4 to Na-Mg-Ca-Cl-HCO3

Note: *screened in the Calivil Formation and Renmark Group; ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

7.2.4.2 Renmark Group

Study period trends

Electrical conductivity and major ion variability in the Calivil Formation was examined for the study period September 2009 to early 2011, based on the available hydrogeochemical data. Trend analysis was undertaken using Mann Kendall analysis and results are presented in Table 7-5.

During the study period, EC increased in 5 out of 8 bores monitored in the Renmark Group. All bores were located west of Hillston. Although slight changes in the relative proportions of major ions were observed, the water type did not change for any bores showing an increasing salinity trend. At monitoring bore GW030406, monitoring bores 2 and 3 are hydraulically connected. During irrigation seasons, large drawdowns occur (up to ~7 m), however during the recovery period, water levels as the monitoring bore 1 (upper aquifer). These seasonal fluctuations are likely to be resulting in leakage and mixing with higher salinity water from the upper aquifer (average EC 1,457 µS/cm).

At GW036284, the upper and lower aquifers are hydraulically connected, and leakage from the higher salinity upper aquifer is leading to an increase in salinity in the lower aquifer.

At GW036304_1, the upper aquifer is not monitored, and no water level change was observed during the monitoring period, so the cause of increasing salinity could not be conclusively determined.

Long-term trends

Only two monitoring bores had historical water quality data. Neither bore showed statistically significant trends in EC a change in water type.

Beneficial use trends

The current beneficial use of groundwater from the Renmark Group is comparable to historical beneficial use (drinking water).

Table 7-8 Short- and long-term trends, Renmark Group, Lower Lachlan GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030405_2	11	Increase	684	718	3	5	ND	ND	ND	ND	ND	ND	ND
GW030405_3	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ND
GW030406_2	11	Increase	909	918	2	1	ND	ND	ND	ND	ND	ND	ND
GW030406_3	13	Increase	1,100	1,158	6	5	ND	ND	ND	ND	ND	ND	ND
GW036284_2	10	Increase	1,240	1,312	6	6	ND	ND	ND	ND	ND	ND	ND
GW036304_1	10	Increase	1,160	1,212	6	4	ND	ND	ND	ND	ND	ND	ND
GW090085_5	10	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW700344_1	3	ID	ID	ID	ID	ID	17	-	-	-	-	-	-
GW701508_1	5	-	-	-	-	-	16	-	-	-	-	-	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

7.2.5 Risks to groundwater quality

Groundwater levels within the eastern part of the Lachlan GMA (centred on Hillston) generally declined by 2 to 10 m since the mid-1990s when large scale irrigation development commenced; however, the results of this study show that in general these declines in water level are associated with significant deterioration in water quality in the Calivil Formation and Renmark group.

Groundwater quality within the Calivil Formation is generally fresh and suitable for drinking water (based on EC). Five bores within the Calivil and Calivil/Renmark formations (GW030106_2, GW042633_1, GW700925_1, GW700507_1 and GW059244_1) located north of Hillston show a long-term increasing trend in salinity with increases ranging from 11 to 122%. However, since EC values are low, these large percentage increases in salinity only equate to increases up to a few hundred µS/cm, and groundwater is still suitable for drinking water.

Within the Renmark Group, there are insufficient data to assess long-term trends. Five monitoring bores located mainly south-west of Hillston showe short-term increasing trends (GW030405_1, GW030406_2, GW030406_3, GW036284_2 and GW036304_1), with EC increasing by 1 to 6%. However, these percentage changes equate to an EC change of only <100 µS/cm, and do not result in a deterioration of beneficial use.

In the eastern part of the Lower Lachlan GMA, the risk to groundwater quality due to pumping is lower than the other GMAs due to the absence of the Shepparton Formation in the eastern part of the catchment (which normally contains more saline groundwater).

8. Lower Murray GMA

8.1 Characterisation of the study area

The Lower Murray GMA is located on the New South Wales side of the Murray River; bounded by Corowa in the east, the junction of the Murray and Wakool Rivers in the west and Billabong Creek in the North (Figure 8-1). The GMA covers an approximate area of 17,000 km^2 (Kulatunga 1999).

8.1.1 Topography and surface hydrology

The Lower Murray GMA is located on the Murray River alluvial floodplain, with the Murray River forming the southern border of the GMA. The Lower Murray GMA is very flat with elevations in the area typically less than 200 m and in some areas less than 100 m.

The Murray River originates in the Australian Alps of NSW and Victoria and flows in a general westerly direction to its outlet on the South Australian coast. The Murray River is regulated by the Hume Dam, upstream of Albury, NSW (NOW 2011b).

In the Lower Murray GMA, a complex series of effluent channels diverge from the river, distributing water across the floodplain. This network of channels was established when the north-south ridge, the Cadell Fault, formed across the then course of the Murray River (NOW 2011b), splitting the river to the south and north (the north branch forming the Edward River). The Edward River re-joins the Murray River approximately 200km downstream. Other major channels in the region are the Wakool River, Niemur River, Yallakool Creek, Billabong Creek and Colligen Creek, all of which are regulated (NOW 2011b). The major tributaries entering the Murray River downstream of Yarrawonga from Victoria are the Goulburn, Campaspe and Loddon Rivers.

The majority of the surface water supply for the Murray irrigation areas is delivered through the man-made Mulwala Canal, which diverts water from the Murray River at Lake Mulwala (Kulatunga 1999). The Mulwala canal is important for supplying water for irrigation, stock, domestic, industrial, recreational and town water supply in the region (Kulatunga 1999).

Several nationally important wetlands are located in the Lower Murray catchment:

- Millewa and Moira National Parks, located on the NSW side of the Murray River, opposite the Barmah Forest Ramsar site (DSEWPC 2011). The wetland occurs on the floodplains of the Murray and Edward Rivers.
- Koondrook-Perricoota State Forests, located on the NSW side of the Murray River, opposite the Gunbower Forest Ramsar site. The flow of water through the Koondrook Forest is dominated by the Burrumburry-Barber Creek system (DSEWPC 2011).

8.1.2 Climate

Average annual rainfall in the Lower Murray GMA varies from 338 mm at Mallan (BoM station 75020) in the west, to 399 mm at Jerilderie (BoM station 074055) in the north-east.

The closest BoM stations to the study area are stations 074106 Tocumwell Airport and station 074128 at Deniliquin (Wilkinson St), which have long-term average annual rainfalls of 446.5 mm and 409.2 mm, respectively. Long-term average monthly rainfall and monthly rainfall for the current study period (2009–2011) for these two BoM stations is shown in Figures 8-2 and 8-3.

Historically, rainfall is fairly uniform throughout the year, with the highest long-term average rainfalls occurring from May to October. During the current study period, monthly rainfall was typically below the long-term average in 2009 and typically above the average in 2010 and early 2011.

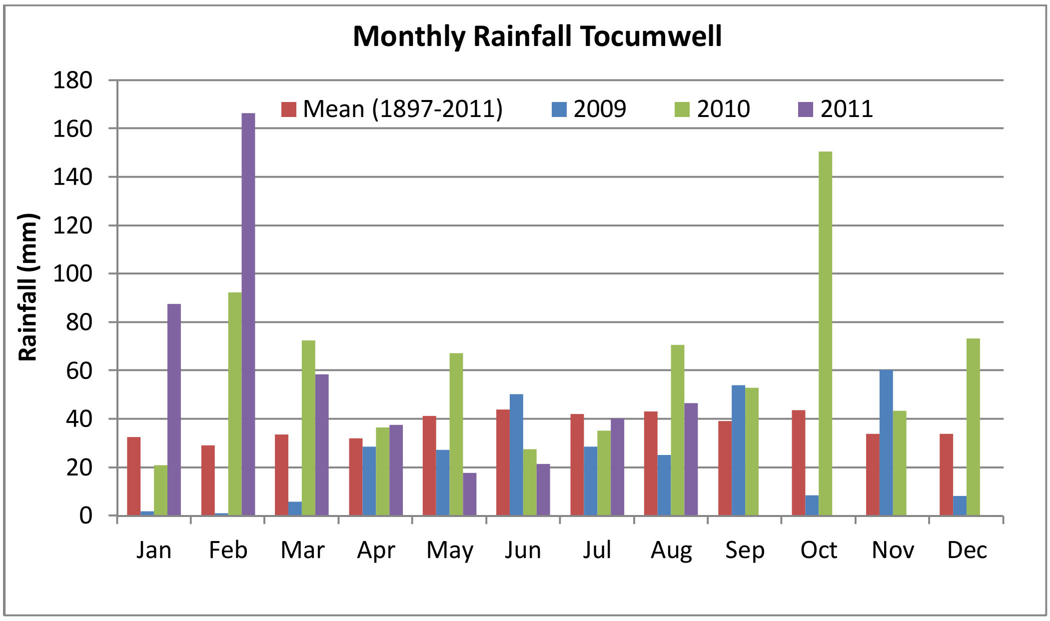


Figure 8-2 **Average monthly rainfall, BoM station 074106 Tocumwell Airport**

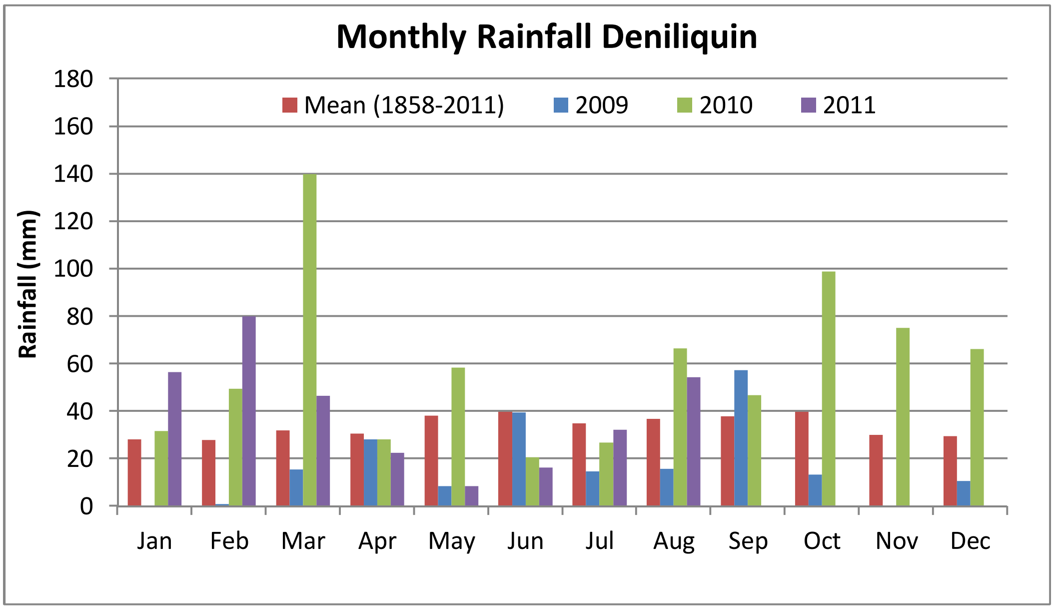


Figure 8-3 **Average monthly rainfall, BoM station 074128 Deniliquin (Wilkinson St)**

The long-term cumulative rainfall residual for Tocumwell and Denilquin are shown on Figure 8-3. The cumulative residual rainfall in Figure 8-3 shows the periods of above average rainfall: 1972–1975, 1988–1989, 1992–1993 and 2009–2011.

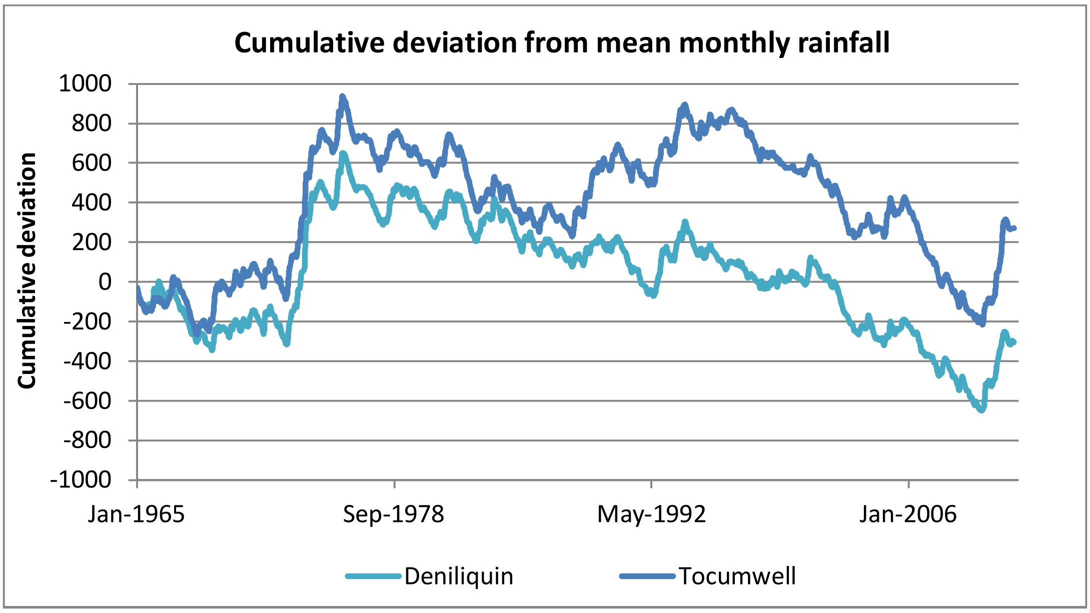


Figure 8-4 **Cumulative deviation from mean monthly rainfall, Deniliquin and Tocumwell (1965–2011)**

8.1.3 Land use

Land use overlying the Lower Murray GMA comprises grazing, dryland and irrigated agriculture (rice, winter wheat, canola and other cereals, legumes and pasture), and forestry. Most of the area has irrigated agriculture based on channel water sources from the Murray River. Surrounding the area of Millewa National Park (located in the centre of the Lower Murray GMA — where the monitoring bores are clustered) the land use includes cropping (wheat and rice) and grazing (primarily sheep and cattle) (DSEWPC 2011).

8.1.4 Hydrogeology

The Lower Murray GMA is within the Murray Geological Basin, a large saucer shaped structure up to 600 m deep, backfilled with sand and clay layers, which represent a 55 million year history of marine conditions, freshwater swamps and Riverine and aeolian (wind-borne) deposits (Kulatunga 1999). Within the Lower Murray GMA, the maximum thickness of sediments is about 350 m near Moulamein (Kulatunga 1999). The maximum thickness at Corowa where the Murray River enters the Murray Basin is about 120 m (Kulatunga 1999). These sedimentary deposits are divided into three geological units based on the deposition period and environment (Kulatunga 1999):

- The Shepparton Formation – the most recent (Pliocene to Recent) major phase of fluvial sedimentation is up to 70 m thick. Overlies the Calivil Formation and consists of clay and silty clays inter-bedded with sand layers. Productive aquifers are in the first 20 m. Two types of abandoned river/stream channels exist in the Shepparton Formation: prior streams, which are remnants of older channels, and ancestral rivers, which are recently abandoned rivers/streams (Kulatunga 1999).

- The Calivil Formation – is approximately 10 million years old and consists of sand and gravel, inter-bedded with clay layers. Overlies the Renmark Group and is typically between 40 to 140 m. The formation thickness reduces towards the east.
- The Renmark Group – the oldest in the sedimentary profile, overlies the basement rock at an approximate depth of 140 to 350 m. It consists of sand and gravel layers up to 40 m thick, inter-bedded with clay layers and lignite. Sand layers in the formation generally constitute important aquifers where low salinity groundwater is available. Some sand layers show favourable aquifer properties to provide high yields, but some areas have poorly sorted sands and gravel reducing the transmissivity of these aquifers.

Groundwater flow in the deep regional aquifers in the Murray Basin is from east to west (Kulatunga 1999). The general flow for the shallow aquifers in the Shepparton Formation is similarly east to west, but local variations can occur depending on the topography (Kulatunga 1999).

The shallow Shepparton aquifers are recharged via rainfall infiltration and through basal leakage from the Murray River, its anabranches and irrigation. The underlying Calivil Formation and Renmark Group are likely recharged from the overlying Shepparton and Calivil formations, respectively (NOW 2011a). Groundwater bores located in close proximity to the creeks, rivers and intensely irrigated areas can have lower salinity water due to constant recharge (Kulatunga 1999).

Increasing groundwater levels in the shallow aquifer, water logging and the subsequent soil salinisation have been a major environmental issue in the Murray Irrigation Districts for over four decades (NOW 2011a). Extraction of shallow groundwater via spearpoints has been encouraged in the Murray Irrigation Districts to mitigate the rising groundwater levels.

Sand beds of the Calivil Formation and Renmark Group are the major productive aquifers in the regional aquifer system (Kulatunga, 1999). Consequently, since 1993 a sharp pressure level decline has been observed in the Calivil and Upper Renmark aquifers in the majority of the Lower Murray GMA. Although, the areas west of Wakool have lesser declines or no change in pressure levels and areas north east of Berrigan have been rising for the past 10 years (Kulatunga 1999).

Hydrographs of monitoring bores included in the current study are shown on Figure 8-5 and a brief summary of groundwater level trends is given in Table 8-1.

Table 8-1 Hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW036283_1	22.8 – 29.8	SF	Water levels have been monitored since 1979. Pipes 2 and 3 show similar water level behaviour indicating a hydraulic connection. There have been several reversals of the vertical hydraulic gradient between Pipe 1 and Pipes 2 and 3. Seasonal drawdowns are evident in Pipes 2 and 3 (up to 10.5 m). Since 1994 the total recovery decline for Pipes 2 and 3 is ~9.6 m.
GW036283_2	53 – 59.1	SF	
GW036283_3	121.9 – 128	CF	
GW036584_1	61 – 65	SF	Water levels have been monitored since 1987. Water levels in Pipes 1, 2 and 3 show similar water level
GW036584_2	93 – 101	CF	

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW036584_3	116.5 – 122.5	CF	behaviour indicating a hydraulic connection. Seasonal drawdowns are evident in all pipes (up to 7 m). Since monitoring commenced the total recovery decline is ~8.5 m.
GW036585_1	42 – 46	SF	Water levels have been monitored since 1986. Pipe 2 and 3 show similar water level behaviour indicating a hydraulic connection. At commencement of monitoring, the pressure head at Pipe 1 was ~0.2 m below that of the Pipes 2 and 3, and ~4.5 m above Pipe 4. There has since been a reversal of the vertical hydraulic gradient, with Pipe 1 now ~9 m above Pipes 2, 3 and 4. There have also been several reversals of the vertical hydraulic gradient between Pipe 4 and Pipes 2 and 3. Seasonal drawdowns are evident in Pipes 2 and 3 (up to 9 m). Since 1994 the total recovery decline for Pipes 2 and 3 is ~12 m.
GW036585_2	109 – 115	CF	
GW036585_3	150 – 156	CF	
GW036585_4	210 – 216	RG	
GW036586_1	48 – 50	SF	Water levels have been monitored since 1987. Pipe 1 shows a dampened water level response indicating there a limited connection between the Shepparton Formation and the deeper aquifers at this location. Pipes 2, 3 and 4 show similar water level behaviour indicating a hydraulic connection. Seasonal drawdowns are evident in all Pipes (up to 11 m). Since 1994 the total recovery declines for Pipes 1, 2, 3 and 4 are ~5 m, ~10 m, ~11 m and ~12 m, respectively.
GW036586_2	110 – 112	CF	
GW036586_3	168 – 174	RG	
GW036586_4	237 – 243	RG	
GW036587_1	9.7 – 15.2	SF	Water levels have been monitored since 1986. Pipes 2, 3 and 4 show similar water level behaviour indicating a hydraulic connection. Pipe 5 had decreasing water levels from 1997, until a significant drop in 2003. Seasonal drawdowns are evident in Pipes 2, 3 and 4 (up to 8 m). Since 1993 the total recovery decline for Pipe 1 was ~2 m, Pipes 2, 3 and 4 was ~11 m, and for Pipe 5 was ~14 m.
GW036587_2	115 – 135	SF/CF	
GW036587_3	165 – 171	RG	
GW036587_4	180 – 190	RG	
GW036587_5	286.5 – 292.5	RG	
GW036588_1	19 – 24	SF	Water levels have been monitored since 1987. All pipes have decreasing water levels from 1994, with total recovery declines up to ~11 m at Pipes 3 and 4. Seasonal drawdowns are evident in Pipes 3 and 4 (up to 8 m) and Pipe 2 shows a dampened water level response indicating a limited connection with Pipes 3 and 4.
GW036588_2	49 – 55	SF	
GW036588_3	97.5 – 103.5	CF	
GW036588_4	146 – 152	CF	
GW036742_1	64 – 70	SF	Water levels have been monitored since 1987. All pipes have decreasing water levels from 1994. Since 1994 the total recovery declines for Pipes 1, 2 and 3 were ~5 m, ~12 m, and ~15 m, respectively. All pipes showed seasonal drawdowns, with the maximum recorded at Pipe 2 (~9 m).
GW036742_2	117 – 137	CF/RG	
GW036742_3	310 – 316	RG	
GW036743_1	64 – 70	SF	Water levels have been monitored since 1987. All pipes have decreasing water levels from 1994. Since
GW036743_2	168 – 174	RG	

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW036743_3	192 – 198	RG	1994 the total recovery decline for Pipe 1 was ~ 7m and for Pipes 2 and 3 was ~11 m. Pipe 1 shows a dampened water level response indicating there is only a limited connection between the Shepparton Formation and the deeper aquifers at this location. Pipes 2 and 3 show similar water level behaviour indicating a hydraulic connection. Seasonal drawdowns are evident in all Pipes (up to 11 m).
GW036744_1	16 – 17	SF	Water levels have been monitored since 1987. Pipe 1 shows a dampened water level response indicating there a limited connection between the Shepparton Formation and the deeper aquifers at this location. Pipes 2 and 3 show similar water level behaviour indicating a hydraulic connection. Seasonal drawdowns are evident in Pipes 2 and 3 (up to 7 m). Since 1994 the total recovery decline is~4.5 m at Pipe 1 and ~9 m at Pipes 2 and 3.
GW036744_2	113 – 119	CF	
GW036744_3	198 – 204	RG	
GW036876_1	63 – 69	SF	Water levels have been monitored since 1990. Pipe 1 shows a dampened water level response indicating only a limited connection between the Shepparton Formation and the deeper aquifer at this location. Seasonal drawdowns are evident in Pipes 1 and 2 (up to 10 m). Since 1994 the total recovery decline is ~6 m.
GW036876_2	142 – 154	CF	

Note: SF-Shepparton Formation, RG-Renmark Group, CF-Calivil Formation.

8.2 Characterisation of groundwater chemistry

Groundwater sampling was undertaken in 16 sampling rounds during the study period (October 2009 to January 2011). 28 monitoring bores were sampled during the study period, with 4 located in the Shepparton Formation, 1 located in the Shepparton and Calivil formations, 13 located in the Calivil Formation, and 1 located in the Calivil Formation and Renmark Group and 9 located in the Renmark Group.

As the study area for the Lower Murray is centred on the Murray Irrigation District, groundwater chemistry trends geographically across the catchment cannot be determined. Groundwater chemistry interpretation is for the Murray Irrigation District only and no assumptions can be made on changes with chemistry along the flow paths in the Lower Murray GMA.

8.2.1 Results

Groundwater chemistry statistics are summarised in Tables 8-2, 8-3 and 8-4 for the Shepparton and Calivil formations and Renmark Group respectively. The results are presented on a cross-section (Figure 8-6). The location of the cross-section is shown on Figure 8-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 8-7, 8-8 and 8-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix G.

A Piper diagram presenting results for the Shepparton and Calivil formations and Renmark

Group is presented in Figure 8-10.

Stable isotope data (^{18}O and ^{2}H) was collected for several monitoring rounds and is presented in Figures 8-11 and 8-12.

Table 8-2 Lower Murray Shepparton Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	59	59	230	5000	2017	260	1679
EC (lab)	µS/cm	63	63	389	7010	3035	427	2463
pH (field)	pH unit	58	58	5.97	8.10	6.63	6.12	0.43
K	mg/L	63	63	1.0	7.7	3.5	1.0	1.9
Na	mg/L	63	63	52	900	390	54	314
Ca	mg/L	63	63	8	210	89	8	77
Mg	mg/L	63	63	10	290	121	11	104
Cl	mg/L	63	63	77	2300	961	82	845
SO$_4$	mg/L	63	63	5.2	170.0	83.8	5.5	67.4
Alkalinity (CaCO$_3$)	mg/L	59	59	60	200	123	62	49
CO$_3$	mg/L	63	1	0.5	1.8	1.0	0.5	0.2
HCO$_3$	mg/L	63	63	74	240	150	76	60
Si	mg/L	59	59	12.0	26.0	18.6	13.0	4.6
F	mg/L	59	57	<0.1	0.75	0.34	0.15	0.18
Al (soluble)	mg/L	59	26	<0.01	0.110	0.019	0.005	0.021
B (soluble)	mg/L	59	30	<0.1	0.20	0.12	0.05	0.06
Br (soluble)	mg/L	59	53	<0.2	9.9	3.7	0.2	3.4
Cu (soluble)	mg/L	59	4	<0.01	0.040	0.011	0.005	0.005
Mn (soluble)	mg/L	59	45	<0.002	0.420	0.091	0.001	0.158
Pb (soluble)	mg/L	2	0	Not calculated				
Sr (soluble)	mg/L	59	59	0.13	3.80	1.53	0.14	1.34
Zn (soluble)	mg/L	59	48	<0.005	0.270	0.027	0.003	0.040
Mn (total)	mg/L	59	42	<0.002	0.420	0.094	0.001	0.162
Ni (total)	mg/L	59	4	<0.01	0.013	0.010	0.005	0.002
Zn (total)	mg/L	59	39	<0.01	2.100	0.074	0.005	0.276
Al (total)	mg/L	58	42	<0.05	0.740	0.123	0.025	0.122
B (total)	mg/L	58	29	<0.1	0.20	0.14	0.05	0.07
Cu (total)	mg/L	58	19	<0.005	0.030	0.007	0.003	0.005
Fe (total)	mg/L	59	30	<0.05	0.500	0.095	0.025	0.106
Pb (total)	mg/L	59	2	<0.02	0.024	0.020	0.010	0.002
N$_2$	mg/L	59	58	<0.05	7.400	1.079	0.080	1.394
NH$_3$	mg/L	59	28	<0.01	0.380	0.044	0.005	0.071
NO$_3$	mg/L	18	16	<0.2	3.1	1.8	0.2	0.9
PO$_4$	mg/L	59	59	0.005	0.043	0.020	0.008	0.011
Total P	mg/L	59	59	0.005	0.063	0.024	0.008	0.014

Note: SD – standard deviation

Table 8-3 Lower Murray Calivil Formation statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	129	129	290	4800	1201	338	1217
EC (lab)	µS/cm	138	138	483	7190	1949	535	1831
pH (field)	pH unit	127	127	5.86	8.28	6.78	6.35	0.38
K	mg/L	138	138	1.3	8.8	3.4	1.5	1.8
Na	mg/L	138	138	77	950	281	90	230
Ca	mg/L	138	138	6	230	43	6	60
Mg	mg/L	138	138	9.7	310	65.3	11	84.1
Cl	mg/L	138	138	58	2300	543	69	626
SO_4	mg/L	138	138	28	410	94	31	106
Alkalinity ($CaCO_3$)	mg/L	129	129	79	230	123	85	20
CO_3	mg/L	138	1	0.5	1.8	1.0	0.5	0.1
HCO_3	mg/L	138	138	94	280	149	100	25
Si	mg/L	129	129	5.2	24.0	13.5	6.5	5.7
F	mg/L	129	127	<0.1	1.30	0.59	0.16	0.26
Al (soluble)	mg/L	129	38	<0.01	0.110	0.014	0.005	0.015
B (soluble)	mg/L	129	57	<0.1	0.20	0.10	0.05	0.03
Br (soluble)	mg/L	129	123	<0.2	8.6	1.9	0.3	2.3
Cu (soluble)	mg/L	129	11	<0.01	0.060	0.011	0.005	0.006
Mn (soluble)	mg/L	129	121	<0.002	0.320	0.068	0.003	0.063
Pb (soluble)	mg/L	16	1	0.01	0.025	0.020	0.01	0.0037
Sr (soluble)	mg/L	129	129	0.11	4.00	0.77	0.12	1.04
Zn (soluble)	mg/L	129	94	<0.005	0.170	0.025	0.003	0.033
Mn (total)	mg/L	129	113	<0.002	1.900	0.085	0.001	0.175
Ni (total)	mg/L	129	14	<0.01	0.040	0.011	0.005	0.004
Zn (total)	mg/L	129	81	<0.01	0.170	0.033	0.005	0.035
Al (total)	mg/L	128	87	<0.05	40.00	1.203	0.025	4.440
B (total)	mg/L	128	76	<0.1	0.20	0.10	0.05	0.03
Cu (total)	mg/L	128	39	<0.005	0.050	0.008	0.003	0.008
Fe (total)	mg/L	129	97	<0.05	19.00	0.853	0.025	1.997
Pb (total)	mg/L	129	16	<0.02	0.130	0.024	0.010	0.018
N_2	mg/L	127	109	<0.05	12.00	1.218	0.025	1.773
NH_3	mg/L	128	90	<0.01	0.890	0.080	0.005	0.132
NO_3	mg/L	23	15	<0.2	3.5	1.6	0.1	1.4
PO_4	mg/L	129	128	<0.005	0.096	0.021	0.008	0.012
Total P	mg/L	128	128	0.008	0.148	0.038	0.015	0.025

Note: SD – standard deviation

Table 8-4 Lower Murray Renmark Group statistics, Oct 2009 to Jan 2011

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	69	69	960	8700	2141	1200	1421
EC (lab)	µS/cm	74	74	1720	10600	3318	2023	1790
pH (field)	pH unit	68	68	6.56	8.86	6.88	6.62	0.34
K	mg/L	74	74	3.1	12.0	5.1	3.5	1.8
Na	mg/L	74	74	270	1900	497	322	263
Ca	mg/L	74	74	13	330	74	27	62
Mg	mg/L	74	74	36	560	118	54	97
Cl	mg/L	74	74	430	4300	1035	555	709
SO_4	mg/L	74	74	2.3	550	115	62.6	79.7
Alkalinity ($CaCO_3$)	mg/L	69	69	110	220	153	120	28
CO_3	mg/L	74	1	0.5	1.8	1.0	0.5	0.2
HCO_3	mg/L	74	74	130	270	186	140	34
Si	mg/L	69	69	4.6	17.0	10.4	4.9	4.0
F	mg/L	69	69	0.25	0.86	0.55	0.39	0.14
Al (soluble)	mg/L	69	32	<0.01	0.140	0.017	0.005	0.022
B (soluble)	mg/L	69	42	<0.1	0.20	0.10	0.05	0.03
Br (soluble)	mg/L	69	69	1.1	18.0	4.0	1.9	2.9
Cu (soluble)	mg/L	69	4	<0.01	0.020	0.010	0.005	0.002
Mn (soluble)	mg/L	69	69	0.013	6.200	0.450	0.030	1.080
Pb (soluble)	mg/L	3	0	Not calculated				
Sr (soluble)	mg/L	69	69	0.28	6.50	1.36	0.49	1.19
Zn (soluble)	mg/L	69	42	<0.00	0.140	0.025	0.003	0.029
Mn (total)	mg/L	69	69	0.011	5.500	0.454	0.030	0.991
Ni (total)	mg/L	69	5	<0.01	0.011	0.010	0.005	0.002
Zn (total)	mg/L	69	40	<0.01	0.890	0.059	0.005	0.122
Al (total)	mg/L	69	36	<0.05	0.340	0.087	0.025	0.063
B (total)	mg/L	69	48	<0.1	0.20	0.11	0.05	0.04
Cu (total)	mg/L	69	17	<0.00	0.030	0.007	0.003	0.007
Fe (total)	mg/L	69	54	<0.05	3.400	0.346	0.025	0.573
Pb (total)	mg/L	69	3	<0.02	0.024	0.020	0.010	0.002
N_2	mg/L	68	65	<0.05	4.600	0.876	0.080	1.261
NH_3	mg/L	69	58	<0.01	0.700	0.172	0.005	0.163
NO_3	mg/L	6	1	<0.2	0.2	0.2	0.1	0.04
PO_4	mg/L	69	69	0.006	0.194	0.033	0.009	0.030
Total P	mg/L	68	68	0.005	0.192	0.044	0.011	0.031

Note: SD – standard deviation

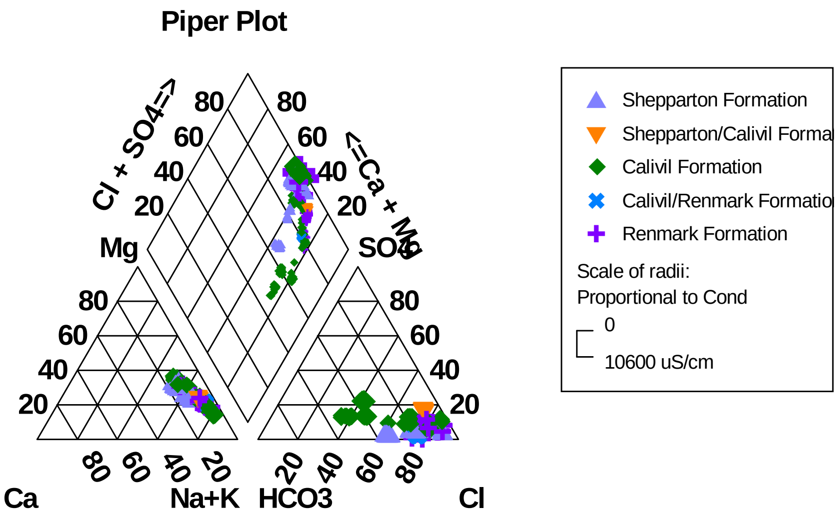


Figure 8-10 Piper diagram for the Shepparton and Calivil formations and Renmark Group during the study period

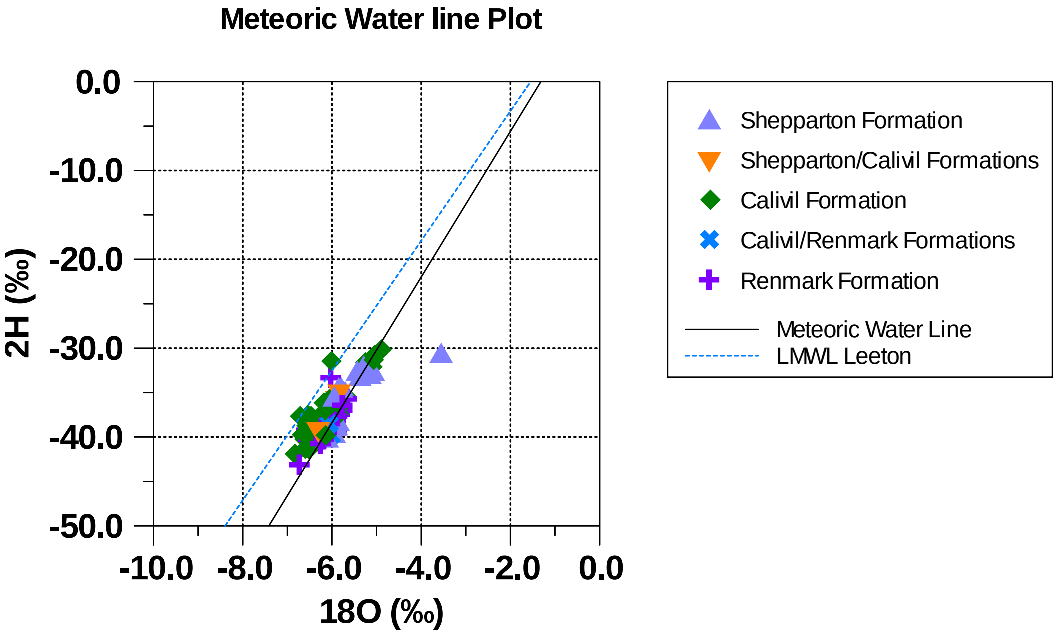


Figure 8-11 Oxygen-18 versus deuterium for groundwater samples from the Lower Murray GMA

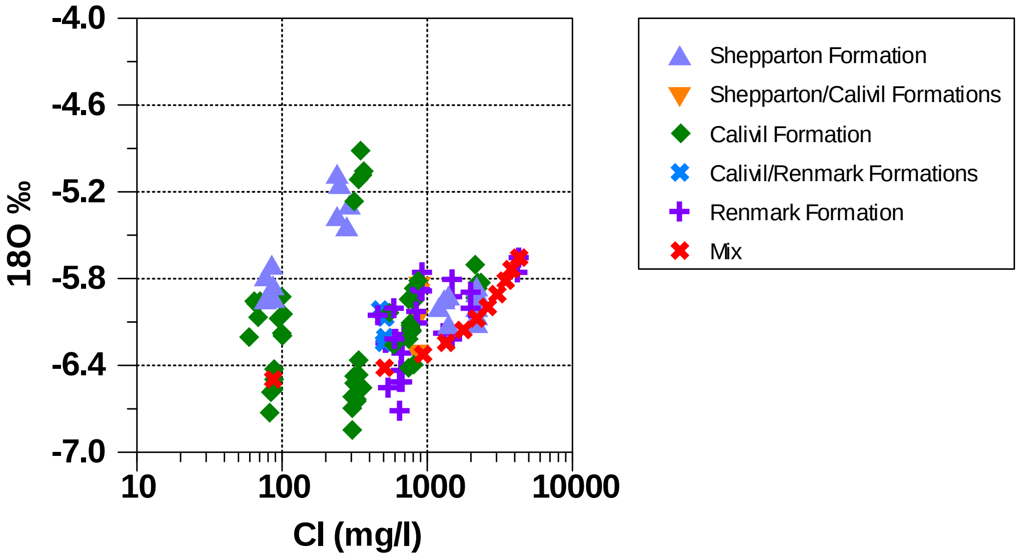


Figure 8-12 **Oxygen-18 versus chloride for groundwater samples from the Lower Murray GMA**

8.2.1.1 Shepparton Formation

Water quality parameters

Salinity in the Shepparton Formation ranges from fresh, 389 µS/cm (GW036588_2) to saline, 7,010 µS/cm (GW036743_1) (Figure 8-8). The highest salinities occurred in the irrigation area to the east of Deniliquin.

Field pH measurements were recorded for 92% of samples from the Shepparton Formation. The pH conditions ranged from slightly acidic (5.97) to slightly alkaline (8.10).

Major and minor ions

Major ion chemistry in the Shepparton Formation is dominated by sodium, magnesium and chloride, with bicarbonate also dominant at monitoring locations with low salinities (typically <1,000 µS/cm). Water types for each monitoring location are presented in piper plots in the report cards in Appendix G.

Dissolved silicon concentrations in the Shepparton Formation ranged from 12 mg/L to 26 mg/L, with an average concentration of 18.6 mg/L.

Bromide was detected in the majority of samples and concentrations ranged up to 9.9 mg/L. Bromide concentrations were well correlated with salinity.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Murray. Total iron was detected in 51% of samples from the Shepparton Formation. Concentrations ranged up to 0.5 mg/L.

Dissolved and total manganese were detected in 76% and 71% of samples respectively, both dissolved and total manganese had maximum concentrations of 0.42 mg/L.

Dissolved zinc was detected in 81% of samples; with a maximum concentration of 0.27 mg/L. Total zinc was detected in 66% of samples; with a maximum concentration of 2.1 mg/L.

Strontium was detected in all samples, with concentrations ranging from 0.13 mg/L to 3.8 mg/L.

Nutrients

Total nitrogen was detected in 98% of samples from the Shepparton Formation. Total nitrogen concentrations ranged from the LOR (0.05 mg/L) to 7.4 mg/L. 39% of samples had total nitrogen concentrations at or above 1 mg/L (these samples were from four monitoring locations: GW036283_2, GW036588_2, GW036743_1, and GW036876_1). The major contributor to total nitrogen in these samples is nitrate. Nitrate was only analysed for in 29% of samples. Of these samples nitrate was detected in 89%, with concentrations ranging up to 3.1 mg/L. Nitrate can be derived from natural sources such as soil degradation or from agricultural sources such as nitrogen based fertilisers or animal manure.

Total and reactive phosphorus were detected in all Shepparton Formation samples. Total phosphorus concentrations ranged from the LOR (0.01 mg/L) to 0.063 mg/L. Reactive phosphorus concentrations ranged from the LOR (0.01 mg/L) to 0.043 mg/L.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) were analysed for selected groundwater samples collected in October to December 2009, and July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^{2}H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 8-11.

Groundwater within the Shepparton Formation (n=25) had isotopic signatures ranging from -6.31‰ to -3.55‰ for $\delta^{18}O$ and -40.1‰ to -30.6‰ for $\delta^{2}H$. Groundwater samples generally plotted on or slightly to the left of the GMWL.

8.2.1.2 Calivil Formation

Water quality parameters

Salinity in the Calivil Formation ranges from fresh, 483 µS/cm (GW036584_2) to saline, 7,190 µS/cm (GW036585_3) (Figure 8-8). There were no distinct spatial trends in EC.

Field pH measurements were recorded for 92% of samples from the Calivil Formation. The pH conditions ranged from slightly acidic (5.86) to slightly alkaline (8.28) and were similar to the overlying Shepparton Formation.

Major and minor ions

Major ion chemistry in the Calivil Formation is dominated by sodium, magnesium and chloride, with bicarbonate also dominant at monitoring locations with low salinities (typically

<2,000 µS/cm) (Figure 8-10). Sulphate was dominant at one monitoring location, GW036588_3. Water types for each monitoring location are presented in piper plots in the report cards in Appendix G.

Dissolved silicon concentrations in the Calivil Formation ranged from 5.2 mg/L to 24 mg/L, with an average concentration of 13.5 mg/L.

Bromide was detected in the majority of samples and concentrations ranged up to 8.6 mg/L. Bromide concentrations were well correlated with salinity.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Dissolved aluminium was detected in 29% of samples, concentrations ranged from 0.01 mg/L to 0.11 mg/L. Total aluminium was detected in 67% of samples, ranging between 0.05 mg/L and 40 mg/L. Two monitoring locations (GW036586_2 and GW036588_3) had high total aluminium concentrations and all other monitoring locations in the Calivil Formation had total aluminium concentrations below 0.5 mg/L.

Only total iron was analysed in the Lower Murray. Total iron was detected in 75% of samples from the Calivil Formation. Concentrations ranged up to 19 mg/L (GW036586_2), although 87% of samples had concentrations below 1 mg/L.

Some total metal (aluminium and iron) concentrations were high at several monitoring locations, in particular, GW036586_2 and GW036588_3. It is thought the steel casing at these locations may be corroding, increasing total aluminium and iron concentrations in the groundwater at these locations.

Dissolved manganese was detected in 94% of samples; with a maximum concentration of 0.32 mg/L. Total manganese was detected 88% of samples; with a maximum concentration of 1.9 mg/L.

Strontium was detected in all samples, with concentrations ranging from 0.11 mg/L to 4 mg/L.

Nutrients

Total nitrogen was detected in 86% of samples from the Calivil Formation. Total nitrogen concentrations ranged from below the detection limit (0.05 mg/L) to 12 mg/L. 36% of samples had total nitrogen concentrations above 1 mg/L (these samples were from 13 different monitoring locations). A major contributor to total nitrogen in some of these samples is nitrate. Nitrate was only analysed for in 18% of samples. Of these samples nitrate was detected in 65%, with concentrations ranging up to 3.5 mg/L.

Total and reactive phosphorus were detected in nearly all Calivil Formation samples. Total phosphorus concentrations ranged from 0.008 mg/L to 0.148 mg/L. Reactive phosphorus concentrations ranged from <0.005 mg/L to 0.096 mg/L. Total and reactive phosphorus concentrations were slightly higher in the Calivil Formation compared with the overlying Shepparton Formation.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H) were analysed for selected groundwater samples collected in October to December 2009, and July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^2H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^2H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 8-11.

Groundwater within the Calivil Formation (n=53) also plotted on or to the left of the GMWL and had isotopic signatures ranging from -6.85‰ to -4.92‰ for $\delta^{18}O$ and -42.0‰ to -30.2‰ for δ^2H.

8.2.1.3 Renmark Group

Water quality parameters

Salinity in the Renmark Group ranges from fresh, 1,720 µS/cm (GW500339_1) to saline, 10,600 µS/cm (GW036742_3) (Figure 8-8). Groundwater within the Renmark Group was generally more saline than the overlying Calivil Formation.

Field pH measurements were recorded for 92% of samples from the Renmark Group. The pH conditions ranged from slightly acidic (6.56) to slightly alkaline (8.86) and were similar to the overlying Calivil Formation.

Major and minor ions

Major ion chemistry in the Renmark Group is typically dominated by sodium, magnesium and chloride. Water types for each monitoring location are presented in piper plots in the report cards in Appendix G.

Dissolved silicon concentrations in the Renmark Group ranged from 4.6 mg/L to 17 mg/L, with an average concentration of 10.4 mg/L.

Bromide was detected in all samples and concentrations ranged up to 18 mg/L. Bromide concentrations were well correlated with salinity.

Metals and metalloids

Groundwater samples were analysed for dissolved and total metals and metalloids (aluminium, boron, copper, iron, lead, manganese, nickel, zinc and strontium).

Only total iron was analysed in the Lower Murray. Total iron was detected in 78% of samples from the Renmark Group. Concentrations ranged up to 3.4 mg/L.

Dissolved and total manganese were detected in all samples. Dissolved manganese concentrations ranged from 0.013 mg/L to 6.2 mg/L. Total manganese concentrations ranged from 0.011 mg/L to 5.5 mg/L.

Strontium was detected in all samples, with concentrations ranging from 0.28 mg/L to 6.5 mg/L. Strontium concentrations were well correlated with salinity.

Nutrients

Total nitrogen was detected in 96% of samples from the Renmark Group. Total nitrogen concentrations ranged up to 4.6 mg/L and 25% of samples had concentrations above 1 mg/L. The nitrogen species contributing to total nitrogen concentrations are uncertain, as nitrate was only analysed for in 8% of samples and ammonia concentrations only ranged up to 0.70 mg/L.

Total and reactive phosphorus were detected in all Renmark Group samples. Total phosphorus concentrations ranged from 0.005 mg/L to 0.192 mg/L. Reactive phosphorus concentrations ranged from 0.006 mg/L to 0.194 mg/L. Total and reactive phosphorus concentrations were higher in the Renmark Group than the two overlying formations (Calivil and Shepparton) and appear to be increasing with depth. Phosphorus in groundwater can be derived from natural processes such as the decay of organic matter or weathering processes, or agricultural sources such as fertilisers or animal manure.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$) were analysed for selected groundwater samples collected in October to December 2009, and July and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^{2}H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 8-11.

Renmark Group groundwaters (n=26) plotted close to Calivil Formation groundwater on or to the left of the GMWL. Groundwater samples had isotopic signatures ranging from -6.72‰ to -5.66‰ for $\delta^{18}O$ and -43.2‰ to -33.4‰ for $\delta^{2}H$.

8.2.2 Processes

8.2.2.1 Shepparton Formation

Dissolution and precipitation

Major ion/chloride ratios are plotted versus chloride concentration to determine hydrogeochemical processes (Figure 8-13). Sodium, potassium and bicarbonate showed curved trends with low ion/chloride ratios, decreasing relative to increasing chloride concentrations. This is potentially related to reverse ion exchange processes, as although no clear trends were identified for Ca/Cl and Mg/Cl ratios, ratios were above the seawater ratios, indicating an excess of calcium and magnesium.

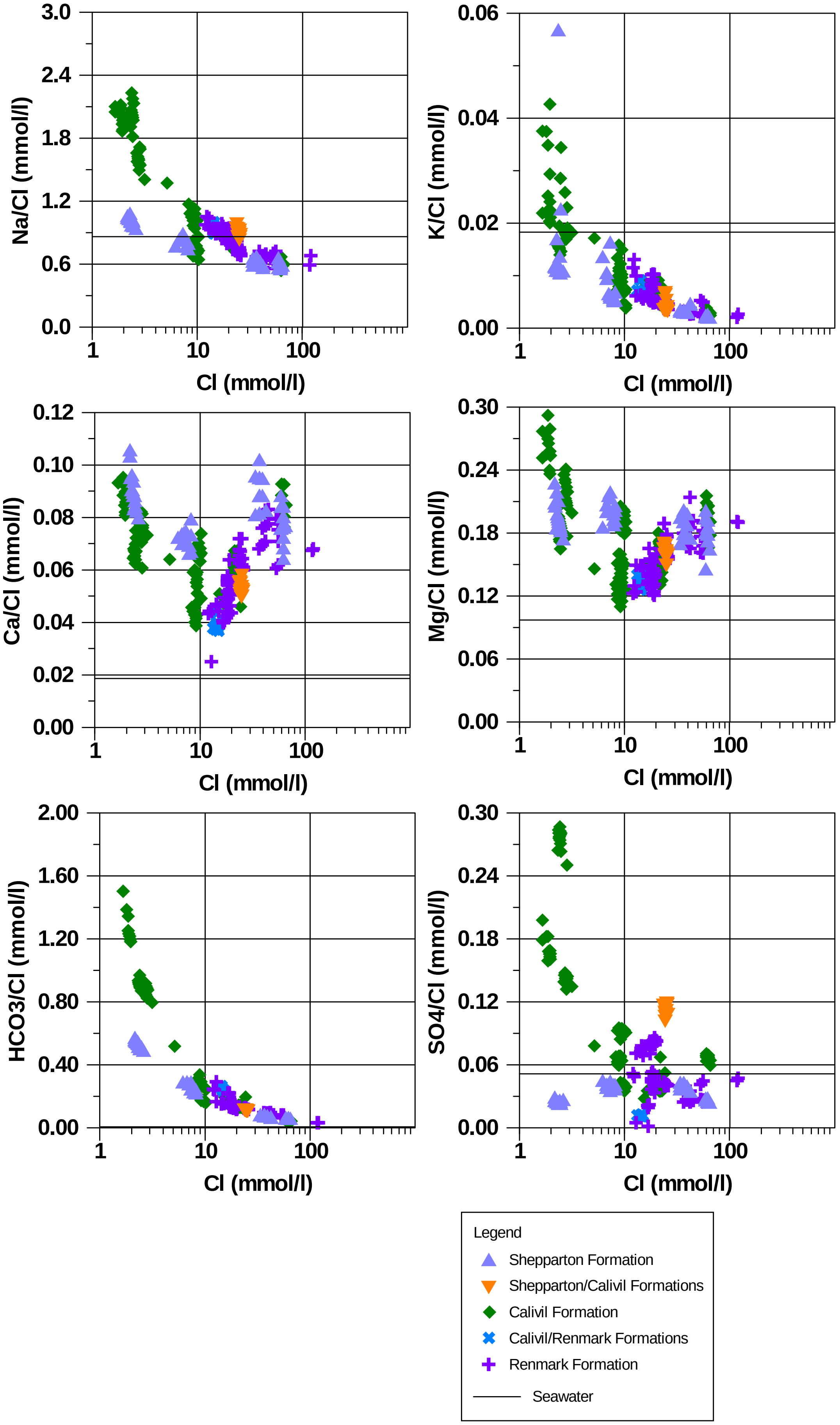


Figure 8-13 Ion/chloride versus chloride graphs for the Lower Murray Catchment

Saturation indices for the Shepparton Formation are plotted in Figure 8-14. Groundwater in the Shepparton Formation was over-saturated with respect to montmorillonite and quartz and in some locations feldspar but was under-saturated with respect to calcite, gypsum and dolomite.

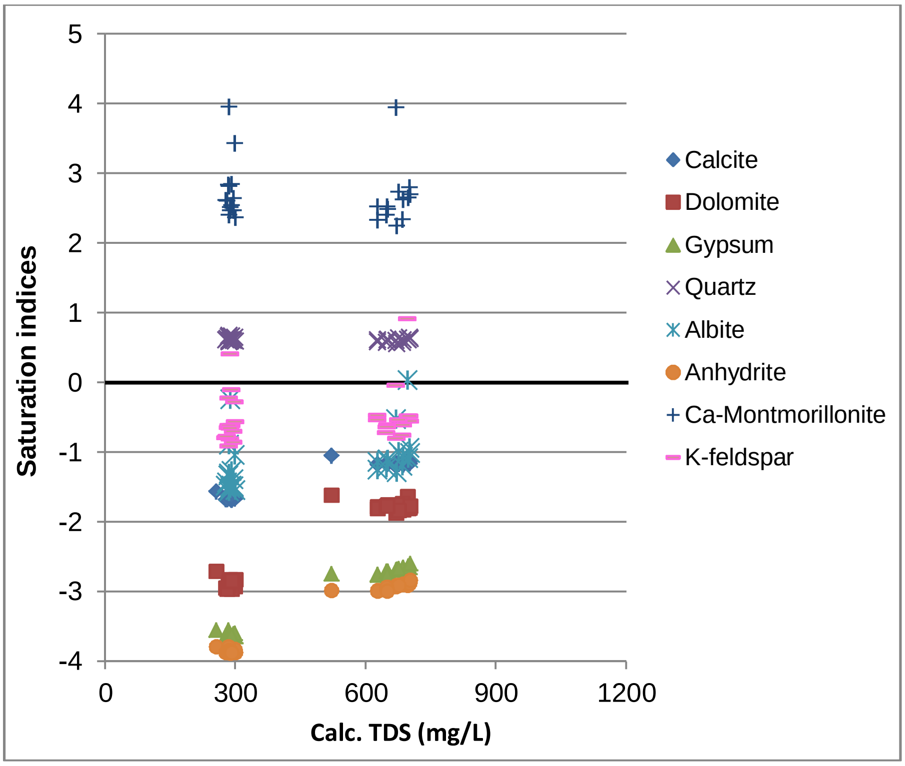


Figure 8-14 Saturation indices versus TDS for the Shepparton Formation

Ion exchange

Figure 8-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The majority of groundwater samples from the Shepparton Formation plot above the 1:1 dissolution line indicating reverse ion exchange processes and an excess of calcium and magnesium.

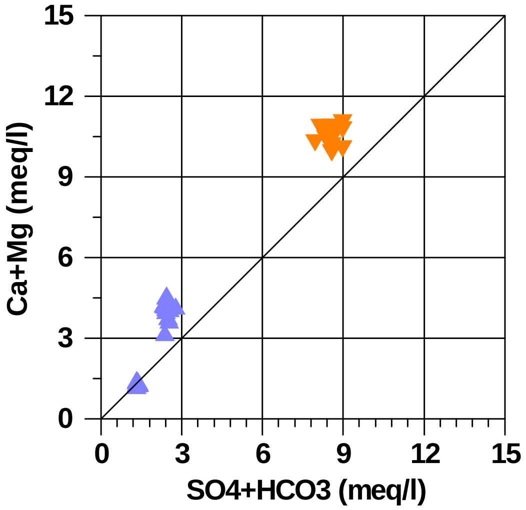


Figure 8-15 Calcium + magnesium versus bicarbonate + sulphate in the Shepparton Formation

Groundwater samples from the Shepparton Formation have isotopic signatures which generally plot on or to the left of the GMWL. This depleted isotopic signature is consistent with winter rainfall in the Murray-Darling Basin.

The isotopic signatures of samples from the Shepparton Formation are similar to those of groundwater from the Calivil Formation and Renmark Group. In some cases this is due to mixing of waters from different aquifers where there is hydraulic connection between shallow and deep aquifers, and in other mixing resulting from the irrigation of deep groundwater.

8.2.2.2 Calivil Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes occurring in the Calivil Formation (Figure 8-13). Sodium, potassium, bicarbonate and sulphate showed curved trends with ion/chloride ratios suggesting mixing between groundwater end members was occurring, in addition to other geochemical processes.

Saturation indices for the Calivil Formation are plotted in Figure 8-16. Groundwater in the Calivil Formation is typically saturated with respect to montmorillonite and quartz but was under-saturated with respect to feldspars, calcite, gypsum and dolomite.

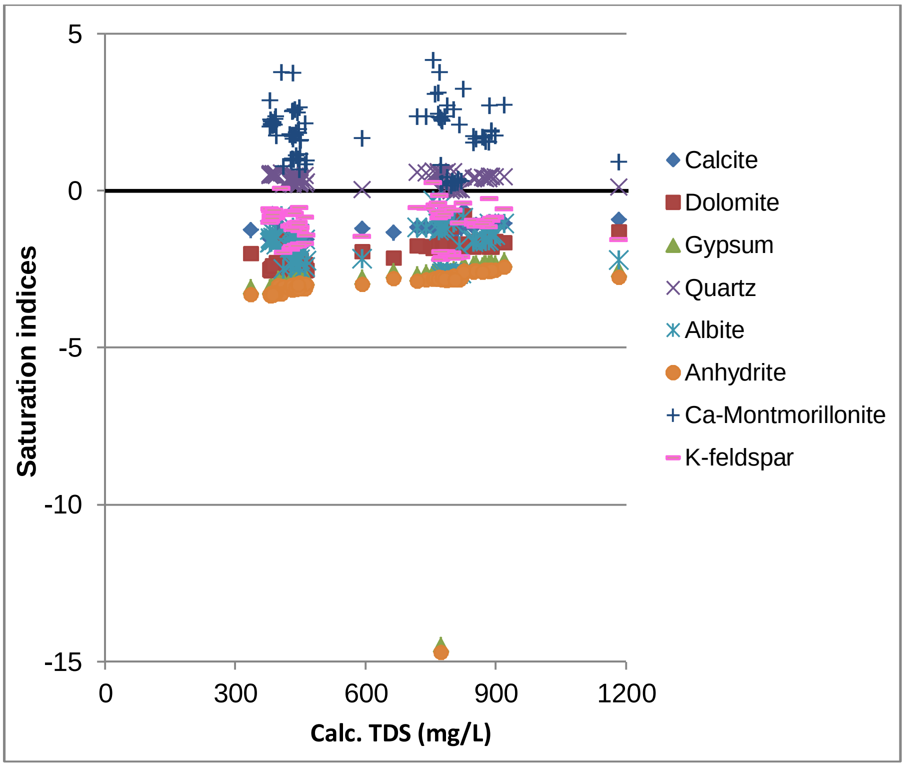


Figure 8-16 **Saturation indices versus TDS for the Calivil Formation**

Ion exchange

Figure 8-17 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The majority of groundwater samples from the Calivil Formation plot above the 1:1 dissolution line indicating reverse ion exchange processes and an excess of calcium and magnesium.

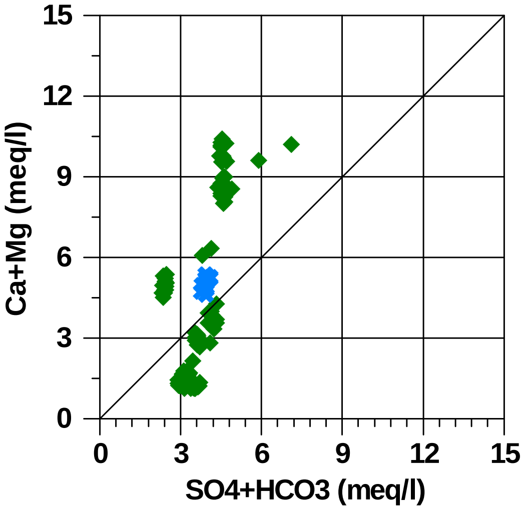


Figure 8-17 **Calcium + magnesium versus bicarbonate + sulphate in the Calivil Formation**

Stable isotopes

Groundwater samples from the Murray catchment plotted on a groundwater evaporation line with the regression equation $\delta^{2}H = 5.6\delta^{18}O - 3.76$. Such a high slope could be attributed to evaporative concentration occurring at the groundwater surface under humidity of ~80% (Clark & Fritz 1997). However, given that samples are beyond the depth of active evaporative processes, groundwater mixing and recharge under palaeoclimatic conditions is more likely to be responsible for the slope of 5.6, rather than evaporative processes. Figure 8-12 is a plot of $\delta^{18}O$ versus Cl-, and shows a mixing curve between two groundwater end members; a fresh end member which has a depleted $\delta^{18}O$ signature, and a more saline end member which has an enriched $\delta^{18}O$ signature. From Figure 8-12 it is clear that the slope of the groundwater line is a largely a product of mixing between two groundwater end members. There are a few outliers to the general trend from both Calivil and Shepparton Formation. These samples are from monitoring bores located on the southern boundary of the catchment near Tocumwal. Mixing with another groundwater or surface water end member may be producing this localised variability in stable isotope composition.

8.2.2.3 Renmark Group

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes occurring in the Renmark Group (Figure 8-13). Sodium, potassium and bicarbonate to chloride ratios showed curved trends, with ion/chloride ratios decreasing relative to increasing chloride concentrations. No clear trends were identified for calcium and magnesium to chloride ratios, although, ratios were above the seawater ratios indicating reverse ion exchange processes.

Saturation indices for the Renmark Group are plotted in Figure 8-18. Groundwater in the Renmark Group is typically saturated with respect to dolomite, montmorillonite, quartz and in some locations calcite.

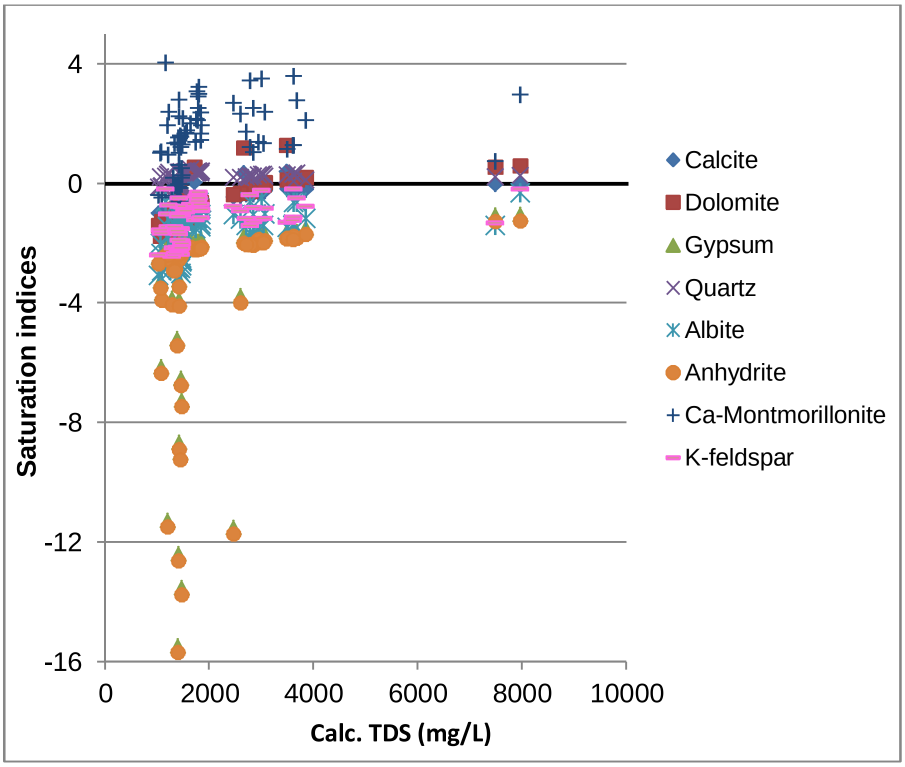


Figure 8-18 Saturation indices versus TDS for the Renmark Group

Ion exchange

Figure 8-19 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The majority of groundwater samples from the Renmark Group plot above the 1:1 dissolution line indicating reverse ion exchange processes and an excess of calcium and magnesium.

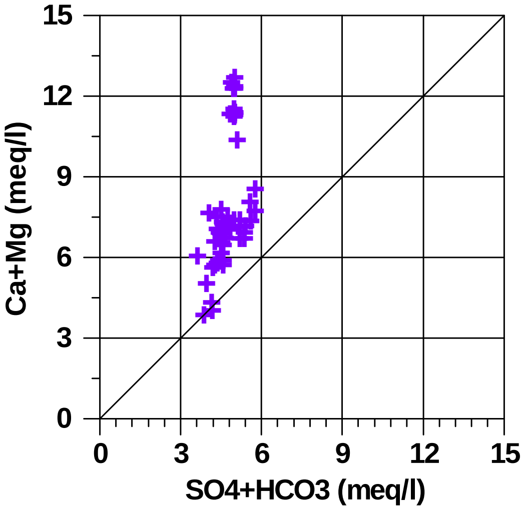


Figure 8-19 Calcium + magnesium versus bicarbonate + sulphate in the Renmark Group

Stable isotopes

As discussed in Section 8.2.2.2 there is some clear overlap in the isotopic signatures of groundwater from the Calivil Formation and Renmark Group, supporting the hydrogeological and chemical data which indicates some mixing occurring between these two aquifers.

8.2.3 **Beneficial use**

The risk to groundwater in the Lower Murray GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered 'at risk'.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Lower Murray GMA.

The *Water Sharing Plan for the Lower Murray Groundwater Sources* defines six objectives; including an objective relating to groundwater quality:

(d) protect groundwater quality from external pollution sources and cross aquifer pollution,

(e) protect the natural surface environment by managing the extraction of poor quality groundwater from aquifers.'

To meet this objective, water quality management is detailed in the Plan:

> '42 Water quality management
>
> (1) An aquifer salinity baseline and Sodium Adsorption Ratio, hereafter ("SAR") baseline for each production bore, against which groundwater quality changes and use parameters are to be measured, should be established as at the commencement of this Plan.
>
> (2) Local access rules may be applied if the aquifer baseline salinity exceeds 650 EC and there is an increase in salinity over a three year period of either 20% or more, or 500 EC or more.'

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 8-5. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in the Lower Murray GMA.

Table 8-5 Correlation analysis of parameters used to assess salinity and sodicity hazards, Lower Murray GMA

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.99	0.988	0.994	0.765
TDS		1	0.982	0.994	0.802
Na^+			1	0.991	0.736
Cl^-				1	0.769
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Lower Murray GMA based on the Australian Drinking Water Guidelines (ADWG) (2011) and ANZECC (2000) guidelines for Primary Industry.

8.2.3.1 Shepparton Formation

The current beneficial use (based on EC) of groundwater from the Shepparton Formation is drinking water supply and irrigation.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Shepparton Formation monitoring locations are provided in Table 8-6. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Shepparton Formation groundwater exceeds pH, sodium, chloride, sulphate, manganese and ammonia in some samples.

Table 8-6 ADWG (2011) values and percentage of samples above guideline values, Shepparton Formation (N=58), Lower Murray GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		40
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		51
Potassium (mg/L)				
Chloride (mg/L)	a	250		68
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		3	
Aluminium (mg/L)	b	0.2		
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	22
Strontium (mg/L)				

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix G. Groundwater from the Shepparton Formation had low sodium hazards, with SARs ranging from 3 to 10 (average 7). Looking at the toxicity of specific ions (Na^+ and Cl^-) and concentrations which can cause foliar injury to crops, 42% samples (n=32) from the Shepparton Formation were suitable for the irrigation of sensitive to moderately sensitive crops, while 58% (n=46) were only suitable for tolerant crops.

8.2.3.2 Calivil Formation

The current beneficial use (based on EC) of groundwater from the Calivil Formation is generally suitable for drinking water in the southern and eastern parts of the study area, and irrigation in the rest of the study area.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Calivil Formation monitoring locations are provided in Table 8-7. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Calivil Formation groundwater exceeds pH, sodium, chloride, sulphate, manganese and ammonia in some samples.

Table 8-7 ADWG (2011) values and percentage of samples above guideline values, Calivil Formation (N=127), Lower Murray GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		16
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		55
Potassium (mg/L)				
Chloride (mg/L)	a	250		66
Sulphate (mg/L)	500	250	0	11
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		30	
Aluminium (mg/L)	b	0.2		
Boron (mg/L)	4		0	

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	28
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		3
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix G. Groundwater from the Calivil Formation had low sodium hazards, with SARs ranging from 4 to 10 (average 7). Looking at the toxicity of specific ions (Na^+ and Cl^-) and concentrations which can cause foliar injury to crops, the Calivil Formation had 59% of samples (n=82) and 61% of samples (n=84), which were suitable for irrigation of sensitive to moderately sensitive crops, based on Na^+ and Cl^-, respectively.

Based on salinity (EC), all samples from the Calivil Formation were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

8.2.3.3 Renmark Group

The current beneficial use (based on EC) of groundwater from the Renmark Group is generally only suitable for irrigation, not drinking water supply.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Renmark Group monitoring locations are provided in Table 8-8. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Renmark Group groundwater exceeds pH, sodium, chloride, manganese and ammonia in some samples.

Table 8-8 ADWG (2011) values and percentage of samples above guideline values, Renmark Group (N=74), Lower Murray GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		1
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		100
Potassium (mg/L)				

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
Chloride (mg/L)	a	250		100
Sulphate (mg/L)	500	250	3	3
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		18	
Aluminium (mg/L)	b	0.2		
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	54
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		4
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix G. Groundwater from the Renmark aquifers generally has a low sodium hazard, although a small percentage of samples (5%, n=4) were classified as having a medium sodium hazard. Sodium Adsorption Ratios in the Renmark Group ranged from 7 to 15 (average 9).

Groundwater from the Renmark aquifers was generally of poorer quality than the overlying aquifers and was not suitable for irrigation of sensitive to moderately sensitive crops (see Table 2-6 and 2-7) based on Na^+ and Cl^-. The majority of samples were suitable for moderately tolerant crops, with 78% (n=69) of samples below the ANZECC (2000) threshold Na^+ concentrations causing foliar damage, and 60% (n=53) below the ANZECC (2000) threshold for Cl^-.

Based on salinity (EC), all samples from the Renmark Group were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines (Table 2-8).

8.2.4 Trends

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2.The results of these analyses are presented in Tables 8-9, 8-10 and 8-11 for the Shepparton and Calivil formations, and Renmark Group respectively.

A brief assessment of salinity trends was undertaken by Alamgir (2011), who found that change in EC over a four year period in the deep production bores in Murray Irrigation Districts indicated a possible 10% (median) decline in water quality in terms of salinity.

8.2.4.1 Shepparton Formation

Study period trends

Salinity increased at four out of five monitoring locations in the Shepparton Formation during the study period. Three of the four locations where a salinity increase was determined, a corresponding increase in all major ions occurred.

The salinity increases at all four monitoring locations in the Shepparton Formation are related to the recovery of groundwater levels in mid-2010. Groundwater levels decreased in late 2009 associated with seasonal drawdown and the recovery of groundwater levels has mobilised salts, resulting in an increase in salinity during 2010. The salinity at the monitoring locations, where a salinity increase was observed, was already brackish to saline and dominated by sodium, magnesium and chloride; hence a change in water type was not observed, except at GW036283_2, where salinity is fresh. A change in water type was observed at GW036283_2 from Na-Mg-Cl-HCO3 to Na-Mg-Cl.

Long-term trends

Four out of five bores monitored in the Shepparton Formation showed a long-term increasing trend in salinity (EC). At GW036283_2, screened in the lower Shepparton Formation, groundwater levels showed an increasing trend from the late 1970s to the mid-1990s, and then a decreasing trend with large seasonal drawdowns from this time, with an overall recovery decline of approximately 9.5 m since 1994. Since 2003 when water quality monitoring commenced, water type has evolved from Na-HCO_3-Cl to Na-Mg-HCO_3-Cl to Na-Mg-Cl. This change in water type is occurring due to reverse ion exchange which is occurring as salinity increases (most likely from leakage from clay aquitards as the aquifer becomes depressurised).

At the other three monitoring bores all screened in the lower Shepparton Formation, water levels have declined since 1994, with large seasonal drawdowns and long-term recovery declines of up to 12 m. Increasing salinity trends are associated with a general increase in all major ions (either saline pore water from aquitards or dissolution of salts). Increasing salinity has resulted in reverse ion exchange occurring, and groundwater is classified as Na-Mg-Cl type water at all three monitoring bores.

Beneficial use trends

Although long-term increases in salinity have occurred at some locations, these changes have not resulted in a change in beneficial use class. However, some deterioration in the quality of drinking water has occurred (deterioration form good to fair quality, or fair to poor quality) and groundwater is now no longer suitable for irrigation of some crops, including rice.

Table 8-9 Short- and long-term trends, Shepparton Formation, Lower Murray GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW036588_2	16	Decrease	473	393	5	-17	89	Decrease	568	393	-28	-31	Na-Cl-HCO3 to Na-Mg-Cl-HCO3
GW036743_1	15	Increase	5,200	7,000	93	35	83	Increase	4,130	7,000	260	69	-
GW036876_1	17	Increase	2,750	4,590	81	67	87	Increase	2,960	4,590	135	55	-
GW036587_2	16	Increase	2,030	3,330	41	64	89	Increase	2,760	3,330	55	21	-
GW036283_2*	15	Increase	826	1,071	14	30	87	Increase	312	1,071	110	243	Na-HCO3-Cl to Na-Mg-Cl-HCO3 to Na-Mg-Cl

Note: * Screened across Shepparton and Calivil formations; ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

8.2.4.2 Calivil Formation

Study period trends

Salinity increased at 6 out of 14 monitoring locations in the Calivil Formation during the study period. Four out of the six locations where a salinity increase was determined, a corresponding increase in most major ions was found. The salinity increases at the 6 monitoring locations in the Calivil Formation are related to the recovery of groundwater levels in mid-2010, similar to the overlying Shepparton Formation. Groundwater levels decreased in late 2009 associated with seasonal drawdown and the recovery of groundwater levels has mobilised salts, resulting in an increase in salinity during 2010.

At monitoring locations where a salinity increase was observed a change in water type was not observed, except at GW036742_2, where a change in water type was observed, from Na-Mg-Cl-HCO3 to Na-Mg-Cl.

Long-term trends

Five out 10 bores monitored within the Calivil Formation showed increasing salinity (EC) trends. At GW0363283_3, the Calivil Formation is hydraulically connected to the overlying Shepparton Formation which also shows an increasing salinity trend at this location. Groundwater type has evolved from Na-Mg-Cl-HCO_3 to Na-Mg-Cl type with increasing salinity.

At GW036584, groundwater salinity in the deeper part of the aquifer (Pipe 3) is higher than the upper part of the aquifer (Pipe 2) and shows a long-term increasing salinity (EC) trend. The higher salinity in the deeper part of the aquifer may be associated with the presence of carbonaceous clays.

Salinity at GW036585 is significantly higher in the lower part of the Calivil Formation (Pipe 3) than the upper part (Pipe 2), and has shown a long-term increasing trend. The reason for this increase is unclear, since the salinity of both the overlying Calivil aquifer and underlying Renmark aquifer is lower than in the lower part of the Calivil Formation.

At GW036586_2, groundwater levels have been declining since 1994. Hydrograph data showed that the lower Shepparton Formation (Pipe 1) and Calivil Formation are hydraulically connected. At this location the Shepparton Formation was slightly more saline than the Calivil Formation and optimised mixing calculations indicate that approximately 5% leakage of Shepparton Formation is contributing to the increasing salinity in the Calivil Formation.

At GW036588_3, groundwater levels have been declining since 1994. Hydrograph data showed that the lower Shepparton Formation (Pipe 2) and Calivil Formation are weakly hydraulically connected. At this location the Shepparton Formation was slightly more saline than the Calivil Formation; however, since 2003 the Shepparton Formation has shown a slight freshening trend while the Calivil Formation has shown a slight increasing trend. The Calivil Formation is hydraulically connected with the Renmark Group at this location at occasional reversals of vertical hydraulic gradient have occurred. Although no current salinity data exists for the Renmark Group at this location, historical data from 2005 indicates that the salinity of the Renmark Group was slightly higher than the overlying Calivil Formation. Therefore mixing between these aquifers is likely to be contributing to the slight increasing salinity trend observed in GW036588_3.

Beneficial use trends

Although long-term increases in salinity have occurred at some locations, these changes have not resulted in a change in beneficial use class. However, some deterioration in the quality of drinking water has occurred (deterioration form good to fair quality, or fair to poor quality) and groundwater is now no longer suitable for irrigation of some crops, including rice.

Table 8-10 Short- and long-term trends, Calivil Formation, Lower Murray GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW036283_3	23	Increase	1,080	1,317	13	22	93	Increase	528	1,317	110	149	Na-Mg-Cl-HCO3 to Na-Mg-Cl
GW036584_2	15	-	-	-	-	-	88	Increase	456	523	10	15	-
GW036584_3	15	-	-	-	-	-	91	-	-	-	-	-	Na-Cl-HCO3 to Na-Mg-CL-HCO3
GW036585_2	15	Increase	1,200	1,304	7	9	86	Decrease	5,780	1,304	-140	-77	Na-Mg-Cl to Na-Cl-HCO3 to Na-Cl
GW036585_3	15	Increase	5,490	7,130	16	30	88	Increase	5,430	7,130	240	29	-
GW036586_2	14	-	-	-	-	-	87	Increase	1,330	1,445	10	9	Na-Cl-HCO3 to Na-Cl to Na-Mg-Cl
GW036588_3	16	-	-	-	-	-	91	Increase	554	631	5	14	-
GW036744_2	13	Increase	2,130	2,801	36	32	86	-	-	-	-	-	-
GW036876_2	16	Increase	2,100	2737	34	30	94	-	-	-	-	-	-
GW057763_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW059260_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW060457_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW500086_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW036742_2*	17	Increase	1,590	1,945	19	22	89	-	-	-	-	-	Na-Mg-Cl-HCO3 to Na-Mg-Cl

Note: * Screened across Calivil Formation and Renmark Group; ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

8.2.4.3 Renmark Group

Study period trends

Salinity increased at two out of the nine monitoring locations in the Renmark Group during the study period. At both locations where a salinity increase was determined, a corresponding increase in major ions (calcium and magnesium) was also found.

The salinity increases at the two monitoring locations are related to the recovery of groundwater levels in mid-2010, similar to the trends in the overlying Shepparton and Calivil formations. Groundwater levels decreased in late 2009 associated with seasonal drawdown and the recovery of groundwater levels has mobilised salts, resulting in an increase in salinity during 2010.

No change in water type was identified at the two monitoring locations where a salinity increase was observed. Both locations had Na-Mg-Cl water types.

Long-term trends

Three monitoring bores in the Renmark Group showed long-term increasing EC trends. At GW036587 large drawdowns have been observed since 1994 in the lower Shepparton, Calivil formations and Renmark Group, and there have been several reversals of hydraulic gradients, indicating that leakage from the overlying more saline aquifer into the Renmark Group has occurred. With increasing salinity, reverse ion exchange has occurred and groundwater chemistry has evolved from Na-Cl-HCO_3 to Na-Mg-Cl. A similar trend is observed at GW036743_2.

At GW036744, the Calivil and Renmark aquifers are hydraulically connected have shown large seasonal drawdowns and reversals of vertical hydraulic gradient. The Calivil aquifer had a higher salinity than the Renmark aquifer when monitoring commenced in 2003, and mixing between groundwater from these two aquifers during pumping and reversal of hydraulic gradients is resulting in a slight freshening of the Calivil Formation and increasing trend in the Renmark Group. With increasing salinity, reverse ion exchange has occurred and groundwater chemistry has evolved from Na-Mg-Cl-HCO_3 to Na-Mg-Cl.

Beneficial use trends

Long-term increases in salinity at some locations within the Renmark Group have resulted in a change in the suitability of groundwater for the irrigation of some crops, including rice.

Table 8-11 Short- and long-term trends, Renmark Group, Lower Murray GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW036586_3	15	Increase	2,020	2,443	25	21	89	-	-	-	-	-	-
GW036587_3	17	-	-	-	-	-	92	Increase	965	2,337	175	142	Na-Cl-HCO3 to Na-Mg-CL-HCO3
GW036742_3	6	-	-	-	-	-	82	Decrease	19,200	6,360	-2,370	-67	-
GW036743_2	15	-	-	-	-	-	87	Increase	1,890	6,450	385	241	-
GW036744_3	13	Increase	2,230	3,120	51	40	89	Increase	1,820	3,120	155	71	Na-Cl-HCO3 to Na-Mg-CL
GW500043_1	2	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW500339_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW500790_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW500978_1	4	-	-	-	-	-	ND	ND	ND	ND	ND	ND	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

8.2.5 Risks to groundwater quality

Groundwater levels within the Lower Murray GMA declined by 5 to 15 m since the mid-1990s and deterioration in water quality (EC) in the three alluvial aquifers is observed during this time.

In the Shepparton Formation, long-term increases in EC are apparent in four out of five monitoring bores, with EC increases ranging from 21 to 243%. Increases in salinity are observed at monitoring bores GW036283_2, GW036876_1, GW036587_2 and GW036743_1, which are located to the east and south-east of Deniliquin. At these locations, large groundwater declines have occurred since the mid-1990s resulting in reversals in hydraulic gradient at some locations. These declines follow a period of rising water levels during the mid-1980s to mid-1990s, when water tables approached the ground surface (2 to 10 m), allowing for evapo-concentration of salts within the unsaturated zone and shallow aquifers. The subsequent increases in salinity in the Shepparton Formation are associated with dissolution and mobilisaiton of these salts, and also mobilisation of saline water from aquitards as water levels have declined.

Within the Calivil Formation, five monitoring bores show long-term increasing salinity trends. These monitoring bores (GW036283_3, GW036584_2, GW036585_2, GW036586_2 and GW036588_3) are located between Deniliquin and Tocumwal in the south of the catchment. Salinity (EC) changes of up to 149% (GW036283_3) are observed. The increasing trends in salinity are attributed to a range of processes, reflecting the heterogeneity of the formation and complex aquifer interactions. For example at monitoring bore GW036584_3, increasing salinity may be linked to aquifer depressurisation resulting in mobilisation of pre water from carbonaceous clays present at this location, whereas at GW036586_2, increasing salinity is related to leakage form the overlying Shepparton Formation. The increase salinity has resulted in deterioration of drinking water quality and at some locations, irrigation water quality, within the Calivil Formation.

In the Murray GMA, groundwater within the Renmark Group is generally more saline than the overlying Calivil Formation and long-term increases in salinity are observed at three monitoring bores (GW036587_3, GW036743_2 and GW036744_3). These bores are again all located in the south of the catchment, between Deniliquin and Tocumwal. Long-term salinity (EC) increases range from 71 to 241% and have resulted in a deterioration of beneficial use. Decreases within the Renmark Group are associated with large seasonal drawdowns and reversal of hydraulic gradients, as well as mobilisation of salts from clays.

Risks to groundwater quality within the Murray GMA are considered to be high and a comprehensive monitoring program should be implemented to prevent further deterioration of beneficial use.

9. Lower Murrumbidgee GMA

9.1 Characterisation of the study area

The Lower Murrumbidgee Groundwater Source is located is located in the central-eastern portion of the Murray Basin, NSW (Figure 9-1). The semi-arid catchment covers approximately 33,000 km^2. It is located between the towns of Narrandera, Booligal, Balranald, and Jerilderie, and is bounded by Billabong Creek and the Edwards River in the south, the Lachlan River to the northwest and exposed Palaeozoic bedrock to the east.

9.1.1 Topography and surface hydrology

Within the Lower Murrumbidgee GMA, the topography is predominantly flat, with a small decreasing gradient to the west. Ground elevations within the GMA range from 162 mAHD in the east at Narrandera to approximately 56 mAHD at Balranald.

The Murrumbidgee River flows for 1,600 km from its headwaters in the Snowy Mountains south-west of Canberra to its confluence with the Murray River. The natural flow in the Murrumbidgee River is augmented by the dams of the Snowy Mountains Hydro-electric Scheme, including Tantagara Reservoir on the Upper Murrumbidgee River, Talbingo and several other storages. The major irrigation dams on are Burrinjuck on the Murrumbidgee River near Yass and the Blowering on the Tumut River upstream of Tumut. The Snowy Mountains Hydro-electric Scheme which diverts surface water through 10,000 km of irrigation channels for western irrigation schemes. The major tributary rivers join the Murrumbidgee River upstream of Wagga Wagga and include: Yass, Molongolo, Queanbeyan, Bredbo, Cotter, Goodradigbee and Tumut. The Murrumbidgee has one major distributary creek, Yanco Creek, and smaller distributary creeks upstream of Maude.

The Murrumbidgee River enters the eastern edge of the Murray Basin at Narrandera and flows in a westerly direction through the central part of the GMA, finishing at its confluence with the Lachlan River at Redbank Weir, near Balranald in South-Western NSW. As the Murrumbidgee River flows across the GMA, the distributary creeks take river flows to floodplain wetlands and lakes. Downstream of Hay, the Murrumbidgee reaches the Lower Murrumbidgee floodplain, the most extensive wetland in the Murrumbidgee catchment.

9.1.2 Climate

The Lower Murrumbidgee GMA is semi-arid and experiences an east-west climatic gradient. Average annual rainfall decreases from about 440 mm at Narrandera to 320 mm at Balranald (Kumar, 2010). The closest BoM weather stations to the current study area are Station 075010 Darlington Point (Bringagee) and Station 075031 Hay (Miller St). The long-term average annual rainfall at these two locations is 382 mm and 367 mm at Darlington Point and Hay, respectively. Long-term average monthly rainfall and average monthly rainfall for the current study period (2009–2011) for these two BoM stations is shown on Figures 9-2 and 9-3. Historically, the majority of rainfall occurs during winter from May to October. During the study period, monthly rainfall was typically below average in the latter part of 2009, and above average for the majority of 2010. The total annual rainfall for 2010 was double the long-term average annual rainfall at 739 mm. The rainfall in January 2011 (last groundwater monitoring round) was higher than the long-term average monthly rainfall for January. Daily rainfall for the monitoring period is shown on the hydrographs in Appendix H.

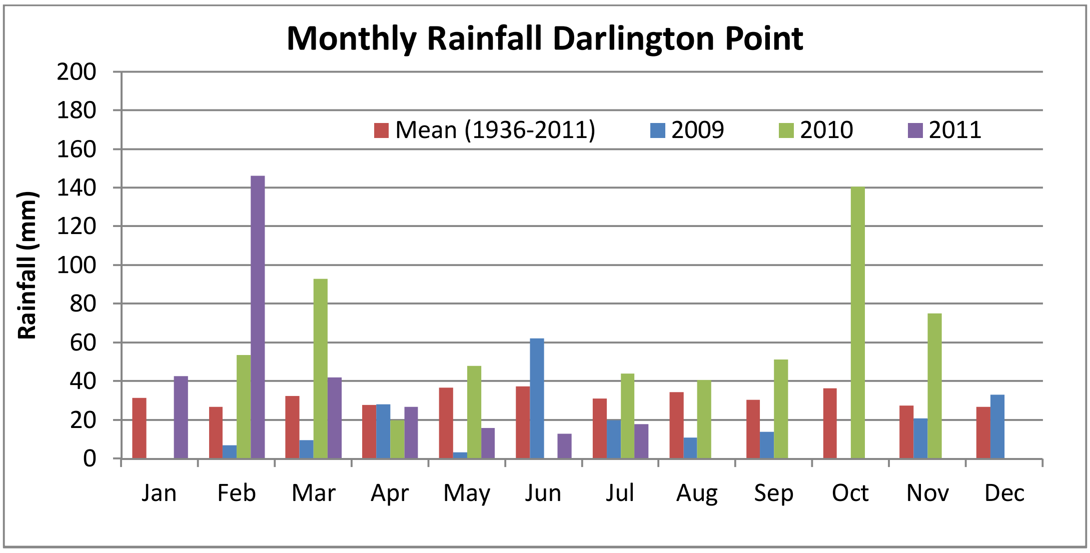


Figure 9-2 **Average monthly rainfall, BoM station 075010 Darlington Point (Bringagee)**

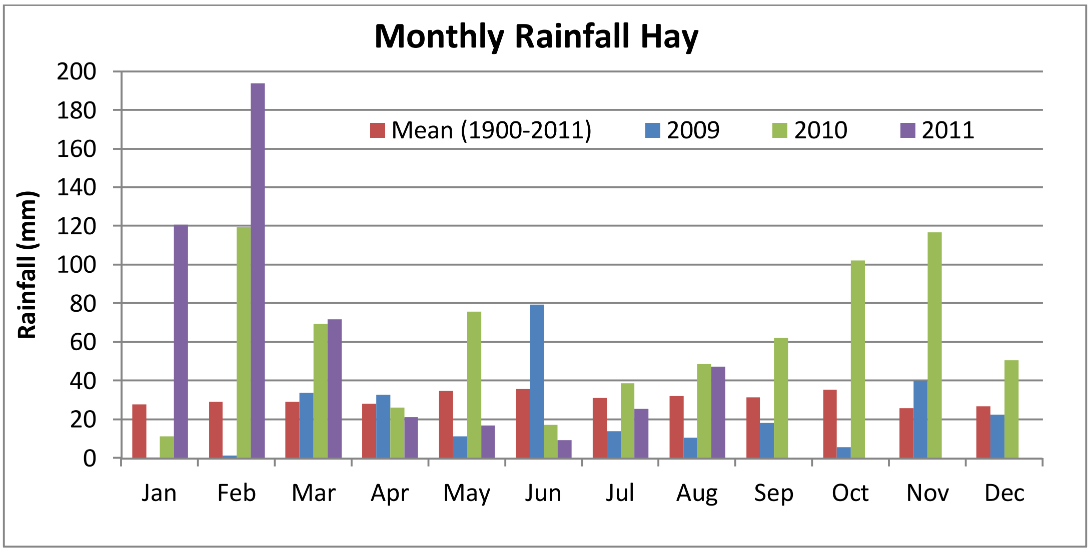


Figure 9-3 **Average monthly rainfall, BoM station 075031 Hay (Miller St)**

The long-term cumulative rainfall residual for Darlington Point and Hay for the period 1965 to 2011 are shown on Figure 9-4. Rainfall generally showed an increasing trend from 1968–2000, and decreasing trend from 2000–2009. During the study period, rainfall was above the long-term averages.

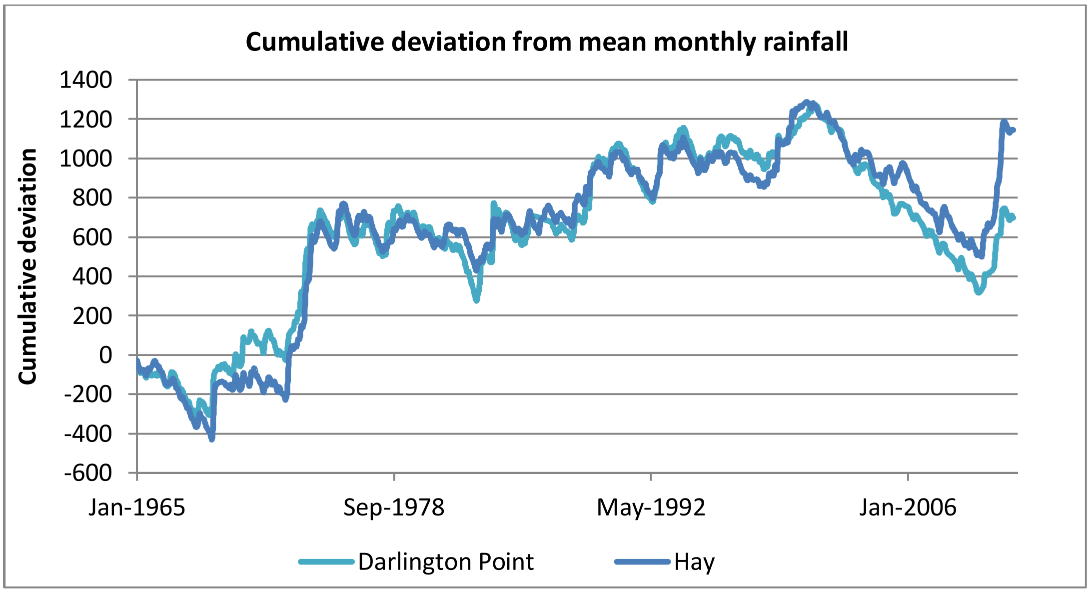


Figure 9-4 **Cumulative deviation from mean monthly rainfall, Darlington Point and Hay (1965 – 2011)**

9.1.3 Land use

Land use in the area includes irrigated horticulture and cropping, dryland cropping and sheep and cattle grazing. Within the Lower Murrumbidgee GMA there are two major two main irrigation areas: the Murrumbidgee Irrigation Area (MIA) (6,600 km^2) established in 1912 to the north of the Murrumbidgee River, and the Coleambally Irrigation Area (CIA) (790 km^2), established in 1970 to the south of the Murrumbidgee River. The main irrigated enterprises in the CIA are rice, sheep/annual pastures, winter crops, soybeans and some horticulture. Crops grown in the MIA include:

- Summer crops – rice, maize, sorghum, corn, soybeans, tomatoes
- Winter crops – wheat, barley, canola, legumes
- Vegetables – carrots, onions, melons, broccoli, cabbage
- Horticulture – grapes, citrus, stone fruit, cherries.

9.1.4 Hydrogeology

The Lower Murrumbidgee catchment is underlain by about 200-400 m of Cenozoic fluvio-lacustrine sediments that range in age from Late Paleocene to Pleistocene and overly Paleozoic and Mesozoic basement rocks (Brown 1989). Within the catchment the sedimentary deposits are divided into three main formations and hydrostratigraphic units:

- Shepparton Formation (upper aquifer) – Late Pliocene to Pleistocene age unit that comprises a complex assemblage of multi-coloured clay and lenses of yellow and brown polymitic sands which were deposited in a fluvio-lacustrine environment.

- Calivil Formation (middle aquifer) – Late to Middle Miocene terrestrial unit comprising pale grey coarse sand and fine grave, pale grey to white kaolinitic clay and thin bands of carbonaceous clay.
- Renmark Group (lower aquifer) - Paleocene to Miocene terrestrial unit comprising grey, medium grained quartz sand, and laterally discontinuous carbonaceous silts and clays, and dark brown lignite.

The Shepparton Formation directly overlies the Calivil Formation and ranges in thickness from 50-70 m thick. The sediments are laterally discontinuous and form a highly heterogeneous aquifer system. The proportion of sand is highly variable but mostly 10 to 30% (Lawson 1992), and mainly restricted to the uppermost 30 m sequence (Woolley & Williams 1978). Hydraulic conductivity of the Shepparton Formation is highly variable. The regional hydraulic conductivity is 2-3 m/day due to the large proportion of sand and clay. Higher hydraulic conductivities occur in sandier lenses.

The Calivil Formation directly overlies and is in hydraulic continuity with the underlying Renmark aquifer systems. The formation ranges in thickness from 50 to 70 m in the eastern part of the GMA to a maximum of 90 m. It is the most productive aquifer within the Lower Murrumbidgee and the highest yielding bores (yields >350 L/s) are located near Darlington Point. The Shepparton Formation which overlies the Calivil Formation acts as a semi confining unit.

The Renmark Group forms the basal confined aquifer. Its thickness is variable and peaks at 366 m within the GMA. Horizontal hydraulic conductivity in the Renmark aquifers averages 3 m/day on a regional scale, but up to 100 m/day within the alluvial fans (Evans & Kellet 1989).

The deeper Calivil and Renmark aquifers generally have better water quality (lower salinity) than the overlying Shepparton Formation. Within these two aquifers, EC increases from <200 µS/cm in the east to >25,000 µS/cm in the west, with groundwater east of Hay generally <1,000 µS/cm. Higher salinity groundwater also occurs in the northern part of the GMA between Leeton and Griffith and the area north of Jerilderie. While the same regional trend is seen in the Shepparton Formation, higher EC hotspots are observed in the MIA and CIA, with EC >30,000 µS/cm (PB and ANU, unpublished).

Regionally, groundwater flow is generally east to west south-west, with localised seasonal variations due to irrigation and groundwater extraction (Kumar 2010). The aquifer systems are almost fully saturated, with watertable depths in the Shepparton Formation ranging from <2 m bgl (localised occurrences only) to approximately 20 m bgl in non-irrigated regions.

Trends in groundwater age determined from radiocarbon data collected in the 1980’s agree with the general flow directions determined from hydraulic gradients (Drury et al. 1984). Groundwater ages generally increase from east to west, and with increasing distance from the Murrumbidgee River, although local perturbations in regional radiocarbon trend occur in areas of heavy pumping. Drury et al. (1984) concluded that recharge to the local aquifer systems is dominated by losses from the Murrumbidgee River via the Shepparton Formation, between Narrandera and Gogeldrie Weir (approximately 30 km north-west).

Generally in the eastern part of the catchment vertical hydraulic gradients indicate there is downward movement of water from the Shepparton Formation to the deeper aquifers, and vertical hydraulic gradients are reversed at the western margin of the Lower Murrumbidgee GMA. However, in areas of heavy abstraction reversal of vertical hydraulic gradients has occurred at some locations.

In general, water levels showed a gentle rising trend from late 1980s to early 1990s. However since the early 1990s water levels have been declining, and this trend has been attributed to the significant increase in usage in 1994/95 and constantly high usage (over 230 GL pa) since 1997/98 (Kumar 2010). Hydrographs in the eastern part of the catchment show seasonal responses to groundwater extractions since the late 1970s and early 1980s. Further west, around Hay, development occurred later during the mid-1990s, and seasonal trends in water levels are observed from this time. The largest seasonal drawdowns are observed around Whitton, Darlington Point, Coleambally and Carrathool. Long-term water level trends show a lack of recovery around Hay, Carrathool and Steam Plains and may indicate that groundwater extractions are occurring at rates higher than aquifer replenishment rates in these areas (Kumar 2010).

Hydrographs of monitoring bores included in the current study are shown on Figure 9-5 and a brief summary of groundwater level trends is given in Table 9-1. During the 2009-2011 study period water level recoveries were observed in most monitoring bores.

Table 9-1 Hydrogeological conditions at each monitoring location

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW030323_1	88.3–94.4	CF	Water levels in both pipes show similar trends, indicating a hydraulic connection between the Calivil and Renmark aquifers. Both pipes showed a slight decreasing trend from the mid-1970s to 1991. From 1991, seasonal fluctuations in water levels occurred and total recovery water levels showed a declining trend. Vertical hydraulic gradients showed seasonal reversals from 1991 to 1997; from 1997, water levels in Pipe 1 have been higher than Pipe 2, indicating downward movement of water from the Calivil to Renmark Group.
GW030323_2	194.4–200.5	RG	
GW030350_1	58.8–63.1	SF	The water level in Pipe 1 increased slightly during the late 1970s. From the early 1980s small seasonal fluctuations relating to pumping were evident, and from 1997 seasonal drawdowns increased and long-term recovery water levels decreased by ~3 m.
GW036211_1	131–143.2	RG	GW036211 is located at Steam Plains. All 3 pipes are screened in the Renmark Group and are in hydraulic connection. The effects of pumping became evident in 1995, with large seasonal drawdowns (up to ~9 m) occurring. Long-term recovery water levels have decreased by ~10 m.
GW036211_2	196.6–202.6	RG	
GW036211_3	256.0–262.1	RG	
GW036275_1	170.1–176.3	RG	GW036275 is located south of Carrathool. The hydrographs show declining water levels within the Renmark Group from the mid-1990s and seasonal drawdowns of up to 10 m. Seasonal reversal of vertical hydraulic gradients has occurred since the early 2000s.
GW036275_2	300.3–306.5	RG	
GW036358_1	62.7–68.7	CF	GW036358 is located west of Darlington Point. The hydrographs show declining trends within the Calivil
GW036358_2	103-6–109.7	CF	

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW036358_3	140.2–146.3	RG	and Renmark aquifers. Seasonal drawdown of up to 25 m is observed in the deeper aquifer. Seasonal fluctuations have decreased since 2007 due to changes in local impact management rules and wetter climatic conditions. The pressure level in the deeper aquifer is lower than that in the shallow aquifer suggesting a downward vertical hydraulic gradient. The similar water level response in the Calivil and Renmark aquifers indicates a good hydraulic connection between the two.
GW036396_1	139.0–145.0	RG	GW036396 is located in near Whitton. The hydrograph for Pipe 1 shows large seasonal drawdowns which appear to be increasing possibly due to increased extractions in the area. The long-term recovery water levels have decreased by up to 10 m.
GW036773_1	57.3–62.8	SF	GW036773 is located east of Colleambally. Hydrographs show that there is a hydraulic connection between shallow and deep aquifers. Seasonal drawdowns are observed in all aquifers and long-term recovery water levels have declined by ~7 m. During irrigation season, vertical hydraulic gradients are reversed, and pressure levels in the Calivil Formation are lower than the Renmark aquifer.
GW036773_2	122.0–128.0	CF	
GW036773_3	166.0–172.0	RG	
GW036799_1	59.0–71.0	RG (Upper)	GW036799 is located west of Hay. Hydrographs show that there is limited hydraulic connection between the Upper Renmark aquifer and the deeper aquifers. Pressure levels in the Lower Renmark show seasonal responses to pumping from 2001, and a long-term drawdown of ~8 m. Pumping in the vicinity of this bore has also caused a reversal in vertical hydraulic gradients.
GW036799_2	225.0–231.0	RG (middle)	
GW036799_3	322–334	RG (lower)	
GW041011_1	16.0–22.0	SF	GW041011 is located south of Carrathool. Hydrographs show there is limited hydraulic connection between the Shepparton Formation and the deeper aquifers. Both deep aquifers show seasonal responses to pumping and water level recovery since 2009.
GW041011_2	97.0–103.0	CF	
GW041011_3	178.0–184.0	RG	
GW041012_1	30.0–34.0	SF	GW041012 is located south-east of Carrathool. Hydrographs show there is limited hydraulic connection between the Shepparton Formation and the deeper aquifers. Both deep aquifers show seasonal responses to pumping and water level recovery since 2009.
GW041012_2	71.0–77.0	CF	
GW041012_3	155.0–161.0	RG	
GW059225_1	107.6–121.3	CF	GW059225 is a pumping bore located south of Colleambally. Water levels show drawdowns of up to 3 m during pumping.
GW273040_1	32.0–35.0	SF	GW0273040 is located in the MIA, east of Carrathool. Hydrographs indicate there is a strong hydraulic connection between the Shepparton and Calivil
GW273040_2	50.0–56.0	CF	
GW273040_3	107.0–113.0	RG	

Bore No.	Slotted interval (mbgl)	Aquifer	Long-term hydrogeological conditions
GW273040_4	140.0–146.0	RG	formations. Pressure levels in the Renmark Group show seasonal responses to pumping and recovery since 2009. Vertical hydraulic gradients indicate that there is downward leakage from shallow to deep aquifers at this location.
GW273041_1	19.0–22.0	SF	GW273041 is located near Colleambally. Hydrographs indicate that the Shepparton Formation is not in hydraulic connection with deeper aquifers, and that the Calivil and Renmark aquifers are connected. Pressure levels in the Calivil and Renmark aquifers show seasonal responses to pumping and recovery since 2009.
GW273041_2	77.0–83.0	CF	
GW273041_3	148.0–154.0	RG	
GW273041_4	185.0–191.0	RG	

Note: SF-Shepparton Formation, RG-Renmark Group, CF-Calivil Formation.

9.2 Characterisation of groundwater chemistry (2009–2011)

Groundwater sampling was undertaken in 15 sampling rounds during the study period (September 2009 to January 2011). 42 monitoring bores were sampled during the study period, with 6 located in the Shepparton Formation, 11 located in the Calivil Formation, 2 located in the Calivil Formation and Renmark Group, 22 located in the Renmark Group, and 1 located in all three formations.

The majority of sampling locations for the current study are focused in the main irrigation areas north and south of the Murrumbidgee River in the eastern part of the catchment (between Narrandera and Hay). One monitoring bore (GW036799) and one pumping bore (GW401876) were sampled west of Hay, half way between Hay and Balranald. Therefore, the following discussion will focus on trends and processes occurring in the eastern part of the catchment only, with some reference to the two western bores for comparison.

9.2.1 Results

Groundwater chemistry statistics are summarised in Tables 9-2, 9-3 and 9-4 for the Shepparton, Calivil and Renmark formations respectively. The results are presented on a cross-section (Figure 9-6). The location of the cross-section is shown on Figure 9-1. The spatial variability of average major ion concentrations, salinity and SAR hazards are presented in Figures 9-7, 9-8 and 9-9 respectively.

A water quality ‘report card’ has been prepared for individual monitoring bores to assess major ion chemistry, salinity and sodium and salinity hazards throughout the monitoring period. Each report contains a Piper diagram, a Wilcox diagram, and time series graphs for salinity and groundwater level. The reports are located in Appendix H.

A Piper diagram presenting major ion chemistry for the Shepparton and Calivil formations and Renmark Group is presented in Figure 9-10.

Stable isotope data (^{18}O and ^{2}H) was collected for several monitoring rounds and is presented in Figures 9-11 and 9-12.

Table 9-2 Lower Murrumbidgee Shepparton Formation statistics, Sep 09–Jan 11

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	61	61	330	26000	5368	2700	7029
EC (lab)	µS/cm	62	62	585	32800	8314	4000	1034
pH (field)	pH unit	58	58	3.58	7.62	6.91	7.08	0.66
K	mg/L	62	62	0.6	8.0	4.2	6.2	2.8
Na	mg/L	62	62	78	3700	1096	615	1116
Ca	mg/L	62	62	4.1	1900	391.9	190	614.7
Mg	mg/L	62	62	4.7	1600	321.8	140	511.4
Cl	mg/L	62	62	77	12000	2634	1200	3977
SO_4	mg/L	62	62	14	1400	579	820	507
Alkalinity ($CaCO_3$)	mg/L	62	62	110	500	311	275	111
CO_3	mg/L	62	5	<1	19	1	1	3
HCO_3	mg/L	62	62	140	610	378	340	138
Si	mg/L	62	62	9	24	16	15	5
F	mg/L	62	62	0.19	2.10	1.01	1.10	0.57
Al (soluble)	mg/L	62	38	<0.01	0.230	0.027	0.010	0.040
B (soluble)	mg/L	62	60	<0.1	2.00	0.58	0.30	0.61
Br (soluble)	mg/L	62	61	<0.2	55.0	10.8	3.9	16.7
Cu (soluble)	mg/L	62	9	<0.01	0.790	0.031	0.005	0.131
Mn (soluble)	mg/L	62	17	<0.002	0.012	0.0015	0.001	0.001
Ni (soluble)	mg/L	6	1	<0.01	0.017	0.007	0.005	0.005
Sr (soluble)	mg/L	62	62	0.08	36.00	6.03	2.20	9.63
Zn (soluble)	mg/L	62	58	<0.005	0.830	0.056	0.018	0.136
Mn (total)	mg/L	62	26	<0.002	0.040	0.003	0.001	0.006
Ni (total)	mg/L	62	9	<0.01	0.090	0.008	0.005	0.012
Zn (total)	mg/L	62	38	<0.01	0.160	0.029	0.017	0.030
Al (total)	mg/L	62	37	<0.05	1.10	0.12	0.06	0.19
B (total)	mg/L	62	62	<0.1	2.9	0.7	0.3	0.7
Cu (total)	mg/L	62	17	<0.005	0.080	0.008	0.003	0.016
Fe (total)	mg/L	62	25	<0.05	1.20	0.11	0.03	0.20
Pb (total)	mg/L	62	4	<0.02	0.044	0.011	0.010	0.005
N_2	mg/L	61	59	<0.05	4.30	1.77	1.90	1.35
NH_3	mg/L	62	6	<0.01	0.02	0.01	0.01	0.003
NO_3	mg/L	35	35	1.6	3.9	2.7	2.9	0.6
PO_4	mg/L	62	62	0.006	0.115	0.033	0.013	0.039
Total P	mg/L	62	62	0.005	0.114	0.034	0.015	0.038

Note: SD – standard deviation

Table 9-3 Lower Murrumbidgee Calivil Formation statistics, Sep 09 to Jan 11

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	83	83	220	6200	1050	400	1694
EC (lab)	µS/cm	83	83	396	8930	1627	694	2436
pH (field)	pH unit	79	79	5.88	11.02	6.70	6.64	0.62
K	mg/L	83	83	1.3	4.5	2.5	2.3	1.0
Na	mg/L	83	83	66	1200	227	100	324
Ca	mg/L	83	83	5.9	350.0	55.2	18.0	101.1
Mg	mg/L	83	83	6	330	54	18	98
Cl	mg/L	83	83	26	2700	438	140	831
SO_4	mg/L	83	83	1.9	570.0	92.2	34.0	153.3
Alkalinity ($CaCO_3$)	mg/L	83	83	71	210	131	130	37
CO_3	mg/L	83	2	<1	4	1	1	0.4
HCO_3	mg/L	83	83	87	260	161	160	45
Si	mg/L	83	83	5.2	17.0	10.3	9.9	2.8
F	mg/L	83	83	0.13	1.10	0.44	0.44	0.20
Al (soluble)	mg/L	83	19	<0.01	0.030	0.008	0.005	0.006
B (soluble)	mg/L	83	24	<0.1	0.30	0.09	0.05	0.08
Br (soluble)	mg/L	83	69	<0.2	11.0	1.7	0.6	3.1
Cu (soluble)	mg/L	83	7	<0.01	0.130	0.007	0.005	0.014
Mn (soluble)	mg/L	83	73	<0.002	0.270	0.058	0.012	0.070
Sr (soluble)	mg/L	83	83	0.09	6.50	0.93	0.25	1.85
Zn (soluble)	mg/L	83	69	<0.005	0.380	0.044	0.022	0.062
Mn (total)	mg/L	83	73	<0.002	0.230	0.058	0.012	0.068
Ni (total)	mg/L	83	0	Not calculated				
Zn (total)	mg/L	83	47	<0.01	0.150	0.030	0.014	0.034
Al (total)	mg/L	83	51	<0.05	1.10	0.14	0.07	0.21
B (total)	mg/L	83	30	<0.1	0.4	0.1	0.1	0.1
Cu (total)	mg/L	83	11	<0.005	0.016	0.004	0.003	0.003
Fe (total)	mg/L	83	59	<0.05	0.85	0.25	0.11	0.28
Pb (total)	mg/L	83	1	<0.02	0.022	0.010	0.010	0.001
N_2	mg/L	82	56	<0.05	6.40	0.79	0.08	1.86
NH_3	mg/L	82	47	<0.01	0.22	0.03	0.01	0.04
NO_3	mg/L	9	8	<0.2	6.1	4.9	5.6	1.8
PO_4	mg/L	82	82	0.008	0.206	0.029	0.019	0.032
Total P	mg/L	82	82	0.005	0.229	0.036	0.029	0.034

Note: SD – standard deviation

Table 9-4 Lower Murrumbidgee Renmark Group statistics, Sep 09 to Jan 11

Parameter	Units	No. samples	No. detects	Min	Max	Mean	Median	SD
TDS	mg/L	168	168	200	2800	559	370	499
EC (lab)	µS/cm	168	168	364	5000	972	646	860
pH (field)	pH unit	161	161	5.30	9.11	6.48	6.45	0.43
K	mg/L	168	168	1.5	16.0	4.3	3.8	3.1
Na	mg/L	168	168	45	800	157	100	151
Ca	mg/L	168	168	4	93	19	15	16
Mg	mg/L	168	168	5.8	120.0	21.4	15.0	19.1
Cl	mg/L	168	168	56	1400	231	140	265
SO_4	mg/L	168	108	0.3	110.0	18.0	3.9	26.7
Alkalinity ($CaCO_3$)	mg/L	168	168	63	330	126	110	55
CO_3	mg/L	168	9	<1	17	1	1	2
HCO_3	mg/L	168	168	77	400	153	130	66
Si	mg/L	168	168	1.9	11.0	6.2	5.9	1.2
F	mg/L	168	168	0.15	1.20	0.53	0.50	0.19
Al (soluble)	mg/L	168	40	<0.01	0.440	0.010	0.005	0.034
B (soluble)	mg/L	168	39	<0.1	0.20	0.06	0.05	0.02
Br (soluble)	mg/L	168	166	<0.2	4.4	0.9	0.6	0.8
Cu (soluble)	mg/L	168	2	<0.01	0.010	0.005	0.005	0.001
Mn (soluble)	mg/L	168	168	0.008	0.490	0.108	0.049	0.123
Ni (soluble)	mg/L	5	4	<0.01	0.027	0.015	0.016	0.008
Sr (soluble)	mg/L	168	168	0.07	1.60	0.30	0.20	0.29
Zn (soluble)	mg/L	168	131	<0.005	0.270	0.036	0.017	0.049
Mn (total)	mg/L	168	166	<0.002	0.470	0.104	0.050	0.121
Ni (total)	mg/L	168	5	<0.01	0.033	0.005	0.005	0.003
Zn (total)	mg/L	168	89	<0.01	1.300	0.041	0.012	0.129
Al (total)	mg/L	168	88	<0.05	9.50	0.22	0.05	0.80
B (total)	mg/L	168	43	<0.1	0.2	0.1	0.1	0.04
Cu (total)	mg/L	168	13	<0.005	0.690	0.010	0.003	0.060
Fe (total)	mg/L	168	150	<0.05	13.00	1.10	0.62	1.57
Pb (total)	mg/L	168	4	<0.02	0.035	0.010	0.010	0.003
N_2	mg/L	168	168	<0.05	0.75	0.25	0.21	0.17
NH_3	mg/L	168	168	0.02	0.70	0.17	0.14	0.15
NO_3	mg/L	3	1	<0.2	0.5	0.2	0.1	0.2
PO_4	mg/L	167	167	0.007	0.716	0.078	0.051	0.096
Total P	mg/L	168	168	0.022	0.861	0.143	0.103	0.134

Note: SD – standard deviation

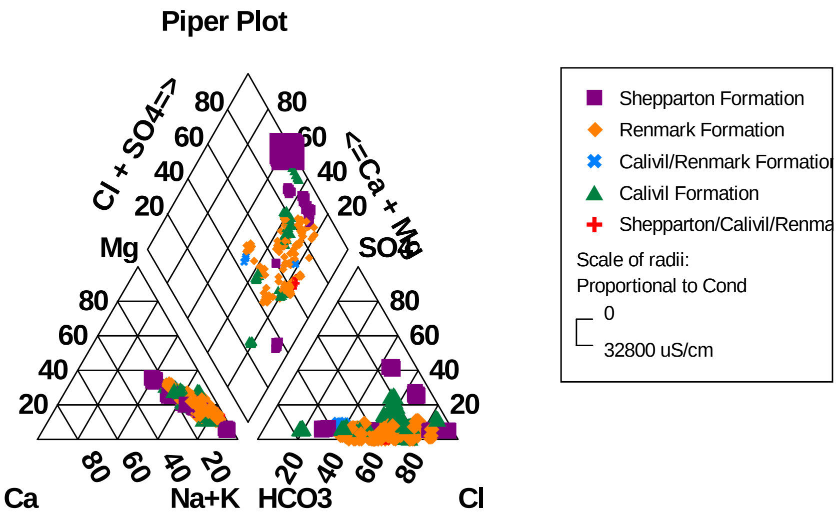


Figure 9-10 Piper diagram for groundwater samples from the Lower Murrumbidgee GMA

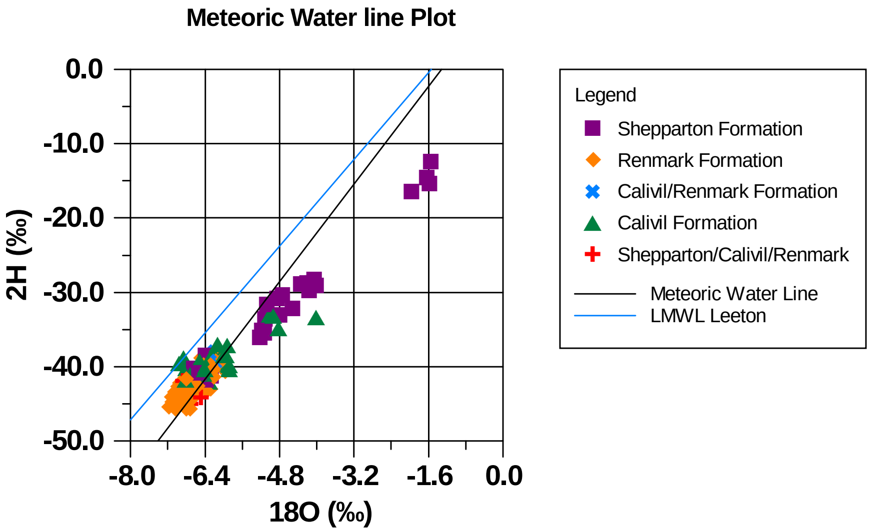


Figure 9-11 Oxygen-18 versus deuterium for groundwater samples from the Lower Murrumbidgee GMA

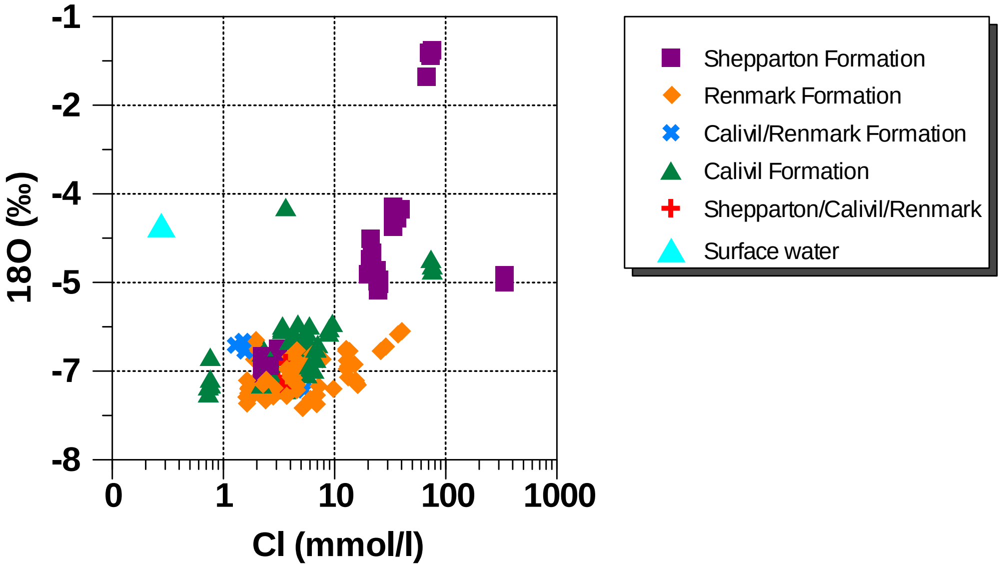


Figure 9-12 Oxygen-18 versus chloride for groundwater samples from the Lower Murrumbidgee GMA

9.2.1.1 Shepparton Formation

Water quality parameters

Groundwater salinity in the Shepparton Formation ranges from fresh (585 µS/cm) to saline (32,000 µS/cm). These EC values equate to Total Dissolved Solids concentrations of 330 mg/L to 26,000 mg/L). Lowest salinity groundwater occurs close to the Murrumbidgee River where river recharge occurs. Salinities are generally higher to the north of the river due to variations in bedrock lithology and topography which impedes groundwater flow in the northern part of the GMA south of Griffith. Salinity anomalies do occur in irrigation areas where rising water tables and evapotranspiration has resulted in the accumulation of salts. Aeolian deposition of cyclic salts has also lead to an accumulation of salts with the formation. Previous studies in the catchment have shown that significant salt stores are present in the upper Shepparton Formation, particularly in the low-permeability silt and clay layers (Timms 2001, Bell 2007).

The pH of groundwater is generally slightly acidic to slightly alkaline, with average pH around neutral (7.1).

Major and minor ions

The average major ion composition for the Shepparton Formation is shown on Figure 9-7. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix H.

As seen in Figure 9-7, the major ion composition is highly variable. Saline groundwaters are typically dominated by sodium (Na^+), magnesium (Mg^{2+}) and chloride (Cl^-), with increasing concentrations of sulphate (SO_4^{2-}) in some bores. The relative proportion of bicarbonate to other major ions is higher in bores with low salinity (fresh) groundwater, and at these locations groundwater is typically Na-Cl-HCO_3 or Na-HCO_3-Cl type water.

Dissolved silicon concentrations ranged from 9 to 24 mg/L, with the lowest concentrations occurring north-west of the Murrumbidgee River. Elevated silicon concentrations are expected in alluvial aquifer systems where silicate mineral weathering and clay transformations are common geochemical processes.

Fluoride concentrations ranged from 0.19 mg/L to 2.1 mg/L, with the highest concentrations occurring to the north of the Murrumbidgee River.

Bromide concentrations ranged from 0.1 mg/L to 55 mg/L, with the highest concentrations associated with highest salinity groundwater.

Metals and metalloids

Groundwater samples were analysed for dissolved metals and metalloids (aluminium, boron, copper, manganese, strontium and zinc) and total metals (aluminium, boron, copper, iron, lead, manganese, nickel and zinc).

Boron was detected in 97% of samples, with concentrations of up to 2 mg/L (dissolved) and 2.9 mg/L (total) detected. The occurrence of boron in the shallow aquifer is not well correlated with salinity, and the highest occurrences were detected in the MIA. Although boron can naturally occur in groundwater from leaching of country rocks, infiltration of meteoric salts, or mixing with adjacent groundwaters, it can also result from contamination by anthropogenic sources. In agricultural catchments it is common to ameliorate boron deficiencies by adding borax or boric acid to irrigation water, and is likely that this is the cause of elevated boron concentrations in the Lower Murrumbidgee.

Aluminium was only detected in 60% of samples, and concentrations ranged from below detection limit to 0.23 mg/L (soluble) and 1.1 mg/L (total). Concentrations are well correlated with salinity.

Zinc was detected in the majority of samples (94%) reaching concentrations of up to 0.83 mg/L (soluble). Iron and manganese concentrations are well correlated (r^2=0.98), and both metals were detected in approximately 40% of samples.

Strontium was detected in all samples, with concentrations ranging from 0.077 mg/L to 36 mg/L. Strontium was well correlated with salinity (r^2=0.99).

With the exception of boron, trace metal concentrations are believed to be naturally occurring and are mainly derived from clay minerals and metal oxides and hydroxides.

Nutrients

Ammonia was generally absent from groundwater, while nitrate was present in all samples for which it was analysed. Nitrate concentrations ranged from 1.6 mg/L to 3.9 mg/L, with the highest concentrations occurring within the main irrigation areas. Total and reactive phosphorus were detected in in all groundwater samples, and reached maximum concentrations of 0.114 mg/L and 0.115 mg/L, respectively. These results indicate that nearly all phosphorus in the system is present as orthophosphate which is the most thermodynamically stable species in natural waters. Phosphorus in groundwater can be derived from natural processes, and it can also be derived in agricultural areas from animal manure and fertilisers.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for selected groundwater samples collected in September to December 2009, and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^{2}H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 9-11. The average surface water sable isotope composition ($\delta^{18}O = -4.30‰$, $\delta^{2}H = -28.0‰$) for 2009-2010 is also plotted on this graph (ANU and PB, unpublished).

In the Shepparton Formation, stable isotope values ranged from –6.72‰ to -1.54‰ for $\delta^{18}O$, and -41.9‰ to -12.5‰ for $\delta^{2}H$. Groundwater samples from the Shepparton Formation show a broad range of isotopic values; however most samples plot to the right of the GMWL and LMWL.

9.2.1.2 Calivil Formation

Water quality parameters

Groundwater was generally fresh (median 694 µS/cm) within the Calivil Formation in the eastern part of the Lower Murrumbidgee GMA, with the lowest salinity groundwater detected in monitoring bores close to the Murrumbidgee River. These findings are consistent with those of previous studies by Timms (2002); Horner et al. (2010) and Kumar (2010). Higher salinity was detected in one monitoring bore located north of Darlington Point in the MIA (EC 8,930 µS/cm). The EC values equate a Total Dissolved Solids range of 220 mg/L to 6,200 mg/L.

The pH values recorded in the field vary significantly from 5.88 to 11.02, although the higher value appears to be anomalous. The median pH for the Calivil Formation is 6.64, indicating that groundwater within the aquifer is generally slightly acidic.

Major and minor ions

The average major ion composition for the Calivil Formation is shown on Figure 9-7. The major ion chemistry is highly variable, ranging from Na-HCO_3 type in water in the lowest salinity bore located near the Murrumbidgee River to Na-Mg-Cl type water in the highest salinity water in the MIA. The majority of groundwater samples have a chemical composition that is a mix of these two end members. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix H.

Dissolved silicon concentrations ranged from 5.2 mg/L to 17 mg/L. There was no apparent spatial trend in the distribution of silica in groundwater; however, the highest silicon concentration was observed in the highest salinity groundwater sample.

Fluoride concentrations were generally lower than in the overlying Shepparton Formation, ranging from 0.13 mg/L to 1.1 mg/L. Bromide concentrations ranged from the LOR (<0.1 mg/L) to 11 mg/L, with bromide below detection limit in low salinity samples. Bromide was well correlated with salinity (r^2=0.99).

Metals and metalloids

Groundwater samples were analysed for dissolved metals and metalloids (aluminium, boron, copper, manganese, strontium and zinc) and total metals (aluminium, boron, copper, iron, lead, manganese, nickel and zinc).

Boron was only detected in 29% of samples from the Calivil Formation and concentrations were lower than the Shepparton Formation, ranging from detection limit (<0.1 mg/L) to 0.3 mg/L. The highest concentrations were detected in the highest salinity groundwater.

Aluminium (dissolved) was only detected in 23% of samples, and concentrations were typically lower than the overlying Shepparton Formation. The maximum concentration was 0.03 mg/L.

Zinc (soluble) was detected in the majority of samples (83%) reaching maximum concentrations of 0.38 mg/L. Unlike the Shepparton Formation, iron and manganese are not well correlated. Manganese (total) was detected in 88% of samples, and the maximum concentration detected was 0.23 mg/L. The highest concentrations were detected in monitoring bores closest to the Murrumbidgee River. Iron (total) was detected in 71% of samples, reaching maximum concentrations of 0.85 mg/L. The highest concentrations were detected in monitoring bores within the main irrigation areas.

Strontium was detected in all samples, with concentrations ranging from 0.087 mg/L to 6.5 mg/L. Strontium was well correlated with salinity (r^2=0.99).

With the exception of boron, trace metal concentrations are believed to be naturally occurring and are mainly derived from clay minerals and metal oxides and hydroxides.

Nutrients

Ammonia was detected in 57% of samples, and concentrations were higher than the Shepparton Formation (maximum 0.22 mg/L). Nitrate was only analysed for 9 samples during the study period. The highest concentration detected was 6.1 mg/L, and the highest nitrate concentrations were detected in the monitoring bore with the highest salinity.

Total and reactive phosphorus were detected in in all groundwater samples, and reached maximum concentrations of 0.229 mg/L and 0.206 mg/L, respectively. These results indicate that nearly all phosphorus in the system is present as orthophosphate which is the most thermodynamically stable species in natural waters.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium (δ^2H), were analysed for selected groundwater samples collected in September to December 2009, and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^2H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^2H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 9-11. The average surface water sable isotope composition ($\delta^{18}O$ = -4.30‰, δ^2H = -28.0‰) for 2009-2010 is also plotted on this graph (ANU and PB, unpublished).

Forty-five samples from the Calivil Formation were analysed for stable isotopes. Stable isotope values for the Calivil Formation ranged from –6.96‰ to -4.01‰ for $\delta^{18}O$, and -44.9‰ to -33.2‰ for δ^2H. The majority of samples plotted on or close to the GMWL; however, one exception was noted. Monitoring bore GW036358_1 located to the north of the Murrumbidgee River near Darlington Point, had enriched isotopic signatures and plotted to the right of the GMWL.

9.2.1.3 Renmark Group

Water quality parameters

Groundwater was generally fresh (median 646 µS/cm) within the Renmark Group in the eastern part of the Lower Murrumbidgee GMA, with the lowest salinity groundwater detected in monitoring bores close to the Murrumbidgee River. Groundwater salinity increased in the western part of the catchment, with EC values reaching 5,000 µS/cm. The EC values equate a Total Dissolved Solids range of 200 mg/L to 2,800 mg/L.

The pH of groundwater in the Renmark Group ranged from acidic (pH 5.30) to alkaline (pH 9.11), although the average pH conditions were slightly acidic (pH 6.48).

Major and minor ions

The average major ion composition for the Renmark Group is shown on Figure 9-7. Individual water types for each monitoring location are presented in piper plots in the report cards in Appendix H.

As seen in Figure 9-7, the major ion chemistry is not as variable as in the overlying Calivil Formation. The majority of groundwater within the eastern part of the Lower Murrumbidgee GMA is classified as $Na-HCO_3-Cl$ or $Na-Cl-HCO_3$ type water. In the western part of the catchment, saline groundwater has a major ion chemistry dominated by Na^+, Mg^{2+} and Cl^-. The major ion chemistry of the majority samples represents a mix between a fresh end member ($Na-HCO_3-Cl$) and saline end member (Na-Mg-Cl).

Dissolved silica concentrations are generally lower than the two overlying aquifers, ranging from 1.9 mg/L to 11 mg/L. There was no apparent spatial trend in the distribution of silica in groundwater; however, the highest silica concentration was observed in the highest salinity groundwater sample.

Fluoride concentrations were similar to the overlying Calivil Formation, ranging from 0.15 mg/L to 1.2 mg/L. Bromide concentrations ranged from below detection limit (<0.1 mg/L) to 4.4 mg/L, with bromide below detection limit in low salinity samples. Bromide was well correlated with salinity (r^2=0.97).

Metals and metalloids

Groundwater samples were analysed for dissolved metals and metalloids (aluminium, boron, copper, manganese, strontium and zinc) and total metals (aluminium, boron, copper, iron, lead, manganese, nickel and zinc).

Boron was only detected in 23% of samples from the Renmark Group and concentrations were lower than the Shepparton Formation, ranging from detection limit (<0.1 mg/L) to 0.2 mg/L. The highest concentrations were detected in the highest salinity groundwater.

Aluminium (dissolved) was only detected in 24% of samples, and concentrations were typically lower than the overlying Shepparton Formation. The maximum concentration was 0.44 mg/L.

Zinc (soluble) was detected in the majority of samples (78%) reaching maximum concentrations of 0.27 mg/L. Unlike the Shepparton Formation, iron and manganese are not well correlated. Manganese (total) was detected in 99% of samples, and the maximum concentration detected was 0.47 mg/L. The highest concentrations were detected in monitoring bores closest to the Murrumbidgee River. Iron (total) was detected in 89% of samples, reaching maximum concentrations of 13 mg/L. The highest concentrations were detected in monitoring bores within the main irrigation areas.

Strontium was detected in all samples, with concentrations ranging from 0.069 mg/L to 1.6 mg/L. Strontium was well correlated with salinity (r^2=0.94).

With the exception of boron trace metal concentrations are believed to be naturally occurring and are mainly derived from clay minerals and metal oxides and hydroxides.

Nutrients

Ammonia was detected in all samples, with concentrations ranging from 0.02 mg/L to 0.7 mg/L. Nitrate was only measured in three samples, and detected in one at a concentration of 0.5 mg/L.

Total and reactive phosphorus concentrations were higher than in the overlying Calivil Formation, reaching maximum concentrations of 0.861 mg/L and 0.716 mg/L, respectively. Higher concentrations may be associated with peat and lignite layers that occur commonly throughout the Renmark Group.

Stable isotopes

Stable isotopes of water, oxygen-18 ($\delta^{18}O$) and deuterium ($\delta^{2}H$), were analysed for selected groundwater samples collected in September to December 2009, and October 2010. Groundwater samples are compared to the Global Meteoric Water Line (GMWL) ($\delta^{2}H = 8.2\delta^{18}O + 10.8$) and a Local Meteoric Water Line (LMWL) for Leeton ($\delta^{2}H = 7.3\delta^{18}O + 11.3$) (Timms 2001) on Figure 9-11. The average surface water sable isotope composition ($\delta^{18}O$ = -4.30‰, $\delta^{2}H$ = -28.0‰) for 2009-2010 is also plotted on this graph (ANU and PB, unpublished).

Eighty-five samples were analysed for stable isotopes in the Renmark Group. Stable isotope values for the Renmark Group ranged from –7.19‰ to -5.98‰ for $\delta^{18}O$, and -45.7‰ to -36.3‰ for $\delta^{2}H$. Groundwater samples from the Renmark Group were generally plotted on or to the left of the GMWL. The most depleted isotopic signatures in the eastern part of the GMA were observed within the deep aquifer.

9.2.2 Processes

9.2.2.1 Shepparton Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 9-13). The wide scatter in samples from the major ion/chloride ratios indicates that multiple processes are influencing groundwater in the Shepparton Formation.

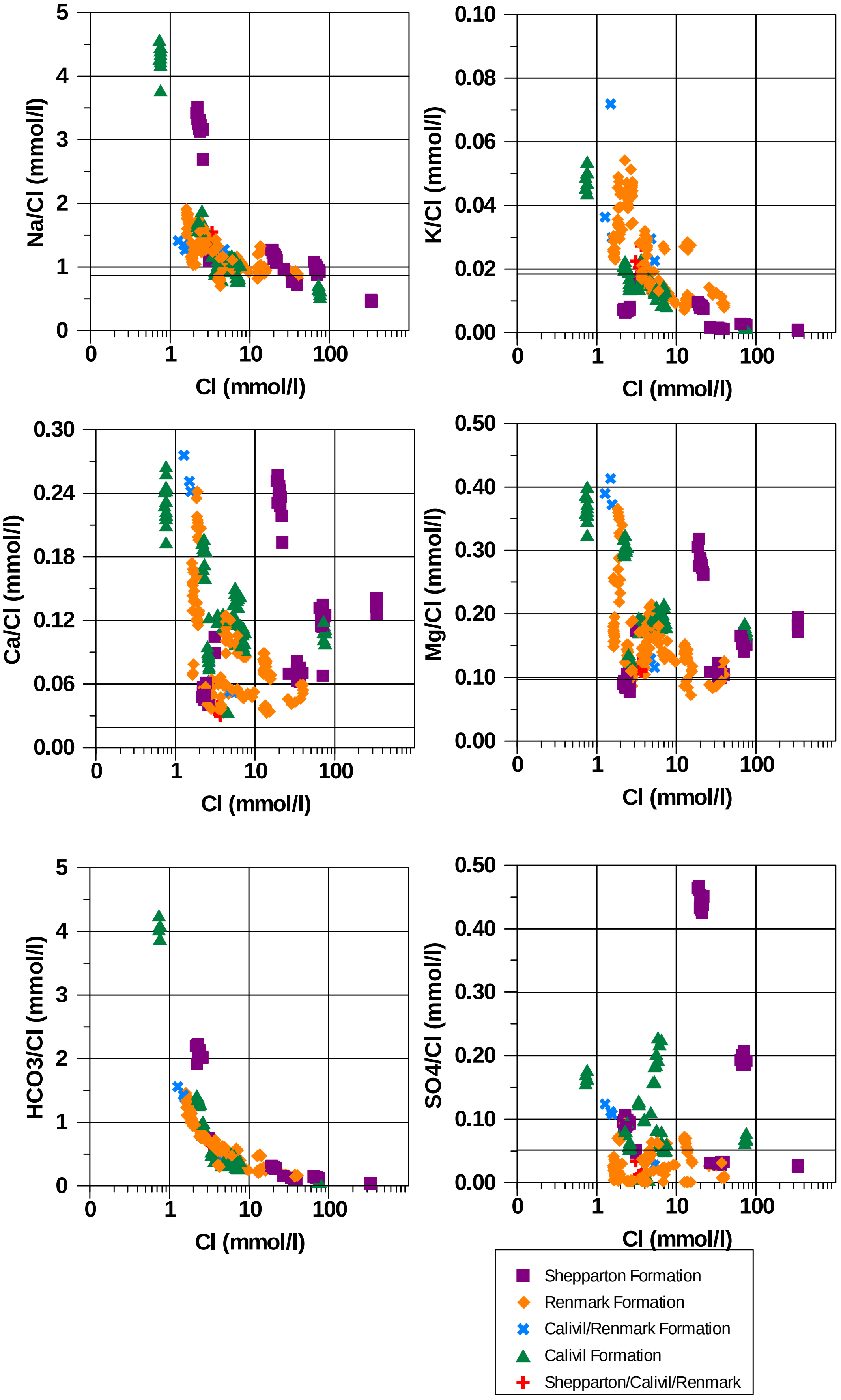


Figure 9-13 Ion/chloride versus chloride graphs for the Lower Murrumbidgee Catchment

In monitoring bores close to the Murrumbidgee River, groundwater has low salinity and Na/Cl above the seawater ratio (0.86). Ratios of Mg/Cl and Ca/Cl are below seawater ratios, which is suggestive that ion exchange is occurring in these parts of the aquifer. The highest salinity groundwaters have Na/Cl ratios below seawater, and Ca/Cl and Mg/Cl above seawater which is indicative or reverse ion exchange. K/Cl ratios are below the seawater ratio (0.018) and HCO_3/Cl concentrations are above the seawater ratio (0.004). Multiple processes including dissolution of carbonates, weathering of aluminosilicates, and redox processes are likely to be contributing elevated HCO_3^- concentrations in the shallow aquifer.

Saturation indices for the Shepparton Formation are plotted in Figure 9-14. Groundwater is oversaturated with respect to quartz and Ca-montmorillonite. Higher salinity groundwater is also oversaturated with respect to calcite, dolomite, K-feldspar and albite. Groundwater is undersaturated with respect to gypsum and anhydrite.

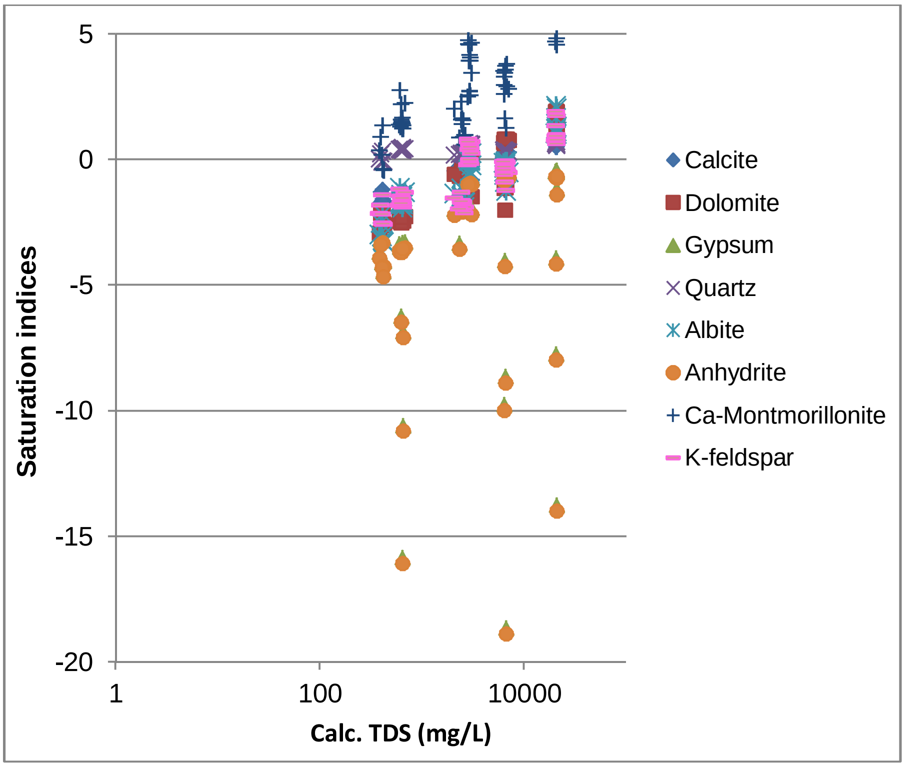


Figure 9-14 Saturation indices versus TDS for the Shepparton Formation

Ion exchange

Figure 9-15 shows the relationship between calcium + magnesium and bicarbonate + sulphate. The most saline groundwater samples in the Shepparton Formation plot above the 1:1 dissolution line, indicating reverse ion exchange is potentially occurring. Reverse ion exchange is typically observed with seawater intrusion, brine contamination or leakage of saline water from aquitards. Timms (2001) clearly defined an increasing trend of Ca^{2+} to Na^+ as groundwater salinity increased at a site in the CIA between 1980 and 1995.

Low salinity samples taken from near the Murrumbidgee River plot below the 1:1 dissolution line, a trend that can be partly attributed to ion exchange.

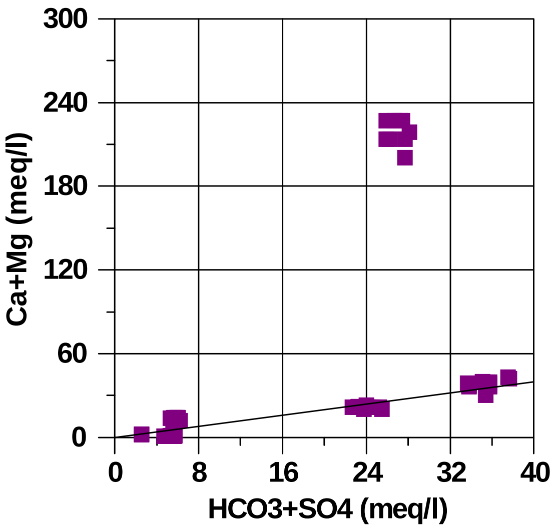


Figure 9-15 Calcium + magnesium versus bicarbonate + sulphate in the Shepparton Formation

Stable isotopes

Groundwater samples from the Shepparton Formation show a broad range of isotopic values; however most samples plot to the right of the GMWL and LMWL. Groundwater samples from GW041011_1 located next to the Murrumbidgee River near Carrathool has an isotopic signature comparable to the average surface water isotopic composition ($\delta^{18}O$ = -4.30‰, $\delta^{2}H$ = -28.0‰) for the Murrumbidgee River, indicating a clear groundwater-surface water connection at this location. A number of samples from the shallow aquifer within the main irrigation areas have an enriched isotopic signature that represents a mix of deeper groundwater and surface water used for irrigation.

9.2.2.2 Calivil Formation

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 9-13). The wide scatter in samples from the major ion/chloride ratios indicates that multiple processes are influencing groundwater in the Calivil Formation.

The highest Na/Cl occurs in the monitoring bores closest to the Murrumbidgee River. Groundwater in these monitoring bores has low salinity and Na/Cl above the seawater ratio (0.86). Ratios of Mg/Cl and Ca/Cl are also above seawater ratios, and weathering of silicate minerals is likely to be occurring due to recharge by river water and shallow groundwater enriched with CO_2. In areas of groundwater recharge, CO_2 hydration results in the lowering of the pH and therefore the reaction capacity of groundwater increases.

Similarly to the Shepparton Formation, the highest salinity groundwater within the Calivil Formation has Na/Cl ratios below seawater, and Ca/Cl and Mg/Cl above seawater which is indicative of reverse ion exchange.

HCO_3/Cl concentrations are above the seawater ratio (0.004), with the highest ratios occurring in monitoring bores closest to the River. Multiple processes including dissolution of carbonates, weathering of aluminosilicates, and redox processes are likely to be contributing elevated HCO_3^- concentrations in the middle aquifer.

Saturation indices in the Calivil Formation are plotted on Figure 9-16. Groundwater is oversaturated with respect to quartz and Ca-montmorillonite. Groundwater is undersaturated with respect to k-feldspar, anhydrite, gypsum and anhydrite. Groundwater is also generally with undersaturated with respect to carbonate and dolomite, with the exception of the anomalous saline groundwater samples.

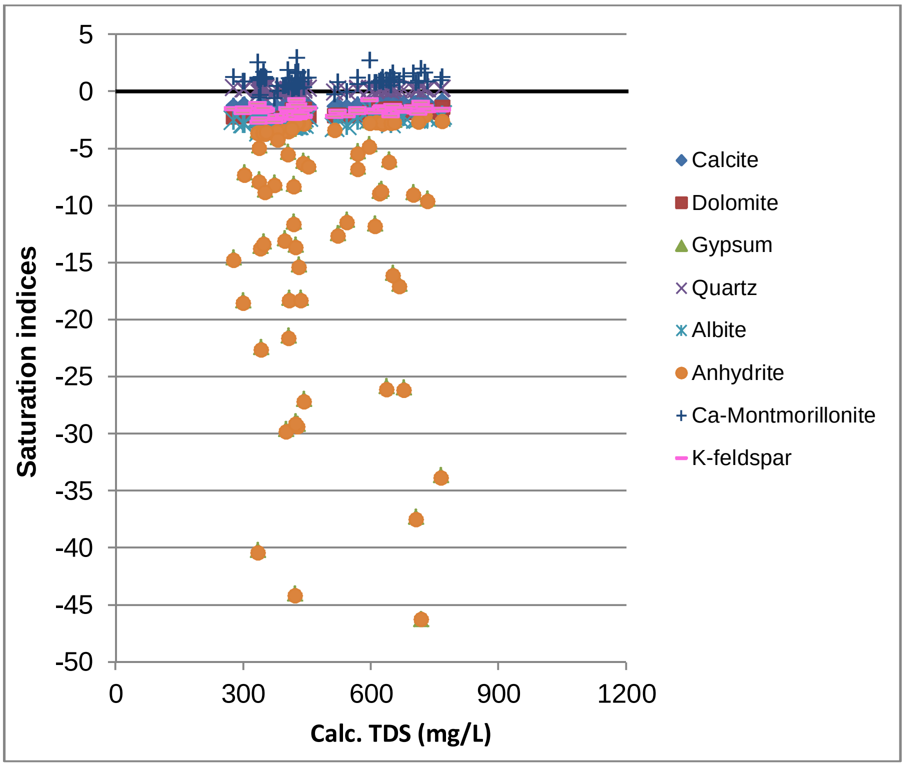


Figure 9-16 Saturation indices versus TDS for the Calivil Formation

Ion exchange

Figure 9-17 shows the relationship between calcium + magnesium and bicarbonate + sulphate. As seen in the overlying Shepparton Formation, the most saline groundwater samples plot above the 1:1 dissolution line, indicating reverse ion exchange is potentially occurring. Low salinity samples taken from near the Murrumbidgee River plot below the 1:1 line, a trend that can be partly attributed to ion exchange.

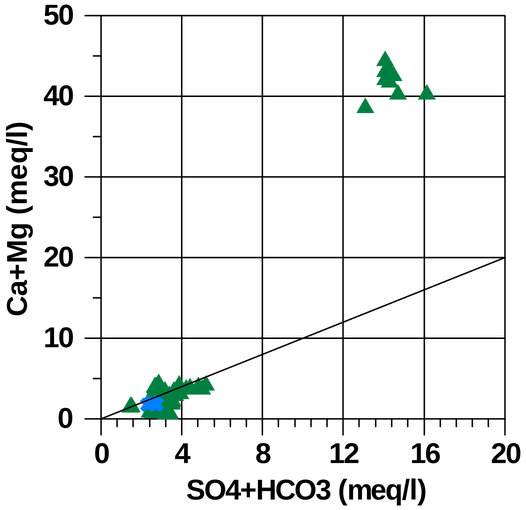


Figure 9-17 Calcium + magnesium versus bicarbonate + sulphate in the Calivil Formation

Stable isotopes

Groundwater samples from the eastern part of the Lower Murrumbidgee catchment plot along an evaporation line with the regression equation of $\delta^2H = 5.28\delta^{18}O + -6.91$. However, given that samples are beyond the depth of active evaporative processes, and no isotopic enrichment trending with increasing salinity (Figure 9-12) is observed, groundwater mixing and recharge under palaeoclimatic conditions is more likely to be responsible for the slope of 5.28, rather than evaporative processes as discussed by Timms (2001).

Geochemical and hydrogeological data and modelling indicates inter-aquifer mixing is occurring. However, the stable isotopic signature of deep groundwater is relatively depleted compared to average modern rainfall which indicates recharge under wetter and cooler climatic conditions. This implies that lateral flow through the aquifer is dominant over vertical leakage. This is supported by the numerical modelling (Section 10) which simulated the observed changes in aquifer salinity by mixing with only a small component of vertical leakage (<0.025% of storage).

9.2.2.3 Renmark Group

Dissolution and precipitation

Major ion/chloride ratios were plotted versus chloride concentration to determine hydrogeochemical processes (Figure 9-13). The majority of groundwater samples in the eastern part of the Lower Murrumbidgee GMA have Na/Cl ratios above the seawater ratio multiple processes are influencing groundwater in the Renmark GroupSimilarly to the Calivil Formation, monitoring bores closest to the river had the highest Na/Cl ratios.

A few monitoring bores located in the main irrigation areas had Na/Cl ratios below seawater ratios suggesting a process such as reverse ion exchange is removing the ions from the system.

West of Hay, groundwater had a seawater Na/Cl ratio, and samples plotted along a straight line (seawater line) with increasing salinity indicating that dissolution of salts or evaporative concentration are the major processes increasing salinity.

The majority of samples have Mg/Cl, Ca/Cl and HCO_3/Cl ratios above seawater ratios. Multiple processes including dissolution of carbonates, weathering of aluminosilicates, and redox processes are likely to be contributing elevated HCO_3^- concentrations in the lower aquifer.

Saturation indices in the Renmark Group are plotted on Figure 9-18. Groundwater is oversaturated with respect to quartz and Ca-montmorillonite. Groundwater is undersaturated with respect to k-feldspar, albite, gypsum and anhydrite. Groundwater is also generally undersaturated with respect to carbonate and dolomite, with the exception of saline groundwater west of Hay.

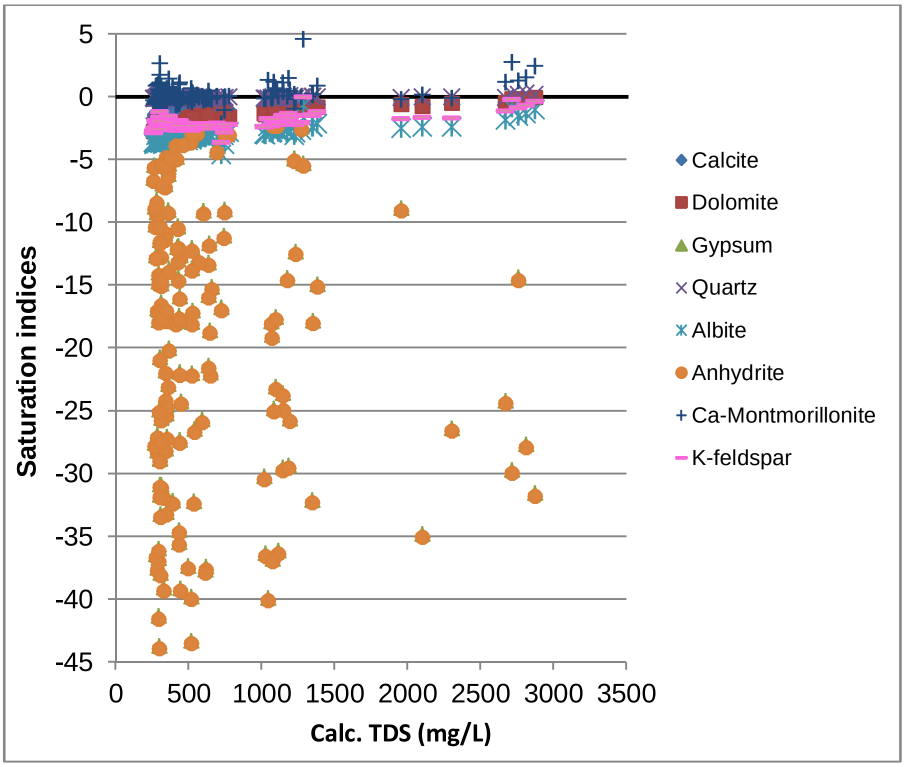


Figure 9-18 Saturation indices versus TDS for the Renmark Group

Ion exchange

Figure 9-19 shows the relationship between calcium + magnesium and bicarbonate + sulphate. A few monitoring bores located in the main irrigation areas plot above the 1:1 dissolution line suggesting a process such as reverse ion exchange is removing the ions from the system. These bores also had an increasing salinity trend. The majority of monitoring bores plot below the 1:1 line, indicating ion exchange may be occurring.

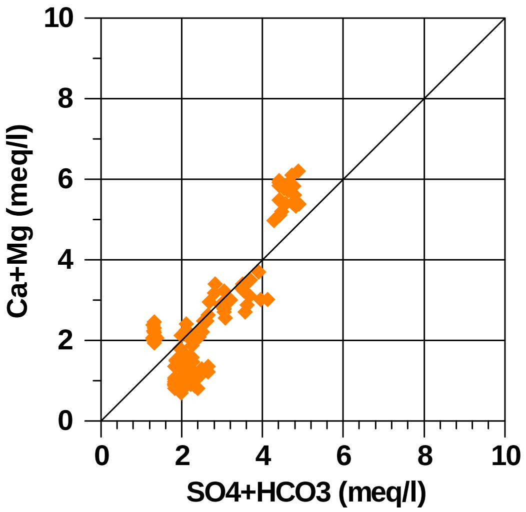


Figure 9-19 Calcium + magnesium versus bicarbonate + sulphate in the Renmark Group

Stable isotopes

Geochemical and hydrogeological data and modelling indicates inter-aquifer mixing is occurring. However, the stable isotopic signature of deep groundwater is relatively depleted compared to average modern rainfall which indicates recharge under wetter and cooler climatic conditions. This implies that lateral flow through the aquifer is dominant over vertical leakage. This is supported by the numerical modelling (Section 10) which simulated the observed changes in aquifer salinity by mixing with only a small component of vertical leakage (<0.025% of storage).

9.2.3 Beneficial use

The risk to groundwater in the Lower Murrumbidgee GMA was assessed by firstly classifying current beneficial use, primarily using EC, and comparing to historical beneficial use. Any areas where the current beneficial use had changed from historical beneficial use are considered “at risk”.

Beneficial use was assessed as per the methodology in Section 2.5.1. The Water Sharing Plan was also used in the assessment of beneficial use for the Lower Murray GMA.

The *Water sharing Plan for the Lower Murrumbidgee Groundwater Sources* defines six objectives, one of which is to ‘protect groundwater quality’.

> ‘37 Water quality management
>
> (1) The beneficial uses of these groundwater sources, based on the beneficial use classes identified in the Australian and New Zealand Environment and Conservation Council Water Quality Guidelines 2001, and the National Health and Medical Research Council Raw Water for Drinking Purposes Guidelines 1996, are

> (a) ecosystem protection and agricultural water for the Shallow Groundwater Source, and
>
> (b) raw water for drinking, ecosystem protection and agricultural water for the Deep Groundwater Source.
>
> Note**:** It is not recommended that the groundwater from these groundwater sources be consumed without prior treatment. Land use activities may have polluted the groundwater in some areas.
>
> (2) Water quality decline will be deemed unacceptable if extraction is likely to cause water quality to decline to a lower beneficial use class.'

Statistical correlation analysis was undertaken between the parameters used to assess salinity and sodicity hazards for irrigation (EC, TDS, Na^+, Cl^- and SAR), and the results are shown in Table 9-5. The correlation analysis shows a strong correlation between EC and TDS, and EC and Na^+, indicating that EC is a good indicator of total salts in the Lower Murray GMA.

Table 9-5 Correlation analysis of parameters used to assess salinity and sodicity hazards, Lower Murrumbidgee GMA

	EC	TDS	Na^+	Cl^-	SAR
EC	1	0.961	0.952	0.981	0.701
TDS		1	0.889	0.975	0.847
Na^+			1	0.907	0.615
Cl^-				1	0.742
SAR					1

The following sections provide a more detailed analysis of water quality and beneficial use classification for the Lower Murrumbidgee GMA based on the Australian Drinking Water Guidelines (2011) and ANZECC (2000) guidelines for Primary Industry.

9.2.3.1 Shepparton Formation

Based on salinity (EC) only, groundwater within the Shepparton Formation in the study area is generally suitable for drinking water or irrigation. There are a couple of exceptions within the main irrigation areas of the CIA and MIA, where groundwater is too saline for irrigation, but may be suitable for stock.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Shepparton Formation monitoring locations are provided in Table 9-6. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Shepparton Formation groundwater exceeds pH, sodium, chloride, sulphate and aluminium in some samples.

Table 9-6 ADWG (2011) values and percentage of samples above guideline values, Shepparton Formation (N=59), Lower Murrumbidgee GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		20
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		76
Potassium (mg/L)				
Chloride (mg/L)	a	250		75
Sulphate (mg/L)	500	250	56	56
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		62	
Aluminium (mg/L)	b	0.2		2
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	0
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

a No health-based value considered necessary; [b] Insufficient data to set a guideline value based on health considerations.

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix H. Groundwater within the Shepparton Formation has SARs ranging from 4 to 18 (average 12), and is therefore classified as having a low to medium sodium hazard (see Table 2-5).

Based on salinity (EC), all samples from the Shepparton formations were suitable for stock water supply. Although, the Shepparton Formation had 14% of samples (n=9) with Ca^{2+} concentrations above the ANZECC (2000) guidelines for stock (<1,000 mg/L) and 21% (n=8) of samples with SO_4^{2-} concentrations above the ANZECC (2000) guidelines for stock (<1,000 mg/L).

9.2.3.2 Calivil Formation

Based on salinity (EC) only, groundwater within the Calivil Formation within the study area (east of Hay) is generally suitable for drinking water. Further out west (west of Hay), groundwater becomes more saline and is suitable for irrigation or stock water supply.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Calivil Formation monitoring locations are provided in Table 9-7. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Calivil Formation groundwater exceeds pH, sodium, chloride, sulphate and manganese in some samples.

Table 9-7 ADWG (2011) values and percentage of samples above guideline values, Calivil Formation (N=85), Lower Murrumbidgee GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		36
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		13
Potassium (mg/L)				
Chloride (mg/L)	a	250		16
Sulphate (mg/L)	500	250	2	12
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		15	
Aluminium (mg/L)	b	0.2		0
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	28
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		0
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix H. Groundwater within the Calivil Formation has a low sodium hazard based on SAR values which range from 2 to 11 (average 5). Based on the ANZECC (2000) guidelines for Na^+ and Cl^- concentrations causing foliar damage (Table 2-6 and 2-7), the majority of samples in the Calivil Formation (90%, n=83), are suitable for irrigation of sensitive to moderately sensitive crops.

Based on salinity (EC), all samples from the Calivil Formation were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

9.2.3.3 Renmark Group

Based on salinity (EC) only, groundwater within the Renmark Group within the study area (east of Hay) is generally suitable for drinking water. Further west (west of Hay), groundwater becomes more saline and is suitable for irrigation or stock water supply.

The ADWG (2011) provide health and aesthetic guideline values for some major ions, metals and nutrients. Guideline values for analytes analysed as part of the monitoring program and the exceedances at the Renmark Group monitoring locations are provided in Table 9-8. Not all chemical parameters have guideline values due to either insufficient data to set a guideline value or no health based guideline value is considered necessary. Renmark Group groundwater exceeds pH, sodium, chloride, aluminium, manganese and ammonia in some samples.

Table 9-8 ADWG (2011) values and percentage of samples above guideline values, Renmark Group (N=168), Lower Murrumbidgee GMA

Analyte	Health guideline value	Aesthetic guideline value	% exceed (health)	% exceed (aesthetic)
pH (pH units)		6.5 – 8.5		56
Calcium (mg/L)				
Magnesium (mg/L)				
Sodium (mg/L)		180		22
Potassium (mg/L)				
Chloride (mg/L)	a	250		23
Sulphate (mg/L)	500	250	0	0
Bicarbonate (mg/L)				
Silica (mg/L)		80		0
Fluoride (mg/L)	1.5		24	
Aluminium (mg/L)	b	0.2		1
Boron (mg/L)	4		0	
Bromide (mg/L)				
Copper (mg/L)	2	1	0	0
Iron (mg/L)	b	0.3		0
Manganese (mg/L)	0.5	0.1	0	31
Strontium (mg/L)				
Zinc (mg/L)	b	3		0
Nitrate (as nitrate) (mg/L)	50		0	
Ammonia (as NH_3) (mg/l)	b	0.5		3
Total Nitrogen as N (mg/L)				
Total Phosphorus (mg/L)				
Reactive phosphorus (mg/L)				

The salinity and sodium hazard for individual bores is shown using the Wilcox diagrams in the Groundwater Quality Report Cards in Appendix H. Groundwater within the Renmark Group has a low sodium hazard, with SARs ranging from 2 to 15 (average of 6). Based on the ANZECC (2000) guidelines for Na^+ and Cl^- concentrations causing foliar damage (Table

2-6 and 2-7), the majority of samples in the Renmark Group (80%, n=134), are suitable for irrigation of sensitive to moderately sensitive crops.

Based on salinity (EC), all samples from the Renmark Group were suitable for stock water supply. Major ion, nutrient and metal concentrations for all samples were below the ANZECC (2000) guidelines as listed in Section 2 (Table 2-8).

9.2.4 **Trends**

A detailed analysis of water quality and water level trends was undertaken as per the methods described in Section 2.5.2.The results of these analyses are presented in Tables 9-9, 9-10 and 9-11 for the Shepparton and Calivil formations, and Renmark Group, respectively.

9.2.4.1 Shepparton Formation

Study period trends

During the study period, decreasing salinity trends were observed at two of the six bores monitored in the Shepparton Formation. Both of these monitoring bores were located within the main irrigation areas, one north of the river in the MIA and one south of the CIA. In both monitoring bores, freshening was associated with an increasing water level, with water levels rising by up to 7 m in one of the monitoring bores (GW036773_1). Although slight changes in the relative proportions of major ions were observed, the water type did not change for either bore.

No significant trends in EC were observed at the other monitoring locations. Water levels also showed no significant changes in these monitoring bores.

Long-term trends

Within the Shepparton Formation four monitoring bores had historical water quality data. No significant trends in salinity (EC) were observed in three out four monitoring bores. At one bore, GW036773_1 located east of Colleambally, a decreasing salinity trend was observed. Hydrographs show that there is a hydraulic connection between shallow and deep aquifers at this location. Seasonal drawdowns are observed in all aquifers and long-term recovery water levels have declined by ~7 m. Occasional changes in vertical hydraulic gradients have been observed. Assuming the decreasing salinity is associated with mixing with groundwater from deeper aquifers (either through change in vertical hydraulic gradient or recharge of irrigation water) the current composition comprises about 10% Calivil groundwater.

Beneficial use trends

The current beneficial use classifications are comparable to historical classifications for the Shepparton aquifer.

Table 9-9 Short- and long-term trends, Shepparton Formation, Lower Murrumbidgee GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030350_1	2	ID	ID	ID	ID	ID	7	-	-	-	-	-	-
GW036773_1	13	Decrease	4,030	3,980	3		22	-	-	-	-	-	-
GW041011_1	12	-	-	-	-	-	13	-	-	-	-	-	Na-HCO3-Cl to Na-Cl
GW041012_1	14	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW273040_1	12	Decrease	10,440	9,170	-75	-12	ND	ND	ND	ND	ND	ND	ND
GW273041_1	9	Decrease	32,800	31,500	5	-4	10	-	-	-	-	-	-

Note: ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

9.2.4.2 Calivil Formation

Study period trends

During the study period, increasing salinity trends were observed in 3 of the 13 bores screened in the Calivil Formation. Two of these bores were located north of the Murrumbidgee River, and one south of the river and Colleambally. During the monitoring period groundwater drawdown only occurred during late 2009/early 2010 and water levels increasing from January 2010. Rising water levels occurred at all three locations over the monitoring period, with maximum water level increases of up to 10 m. Salinity increases did not result in a change of the relative proportion of major ions and therefore a change in water type did not result from the increase in salinity.

No significant trends in EC were observed at the other monitoring locations.

Long-term trends

Within the Calivil Formation, two monitoring bores had long-term increasing trends in salinity (EC). Monitoring bore GW036358_1 is located west of Darlington Point. The hydrographs for this monitoring bore show declining trends with seasonal drawdowns of up to 25 m is observed. Seasonal fluctuations have decreased since 2007 due to changes in local impact management rules and wetter climatic conditions. Although the Shepparton Formation is not monitored at this location, a nearby monitoring bore (GW273040_1) screened in the Shepparton Formation, indicate the groundwater is saline in the shallow aquifer (average 9,170 µS/cm). Optimised mixing calculations undertaken suggest that at GW036358_1, approximately 20% of the composition is derived from leakage of saline water from the Shepparton Formation. Reverse ion exchange is occurring as the groundwater salinity increases at this location. Groundwater chemistry has evolved from Na-Mg-Cl-HCO_3 type water to Na-Mg-Cl type water with increasing salinity.

At GW036773_2, the Shepparton and Calivil formations are hydraulically connected. Large seasonal drawdowns are evident in both aquifers and leakage from the Shepparton Formation with average EC of 3,930 µS/cm (2009–2011) may be contributing to the increasing salinity in the Calivil Formation (average EC 1,040 µS/cm).

Beneficial use trends

The current beneficial use classifications are comparable to historical classifications for the Calivil Formation. One exception was observed in a monitoring in the MIA where increasing salinity has resulted in groundwater no longer being suitable for irrigation of all crops including rice.

Table 9-10 Short- and long-term trends, Calivil Formation, Lower Murrumbidgee GMA

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW030323_1	10	Increase	965	1,090	7	13	15	-	-	-	-	-	-
GW036358_1	10	Increase	7,000	8,690	90	24	12	Increase	2,560 (07/79)	8,690	185	239	Na-Mg-Cl-HCO3 to Na-Mg-Cl
GW036358_2	10	-	-	-	-	-	12	-	-		-		-
GW036773_2	13	-	-	-	-	-	21	Increase	765 (02/01)	1,075	10	41	-
GW039406_1	7	-	-	-	-	-	9	-	-	-	-	-	-
GW041011_2	11	Increase	570	622	5	9	12	-	-	-	-	-	-
GW041012_2	14	-	-	-	-	-	ND	ND	ND	ND	ND	ND	-
GW059225_1	3	ID	ID	ID	ID	ID	4	-	-	-	-	-	-
GW273040_2	3	ID	ID	ID	ID	ID	4	-	-	-	-	-	-
GW273041_2	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW400015_1	2	ID	ID	ID	ID	ID	3	ID	ID	ID	ID	ID	ID
GW403205_1*	3	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW500972_1*	2	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID

Note: * Screened across Calivil Formation and Renmark Group; ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

9.2.4.3 Renmark Group

Study period trends

During the study period, increasing salinity trends were observed in 6 out of 23 bores monitored in the Renmark Group. Increasing salinity trends were mainly observed within the CIA near Colleambally and the MIA near Darlington Point. Increasing salinity was also observed in the Lower Renmark unit at Steam Plains and in the Upper Renmark unit west of Hay. Salinity increases did not result in a change of the relative proportion of major ions and therefore a change in water type did not occur in any of the monitoring bores where a salinity increase occurred. At Steam Plains, a slight drawdown occurred during April 2010, however, throughout the rest of the monitoring period the water levels showed an increasing trend. Water levels in Pipe 3 were Pipe 1 and 2 at the start of the monitoring period, however after recovery from pumping in April 2010, reversal of vertical gradients occurred, and leakage of saline groundwater from the overlying aquifers (average EC of 865 µS/cm) may be contributing to the increasing salinity in the lower part of the Renmark Group at this location.

At GW036358 located in the MIA north of the Murrumbidgee River, the difference in water levels between upper Calivil aquifer (Pipe 1) and the deeper Calivil and Renmark aquifers was ~5 m at the start of the monitoring period; however after recovery from pumping (August 2010), there was less than 0.2 m difference in water level between the shallow and deep aquifers. Therefore leakage of saline groundwater from the upper Calivil Formation (average EC 8,106 µS/cm) may be contributing to the increasing salinity in the Renmark Group at this location.

At GW036773 located in the CIA, a reversal in the vertical hydraulic gradient occurred during the monitoring period, and from February 2010, the vertical gradient indicated that groundwater was moving downwards from the Shepparton to the deeper aquifers. Leakage of saline groundwater from the Shepparton Formation (average EC 3,982 µS/cm) and Calivil Formation (average EC 1,040 µS/cm) may be contributing to the increasing salinity in the Renmark Group at this location.

At GW273041_4, the vertical difference in water levels between the Shepparton Formation and Renmark Group decreased from over 25 m in the peak of the irrigation season (January 2010) to ~12 m in January 2011. Increasing salinity may be due to leakage form overlying aquifers. At this location the average EC of the Shepparton Formation is 32,111 µS/cm.

West of Hay, water level in the upper Renmark Group was relatively stable during the monitoring period, and there were no changes in vertical hydraulic gradients. Therefore the reason for the increasing salinity is unclear.

Long-term trends

At GW036358_3, the Renmark Group is hydraulically connected to the overlying Calivil Formation which also has increasing salinity. Optimised mixing calculations undertaken suggest that at GW036358_3, approximately 8% of the composition is derived from leakage of water from the Calivil Formation.

Beneficial use trends

The current beneficial use classifications are comparable to historical classifications for the Renmark aquifer.

Table 9-11 Short- and long-term trends, Renmark Group, Lower Murrumbidgee GMA

	Short-term trends 2009–2011						Long-term trends						
Bore ID	N	EC trend	Initial EC (µS/cm)	Final EC	Rate of change (µS/cm/ month)	% change	n	EC trend	Initial EC (µS/cm)	Final EC* (µS/cm)	Rate of change (µS/cm/ year)	% change	Change in water type
GW030323_2	1	ID	ID	ID	ID	ID	10	-	-	-	-	-	-
GW036211_1	14	Decrease	1,240	697	-30	-44	17	-	-	-	-	-	Na-Mg-Cl to Na-Mg-Cl-HCO3
GW036211_2	14	-	-	-	-	-	15	-	-	-	-	-	-
GW036211_3	16	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW036275_1	2	ID	ID	ID	ID	ID	5	-	-	-	-	-	-
GW036275_2	2	ID	ID	ID	ID	ID	6	Decrease	1,170 (03/78)	1,090	2	-7	-
GW036358_3	12	Increase	769	833	5	8	14	Increase	710 (06/79)	847	5	19	Na-HCO3-Cl to Na-Mg-Cl-HCO3
GW036396_1	12	Increase	1,570	1,785	10	14	13	-	-	-	-	-	-
GW036773_3	14	Increase	577	632	5	10	22	-	-	-	-	-	-
GW036799_2	4	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW036799_3	4	-	-	-	-	-	ND	ND	ND	ND	ND	ND	ND
GW041011_3	12	-	-	-	-	-	13	-	-	-	-	-	-
GW041012_3	14	-	-	-	-	-	15	-	-	-	-	-	-
GW273040_3	9	-	-	-	-	-	10	-	-	-	-	-	-
GW273040_4	8	-	-	-	-	-	9	-	-	-	-	-	-
GW273041_3	9	-	-	-	-	-	10	-	-	-	-	-	-

Short-term trends 2009–2011							Long-term trends						
Bore ID	**N**	**EC trend**	**Initial EC (µS/cm)**	**Final EC**	**Rate of change (µS/cm/ month)**	**% change**	**n**	**EC trend**	**Initial EC (µS/cm)**	**Final EC* (µS/cm)**	**Rate of change (µS/cm/ year)**	**% change**	**Change in water type**
GW273041_4	9	Increase	419	443	5	6	10	-	-	-	-	-	-
GW400023_1	5	-	-	-	-	-	5	-	-	-	-	-	-
GW400232_1	N	ND	ND	ND	ND	ND	1	ID	ID	ID	ID	ID	ID
GW401876_1	1	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW404126_1	2	ID	ID	ID	ID	ID	ND	ND	ND	ND	ND	ND	ID
GW036799_1	4	Increase	4,200	5,000	50	19	ND	ND	ND	ND	ND	ND	ND
GW400976_1*	5	Increase	577	631	10	9	ND	ND	ND	ND	ND	ND	ND

Note: *Screened across Shepparton and Calivil formations and Renmark Group; ND: no data; ID: insufficient data for Mann Kendall analysis; - No trend or change; (mm/yy) Date of initial sampling

9.2.5 Risks to groundwater quality

Groundwater levels within the Lower Murrumbidgee GMA showe an increasing trend from the late 1980s to early 1990s. However since the early 1990s water levels have declined with hydrographs in the eastern part of the catchment showing seasonal responses to groundwater extractions since the late 1970s and early 1980s. Localised increases in salinity (EC) have resulted in deterioration of beneficial use in some parts of the three alluvial aquifers.

Salinity is highly variable in the Shepparton Formation, ranging from fresh to saline. There is a lack of historical data available to assess long-term trends in the shallow aquifer. However, short-term trend analysis shows that salinity decreased at a number of monitoring bores in the main irrigation areas (GW036773_1, GW273040_1 and GW273041_1).

Within the Calivil Formation, two monitoring bores show long-term increasing salinity trends (GW036358_1 and GW036773_2). Monitoring bore GW036358_1, located west of Darlington Point, shows the largest increase of EC, with EC increasing by 239% since 1979. This increase in salinity has resulted in a decline in beneficial use at this location. The majority of other bores monitored as part of this study either show no significant trend or have insufficient data for trend analysis.

Within the Renmark Group, one monitoring bore (GW036358_3) shows a long-term increase in EC of 19%. However, this has not resulted in a deterioration of beneficial use. The majority of bores show either no significant long-term increasing trends in salinity, or have insufficient data to assess trends.

10. Numerical modelling to predict groundwater quality change

10.1 Numerical modelling

The NSW Office of Water has constructed and calibrated a 3-layer numerical model for the Lower Murrumbidgee catchment. The model has been updated and developed over a number of years to estimate groundwater levels, flow and net water fluxes between model cells representing key pumping sites and river reaches for the purpose of groundwater management and policy development in the sub-catchment. Because of this main purpose, solute transport was not included in the NOW model. However it was anticipated that output from the numerical model could be coupled with the water quality monitoring data to determine solute fluxes and potentially to predict trends in water quality in key areas.

With reference to the project brief and Parsons Brinkerhoff's proposal, the following broad scope items relate to numerical modelling of solute fluxes and water quality trends:

(1) Couple the groundwater quality monitoring data with output from the numerical model to estimate salt fluxes across the model domain and to assist in the interpretation of hydrochemical processes taking place.

(2) Provide advice as to how numerical modelling can be used to estimate groundwater quality change under planned groundwater management scenarios. Specifically: What technologies and techniques are available for predicting groundwater salinity and quality changes? Can NOW's current model be readily coupled with a solute transport model to predict water quality impacts?

(3) Parsons Brinckerhoff proposed a brief workshop to discuss the adopted approach to mass balance calculations and to discuss other potential options for predicting salinity impacts. A workshop was held at the NOW office in Parramatta on 26 September 2011 and was attended by Mike Williams, David O'Neill, and Don Mampitiya (NOW); Noel Merrick (Heritage Computing) and Stuart Brown (Parsons Brinckerhoff).

Parsons Brinckerhoff was not given access to the groundwater model. However, the model was run by NOW to calculate net groundwater fluxes for each model cell at the location of monitoring and pumping wells for the 2009 to 2020 period (incorporating the 10 year Water Sharing Plan period), and those flux calculations were provided to Parsons Brinckerhoff. The data include the groundwater flux into and out of each cell face (6) as well as fluxes relating to recharge, change in storage, river interactions and evapotranspiration (although no evapotranspiration was noted in the budget data supplied). As such, the data provided could not be used to determine solute fluxes across the model domain, but rather just in the model cells for which data were provided. Furthermore, it was agreed at the workshop that Parsons Brinckerhoff should provide one or more worked examples of mass flux calculations as a proof of concept to make best use of the time and budget allocated to this aspect of the project.

10.2 Mass balance modelling

At the workshop held on 26 September 2011, Parsons Brinckerhoff proposed a method for predicting overall trends in groundwater quality based on the modelled water fluxes at monitored locations and the 2009–2011 monitoring data collected by NOW. The method was agreed in principle as a first-order estimate of water quality trends (as approximated by TDS) that may be driven by regional scale groundwater fluxes assuming that the monitoring water quality is representative of the regional water quality.

The groundwater flux data provided by NOW was presented as the net flux for each cell in each monthly stress period for a total run time of 132 months (11 years) from July 2009 to June 2020. The water quality in terms of the concentration, C (in mg/L) of a solute (or measure of salinity such as TDS) in each cell for the monthly time step ti was calculated as follows (for Layer 2 in this example):

$$C_{L2,t_i} =$$

$$\frac{[(S_{L2,t_{i-1}} \text{x}\, \mathrm{C}_{L2,t_{i-1}}) + (\mathrm{Q}_{INAq} \,\text{x}\, \mathrm{C}_{L2,t_{i-1}}) + (\mathrm{Q}_{INAbv} \text{x}\, \mathrm{C}_{L1,t_{i-1}}) + (\mathrm{Q}_{INBlw} \text{x}\, \mathrm{C}_{L3,t_{i-1}}) + (\mathrm{Q}_{INRIV} \text{x}\, \mathrm{C}_{RIV}) - (\sum Q_{Out} \,\text{x}\, \mathrm{C}_{L2,t_{i-1}})]}{S_{L2,t_i}}$$

Where S is the storage in the cell (cell volume multiplied by assumed porosity – in this case, 0.3); QINAq is the flux into the cell from adjacent cells in the same aquifer (L2); QINAbv is the flux from the cell above (or recharge in the case of Layer 1); QINBlw is the flux into the cell from the cell below (L3); QINRIV is the flux into the cell from a MODFLOW River boundary (only noted in cell R35C82, Layer 1); ΣQOut is the sum of all fluxes out of the cell; C is an estimate of the solute concentration (or TDS, in mg/L) at each of the respective sources, as indicated (derived from monitoring data). Note that the concentration applied to ΣQOut is that of the host cell. The subscripts ti and ti-1 refer to the time step i and the previous time step respectively. This would not be true of fluxes out due to evapotranspiration if EVT was included in the model. The concentration applied to the recharge flux in Layer 1 is assumed to be the average TDS of pumping wells to simulate irrigation induced recharge.

Therefore the calculations are essentially a weighted average of the water quality at each cell at each time-step based on the model-calculated fluxes of groundwater and the estimates of water quality derived from the NOW monitoring data from the relevant source cells. The calculated TDS in each cell and time step is carried forward as the source water quality for the next step so that a net water quality trend is obtained.

Initial TDS for each aquifer unit at each location is based on the observed TDS at the representative monitoring bore in October 2009 or the next closest date, as it was found that there is more complete sampling coverage in October than September 2009. The water quality of recharge in the upper aquifer unit (Shepparton Fm) is assumed to be approximately equal to the average abstraction water quality at each location or an average of the abstraction water quality over the Lower Murrumbidgee sub catchment if no site specific data are available. This follows the assumption that the majority of recharge to the upper aquifer in irrigation areas is essentially infiltration of unmodified irrigation water.

A MODFLOW river boundary was present only in one of the model cell locations assessed (R34C92, L1). For the purpose of modelling, the river water quality was assumed to be 50 mg/L TDS. At this cell location, modelled seepage into the aquifer from the river is amounts to only 0.005% of the upper aquifer storage in the model cell per month and therefore the calculated water quality trends will be relatively insensitive to the river water quality.

It is worth noting that no terms for reactive transport or retardation are included, as such analysis is beyond the scope of this exercise. In addition, groundwater mass transfer and mixing is assumed to be instantaneous and the aquifer cells homogenous with respect to the estimated water quality. All of these assumptions are obviously questionable in light of results of the monitoring presented in this report, as is discussed elsewhere in this report.

10.3 Results

TDS trends can only be calculated where there are sufficient monitoring data for each source cell (monitoring in each of the three aquifer units). This was found to be the case in only five of the 15 modelled cell locations. The simulated trends in groundwater TDS in each aquifer for the 11 year period between 2010 and 2021 at those five model cell locations are plotted in Figures 10-1 and 10-2. Also shown in Figures 10-1 and 10-2 are observed TDS values at representative monitoring bores for the monitoring period September 2009 to January 2011. A summary of the main input parameters and calculated trends (in mg/L per year) is shown in Table 10-1. Significant adverse trends and freshening trends (> ±10 mg/L/yr) assuming porosities of 0.3 and 0.2 are highlighted.

A Microsoft Excel spreadsheet containing the calculations accompanies this report (Appendix I). The spreadsheet has been constructed so that key input parameters such as source water quality and aquifer porosity can be varied within the "Inputs" worksheet and the graphs and summary data on the same worksheet will automatically update.

Table 10-1 Calculated trends in groundwater quality at selected locations

Bore ID	Model Row/column	Aquifer	Initial TDS (mg/L)	Recharge TDS (mg/L)	TDS Trend (mg/L per yr) Porosity = 0.3	TDS Trend (mg/L per yr) Porosity = 0.2
GW273040	R30C99	Shepparton	7000	390	-42.6	-62.5
GW404126		Calivil Fm(L2)	590		**24.3**	**35.4**
		Renmark Fm	580		6.5	**12.8**
GW036358	R33C102	Shepparton	5000	390	-1.2	-1.8
		Calivil Fm(L2)	350		**10.2**	**15.1**
		Renmark Fm	430		0.0	0.0
GW041012	R34C92	Shepparton	470	340	-1.1	-1.7
GW400023		Calivil Fm(L2)	240		0.6	0.9
		Renmark Fm	250		0.0	0.0
GW041011	R35C83	Shepparton	2500	390	-0.6	-1.0
		Calivil Fm(L2)	320		1.7	2.6
		Renmark Fm	380		0.0	0.0
GW036773	R51C108	Shepparton	2800	390	-11.2	-16.7
GW039406		Calivil Fm(L2)	520		5.6	8.1
		Renmark Fm	350		0.0	0.0

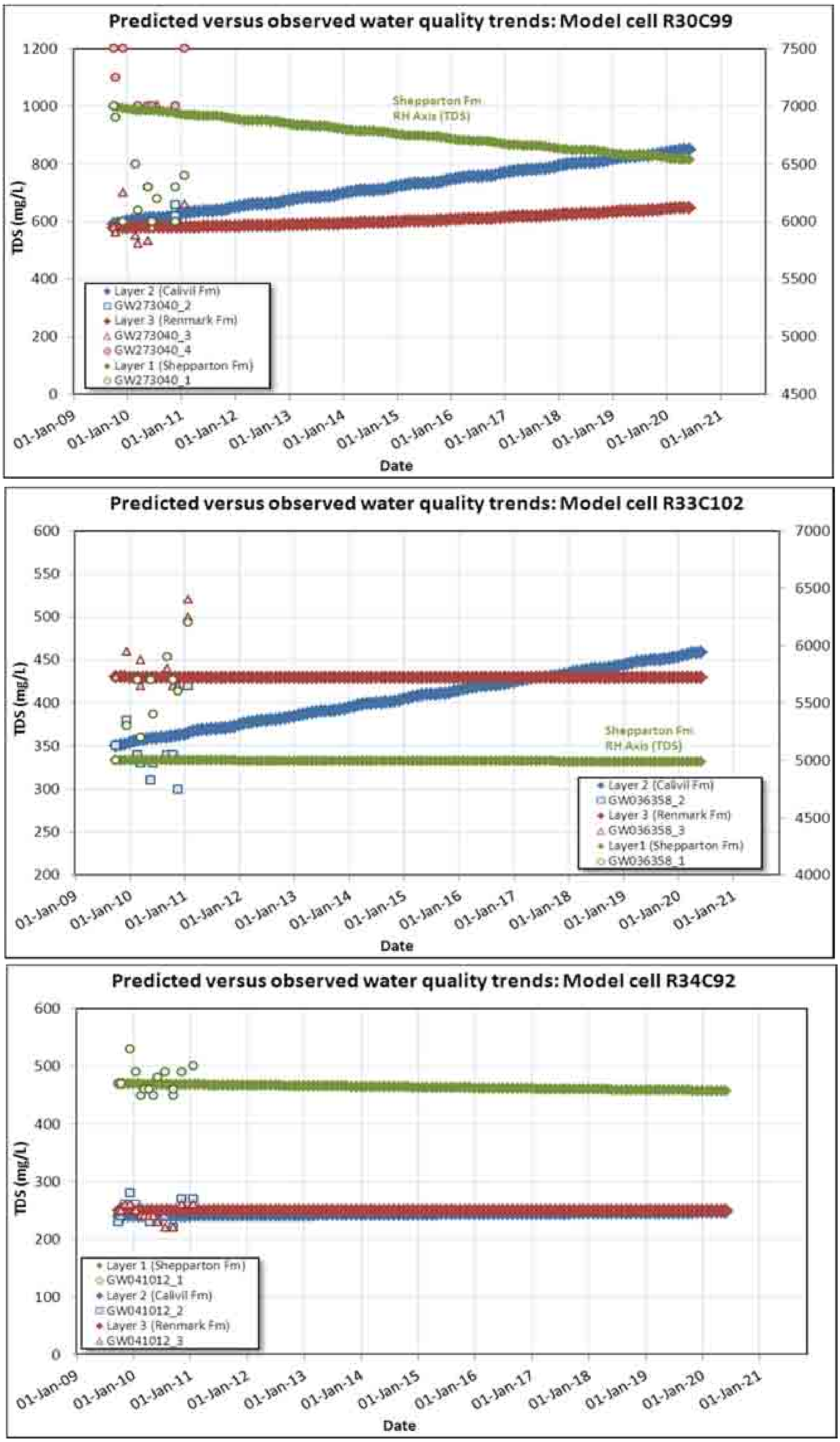


Figure 10-1a Predicted trends in groundwater quality (assuming Porosity of 0.3)

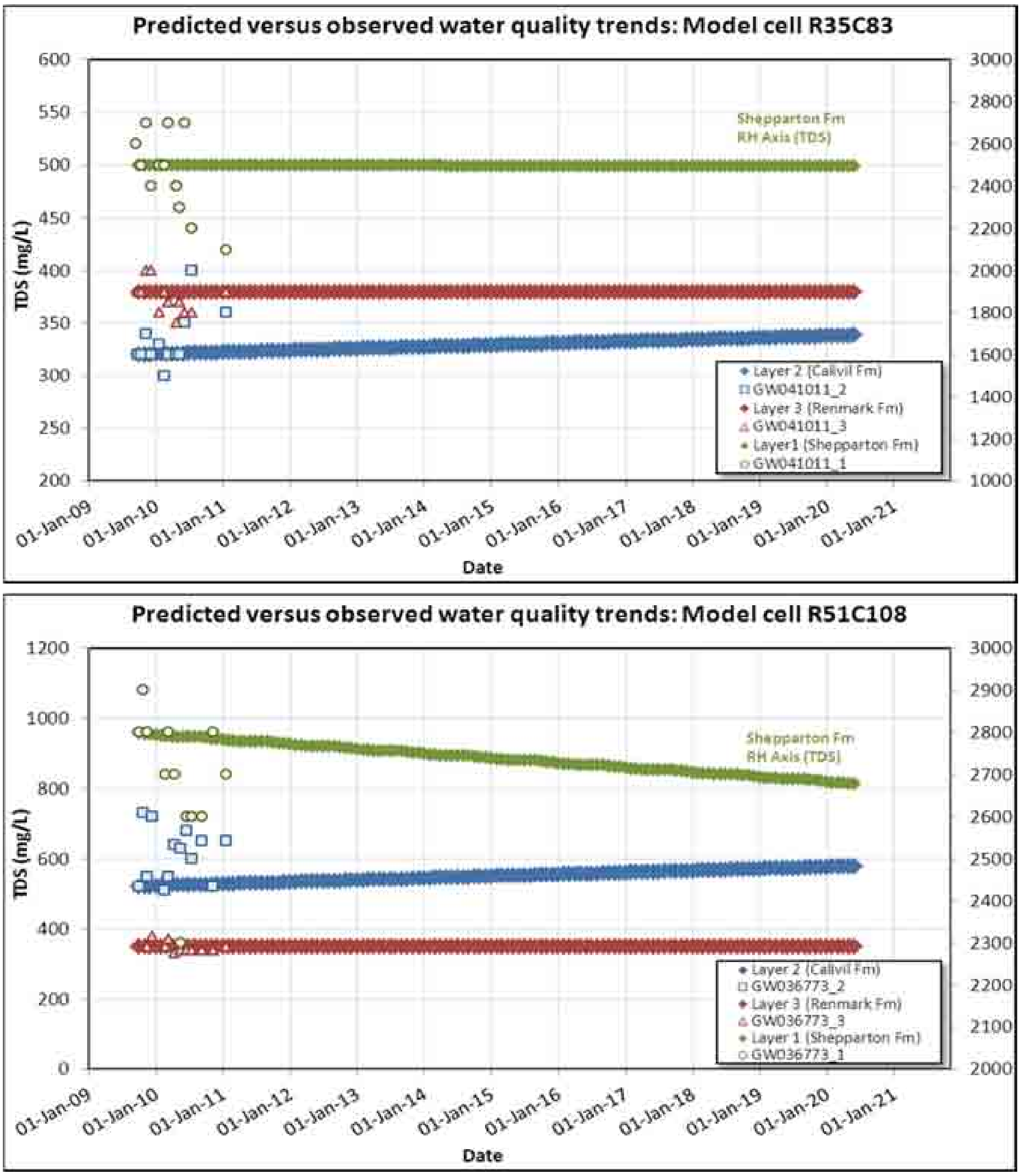


Figure 10-1b Predicted trends in groundwater quality (assuming Porosity of 0.3)

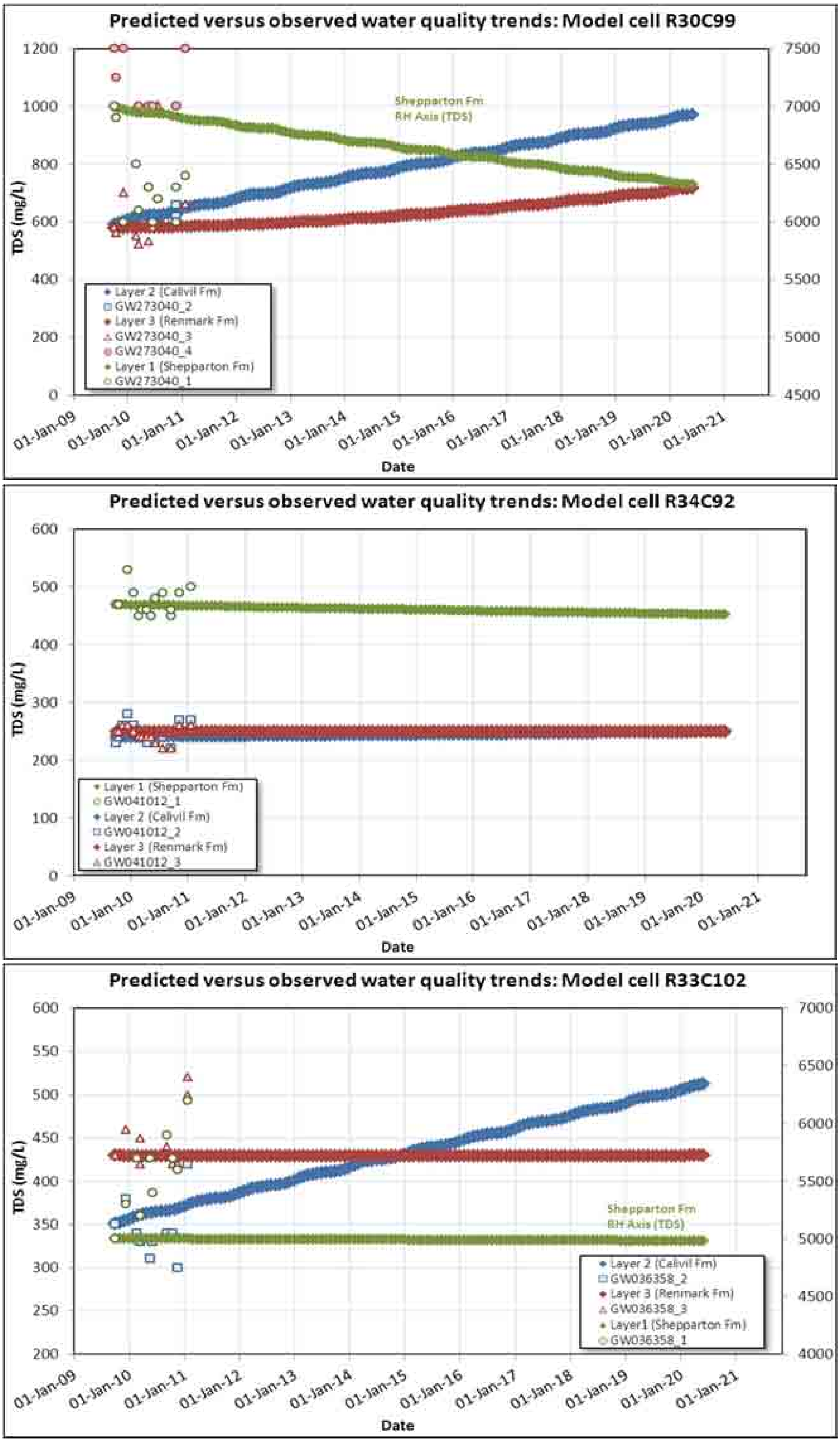


Figure 10-2a Predicted trends in groundwater quality (assuming Porosity of 0.2)

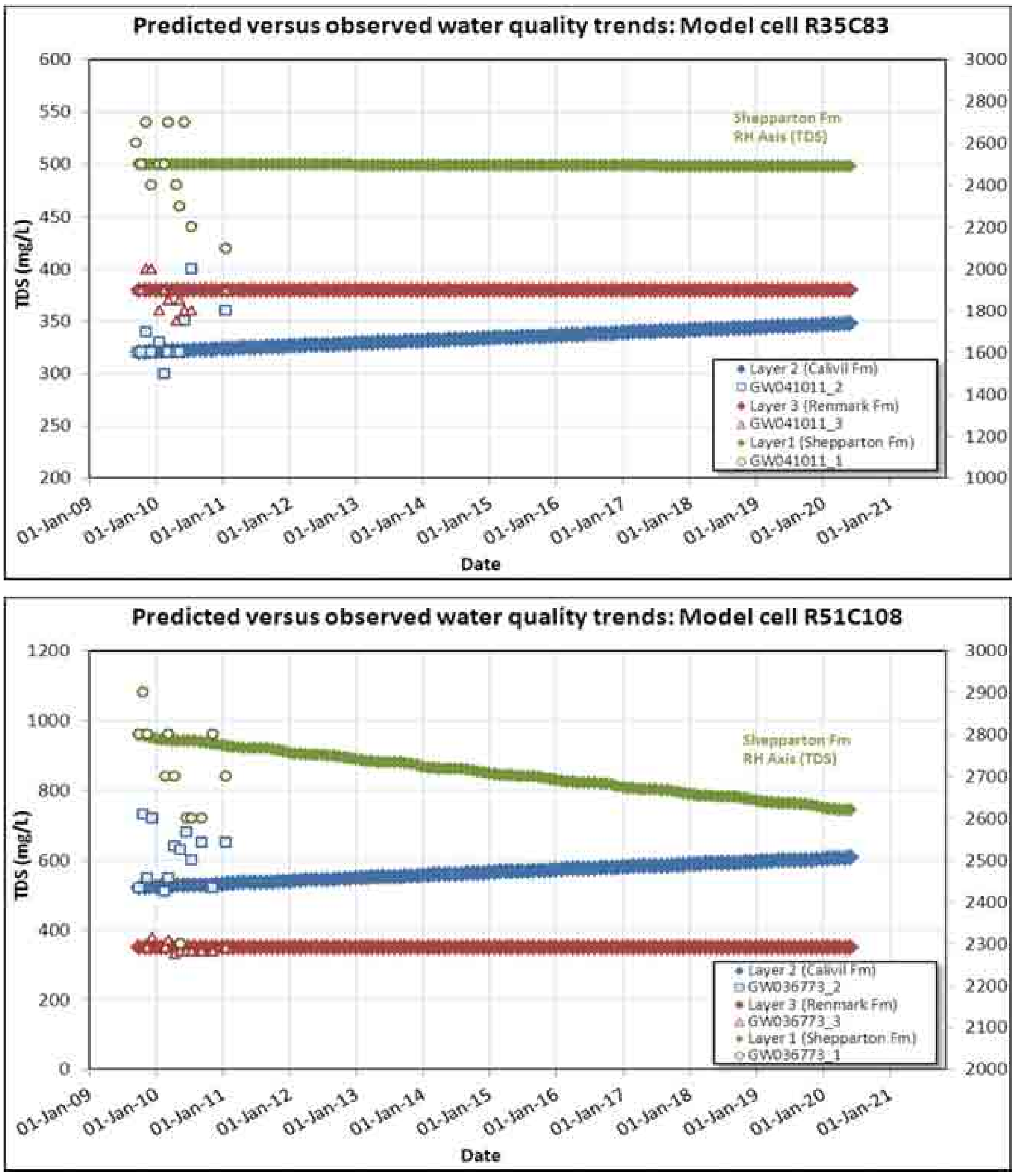


Figure 10-2b Predicted trends in groundwater quality (assuming Porosity of 0.2)

With reference to the calculated groundwater quality trends presented in Figure 10-1 and Table 10-1, the following observations were made:

- The most pronounced adverse trends in water quality occur in Layer 2 (Calivil Fm) at locations where there is both a high downward flux from Layer 1 (Shepparton Fm) and poor water quality in Layer 1. This is most apparent at model locations R30C99 and R33C102 where groundwater TDS is predicted to increase by 24.3 mg/L and 10.2 mg/L per year (or 243 mg/L and 102 mg/L over the 10 year WSP period). These trends imply that there is potential for water quality to transgress and exceed the drinking water quality guideline (800 mg/L TDS) at model location R30C99 within the 10 year Water Sharing Plan period, and perhaps at other locations over longer timeframes.

- The calculations imply that groundwater quality may improve over time in the more saline upper aquifer (model layer 1; Shepparton Fm) due to the relatively high modelled flux of irrigation water recharge. The freshening effect is most pronounced at model location R30C99 where the TDS may decline by 42.6 mg/L per year (426 mg/L in 10 years).

- Other locations and aquifers show more subtle trends that are unlikely to be detectable above natural variations over a ten year WSP period, but may be important over longer periods.

- In many cases the observed groundwater TDS at representative monitoring bores over the 2009–2011 monitoring period shows significant scatter about the predicted trend line with either no apparent trend or one that diverges from the predicted trend. This suggests that local scale aquifer properties and hydrochemical processes control water quality over the short to medium term (seasonal / yearly) and that many more years of data would be required to demonstrate a statistical trend of the magnitudes predicted.

10.4 Sensitivity

Predicted water quality trends are sensitive to the magnitude of the groundwater flux relative to the initial aquifer storage as well as the initial concentrations (TDS) selected for each source. The initial storage estimate is reliant on an estimate of the aquifer porosity and therefore the predicted trend line gradient is sensitive to the estimate of porosity also. To determine the sensitivity of the water quality trend predictions to the estimated porosity, the mass flux analysis was run with porosity (for all aquifers) set at 30% (0.3) and 20% (0.2). Results of both runs are included in Table 10-1 and Figures 10-1 and 10-2. Because the aquifer storage term is by far the dominant term in the mass flux equation, an increase in porosity of 50% (from 0.2 to 0.3) results in a decrease in the predicted water quality trend of a similar magnitude (~ 50%).

Some of the apparent trends in TDS noted in the monitoring (e.g. possible adverse trend in GW041011_2 and a possible freshening trend in GW041011_1) cannot be matched by varying the estimate of porosity within a realistic range, further suggesting that mechanisms other than simple mass flux and mixing control groundwater quality at some locations.

10.5 Limitations

The mass balance approach to predicting trends in groundwater quality presented here is certainly useful in identifying areas within the sub-catchment that may be at risk of increasing salination due to regional groundwater flow and abstraction-induced fluxes over long time-frames. In particular, out of the five locations assessed in this study, the method indicates potential risks in the Calivil Formation in the areas represented in the groundwater model by cells R30C99 and R33C102. The method may be of further use in assessing the relative impact of different pumping regimes on the salt flux and potential salinity trends on a sub-regional scale.

However there are some significant limitations to the approach which make it ineffective for predicting groundwater quality over shorter time-frames and in relation to individual monitoring points:

(1) The mass balance model is based on fluxes generated from a regional scale numerical model with a cell size of 2.5 km whereas the aquifers are known to be heterogeneous at smaller scales than this.

(2) Hydrochemical processes other than simple mixing are likely to control some aspects of the groundwater quality (e.g. ion exchange, mineral dissolution and precipitation). In addition, salt stored in aquitard units may play an important part in solute transport. These processes will also operate a range of scales.

(3) The mass balance model assumes instantaneous transfer of mass and efficient mixing of groundwaters in each monthly time step. In reality groundwater fluxes and solute transport may be delayed significantly by aquitard layers. These delay effects may perturb any long-term trends. The magnitude of the delay would be dependent on the thickness, distribution and hydraulic properties of the aquitard (Ali et al., 2004).

(4) Due to a combination of some or all of these effects and the natural variability of groundwater quality on a local scale, it may not be possible to verify trends in groundwater quality for several years or decades.

10.6 Future directions

On the basis of discussions during the modelling workshop held on the 26 September 2011, and insights gained during the course of this project, the following recommendations are made for future efforts to assess long-term trends in groundwater quality.

- Mass balance approaches, despite their limitations on a local scale, do provide a means to assess potential trends in water quality on a subregional scale, based on calibrated groundwater fluxes and estimated of existing salinity distributions from monitoring data. Based on the limited analysis carried out in this study it would be worth incorporating a mass flux analysis step similar the approach used here each time the catchment numerical model is run in order to identify areas that are at risk of deteriorating water quality under the assumed abstraction rates of the proposed water sharing plan.

- A second option would be to couple a solute transport module such as MT3DMS to the existing regional MODFLOW model to provide estimates of solute fluxes and salinity trends at key locations at the same time that the model is run for groundwater flow and level predictions. The predictive ability and limitations of such a model would be similar to the mass balance approach tested here, since it would be essentially based on the same data and fluxes. Experience at other catchments (e.g. Merrick et al. 2005) suggests that calibration of such solute models can be problematic and time-consuming in the absence of detailed data on initial salt distributions and, ultimately, may not provide superior results to flux/mass balance calculations.

- Some of the trends noted in the 2009–2011 monitoring data indicate local variability in water quality that is an order of magnitude greater than that of the relatively subtle trends predicted from the mass balance approach. In order to model these groundwater quality trends effectively, it will be necessary to improve our conceptual understanding of the groundwater flow and reactive transport mechanisms that operate on those local scales. This may require more targeted aquifer characterisation studies and monitoring at key locations which would include core logging and analysis, aquifer testing and multi-level piezometer installations. The combination of detailed aquifer characterisation with hydrochemical and isotopic analysis would allow the identification (or exclusion) and quantification of solute transport processes and the refinement of conceptual models of salination in the important irrigation areas of the catchment.

11. Key findings and recommendations

11.1 Data quality

Key Finding – None of the catchments were monitored for the full 18 months and the number of bores sampled during monitoring events varied. These data gaps affected the ability to assess water quality trends and identify risks to groundwater quality. The data collected from the Lower Macquarie catchment were inadequate to assess trends and identify risks.

Recommendation 1 – Where a groundwater quality monitoring program is established for a catchment, it should be implemented as planned. This will ensure adequate data is collected to assess trends and identify risks to groundwater quality.

Recommendation 2 – Install dedicated sampling equipment (micropurge pumps) and water level loggers in monitoring bores, particularly those located in high risk areas. This will improve adherence to planned groundwater monitoring programs and increase the quantity and quality of data collected.

Recommendation 3 – Monitor baseline groundwater quality in the Lower Macquarie catchment to assess water quality trends and risks to groundwater quality (refer to Table 11-1 for details).

Table 11-1 Baseline monitoring for the Lower Macquarie

	Baseline program
Frequency	Monthly
Duration	18 months
Parameters	Groundwater level, major ions, metals, nutrients, stable isotopes
Bores	Monitoring bores and production bores
Number of locations	Minimum of five (5) in each aquifer, preferably at nested locations
Location	Close to main irrigation areas
Aquifers	Narrabri, Gunnedah and Cubbaroo formations

Key Finding – The data quality review identified a number of issues with the accuracy of the data in the TRITON database and the sampling techniques used during the 2009–2011 groundwater monitoring program.

Recommendation 4 – Review database entry and database management processes to identify areas for improvement.

Recommendation 5 – Hold a workshop to train (or provide revision for) staff monitoring groundwater to ensure appropriate groundwater sampling, sample handling and sample transport techniques are used as per Parsons Brinckerhoff (2009).

> *Recommendation 6* – Regularly audit groundwater monitoring programs. This may include auditing field staff during monitoring or reviewing field notes and laboratory analytical reports. Frequently auditing groundwater monitoring programs will ensure early detection of issues and improve the quality of data collected.

11.2 Early detection of risks to beneficial use

Key Finding - The results indicate that changes in beneficial use have occurred at bores in the Upper Namoi, Lower Namoi, Lower Murray and Lower Murrumbidgee since monitoring began. The results also indicate there are increasing trends in salinity at bores in all catchments (except the Lower Macquarie where there was insufficient data for analysis).

> *Recommendation 7* – Monitor groundwater level and quality quarterly in moderate to high risk aquifers and annual groundwater level and quality monitoring in low risk aquifers to provide for early detection of deterioration in beneficial use (refer to Table 11-2). Moderate to high risk aquifers are defined as aquifers at risk of deterioration in beneficial use. Low risk aquifers are defined as aquifers of low beneficial use and/or aquifers at low risk of deterioration in beneficial use.

Key Finding – The results indicate that major ion chemistry is well correlated with salinity in all six catchments.

> *Recommendation 8* – Use EC and SAR as key indicators of deterioration in beneficial use (refer to Table 11-2) and develop catchment-specific triggers for EC and SAR against which monitoring results can be compared. The actions to be taken when triggers are exceeded would be developed as part of the WSP process. One of the actions should be to instigate a more comprehensive monitoring program to better define trends and understand the processes leading to changes in groundwater quality (refer to Table 11-2).

Table 11-2 Groundwater monitoring strategy

	Moderate to high risk aquifers*	Low risk aquifers^
Standard program	Quarterly - Groundwater level, EC and SAR Annual – Major ions, metals, nutrients	Annual - Groundwater level, EC and SAR
Enhanced program where triggers exceeded	Monthly – Groundwater level, EC and SAR Quarterly – Major ions, metals, nutrients	Quarterly – Groundwater level, EC and SAR Annual – Major ions, metals, nutrients
Bores	Monitoring bores (no production bores)	Monitoring bores (no production bores)
Number of locations	Minimum of five (5) in each aquifer to be monitored, preferably at nested locations	Minimum of five (5) in each aquifer to be monitored, preferably at nested locations
Location and aquifers	• Upper Namoi Zone 3 – Gunnedah • Lower Namoi around Cryon – Gunnedah and Cubbaroo • Lower Murray – Shepparton, Calivil and Renmark • Lower Murrumbidgee MIA and CIA – Shepparton, Calivil, Renmark	• Upper Namoi Zone 3 – Narrabri • Lower Namoi around Cryon – Narrabri • Lower Lachlan – Calivil and Renmark • Lower Murrumbidgee outside the MIA and CIA – Shepparton, Calivil, Renmark

* Moderate to high risk aquifers include aquifers at risk of changes in beneficial use, for example due to increasing trends in salinity

^ Low risk aquifers include aquifers of low beneficial use and aquifers at low risk of deterioration in beneficial use

Key Finding – The results indicate that water quality hotspots, where groundwater quality is deteriorating, exist within aquifer systems. Water quality hotspots may form due to heterogeneity of aquifer stratigraphy; complex physical and chemical aquifer interactions; seasonality of pumping regimes; variation in the local intensity of groundwater extraction; and/or climatic variability.

> *Recommendation 9* – The bores selected for monitoring networks should include bores targeting water quality hotspots, as well as bores outside water quality hotspots, so that the spatial patterns of hotspot trends within the context of the broader catchment can be explored. The current study identified water quality hotspots at the bores in Table 11-3 based on long-term trends in water quality.

Table 11-3 Water quality hotspots

Catchment	Aquifer	Locations identified as water quality hotspots
Upper Namoi	Narrabri Formation	None
	Gunnedah Formation	GW036038, GW036166, GW036213
Lower Namoi	Narrabri Formation	GW036040
	Gunnedah Formation	GW036314, GW036320, GW036340, GW036364
	Cubbaroo Formation	GW036398, GW036406
Lower Macquarie	Gunnedah Formation	Inadequate data
	Cubbaroo Formation	GW030215, otherwise inadequate data
Lower Lachlan	Calivil Formation	None
	Renmark Group	Inadequate data
Lower Murray	Shepparton Formation	GW036283, GW036876, GW036587, GW036743
	Calivil Formation	GW036283, GW036584, GW036585, GW036586, GW036588
	Renmark Group	GW036587, GW036743, GW036744
Lower Murrumbidgee	Shepparton Formation	None
	Calivil Formation	GW036358, GW036773
	Renmark Group	GW036358

Key Finding – The scope of this study was defined by the aquifers and bores selected by the NSW Office of Water and, as such, the recommended monitoring program is focused on these areas. It is recognised that risks to groundwater quality may occur in other parts of the aquifers studied and in other groundwater systems across the state.

> *Recommendation 10* – Make a statewide review of groundwater quality in aquifer systems across the state at regular intervals to ensure that ongoing groundwater monitoring programs target the aquifer systems at highest risk of deterioration in groundwater quality. These reviews may be similar to 'key sites' annual programs.

11.3 Understanding processes driving changes in groundwater quality

Key Finding – The results indicate that within aquifer systems there is substantial variability in groundwater chemistry and that changes in groundwater chemistry have occurred since monitoring began. However, the processes leading to these changes could not be conclusively determined as some end members were not monitored and aquifers were not clearly defined.

> *Recommendation 11* – Monitoring of end members, including surface water, irrigation water, pore water from aquitards, shallow aquifers, adjacent aquifers and underlying bedrock aquifers should be undertaken in future monitoring programs to better characterise and understand the hydrogeochemical processes leading to changes in water quality.

Key Finding – The results indicate that increasing trends in salinity in productive aquifers are due to leakage of saline groundwater from shallow aquifers at some locations. Leakage of saline groundwater from shallow aquifers occurs where productive aquifers are depressurised and aquitards are thin or absent.

> *Recommendation 12* – Delineate the extent and continuity, and investigate the thickness and permeability, of clay aquitards underlying shallow saline aquifers, particularly where they overlie fresh aquifers. This will improve understanding of where risks to groundwater quality exist.

Key Finding – The results indicate that increasing trends in salinity in productive aquifers may be due to leakage of saline pore waters from clay aquitards at some locations. Leakage of saline pore waters from aquitards may occur due to aquifer depressurisation.

> *Recommendation 13* – Undertake a research program to improve understanding of the physical and chemical properties of aquitards and associated pore waters. This might involve collecting core samples for laboratory testing, installing monitoring bores in aquitards, and mapping aquitards using geophysics and numerical modelling.

11.4 Predicting future changes in groundwater quality using numerical modelling

Key Finding – The modelling trial indicated that, despite a number of limitations on local scales, mass balance approaches provide a means to assess potential trends in water quality on a subregional scale, based on calibrated groundwater fluxes and estimates of existing salinity distributions from monitoring data.

> *Recommendation 14* –When the catchment numerical model is run as part of the WSP review process , carry out a mass flux analysis step similar to the approach used in this study to identify areas at risk of deteriorating water quality under the assumed abstraction rates of the proposed WSP,.

Key Finding – Analysis of solute fluxes is only possible where there are adequate estimates of groundwater quality from monitoring in all adjacent aquifers at each location. In the Lower Murrumbidgee, modelling could only be undertaken at five locations due to limitations in the existing monitoring network.

> *Recommendation 15* – Augment the existing groundwater monitoring network by installing piezometers in non-productive aquifers that are next to existing piezometers that are screened within productive aquifers.

Key Finding – To model local groundwater quality trends more effectively using hydrogeochemical process-based models, it is necessary to improve our conceptual understanding of groundwater flow and reactive transport mechanisms that operate on those local scales.

> *Recommendation 16* – Undertake a research program to improve understanding of solute transport and salinisation mechanisms in high risk areas. In addition to the scope under Recommendation 12, the research could include the use of isotopic dating and tracer techniques to place constraints on groundwater residence times, groundwater fluxes and the origin of solutes.

12. Statement of limitations

12.1 Scope of services

This environmental site assessment report (the report) has been prepared in accordance with the scope of services set out in the contract, or as otherwise agreed, between the client and Parsons Brinckerhoff (scope of services). In some circumstances the scope of services may have been limited by a range of factors such as time, budget, access and/or site disturbance constraints.

12.2 Reliance on data

In preparing the report, Parsons Brinckerhoff has relied upon data, surveys, analyses, designs, plans and other information provided by the client and other individuals and organisations, most of which are referred to in the report (the data). Except as otherwise stated in the report, PB has not verified the accuracy or completeness of the data. To the extent that the statements, opinions, facts, information, conclusions and/or recommendations in the report (conclusions) are based in whole or part on the data, those conclusions are contingent upon the accuracy and completeness of the data. Parsons Brinckerhoff will not be liable in relation to incorrect conclusions should any data, information or condition be incorrect or have been concealed, withheld, misrepresented or otherwise not fully disclosed to Parsons Brinckerhoff.

12.3 Environmental conclusions

In accordance with the scope of services, PB has relied upon the data collected by NSW Office of Water in the preparation of the report. The nature and extent of monitoring and/or testing conducted is described in the report.

On all sites, varying degrees of non-uniformity of the vertical and horizontal soil or groundwater conditions are encountered. Hence no monitoring, common testing or sampling technique can eliminate the possibility that monitoring or testing results/samples are not totally representative of soil and/or groundwater conditions encountered. The conclusions are based upon the data and the environmental field monitoring and/or testing and are therefore merely indicative of the environmental condition of the site at the time of preparing the report, including the presence or otherwise of contaminants or emissions.

Also, it should be recognised that site conditions, including the extent and concentration of analytes, can change with time.

Within the limitations imposed by the scope of services, the interpreting and preparation of this report have been undertaken and performed in a professional manner, in accordance with generally accepted practices and using a degree of skill and care ordinarily exercised by reputable environmental consultants under similar circumstances. No other warranty, expressed or implied, is made.

12.4 Report for benefit of client

The report has been prepared for the benefit of the client (and no other party), but may be relied upon by the NSW Office of Water acting in its capacity as the administering authority. Parsons Brinckerhoff assumes no responsibility and will not be liable to any other person or organisation for or in relation to any matter dealt with or conclusions expressed in the report, or for any loss or damage suffered by any other person or organisation arising from matters dealt with or conclusions expressed in the report (including without limitation matters arising from any negligent act or omission of Parsons Brinckerhoff or for any loss or damage suffered by any other party relying upon the matters dealt with or conclusions expressed in the report). Except as provided below, parties other than the client should not rely upon the report or the accuracy or completeness of any conclusions and should make their own enquiries and obtain independent advice in relation to such matters.

The NSW Office of Water in its capacity as the administering authority may consider and rely upon the report for the purposes of making a decision.

12.5 Other limitations

Parsons Brinckerhoff will not be liable to update or revise the report to take into account any events or emergent circumstances or facts occurring or becoming apparent after the date of the report.

13. References

Ali, A, Merrick, NP, Williams, RM, Mampitiya, D, D'hautefeuille, F and Sinclair, P, 2004, Land Settlement due to Groundwater Pumping in the Lower Namoi Valley of NSW. CD Proceedings, Ninth Murray-Darling Basin Groundwater Workshop, Bendigo, 17-19 February, 2004.

Andersen, MS, Meredith, K, Timms, W and I Acworth. 2008. Investigation of $\delta^{18}O$ and $\delta^{2}H$ in the Namoi River catchment – elucidating recharge sources and the extent of surface water/groundwater interaction. Invited paper to the Annual IAH conference in Toyama, Japan 2008.

ANZECC. 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Environment and Conservation Council.

Australian and New Zealand Standard, AS/NZS 5667.1:1998 Water Quality Sampling

Barrett, C. Williams, RM., Sincalir, P. 2006. Groundwater chemistry changes due to mixing-Lower Namoi Valley, New South Wales. Murray-Darling Basin Workshop, Canberra.

Bell, J. 2007. Cyclic deposition of salt-laden dusts as an explanation of salinization in a groundwater recharge zone, Colleambally Irrigation Area, Riverine Plain, NSW. PhD thesis, University of New South Wales.

Brown, C.M. 1989. Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia,' in *BMR Journal of Australian Geology and Geophysics*, vol.11,pp.127-146.

Clark, I., and Fritz, P. 1997. Environmental Isotopes in Hydrogeology. CRC Press LLC, Bocca Raton, New York, 328pp.

Coram, J. 1999. Groundwater Recharge in the Mooki River catchment, northern New South Wales. Land and Water Sciences Division, Bureau of Rural Sciences Report.

CSIRO 2007, 'Water availability in the Namoi', A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project, CSIRO, Australia.

Dent, B. Merrick, N. Milne-Holme, W. Kelly, B. Yates D. 2007, 'Groundwater Knowledge and Gaps in the Macquarie - Bogan Catchments Central West Management Area', National Centre for Groundwater Management University of Technology, Sydney.

Department of Land and Water Conservation (DLWC) 1999, 'Lower Macquarie Groundwater Management Area 008 Groundwater Status Report', Department of Land and Water Conservation, Central West Region.

Department of Land and Water Conservation (DLWC) 2000, 'Draft Upper Namoi Valley Groundwater Status Report 1999', Department of Land and Water Conservation.

Department of Land and Water Conservation. 1997. The NSW State Groundwater Policy Framework Document. Department of Land and Water Conservation, Sydney.

Department of Land and Water Conservation. 1998. The NSW Groundwater Quality Protection policy. Department of Land and Water Conservation, Sydney.

Department of Primary Industry and Natural Resources (DIPNR) 2004, Draft Upper Namoi Valley Groundwater Status Report, Department of Infrastructure, Planning and Natural Resources, Barwon Region.

Department of Sustainability, Environment, Water, Population and Communities (DSEWPC) 2011, Directory of Important Wetlands in Australia, viewed 9 November 2011, <http://www.environment.gov.au/cgi-bin/wetlands/search.pl?smode=DOIW>.

Drury, L.W., Calf, G.E. & Dharmasiri, J.K. 1984. Radicarbon dating of groundwater in tertiary sediments of the Eastern Murray basin. Australian Journal of Soil research, vol.22, pp.379-387.

Evans, W.R. & Kellet, J.R. 1989. The hydrogeology of the Murray Basin, southeastern Australia. In *BMR Journal of Australian Geology and Geophysics,* vol.11,pp.147-166.

Green, D., Petrovic, J., Moss, P., Burrell, M. 2011, 'Water resources and management overview: Namoi catchment', NSW Office of Water, Sydney.

Hope, M. 2003,'Greater Macquarie Catchment Irrigation Profile', the Water Use Efficiency Advisory Unit, NSW Agriculture.

Horner, K.N., McPhail, D.C. & McLean, W. 2010, 'Quantifying groundwater dynamics in a semi-arid silicate aquifer, Murray Basin, Australia', *XXXVIII IAH Congress Groundwater Quality Sustainability*, University of Silesia Press, Krakow Poland, 12-17 September 2010, pp. 1577-1582

Kellett J.R. 1989. The Ivanhoe Block – its structure, hydrogeology and effect on gorundwaters of the Riverine Plain of New South Wales. BMR Journal 11 (2/3).

Kulatunga N 1999, 'Groundwater Status Report – Murray Valley Alluvium Sediments, GWMA 016', Department of Land and Water Conservation.

Kumar, P.B. 2010. Lower Murrumbidgee Groundwater Sources: Groundwater managemet Area 002 Groundwater Status Report – 2009, NSW Office of Water, Sydney

Lamontagne, S., Taylor, A.R., Cook, P.G., Hamilton, S. 2011b, 'Interconnection of surface and groundwater systems – River losses from losing/disconnected streams: Macquarie River site report', CSIRO: Water for a Healthy Country National Research Flagship, Adelaide.

Lamontagne, S., Taylor, A.R., Cook, P.G., Hamilton, S. 2011d, 'Interconnection of surface and groundwater systems – River losses from losing/disconnected streams: Lachlan River site report', CSIRO: Water for a Healthy Country National Research Flagship, Adelaide.

Lamontagne, S., Taylor, A.R., Cook, P.G., Smithson, A. 2011a, 'Interconnection of surface and groundwater systems – River losses from losing/disconnected streams: Namoi River site report', CSIRO: Water for a Healthy Country National Research Flagship, Adelaide.

Lamontagne, S., Taylor, A.R., Crosbie, R.S., Cook, P.G. 2011c, 'Interconnection of surface and groundwater systems – River losses from losing/disconnected streams: Billabong Creek site report', CSIRO: Water for a Healthy Country National Research Flagship, Adelaide.

Lavitt, 1999 'Integrated Approach to Geology, Hydrogeology and Hydrogeochemistry in the Lower Mooki River Catchment, New South Wales, Australia', PhD thesis, University of New South Wales.

Lavitt, N. 1999. Integrated approach to geology, hydrogeology and hydrogeochemistry in the Lower Mooki River catchment. PhD thesis, University of New South Wales.

Lawson, S. and ver der Lely, A. 1992. Colleambally deep bore project, analysis of long term pumping test-summary report. Technical report, Water Resources Commission, NSW, 1992.

McLean, W. A. 2003. Hydrogeochemical evolution and variability in a stressed alluvial aquifer system: Lower Namoi River catchment, NSW. PhD thesis, University of NSW (unpublished).

Merrick, N. P., Middlemis, H., and Williams, R. M., 2005, Dynamic River-Aquifer Interaction Modelling and Optimal Interception of Saline Groundwater Discharge. In Acworth, Macky & Merrick (eds.), CD Proceedings, Where Waters Meet International Conference, Auckland, 29 November – 1 December, 2005. New Zealand Hydrological Society. ISBN 0-473-10627-2.

Namoi Catchment Management Authority (NCMA) 2011, Mooki Plains Sub-catchment, viewed 3 November 2011, <http://www.namoi.cma.nsw.gov.au/123.html>.

National Health and Medical Research Council. 2011. Australian Drinking Water Guidelines.

NSW Agriculture 2003. Lachlan Catchment Irrigation Profile. Report prepared by the New South Wales Agriculture for the Water Efficiency Advisory Unit, Dubbo.

NSW Office of Water (NOW) 2011a, 'Lower Murray Groundwater Source Groundwater Management Area 016 Groundwater Status Report – 2010', NSW Office of Water.

NSW Office of Water (NOW) 2011b, Murray Riverina catchment, viewed 9 November 2011, <http://www.water.nsw.gov.au/Water-management/Basins-and-catchments/Murray-Riverina-catchment/default.aspx>.

Parkhurst, D. L., and Appelo, C. A. J. 1999. User's guide to PHREEQC (version 2) – a computer program for speciation, batch-reaction, one dimensional transport, and inverse geochemical calculations. USGS Water Resources Investigations Report 99-4259: 312pp.

Parsons Brinckerhoff, 2009. Scope of works for hydrogeochemical sampling program – selected NSW sites. PR_4897, July 2009.

Piper, AM 1944, 'A graphic procedure in the geochemical interpretation of water-analyses'. *Am. Geophys. Union Trans*, vol. 25, pp. 914–923.

Rozanski, K., Araguas-Araguas, L., and Gonfiantini, R. 1993. Isotopic patterns in modern global precipitation. In Continental Isotope Indicators of Climate. American Geophysical Union Monograph. Cited by Clark and Fritz, 1997.

Timms, W. A. 2001. The importance of aquitard windows in development of alluvial groundwater systems: Lower Murrumbidgee, Australia. PhD thesis, University of New South Wales (unpublished).

Timms, W. A., and Acworth, R. I. 2002. Induced leakage due to groundwater pumping and flood irrigation at the Pullaming Agricultural Field Station, Liverpool Plains. Water Research Laboratory Research Report No. 208.

URS 2006. Scientific Expert Review for the Lower Lachlan Groundwater Sharing Plan. Prepared for Natural Resources Commission 2 November 2006.

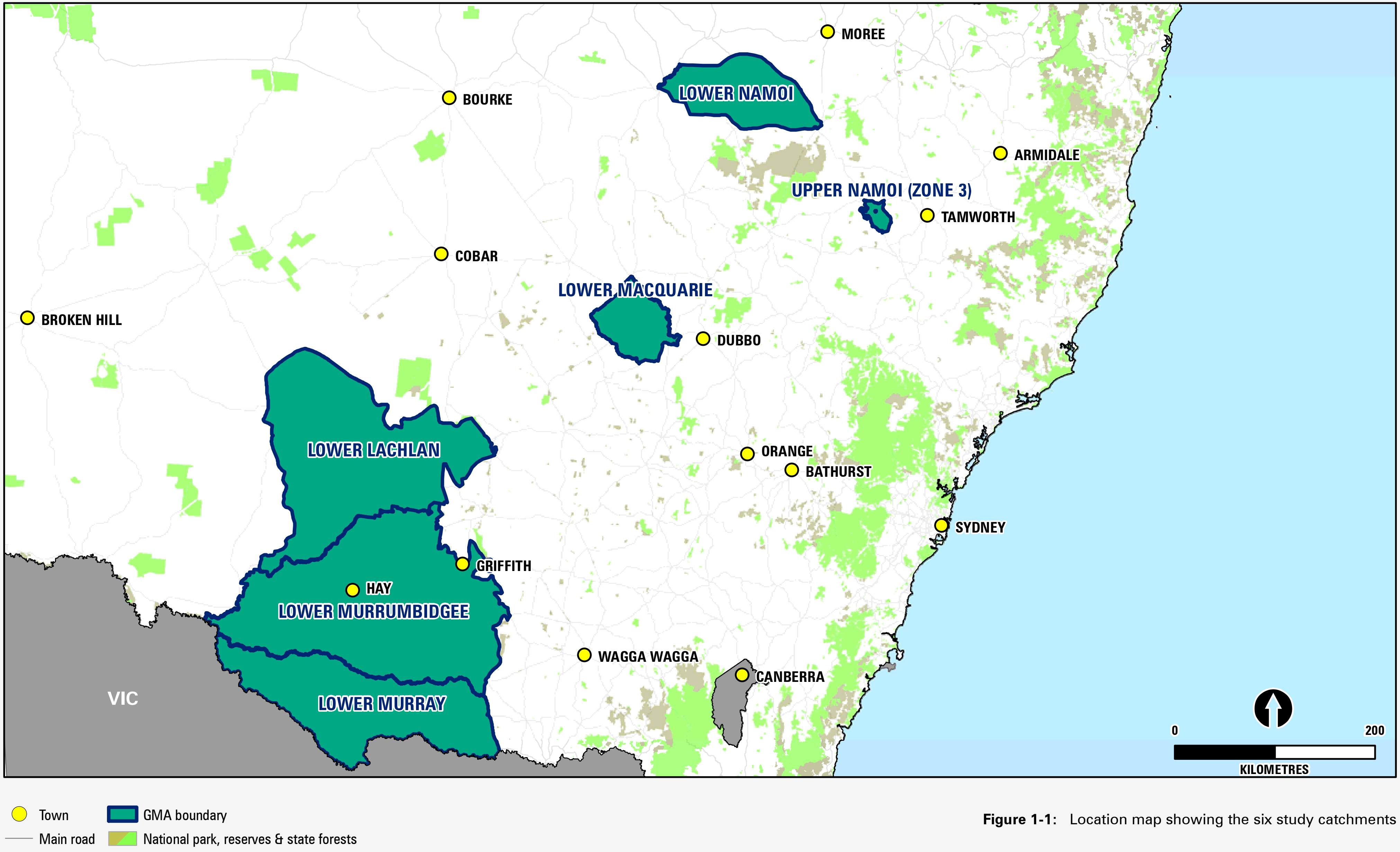
Wilcox, L. V. 1948. The quality of water for irrigation. US Dept. Agric. Tech. Bull. 962:1-40.
Williams, R.M. 1986. The Cainozoic geology, hydrogeology and hydrochemistry of the unconsolidated sediments associated with the Namoi River in the Lower Namoi Valley, NSW. Tech. Rep. DWR Hydro Rept. 1986/4

Woolley, D.R and Williams, R.M. 1978. Tertiary stratigraphy and hydrogeology of the eastern part of the Murray Basin, N.S.W. In Storier and Kelly (eds): *The Hydrogeology of the Riverine Plain of South-East Australia*. Riverine Branch, Australian Society of Soil Science, Inc., 1978.

Figures

PARSONS BRINCKERHOFF

CHARACTERISATION OF HYDROGEOCHEMISTRY AND RISKS TO GROUNDWATER QUALITY
NSW OFFICE OF WATER



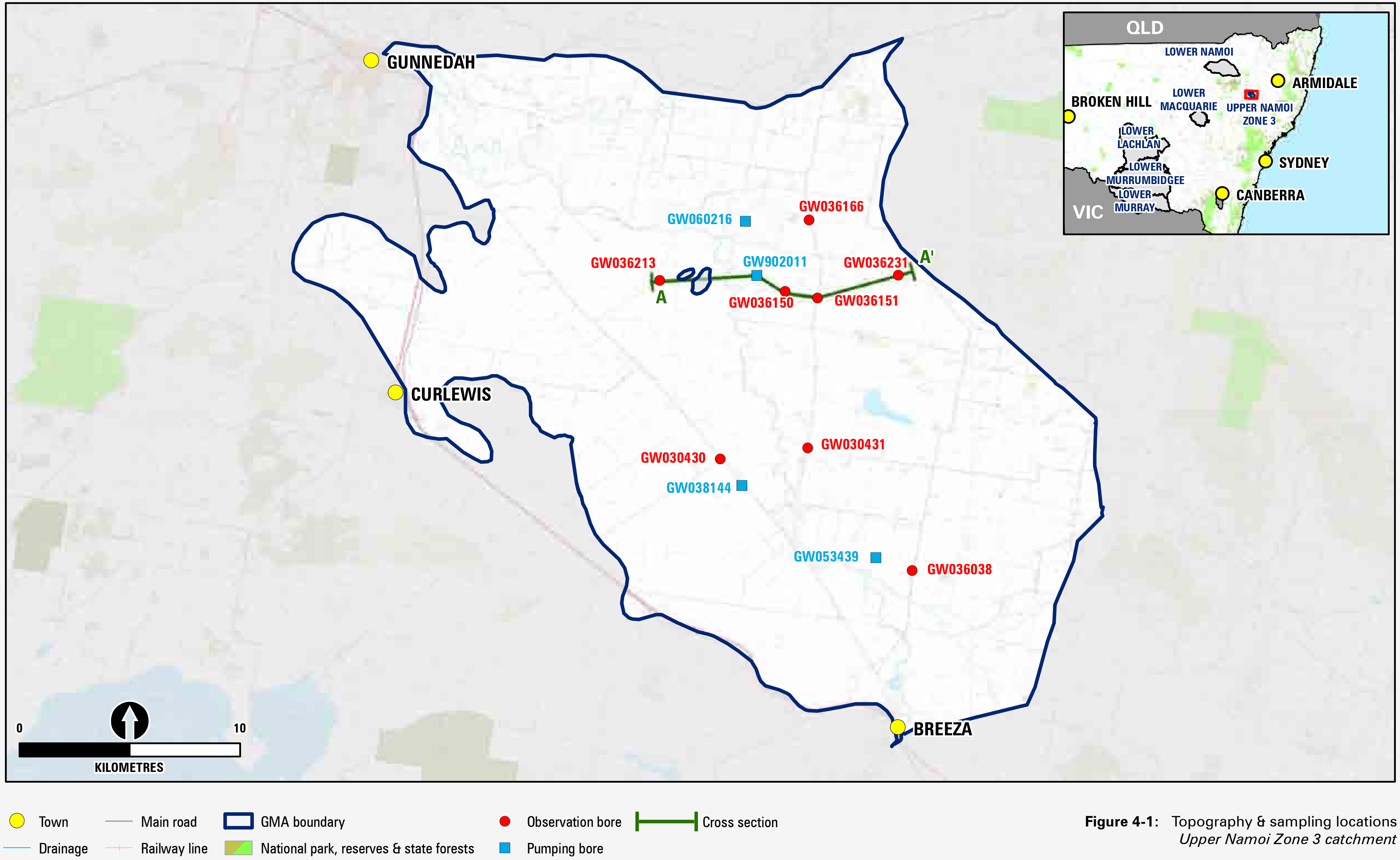
\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F031_B1.mxd // kumarg // 08/12/2011

Figure 1-1: Location map showing the six study catchments

PARSONS BRINCKERHOFF

CHARACTERISATION OF HYDROGEOCHEMISTRY AND RISKS TO GROUNDWATER QUALITY

NSW OFFICE OF WATER



\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F006_B1.mxd // kumarg // 09/12/2011

Figure 4-1: Topography & sampling locations
Upper Namoi Zone 3 catchment

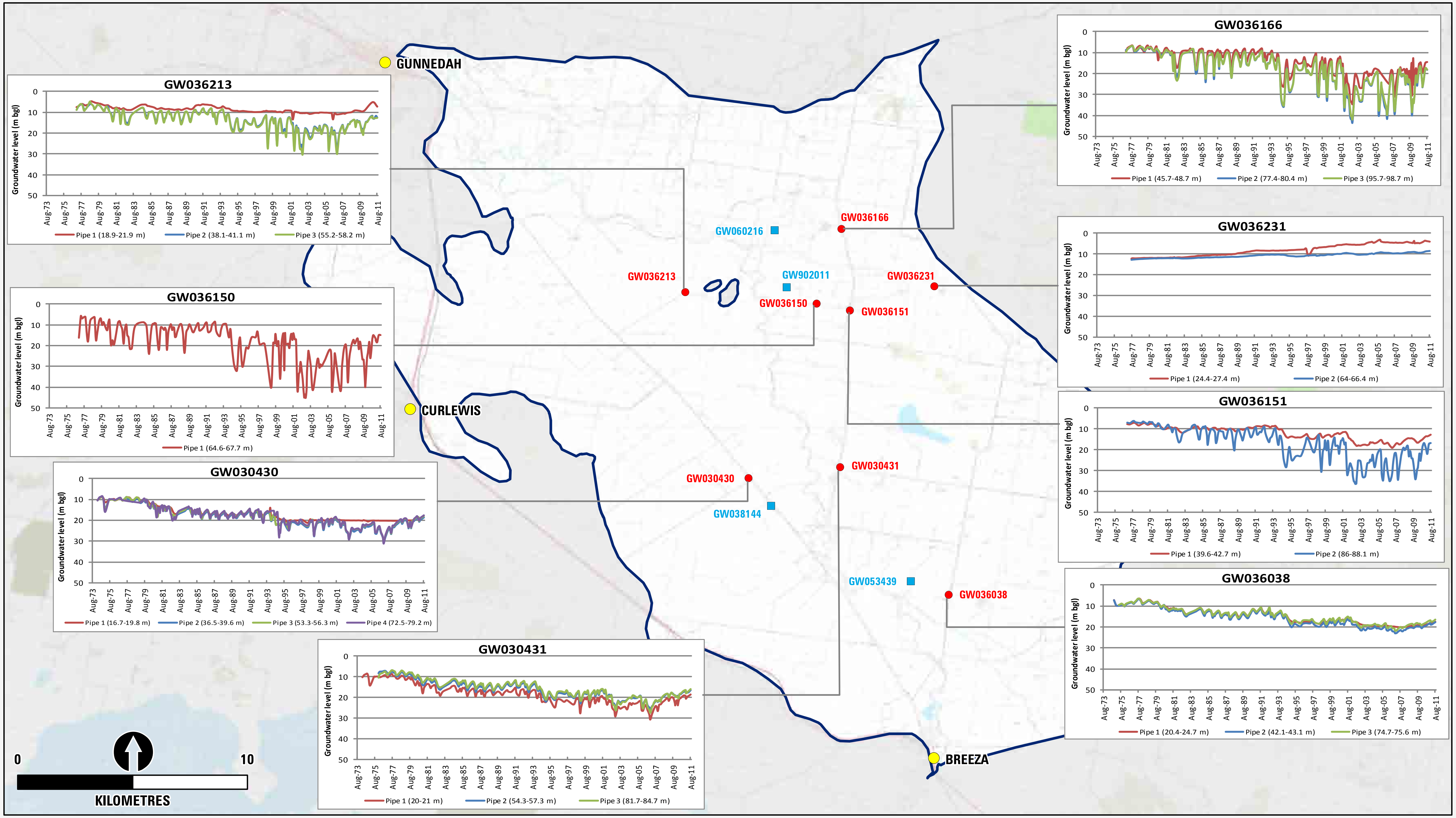


Figure 4-5: Hydrograph data - *Upper Namoi Zone 3 catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F007_A1.mxd // kumarg // 13/11/2011

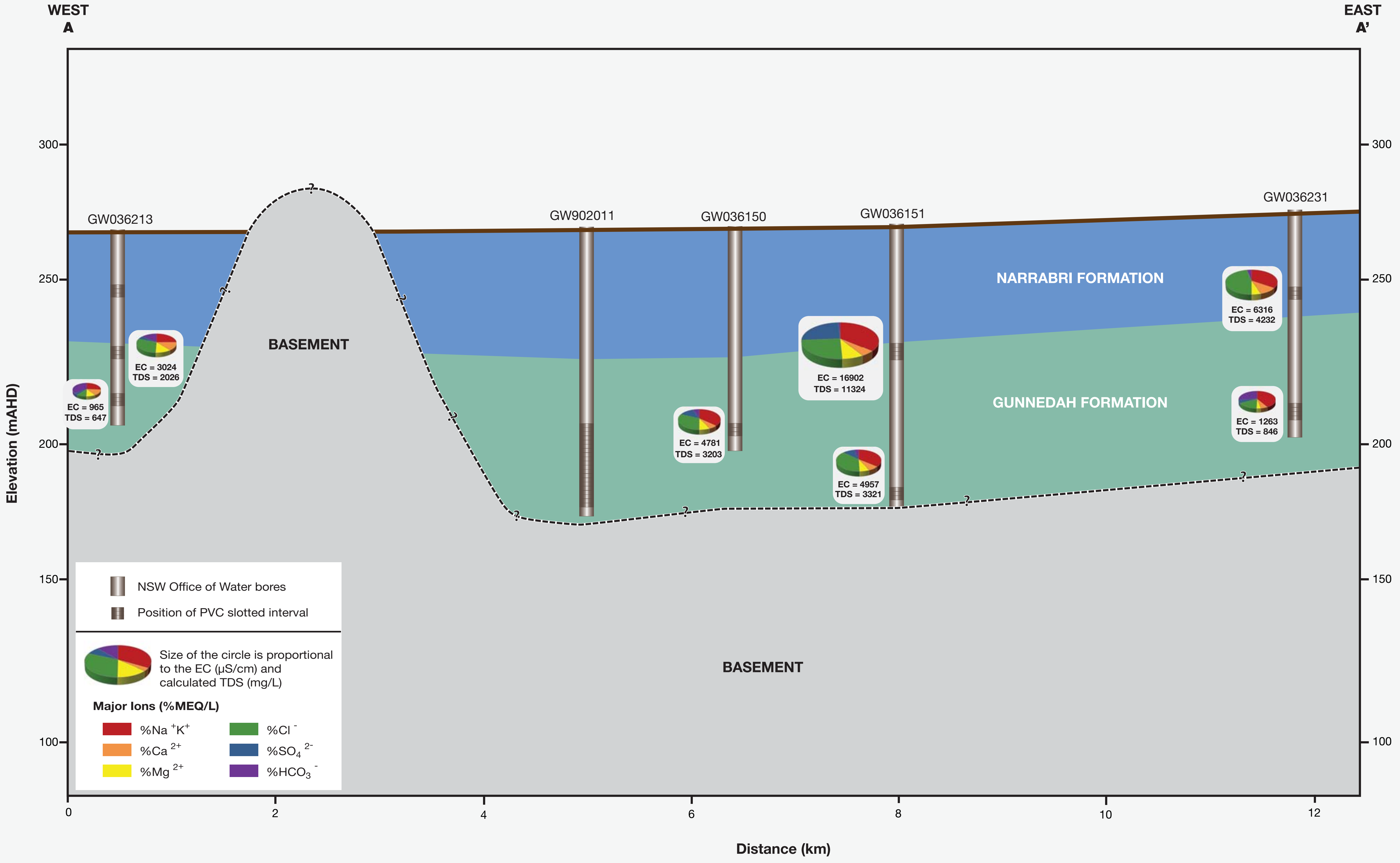


Figure 4-6 Conceptual hydrogeological cross-section - Upper Namoi

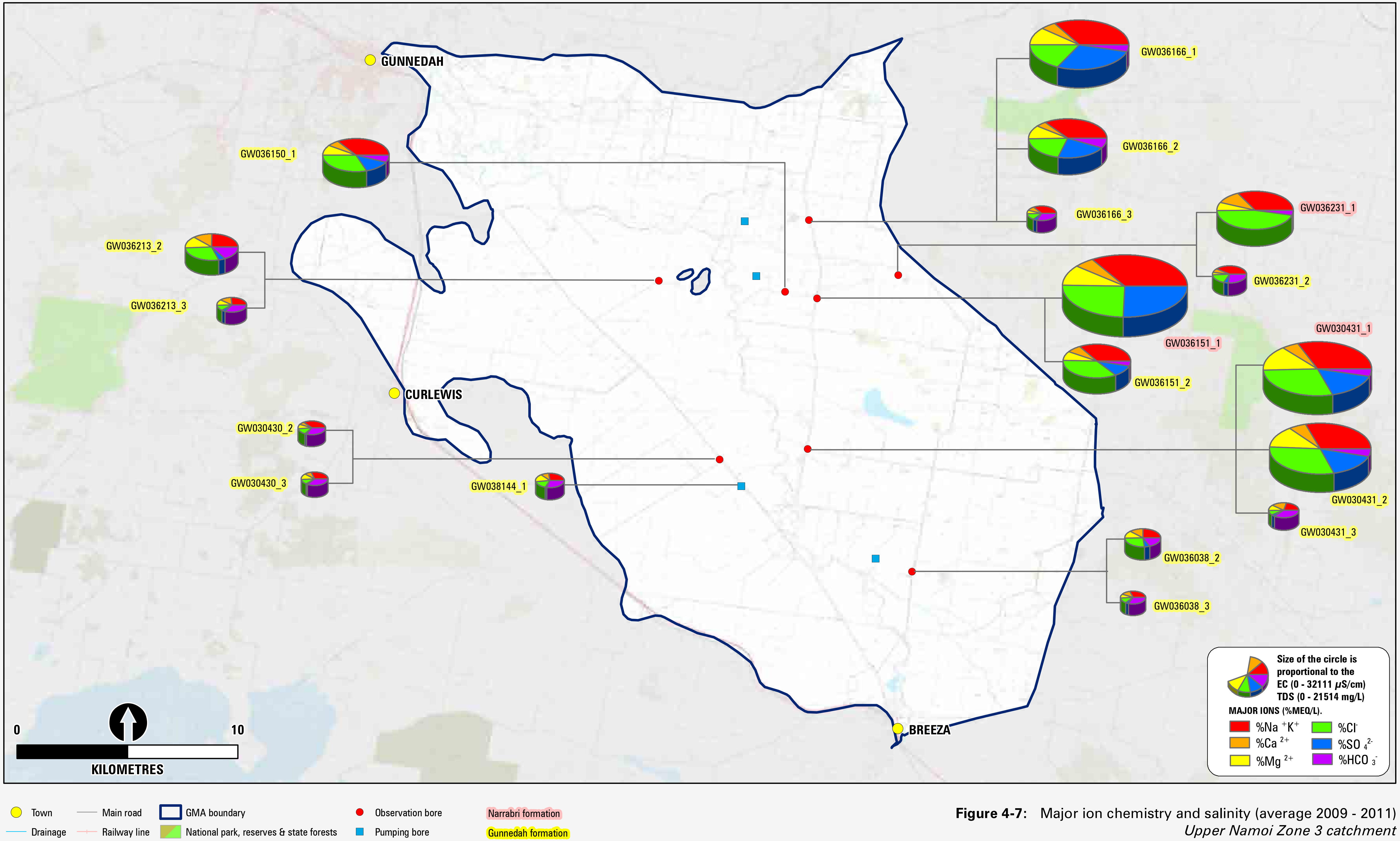


Figure 4-7: Major ion chemistry and salinity (average 2009 - 2011)
Upper Namoi Zone 3 catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F013_B1.mxd // kumarg // 08/12/2011

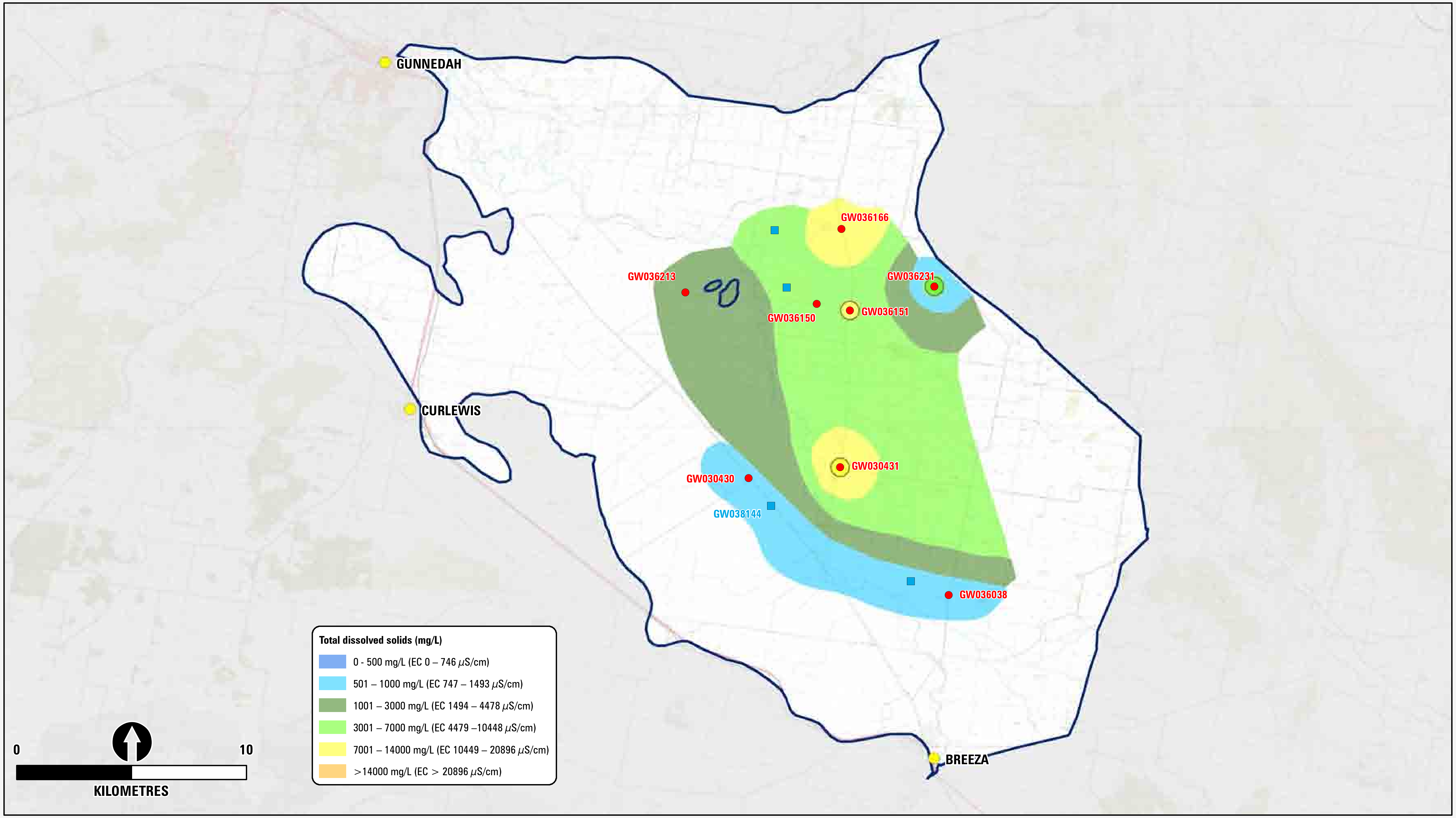


Figure 4-8: Average calculated total dissolved solids (2009 -2011)
Upper Namoi Zone 3 catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F019_B1.mxd // kumarg // 09/12/2011

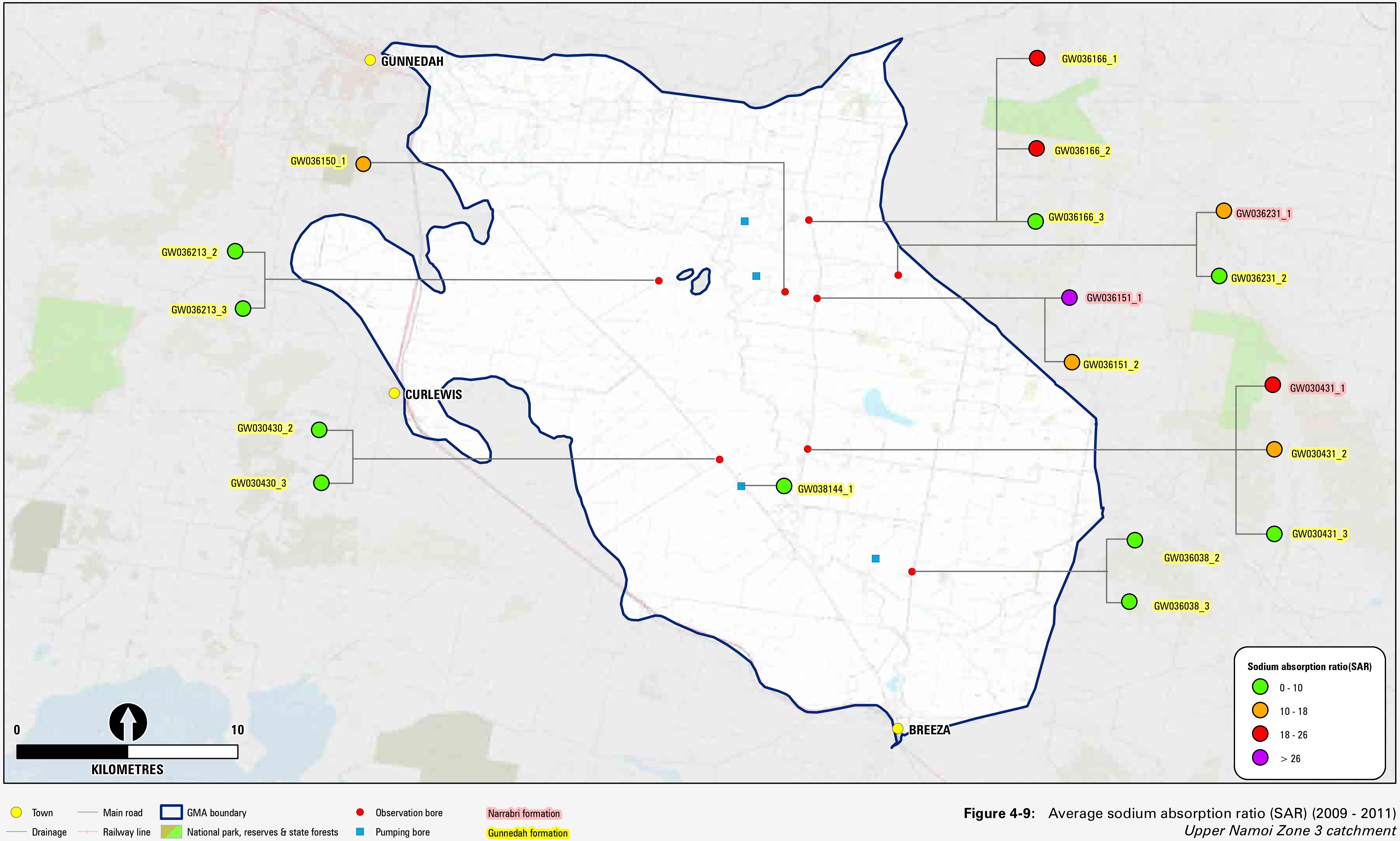
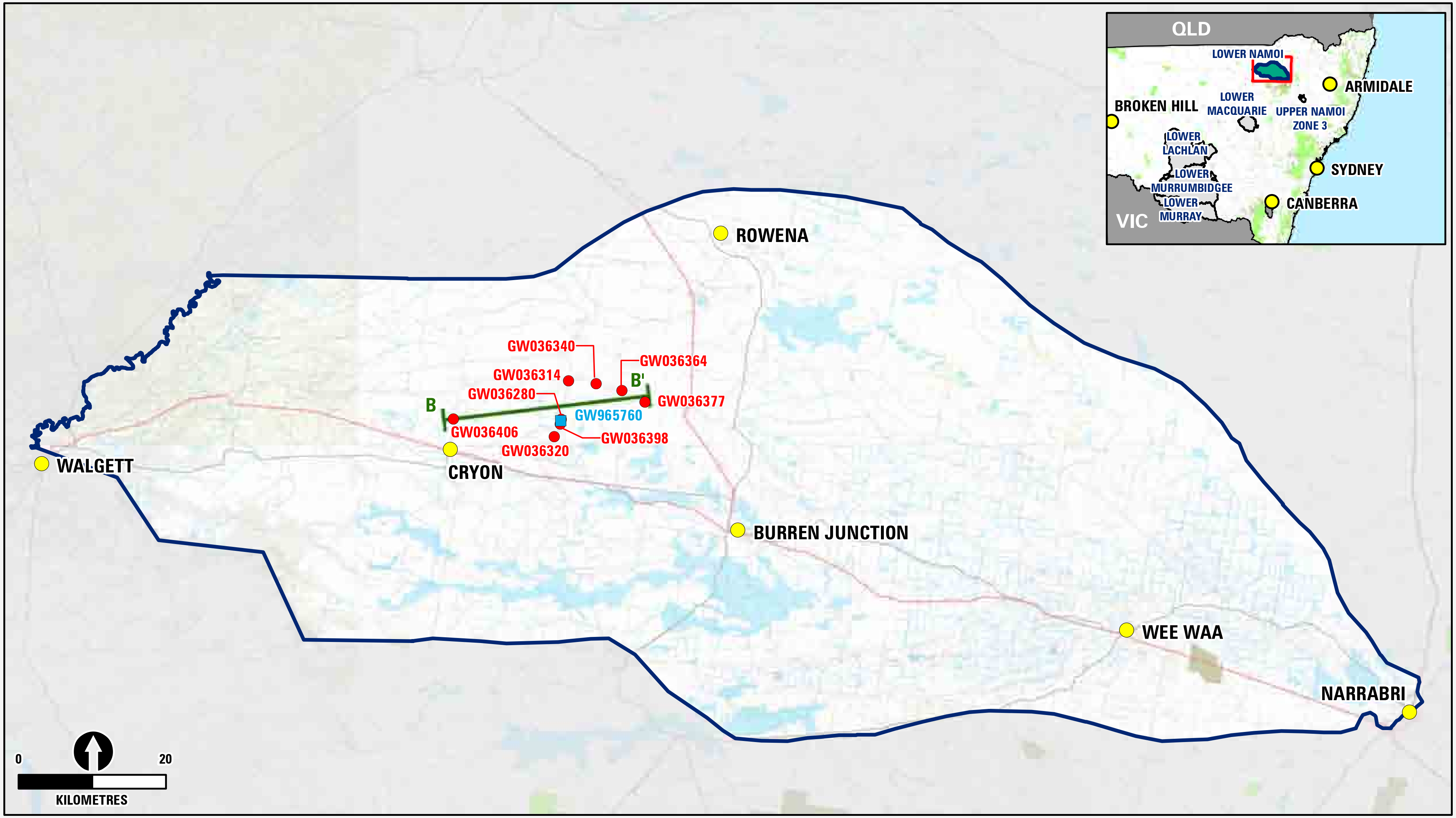


Figure 4-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Upper Namoi Zone 3 catchment

\\APSYDNAS02\proj\E\Energy_Aus\2123852A_ENERGY_AUSTRALIA_CABLE_DELIVE\10_GIS\Projects\ESRI\2114803A_GIS_F025_A2.mxd // kumarg // 18/11/2011



● Town
— Drainage
— Main road
-+- Railway line
▭ GMA boundary
🟩 National park, reserves & state forests
● Observation bore
■ Pumping bore
⊢⊣ Cross section

Figure 5-1: Topography & sampling locations
Lower Namoi catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F005_B1.mxd // kumarg // 08/12/2011

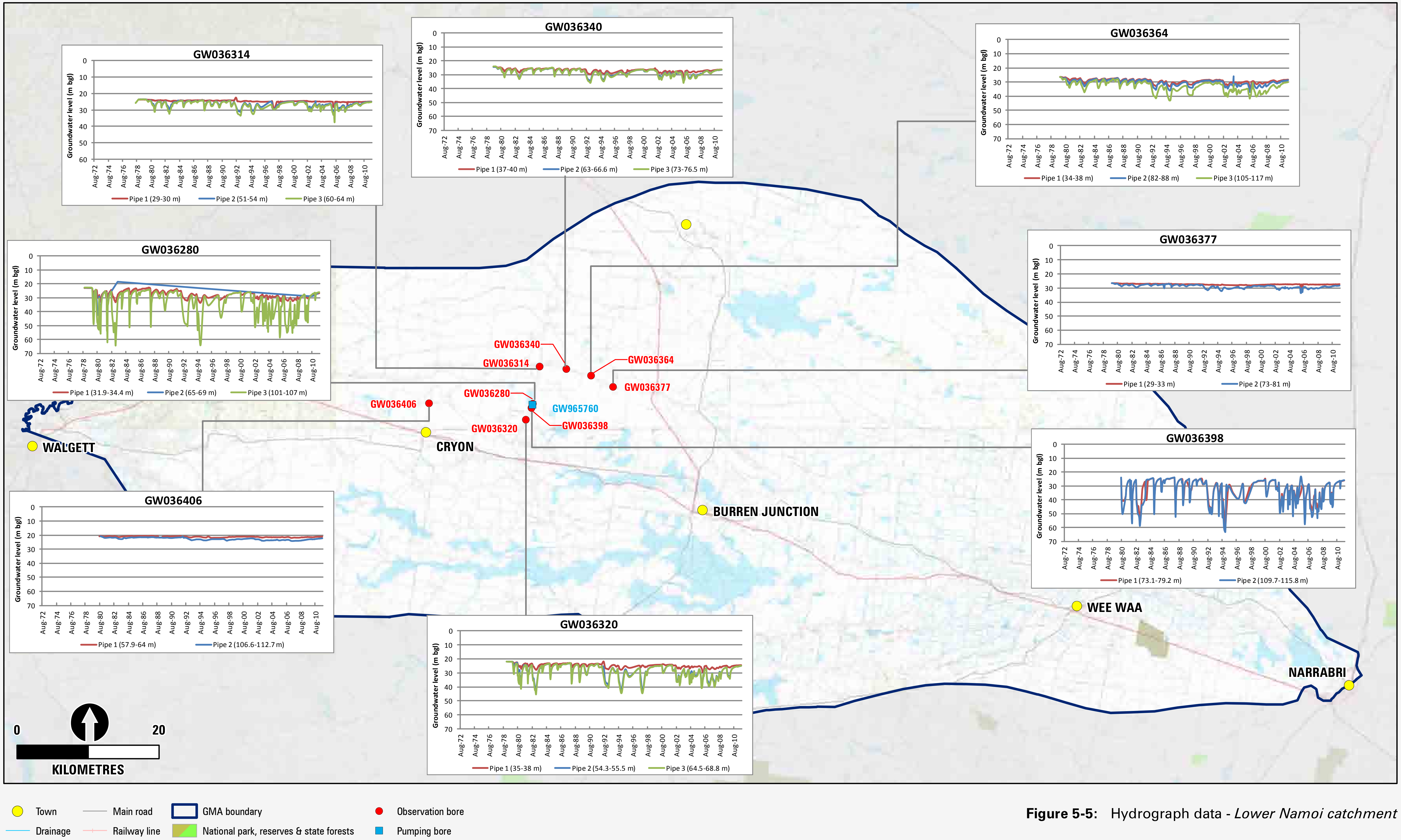


Figure 5-5: Hydrograph data - *Lower Namoi catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F008_A1.mxd // kumarg // 13/11/2011

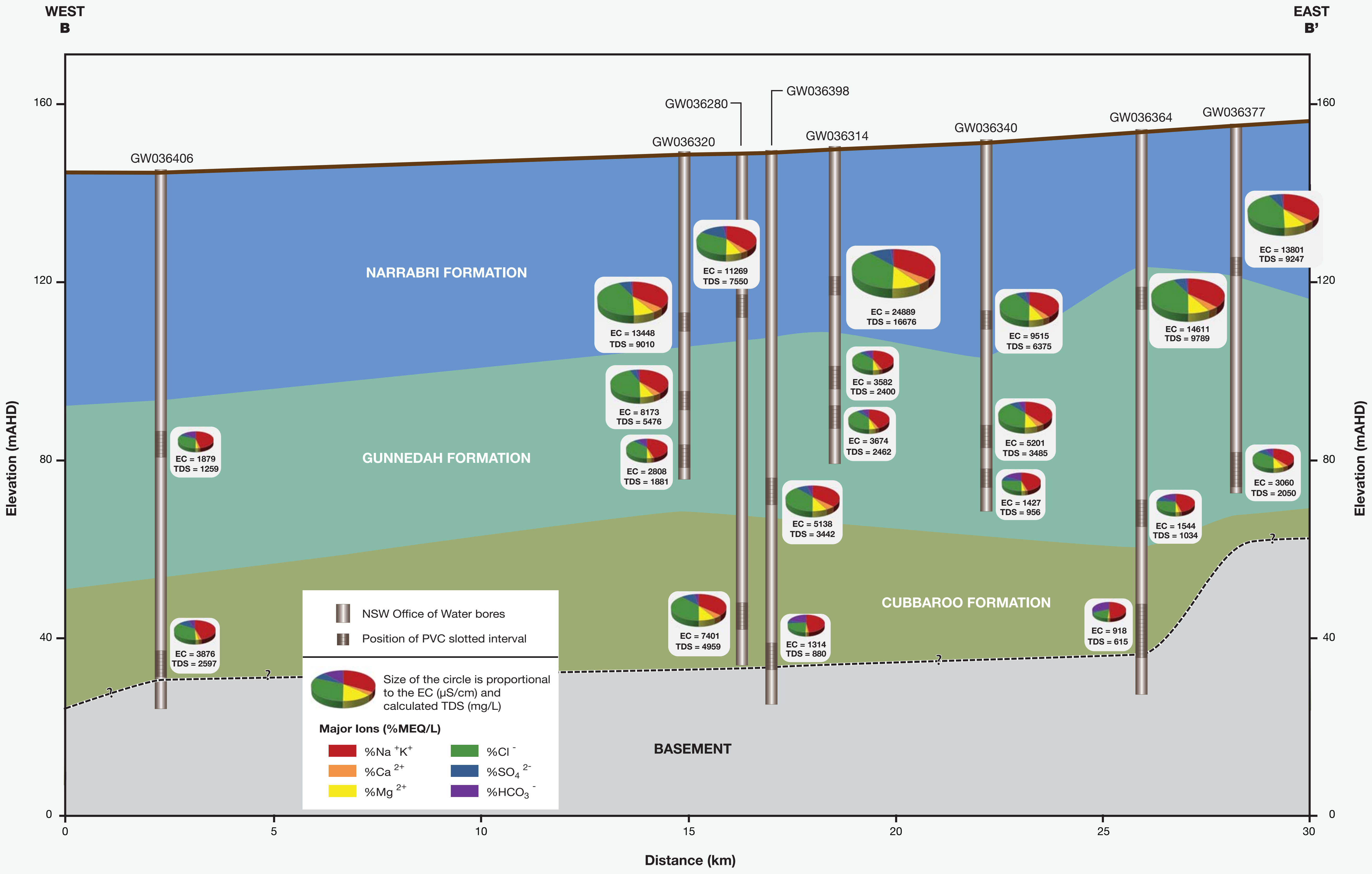
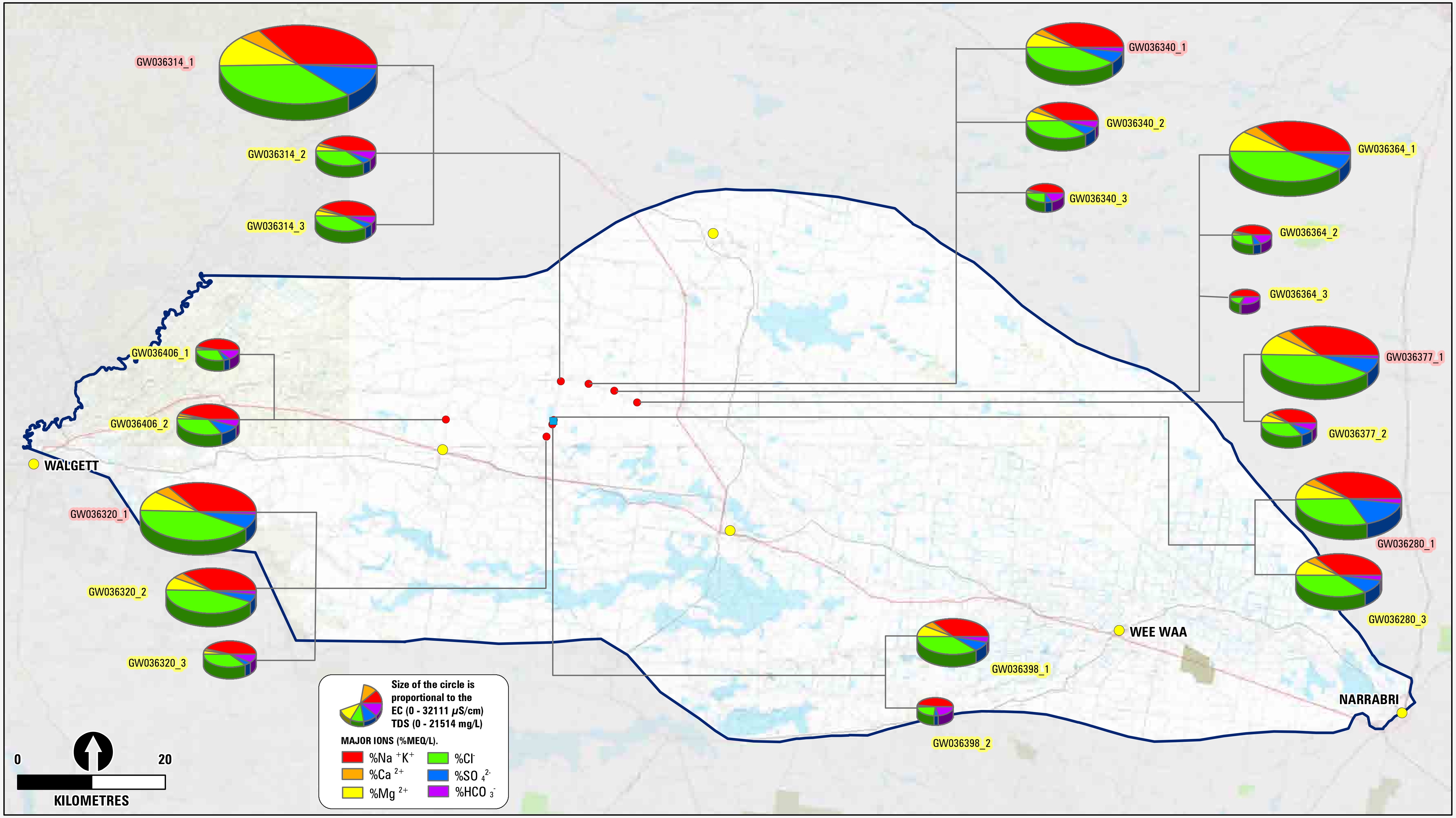


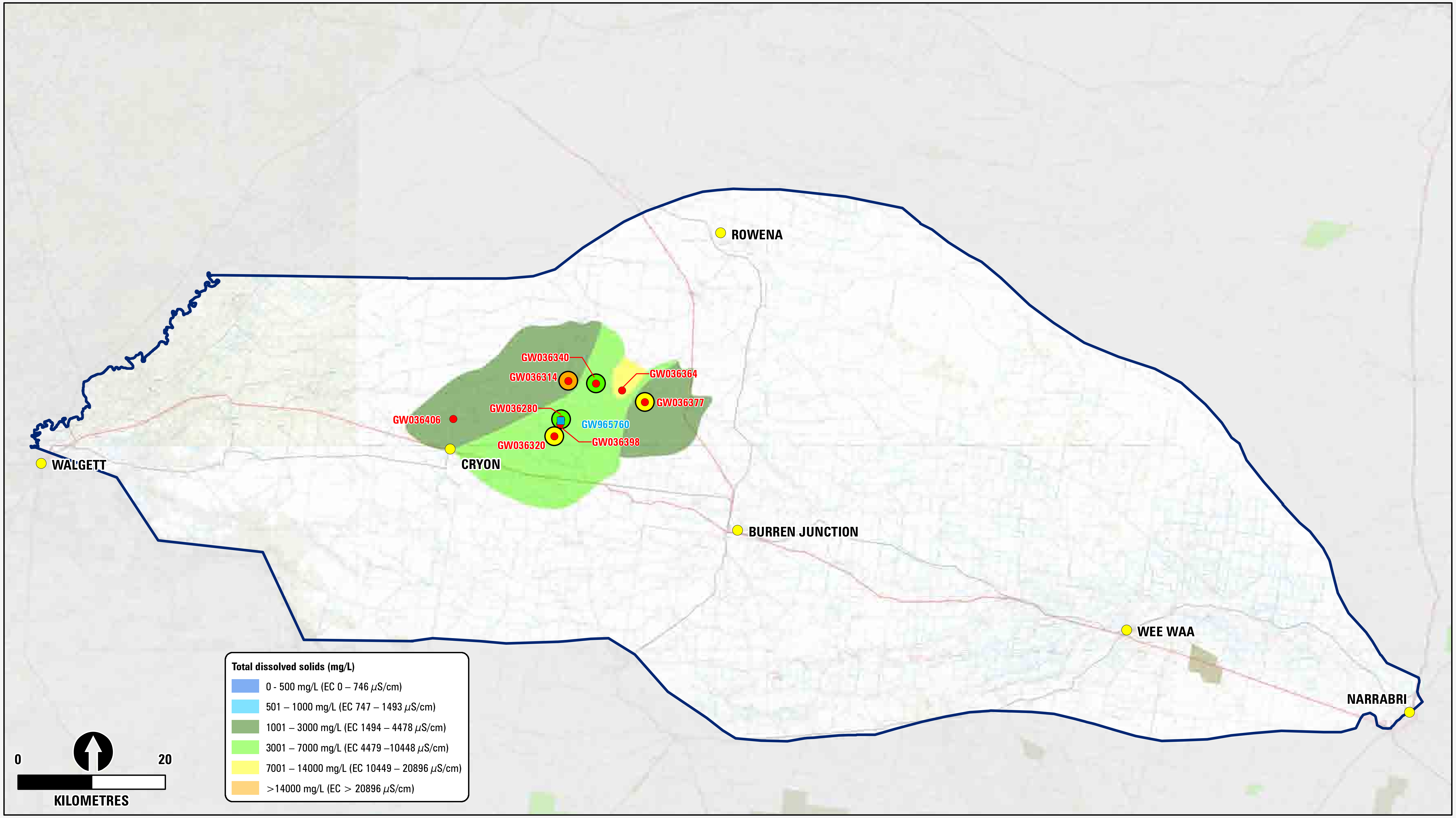
Figure 5-6 Conceptual hydrogeological cross-section - Lower Namoi



● Town
— Main road
▭ GMA boundary
● Observation bore
Narrabri formation
— Drainage
— Railway line
▨ National park, reserves & state forests
■ Pumping bore
Gunnedah/Cubbaroo formations

Figure 5-7: Major ion chemistry and salinity (average 2009 - 2011)
Lower Namoi catchment

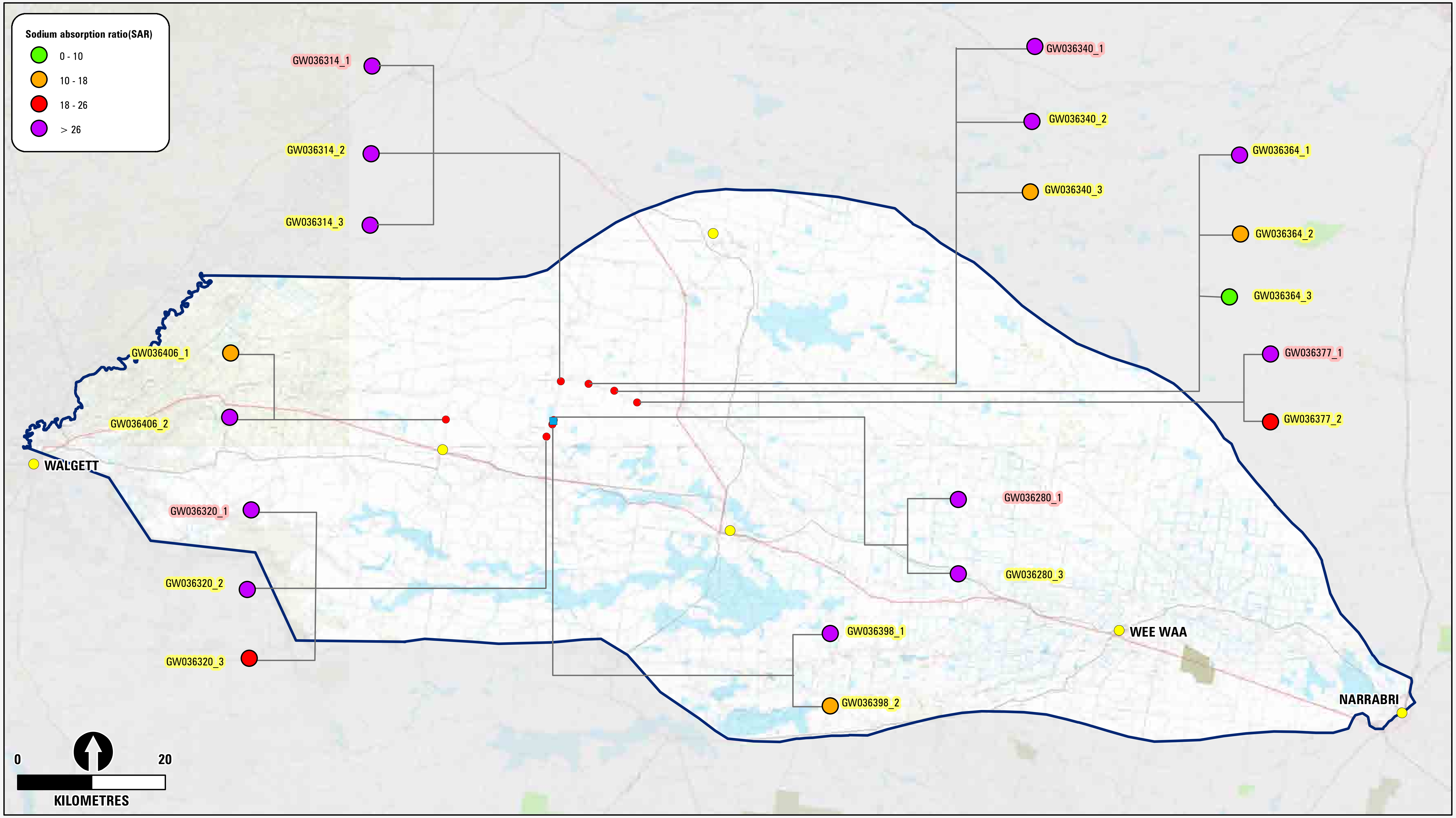
\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F014_B1.mxd // kumarg // 08/12/2011



● Town
Drainage
Main road
Railway line
GMA boundary
National park, reserves & state forests
● Observation bore
■ Pumping bore
● TDS shallow aquifer (Narrabri Formation)
Inferred TDS deep aquifer (Gunnedah and Cubbaroo formations)

Figure 5-8: Average calculated total dissolved solids (2009 -2011)
Lower Namoi catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F020_B1.mxd // kumarg // 09/12/2011



\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F026_A2.mxd // kumarg // 17/11/2011

Figure 5-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Lower Namoi catchment

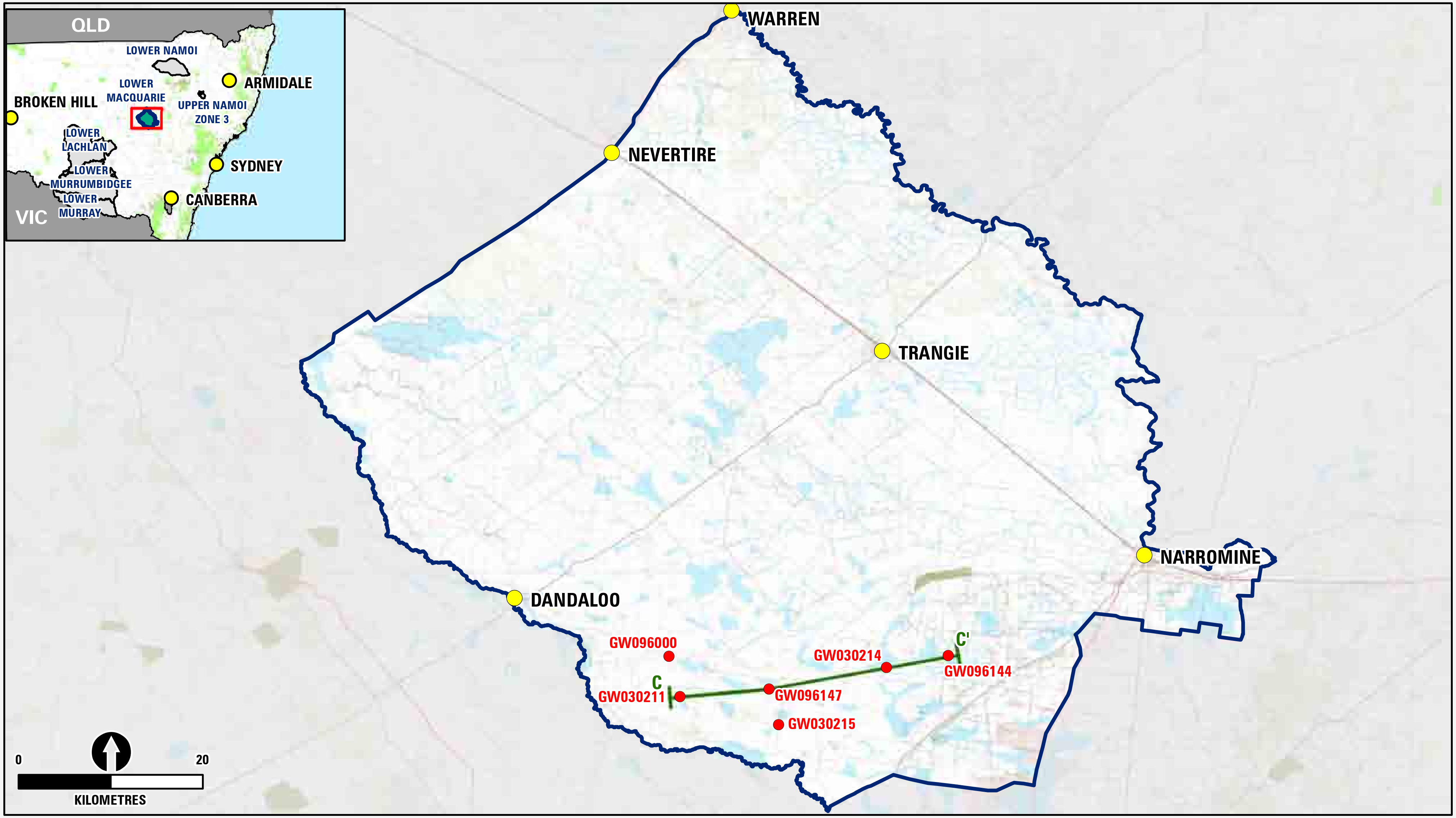


Figure 6-1: Topography & sampling locations
Lower Macquarie catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F003_B1.mxd // kumarg // 08/12/2011

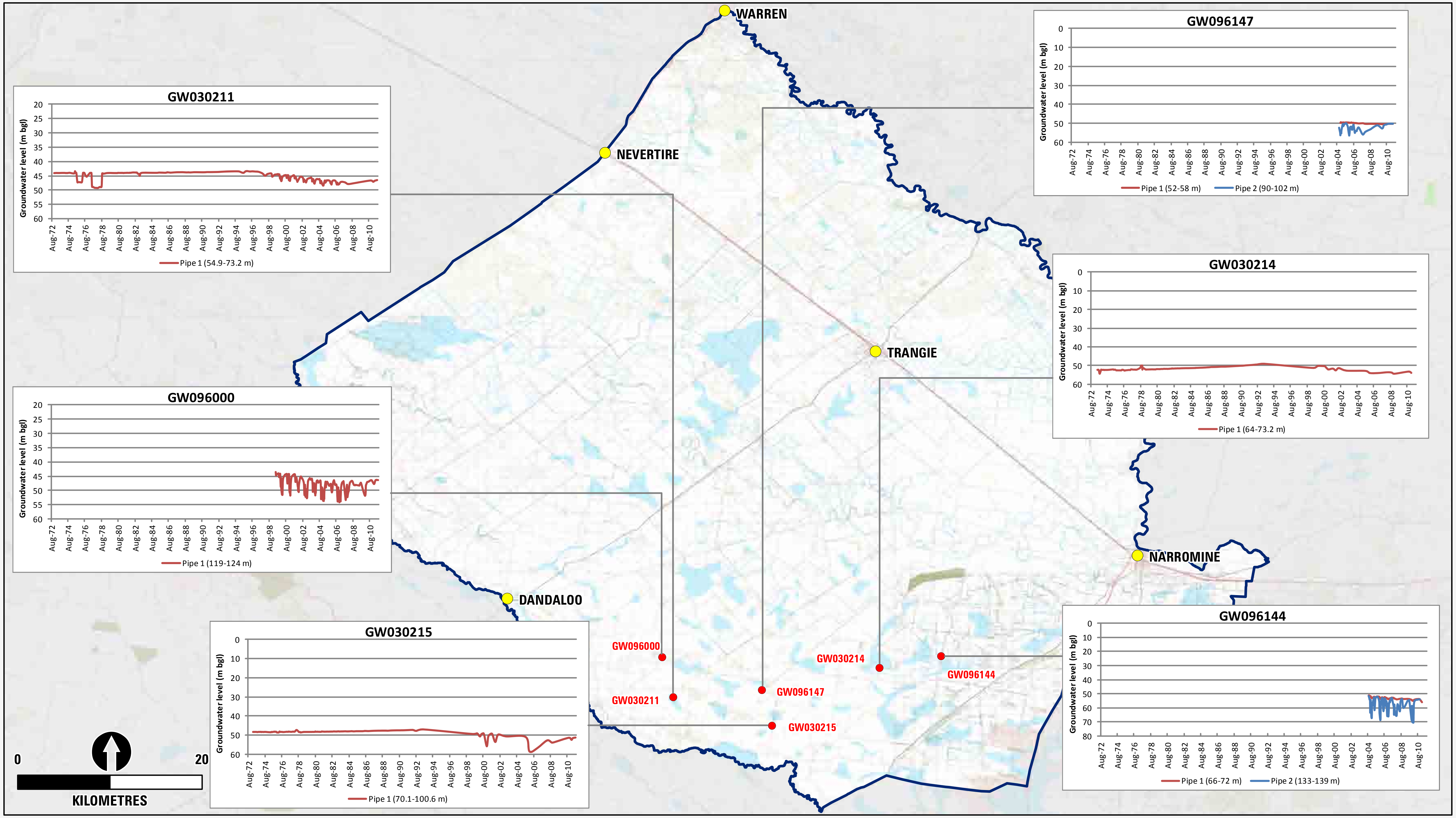


Figure 6-5: Hydrograph data - *Lower Macquarie catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F009_A1.mxd // kumarg // 13/11/2011

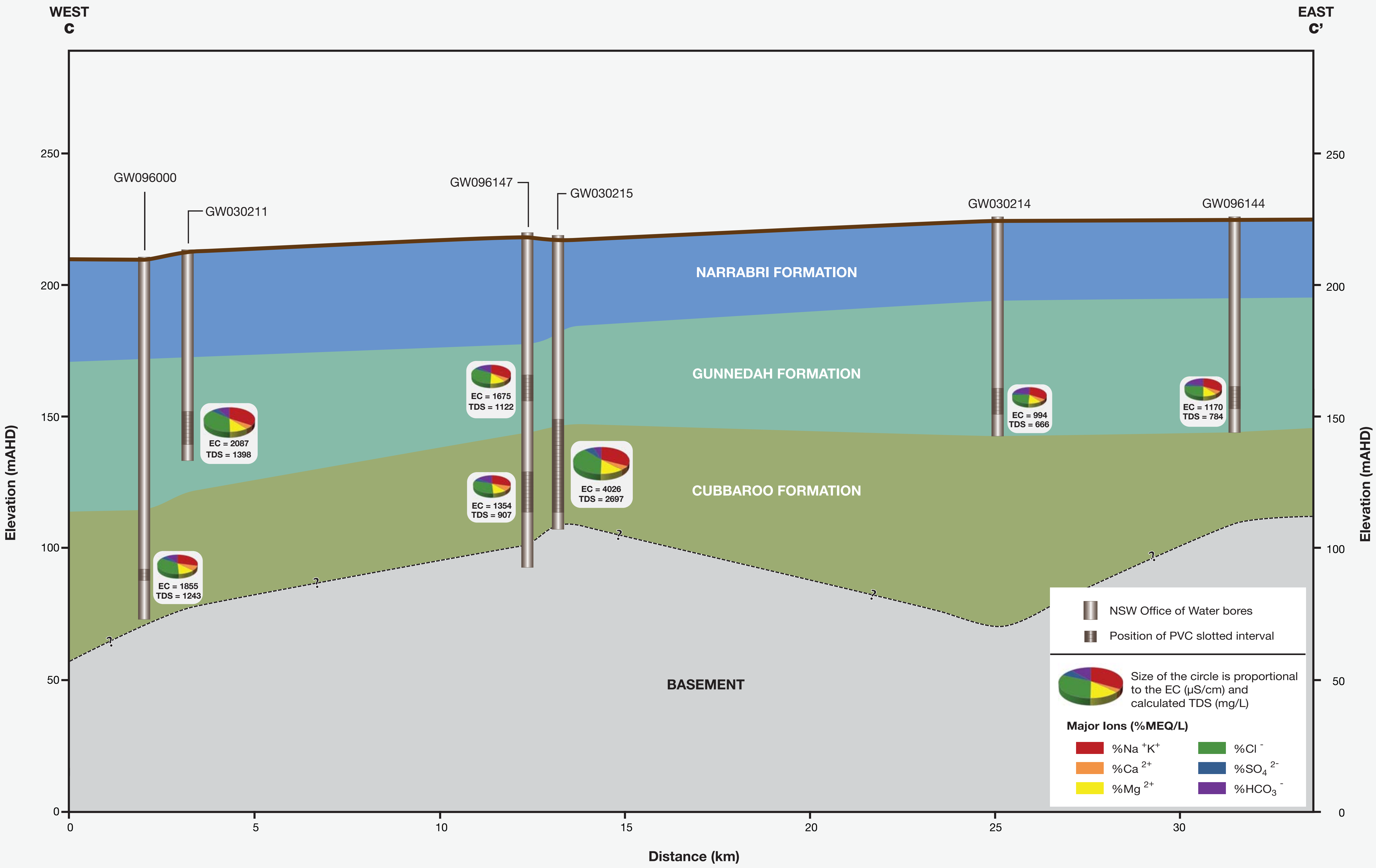


Figure 6-6 Conceptual hydrogeological cross-section - Lower Macquarie

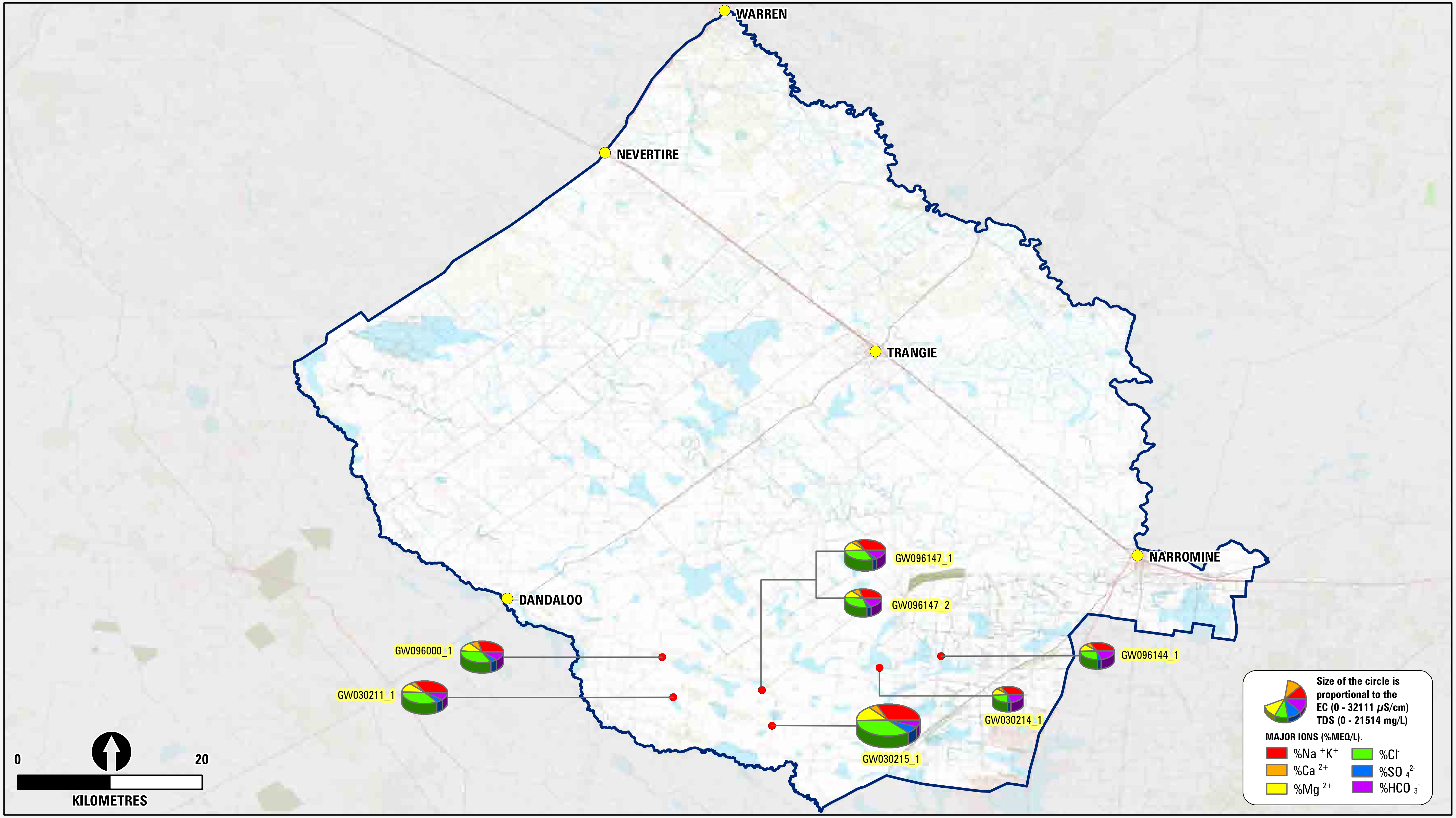


Figure 6-7: Major ion chemistry and salinity (average 2009 - 2011)
Lower Macquarie catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F015_B1.mxd // kumarg // 08/12/2011

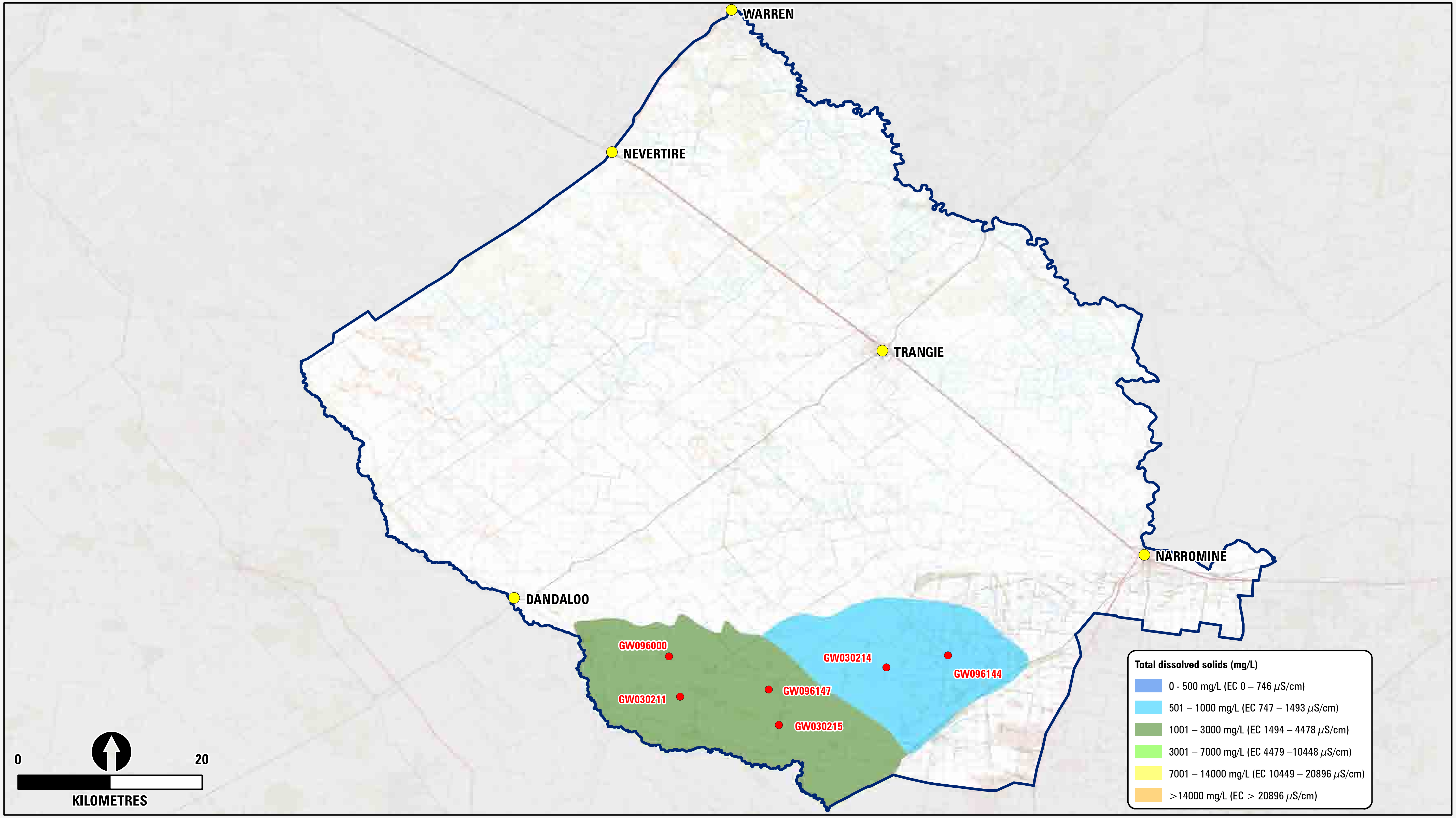


Figure 6-8: Average calculated total dissolved solids (2009 -2011)
Lower Macquarie catchment

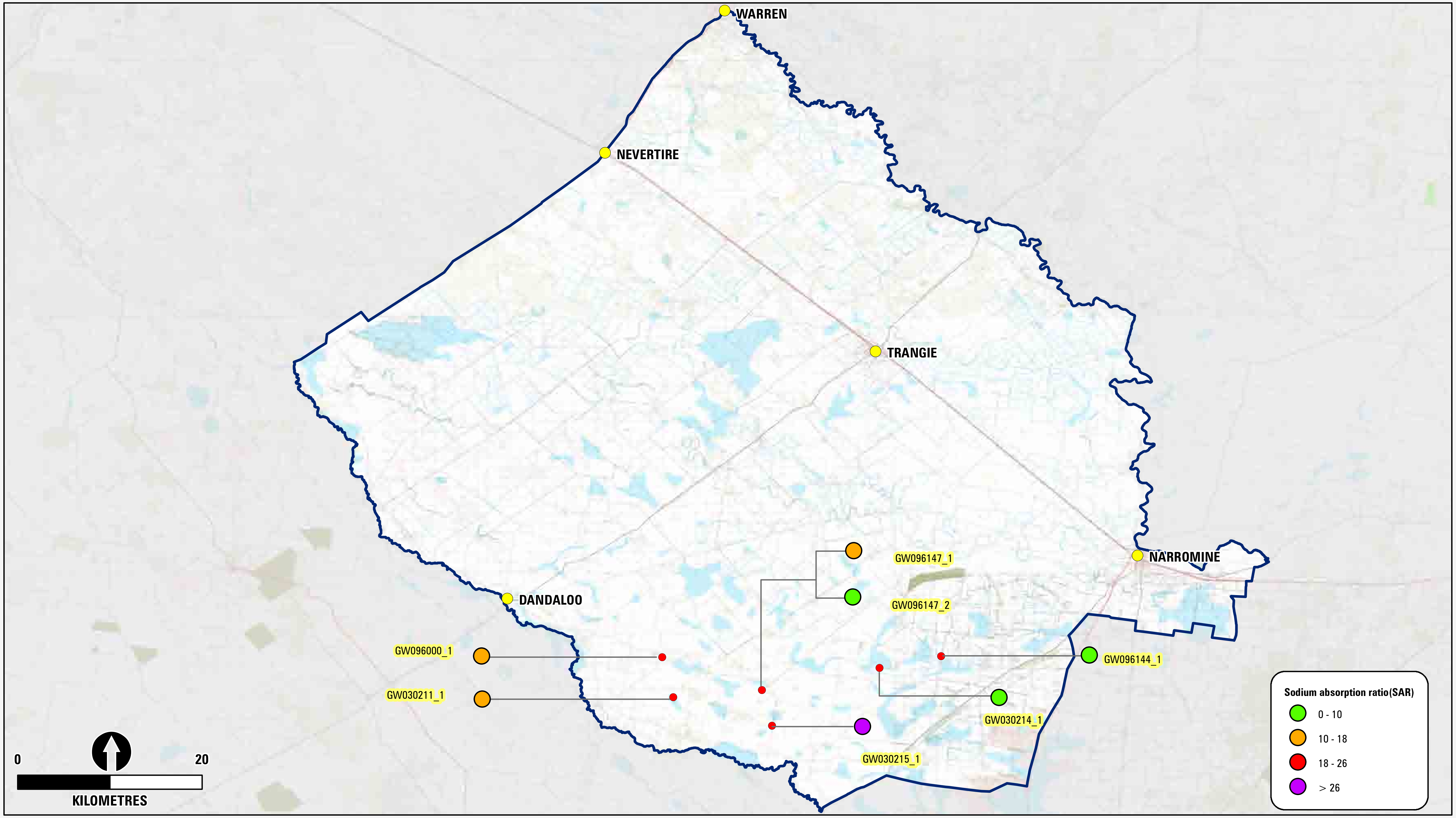


Figure 6-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Lower Macquarie catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F027_A2.mxd // kumarg // 17/11/2011

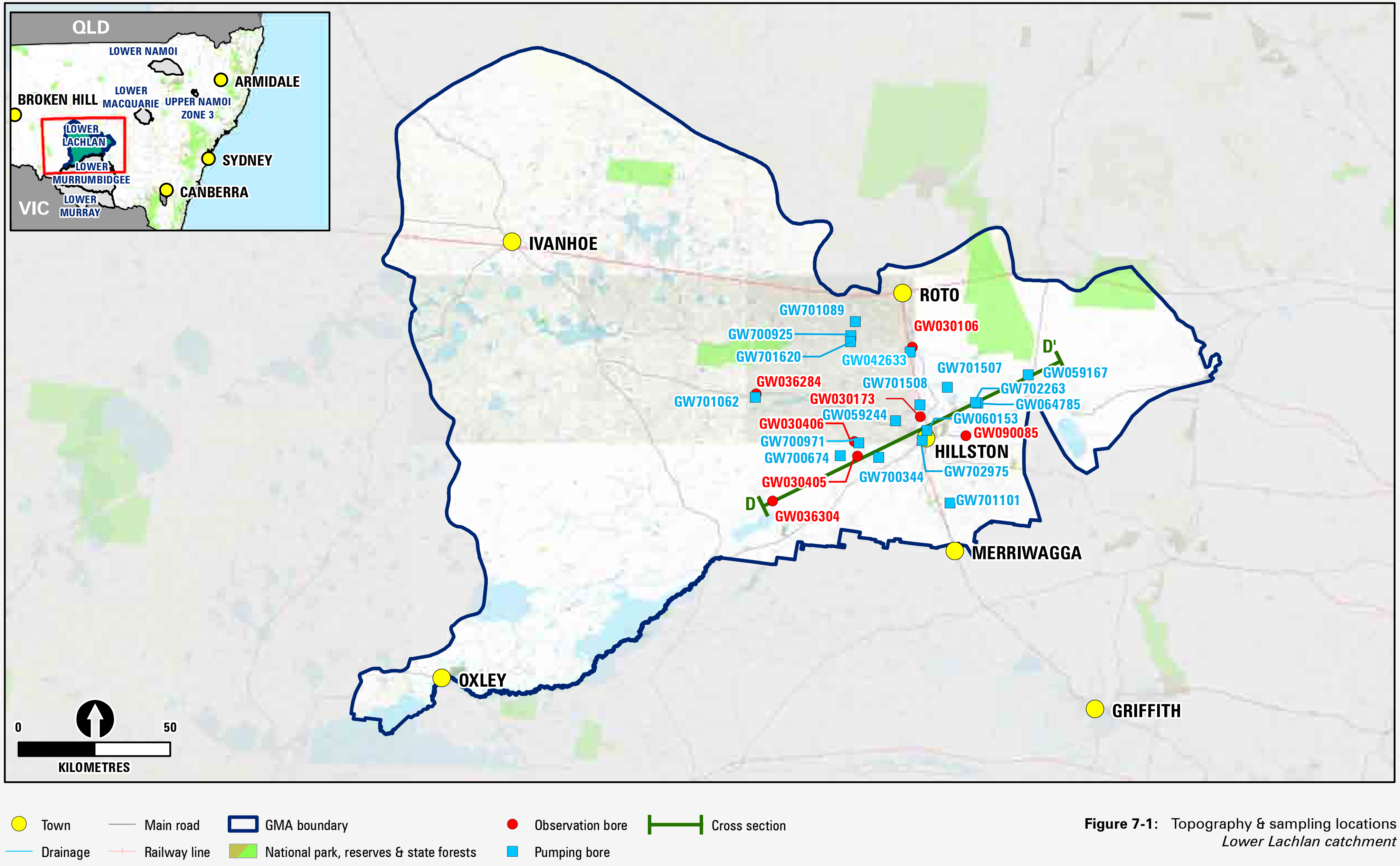


Figure 7-1: Topography & sampling locations
Lower Lachlan catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F001_B1.mxd // kumarg // 09/12/2011

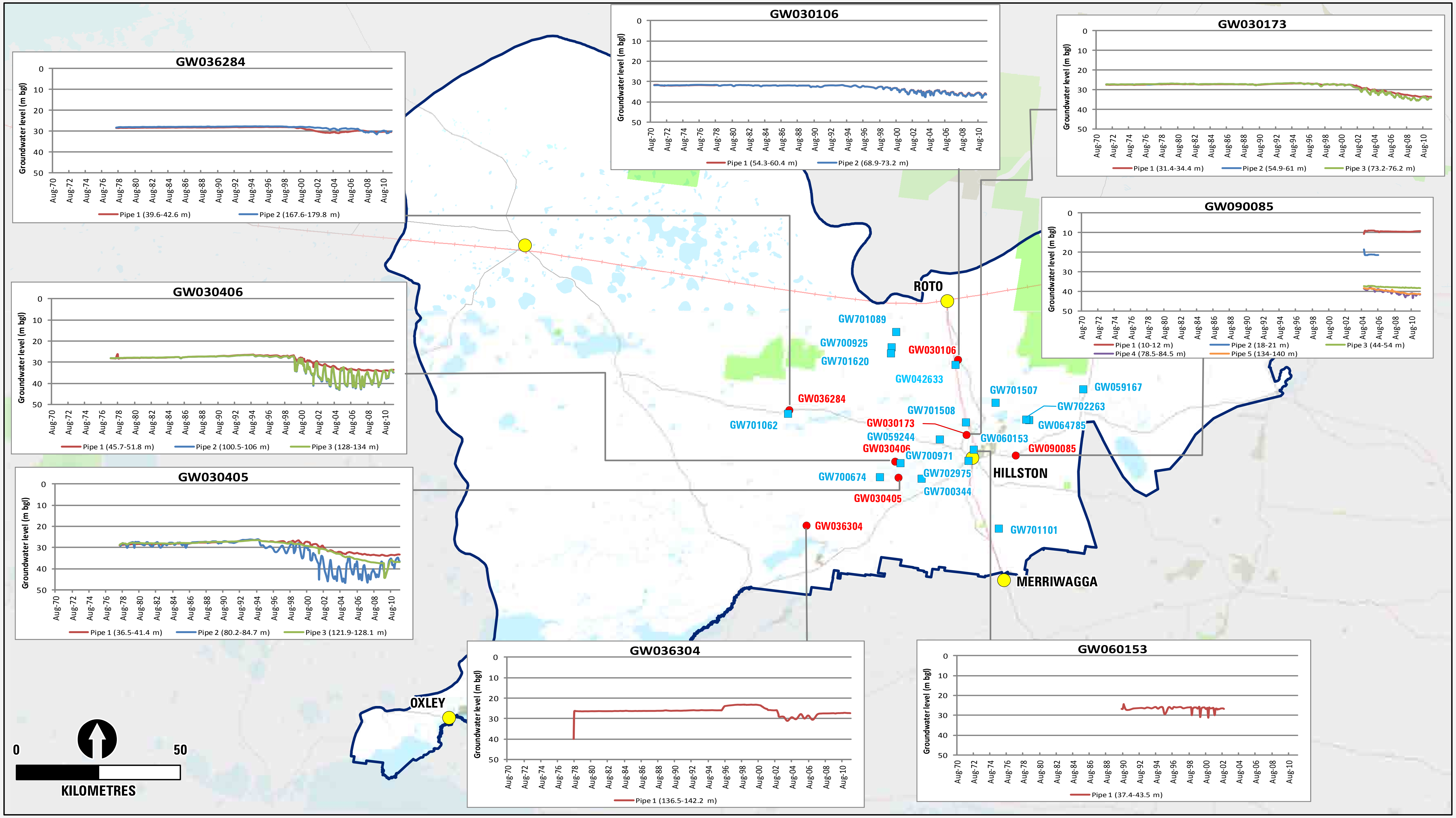


Figure 7-5: Hydrograph data - *Lower Lachlan catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F010_A1.mxd// kumarg // 13/11/2011

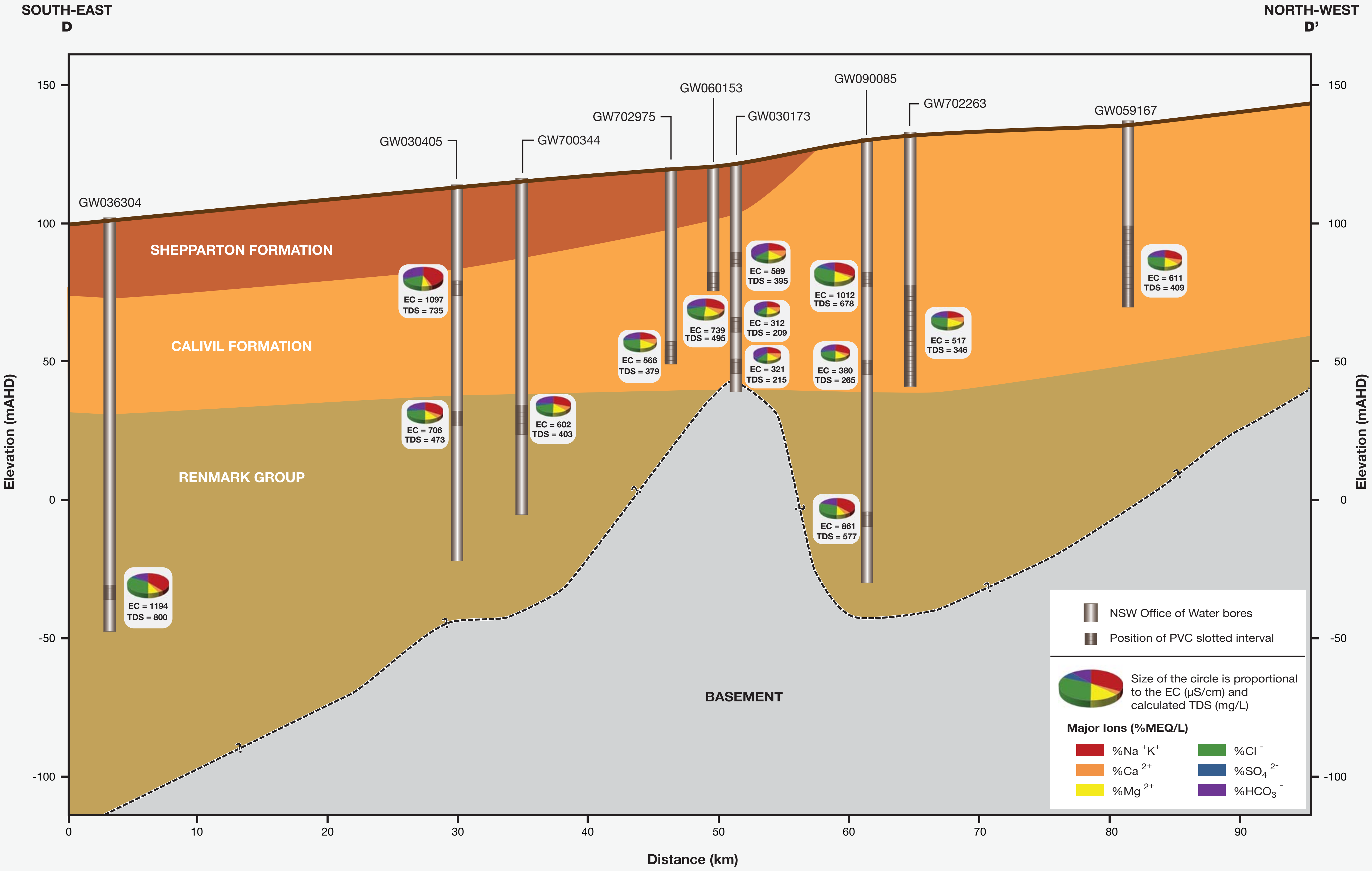


Figure 7-6 Conceptual hydrogeological cross-section - Lower Lachlan

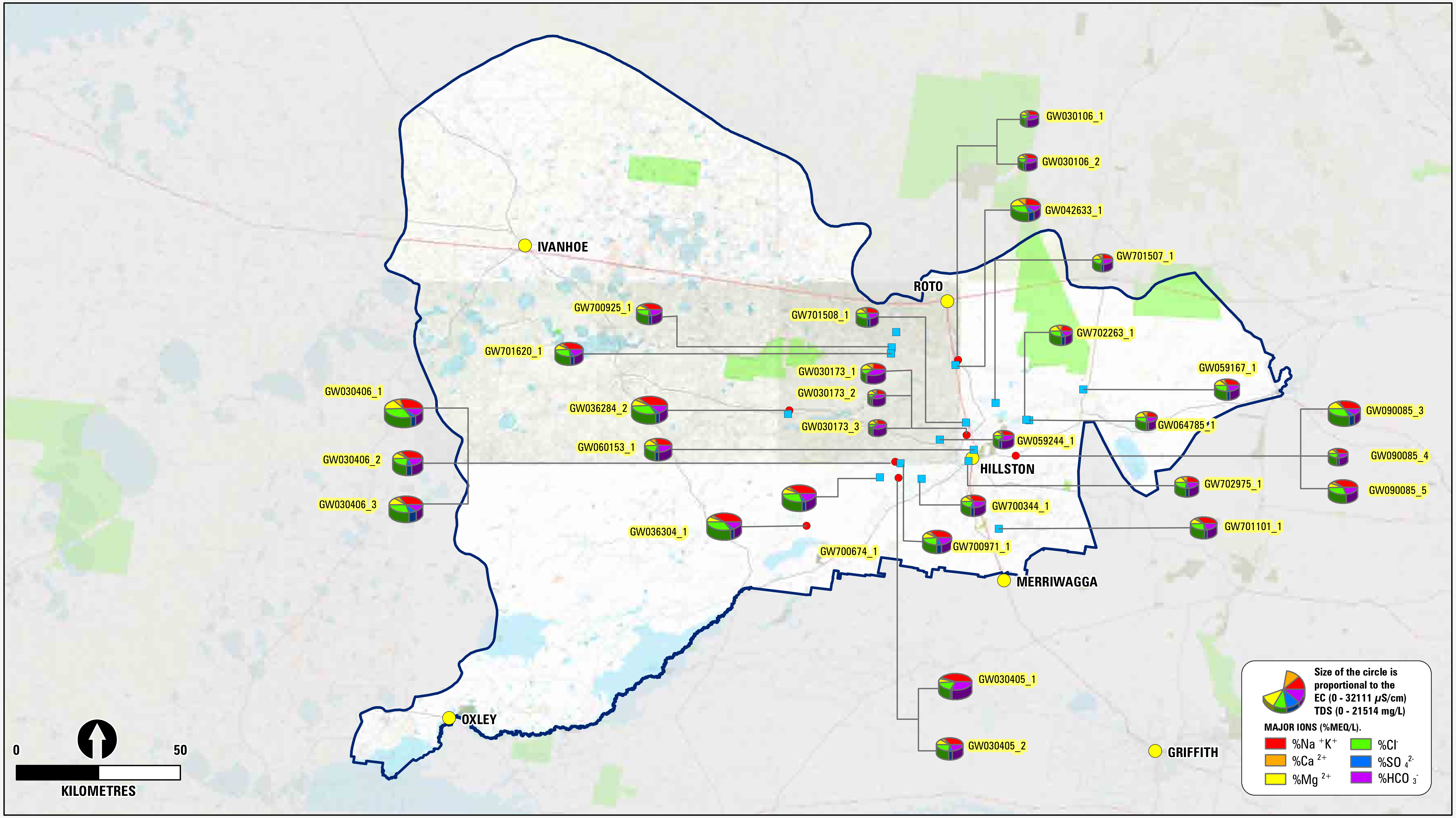


Figure 7-7: Major ion chemistry and salinity (average 2009 - 2011)
Lower Lachlan catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F016_B1.mxd // kumarg // 08/12/2011

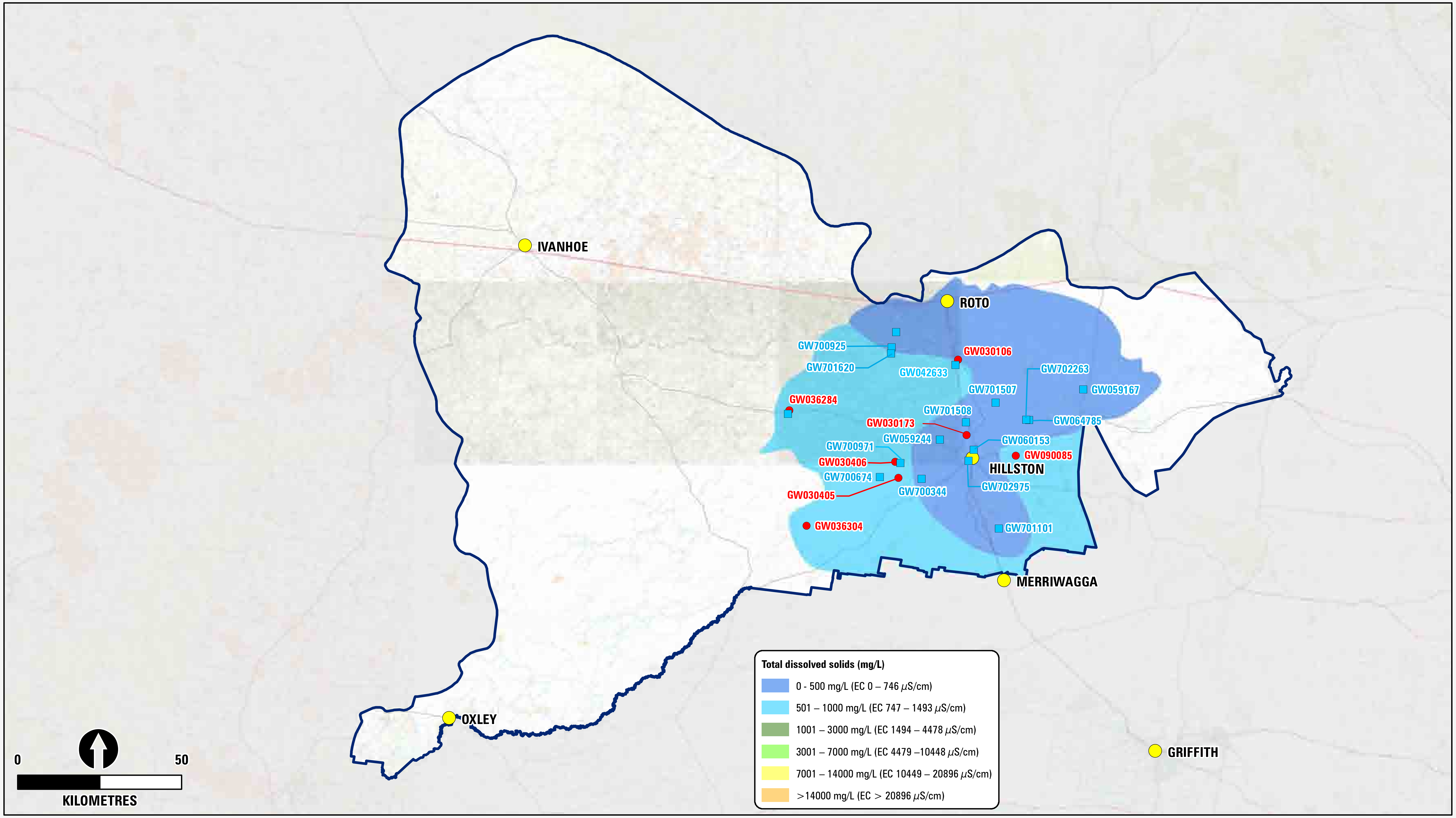
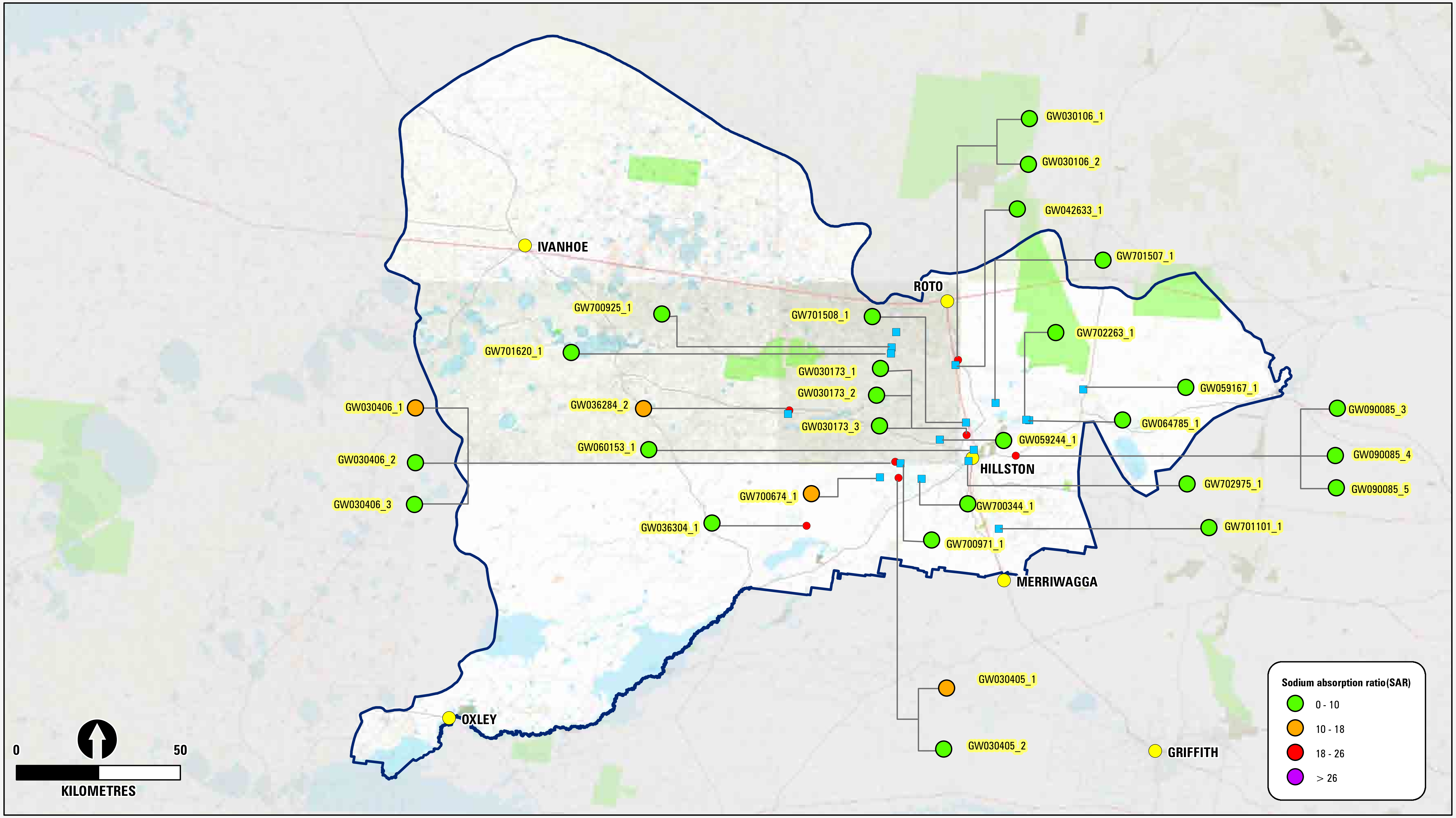


Figure 7-8: Average calculated total dissolved solids (2009 -2011)
Lower Lachlan catchment

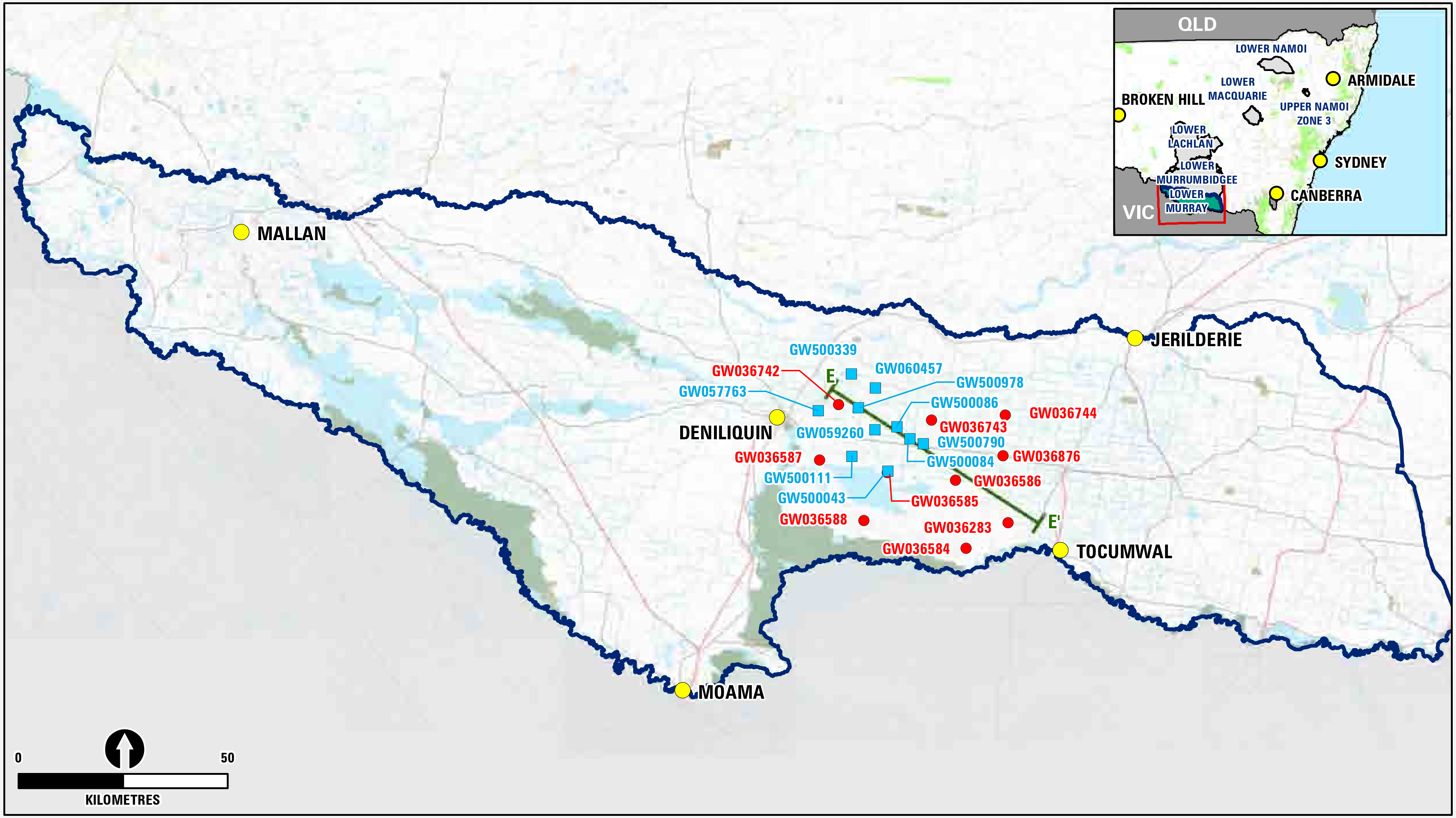
\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY10_GIS\Projects\ESRI\2114803A_GIS_F022_B1.mxd // kumarg // 09/12/2011



● Town
— Drainage
— Main road
— Railway line
▭ GMA boundary
▨ National park, reserves & state forests
● Observation bore
■ Pumping bore
Calivil/Renmark formations

Figure 7-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Lower Lachlan catchment

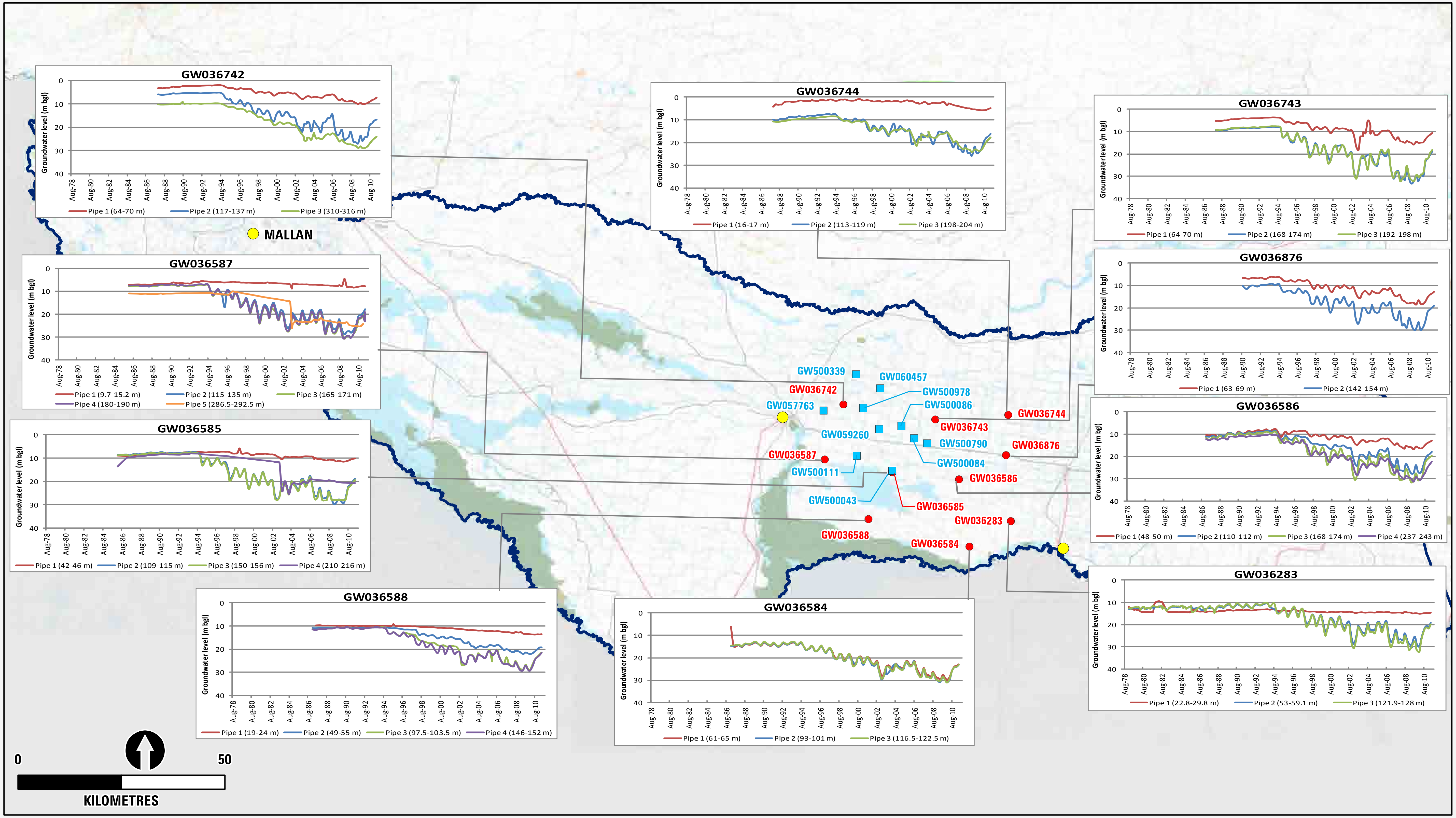
\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F028_A2.mxd // kumarg // 17/11/2011



● Town
— Main road
▭ GMA boundary
● Observation bore
⊢⊣ Cross section
— Drainage
— Railway line
🟩 National park, reserves & state forests
■ Pumping bore

Figure 8-1: Topography & sampling locations
Lower Murray catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F002_B1.mxd // kumarg // 09/12/2011



● Town
— Main road
▭ GMA boundary
● Observation bore
— Drainage
— Railway line
🟩 National park, reserves & state forests
🟦 Pumping bore

Figure 8-5: Hydrograph data - *Lower Murray catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F011_A1.mxd// kumarg // 18/11/2011

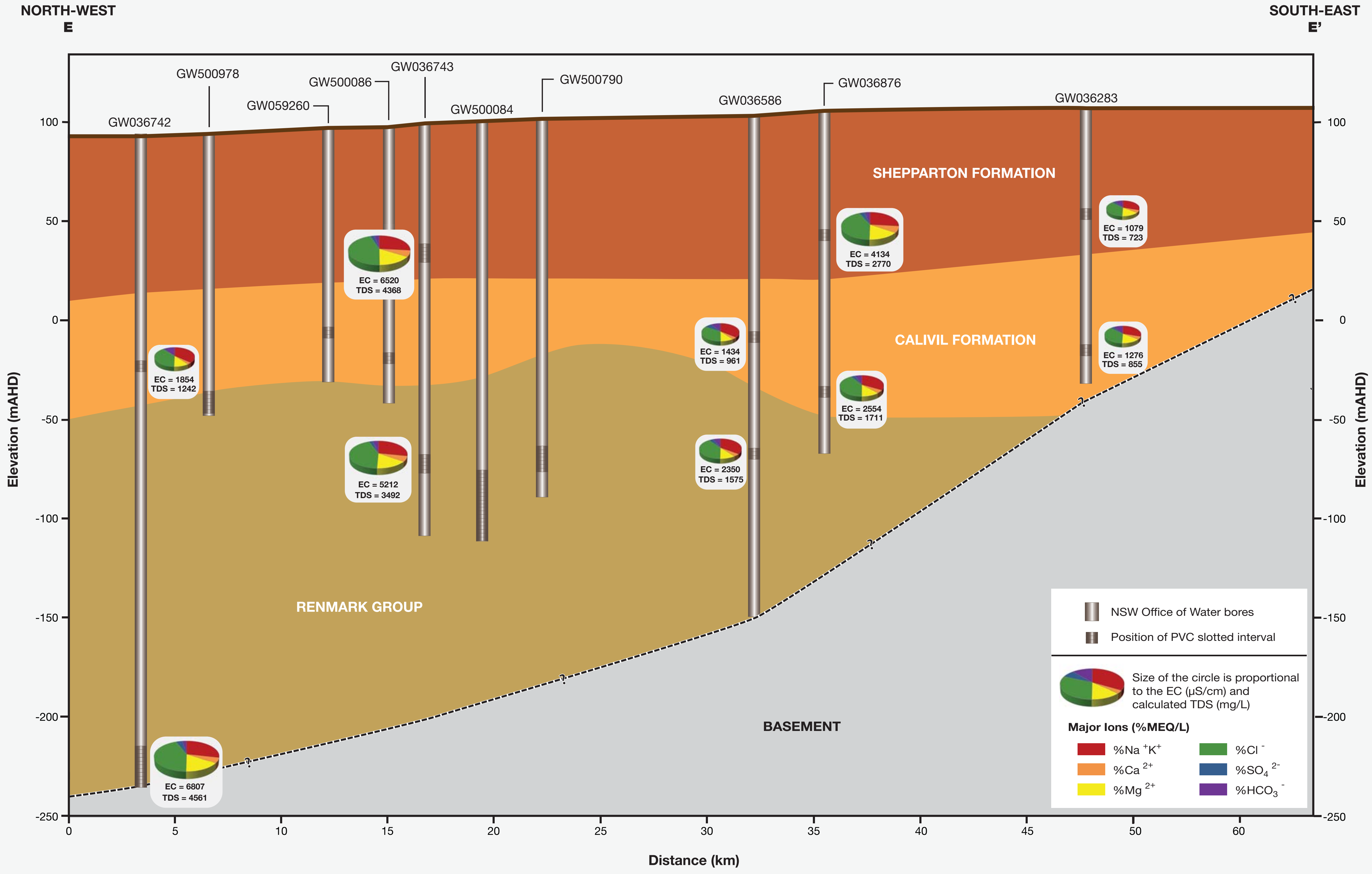
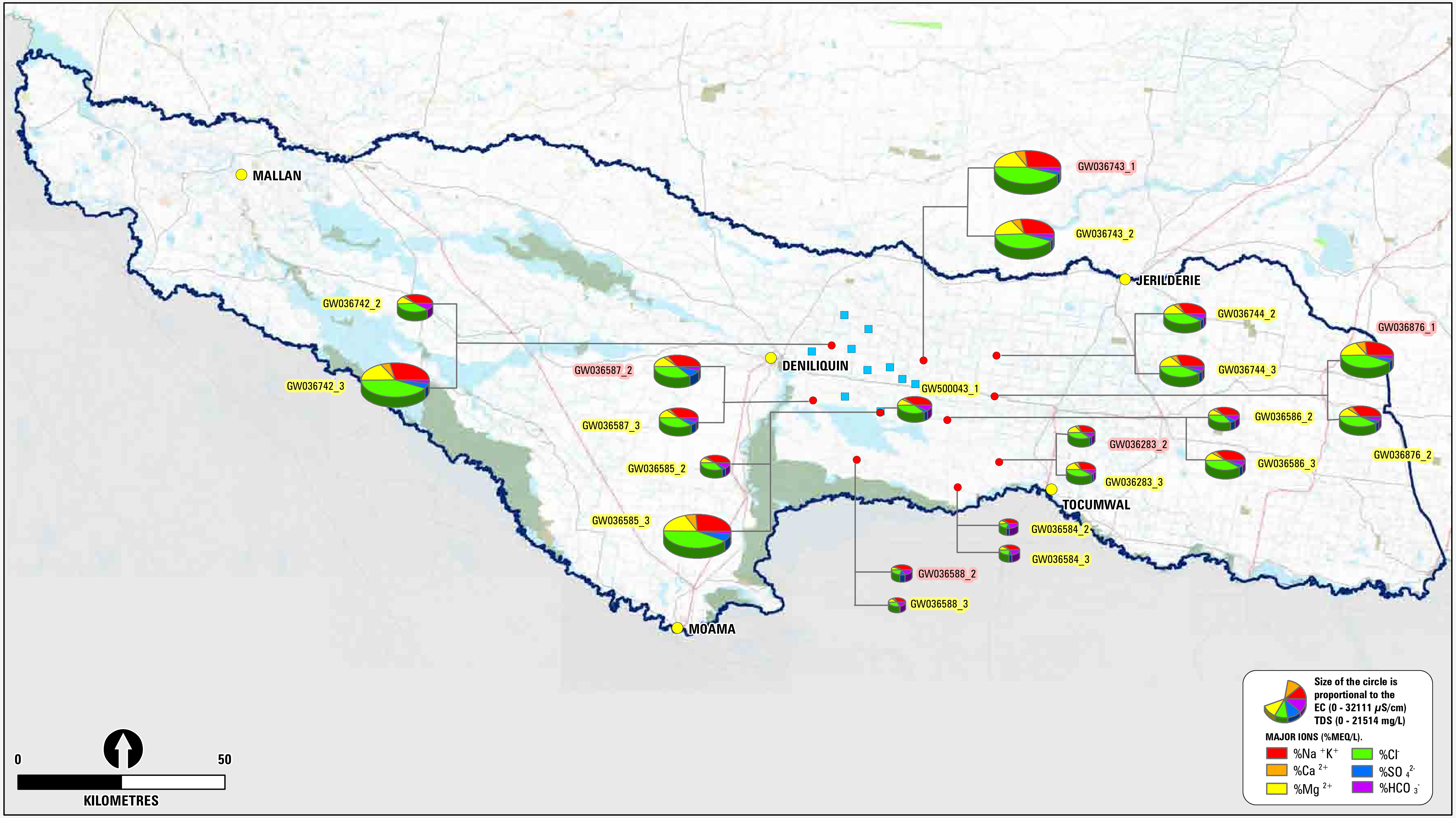


Figure 8-6 Conceptual hydrogeological cross-section - Lower Murray



● Town
— Main road
▭ GMA boundary
● Observation bore
Shepparton formation
— Drainage
— Railway line
▨ National park, reserves & state forests
■ Pumping bore
Calivil/Renmark formations

Figure 8-7: Major ion chemistry and salinity (average 2009 - 2011)
Lower Murray catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F017_B1.mxd // kumarg // 08/12/2011

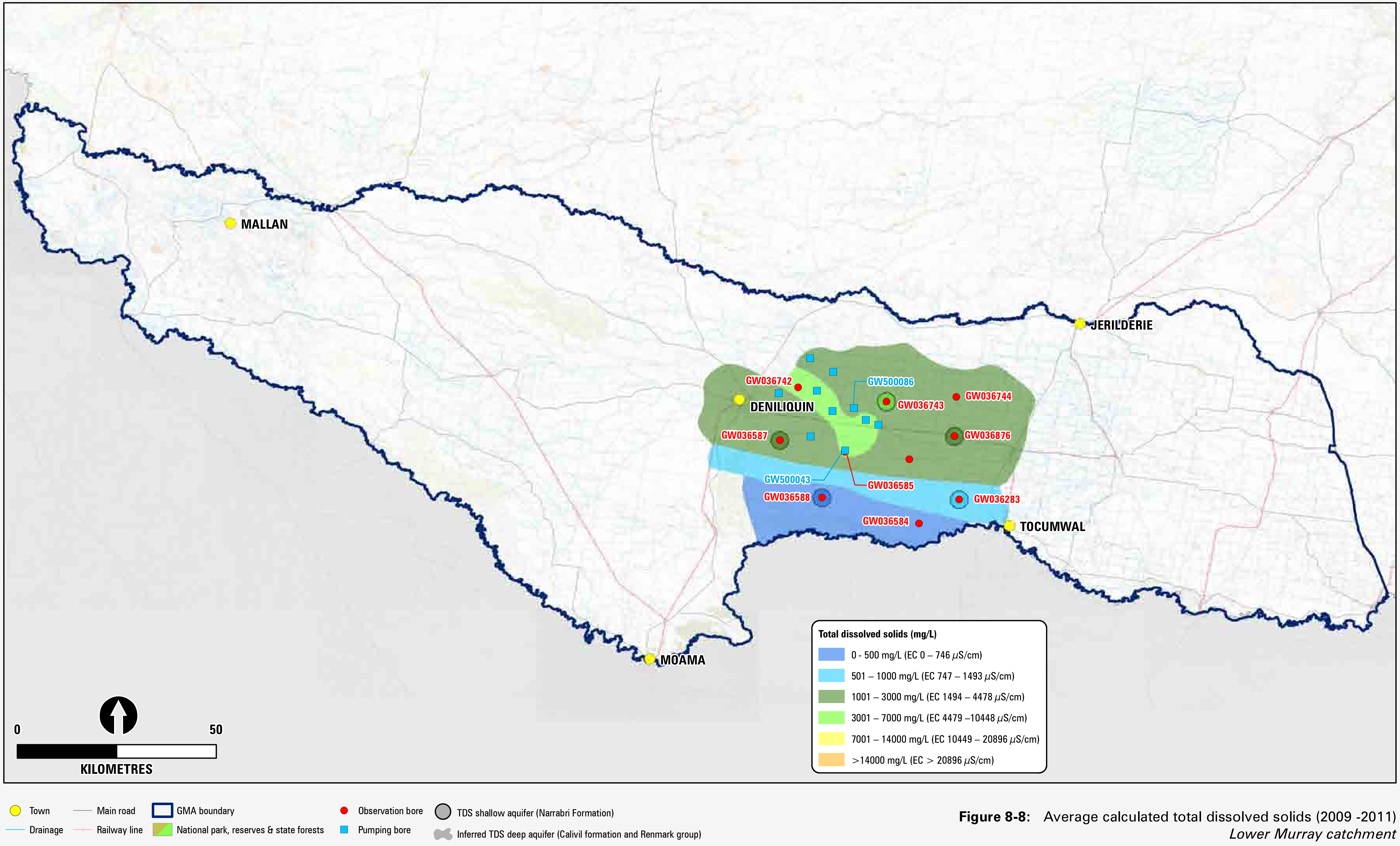
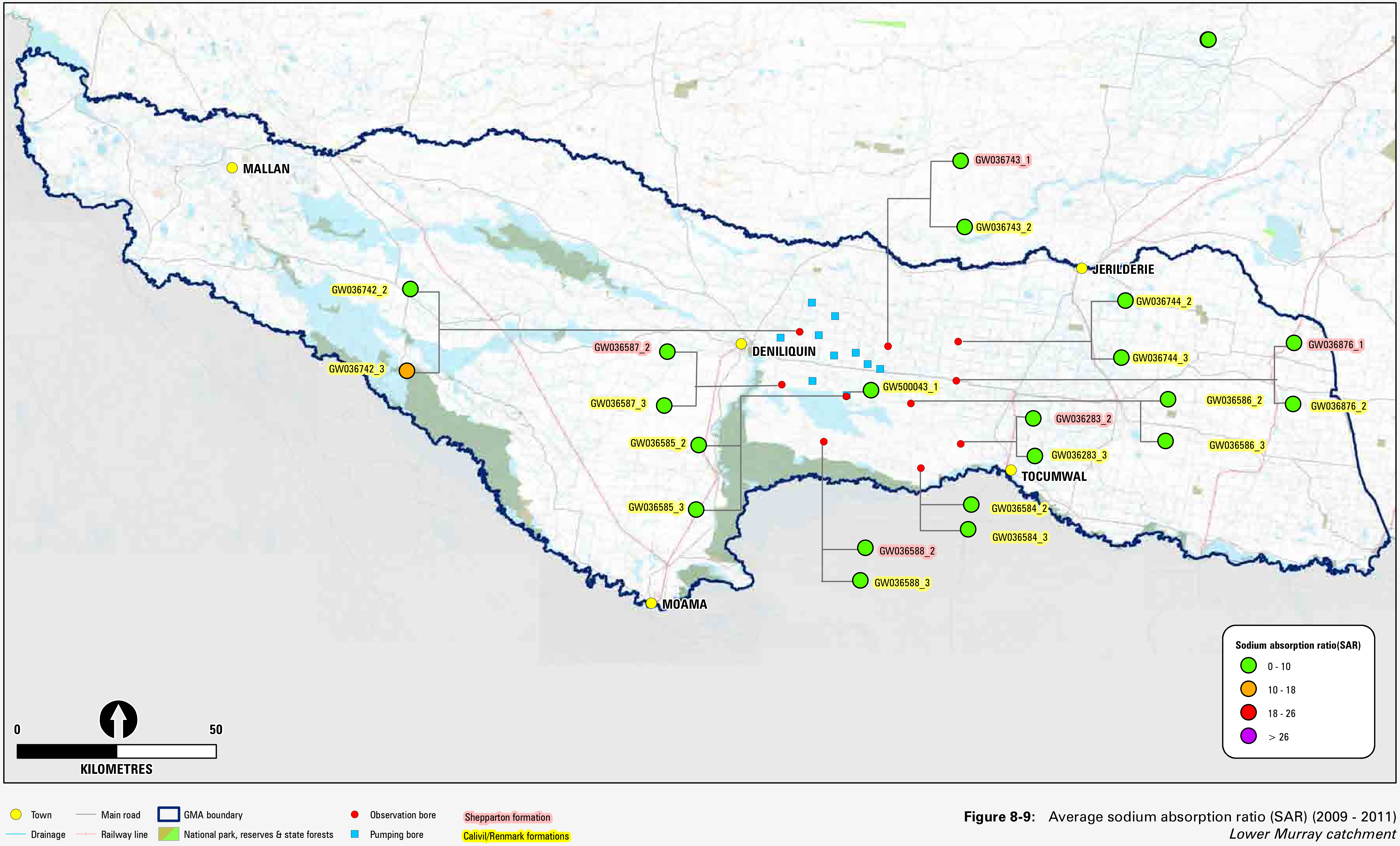


Figure 8-8: Average calculated total dissolved solids (2009 -2011)
Lower Murray catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F023_B1.mxd // kumarg // 09/12/2011



\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F029_A2.mxd // kumarg // 18/11/2011

Figure 8-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Lower Murray catchment

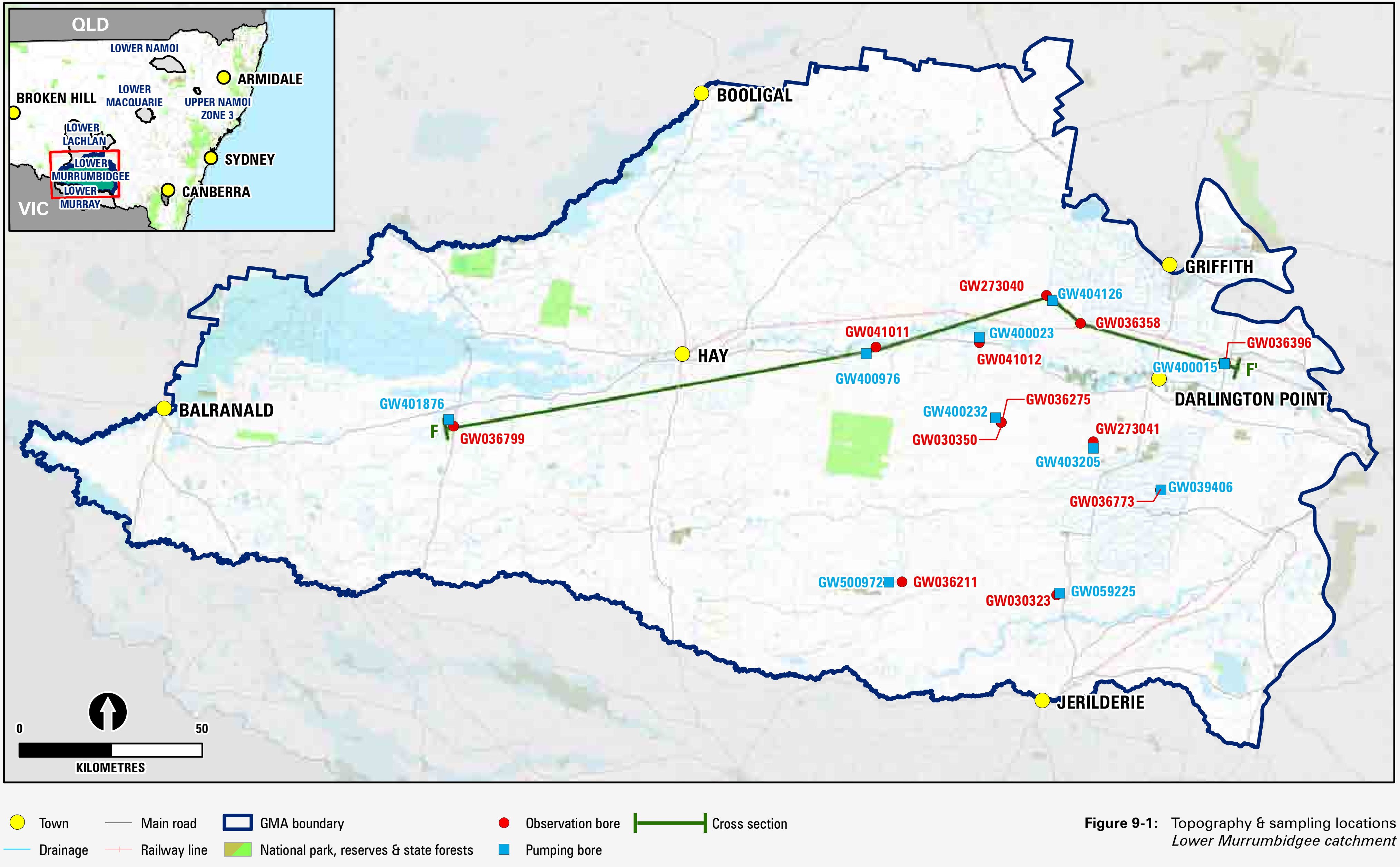
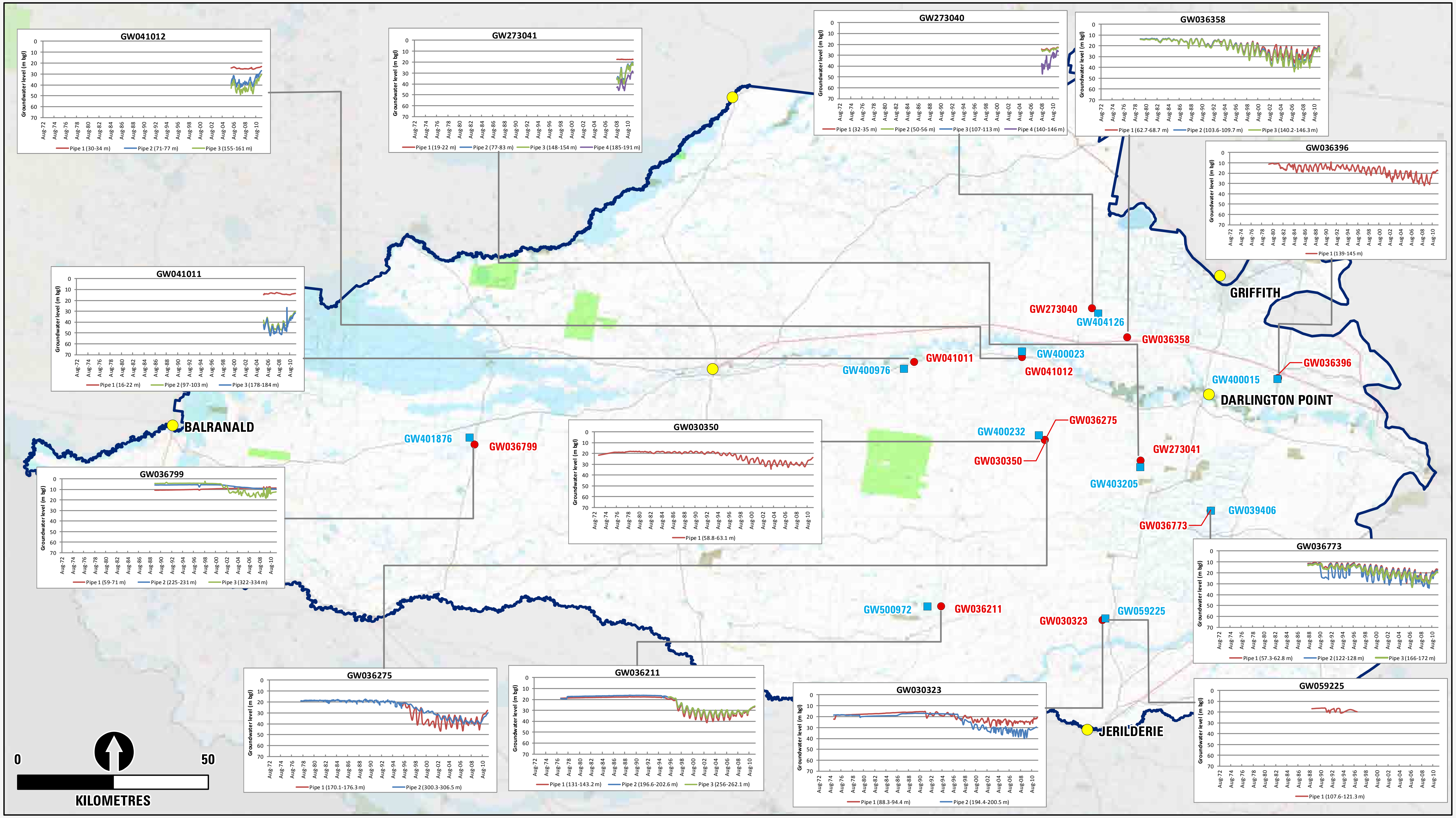


Figure 9-1: Topography & sampling locations
Lower Murrumbidgee catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803A_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F004_B1.mxd // kumarg // 08/12/2011



● Town
— Main road
▭ GMA boundary
● Observation bore
— Drainage
— Railway line
🟩 National park, reserves & state forests
■ Pumping bore

Figure 9-5: Hydrograph data - *Lower Murrumbidgee catchment*

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F012_A1.mxd // kumarg // 11/11/2011

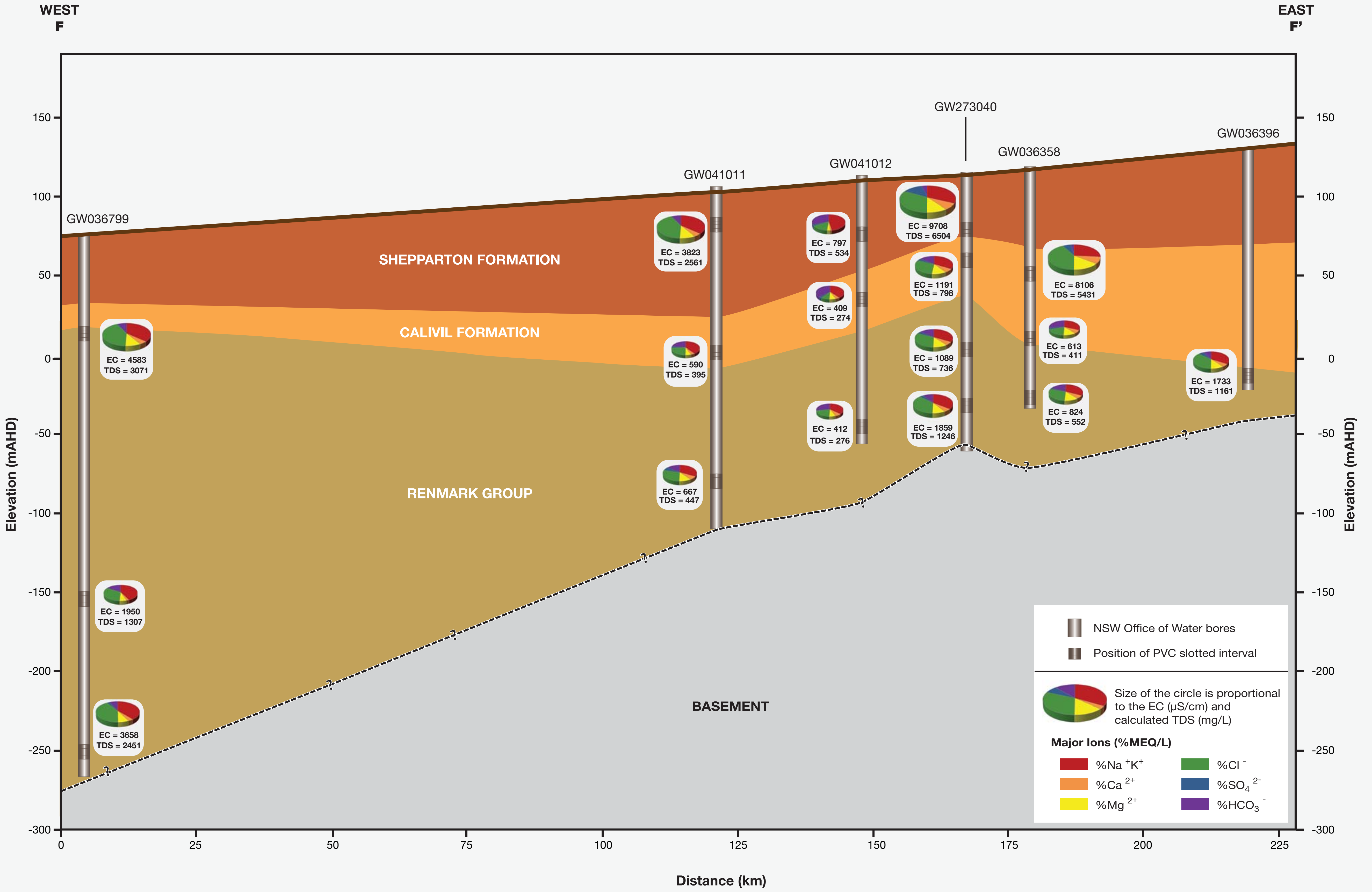
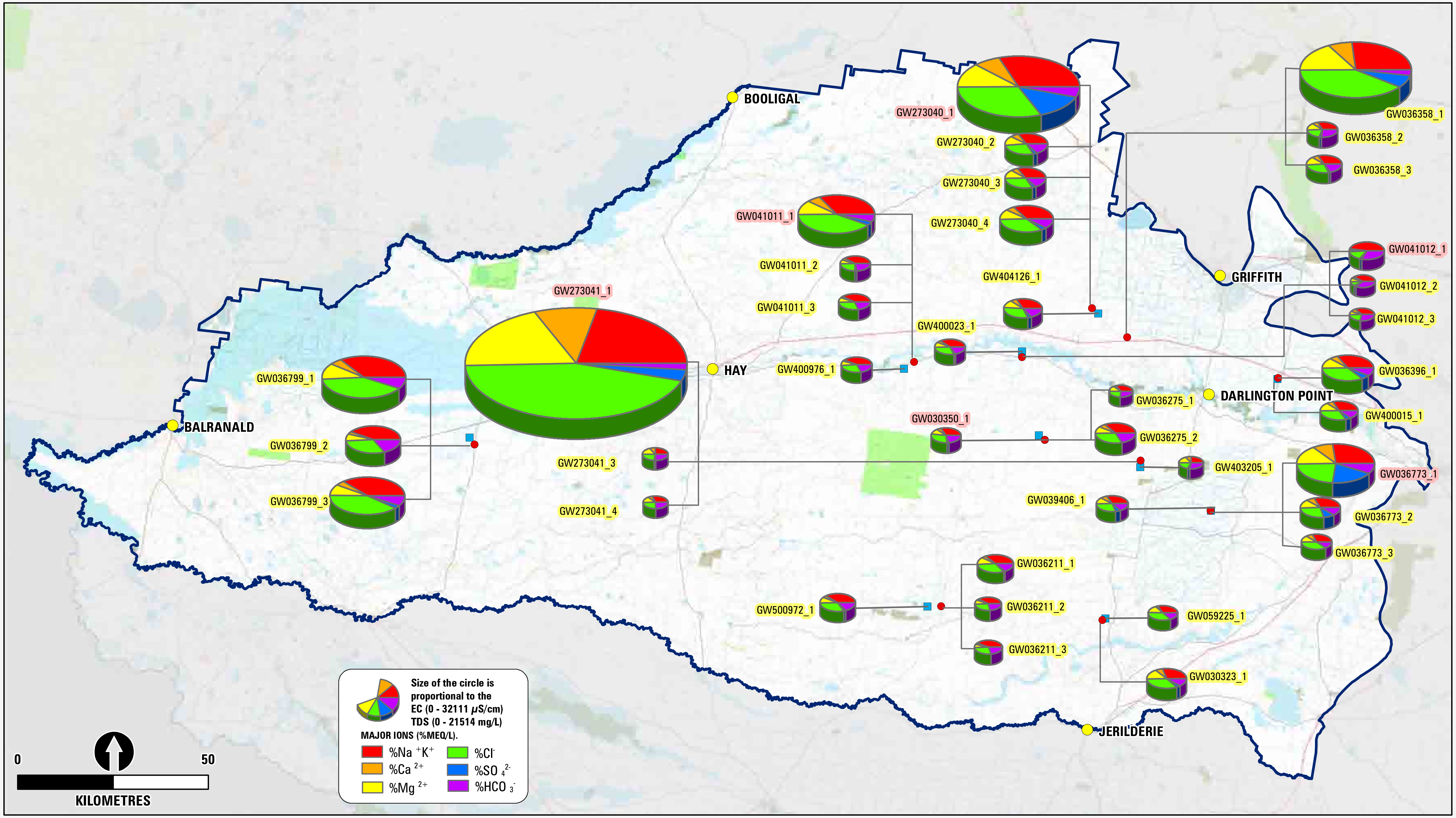


Figure 9-6 Conceptual hydrogeological cross-section - Lower Murrumbidgee



🟡 Town
Drainage
Main road
Railway line
GMA boundary
National park, reserves & state forests
🔴 Observation bore
🟦 Pumping bore
Shepparton formation
Calivil/Renmark formations

Figure 9-7: Major ion chemistry and salinity (average 2009 - 2011)
Lower Murrumbidgee catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F018_B1.mxd // kumarg // 09/12/2011

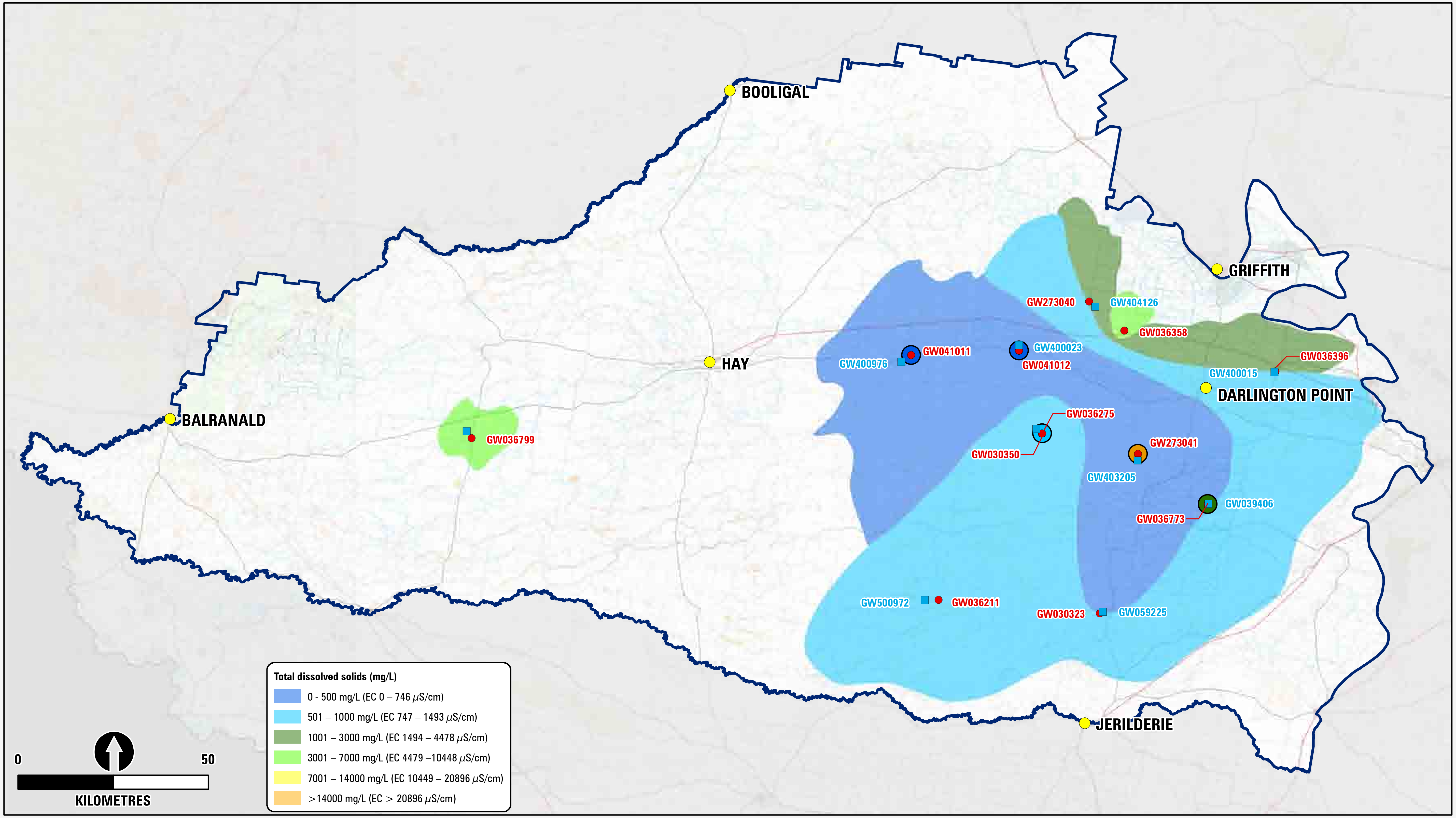


Figure 9-8: Average calculated total dissolved solids (2009 -2011)
Lower Murrumbidgee catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F024_B1.mxd // kumarg // 09/12/2011

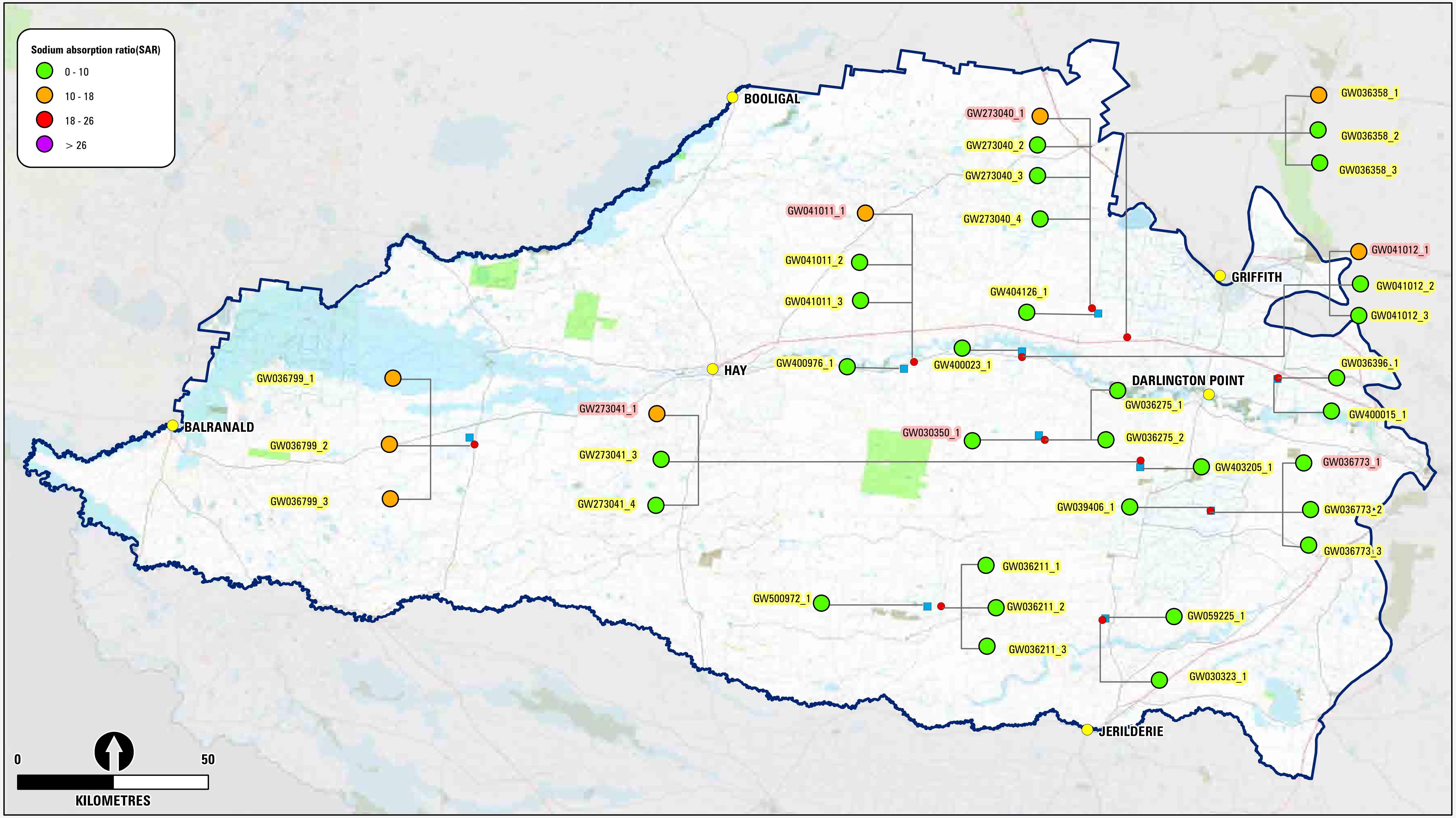


Figure 9-9: Average sodium absorption ratio (SAR) (2009 - 2011)
Lower Murrumbidgee catchment

\\APSYDNAS02\proj\N\NSW_Office_of_Water\2114803a_NSW_GROUNDWATER_QUALITY_STUDY\10_GIS\Projects\ESRI\2114803A_GIS_F030_A2.mxd // kumarg // 17/11/2011

Appendix

A

Water quality data set

CD – NSW Office of Water - water quality data set

Contents

Upper Namoi GMA ‘Zone 3’ water quality data 1993-2011 – UpperNamoiWqtData.xls

Lower Namoi GMA water quality data 1999-2011 – LowerNamoiWqtData.xls

Lower Macquarie GMA water quality data 2003-2010 – LowerMacquarieWqtData.xls

Lower Lachlan GMA water quality data 2000-2011 – LowerLachlanWqtData.xls

Lower Muray GMA water quality data 2003-2010 – LowerMurrayWqtData.xls

Lower Murrumbidgee GMA water quality data 1973-2011 – LowerMurrumbidgeeWqtData.xls

Appendix

B

Quality Assurance / Quality Control Results

Table B-1 Relative percentage difference calculations for duplicates and primary samples

Where >10%

Station ID	GW030106_2	GW030106_2	RPD (%dif)	GW030106_2	GW030106_2	RPD (%dif)	GW030106_2	GW030106_2	RPD (%dif)
Sampling Date	20-Apr-2010	20-Apr-2010		08-Jun-10	8-Jun-2010		1-Jul-2010	1-Jul-2010	
Aluminium (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Aluminium (Total)	< 0.05	< 0.05		< 0.05	< 0.05		< 0.05	0.15	
Ammonia	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Bicarbonate as HCO3	120	120	0.00	120	120	0.00	120	120	0.00
Boron (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Boron (Total)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Bromide	< 0.2	< 0.2		< 0.2	< 0.2		< 0.2	< 0.2	
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	9.7	9.6	1.04	9.0	9.1	1.10	9.5	9.7	2.08
Chloride	30	37	20.90	37	38	2.67	37	37	0.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.32	0.33	3.08	0.30	0.32	6.45	0.33	0.28	16.39
Iron (Total)	< 0.05	< 0.05		< 0.05	< 0.05		< 0.05	< 0.05	
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1			< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	9.9	9.7	2.04	9.2	9.4	2.15	9.1	9.3	2.17
Manganese (Soluble)	< 0.002	< 0.002		0.6e-4	< 0.002		< 0.002	< 0.002	
Manganese (Total)	< 0.002	< 0.002		< 0.002	< 0.002		< 0.002	< 0.002	
Nickel (Soluble)	< 0.01								
Nickel (Total)	0.010	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N									
Oxidised Nitrogen as N	0.02	0.03	40.00	0.03	0.03	0.00	0.03	0.02	40.00
Reactive Phosphorus (Filtered)	0.030	0.029	3.39	0.023	0.027	16.00	0.029	0.026	10.91
Potassium (Soluble)	2.8	2.8	0.00	2.8	2.9	3.51	2.6	2.7	3.77
Silicon (Soluble)	8.5	8.3	2.38	8.8	8.9	1.13	8.4	8.4	0.00
Sodium (Soluble)	48	47	2.11	45	45	0.00	42	42	0.00
Strontium (Soluble)	0.15	0.15	0.00	0.15	0.15	0.00	0.16	0.16	0.00
Sulphate	13	15	14.29	15	15	0.00	15	15	0.00
Total Alkalinity	100	99	1.01	99	100	1.01	100	99	1.01
Total Dissolved Solids	210	190	10.00	180	170	5.71	180	200	10.53
Total Nitrogen	< 0.05	< 0.05		< 0.05	< 0.05		0.09	< 0.05	
Total Phosphorus	0.032	0.030	6.45	0.029	0.031	6.67	0.031	0.026	17.54
Zinc (Soluble)	< 0.005	< 0.005		< 0.005	< 0.005		0.007	0.007	0.00
Zinc (Total)	< 0.01	< 0.01		< 0.01	< 0.01		0.020	0.030	40.00
EC @ 25C	343	340	0.88	353	352	0.28	361	351	2.81
Field EC		314			338			303	

Where >10%

Station ID	GW030406_3	GW030406_3	RPD (%dif)	GW030406_3	GW030406_3	RPD (%dif)	GW030430_2	GW030430_2	RPD (%dif)
Sampling Date	10-Nov-2010	10-Nov-2010		7-Dec-2010	7-Dec-2010		29-Jun-2010	29-Jun-2010	
Aluminium (Soluble)	< 0.01	< 0.01		0.010	< 0.01		< 0.01	< 0.01	
Aluminium (Total)	0.12	0.13	8.00	< 0.05	< 0.05		< 0.05	< 0.05	
Ammonia	0.09	0.08	11.76	0.07	0.06	15.38	< 0.01	0.02	
Bicarbonate as HCO3	160	160	0.00	160	160	0.00	360	360	0.00
Boron (Soluble)	0.1	0.1	0.00	0.2	0.2	0.00	< 0.1	< 0.1	
Boron (Total)	0.1	0.1	0.00	0.1	0.1	0.00	0.1	< 0.1	
Bromide	0.9	0.8	11.76	0.9	1.0	10.53	0.4	0.3	28.57
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	2.9	
Calcium (Soluble)	27	27	0.00	25	26	3.92	24	21	13.33
Chloride	210	210	0.00	230	230	0.00	82	82	0.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.44	0.42	4.65	0.48	0.46	4.26	0.13	0.10	26.09
Iron (Total)	0.050	0.060	18.18	< 0.05	< 0.05		< 0.05	< 0.05	
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	31	31	0.00	29	30	3.39	17	15	12.50
Manganese (Soluble)	0.019	0.020	5.13	0.015	0.017	12.50	< 0.002	< 0.002	
Manganese (Total)	0.018	0.018	0.00	0.019	0.019	0.00	< 0.002	< 0.002	
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N							0.4		
Oxidised Nitrogen as N	0.03	0.02	40.00	< 0.01	< 0.01			0.40	
Reactive Phosphorus (Filtered)	0.025	0.052	70.13	0.035	0.049	33.33	0.041	0.043	4.76
Potassium (Soluble)	4.3	4.4	2.30	4.6	4.4	4.44	1.2	1.1	8.70
Silicon (Soluble)	5.8	5.8	0.00	5.0	5.2	3.92	9.2	8.6	6.74
Sodium (Soluble)	170	170	0.00	160	170	6.06	160	160	0.00
Strontium (Soluble)	0.47	0.47	0.00	0.44	0.47	6.59	0.51	0.49	4.00
Sulphate	88	88	0.00	98	96	2.06	22	22	0.00
Total Alkalinity	130	130	0.00	130	130	0.00	300	300	0.00
Total Dissolved Solids	670	650	3.03	620	620	0.00	450	500	10.53
Total Nitrogen	0.11	0.15	30.77	0.21	0.15	33.33	0.29	0.36	21.54
Total Phosphorus	0.066	0.068	2.99	0.063	0.052	19.13	0.075	0.083	10.13
Zinc (Soluble)	< 0.005	< 0.005		< 0.005	< 0.005		0.020	0.007	96.30
Zinc (Total)	< 0.01	< 0.01		< 0.01	< 0.01		0.017	0.018	5.71
EC @ 25C	1159	1141	1.57	1152	1158	0.52	838	856	2.13
Field EC		1154			1152			854	

Where >10%

Station ID	**GW030431_3**	**GW030431_3**	**RPD (%dif)**	**GW030431_3**	**GW030431_3**	**RPD (%dif)**	**GW036151_1**	**GW036151_1**	**RPD (%dif)**
Sampling Date	13-May-10	13-May-2010		28-Oct-10	28-Oct-2010		11-Mar-10	11-Mar-2010	
Aluminium (Soluble)	0.010	0.010	0.00	0.020	0.020	0.00	0.14	0.10	33.33
Aluminium (Total)	< 0.05	< 0.05		0.10	0.13	26.09	0.43	0.46	6.74
Ammonia	< 0.01	< 0.01		0.02	0.02	0.00	< 0.01	0.01	
Bicarbonate as HCO3	440	440	0.00	430	430	0.00	220	230	4.44
Boron (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		1.4	1.4	0.00
Boron (Total)	< 0.1	< 0.1		< 0.1	< 0.1		0.8	0.8	0.00
Bromide	0.2	0.2	0.00	0.3	0.2	40.00	16	17	6.06
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	76	76	0.00	76	74	2.67	540	540	0.00
Chloride	51	52	1.94	51	51	0.00	3900	3900	0.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		0.34	0.030	167.57
Fluoride	0.30	0.26	14.29	0.35	0.23	41.38	0.73	0.56	26.36
Iron (Total)	< 0.05	< 0.05		< 0.05	< 0.05		0.30	0.27	10.53
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		0.048	0.050	4.08
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	22	21	4.65	21	21	0.00	450	450	0.00
Manganese (Soluble)	0.003	0.003	0.00	0.005	0.005	0.00	0.003	0.002	40.00
Manganese (Total)	< 0.002	< 0.002		< 0.002	0.0030		0.016	0.016	0.00
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	0.011	
Nitrate - N							5.0	5.5	9.52
Oxidised Nitrogen as N	0.22	0.21	4.65	0.21	0.21	0.00			
Reactive Phosphorus (Filtered)	0.431	0.440	2.07	0.471	0.457	3.02	0.011	0.013	16.67
Potassium (Soluble)	3.4	3.4	0.00	3.6	3.5	2.82	5.4	5.4	0.00
Silicon (Soluble)	39	38	2.60	41	40	2.47	8.5	8.4	1.18
Sodium (Soluble)	87	86	1.16	89	88	1.13	3900	3900	0.00
Strontium (Soluble)	0.82	0.81	1.23	0.84	0.82	2.41	14	14	0.00
Sulphate	33	34	2.99	32	32	0.00	5500	5500	0.00
Total Alkalinity	360	360	0.00	350	350	0.00	180	190	5.41
Total Dissolved Solids	550	600	8.70	570	610	6.78	15000	15000	0.00
Total Nitrogen	0.22	0.21	4.65	0.22	0.23	4.44	6.0	5.8	3.39
Total Phosphorus	0.425	0.430	1.17	0.472	0.489	3.54	0.024	0.024	0.00
Zinc (Soluble)	0.019	0.017	11.11	0.027	0.027	0.00	0.006	0.011	58.82
Zinc (Total)	0.020	0.030	40.00	0.030	0.040	28.57	0.19	0.040	130.43
EC @ 25C	863	1100	24.15	870	874	0.46	17000	16600	2.38
Field EC		873			868			18940	

Where >10%

Station ID	GW036211_3	GW036211_3	RPD (%dif)	GW036211_3	GW036211_3	RPD (%dif)	GW036213_3	GW036213_3	RPD (%dif)
Sampling Date	27-Jul-2010	27-Jul-2010		9-Nov-2010	9-Nov-2010		31-Jan-11	31-Jan-2011	
Aluminium (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		0.020	0.020	0.00
Aluminium (Total)	< 0.05	< 0.05		0.11	0.11	0.00	< 0.05	< 0.05	
Ammonia	0.39	0.42	7.41	0.03	0.41	172.73	< 0.01	< 0.01	
Bicarbonate as HCO3	120	120	0.00	120	120	0.00	440	440	0.00
Boron (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Boron (Total)	< 0.1	< 0.1		< 0.1	< 0.1		0.1	0.1	0.00
Bromide	0.5	0.5	0.00	0.4	0.4	0.00	0.4	0.3	28.57
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	5.7	5.6	1.77	5.5	6.3	13.56	64	64	0.00
Chloride	98	98	0.00	98	98	0.00	70	130	60.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.66	0.69	4.44	0.77	0.77	0.00	0.25	0.23	8.33
Iron (Total)	0.22	< 0.05		0.27	0.28	3.64	0.15	0.15	0.00
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	6.7	6.7	0.00	7.2	7.5	4.08	26	25	3.92
Manganese (Soluble)	0.036	0.036	0.00	0.035	0.036	2.82	0.004	0.004	0.00
Manganese (Total)	0.030	< 0.002		0.030	0.030	0.00	0.0039	0.0036	8.00
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N									
Oxidised Nitrogen as N	< 0.01	0.01		0.11	0.01	166.67	0.20	0.25	22.22
Reactive Phosphorus (Filtered)	0.136	0.144	5.71	0.160	0.153	4.47	0.248	0.227	8.84
Potassium (Soluble)	4.8	4.8	0.00	5.0	5.1	1.98	3.0	2.8	6.90
Silicon (Soluble)	5.6	5.7	1.77	6.3	6.3	0.00	30	29	3.39
Sodium (Soluble)	92	94	2.15	92	96	4.26	130	130	0.00
Strontium (Soluble)	0.099	0.099	0.00	0.11	0.11	0.00	0.99	0.99	0.00
Sulphate	< 0.5	< 0.5		< 0.5	< 0.5		44	67	41.44
Total Alkalinity	100	100	0.00	100	100	0.00	360	360	0.00
Total Dissolved Solids	260	260	0.00	330	320	3.08	590	600	1.68
Total Nitrogen	0.45	0.45	0.00	0.56	0.48	15.38	0.27	0.26	3.77
Total Phosphorus	0.165	0.161	2.45	0.167	0.165	1.20	0.289	0.281	2.81
Zinc (Soluble)	0.010	0.01	0.00	0.018	0.024	28.57	0.031	0.015	69.57
Zinc (Total)	< 0.01	0.030		0.015	0.017	12.50	0.030	0.020	40.00
EC @ 25C	514	513	0.19	523	522	0.19	978	1002	2.42
Field EC		512			515			882	

Where >10%

Station ID	GW036358_3	GW036358_3	RPD (%dif)	GW036358_3	GW036358_3	RPD (%dif)	GW036396_1	GW036396_1	RPD (%dif)
Sampling Date	15-Mar-2010	15-Mar-2010		24-Jan-2011	24-Jan-2011		3-Dec-2009	3-Dec-2009	
Aluminium (Soluble)	< 0.01	< 0.01		< 0.01	0.010		< 0.01	0.010	
Aluminium (Total)	0.10	0.080	22.22	< 0.05	< 0.05		< 0.05	< 0.05	
Ammonia	0.04	0.04	0.00	0.04	0.04	0.00	0.05	0.06	18.18
Bicarbonate as HCO3	160	160	0.00	160	160	0.00	160	160	0.00
Boron (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		0.1	0.1	0.00
Boron (Total)	< 0.1	< 0.1		< 0.1	< 0.1		0.1	0.1	0.00
Bromide	0.7	0.7	0.00	0.8	0.8	0.00	1.7	2.0	16.22
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	21	21	0.00	22	22	0.00	41	42	2.41
Chloride	160	160	0.00	160	160	0.00	460	450	2.20
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	0.0068		< 0.005	< 0.005	
Fluoride	0.42	0.43	2.35	0.46	0.45	2.20	0.47	0.44	6.59
Iron (Total)	0.44	0.45	2.25	0.41	0.40	2.47	0.080	0.060	28.57
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	22	22	0.00	23	23	0.00	46	47	2.15
Manganese (Soluble)	0.009	0.01	10.53	0.009	0.009	0.00	0.041	0.042	2.41
Manganese (Total)	0.0086	0.0090	4.55	0.0092	0.0090	2.20	0.040	0.040	0.00
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N									
Oxidised Nitrogen as N	< 0.01	< 0.01		< 0.01	0.03		0.02	< 0.01	
Reactive Phosphorus (Filtered)	0.018	0.015	18.18	0.017	0.018	5.71	0.064	0.056	13.33
Potassium (Soluble)	2.6	2.6	0.00	2.7	2.7	0.00	4.1	4.2	2.41
Silicon (Soluble)	5.3	5.3	0.00	5.1	5.0	1.98	6.0	6.0	0.00
Sodium (Soluble)	120	120	0.00	120	120	0.00	290	290	0.00
Strontium (Soluble)	0.31	0.31	0.00	0.36	0.35	2.82	0.83	0.84	1.20
Sulphate	20	21	4.88	22	22	0.00	85	85	0.00
Total Alkalinity	130	130	0.00	130	130	0.00	130	130	0.00
Total Dissolved Solids	420	450	6.90	500	520	3.92	1200	1200	0.00
Total Nitrogen	0.07	0.08	13.33	0.07	0.08	13.33	0.11	0.17	42.86
Total Phosphorus	0.028	0.032	13.33	0.028	0.030	6.90	0.061	0.057	6.78
Zinc (Soluble)	0.071	0.10	33.92	< 0.005	< 0.005		0.067	0.039	52.83
Zinc (Total)	0.040	0.030	28.57	< 0.01	< 0.01		0.020	0.040	66.67
EC @ 25C	831	826	0.60	847	833	1.67	1680	1670	0.60
Field EC		840			839			1,808	

Where >10%

Station ID	**GW036396_1**	**GW036396_1**	**RPD (%dif)**	**GW036587_3**	**GW036587_3**	**RPD (%dif)**	**GW036742_2**	**GW036742_2**	**RPD (%dif)**
Sampling Date	22-Feb-2010	22-Feb-2010		26-Oct-10	26-Oct-2010		15-Dec-10	15-Dec-2010	
Aluminium (Soluble)	< 0.01	< 0.01		0.010	0.010	0.00	0.010	< 0.01	
Aluminium (Total)	< 0.05	< 0.05		0.090	0.090	0.00	0.12	0.11	8.70
Ammonia	0.04	0.04	0.00	0.13	0.12	8.00	0.19	0.19	0.00
Bicarbonate as HCO3	160	160	0.00	140	140	0.00	220	220	0.00
Boron (Soluble)	0.1	0.1	0.00	< 0.1	< 0.1		< 0.1	< 0.1	
Boron (Total)	0.1	0.1	0.00	< 0.1	< 0.1		< 0.1	< 0.1	
Bromide	1.7	1.8	5.71	2.2	1.9	14.63	2.3	2.1	9.09
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	37	37	0.00	27	27	0.00	22	23	4.44
Chloride	460	450	2.20	540	520	3.77	520	530	1.90
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.52	0.58	10.91	0.80	0.80	0.00	0.77	0.77	0.00
Iron (Total)	< 0.05	< 0.05		0.51	0.47	8.16	0.87	1.0	13.90
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	44	44	0.00	55	53	3.70	45	51	12.50
Manganese (Soluble)	0.038	0.038	0.00	0.17	0.17	0.00	0.098	0.12	20.18
Manganese (Total)	0.040	0.040	0.00	0.18	0.17	5.71	0.10	0.11	9.52
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N									
Oxidised Nitrogen as N	< 0.01	< 0.01		0.03	0.02	40.00	< 0.01	0.02	
Reactive Phosphorus (Filtered)	0.058	0.061	5.04	0.049	0.048	2.06	0.011	0.020	58.06
Potassium (Soluble)	4.0	4.1	2.47	3.5	3.3	5.88	3.5	3.7	5.56
Silicon (Soluble)	5.7	5.7	0.00	13	12	8.00	6.2	6.9	10.69
Sodium (Soluble)	270	270	0.00	310	310	0.00	300	320	6.45
Strontium (Soluble)	0.78	0.78	0.00	0.51	0.51	0.00	0.38	0.43	12.35
Sulphate	86	85	1.17	110	110	0.00	17	15	12.50
Total Alkalinity	130	130	0.00	110	110	0.00	180	180	0.00
Total Dissolved Solids	1000	1000	0.00	1200	1200	0.00	1000	1000	0.00
Total Nitrogen	0.12	0.10	18.18	0.15	0.16	6.45	0.21	0.27	25.00
Total Phosphorus	0.060	0.062	3.28	0.054	0.051	5.71	0.051	0.055	7.55
Zinc (Soluble)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	0.006	
Zinc (Total)	< 0.01	< 0.01		< 0.01	0.29		0.020	0.020	0.00
EC @ 25C	1670	1720	2.95	2124	2051	3.50	1945	1934	0.57
Field EC		1,814			2060			1940	

Where >10%

Station ID	GW036773_3	GW036773_3	RPD (%dif)	GW036876_1	GW036876_1	RPD (%dif)	GW041012_1	GW041012_1	RPD (%dif)
Sampling Date	16-Jun-2010	16-Jun-2010		14-Dec-10	14-Dec-2010		16-Sep-2010	16-Sep-2010	
Aluminium (Soluble)	< 0.01	0.010		< 0.01	< 0.01		< 0.01	0.010	
Aluminium (Total)	< 0.05	< 0.05		0.15	0.16	6.45	0.13	0.13	0.00
Ammonia	0.15	0.13	14.29	< 0.01	< 0.01		< 0.01	< 0.01	
Bicarbonate as HCO3	78	79	1.27	170	180	5.71	300	300	0.00
Boron (Soluble)	< 0.1	< 0.1		0.2	0.1	66.67	0.3	0.3	0.00
Boron (Total)	< 0.1	< 0.1		0.2	0.2	0.00	0.3	0.3	0.00
Bromide	0.6	0.6	0.00	6.0	5.8	3.39	0.3	0.3	0.00
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	20	18	10.53	140	140	0.00	4.5	4.5	0.00
Chloride	150	150	0.00	1500	1500	0.00	83	83	0.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		0.012	0.011	8.70	< 0.005	< 0.005	
Fluoride	0.20	0.21	4.88	0.54	0.53	1.87	1.3	1.3	0.00
Iron (Total)	3.2	3.4	6.06	0.50	0.060	157.14	< 0.05	0.050	
Lead (Total)	0.028	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	15	13	14.29	180	180	0.00	4.7	4.8	2.11
Manganese (Soluble)	0.19	0.17	11.11	0.004	0.003	28.57	< 0.002	< 0.002	
Manganese (Total)	0.19	0.20	5.13	0.0056	0.0025	76.54	< 0.002	< 0.002	
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N									
Oxidised Nitrogen as N	0.02	0.01	66.67	0.27	0.20	29.79	0.24	0.28	15.38
Reactive Phosphorus (Filtered)	0.011	0.010	9.52	0.005	0.008	46.15	0.109	0.115	5.36
Potassium (Soluble)	4.5	4.9	8.51	7.7	7.5	2.63	0.58	0.58	0.00
Silicon (Soluble)	6.7	5.8	14.40	15	15	0.00	15	15	0.00
Sodium (Soluble)	78	67	15.17	570	550	3.57	170	170	0.00
Strontium (Soluble)	0.23	0.20	13.95	2.4	2.4	0.00	0.078	0.081	3.77
Sulphate	< 0.5	< 0.5		140	140	0.00	20	20	0.00
Total Alkalinity	64	64	0.00	140	140	0.00	250	250	0.00
Total Dissolved Solids	340	340	0.00	3100	3100	0.00	460	450	2.20
Total Nitrogen	0.18	0.18	0.00	0.28	0.25	11.32	0.24	0.25	4.08
Total Phosphorus	0.085	0.082	3.59	0.005	0.008	46.15	0.104	0.105	0.96
Zinc (Soluble)	0.026	0.036	32.26	0.006	0.014	80.00	0.011	0.009	20.00
Zinc (Total)	< 0.01	< 0.01		0.010	< 0.01		< 0.01	< 0.01	
EC @ 25C	614	617	0.49	4500	4590	1.98	778	781	0.38
Field EC		627			4400			793	

Where >10%

Station ID	GW090085_5	GW090085_5	RPD (%dif)	GW273040_1	GW273040_1	RPD (%dif)	GW036038_3		RPD (%dif)
Sampling Date	30-Nov-2009	30-Nov-2009		21-May-2010	21-May-2010		12-Jan-2010	13-Jan-2010	
Aluminium (Soluble)	< 0.01	< 0.01		0.020	0.040	66.67	< 0.01	< 0.01	
Aluminium (Total)	0.080	0.080	0.00	< 0.05	0.050		< 0.05	< 0.05	
Ammonia	0.02	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Bicarbonate as HCO3	200	200	0.00	530	530	0.00	280	280	0.00
Boron (Soluble)	0.1	0.1	0.00	1.8	1.8	0.00	< 0.1	< 0.1	
Boron (Total)	0.1	0.1	0.00	1.7	2.1	21.05	< 0.1	< 0.1	
Bromide	< 0.2	0.7		8.9	8.5	4.60	0.2	0.2	0.00
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	16	16	0.00	320	340	6.06	32	32	0.00
Chloride	170	170	0.00	2500	2500	0.00	58	58	0.00
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.16	0.20	22.22	0.76	0.86	12.35	0.20	0.23	13.95
Iron (Total)	1.5	1.4	6.90	< 0.05	< 0.05		< 0.05	< 0.05	
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)		< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	15	15	0.00	240	260	8.00	12	12	0.00
Manganese (Soluble)	0.048	0.047	2.11	< 0.002	< 0.002		< 0.002	< 0.002	
Manganese (Total)	0.040	0.040	0.00	< 0.002	< 0.002		< 0.002	< 0.002	
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N				3.4	2.8	19.35			
Oxidised Nitrogen as N	0.01	< 0.01					0.20	0.21	4.88
Reactive Phosphorus (Filtered)	0.142	0.136	4.32	0.016	0.015	6.45	0.013	0.017	26.67
Potassium (Soluble)	4.7	4.8	2.11	6.6	6.5	1.53	1.6	1.6	0.00
Silicon (Soluble)	6.6	6.5	1.53	11	12	8.70	16	16	0.00
Sodium (Soluble)	150	150	0.00	1400	1500	6.90	96	95	1.05
Strontium (Soluble)	0.30	0.29	3.39	5.1	5.1	0.00	0.55	0.54	1.83
Sulphate	< 0.5	< 0.5		1300	1300	0.00	30	31	3.28
Total Alkalinity	160	170	6.06	430	430	0.00	230	230	0.00
Total Dissolved Solids	480	500	4.08	6300	6300	0.00	460	480	4.26
Total Nitrogen	0.14	0.16	13.33	3.3	3.3	0.00	0.19	0.20	5.13
Total Phosphorus	0.597	0.584	2.20	0.016	0.016	0.00	0.021	0.021	0.00
Zinc (Soluble)	0.080	0.022	113.73	0.092	0.085	7.91	< 0.005	< 0.005	
Zinc (Total)	0.030	0.030	0.00	0.090	0.070	25.00	< 0.01	< 0.01	
EC @ 25C	850	856	0.70	9620	9620	0.00	702	664	5.56
Field EC		650			9670		695		

Where >10%

Station ID	GW036406_1		RPD (%dif)	GW036166_2		RPD (%dif)	GW036398_1		RPD (%dif)
Sampling Date	19-Jan-2010	20-Jan-2010		4-Feb-2010	4-Feb-2010		10-Feb-2010	11-Feb-2010	
Aluminium (Soluble)	< 0.01	< 0.01		< 0.01	0.010		0.010	< 0.01	
Aluminium (Total)	< 0.05	< 0.05		0.050	0.070	33.33	< 0.05	< 0.05	
Ammonia	0.02	0.02	0.00	< 0.01	< 0.01		< 0.01	0.05	
Bicarbonate as HCO3	280	280	0.00	620	< 1		240	250	4.08
Boron (Soluble)	< 0.1	0.1		0.7	0.7	0.00	< 0.1	< 0.1	
Boron (Total)	< 0.1	< 0.1		0.8	0.8	0.00	< 0.1	< 0.1	
Bromide	1.6	1.7	6.06	4.0	4.6	13.95	5.0	6.3	23.01
Carbonate as CO3	14	14	0.00	< 1	< 1		< 1	< 1	
Calcium (Soluble)	9.9	10	1.01	160	160	0.00	120	120	0.00
Chloride	430	430	0.00	1200	1200	0.00	1600	1500	6.45
Copper (Soluble)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	< 0.005	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	< 0.1	0.10		0.79	0.81	2.50	< 0.1	< 0.1	
Iron (Total)	< 0.05	< 0.05		0.060	0.18	100.00	< 0.05	< 0.05	
Lead (Total)	< 0.02	< 0.02		< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	8.3	8.9	6.98	180	180	0.00	110	110	0.00
Manganese (Soluble)	0.15	0.17	12.50	0.004	0.004	0.00	0.004	0.003	28.57
Manganese (Total)	0.16	0.17	6.06	0.0072	0.0070	2.82	0.0046	0.0047	2.15
Nickel (Soluble)									
Nickel (Total)	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N				6.1	6.5	6.35			
Oxidised Nitrogen as N	0.02	0.01	66.67				0.16	0.15	6.45
Reactive Phosphorus (Filtered)	0.098	0.082	17.78	0.032	0.025	24.56	0.068	0.038	56.60
Potassium (Soluble)	1.1	1.2	8.70	2.8	2.7	3.64	4.2	4.1	2.41
Silicon (Soluble)	14	14	0.00	12	12	0.00	20	19	5.13
Sodium (Soluble)	400	420	4.88	1400	1400	0.00	950	960	1.05
Strontium (Soluble)	0.26	0.28	7.41	3.4	3.4	0.00	3.1	3.0	3.28
Sulphate	98	99	1.02	2000	2000	0.00	390	380	2.60
Total Alkalinity	250	250	0.00	510	< 1		200	200	0.00
Total Dissolved Solids	1100	1100	0.00	5100	4900	4.00	3300	3400	2.99
Total Nitrogen	0.05	< 0.05		6.0	6.1	1.65	0.35	0.76	73.87
Total Phosphorus	0.098	0.080	20.22	0.040	0.035	13.33	0.112	0.074	40.86
Zinc (Soluble)	< 0.005	0.009		0.041	0.096	80.29	0.075	0.067	11.27
Zinc (Total)	0.011	0.013	16.67	0.060	0.070	15.38	0.080	0.050	46.15
EC @ 25C	2000	1990	0.50	6820	6930	1.60	5130	5410	5.31
Field EC	2010			7530			5680		

Where >10%

Station ID	GW036280_3		RPD (%dif)	GW036398_1		RPD (%dif)	GW036398_1		RPD (%dif)
Sampling Date	24-Mar-2010	23-Mar-2010		2-Jun-2010	2-Jun-2010		6-Jul-2010	5-Jul-2010	
Aluminium (Soluble)	0.020	0.030	40.00	< 0.01	< 0.01		< 0.01	< 0.01	
Aluminium (Total)	< 0.05	0.080		0.060	0.060	0.00	0.21	< 0.05	
Ammonia	< 0.01	< 0.01		< 0.01	< 0.01		< 0.01	0.03	
Bicarbonate as HCO3	270	270	0.00	250	250	0.00	250	250	0.00
Boron (Soluble)	0.1	0.3	100.00	< 0.1	< 0.1		< 0.1	0.1	
Boron (Total)	0.2	0.1	66.67	< 0.1	< 0.1		< 0.1	< 0.1	
Bromide	11	9.1	18.91	4.9	4.9	0.00	3.4	2.8	19.35
Carbonate as CO3	< 1	< 1		< 1	< 1		< 1	< 1	
Calcium (Soluble)	190	180	5.41	91	82	10.40	73	74	1.36
Chloride	2800	2800	0.00	1300	1300	0.00	1200	810	38.81
Copper (Soluble)	< 0.01	0.010		< 0.01	< 0.01		< 0.01	< 0.01	
Copper (Total)	0.0095	< 0.005		< 0.005	< 0.005		< 0.005	< 0.005	
Fluoride	0.15	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Iron (Total)	< 0.05	0.62		< 0.05	< 0.05		0.13	< 0.05	
Lead (Total)	0.032	0.030	6.45	< 0.02	< 0.02		< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1		< 0.1	< 0.1		< 0.1	< 0.1	
Magnesium (Soluble)	230	230	0.00	89	80	10.65	70	72	2.82
Manganese (Soluble)	< 0.002	0.002		0.003	0.003	0.00	0.003	0.003	0.00
Manganese (Total)	< 0.002	0.0055		0.0042	0.0039	7.41	0.0082	< 0.002	
Nickel (Soluble)		< 0.01							
Nickel (Total)	< 0.01	0.021		< 0.01	< 0.01		< 0.01	< 0.01	
Nitrate - N	0.8	0.8	0.00						
Oxidised Nitrogen as N				0.13	0.09	36.36	0.08	0.08	0.00
Reactive Phosphorus (Filtered)	0.063	0.075	17.39	0.053	0.033	46.51	0.074	0.079	6.54
Potassium (Soluble)	4.6	4.1	11.49	3.0	3.1	3.28	2.4	2.5	4.08
Silicon (Soluble)	10	9.9	1.01	18	17	5.71	16	16	0.00
Sodium (Soluble)	1700	1700	0.00	810	760	6.37	710	720	1.40
Strontium (Soluble)	5.9	6.0	1.68	2.4	2.2	8.70	2.0	2.0	0.00
Sulphate	940	930	1.07	330	340	2.99	310	250	21.43
Total Alkalinity	220	220	0.00	210	210	0.00	210	210	0.00
Total Dissolved Solids	6000	6200	3.28	2700	2700	0.00	2700	2700	0.00
Total Nitrogen	1.0	1.0	0.00	0.13	0.10	26.09	0.10	0.12	18.18
Total Phosphorus	0.073	0.079	7.89	0.075	0.048	43.90	0.090	0.086	4.55
Zinc (Soluble)	0.10	0.055	58.06	0.010	0.008	22.22	0.005	0.005	0.00
Zinc (Total)	0.070	0.16	78.26	0.012	0.012	0.00	0.016	0.011	37.04
EC @ 25C	9300	9210	0.97	4970	4880	1.83	4480	4450	0.67
Field EC	10030			4890			4550		

Where >10%

Station ID	**GW036398_1**		**RPD (%dif)**
Sampling Date	13-Oct-2010	12-Oct-2010	
Aluminium (Soluble)	< 0.01	< 0.01	
Aluminium (Total)	0.11	0.090	20.00
Ammonia	< 0.01	< 0.01	
Bicarbonate as HCO3	260	260	0.00
Boron (Soluble)	< 0.1	< 0.1	
Boron (Total)	< 0.1	< 0.1	
Bromide	4.0	4.5	11.76
Carbonate as CO3	< 1	< 1	
Calcium (Soluble)	66	66	0.00
Chloride	1000	1000	0.00
Copper (Soluble)	0.010	< 0.01	
Copper (Total)	< 0.005	< 0.005	
Fluoride	0.1	< 0.1	
Iron (Total)	0.10	0.13	26.09
Lead (Total)	< 0.02	< 0.02	
Lithium (Soluble)	< 0.1	< 0.1	
Magnesium (Soluble)	65	64	1.55
Manganese (Soluble)	0.002	0.003	40.00
Manganese (Total)	< 0.002	< 0.002	
Nickel (Soluble)			
Nickel (Total)	< 0.01	< 0.01	
Nitrate - N			
Oxidised Nitrogen as N	0.08	0.07	13.33
Reactive Phosphorus (Filtered)	0.074	0.090	19.51
Potassium (Soluble)	2.5	2.6	3.92
Silicon (Soluble)	19	18	5.41
Sodium (Soluble)	690	670	2.94
Strontium (Soluble)	1.8	1.7	5.71
Sulphate	260	270	3.77
Total Alkalinity	220	220	0.00
Total Dissolved Solids	2200	2300	4.44
Total Nitrogen	0.08	0.09	11.76
Total Phosphorus	0.093	0.090	3.28
Zinc (Soluble)	0.009	< 0.005	
Zinc (Total)	0.040	0.020	66.67
EC @ 25C	3910	3890	0.51
Field EC	4030		

Table B-2 Field blank sample results

Catchment	**Murrumbidgee**	**Macquarie**	**Macquarie**	**Macquarie**	**Macquarie**	**Macquarie**	**Macquarie**	**Macquarie**	**Unknown**
Sample date	**16-Mar-2010**	**21-Oct-2009**	**2-Dec-2009**	**16-Oct-2009**	**20-Oct-2009**	**23-Oct-2009**	**21-Oct-2009**	**16-Oct-2009**	**31-Jan-11**
Aluminium (Soluble)	0.03								P
Aluminium (Total)	< 0.05								< 0.05
Ammonia	0.1								< 0.01
Bicarbonate as HCO3	5.4	5.8	5.8	5.3	5.3	5.3	5.3	5.3	5.4
Boron (Soluble)	< 0.1								P
Boron (Total)	0.1								< 0.1
Bromide	< 0.2								P
Calcium (Soluble)	4								P
Carbonate as CO3	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Chloride	< 0.5								P
Conductivity	2.96	4.14	3.99	4.23	4.14	4.04	3.94	4.34	4
Copper (Soluble)	< 0.01								P
Copper (Total)	< 0.005								< 0.005
Fluoride	< 0.1								P
Iron (Total)	< 0.05								< 0.05
Lead (Total)	< 0.02								< 0.02
Lithium (Soluble)	< 0.1								< 0.1
Magnesium (Soluble)	0.05								P
Manganese (Soluble)	< 0.002								P
Manganese (Total)	0.04								< 0.002
Nickel (Total)	< 0.01								< 0.01
Nitrate - N									
Oxidised Nitrogen as N	0.04								0.01
Potassium (Soluble)	< 0.05								P
Reactive Phosphorus (Filtered)	0.014								< 0.005
Silicon (Soluble)	< 0.05								P
Sodium (Soluble)	< 0.05								P
Strontium (Soluble)	0.001								P
Sulphate	< 0.5								
Total Alkalinity	4.5	4.8	4.8	4.4	4.4	4.4	4.4	4.4	4.4
Total Dissolved Solids	5	< 5	< 5	< 5	< 5	< 5	< 5	5	< 5
Total Nitrogen	0.42								0.05
Total Phosphorus	0.035								0.009
Zinc (Soluble)	0.11								P
Zinc (Total)	< 0.01								< 0.01

Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Catchment	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Sample date	**25-Jan-2011**	**18-Jan-2011**	**20-Sep-2010**	**13-Oct-2010**	**13-May-2010**	**17-Dec-2009**	**22-Jan-2010**	**22-Feb-2010**	**16-Feb-2010**
Aluminium (Soluble)	P	P	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	< 0.01
Aluminium (Total)	< 0.05	< 0.05	0.29	0.06	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Ammonia	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	0.04	0.06	0.01
Bicarbonate as HCO3	P	6.3	4.9	5.4	4.6	4.1	6.7	4.2	4.9
Boron (Soluble)	P	P	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Boron (Total)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.2
Bromide	P	P	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Calcium (Soluble)	P	P	0.07	< 0.05	< 0.05	0.09	< 0.05	< 0.05	< 0.05
Carbonate as CO3		< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Chloride	P	P	0.8	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Conductivity	2	4	2	6	5.14	8.84	27.4	3.76	3.07
Copper (Soluble)	P	P	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Copper (Total)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Fluoride	P	P	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Iron (Total)	< 0.05	< 0.05	0.31	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Lead (Total)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lithium (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Magnesium (Soluble)	P	P	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Manganese (Soluble)	P	P	< 0.002	< 0.002	1.00E-05	< 0.002	< 0.002	< 0.002	< 0.002
Manganese (Total)	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	0.0039
Nickel (Total)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Nitrate - N									< 0.2
Oxidised Nitrogen as N	0.02	0.01	0.02	< 0.01	0.01	0.28	< 0.01	0.01	
Potassium (Soluble)	P	P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Reactive Phosphorus (Filtered)	0.008	0.007	0.007	0.008	< 0.005	0.007	0.007	0.007	0.007
Silicon (Soluble)	P	P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Sodium (Soluble)	P	P	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Strontium (Soluble)	P	P	< 0.001	< 0.001	5.00E-05	< 0.001	4.00E-05	< 0.001	< 0.001
Sulphate			< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Total Alkalinity	P	5.2	4	4.4	3.8	3.4	5.5	3.4	4.1
Total Dissolved Solids	P	< 5		< 5	< 5	10	< 5	< 5	
Total Nitrogen	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.32	0.14	0.16	10
Total Phosphorus	0.01	0.01	0.005	0.006	0.01	0.009	0.007	0.011	0.013
Zinc (Soluble)	P	P	< 0.005	< 0.005	< 0.005	0.16	0.052	0.012	< 0.005
Zinc (Total)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.08	0.05	0.04	0.03

Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Catchment	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**
Sample date	**30-Nov-2009**	**3-Mar-2010**	**20-May-2010**	**10-Nov-2010**	**22-Sep-2010**	**26-May-2010**	**16-Aug-2010**	**21-Apr-2010**	**10-Nov-2010**
Aluminium (Soluble)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.04	0.04	0.03	< 0.01
Aluminium (Total)	< 0.05	0.08	< 0.05	0.18	0.11	0.06	< 0.05	< 0.05	0.09
Ammonia	0.03	0.03	< 0.01	0.01	< 0.01	< 0.01	0.02	< 0.01	< 0.01
Bicarbonate as HCO3	3.6	4.5	3.9	3.7	6.8	44	45		4.9
Boron (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Boron (Total)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Bromide	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Calcium (Soluble)	< 0.05	< 0.05	< 0.05	0.17	< 0.05	3.5	5.5	0.24	0.5
Carbonate as CO3	< 1	< 1	< 1	< 1	< 1	< 1	< 1		< 1
Chloride	< 0.5	< 0.5	< 0.5	0.7	0.6	4.2	4.9	< 0.5	0.5
Conductivity	2.27	2.77	2.46	2	5	131	136	3.9	4
Copper (Soluble)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01
Copper (Total)	< 0.005	< 0.005	0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.04	< 0.005
Fluoride	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1.2	0.86	< 0.1	< 0.1
Iron (Total)	< 0.05	< 0.05	< 0.05	0.08	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Lead (Total)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lithium (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Magnesium (Soluble)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	1.6	2	0.29	0.3
Manganese (Soluble)	< 0.002	< 0.002	8.00E-05	< 0.002	< 0.002	0.002	0.002	0.006	0.003
Manganese (Total)	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	0.0024	< 0.002	0.0046	< 0.002
Nickel (Total)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.01	< 0.01
Nitrate - N									
Oxidised Nitrogen as N	0.01	0.02	< 0.01	0.04	0.03	0.18	0.21	0.04	0.02
Potassium (Soluble)	< 0.05	0.1	< 0.05	< 0.05	0.06	1.2	1.6	< 0.05	0.1
Reactive Phosphorus (Filtered)	0.008	0.01	0.011	0.007	0.008	0.005	0.009	0.009	0.006
Silicon (Soluble)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.63	1.2	1.7	0.08
Sodium (Soluble)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	21	17	3.4	2.4
Strontium (Soluble)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.027	0.04	0.007	0.006
Sulphate	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	15	18	< 0.5	< 0.5
Total Alkalinity	2.9	3.6	3.2	3.1	5.6	36	37		4
Total Dissolved Solids	< 5	< 5	< 5	< 5	7.5	68	74	5	5
Total Nitrogen	0.17	0.07	< 0.05	0.38	< 0.05	0.23	0.29	< 0.05	< 0.05
Total Phosphorus	0.008	0.01	0.011	0.013	0.007	0.014	0.01	0.011	0.009
Zinc (Soluble)	0.076	0.016	0.026	0.009	< 0.005	0.009	0.029	0.016	< 0.005
Zinc (Total)	0.03	0.03	0.018	0.016	0.012	0.013	0.02	0.09	< 0.01

Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Catchment	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Sample date	16-Oct-2009	2-Jun-2010	4-Aug-2010	7-Dec-2010	22-Sep-2010	5-Jul-2010	28-Oct-2010	29-Jun-2010	3-Dec-2009	20-Apr-2010
Aluminium (Soluble)	0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01	0.01	< 0.01	0.01	< 0.01
Aluminium (Total)	< 0.05	< 0.05	< 0.05	< 0.05	0.1	< 0.05	0.08	< 0.05	< 0.05	< 0.05
Ammonia	< 0.01	< 0.01	< 0.01	0.01	0.01	< 0.01	0.02	< 0.01	0.01	< 0.01
Bicarbonate as HCO3		< 1	6.3	6.3	7.3	6.8	4.9	7.8	4	8.4
Boron (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Boron (Total)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Bromide	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Calcium (Soluble)	< 0.05	< 0.05	0.09	0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Carbonate as CO3		< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Chloride	< 0.5	< 0.5	0.7	0.9	0.8	< 0.5	0.6	< 0.5	< 0.5	< 0.5
Conductivity	6.03	325	7.3	4	5	5.78	5	7.36	3.03	4.76
Copper (Soluble)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Copper (Total)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005
Fluoride	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Iron (Total)	< 0.05	< 0.05	0.05	< 0.05	< 0.05	0.08	< 0.05	< 0.05	< 0.05	0.16
Lead (Total)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lithium (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Magnesium (Soluble)	< 0.02	0.04	0.03	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Manganese (Soluble)	< 0.002	0.003	< 0.002	< 0.002	< 0.002	< 0.002	0.002	< 0.002	< 0.002	< 0.002
Manganese (Total)	< 0.002	0.0036	< 0.002	0.0039	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002
Nickel (Total)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Nitrate - N		0.5								
Oxidised Nitrogen as N	< 0.01		0.01	0.02	0.03	0.02	< 0.01	0.02		0.02
Potassium (Soluble)	< 0.05	0.72	< 0.05	0.11	< 0.05	0.12	< 0.05	0.1	< 0.05	0.08
Reactive Phosphorus (Filtered)	0.008	0.792	0.01	0.006	0.006	0.011	0.008	0.012	0.01	0.009
Silicon (Soluble)	< 0.05	1.1	< 0.05	< 0.05	< 0.05	0.05	< 0.05	0.06	< 0.05	< 0.05
Sodium (Soluble)	2.1	1.1	1.1	0.82	0.81	0.7	0.68	0.62	0.57	0.54
Strontium (Soluble)	2.00E-06	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Sulphate	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Total Alkalinity		< 1	5.2	5.2	6	5.6	4	6.4	3.2	6.9
Total Dissolved Solids	< 5	21	< 5	7.5	5	7.5	< 5	5	< 5	6.2
Total Nitrogen	< 0.05	4.7	< 0.05	0.06	< 0.05	< 0.05	< 0.05	< 0.05		0.05
Total Phosphorus	0.009	0.821	0.012	0.006	< 0.005	0.012	0.005	0.015		0.005
Zinc (Soluble)	0.062	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.052	< 0.005
Zinc (Total)	0.03	< 0.01	< 0.01	< 0.01	< 0.01	0.012	< 0.01	< 0.01	0.09	< 0.01

Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Catchment	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**
Sample date	**11-May-2010**	**1-Jul-2010**	**23-Mar-2010**	**4-Feb-2010**	**11-Feb-2010**	**10-Mar-2010**	**9-Apr-2010**	**Sep-2010**	**Dec-2010**	**Dec-2010**
Aluminium (Soluble)	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	0.34	< 0.01	0.24
Aluminium (Total)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.46	0.11	0.33
Ammonia	< 0.01	< 0.01	0.02	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.02	0.02
Bicarbonate as HCO3	5.8	6.8	9.4	5.3	3.9	4.9		< 1	12	< 1
Boron (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Boron (Total)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Bromide	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Calcium (Soluble)	< 0.05	< 0.05	< 0.05	0.25	0.09	< 0.05	< 0.05	0.23	0.42	0.3
Carbonate as CO3	< 1	< 1	< 1	< 1	< 1	< 1		< 1	< 1	< 1
Chloride	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	18	4.7	11
Conductivity	4.3	3.63	2.79	4.52	1.96	3.38	2.8	149	81	88
Copper (Soluble)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.18	< 0.01
Copper (Total)	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	0.18	0.03
Fluoride	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.34	0.57
Iron (Total)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Lead (Total)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	0.11	< 0.02
Lithium (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Magnesium (Soluble)	< 0.02	< 0.02	0.03	0.04	< 0.02	< 0.02	< 0.02	4.5	0.24	2.9
Manganese (Soluble)	< 0.002	< 0.002	0.005	0.003	0.005	0.005	0.004	0.016	0.002	0.011
Manganese (Total)	< 0.002	< 0.002	0.0049	0.0046	0.0048	0.0045	0.0057	0.017	< 0.002	0.012
Nickel (Total)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.032	< 0.01
Nitrate - N										3.6
Oxidised Nitrogen as N	< 0.01	0.01	0.01	< 0.01	0.01	0.57	0.01		0.09	
Potassium (Soluble)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	0.05	1.4	1	0.8
Reactive Phosphorus (Filtered)	0.011	0.009	0.012	0.011	0.012	0.009	0.022	0.011	< 0.005	0.007
Silicon (Soluble)	< 0.05	< 0.05	1.7	1.7	1.9	1.8	1.5	4.4	0.07	2.7
Sodium (Soluble)	0.45	0.4	0.2	0.19	0.1	0.08	0.06	16	15	9.6
Strontium (Soluble)	< 0.001	< 0.001	< 0.001	0.007	< 0.001	< 0.001	< 0.001	0.009	0.003	0.007
Sulphate	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	1.4	14	7.5
Total Alkalinity	4.8	5.6	7.7	4.3	3.2	4		< 1	9.6	< 1
Total Dissolved Solids	5	< 5		< 5	< 5	8.8	7.5	89	41	48
Total Nitrogen	0.05	< 0.05	0.09	< 0.05	0.06	0.57	0.08		0.25	4.8
Total Phosphorus	0.011	0.007	0.021	0.007	0.011	0.008	0.033	0.016	0.01	0.011
Zinc (Soluble)	< 0.005	< 0.005	0.005	< 0.005	0.21	0.017	0.015	0.007	0.022	0.007
Zinc (Total)	< 0.01	< 0.01	0.12	0.04	0.02	0.013	0.09	0.012	0.04	0.018

Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Catchment	**Unknown**	**Unknown**	**Unknown**	**Unknown**	**Unknown**
Sample date	**Jul-2010**	**Oct-2010**	**Apr-2010**	**May-2010**	**Jun-2010**
Aluminium (Soluble)	0.04	0.03	< 0.01	0.05	< 0.01
Aluminium (Total)	< 0.05	0.13	< 0.05	0.07	< 0.05
Ammonia	0.01	0.01	0.04	0.02	< 0.01
Bicarbonate as HCO3	41	49		30	7.3
Boron (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Boron (Total)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Bromide	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Calcium (Soluble)	4.5	5.4	< 0.05	3.7	< 0.05
Carbonate as CO3	< 1	< 1		< 1	< 1
Chloride	4.1	5.4	< 0.5	4.9	< 0.5
Conductivity	129	162	2.29	126	3.76
Copper (Soluble)	0.02	< 0.01	< 0.01	< 0.01	< 0.01
Copper (Total)	0.011	0.0064	< 0.005	0.011	< 0.005
Fluoride	0.96	1	< 0.1	1.2	< 0.1
Iron (Total)	< 0.05	< 0.05	< 0.05	0.11	< 0.05
Lead (Total)	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Lithium (Soluble)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Magnesium (Soluble)	1.9	2.2	< 0.02	1.6	< 0.02
Manganese (Soluble)	0.002	< 0.002	< 0.002	0.003	< 0.002
Manganese (Total)	< 0.002	0.002	< 0.002	0.0032	< 0.002
Nickel (Total)	< 0.01	< 0.01	< 0.01	0.011	< 0.01
Nitrate - N					
Oxidised Nitrogen as N	0.14	0.22	< 0.01	0.25	0.02
Potassium (Soluble)	1.4	1.8	< 0.05	1.2	0.18
Reactive Phosphorus (Filtered)	0.011	0.007	0.007	0.011	0.009
Silicon (Soluble)	1.1	1.4	< 0.05	0.81	< 0.05
Sodium (Soluble)	21	21	< 0.05	17	0.31
Strontium (Soluble)	0.035	0.041	< 0.001	0.027	< 0.001
Sulphate	16	24	< 0.5	15	< 0.5
Total Alkalinity	34	40		24	6
Total Dissolved Solids	71	79	5.7	66	< 5
Total Nitrogen	0.26	0.33	0.11	0.39	< 0.05
Total Phosphorus	0.012	0.008	0.011	0.013	0.01
Zinc (Soluble)	0.015	0.012	0.022	0.021	< 0.005
Zinc (Total)	0.011	0.02	0.03	0.04	< 0.01

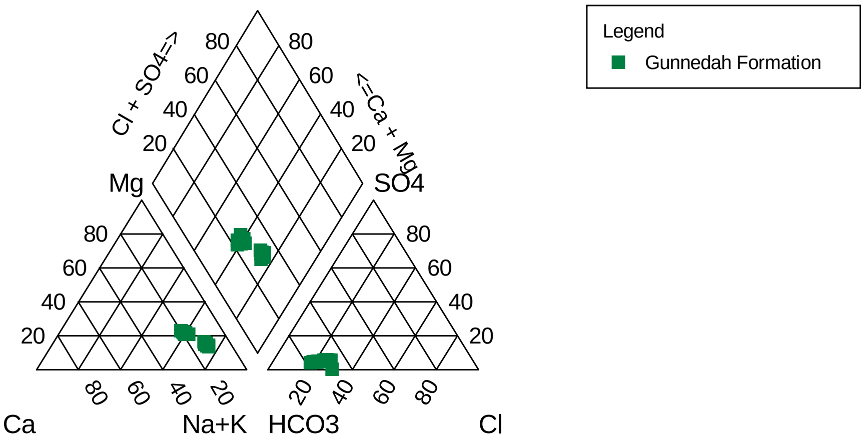
Note: Highlighted cells indicate concentration is greater than 1 order of magnitude above the laboratory detection limit

Appendix

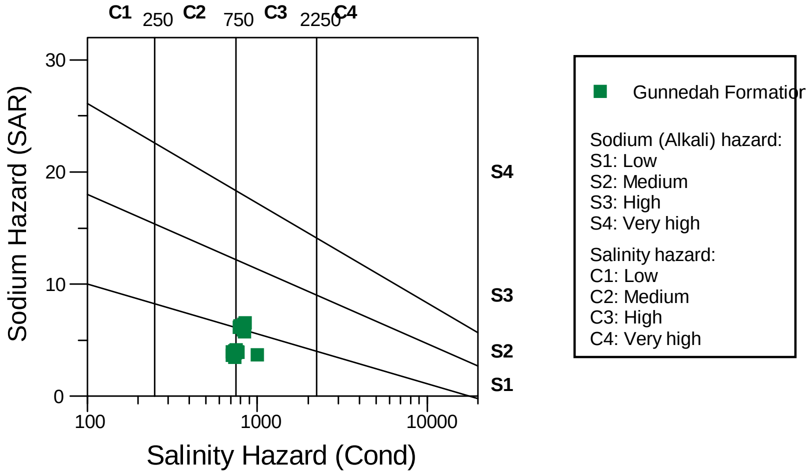
C

Upper Namoi GMA “Zone 3” – Water Quality Report Cards

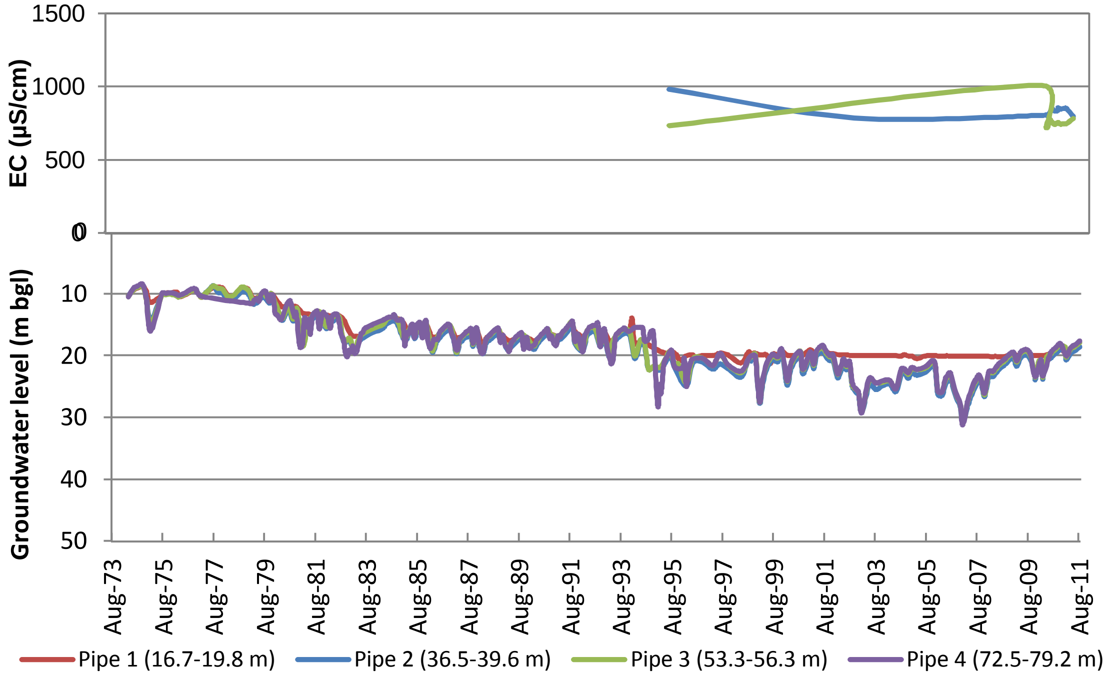
Figure C-1 Chemistry Summary GW030430



a. Piper plot showing water type: Na-HCO$_3$-Cl, Na-Mg-HCO3, Na-Mg-HCO3-Cl and Na-Mg-Ca-HCO3 (Narrabri Formation)



b. Wilcox plot showing medium to high salinity and low to medium SAR ratings

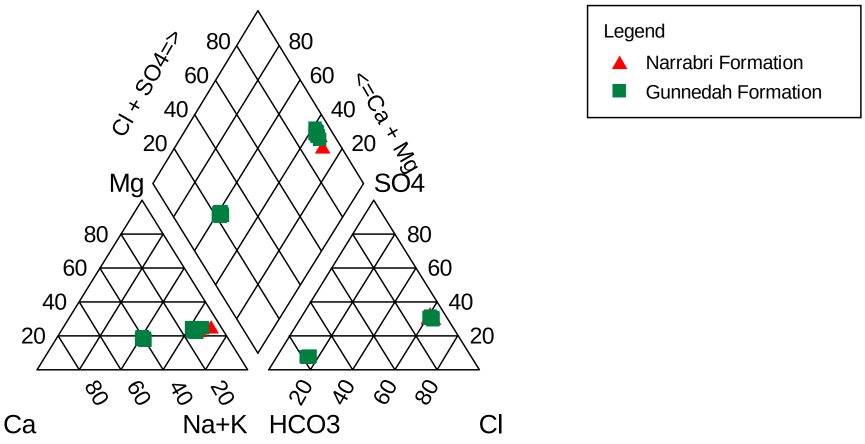


c. Water level and electrical conductivity from August 1973 to August 2011

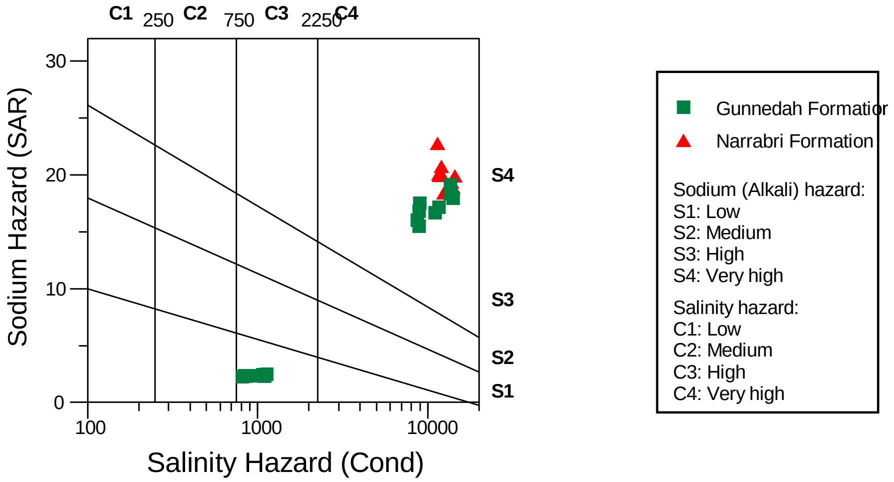
Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

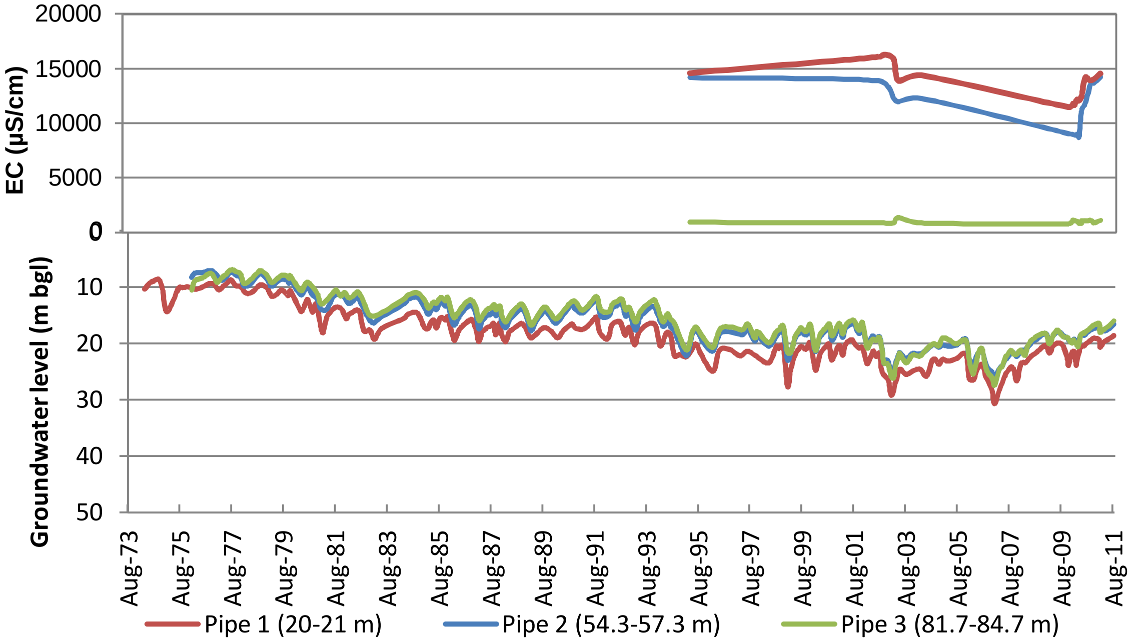
Figure C-2 Chemistry Summary GW030431



a. Piper plot showing water type: Na-Mg-Cl-SO4 (Narrabri Formation) and Na-Mg-Cl-SO4 Na-Ca-HCO_3 and Ca-Na-HCO3 (Gunnedah Formation)



b. Wilcox plot showing high and very high salinity and low and very high SAR ratings

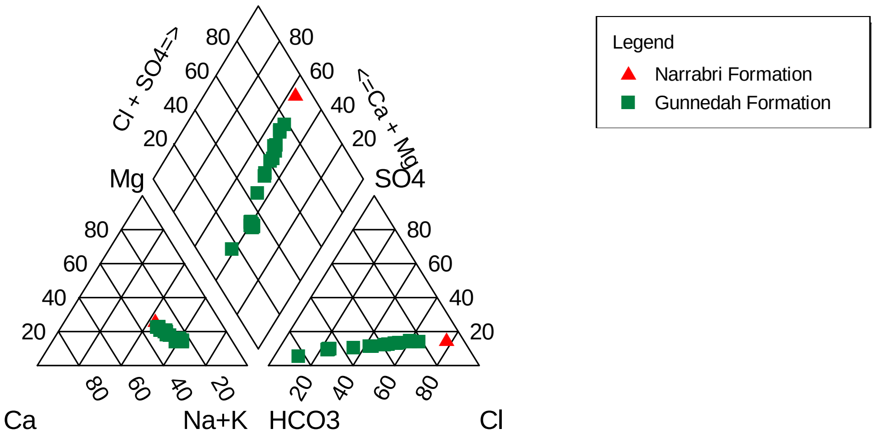


c. Water level and electrical conductivity from August 1973 to August 2011

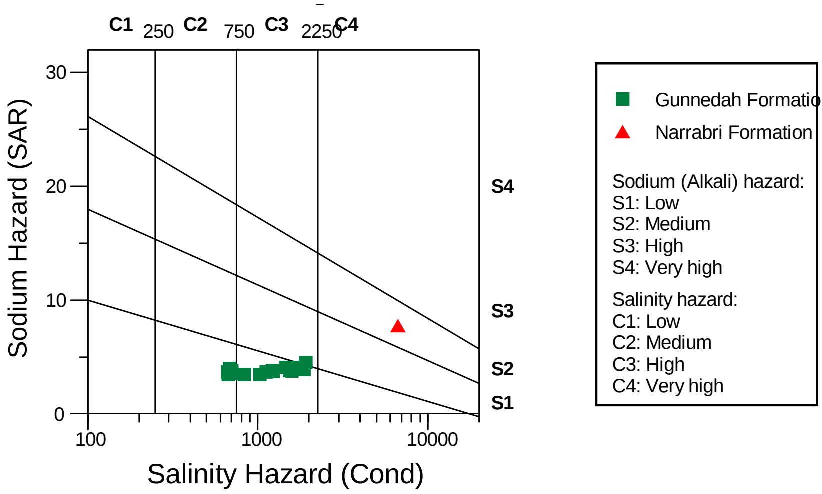
Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

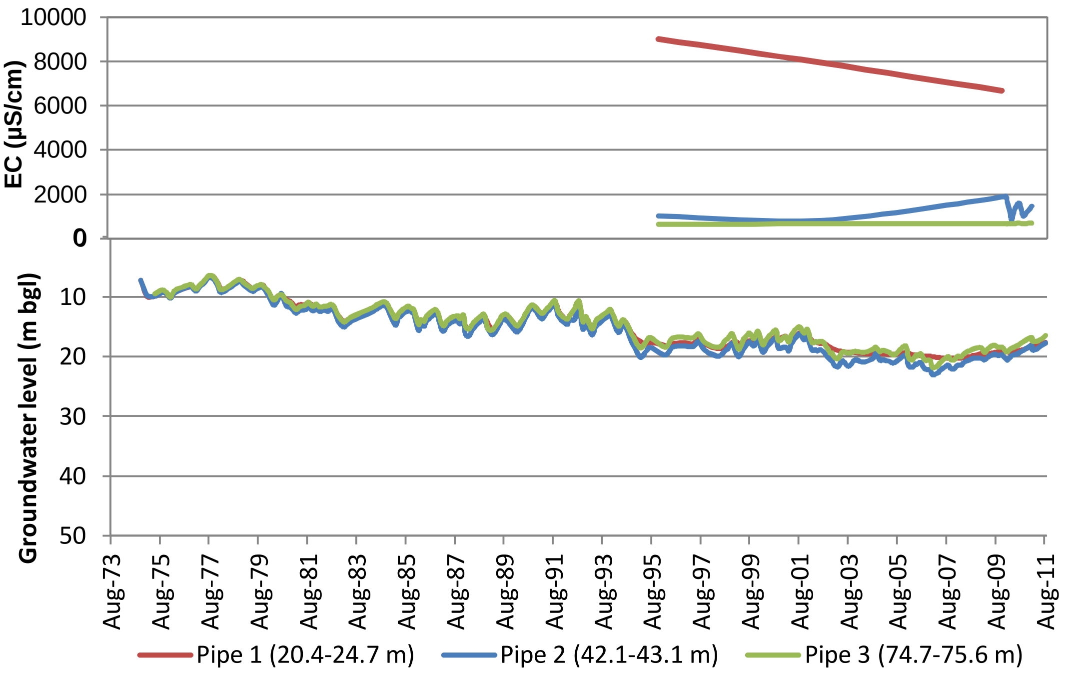
Figure C-3 Chemistry Summary GW036038



a. Piper plot showing water type: Na-Ca-Mg-Cl (Narrabri Formation) and Na-Ca-Mg-Cl-HCO3, Na-Ca-HCO$_3$ and Na-Ca-HCO$_3$-Cl (Gunnedah Formation)



b. Wilcox plot showing very high salinity and SAR ratings



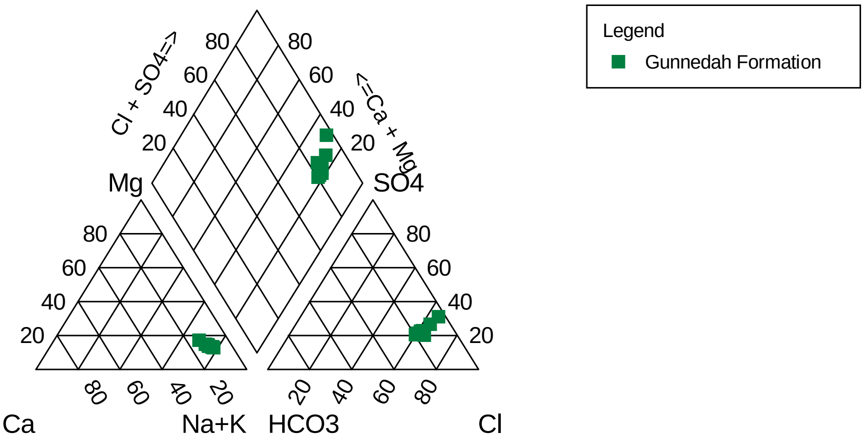
c. Water level and electrical conductivity from August 1973 to August 2011

Client: NSW Office of Water

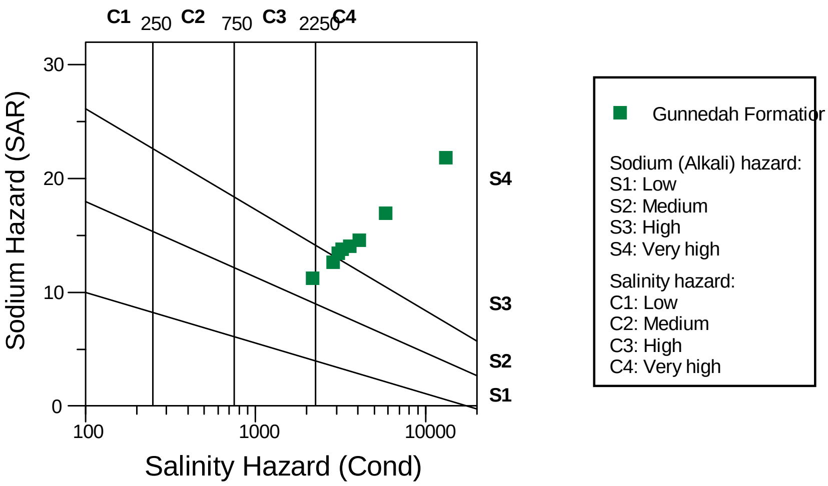
Location: Upper Namoi GMA

Project: Characterisation of hydrogeochemistry and risks to groundwater quality

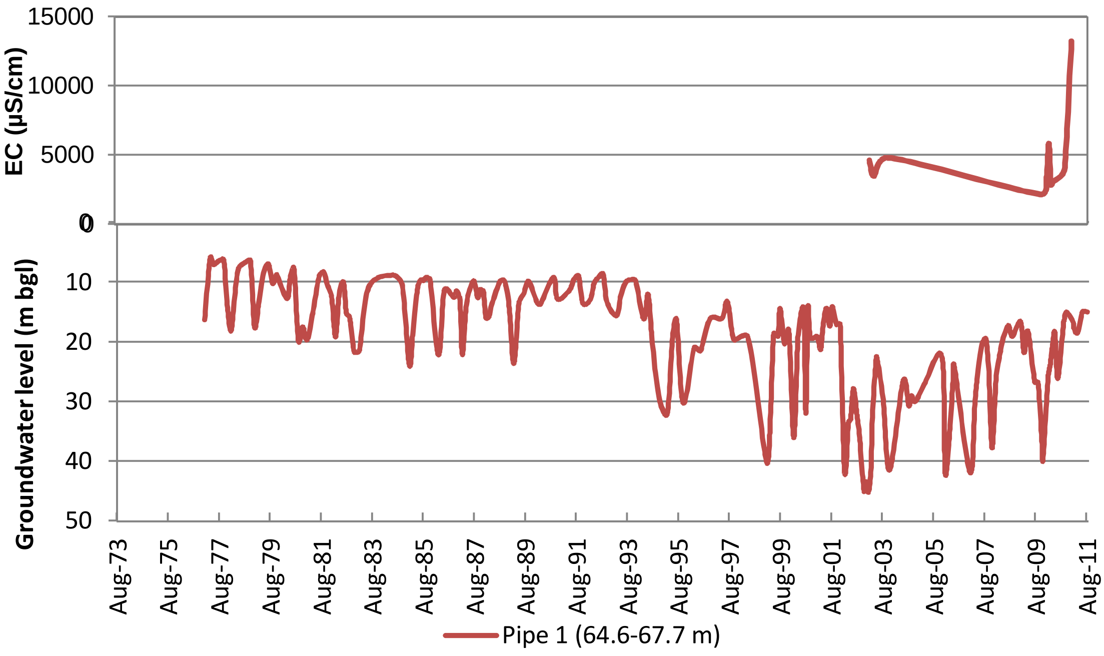
Figure C-4 Chemistry Summary GW036150



a. Piper plot showing water type: Na-Cl and Na-Cl-SO4 (Gunnedah Formation)



b. Wilcox plot showing high to very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1973 to August 2011

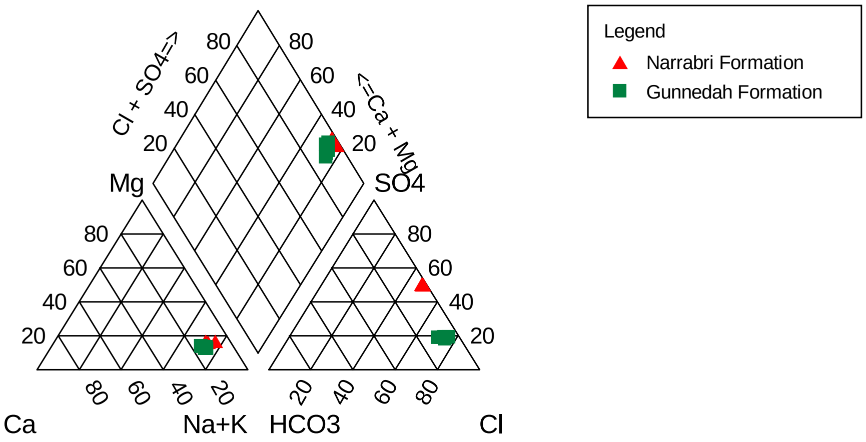
Client: NSW Office of Water

Location: Upper Namoi GMA

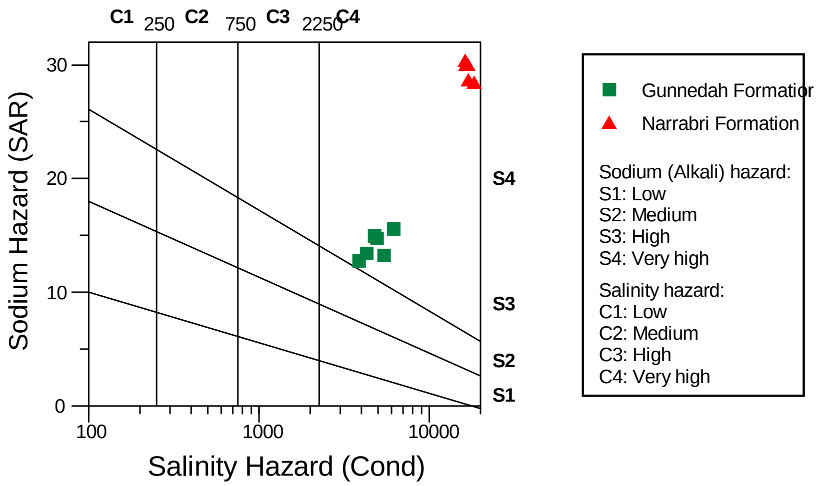
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

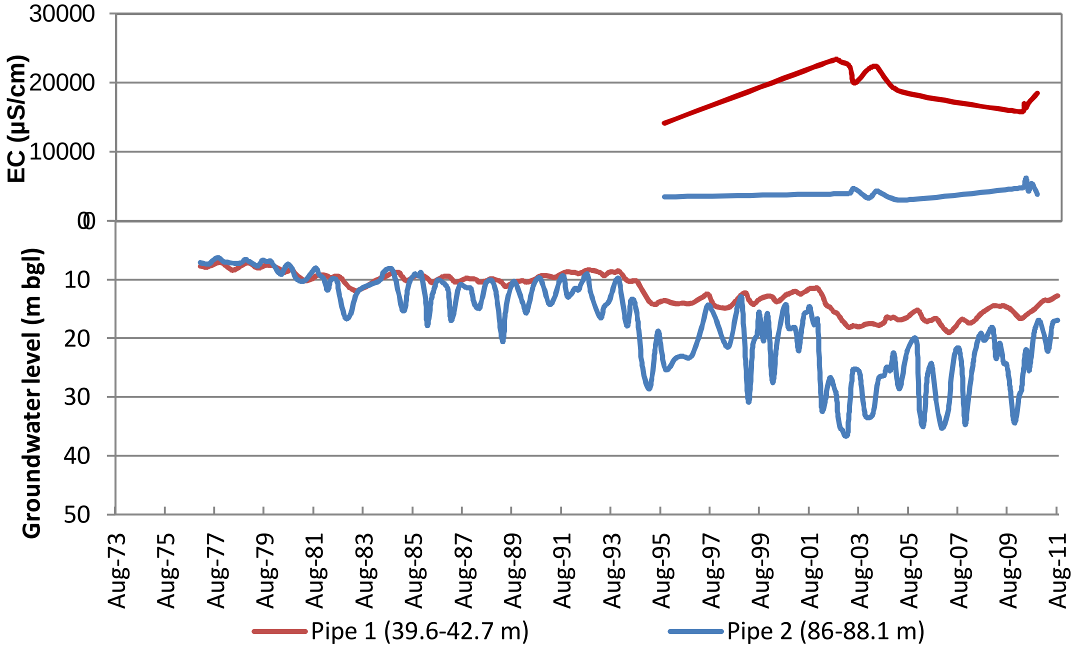
Figure C-5 Chemistry Summary GW036151



a. Piper plot showing water type: Na-SO_4-Cl (Narrabri Formation) and Na-Cl (Gunnedah Formation)



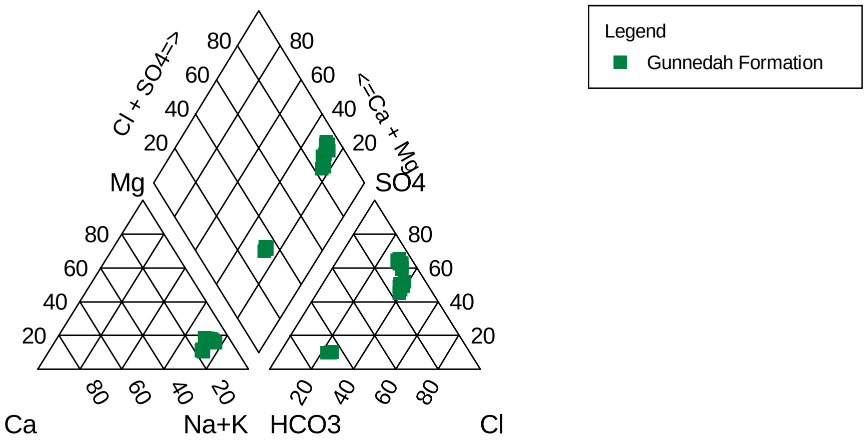
b. Wilcox plot showing very high salinity and SAR ratings



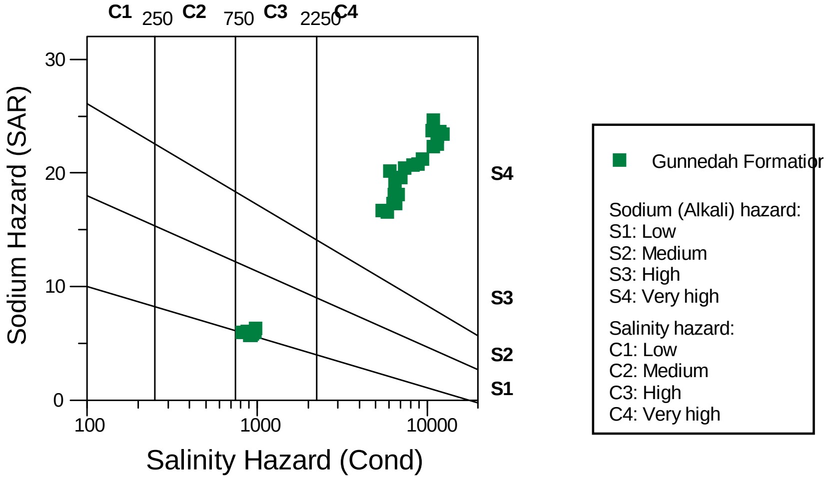
c. Water level and electrical conductivity from August 1973 to August 2011

Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

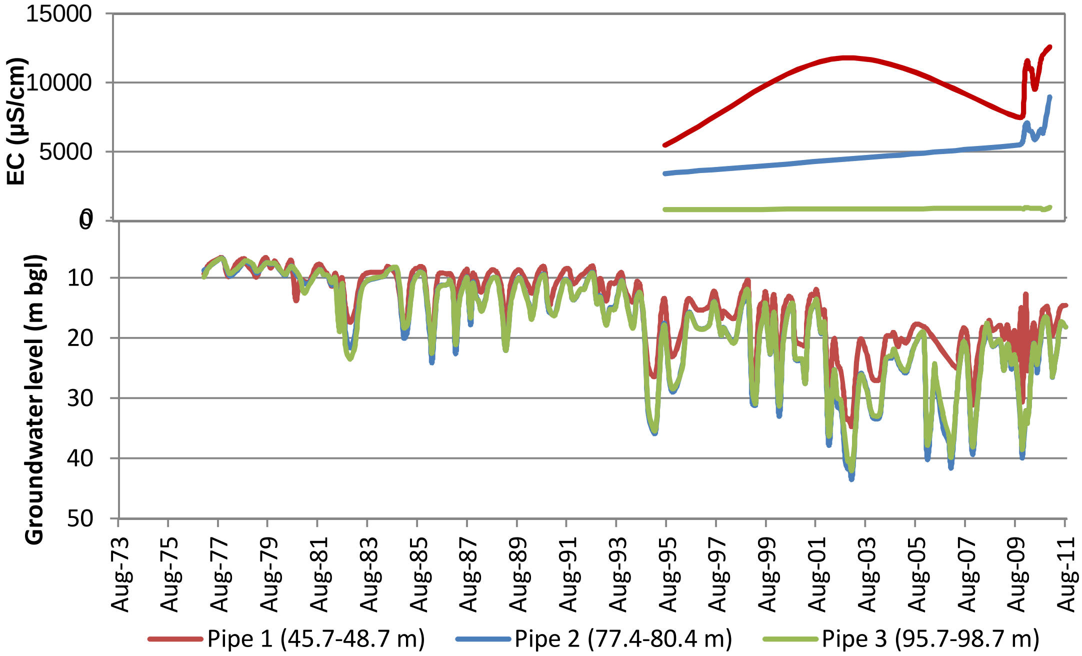
Figure C-6 Chemistry Summary GW036166



a. Piper plot showing water type: Na-SO_4-Cl and Na-HCO3-Cl (Gunnedah Formation)



b. Wilcox plot showing high to very high salinity and medium and very high SAR ratings

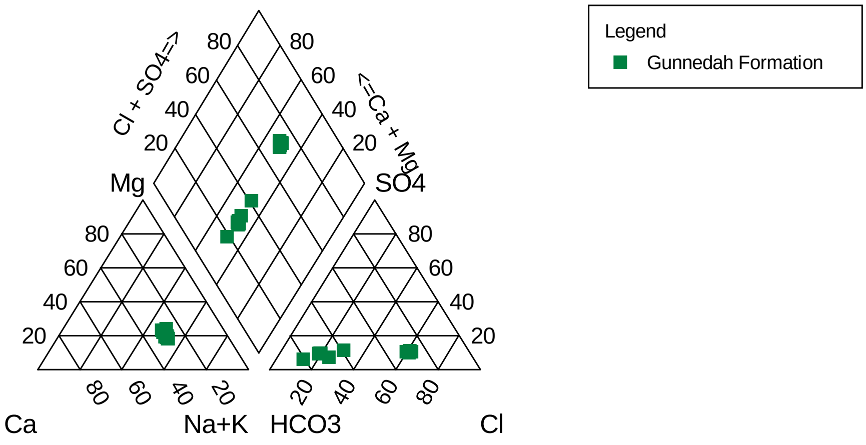


c. Water level and electrical conductivity from August 1973 to August 2011

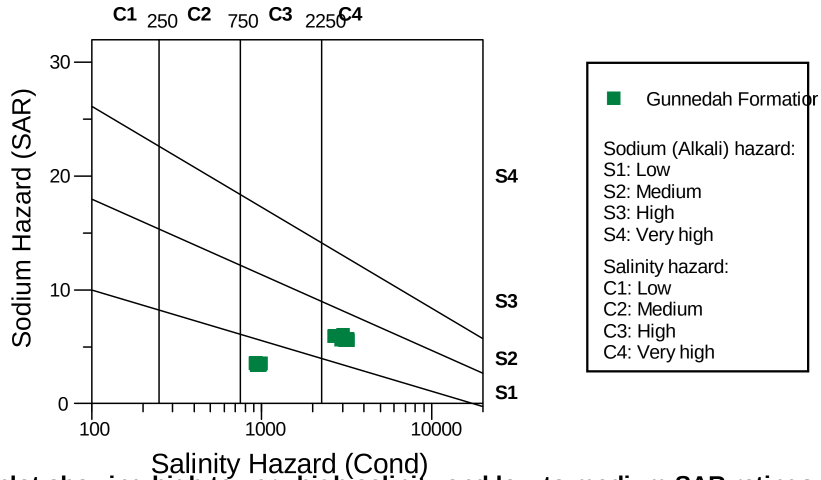
Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS
BRINCKERHOFF

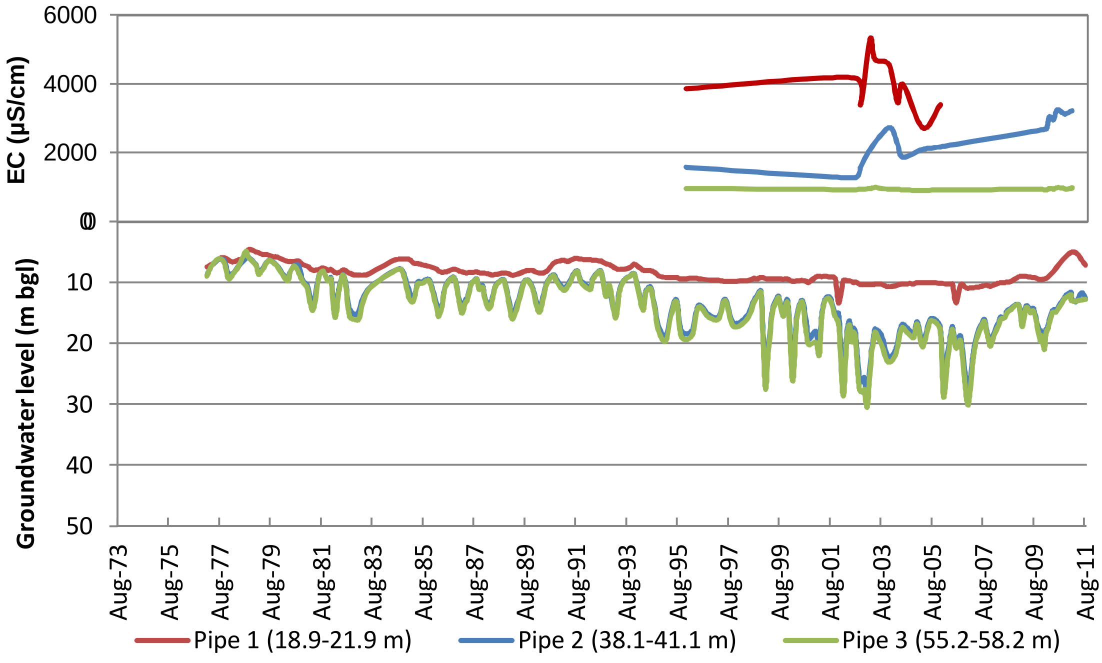
Figure C-7 Chemistry Summary GW036213



a. Piper plot showing water type: Na-Ca-Mg-Cl-HCO_3, Na-Ca-HCO3-Cl, Na-Ca-Mg-HCO3 and Na-Ca-HCO3 (Gunnedah Formation)



b. Wilcox plot showing high to very high salinity and low to medium SAR ratings

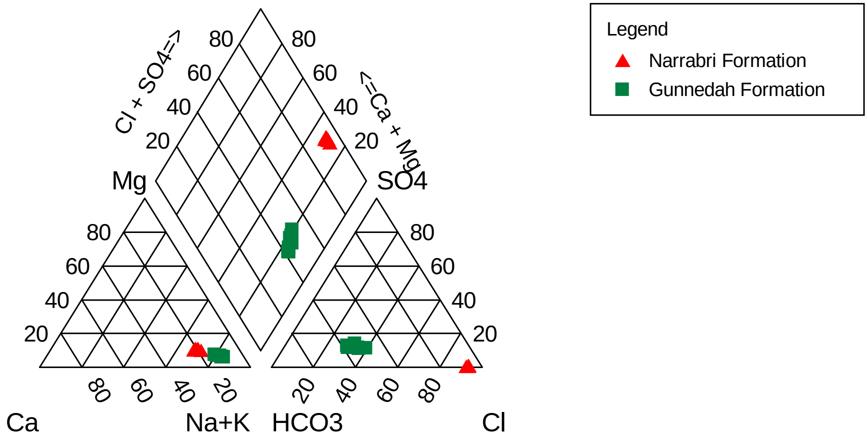


c. Water level and electrical conductivity from August 1973 to August 2011

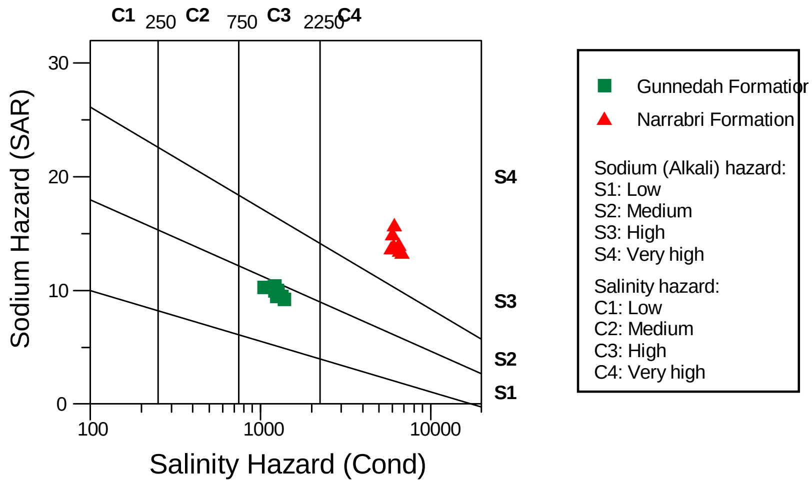
Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

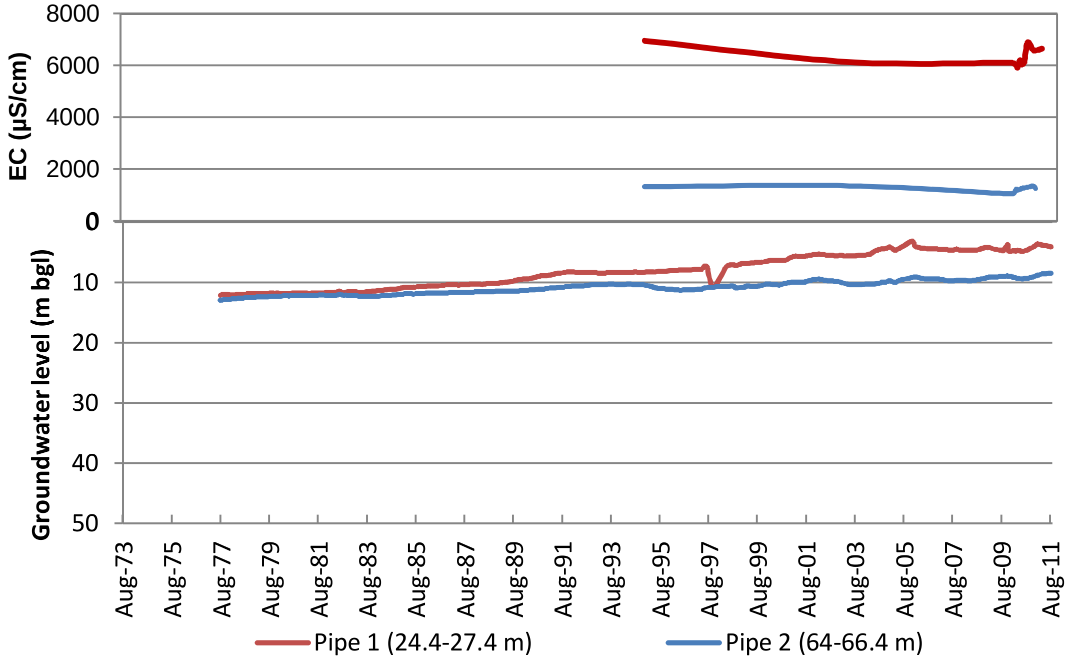
Figure C-8 Chemistry Summary GW036231



a. Piper plot showing water type: Na-Ca-Cl and Na-Cl (Narrabri Formation) and Na-HCO3-Cl (Gunnedah Formation)



b. Wilcox plot showing very high salinity and SAR ratings in Gunnedah Formation and high salinity and medium SAR ratings in the Narrabri Formation.



c. Water level and electrical conductivity from August 1973 to August 2011

Client: NSW Office of Water
Location: Upper Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

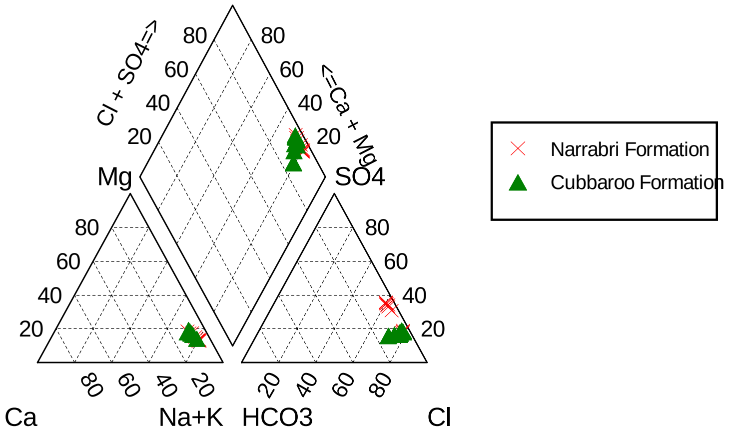
PARSONS BRINCKERHOFF

Appendix

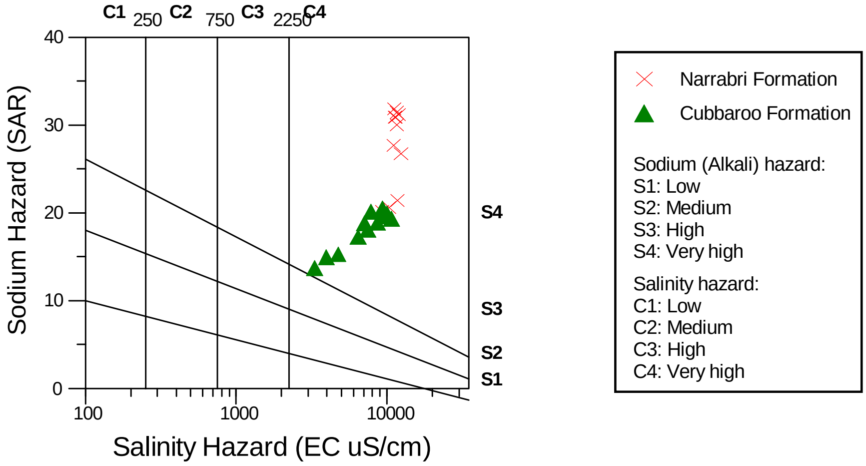
D

Lower Namoi GMA – Water Quality Report Cards

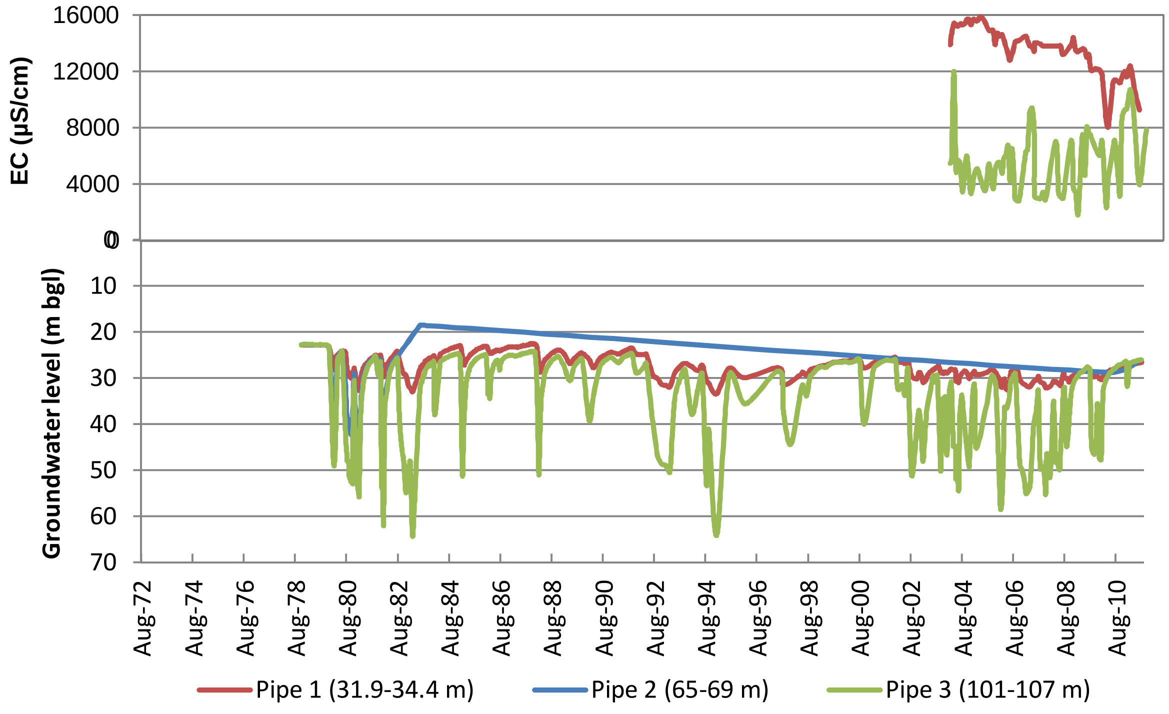
Figure D-1 Chemistry Summary GW036280



a. Piper plot showing water type: Na-Cl and Na-Cl-SO4 (Narrabri Formation) and Na-Cl (Cubbaroo Formation)



b. Wilcox plot showing very high salinity and SAR ratings

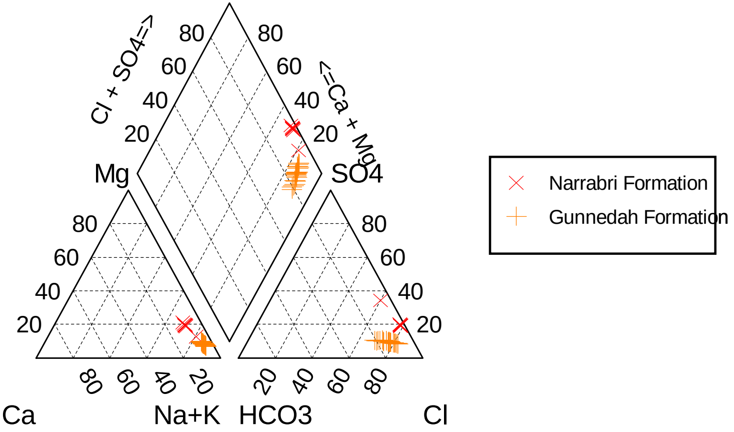


c. Water level and electrical conductivity from August 1972 to August 2011

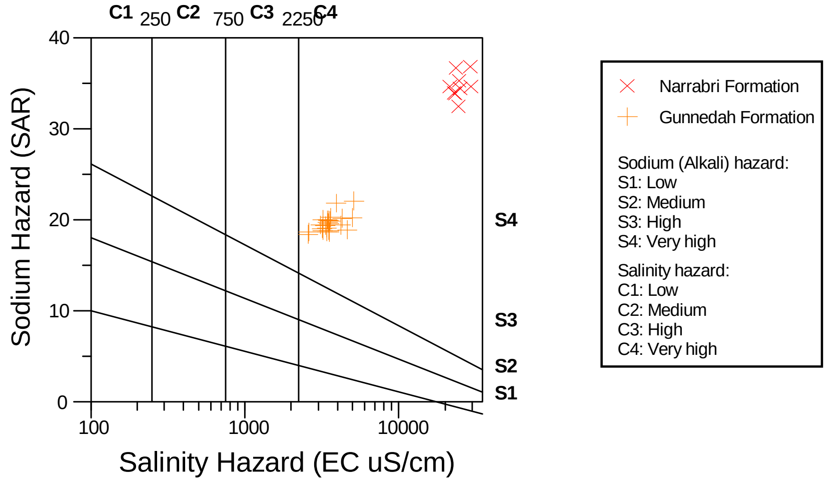
Client: NSW Office of Water
Location: Lower Namoi GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

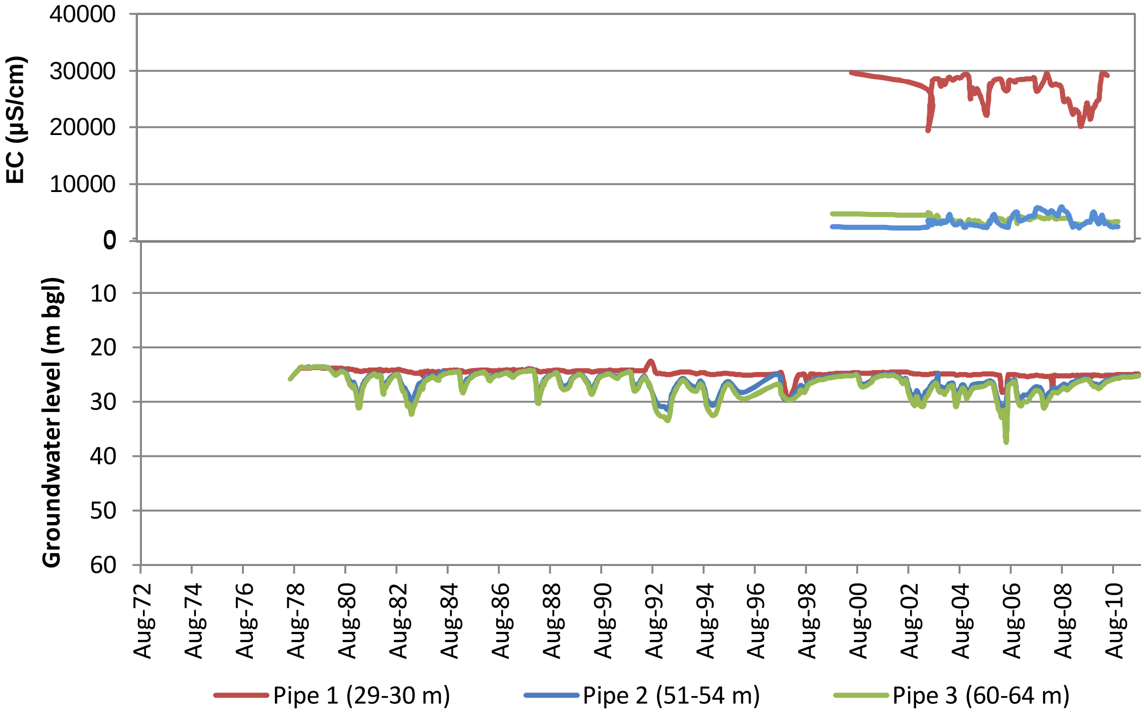
Figure D-2 Chemistry Summary GW036314



a. Piper plot showing water type: Na-Cl, Na-Mg-Cl and Na-Cl-SO4 (Narrabri Formation) and Na-Cl and Na-Cl-HCO3 (Gunnedah Formation)



b. Wilcox plot showing very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

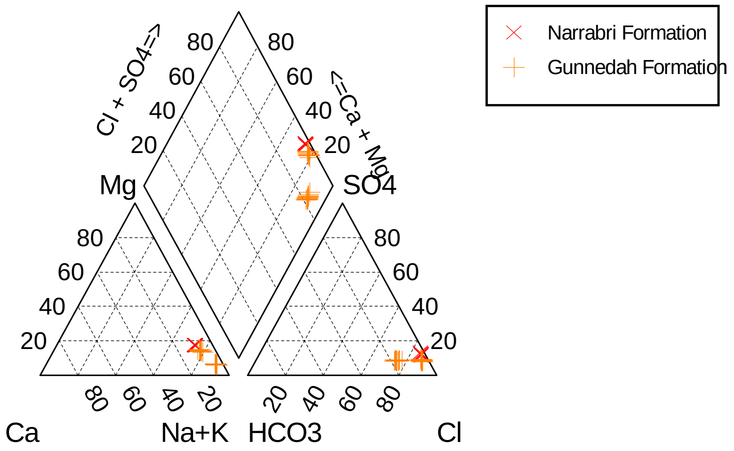
Client: NSW Office of Water

Location: Lower Namoi GMA

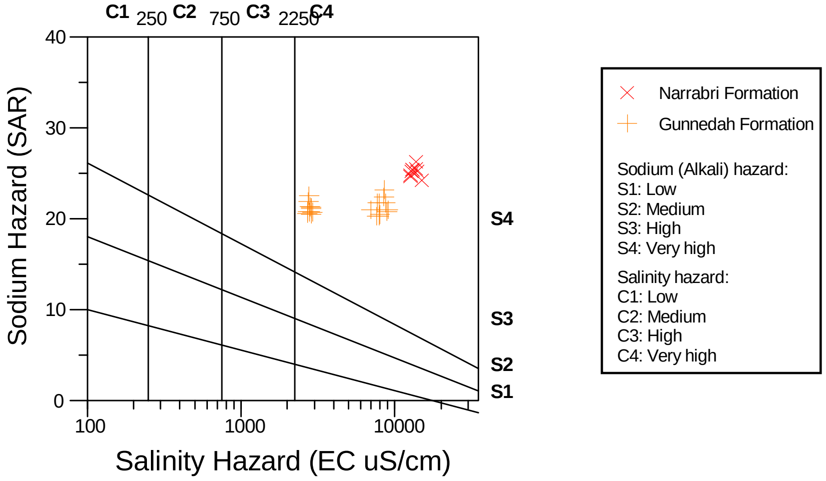
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

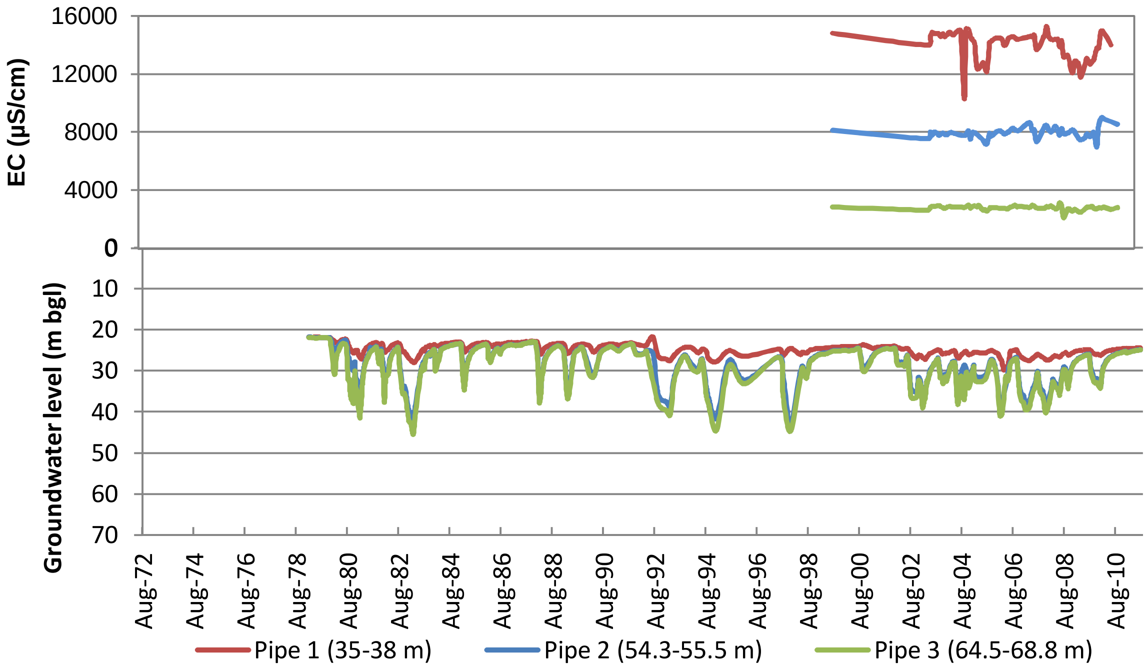
Figure D-3 Chemistry Summary GW036320



a. Piper plot showing water type: Na-Cl (Narrabri and Gunnedah Formations)



b. Wilcox plot showing very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

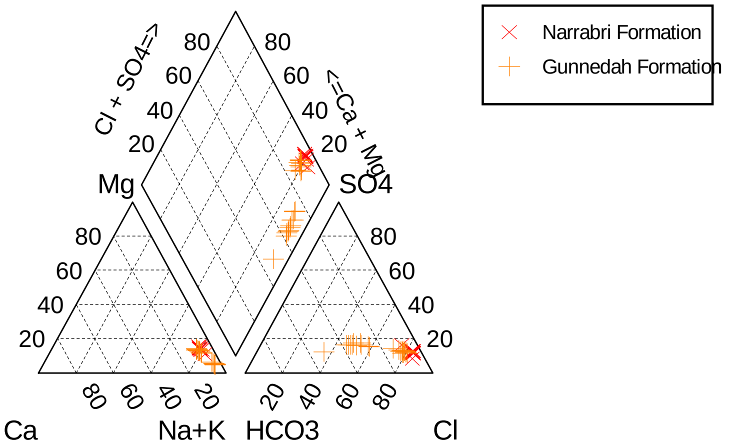
Client: NSW Office of Water

Location: Lower Namoi GMA

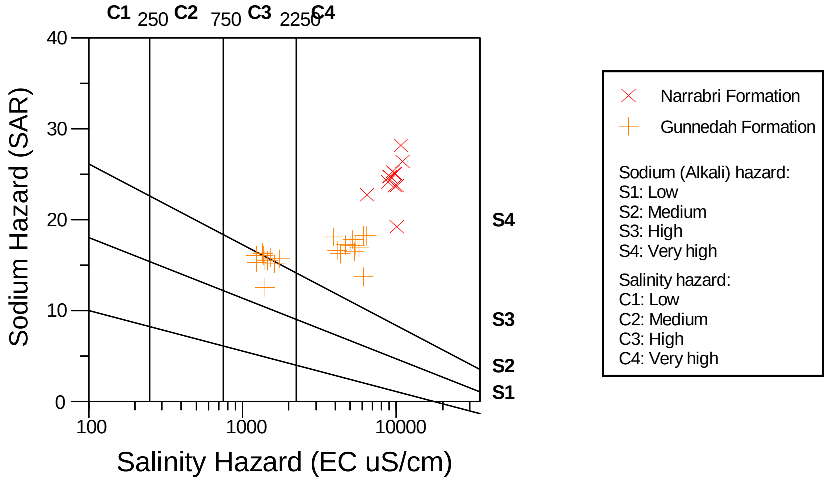
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

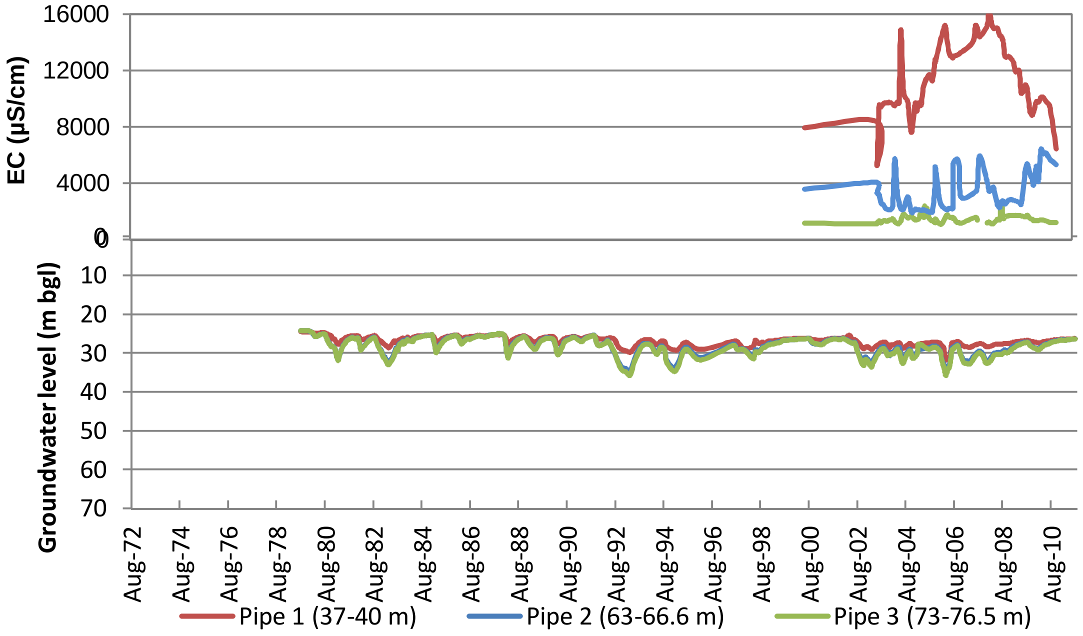
Figure D-4 Chemistry Summary GW036340



a. Piper plot showing water type: Na-Cl (Narrabri Formation) and Na-Cl and Na-Cl-HCO3 (Gunnedah Formation)



b. Wilcox plot showing high to very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

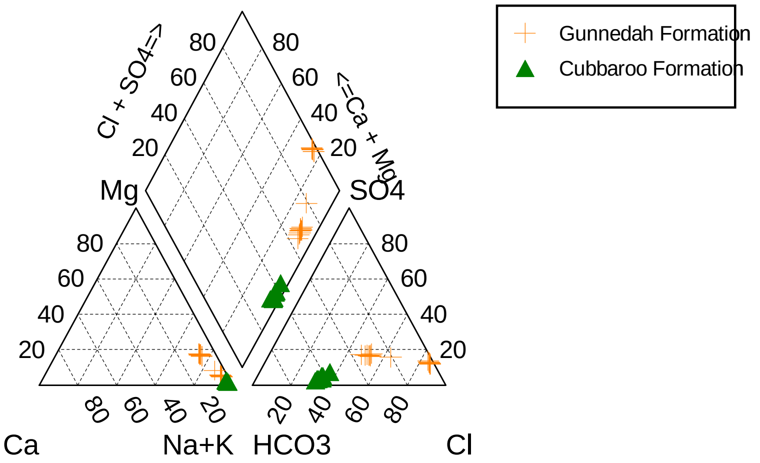
Client: NSW Office of Water

Location: Lower Namoi GMA

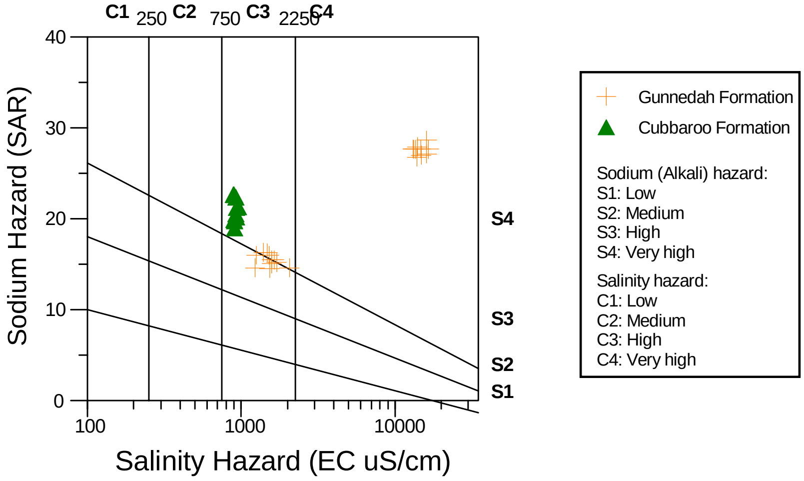
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

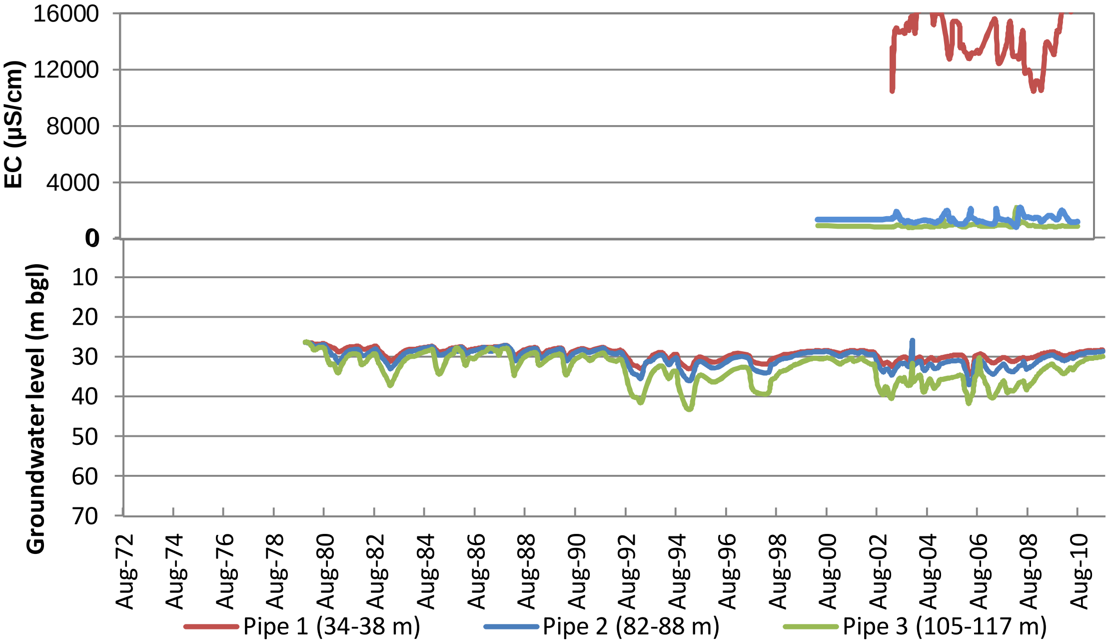
Figure D-5 Chemistry Summary GW036364



a. Piper plot showing water type: Na-Cl and Na-Cl-HCO3 (Gunnedah Formation) and Na-HCO3-Cl (Cubbaroo Formation)



b. Wilcox plot showing high to very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

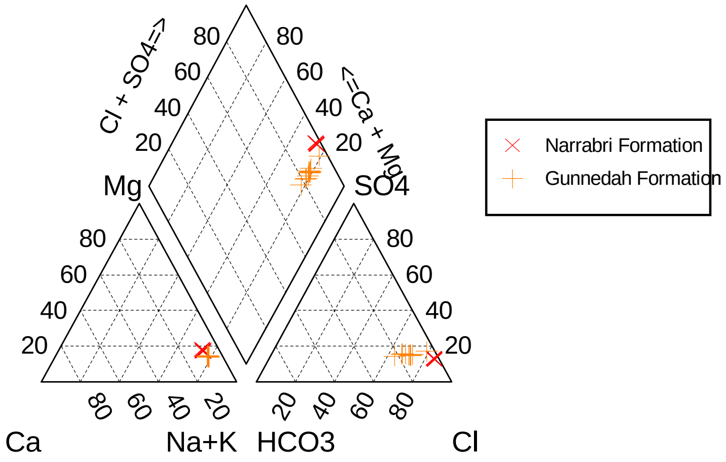
Client: NSW Office of Water

Location: Lower Namoi GMA

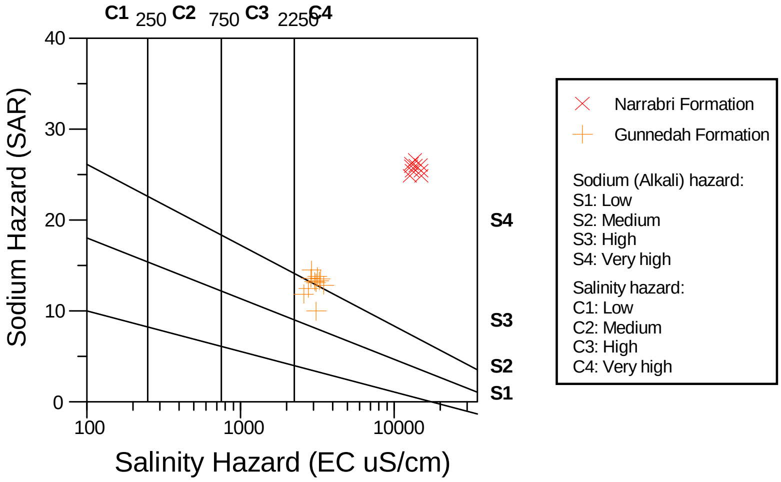
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

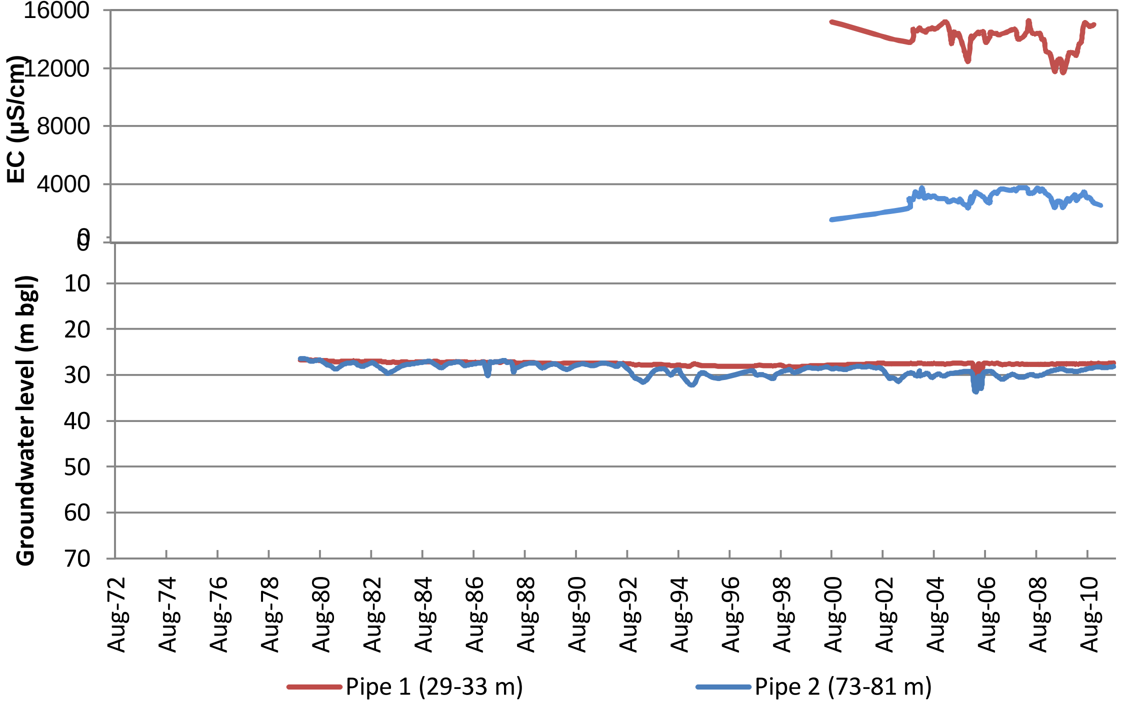
Figure D-6 Chemistry Summary GW036377



a. Piper plot showing water type: Na-Cl (Narrabri Formation) and Na-Cl and Na-Cl-HCO3 (Gunnedah Formation)

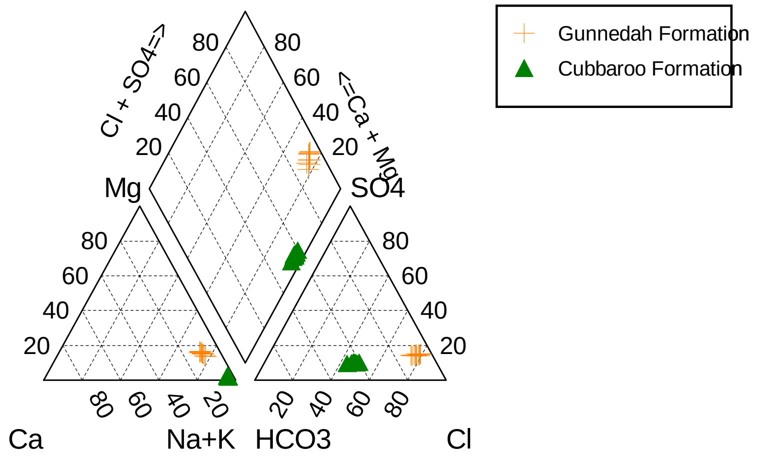


b. Wilcox plot showing very high salinity and high to very high SAR ratings

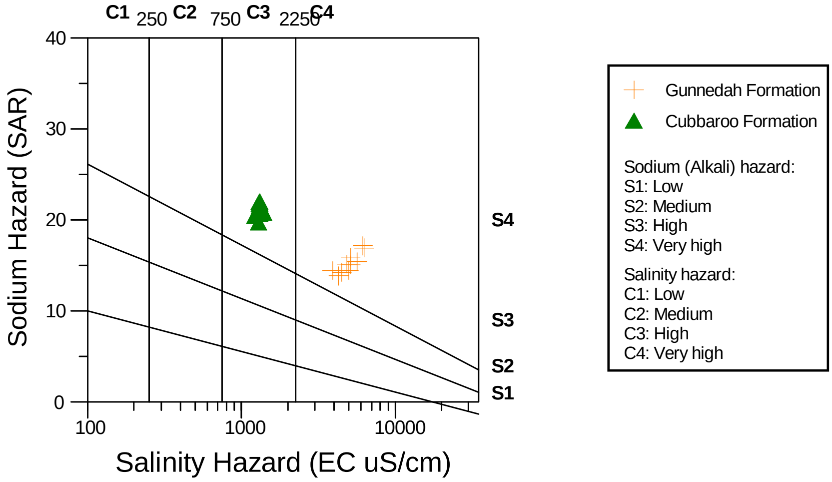


c. Water level and electrical conductivity from August 1972 to August 2011

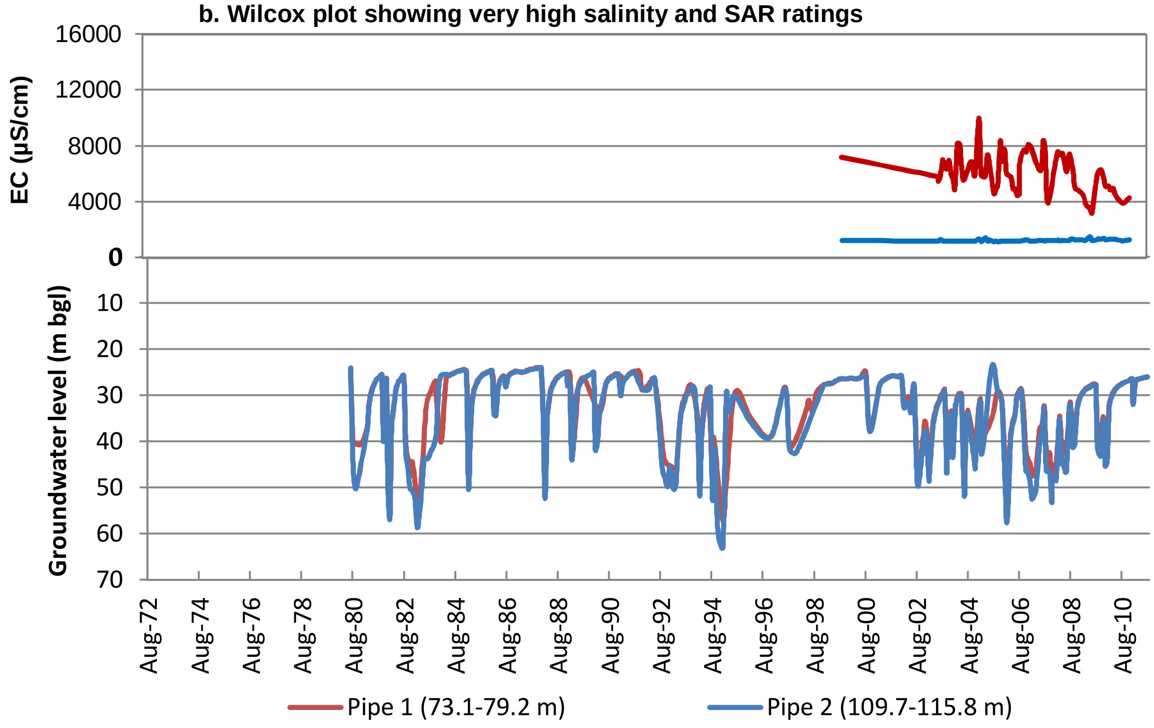
Figure D-7 Chemistry Summary GW036398



a. Piper plot showing water type: Na-Cl (Gunnedah Formation) and Na-Cl-HCO3 and Na-HCO3-Cl (Cubbaroo Formation)



b. Wilcox plot showing very high salinity and SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

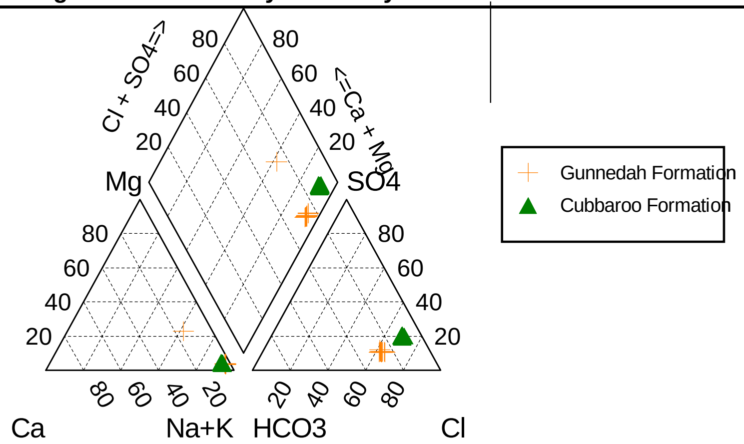
Client: NSW Office of Water

Location: Lower Namoi GMA

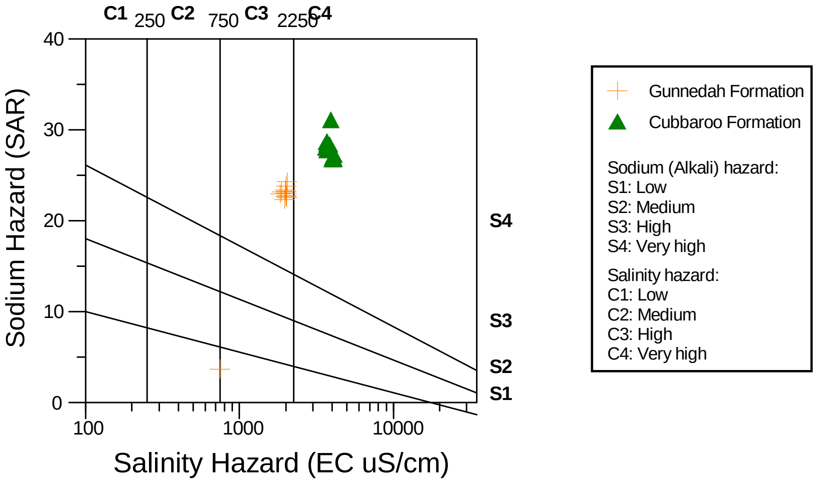
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

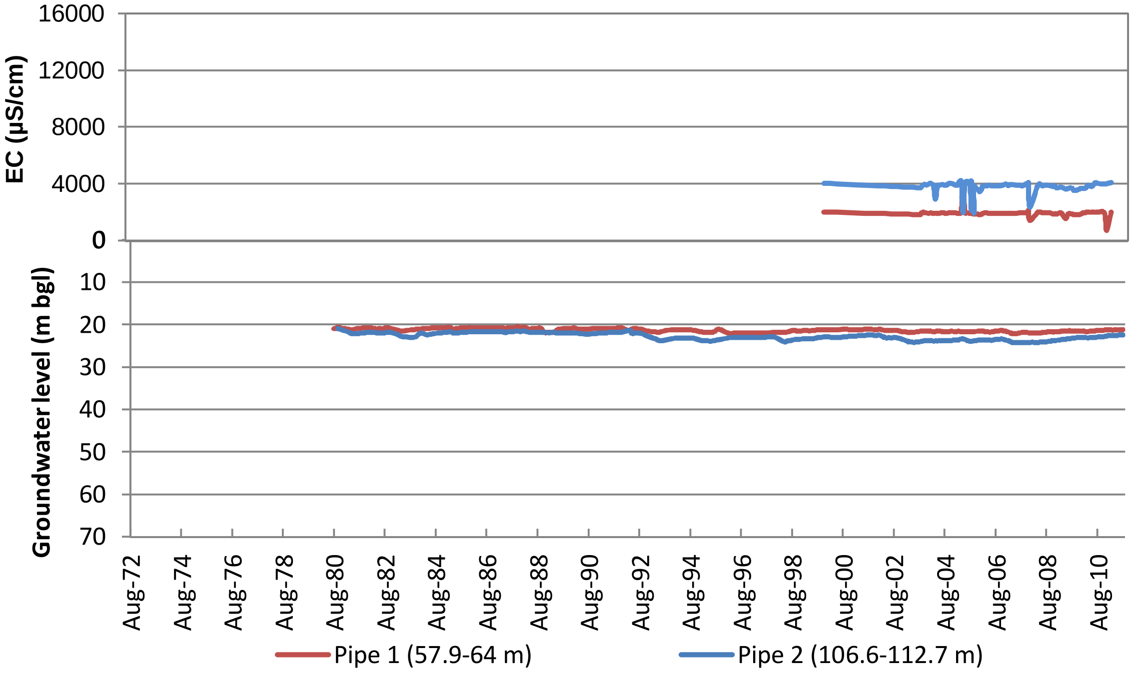
Figure D-8 Chemistry Summary GW036406



a. Piper plot showing water type: Na-Cl-HCO3 and Na-Mg-Cl-HCO3 (Gunnedah Formation) and Na-Cl and Na-Cl-SO4 (Cubbaroo Formation)



b. Wilcox plot showing very high salinity and SAR ratings, with one low SAR and medium salinity rating at GW036406/1 on 11/11/10



c. Water level and electrical conductivity from August 1972 to August 2011

Client: NSW Office of Water

Location: Lower Namoi GMA

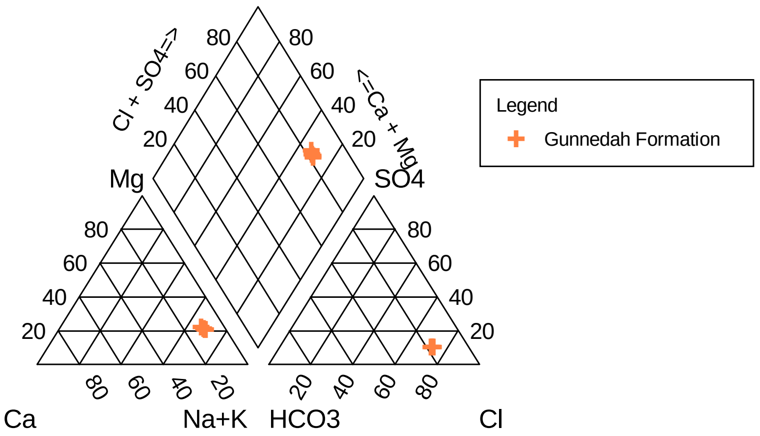
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

Appendix

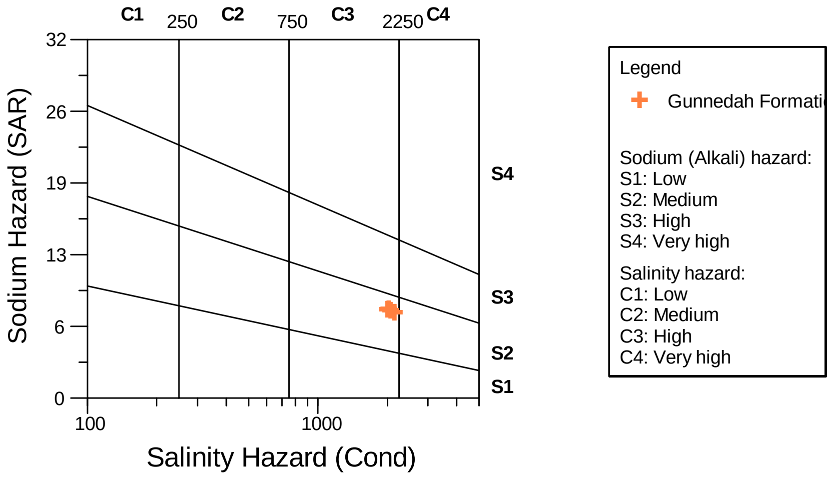
E

Lower Macquarie GMA – Water Quality Report Cards

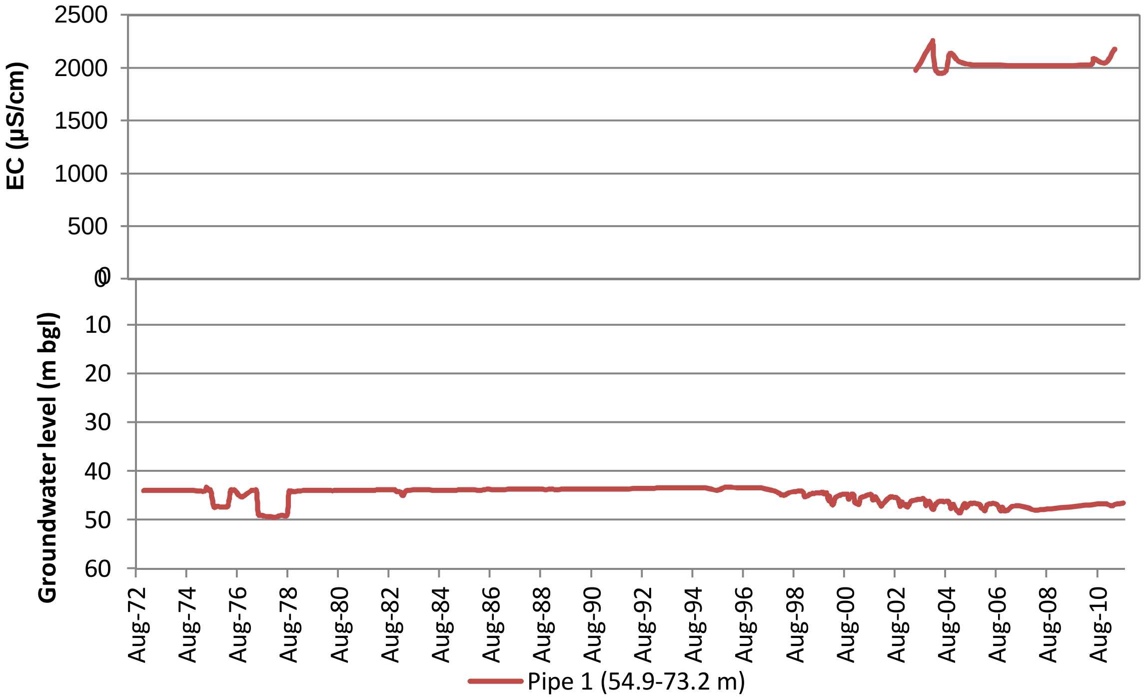
Figure E-1 Chemistry Summary GW030211



a. Piper plot showing water type: Na-Cl and Na-Mg-Cl (Gunnedah Formation)



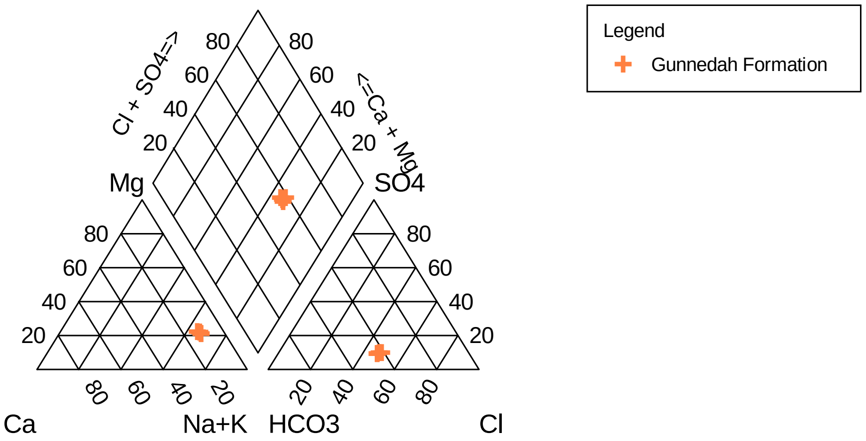
b. Wilcox plot showing high salinity and medium SAR ratings



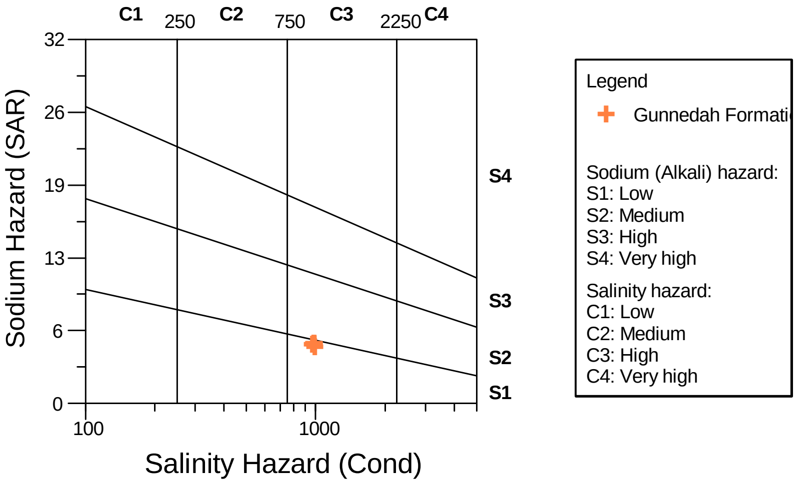
c. Water level and electrical conductivity from August 1972 to August 2011

Client: NSW Office of Water
Location: Lower Macquarie GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

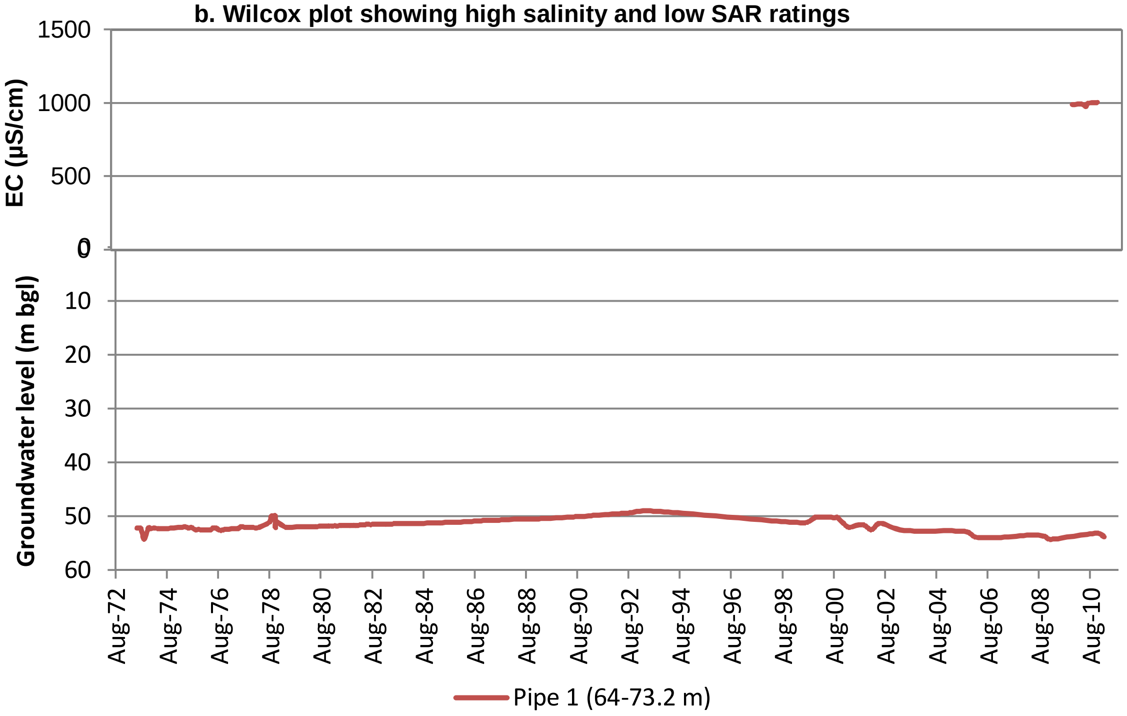
Figure E-2 Chemistry Summary GW030214



a. Piper plot showing water type: Na-Mg-Cl-HCO_3 (Gunnedah Formation)



b. Wilcox plot showing high salinity and low SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

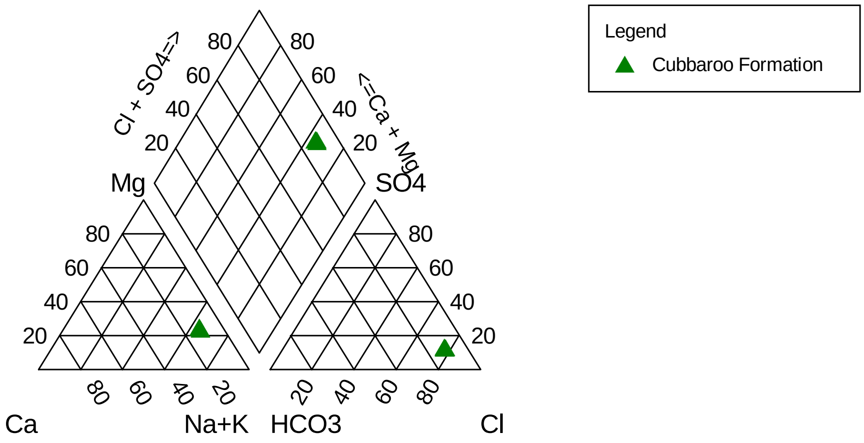
Client: NSW Office of Water

Location: Lower Macquarie GMA

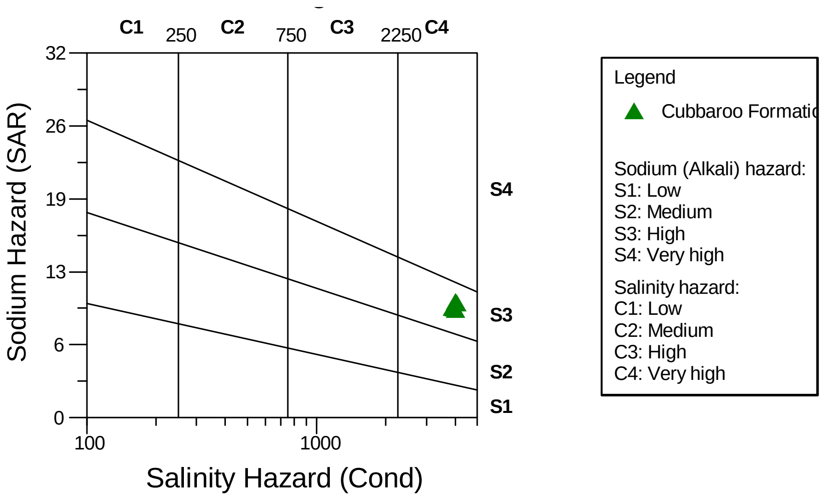
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

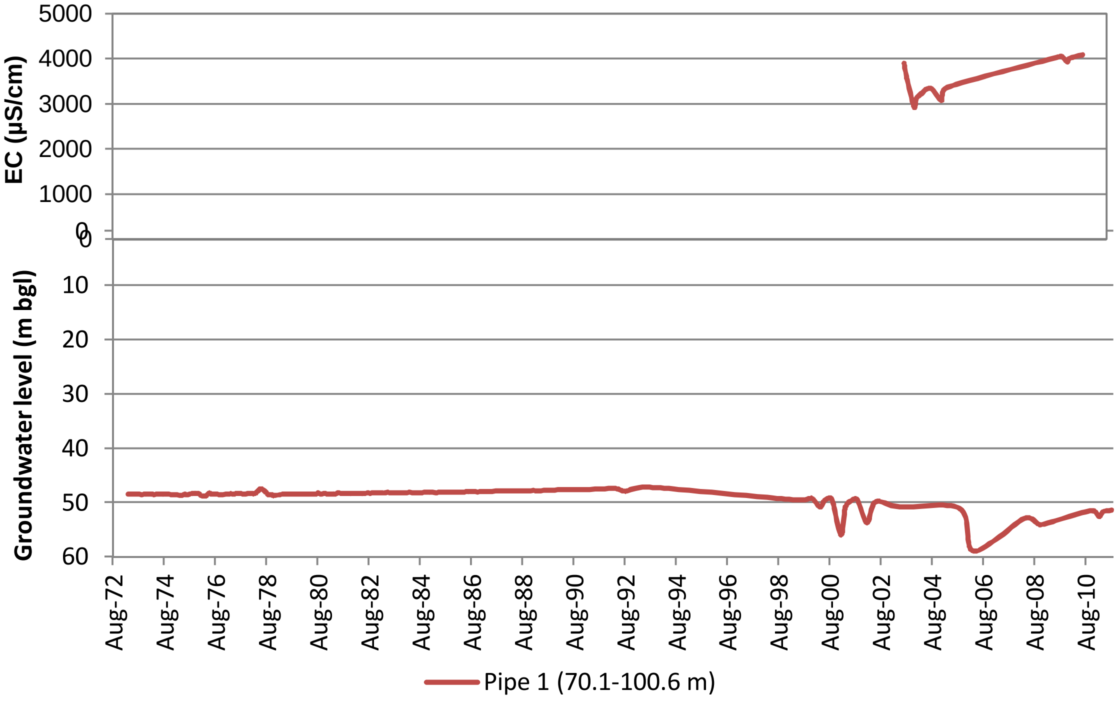
Figure E-3 Chemistry Summary GW030215



a. Piper plot showing water type: Na-Mg-Cl (Cubbaroo Formation)



b. Wilcox plot showing very high salinity and high SAR ratings

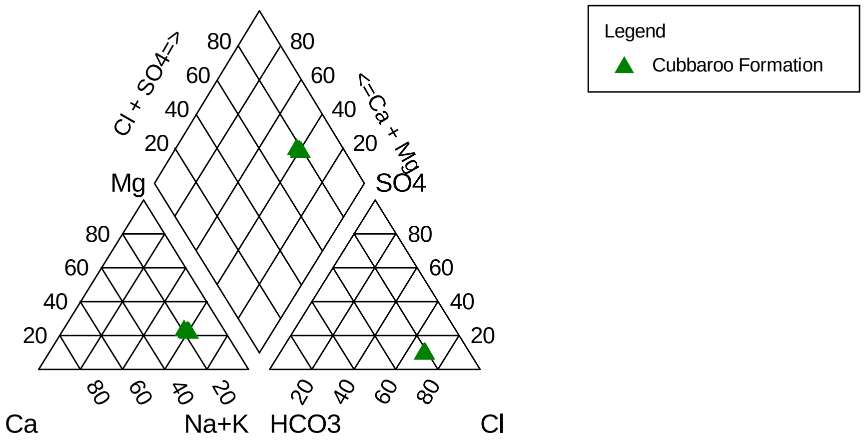


c. Water level and electrical conductivity from August 1972 to August 2011

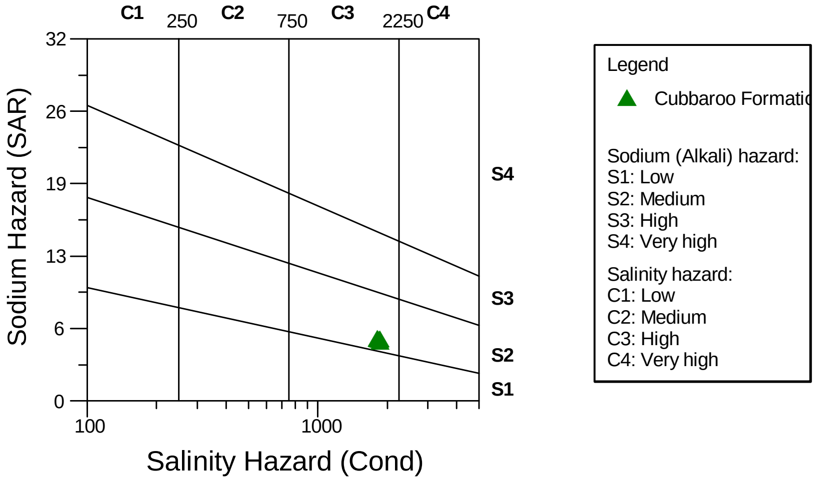
Client: NSW Office of Water
Location: Lower Macquarie GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

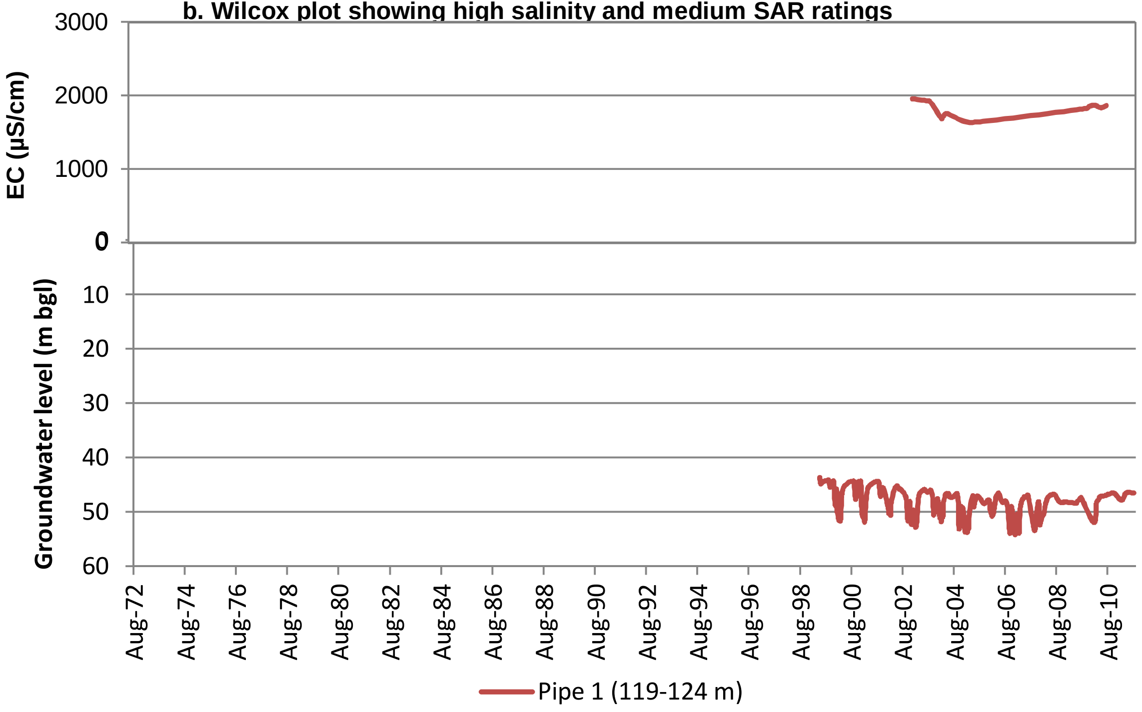
Figure E-4 Chemistry Summary GW096000



a. Piper plot showing water type: Na-Mg-Cl-HCO_3 (Cubbaroo Formation)



b. Wilcox plot showing high salinity and medium SAR ratings

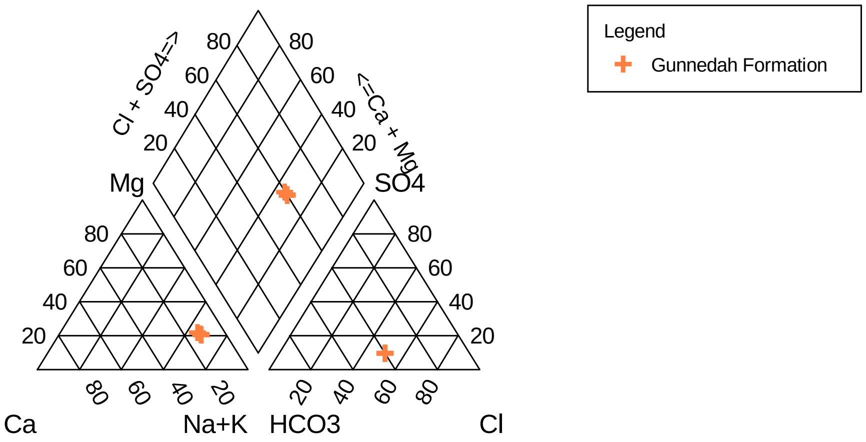


c. Water level and electrical conductivity from August 1972 to August 2011

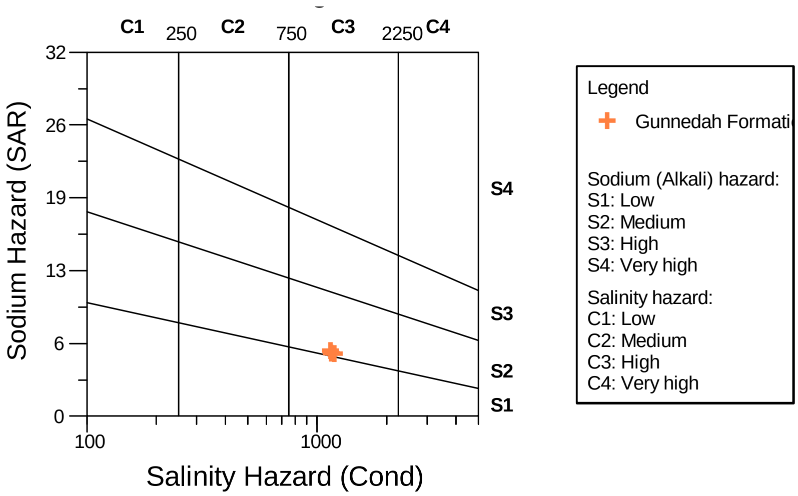
Client: NSW Office of Water
Location: Lower Macquarie GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

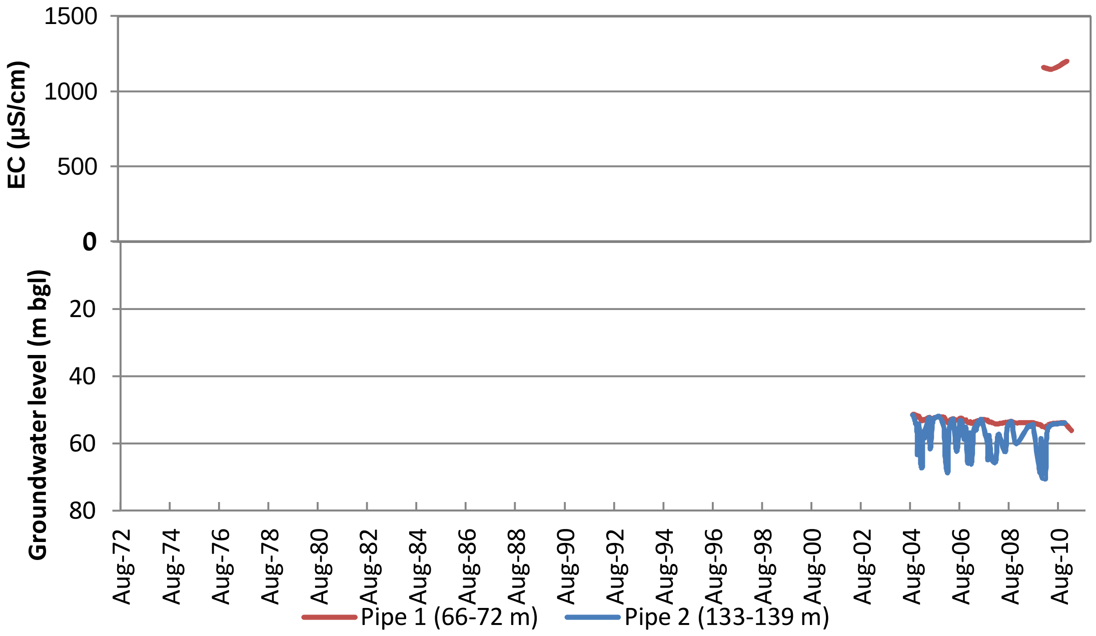
Figure E-5 Chemistry Summary GW096144



a. Piper plot showing water type: Na-Mg-Cl-HCO$_3$ (Gunnedah Formation)



b. Wilcox plot showing high salinity and medium SAR ratings

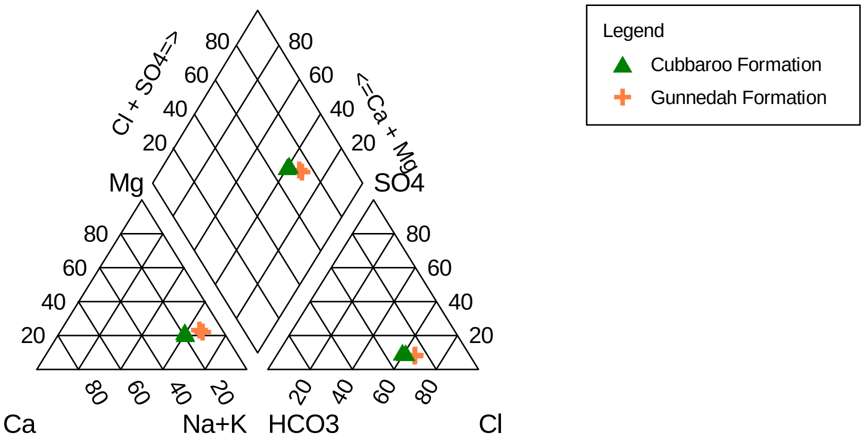


c. Water level and electrical conductivity from August 1972 to August 2011

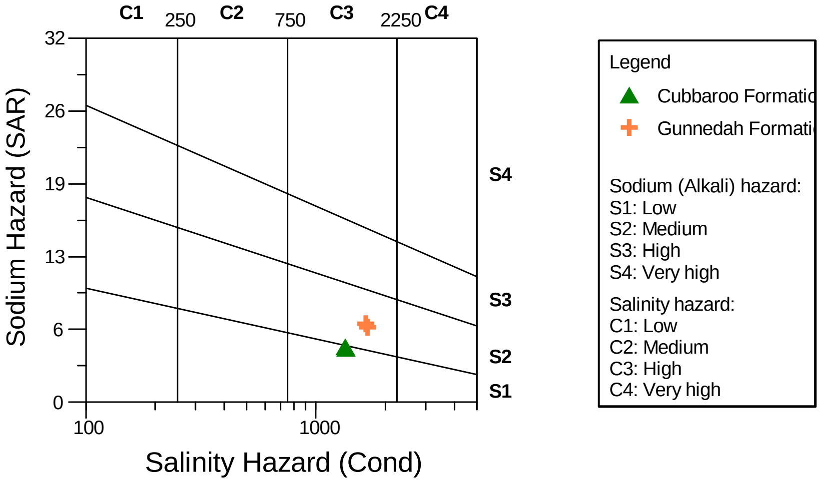
Client: NSW Office of Water
Location: Lower Macquarie GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

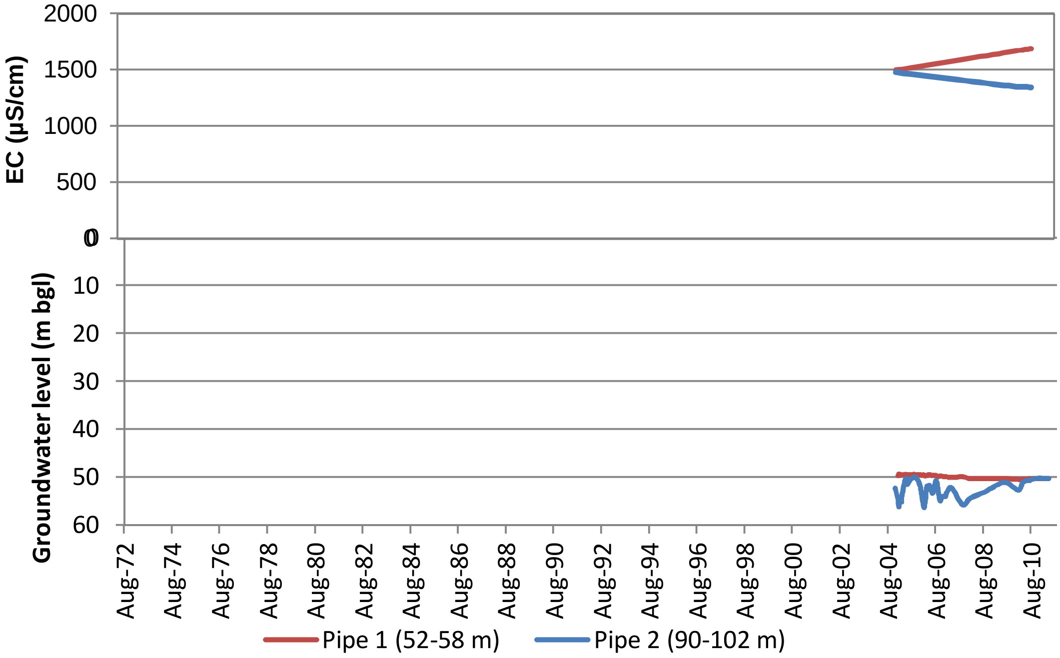
Figure E-6 Chemistry Summary GW096147



a. Piper plot showing water type: Na-Mg-Cl-HCO_3 (Gunnedah Formation) and Na-Mg-Cl-HCO3 and Na-Cl-HCO3 (Cubbaroo Formation)



b. Wilcox plot showing high salinity and low to medium SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

Client: NSW Office of Water

Location: Lower Macquarie GMA

Project: Characterisation of hydrogeochemistry and risks to groundwater quality

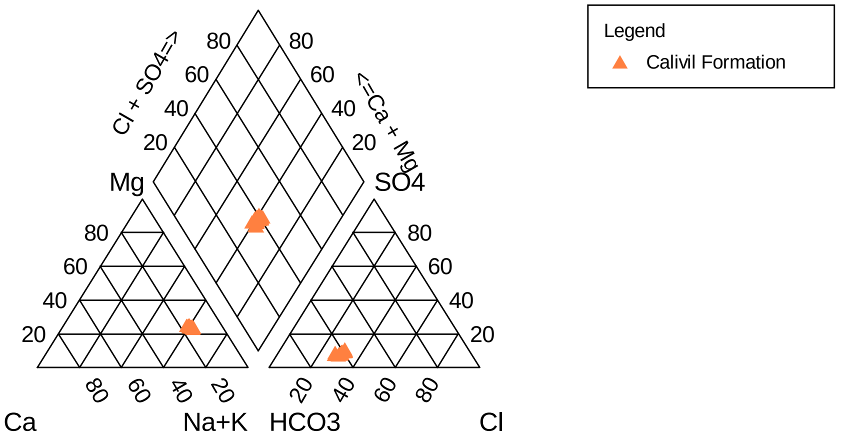
PARSONS BRINCKERHOFF

Appendix

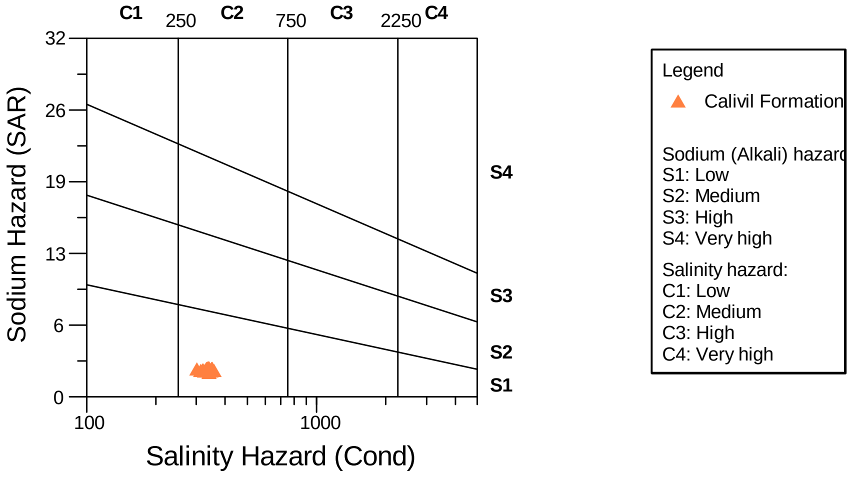
F

Lower Lachlan GMA – Water Quality Report Cards

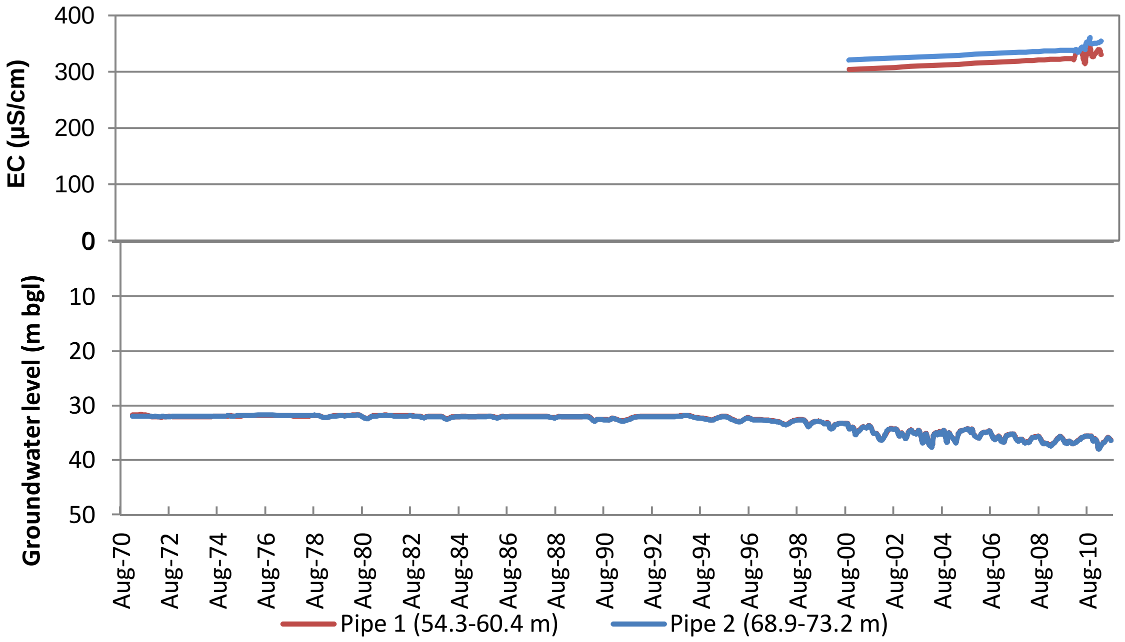
Figure F-1 Chemistry Summary GW030106



a. Piper plot showing water type: Na-Mg-HCO3-Cl (Calivil Formation)



b. Wilcox plot showing medium salinity and low SAR ratings

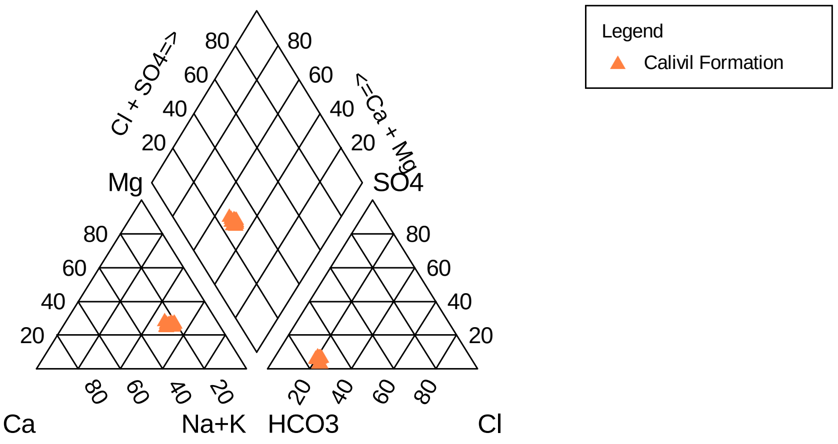


c. Water level and electrical conductivity from August 1970 to August 2011

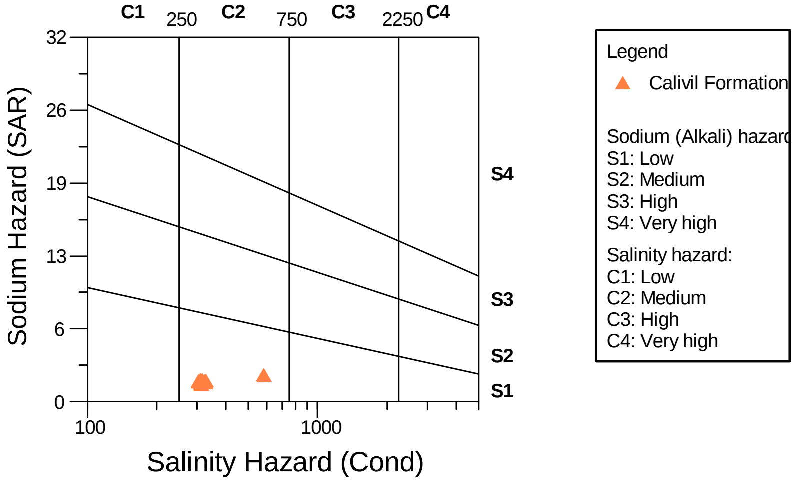
Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

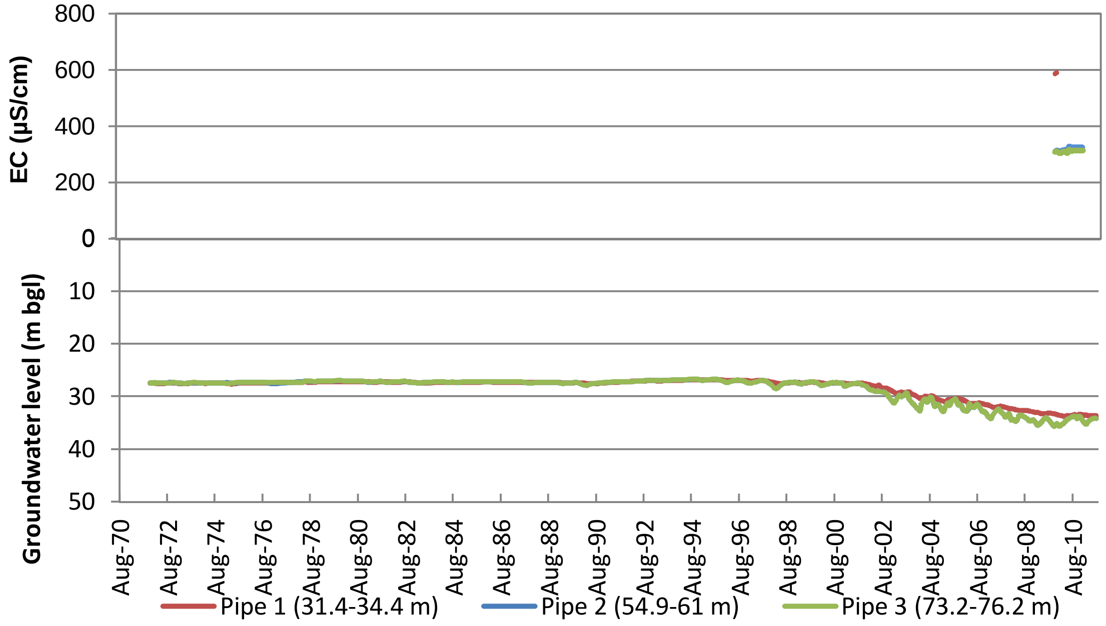
Figure F-2 Chemistry Summary GW030173



a. Piper plot showing water type: Na-Mg-Ca-HCO3-Cl, Na-Mg-Ca-HCO3 and Na-HCO3-Cl



b. Wilcox plot showing medium salinity and low SAR ratings

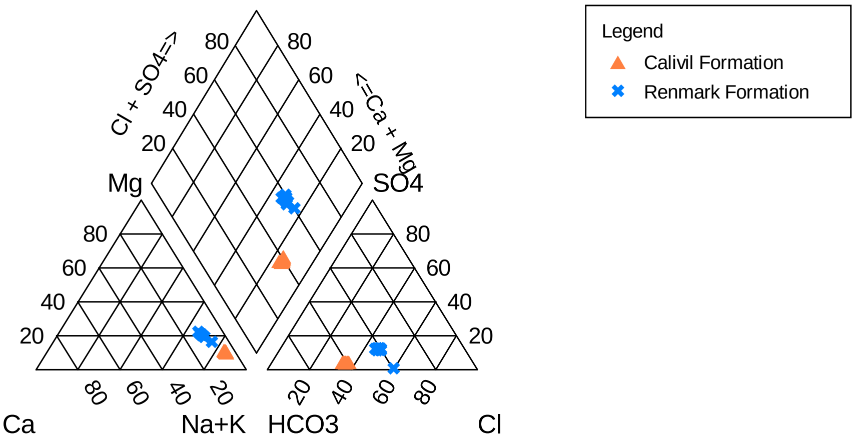


c. Water level and electrical conductivity from August 1970 to August 2011

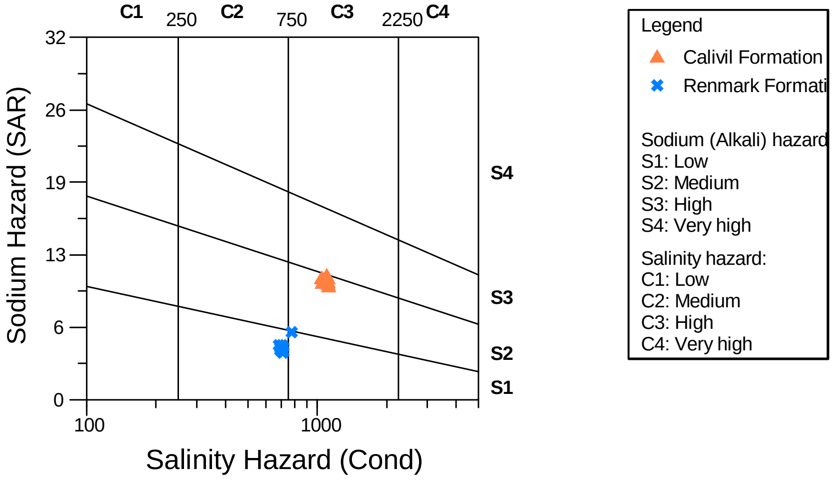
Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

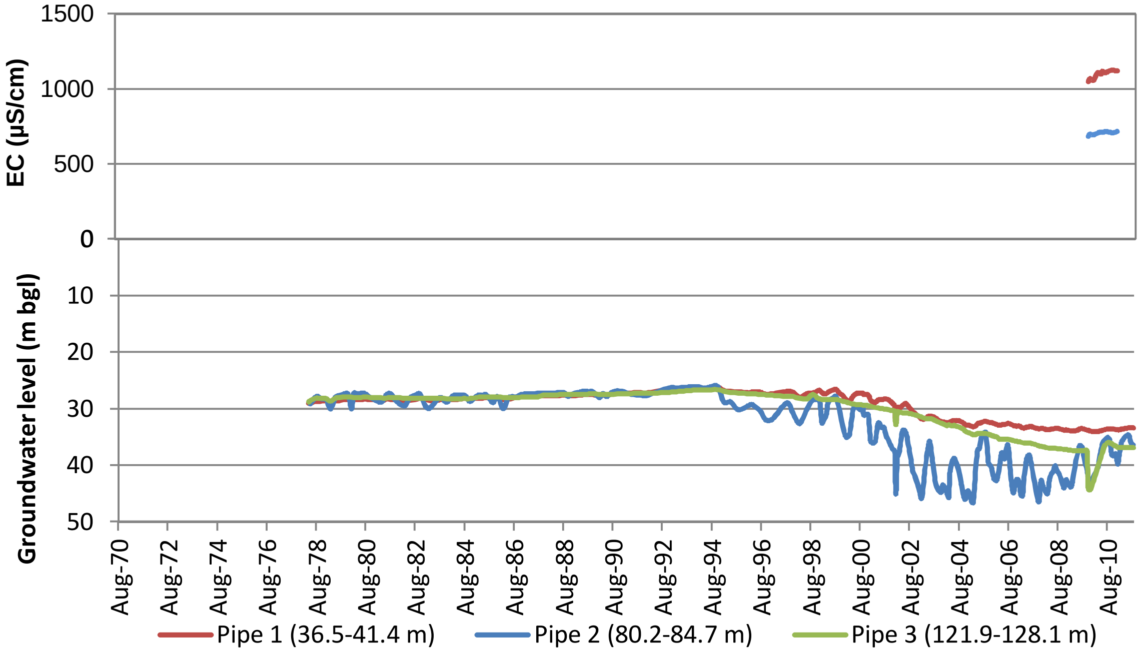
Figure F-3 Chemistry Summary GW030405



a. Piper plot showing water type: Na-HCO3-Cl (Calivil Formation) and Na-Mg-Cl-HCO3, Na-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium salinity and low SAR ratings

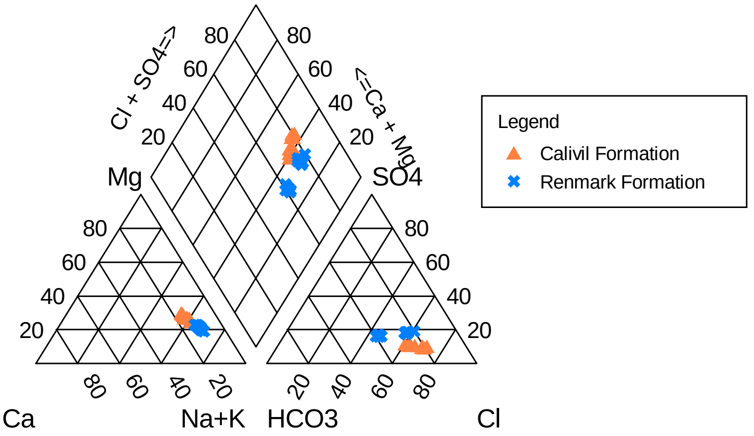


c. Water level and electrical conductivity from August 1970 to August 2011

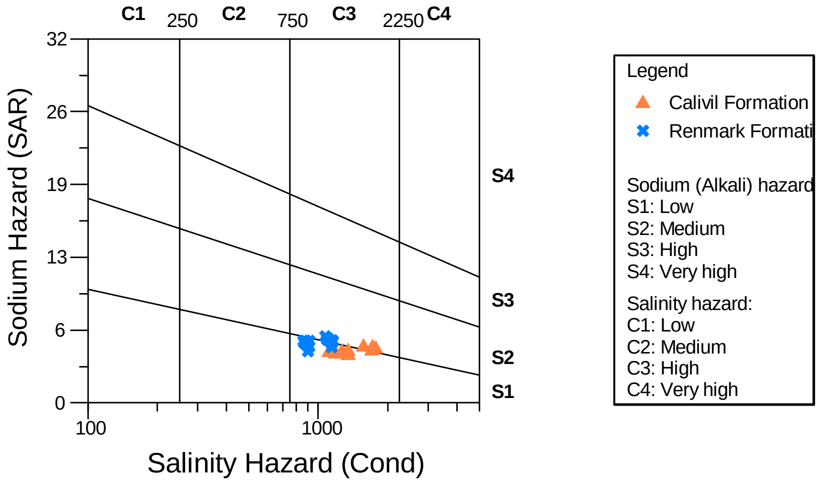
Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

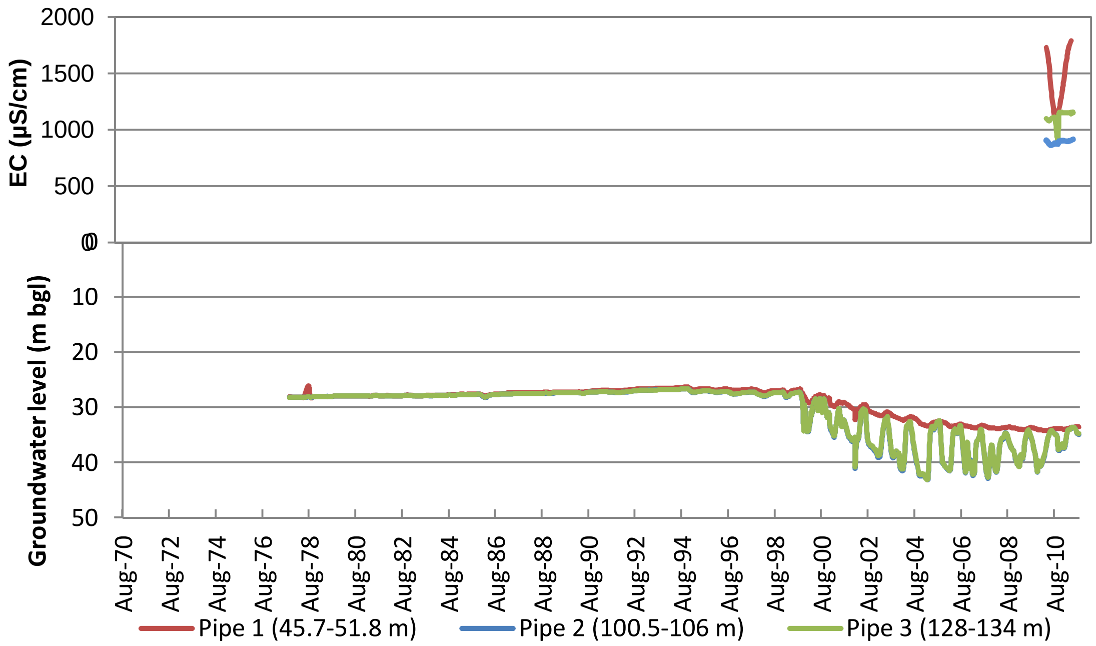
Figure F-4 Chemistry Summary GW030406



a. Piper plot showing water type: Na-Mg-Cl and Na-Mg-Cl-HCO3 (Calivil Formation); Na-Mg-Cl-HCO3, Na-Mg-Cl and Na-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing high salinity and low to medium SAR ratings

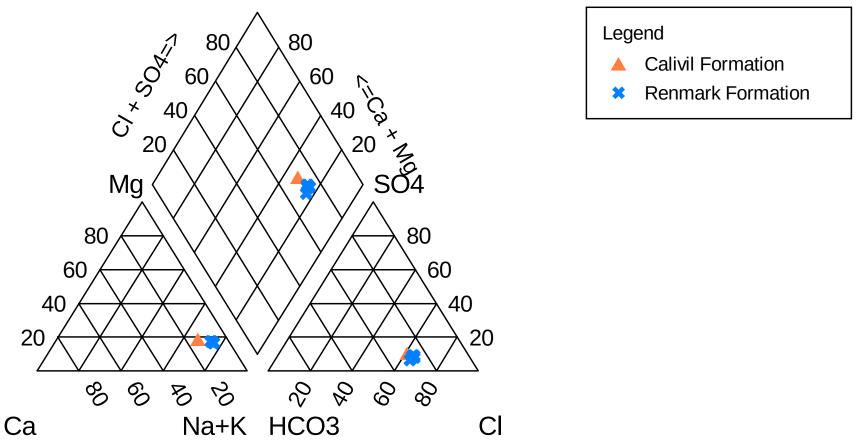


c. Water level and electrical conductivity from August 1970 to August 2011

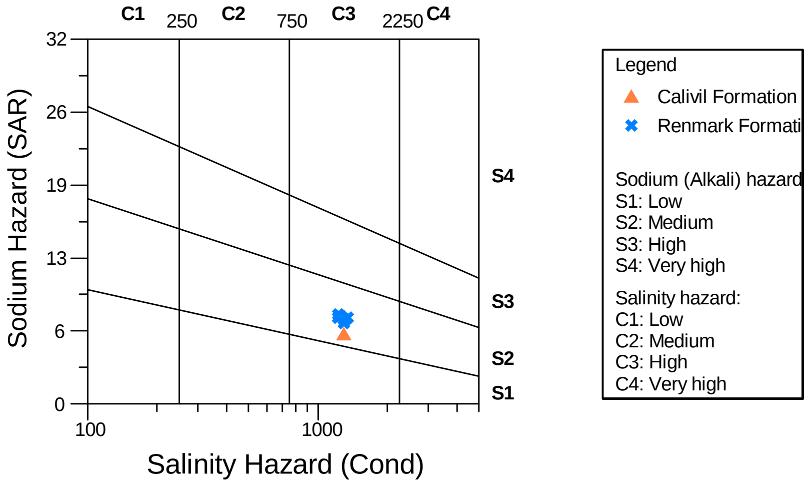
Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

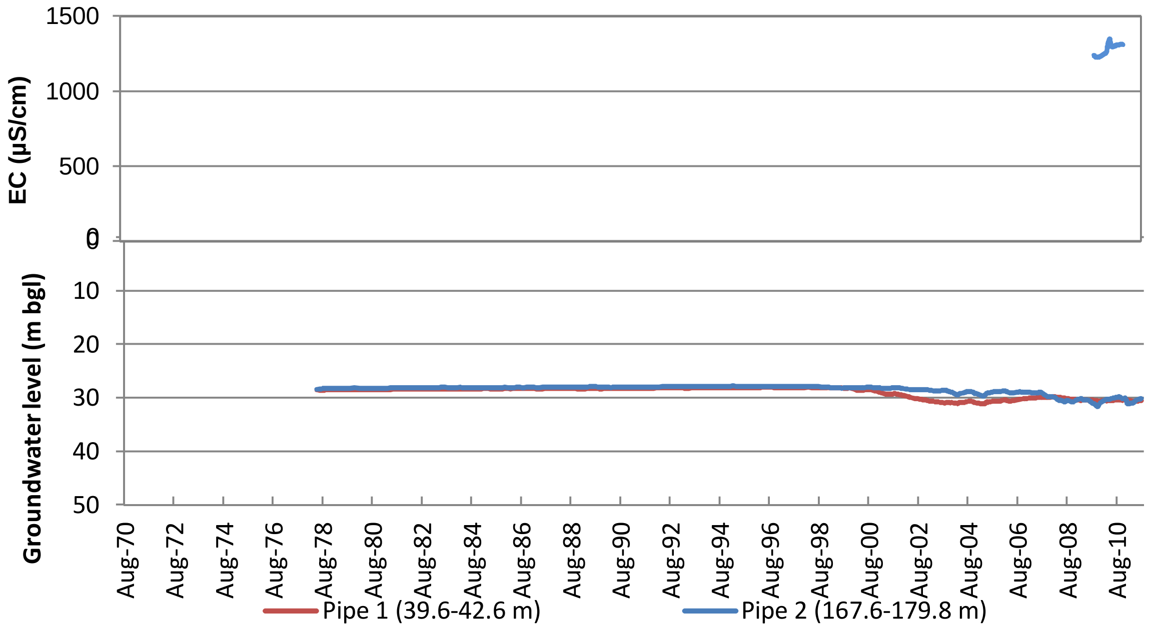
Figure F-5 Chemistry Summary GW036284



a. Piper plot showing water type: Na-Cl-HCO3 (Calivil and Renmark Formations)



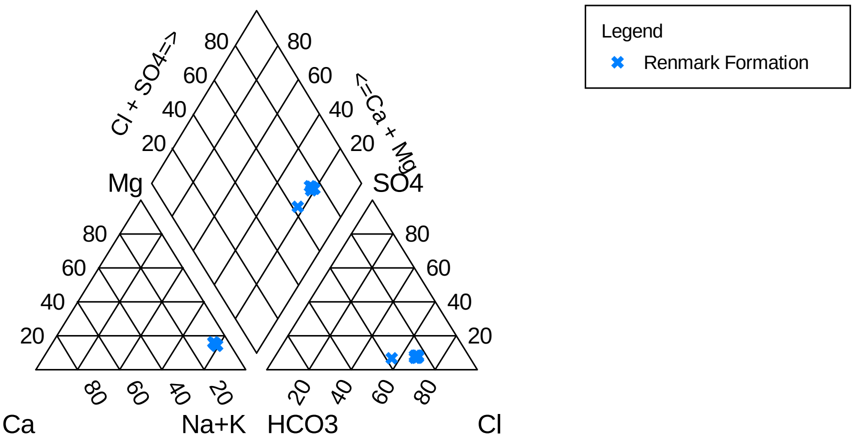
b. Wilcox plot showing high salinity and medium SAR ratings



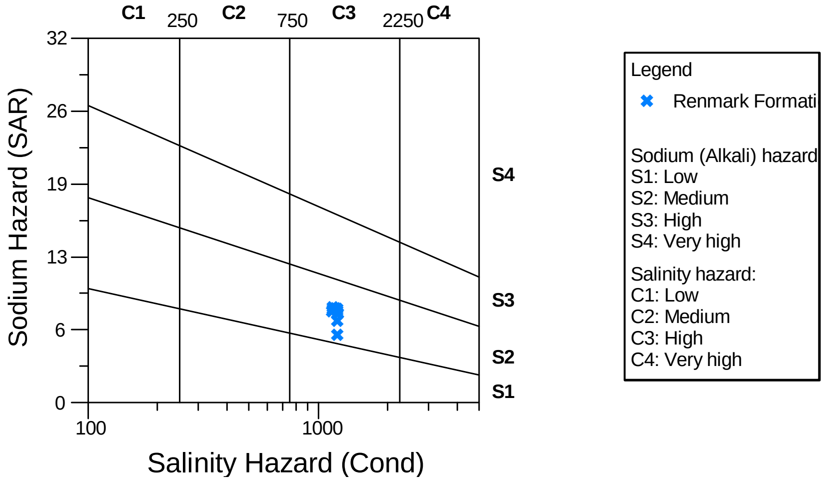
c. Water level and electrical conductivity from August 1970 to August 2011

Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

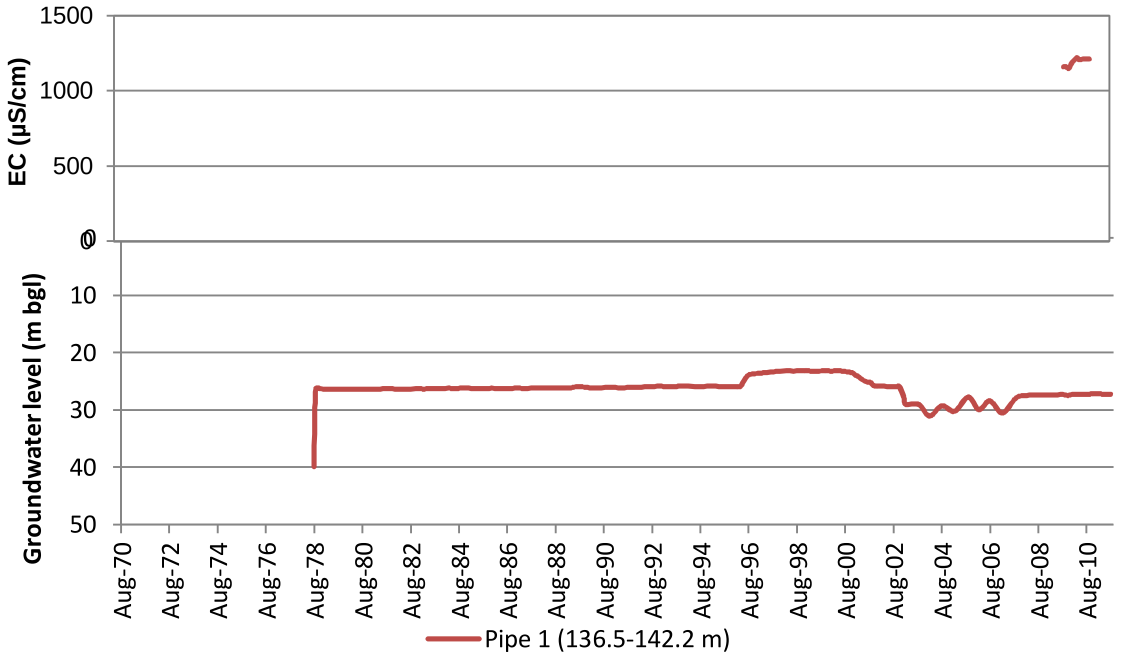
Figure F-6 Chemistry Summary GW036304



a. Piper plot showing water type: Na-Cl-HCO3 (Renmark Formation)



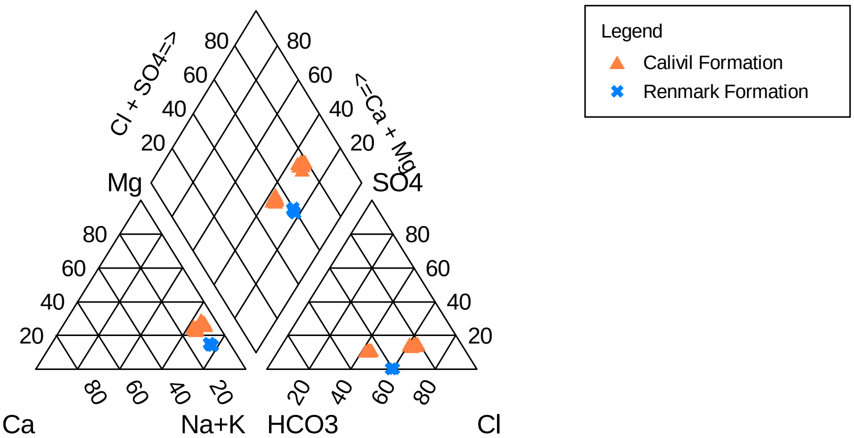
b. Wilcox plot showing high salinity and medium SAR ratings



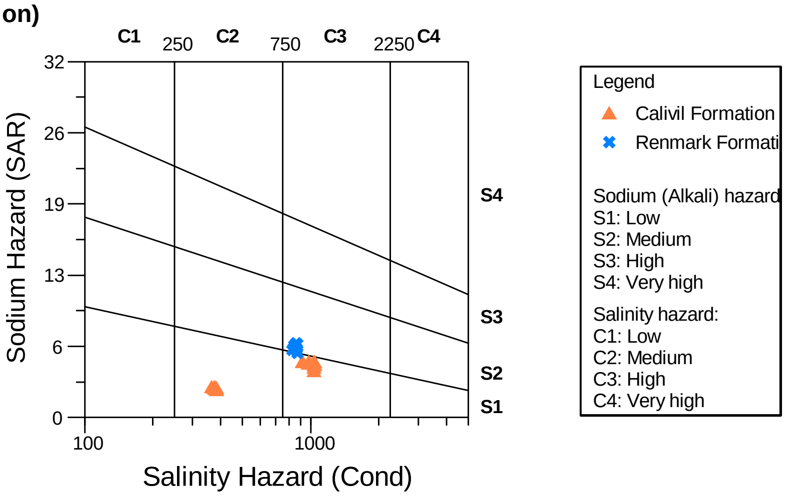
c. Water level and electrical conductivity from August 1970 to August 2011

Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

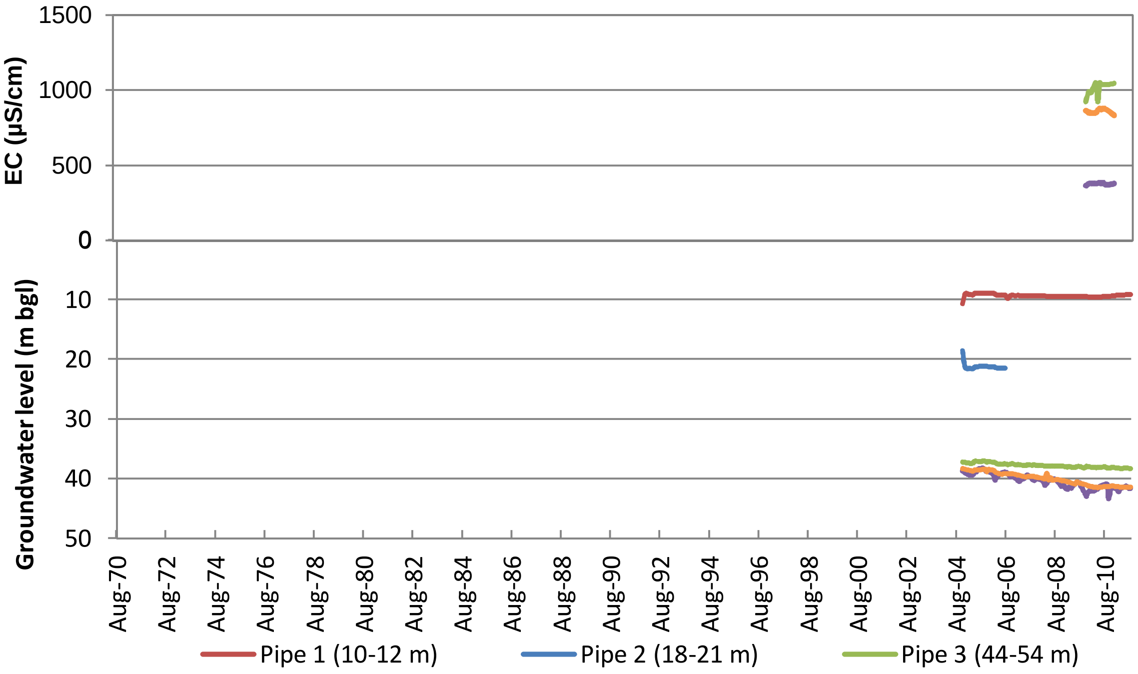
Figure F-7 Chemistry Summary GW090085



a. Piper plot showing water type:Na-Mg-Cl and Na-Mg-Cl-HCO3 (Calivil Formation) and Na-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to high salinity and low to medium SAR ratings



c. Water level and electrical conductivity from August 1970 to August 2011

Client: NSW Office of Water
Location: Lower Lachlan GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

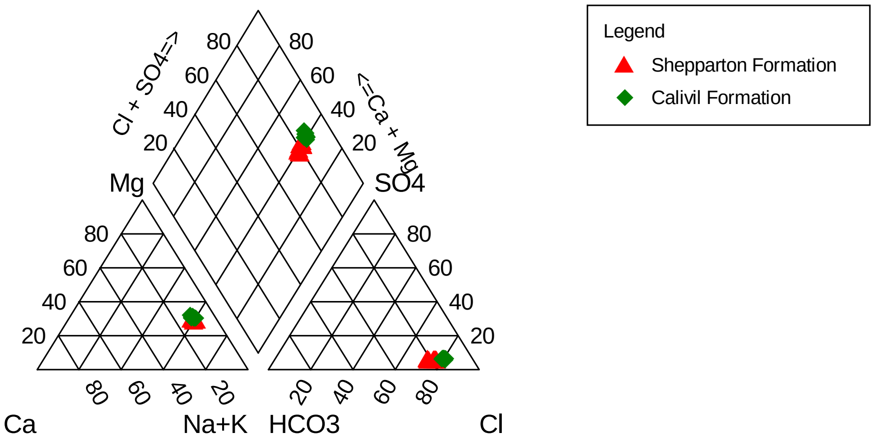
PARSONS BRINCKERHOFF

Appendix

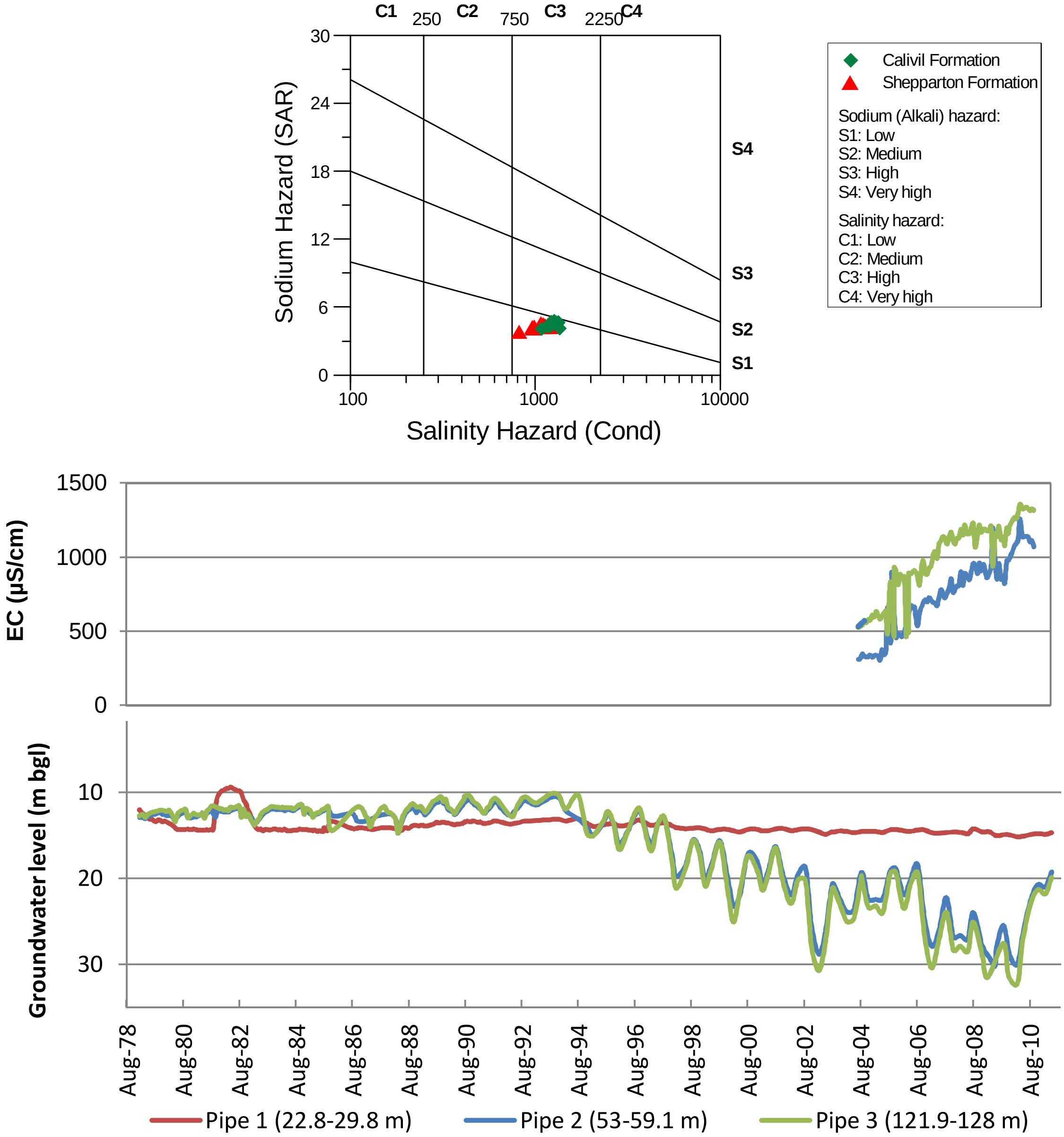
G

Lower Muray GMA – Water Quality Report Cards

Figure G-1 Chemistry Summary GW036283



a. Piper plot showing water type: Na-Mg-Cl Shepparton and Calivil Formation (Cubbaroo Formation)



c. Water level and electrical conductivity from August 1978 to August 2011

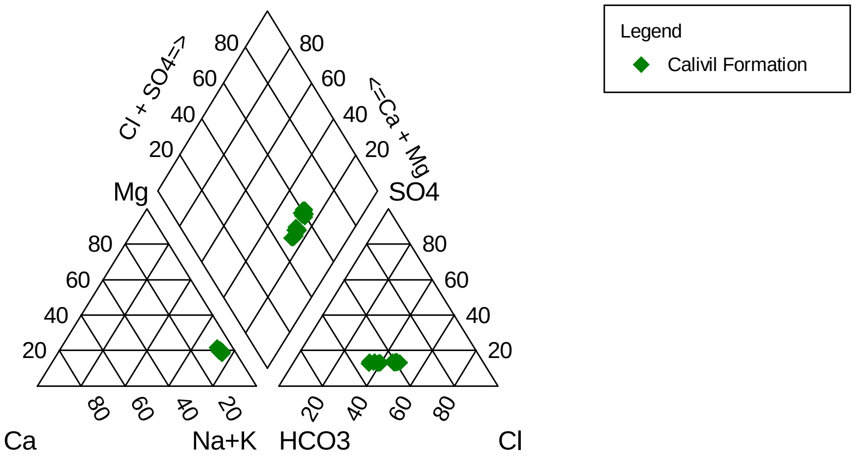
Client: NSW Office of Water

Location: Lower Murray GMA

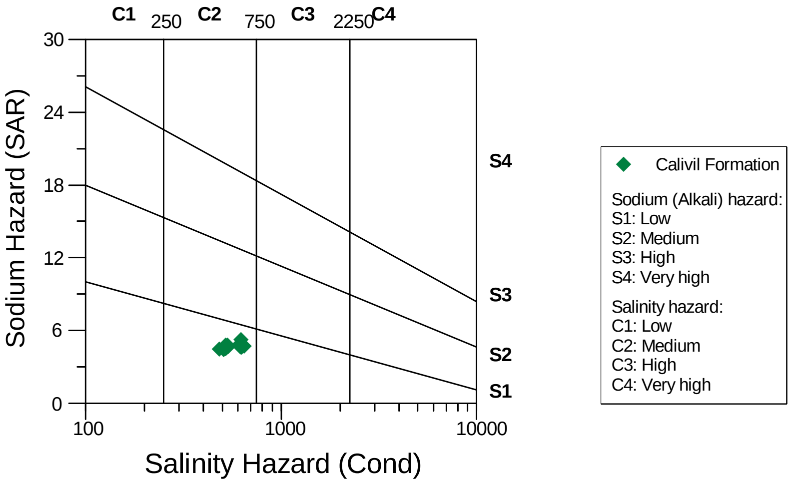
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

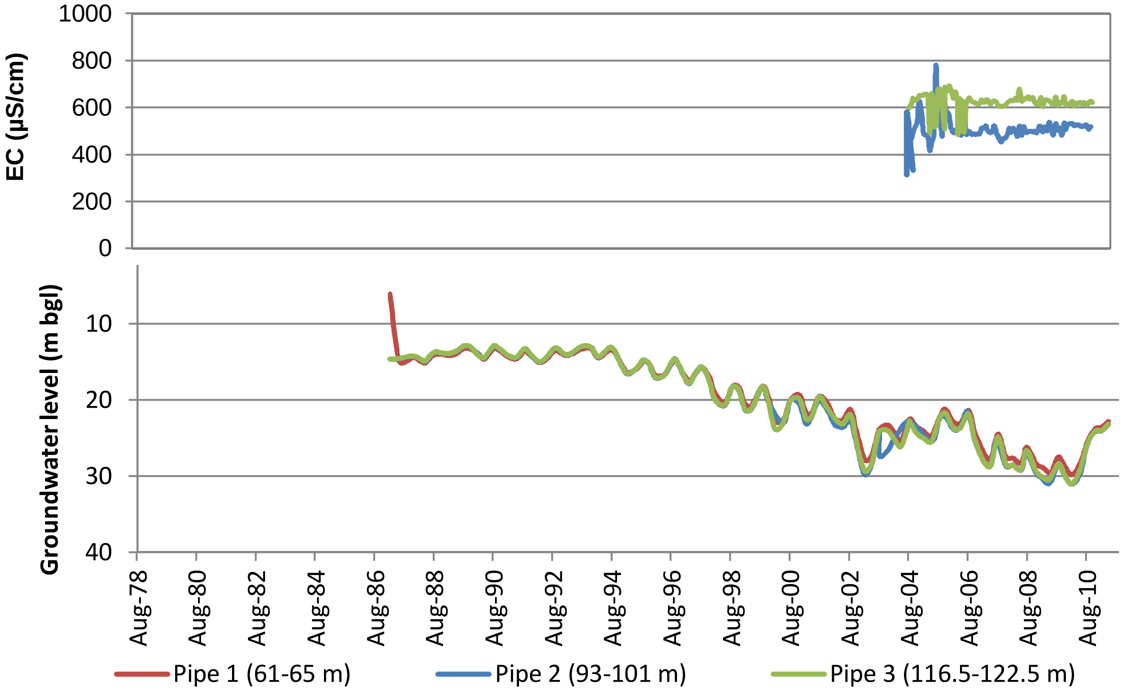
Figure G-2 Chemistry Summary GW036584



a. Piper plot showing water type: Na-HCO3-Cl, Na-HCO3-Mg-Cl (Calivil Formation)



b. Wilcox plot showing medium salinity and low SAR ratings



c. Water level and electrical conductivity from August 1978 to August 2011

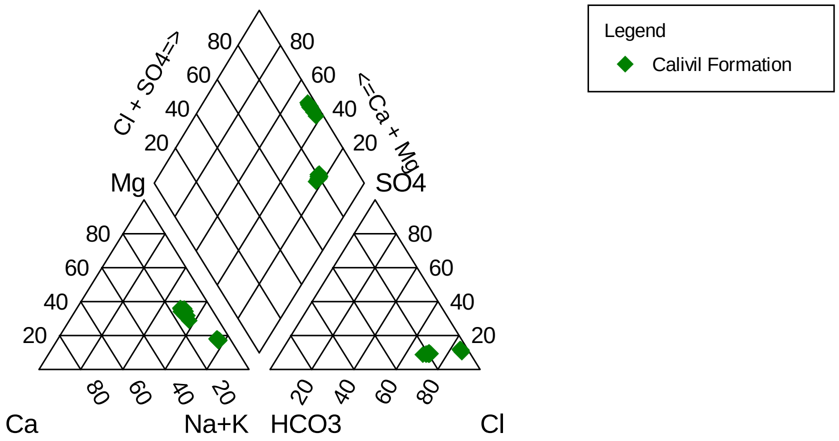
Client: NSW Office of Water

Location: Lower Murray GMA

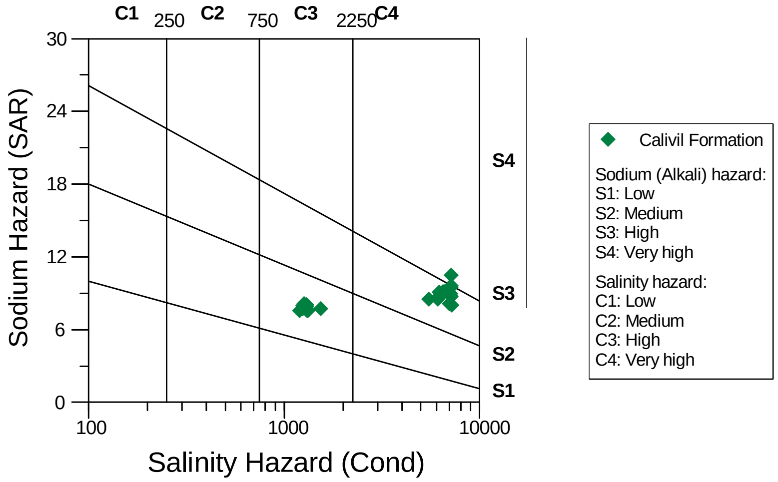
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

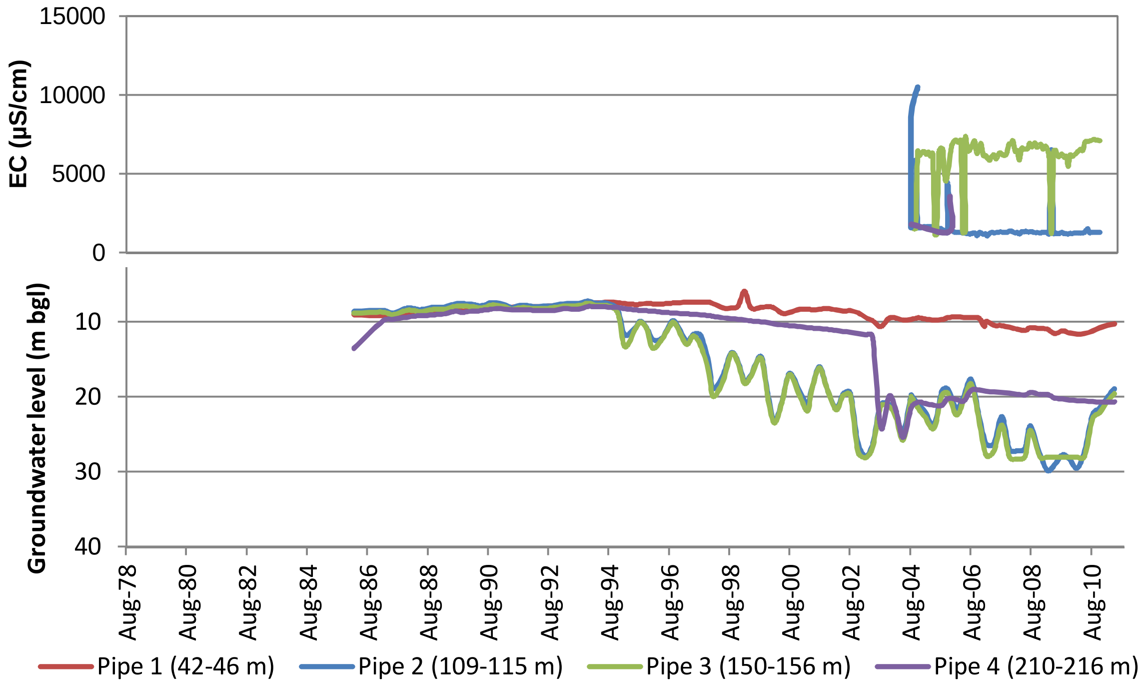
Figure G-3 Chemistry Summary GW036585



a. Piper plot showing water type: Na-Cl and Na-Mg-Cl and Na-Cl-HCO3 (Calivil Formation)



b. Wilcox plot showing high to very high salinity and low to medium SAR ratings

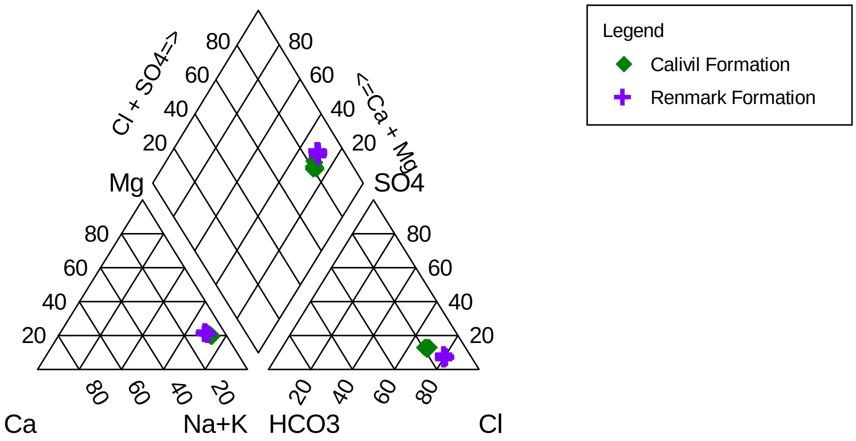


c. Water level and electrical conductivity from August 1978 to August 2011

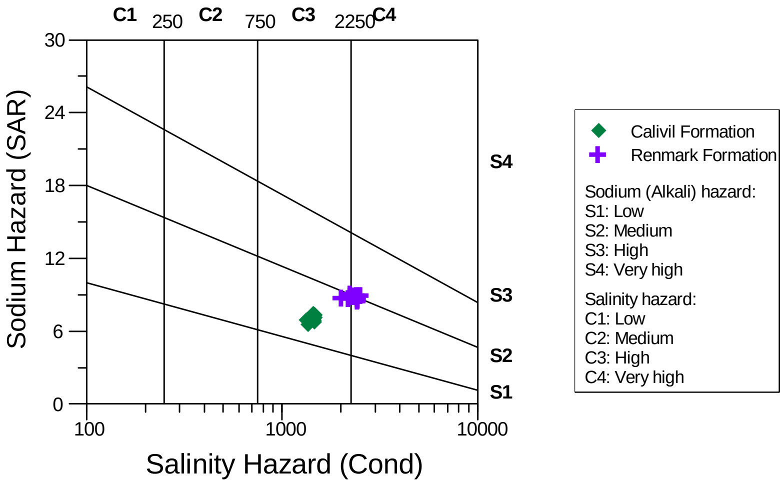
Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS
BRINCKERHOFF

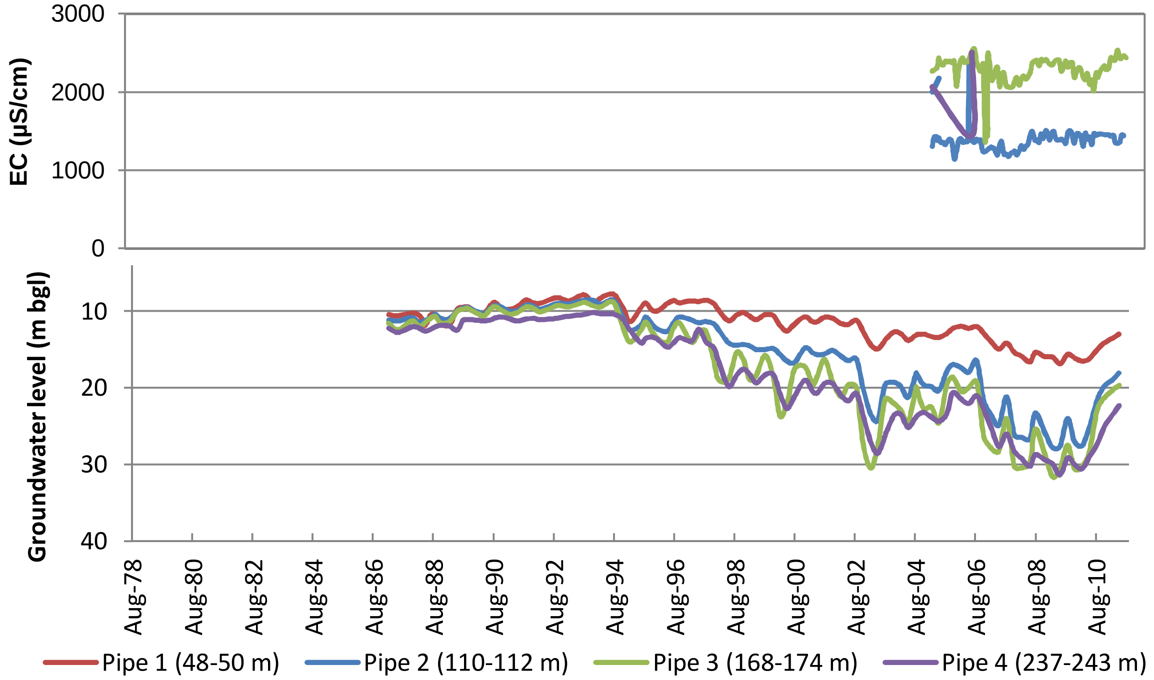
Figure G-4 Chemistry Summary GW036586



a. Piper plot showing water type: Na-Cl (CalivilFormation) and Na-Mg-Cl (Renmark Formation)



b. Wilcox plot showing high to very high salinity and medium to high SAR ratings

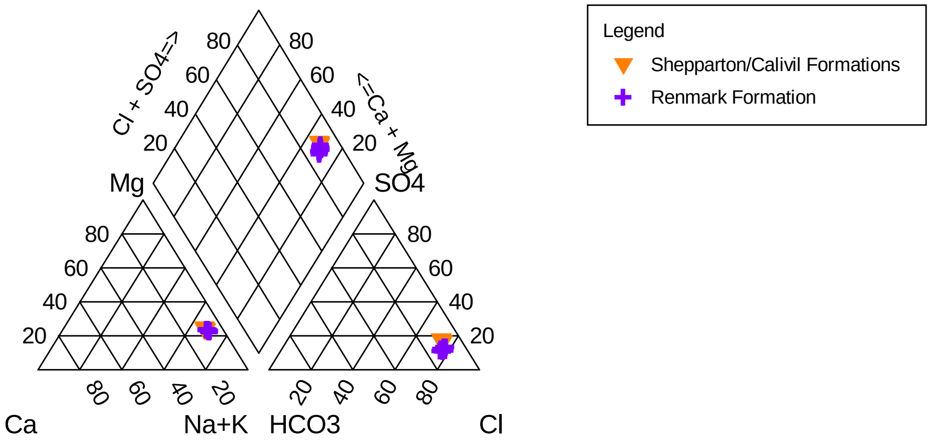


c. Water level and electrical conductivity from August 1978 to August 2011

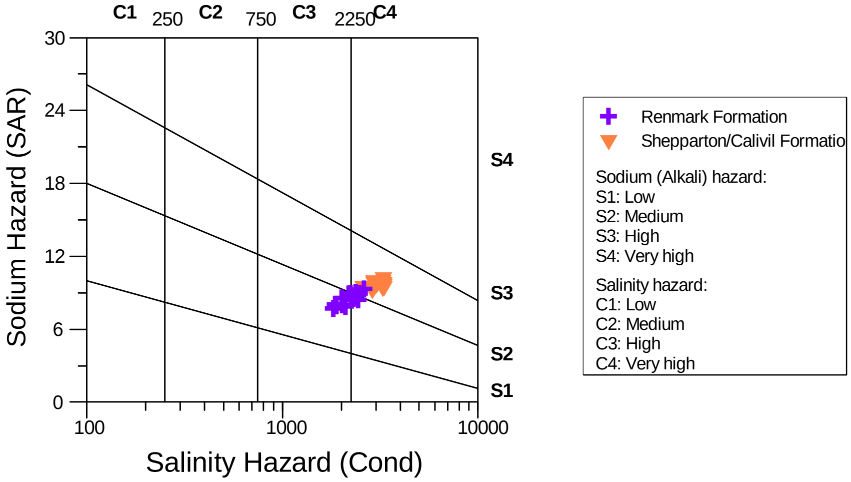
Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

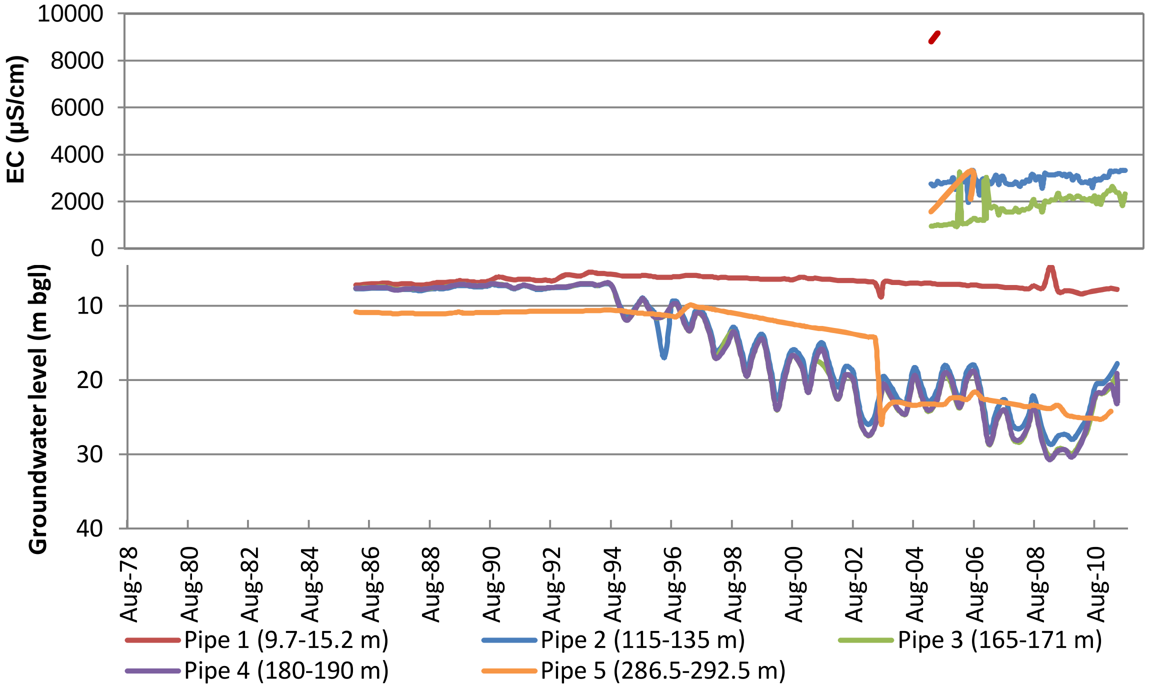
Figure G-5 Chemistry Summary GW036587



a. Piper plot showing water type: Na-Mg-Cl (Shepparton and Renmark Formations)



b. Wilcox plot showing high to very high salinity and medium to high SAR ratings



c. Water level and electrical conductivity from August 1978 to August 2011

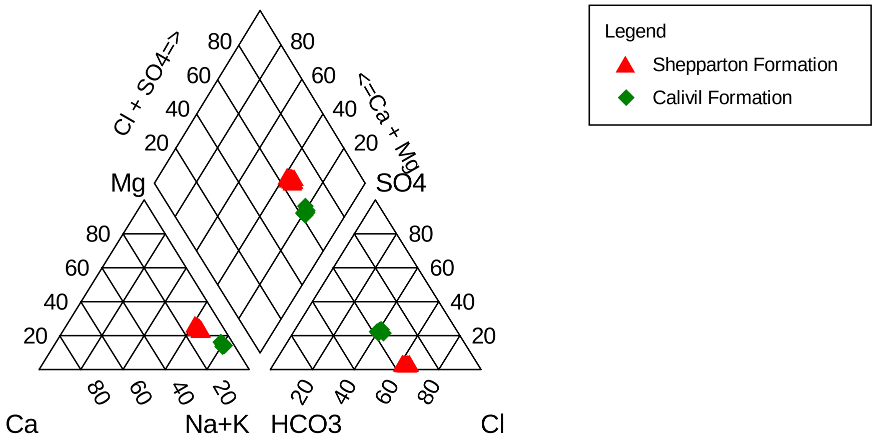
Client: NSW Office of Water

Location: Lower Murray GMA

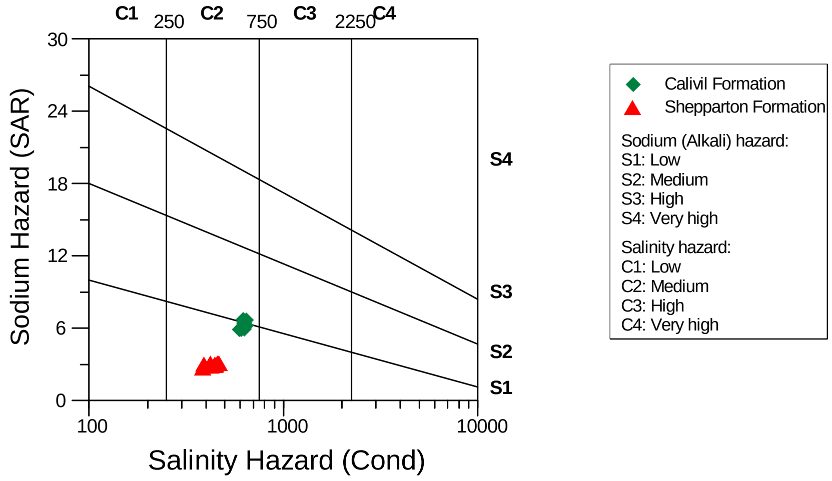
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

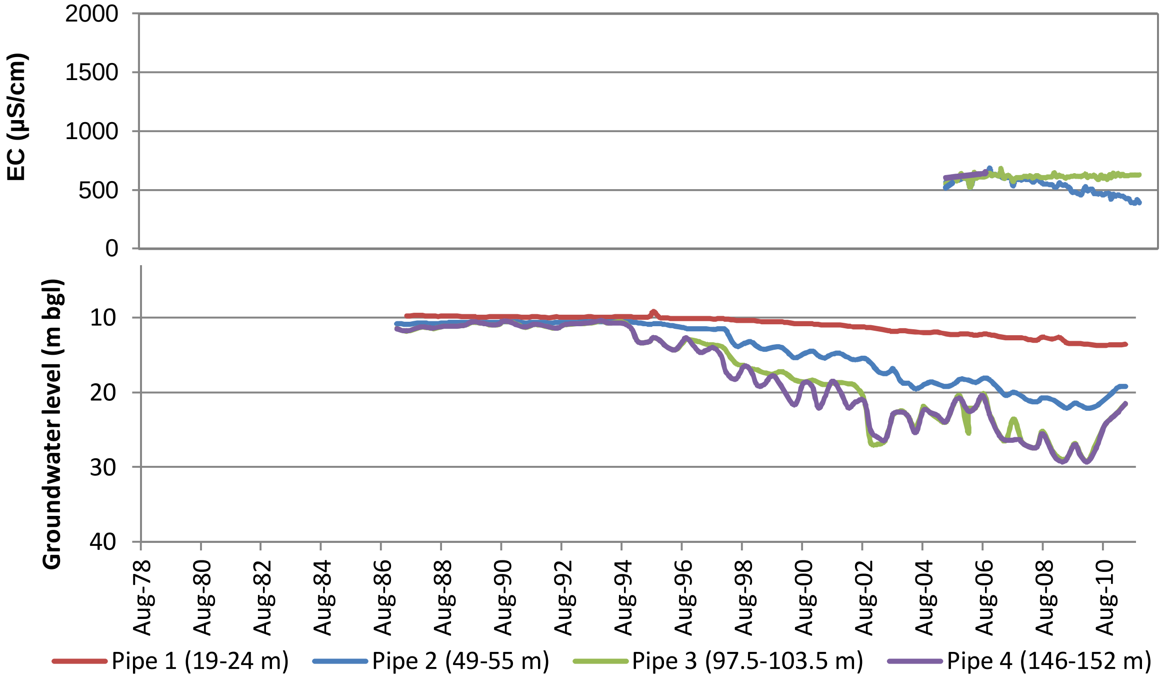
Figure G-6 Chemistry Summary GW036588



a. Piper plot showing water type: Na-Mg-Cl-HCO3 (Shepparton Formation) and Na-Cl-HCO3-SO4 (Calivil Formation)

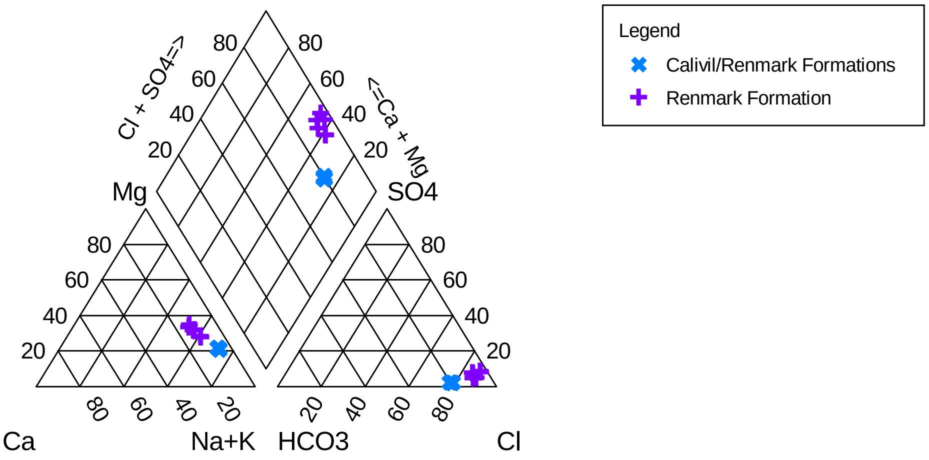


b. Wilcox plot showing medium salinity and low to medium SAR ratings

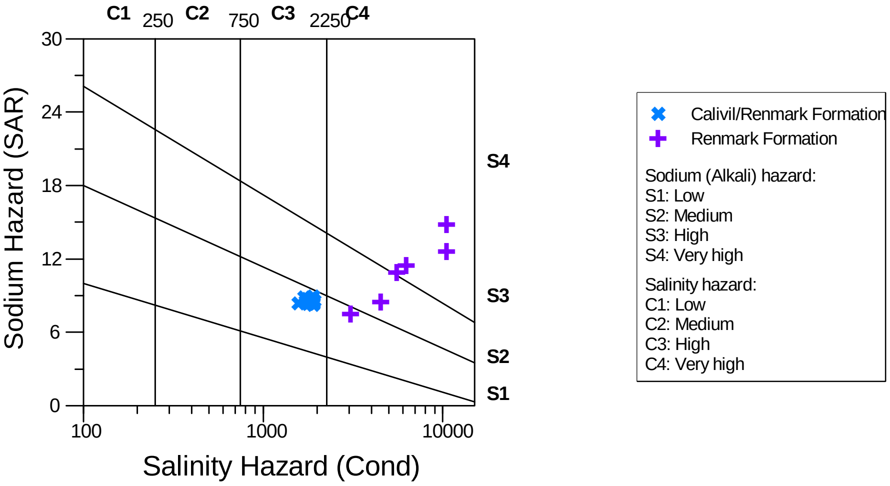


c. Water level and electrical conductivity from August 1978 to August 2011

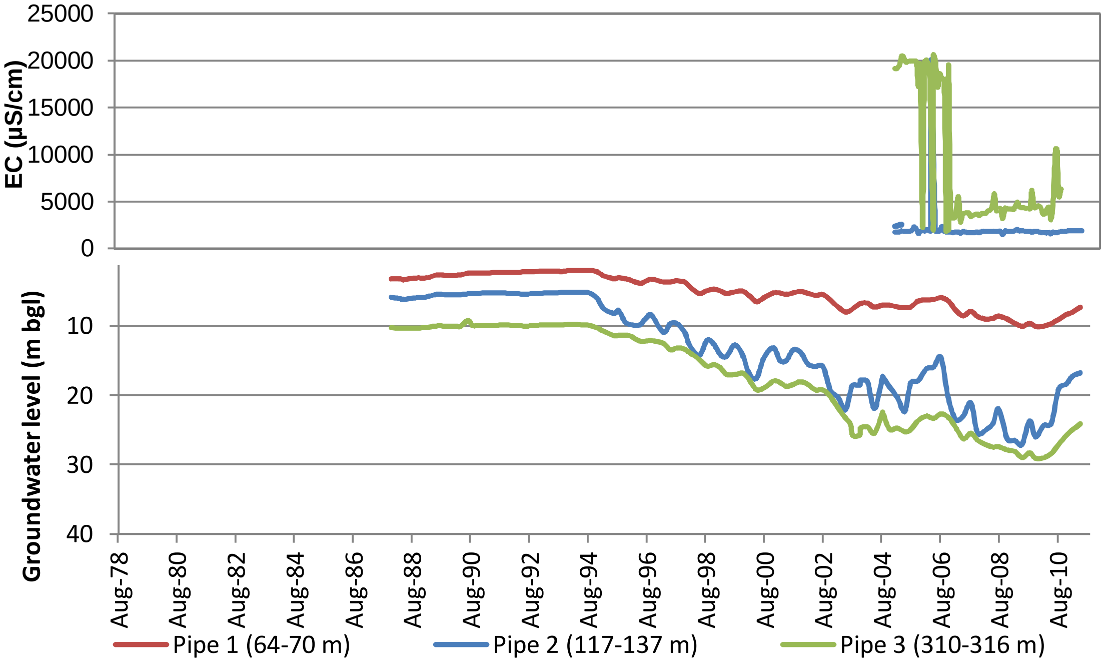
Figure G-7 Chemistry Summary GW036742



a. Piper plot showing water type: Na-Mg-Cl Calivil Formation and Renmark Formation)



b. Wilcox plot showing high to very high salinity and medium to very high SAR ratings

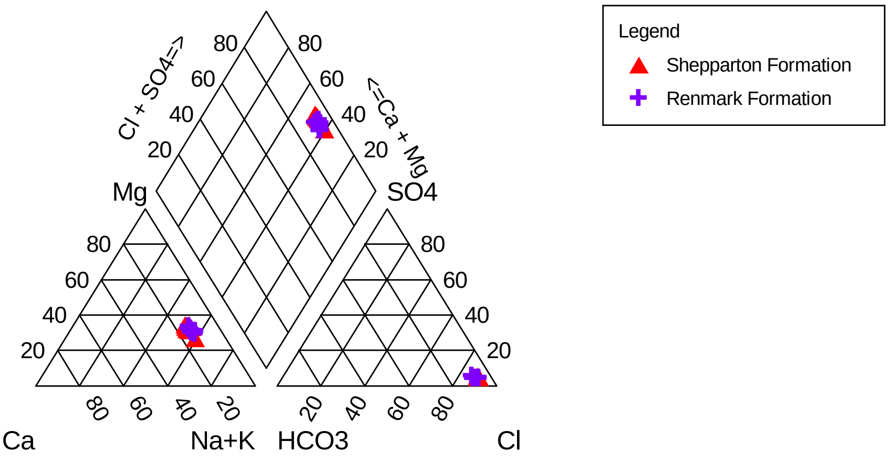


c. Water level and electrical conductivity from August 1978 to August 2011

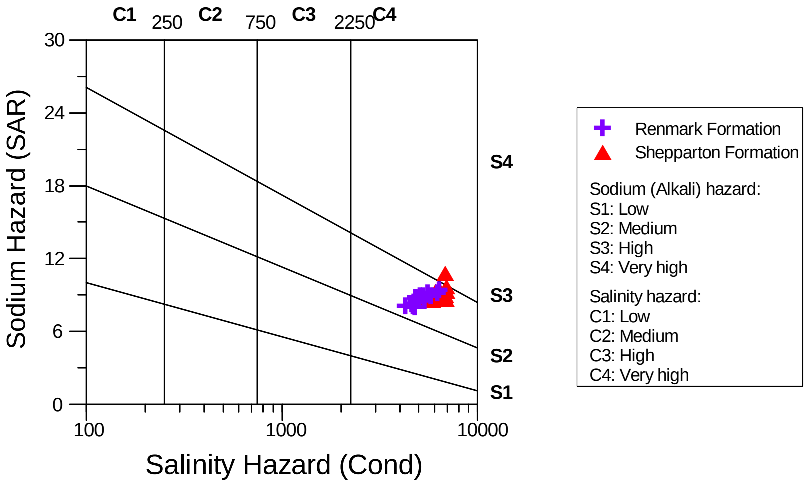
Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

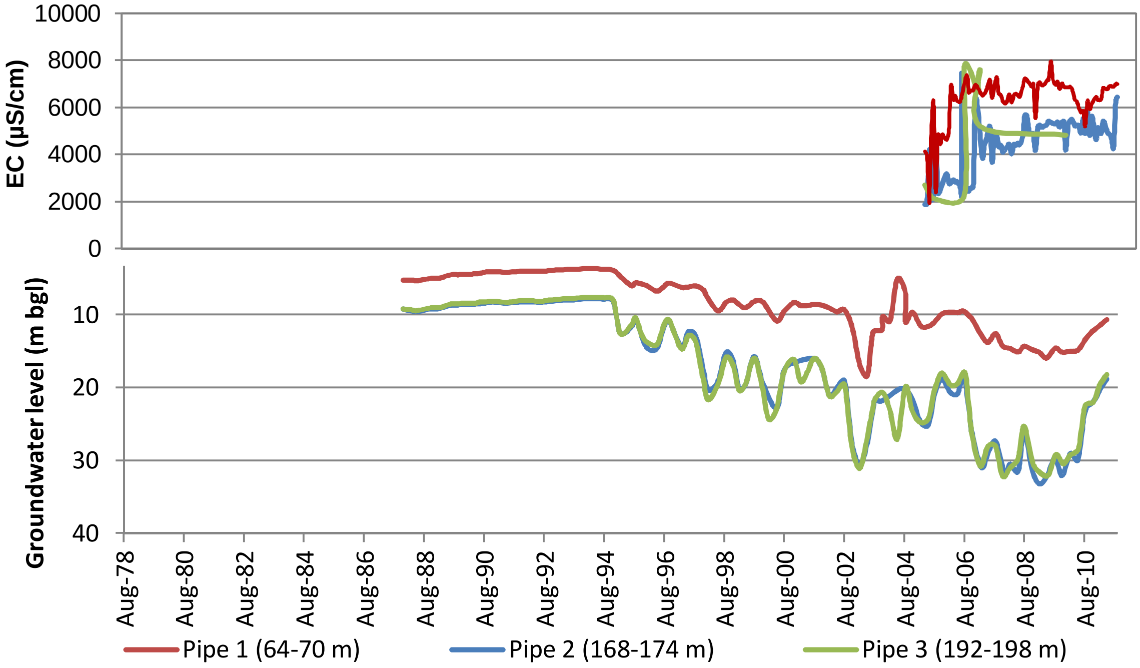
Figure G-8 Chemistry Summary GW036743



a. Piper plot showing water type: Na-Mg-Cl (Shepparton Formation and Renmark Formation)



b. Wilcox plot showing very high salinity and high to very high SAR ratings



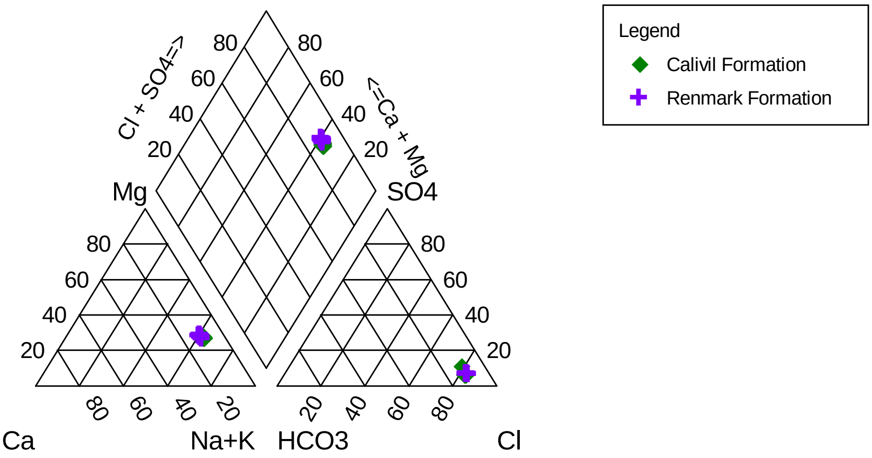
c. Water level and electrical conductivity from August 1978 to August 2011

Client: NSW Office of Water

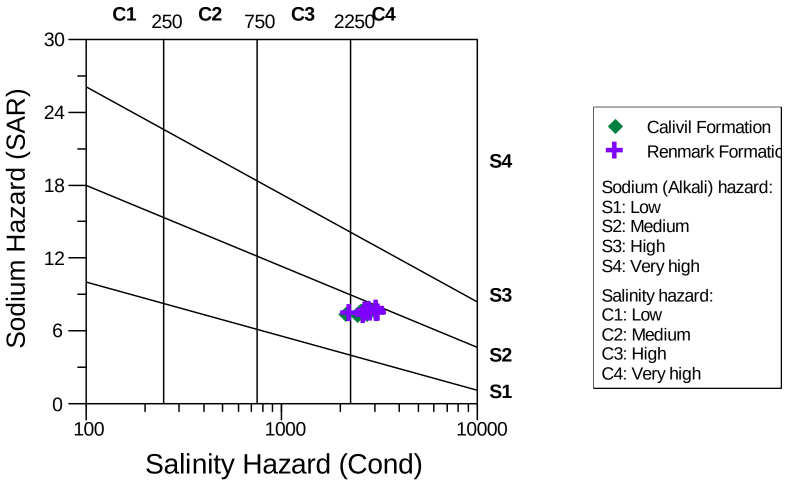
Location: Lower Murray GMA

Project: Characterisation of hydrogeochemistry and risks to groundwater quality

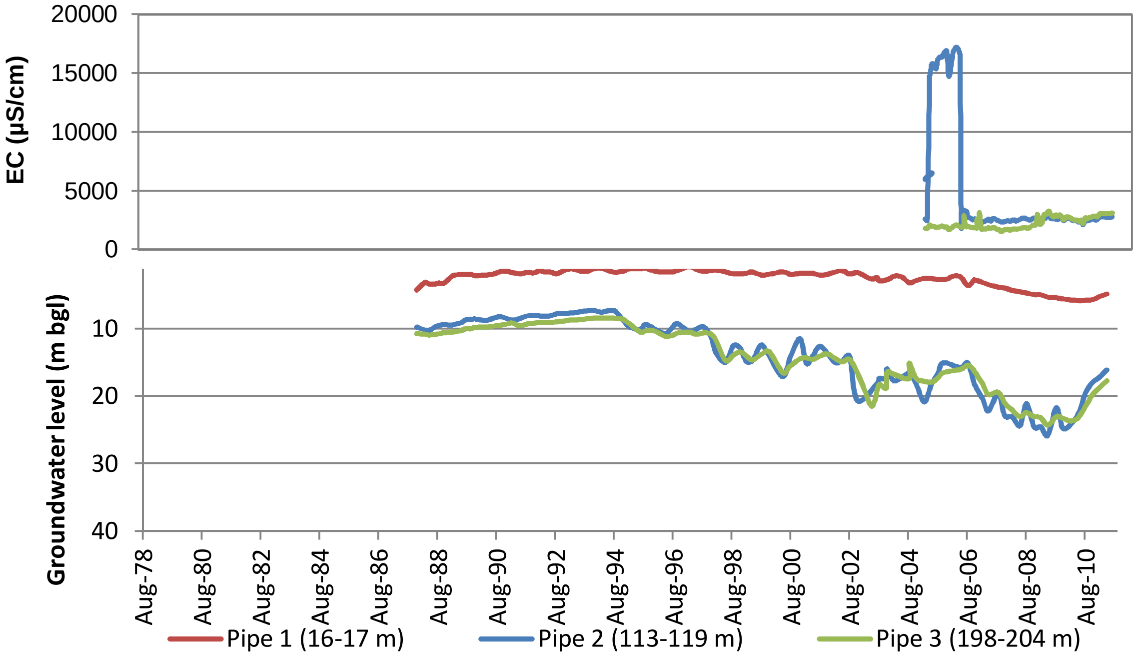
Figure G-9 Chemistry Summary GW036744



a. Piper plot showing water type: Na-Mg-Cl (Calivil Formation and Renmark Formation)



b. Wilcox plot showing high to very high salinity medium to high SAR ratings

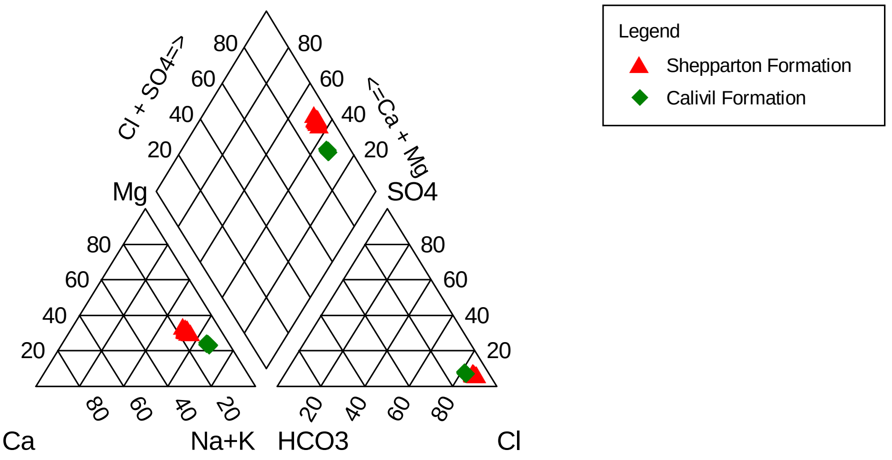


c. Water level and electrical conductivity from August 1978 to August 2011

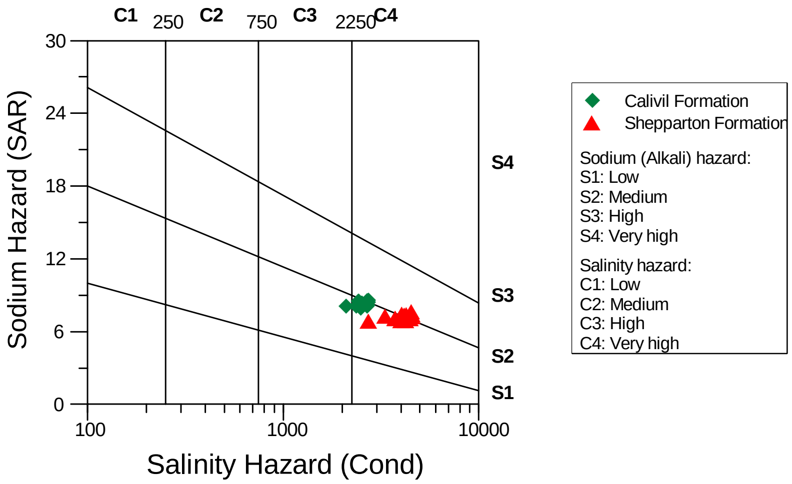
Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

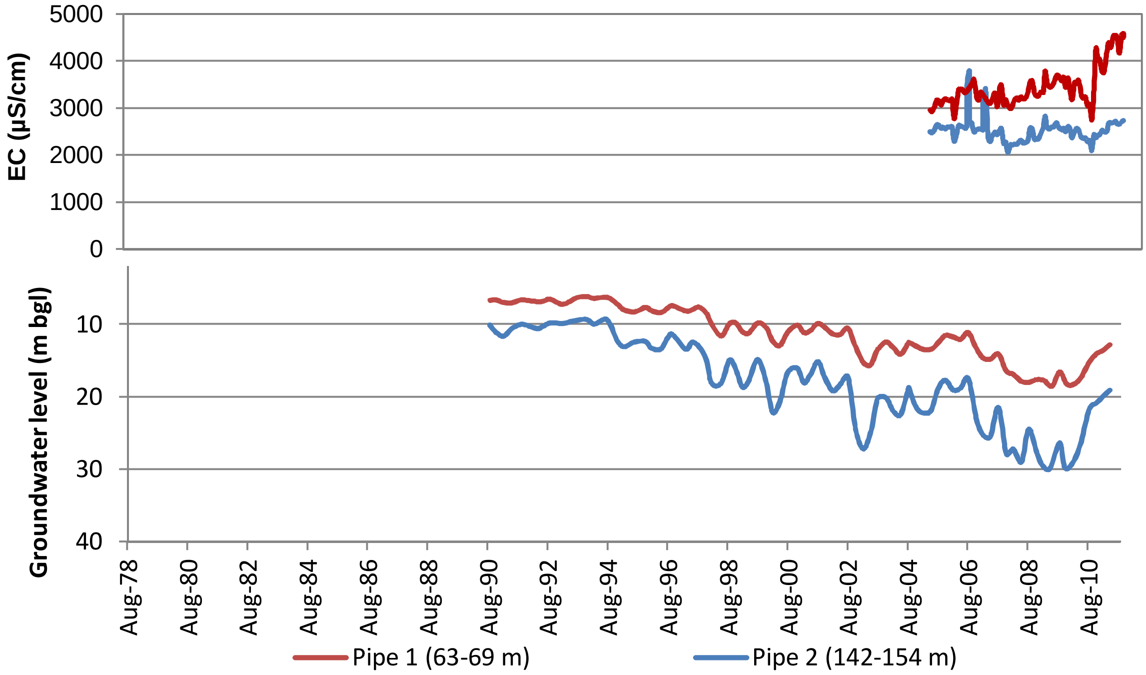
Figure G-10 Chemistry Summary GW036876



a. Piper plot showing water type: Na-Mg-Cl (Shepparton Formation and Calivil Formation)



b. Wilcox plot showing high to very high salinity and medium to highSAR ratings



c. Water level and electrical conductivity from August 1978 to August 2011

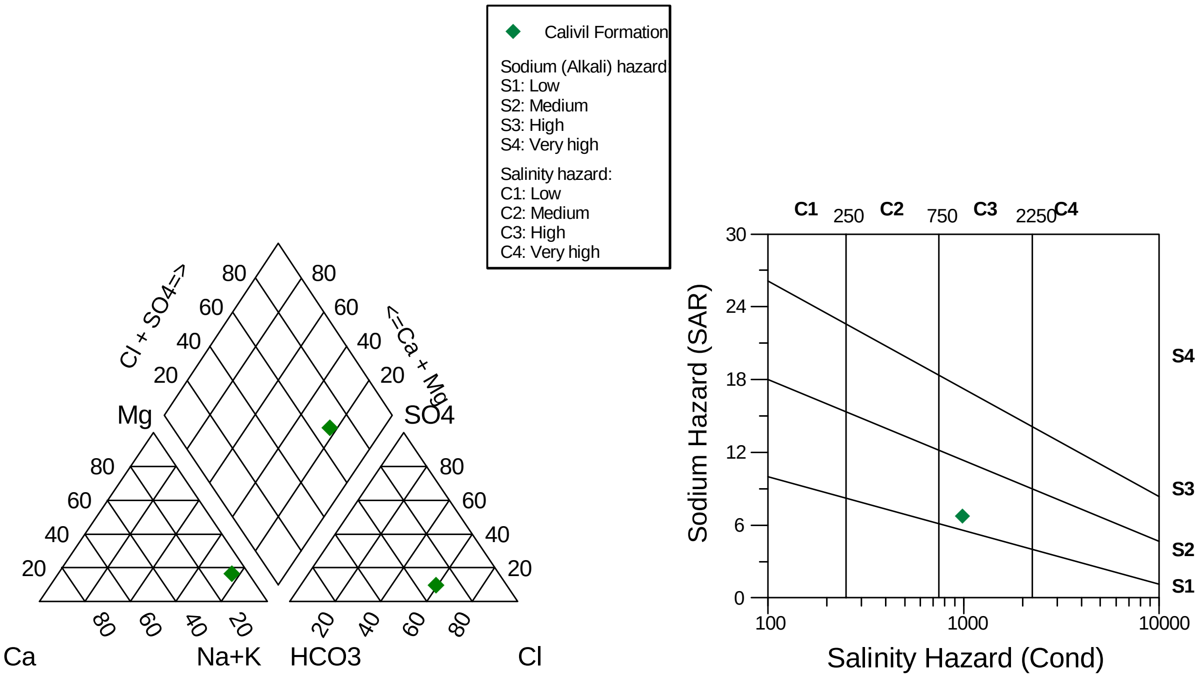
Client: NSW Office of Water

Location: Lower Murray GMA

Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-11 Chemistry Summary GW057763



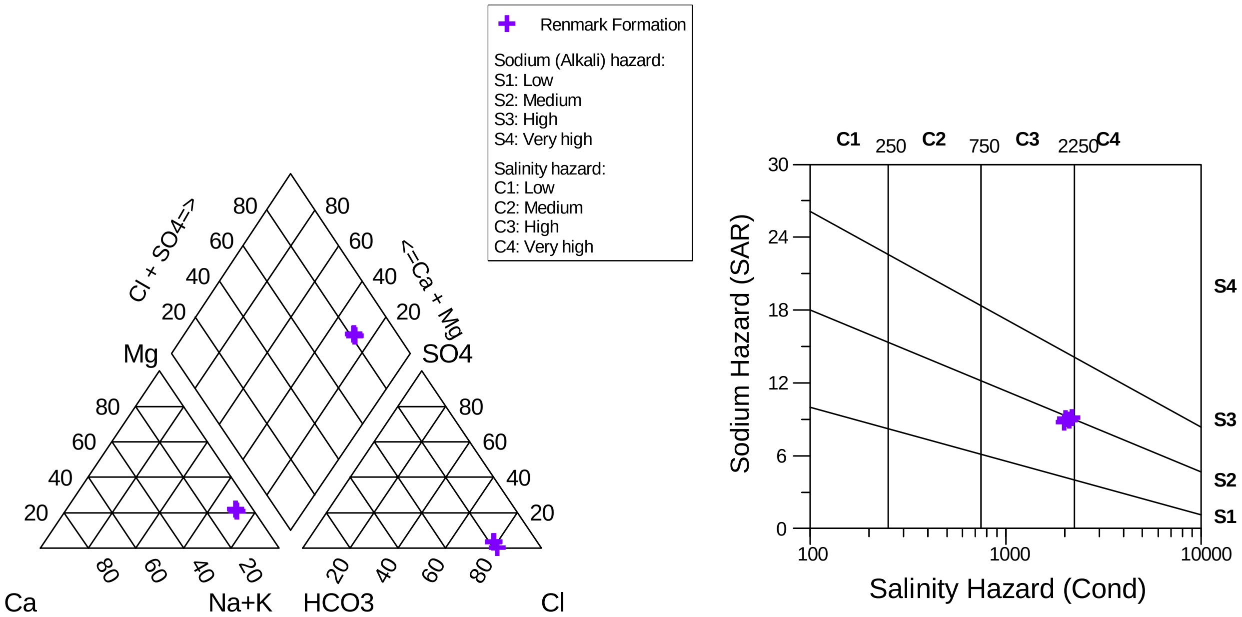
a. Piper plot showing water type: Na-Cl-HCO3 (Calivil Formation)

b. Wilcox plot showing high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-17 Chemistry Summary GW500978



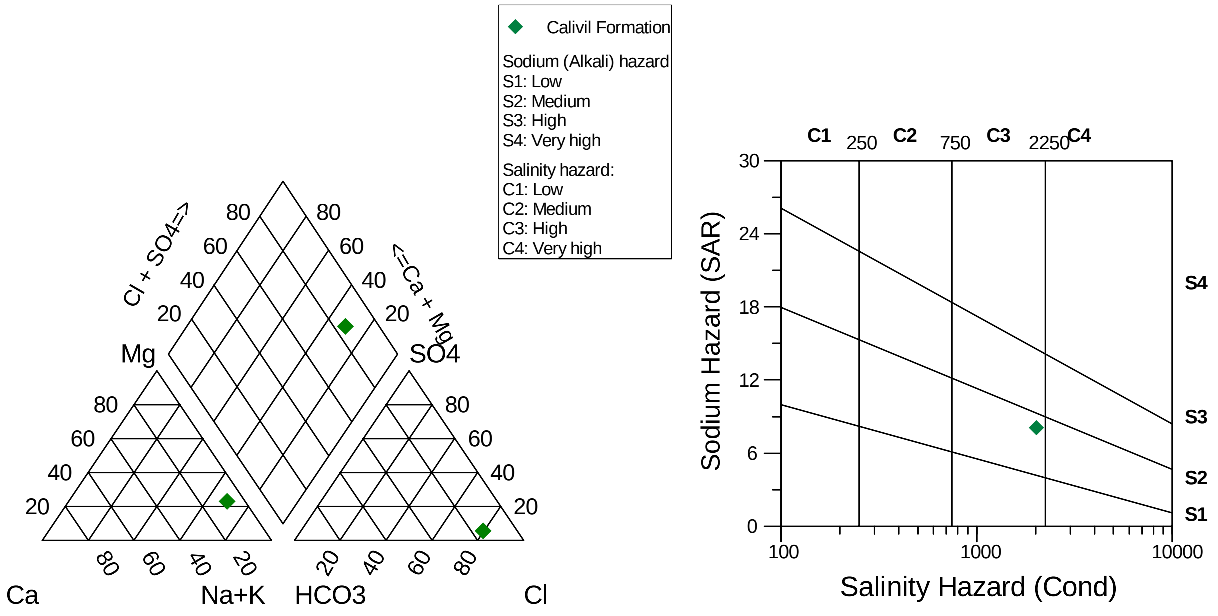
a. Piper plot showing water type: Na-Mg-Cl (Renmark Formation)

b. Wilcox plot showing high to very high salinity and medium to high SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-12 Chemistry Summary GW059260



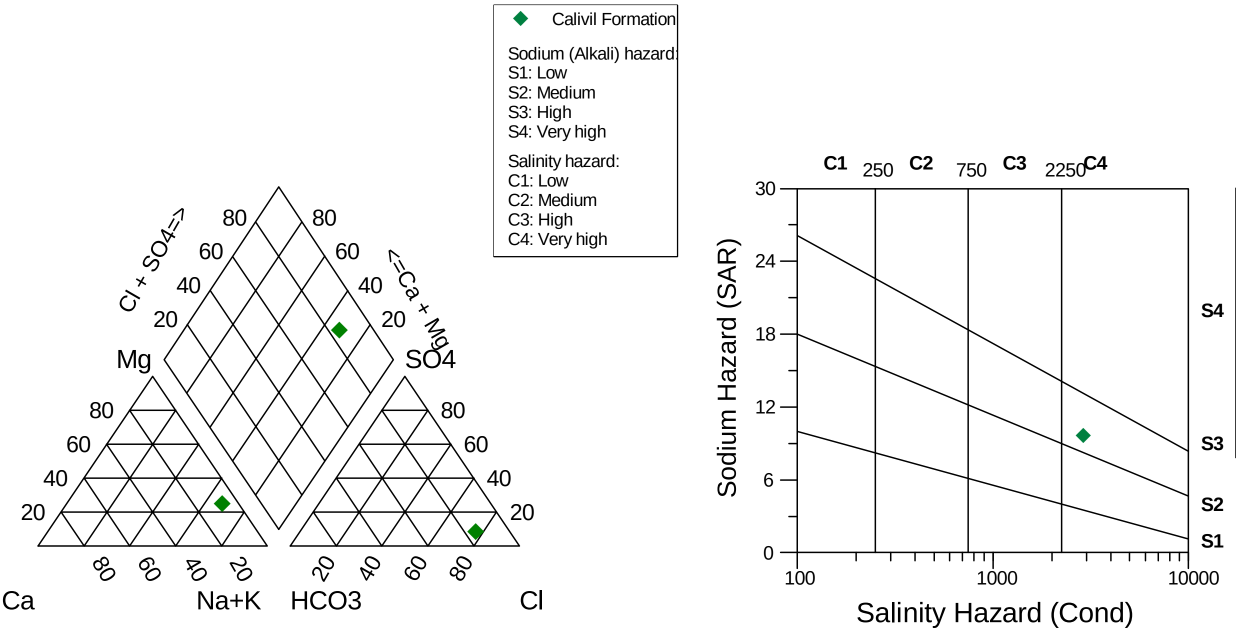
a. Piper plot showing water type: Na-Mg-Cl (Calivil Formation)

b. Wilcox plot showing high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-13 Chemistry Summary GW060457



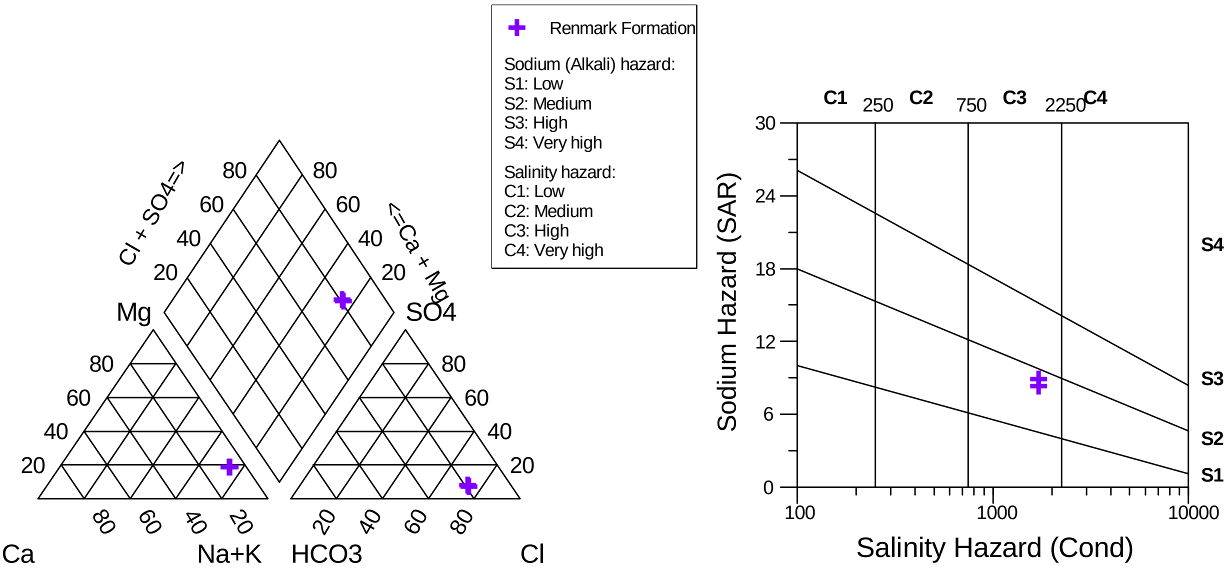
a. Piper plot showing water type: Na-Mg-Cl (Calivil Formation)

b. Wilcox plot showing high to very high salinity and medium to highSAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-14 Chemistry Summary GW500043



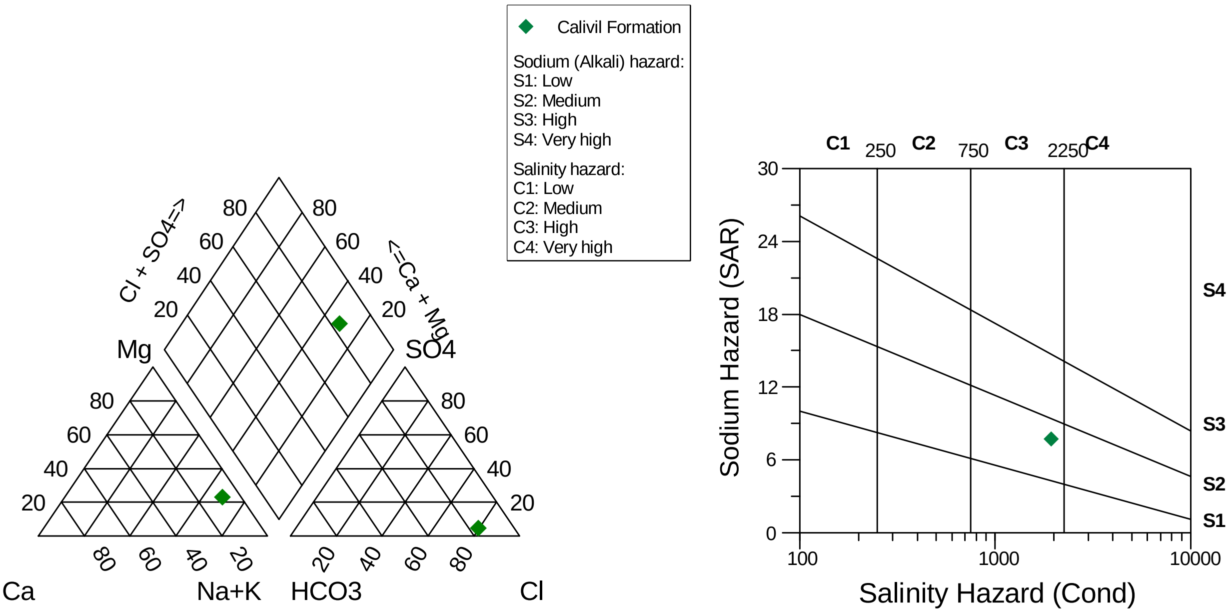
a. Piper plot showing water type: Na-Cl (Renmark Formation)

b. Wilcox plot showing high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-15 Chemistry Summary GW500086



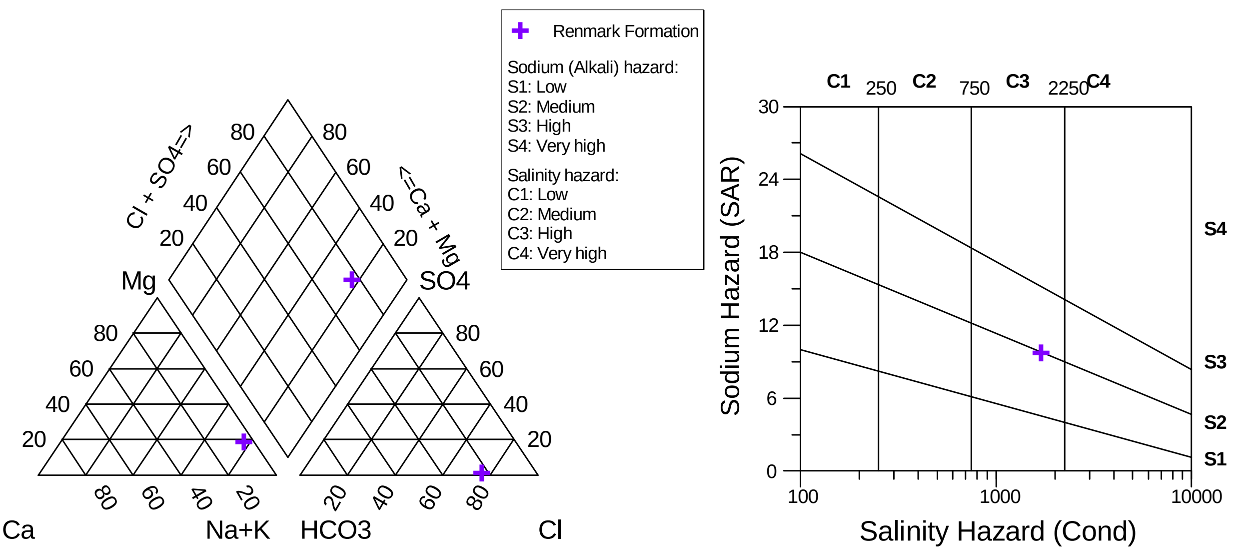
a. Piper plot showing water type: Na-Mg-Cl (Calivil Formation)

b. Wilcox plot showing high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-16 Chemistry Summary GW500339



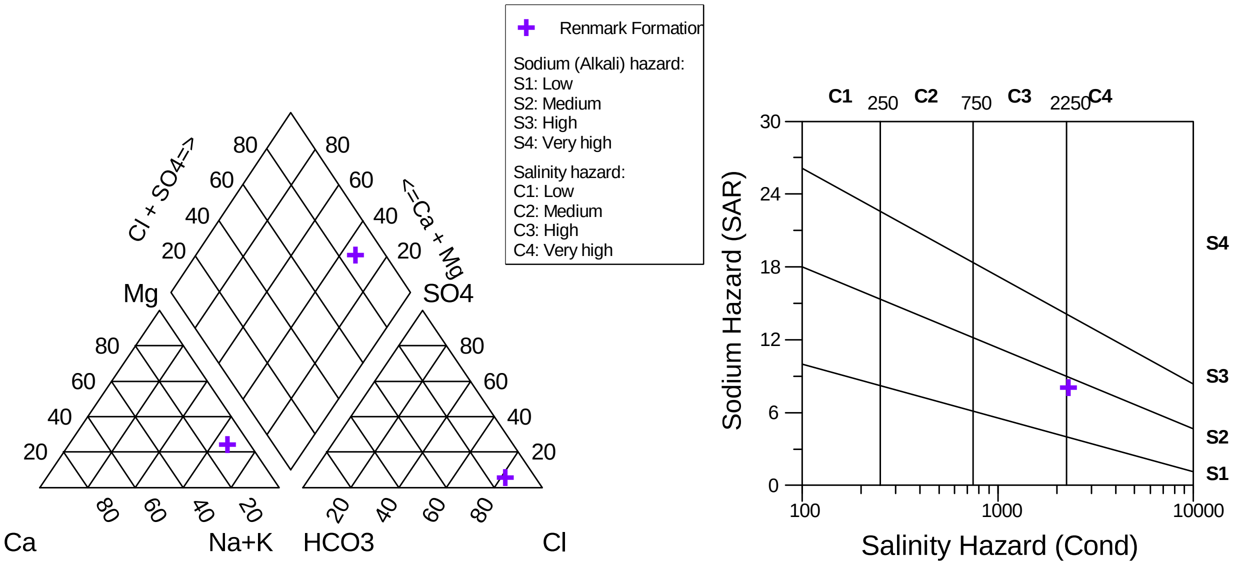
a. Piper plot showing water type: Na-Cl-HCO3 (Renmark Formation)

b. Wilcox plot showing high salinity and medium to high SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure G-17 Chemistry Summary GW500790



a. Piper plot showing water type: Na-Mg-Cl (Renmark Formation)

b. Wilcox plot showing high to very high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murray GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

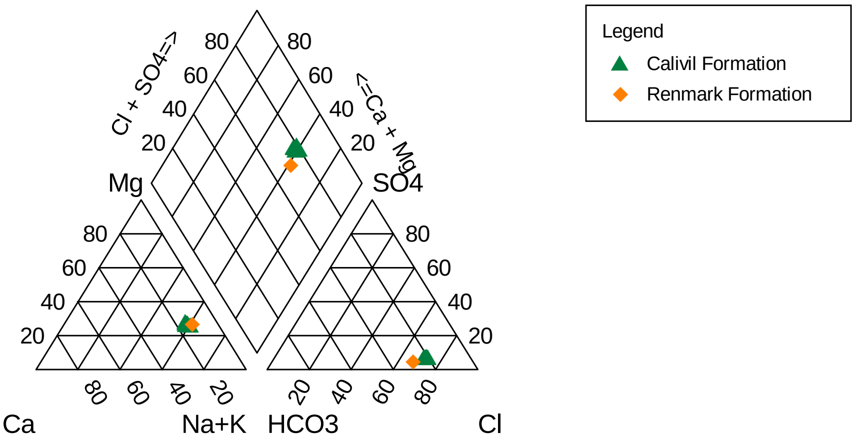
PARSONS BRINCKERHOFF

Appendix

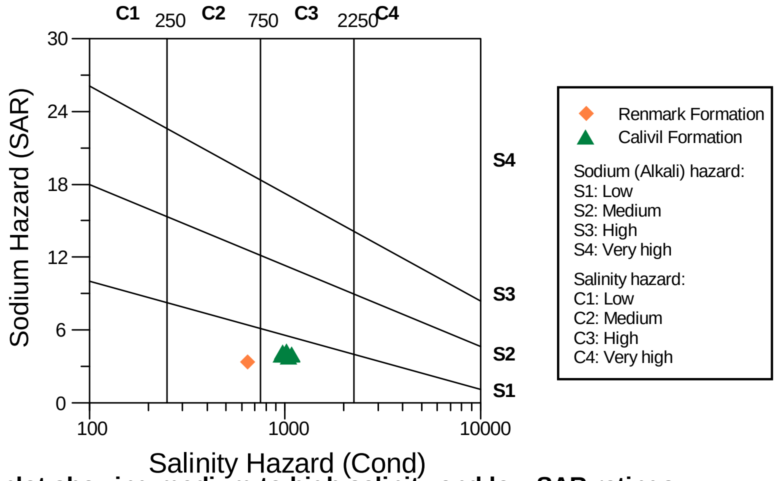
H

Lower Murrumbidgee GMA – Water Quality Report Cards

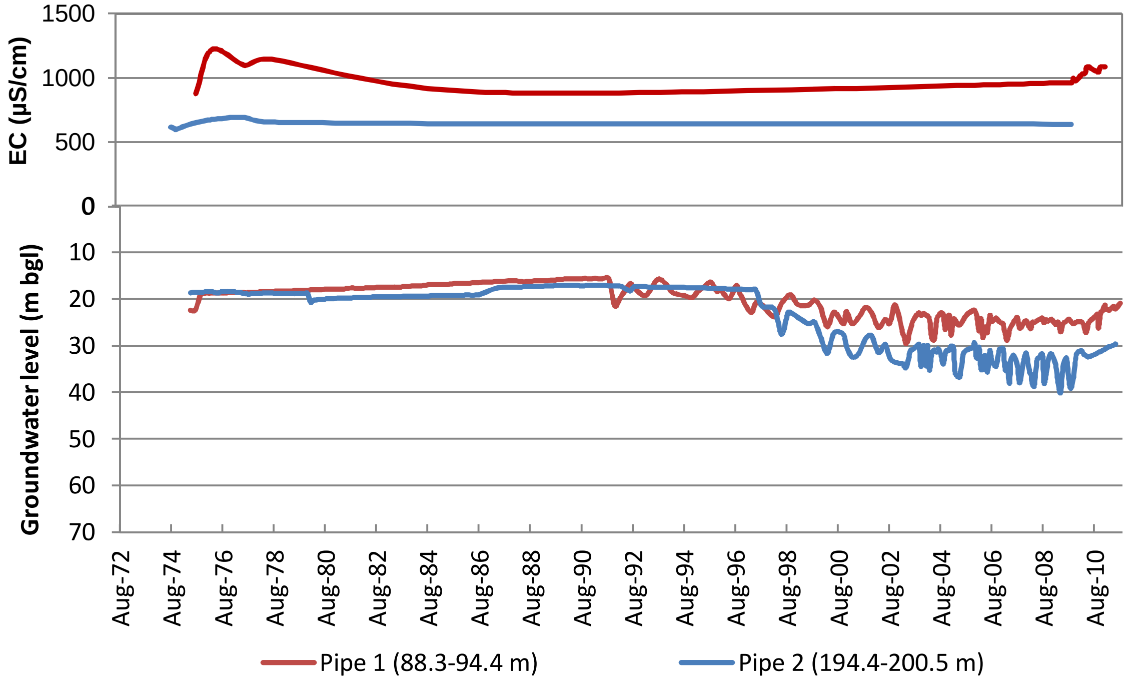
Figure H-1 Chemistry Summary GW030323



a. Piper plot showing water type: Na-Mg-Cl and Na-Mg-Cl-HCO3 (Calivil Formation), and Na-Mg-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to high salinity and low SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

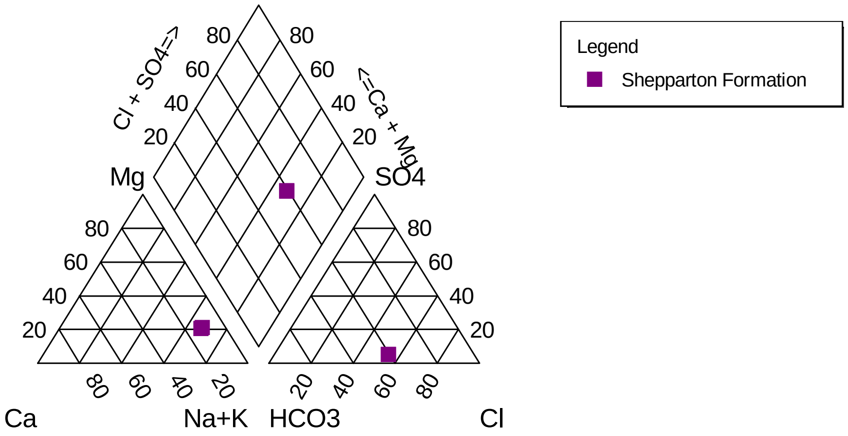
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

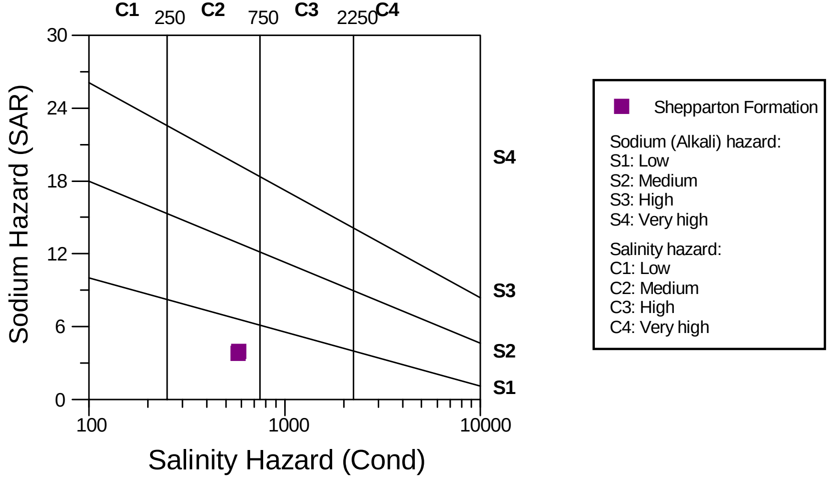
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

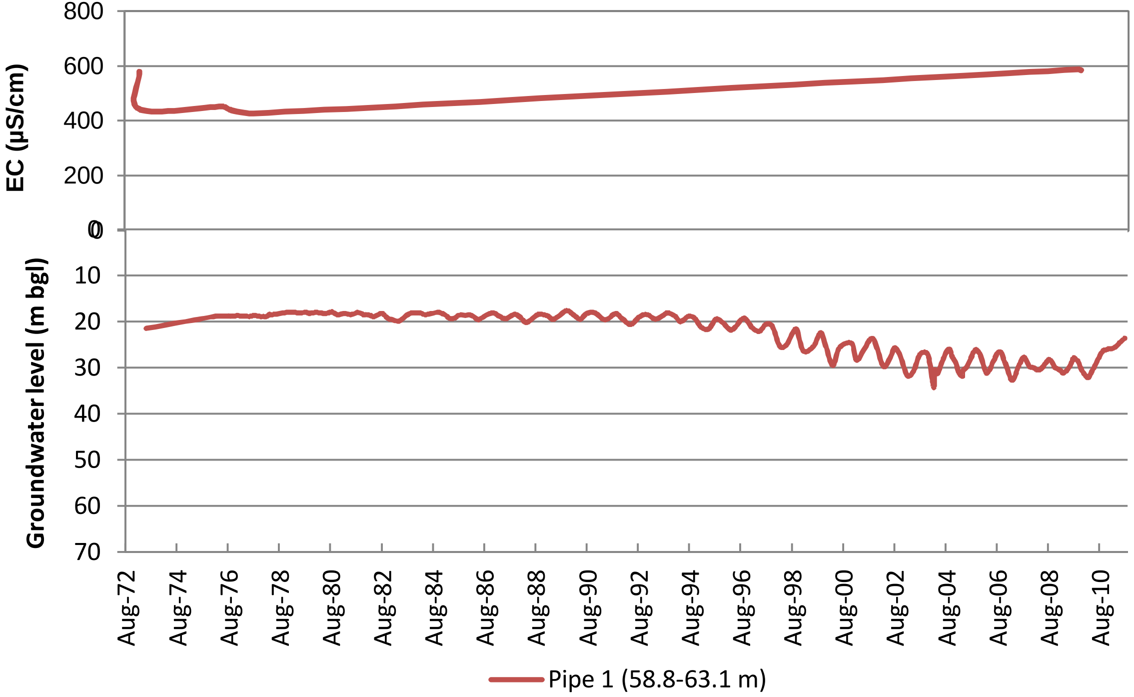
Figure H-2 Chemistry Summary GW030350



a. Piper plot showing water type: Na-Mg-Cl-HCO3 and Na-Cl-HCO3 (Shepparton Formation)



b. Wilcox plot showing medium salinity and low SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

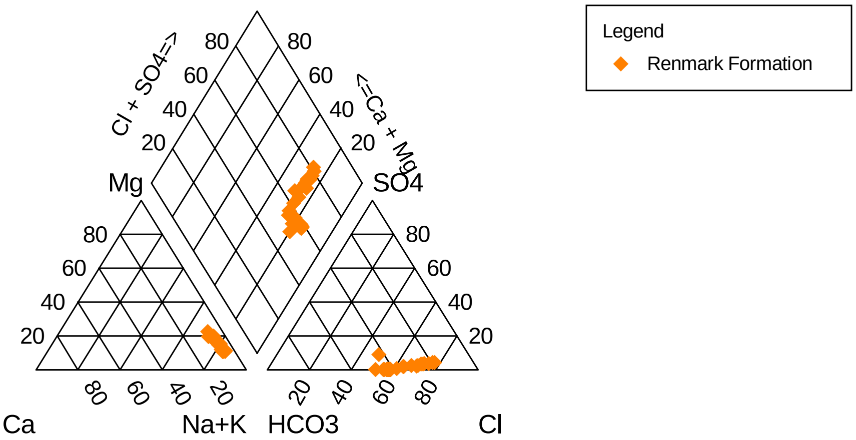
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

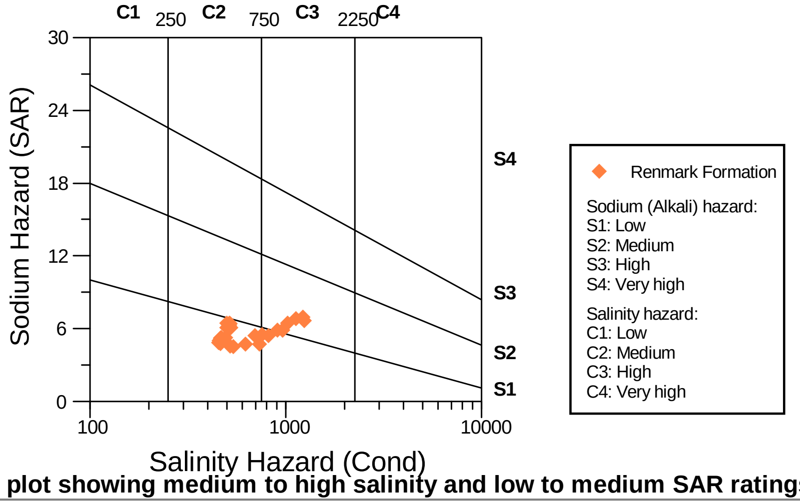
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

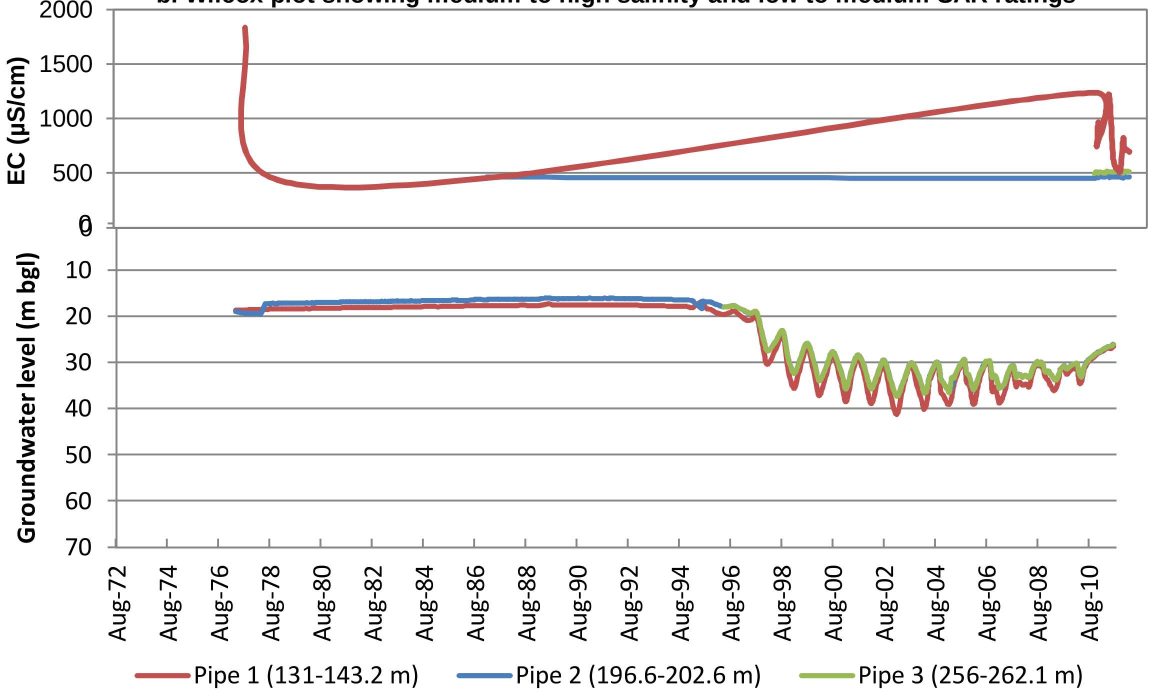
Figure H-3 Chemistry Summary GW036211



a. Piper plot showing water type: Na-Cl, Na-Cl-HCO3 and Na-Mg-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to high salinity and low to medium SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

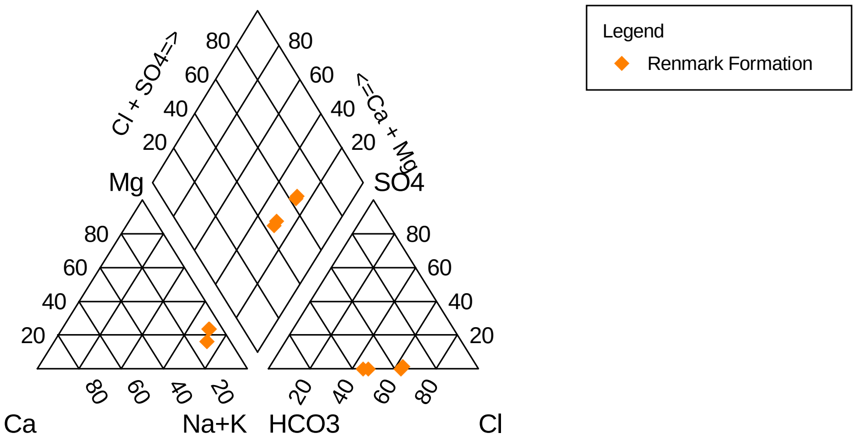
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

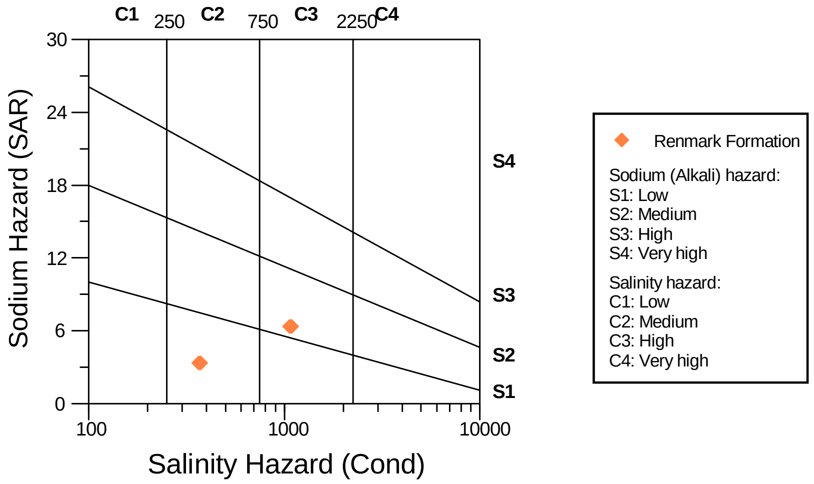
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

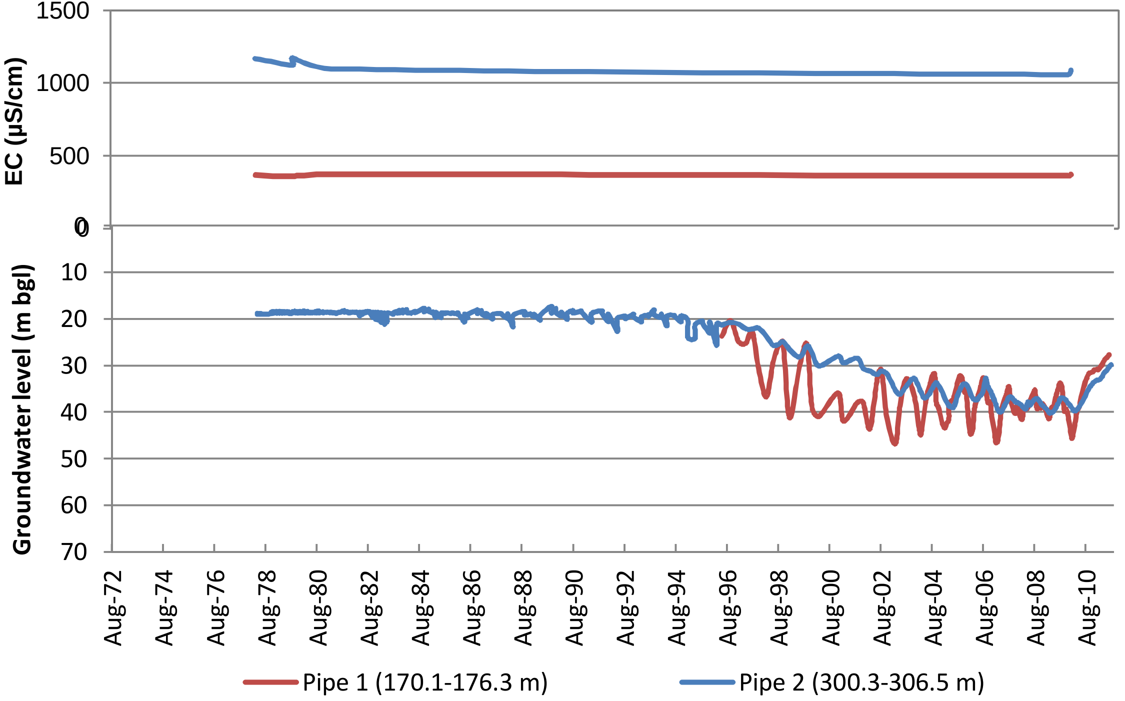
Figure H-4 Chemistry Summary GW036275



a. Piper plot showing water type: Na-Mg-HCO3-Cl and Na-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to high salinity and low to medium SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

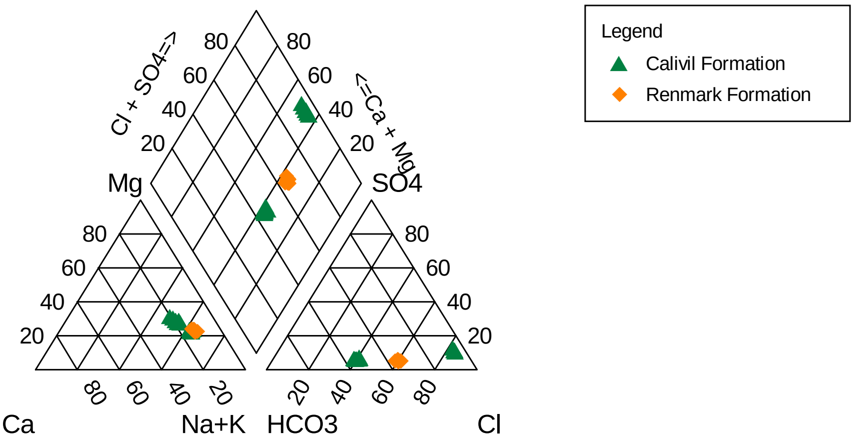
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

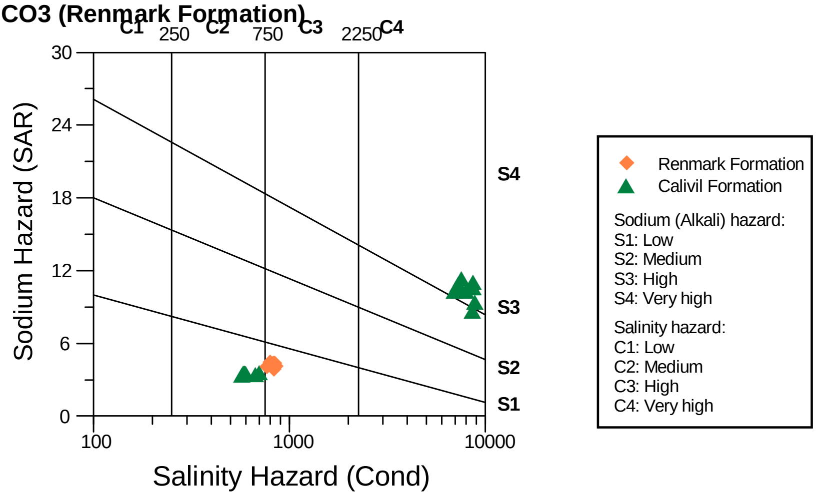
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

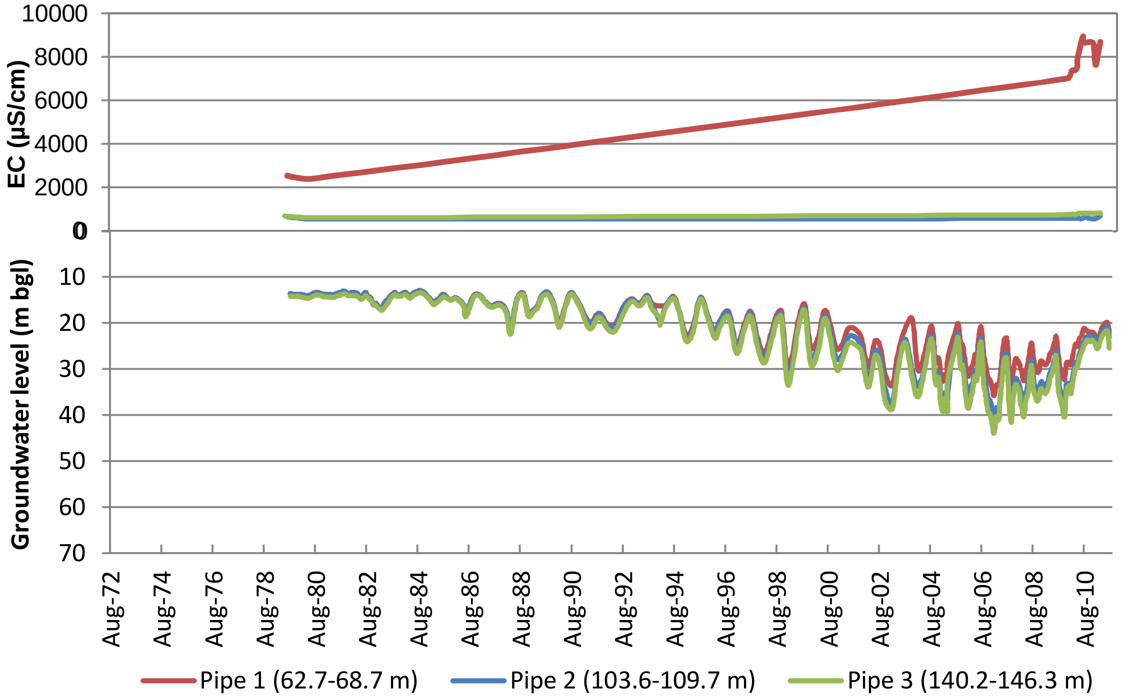
Figure H-5 Chemistry Summary GW036358



a. Piper plot showing water type: Na-Mg-Cl and Na-Mg-HCO3-Cl (Calivil Formation), and Na-Mg-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to very high salinity and low to very high SAR ratings

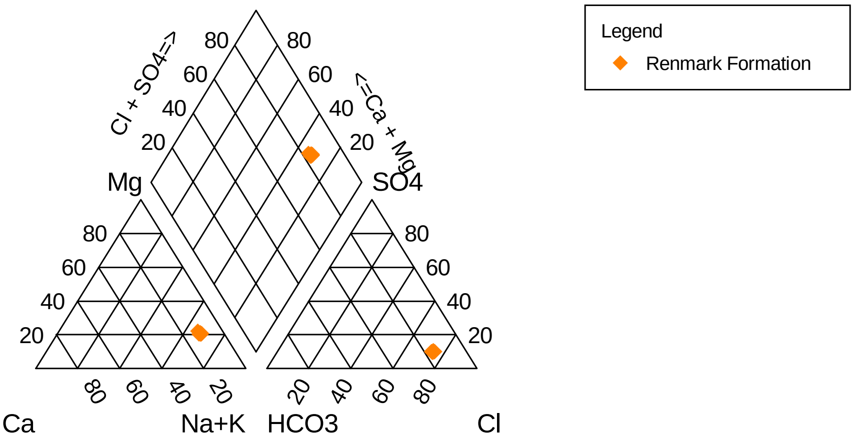


c. Water level and electrical conductivity from August 1972 to August 2011

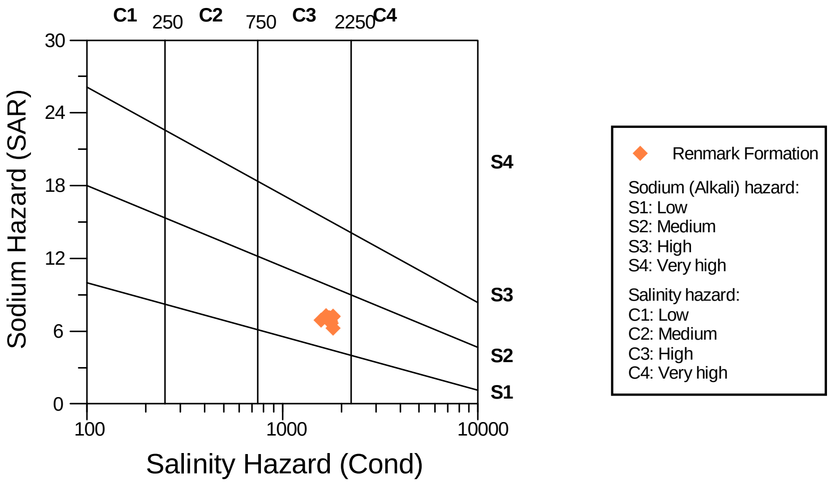
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

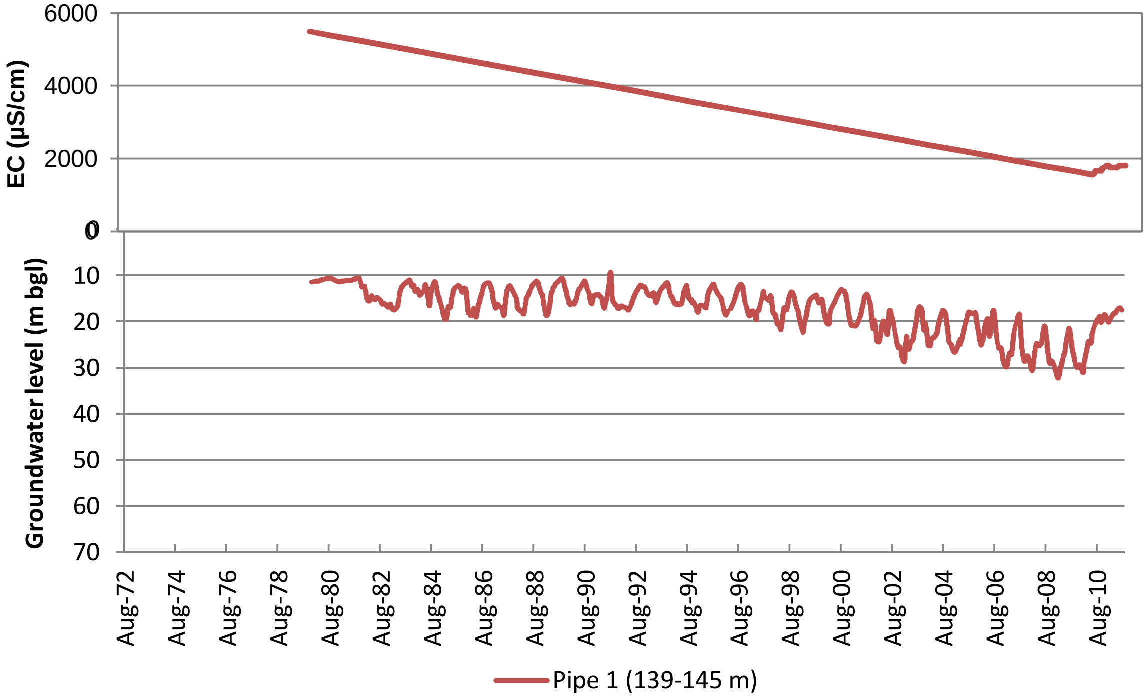
Figure H-6 Chemistry Summary GW036396



a. Piper plot showing water type: Na-Mg-Cl and Na-Cl (Renmark Formation)



b. Wilcox plot showing high salinity and medium SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

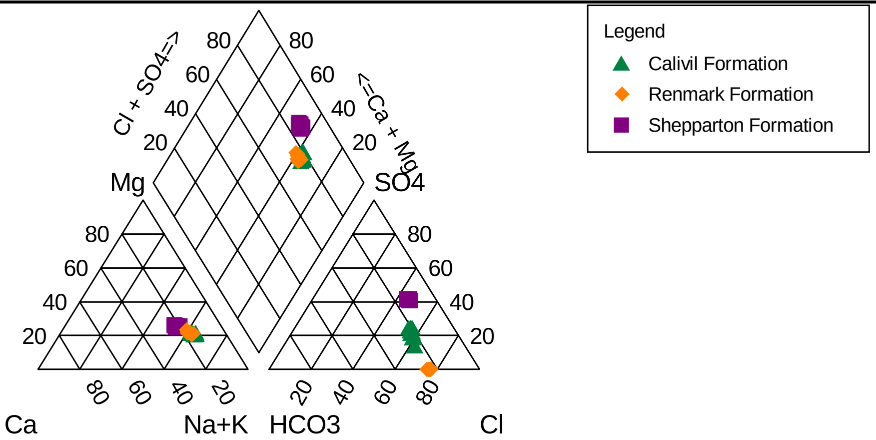
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

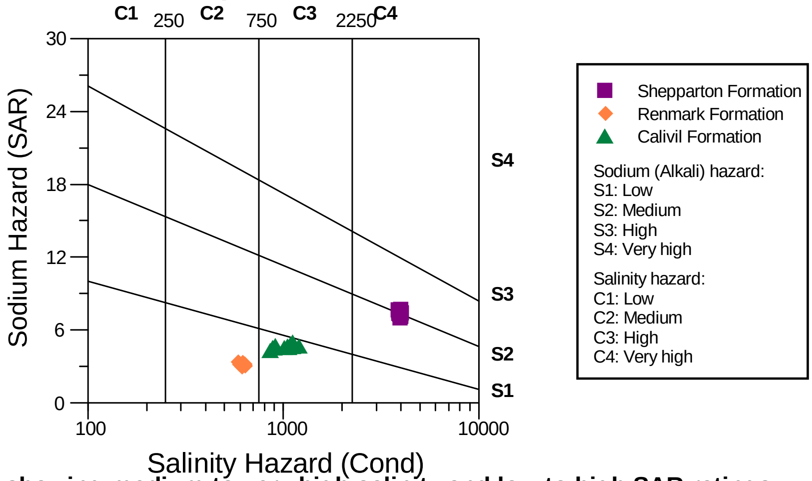
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

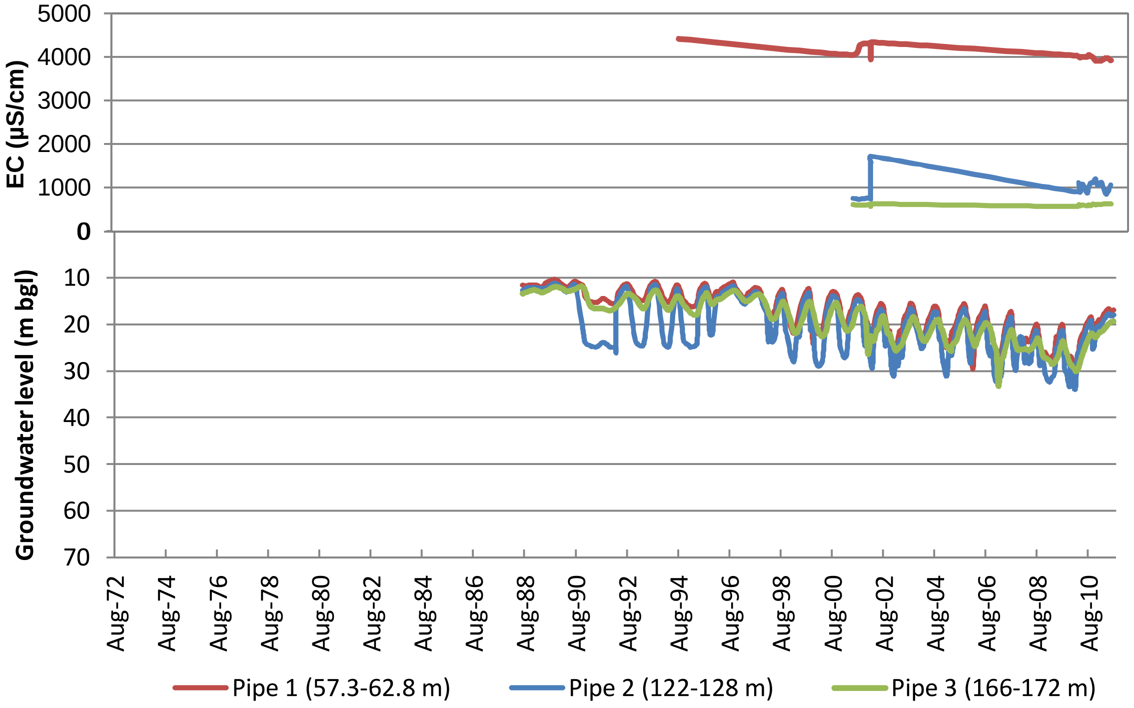
Figure H-7 Chemistry Summary GW036773



a. Piper plot showing water type: Na-Mg-Ca-Cl-SO4 and Na-Mg-Cl-SO4 (Shepparton Formation) and Na-Mg-Cl-HCO3-SO4, Na-Mg-Cl-SO4 and Na-Mg-Cl-HCO3 (Calivil Formation), and Na-Mg-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to very high salinity and low to high SAR ratings

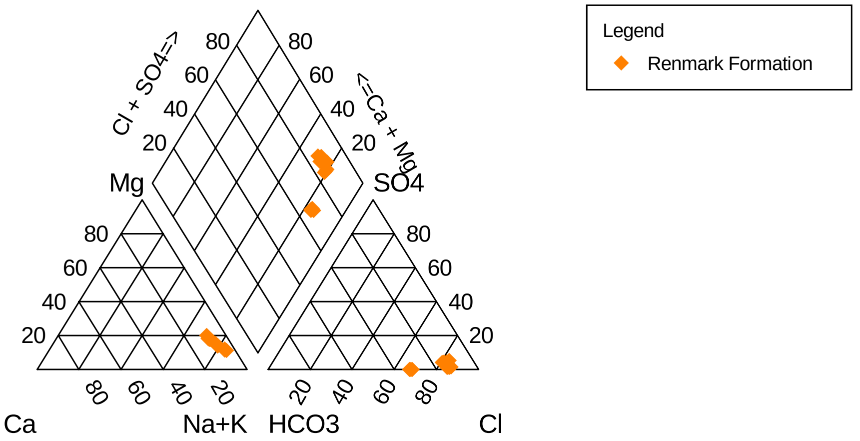


c. Water level and electrical conductivity from August 1972 to August 2011

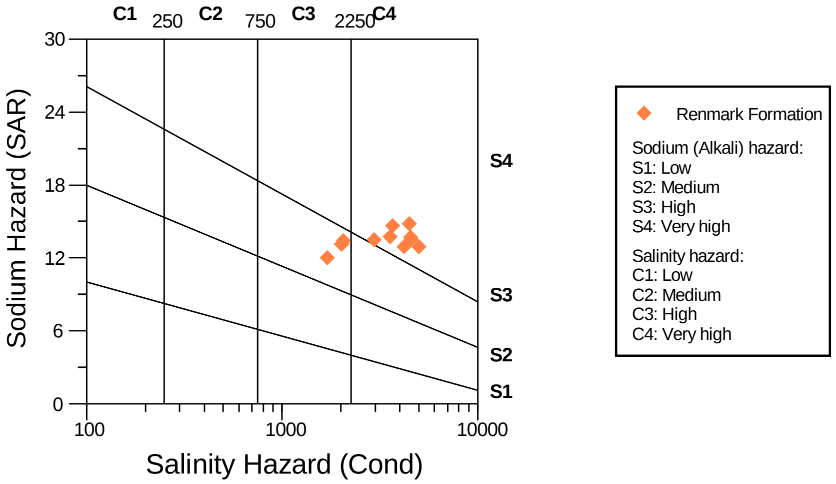
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS
BRINCKERHOFF

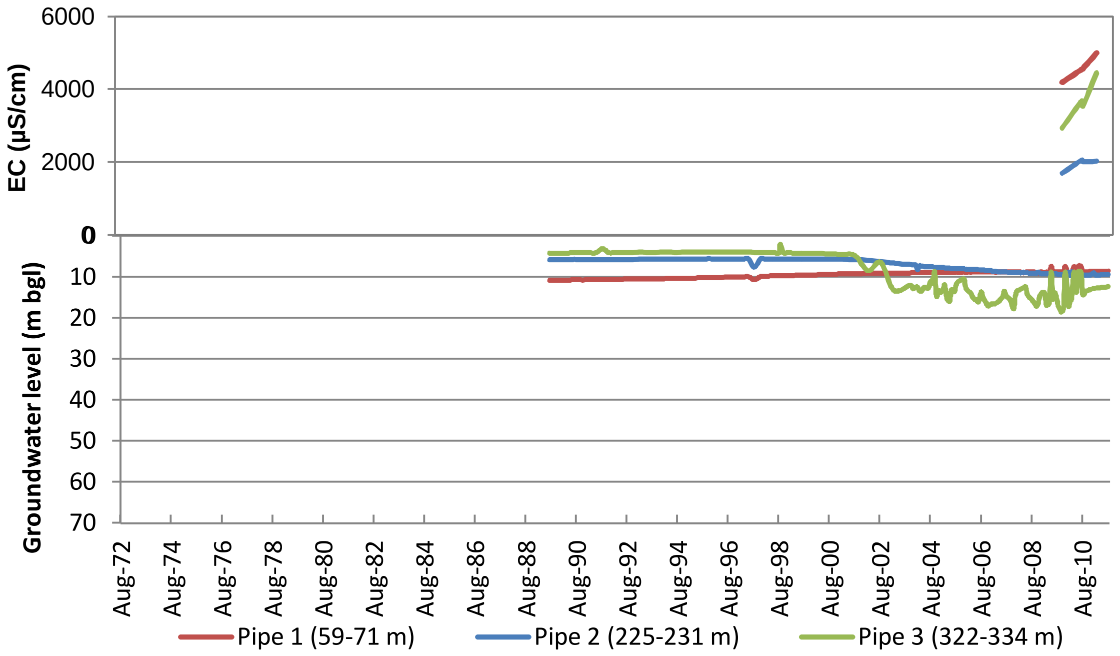
Figure H-8 Chemistry Summary GW036799



a. Piper plot showing water type: Na-Cl, Na-Mg-Cl and Na-Cl-HCO3 (Renmark Formation)



b. Wilcox plot showing medium to very high salinity and high to very high SAR ratings

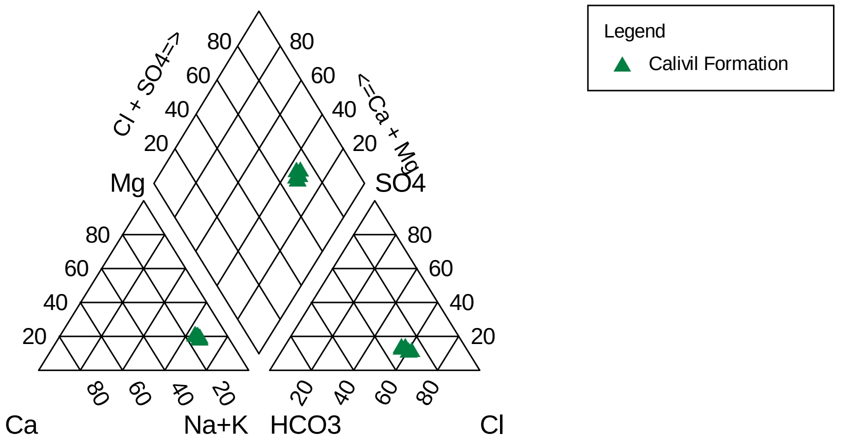


c. Water level and electrical conductivity from August 1972 to August 2011

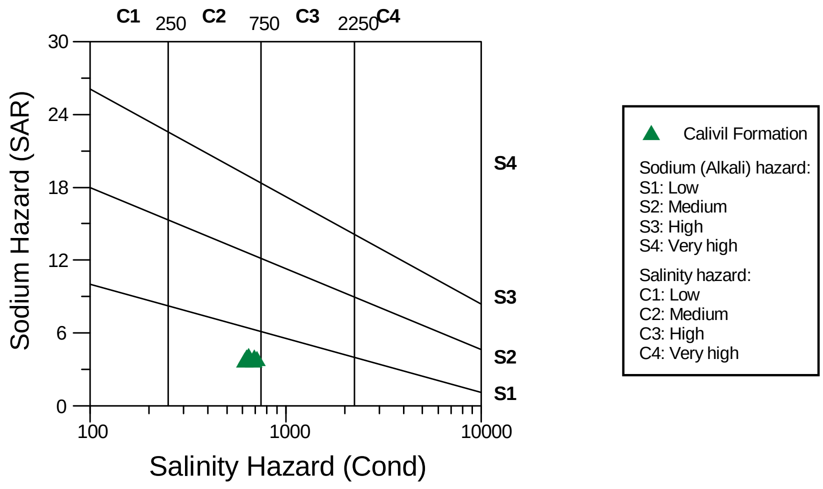
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

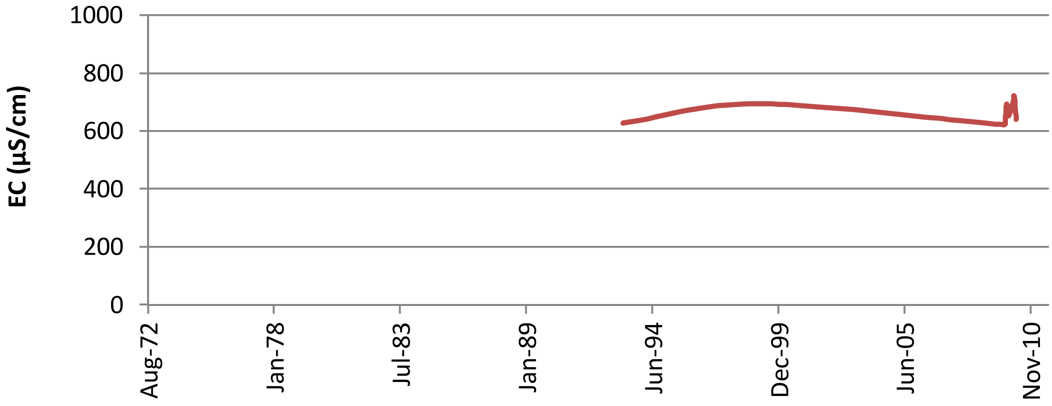
Figure H-9 Chemistry Summary GW039406



a. Piper plot showing water type: Na-Cl-HCO3 and Na-Mg-Cl-HCO3 (Calivil Formation)



b. Wilcox plot showing medium salinity and low SAR ratings

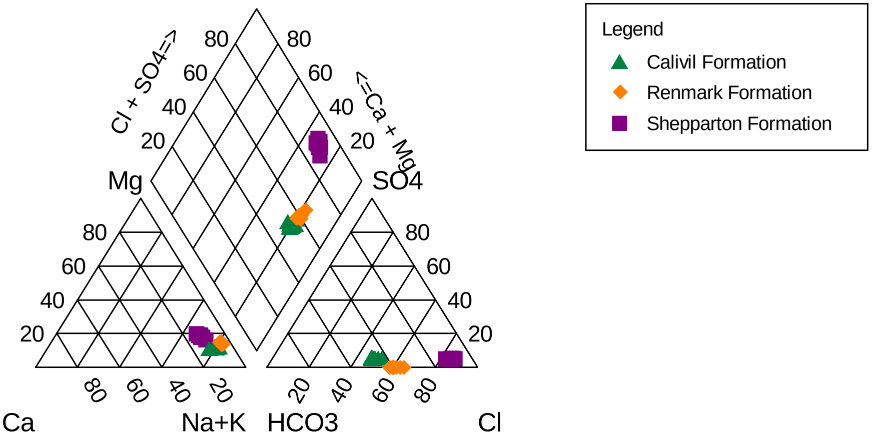


c. Electrical conductivity from August 1972 to August 2011

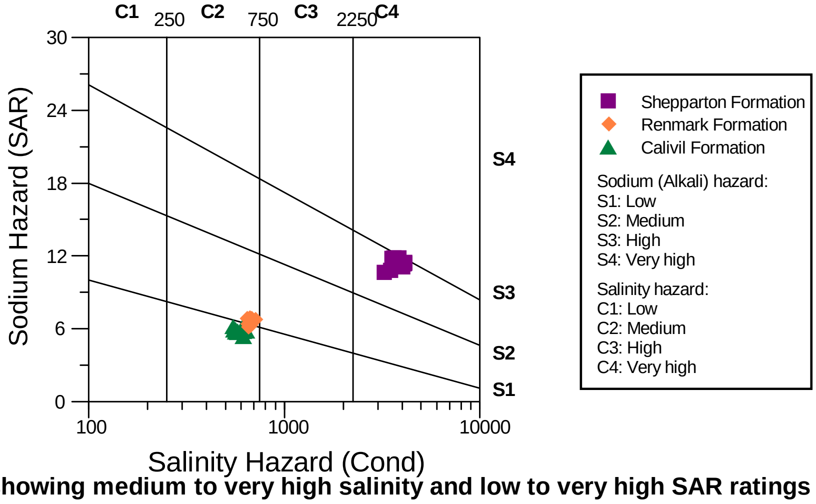
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

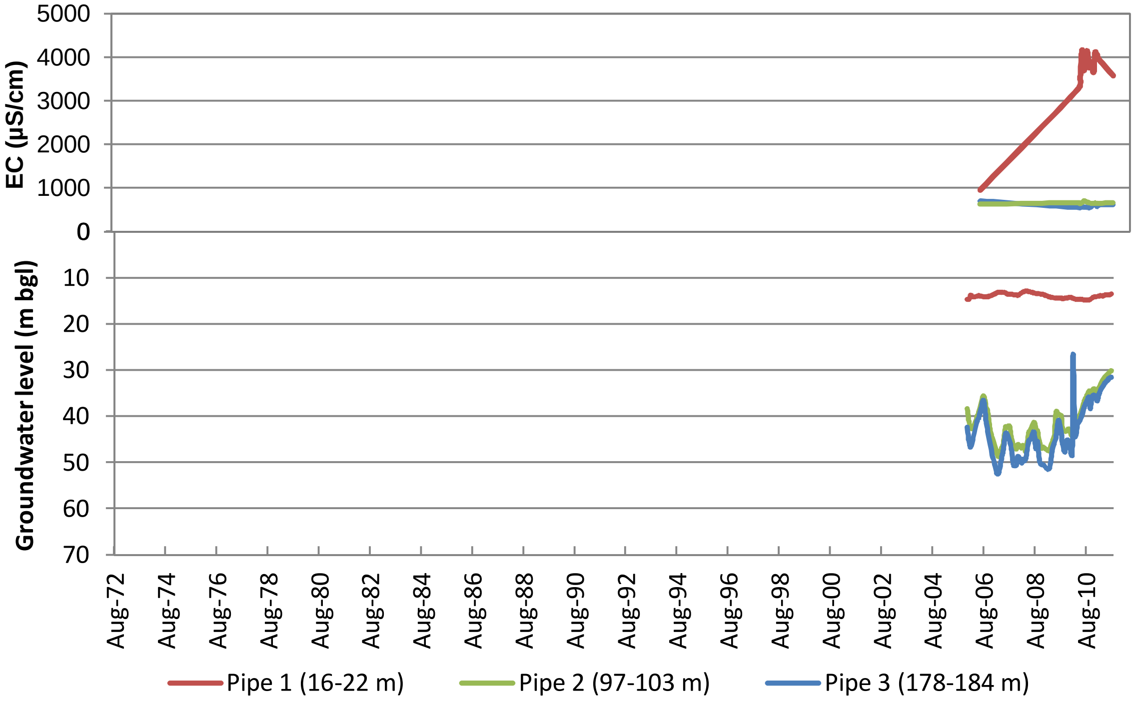
Figure H-10 Chemistry Summary GW041011



a. Piper plot showing water type: Na-Cl and Na-Mg-Cl (Shepparton), Na-Cl-HCO3 (Calivil) and Na-Cl-HCO3 (Renmark)



b. Wilcox plot showing medium to very high salinity and low to very high SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

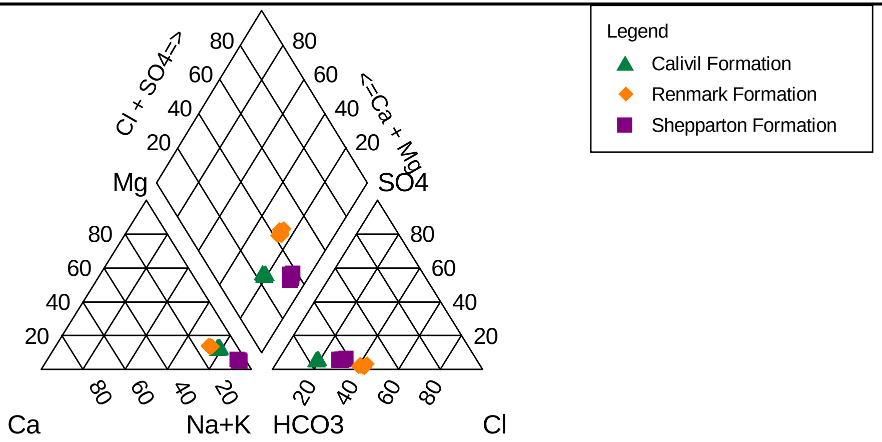
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

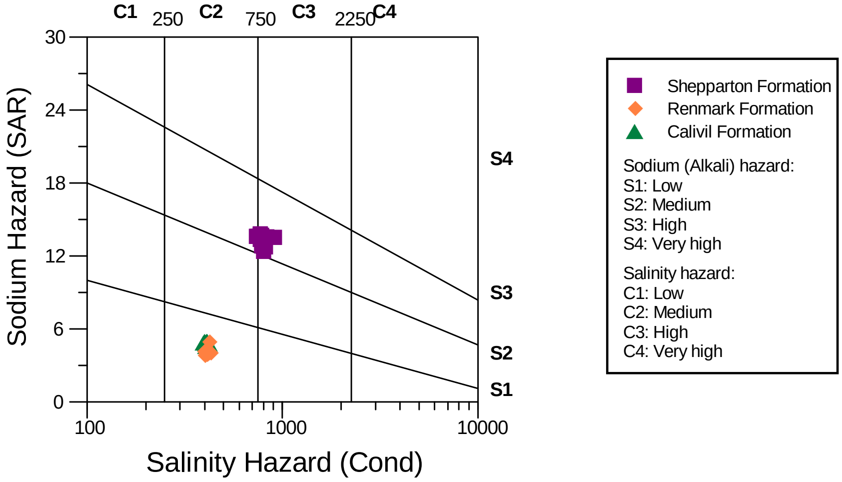
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

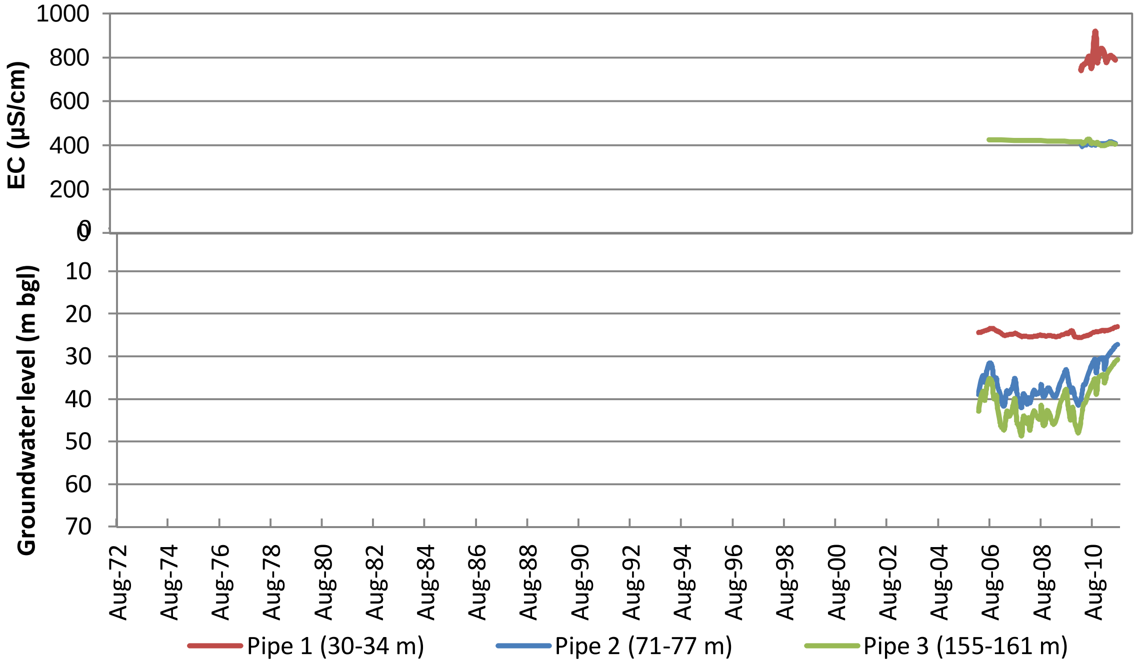
Figure H-11 Chemistry Summary GW041012



a. Piper plot showing water type: Na-HCO3-Cl (Shepparton Formation), and Na-HCO3 (Calivil Formation), and Na-HCO3-Cl (Renmark Formation)



b. Wilcox plot showing medium to high salinity and low to high SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

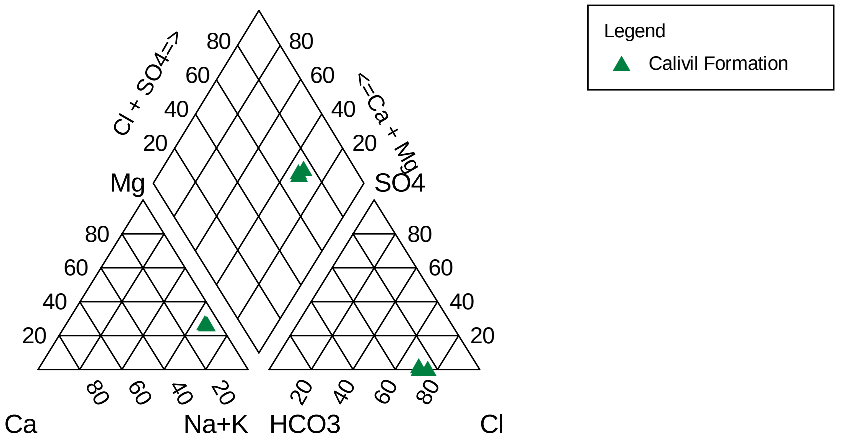
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

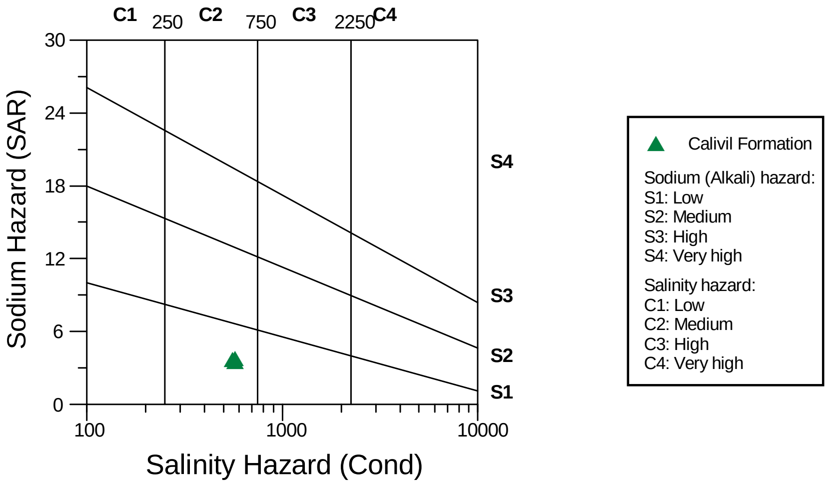
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

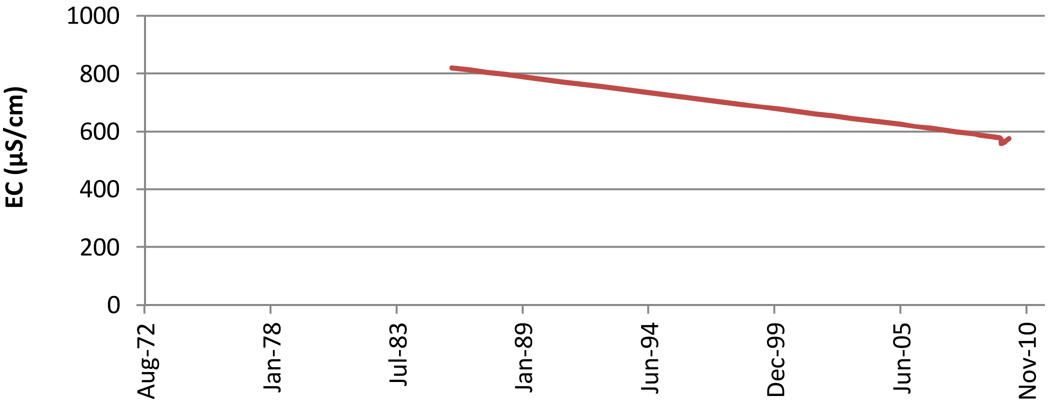
Figure H-12 Chemistry Summary GW059225



a. Piper plot showing water type: Na-Mg-Cl-HCO3 (Calivil Formation)



b. Wilcox plot showing medium salinity and low SAR ratings

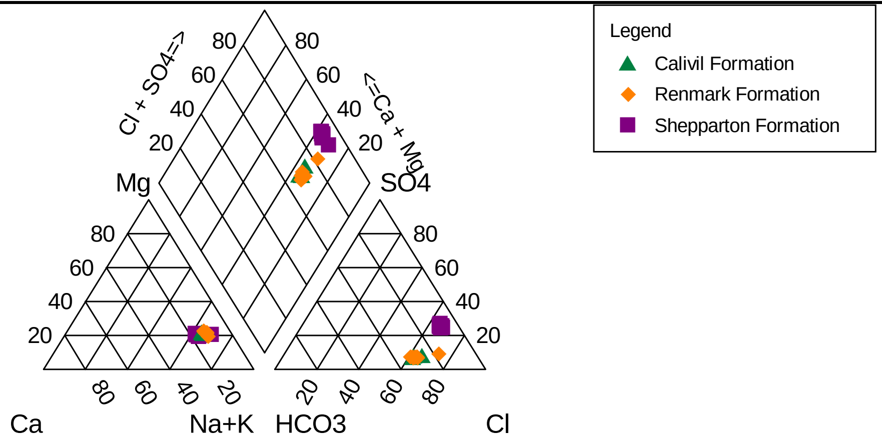


c. Electrical conductivity from August 1972 to August 2011

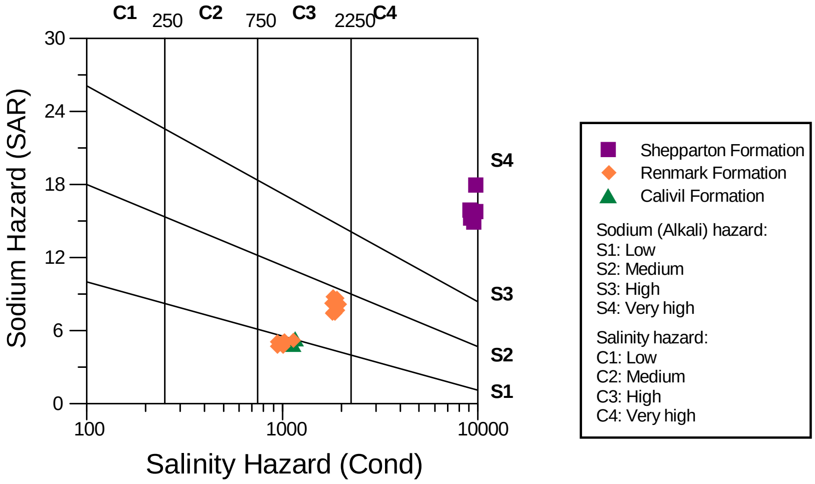
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

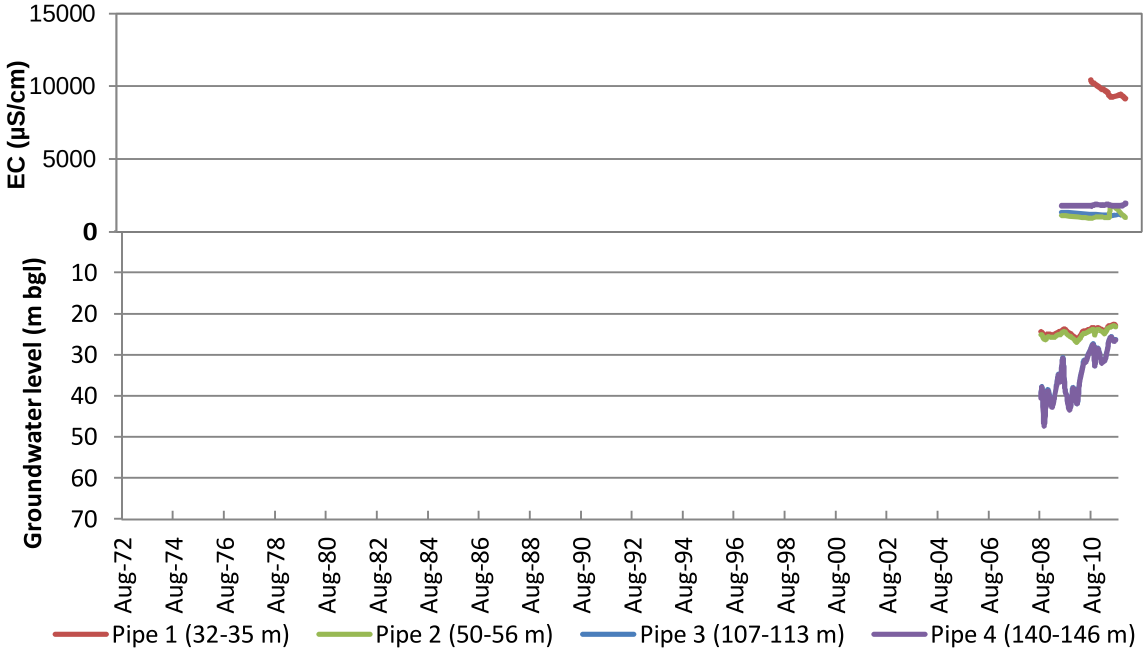
Figure H-13 Chemistry Summary GW273040



a. Piper plot showing water type: Na-Mg-Cl-SO4 and Na-Cl-SO4 (Shepparton), Na-Mg-Cl-HCO3 and Na-Mg-Cl (Calivil), and Na-Mg-Cl, Na-Cl Na-Mg-Cl-HCO3 and Na-Cl-HCO3 (Renmark)



b. Wilcox plot showing high to very high salinity and low to very high SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

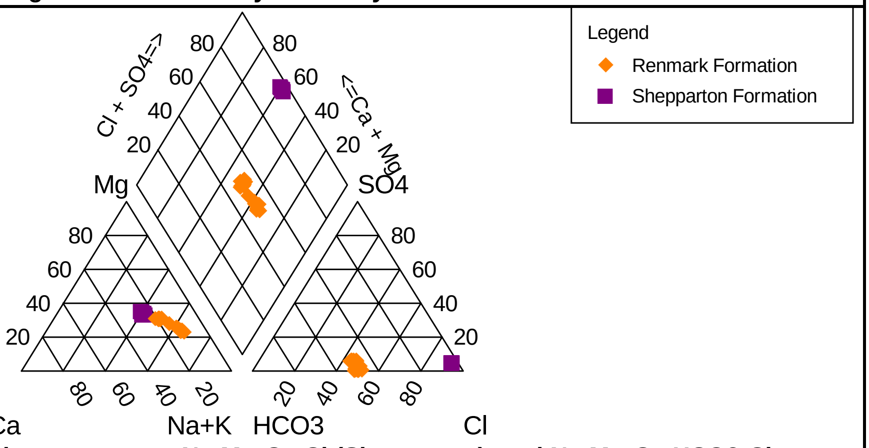
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

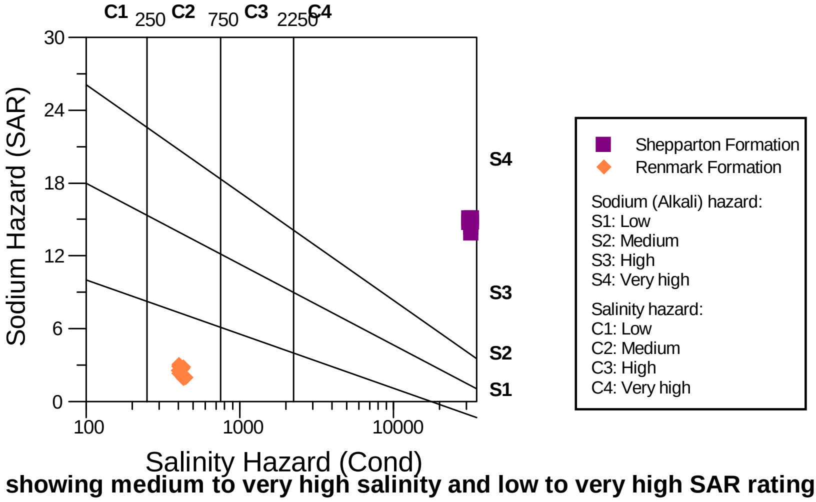
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

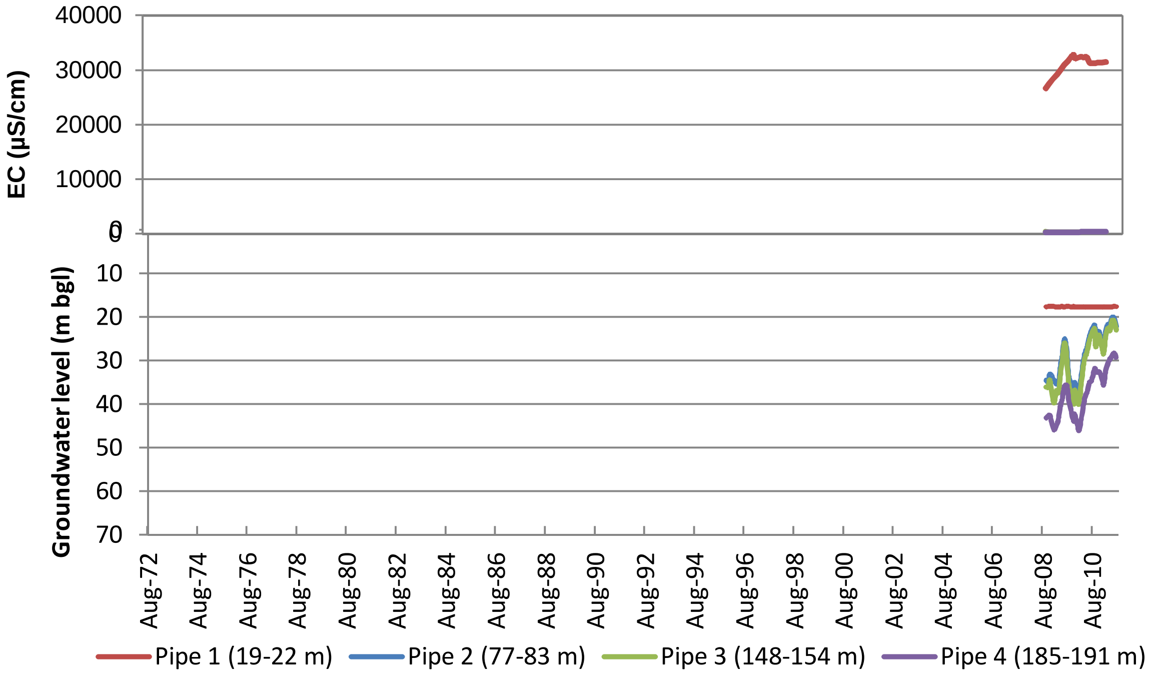
Figure H-14 Chemistry Summary GW273041



a. Piper plot showing water type: Na-Mg-Ca-Cl (Shepparton), and Na-Mg-Ca-HCO3-Cl, Na-Mg-HCO3-Cl and Na-Mg-Cl-HCO3 (Renmark)



b. Wilcox plot showing medium to very high salinity and low to very high SAR ratings



c. Water level and electrical conductivity from August 1972 to August 2011

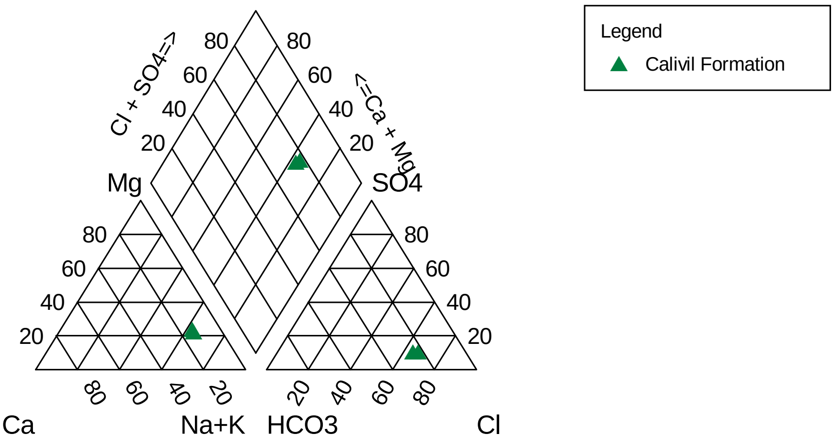
Client: NSW Office of Water

Location: Lower Murrumbidgee GMA

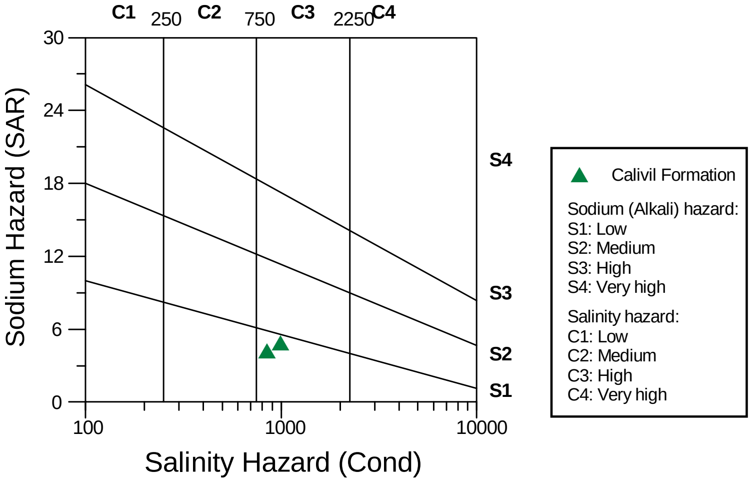
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

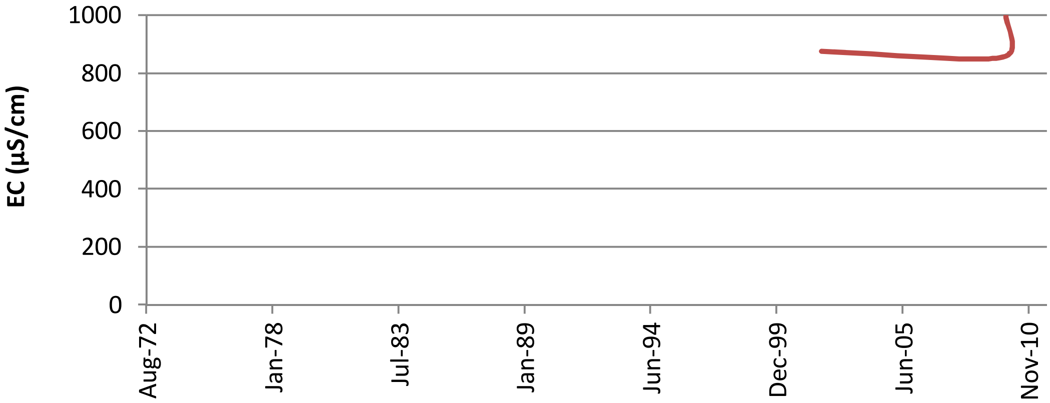
Figure H-15 Chemistry Summary GW400015



a. Piper plot showing water type: Na-Mg-Cl-HCO3 (Calivil Formation)



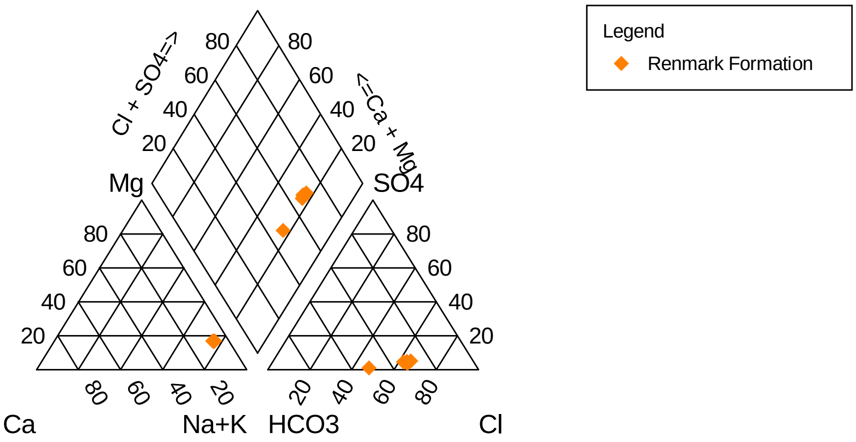
b. Wilcox plot showing high salinity and low SAR ratings



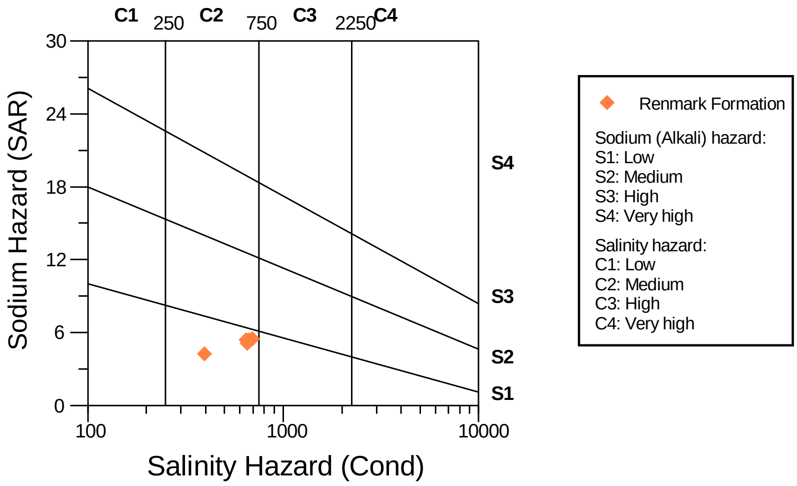
c. Electrical conductivity from August 1972 to August 2011

Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

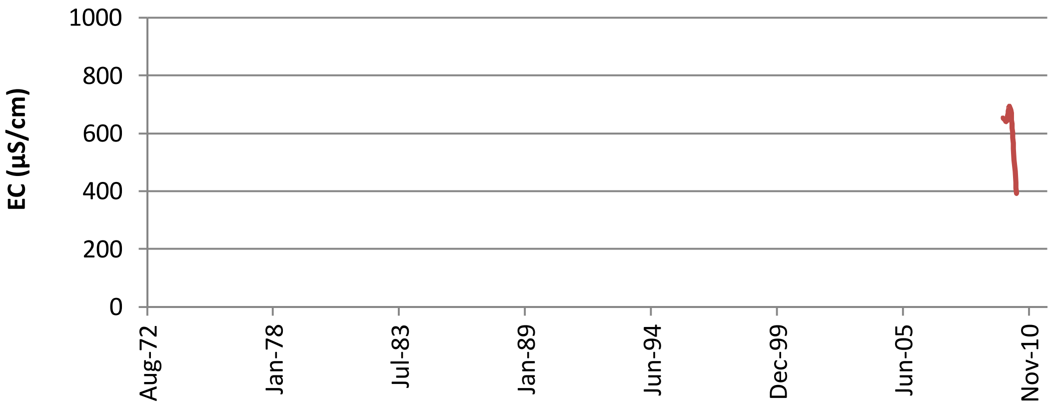
Figure H-16 Chemistry Summary GW400023



a. Piper plot showing water type: Na-Cl-HCO3 (Renmark Formation)

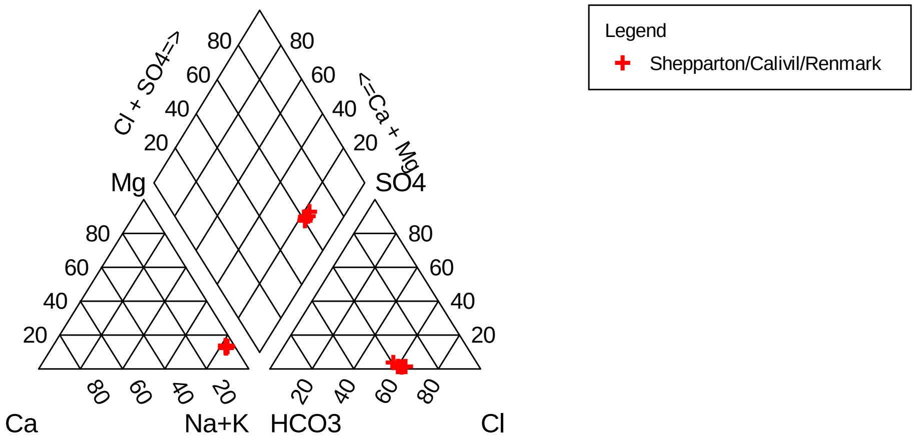


b. Wilcox plot showing medium salinity and low SAR ratings

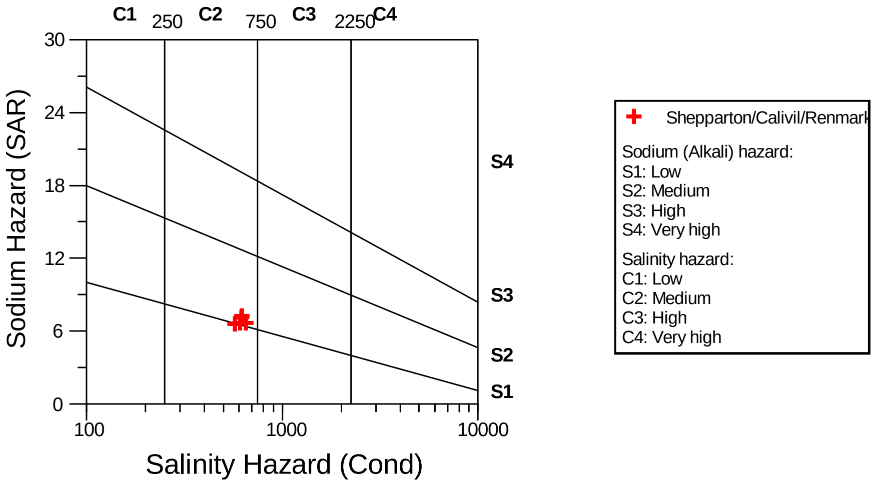


c. Electrical conductivity from August 1972 to August 2011

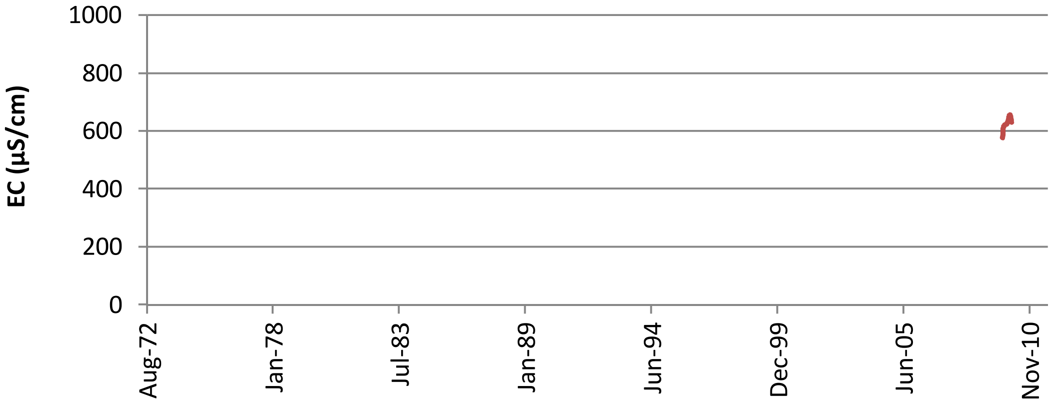
Figure H-17 Chemistry Summary GW400976



a. Piper plot showing water type: Na-Cl-HCO3 (Shepparton, Calivil & Renmark Formation)



b. Wilcox plot showing medium salinity and low to medium SAR ratings

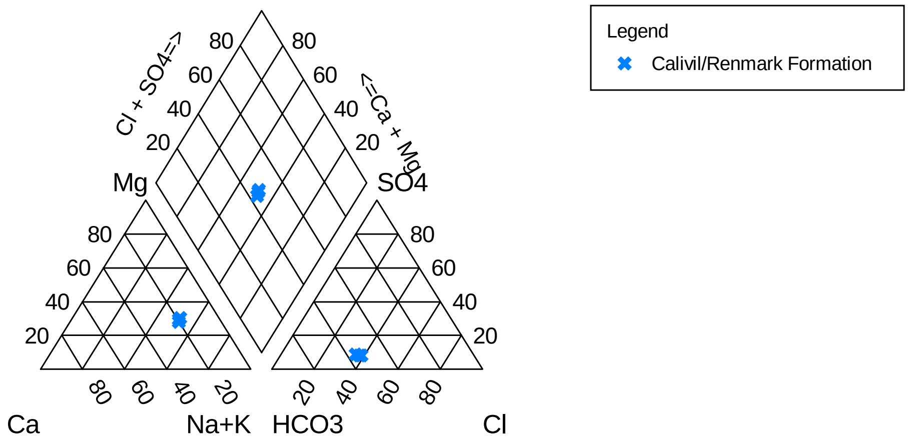


c. Electrical conductivity from August 1972 to August 2011

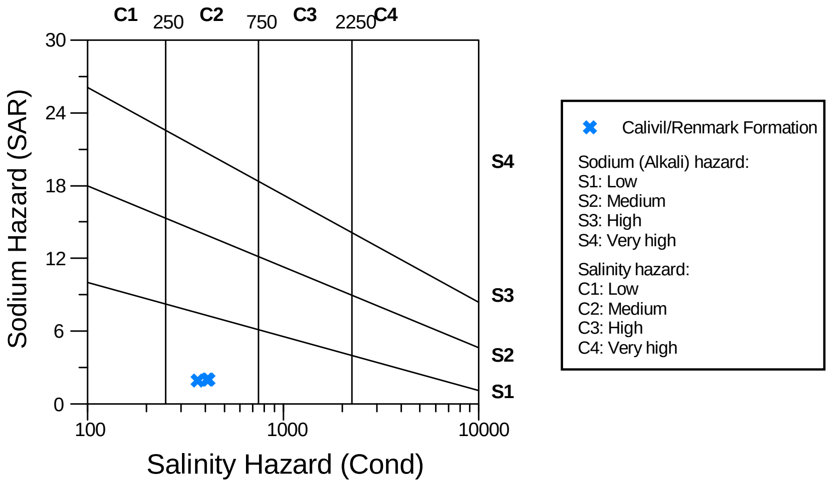
Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

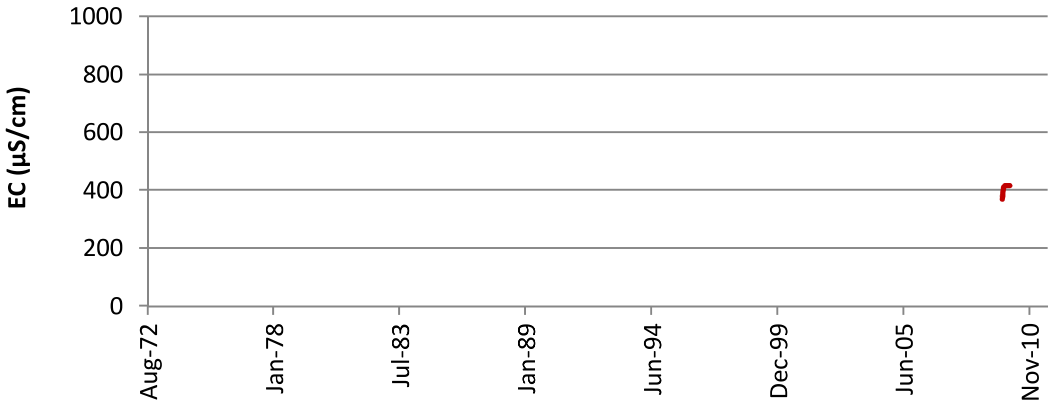
Figure H-18 Chemistry Summary GW403205



a. Piper plot showing water type: Na-Cl-HCO3 (Calivil & Renmark)



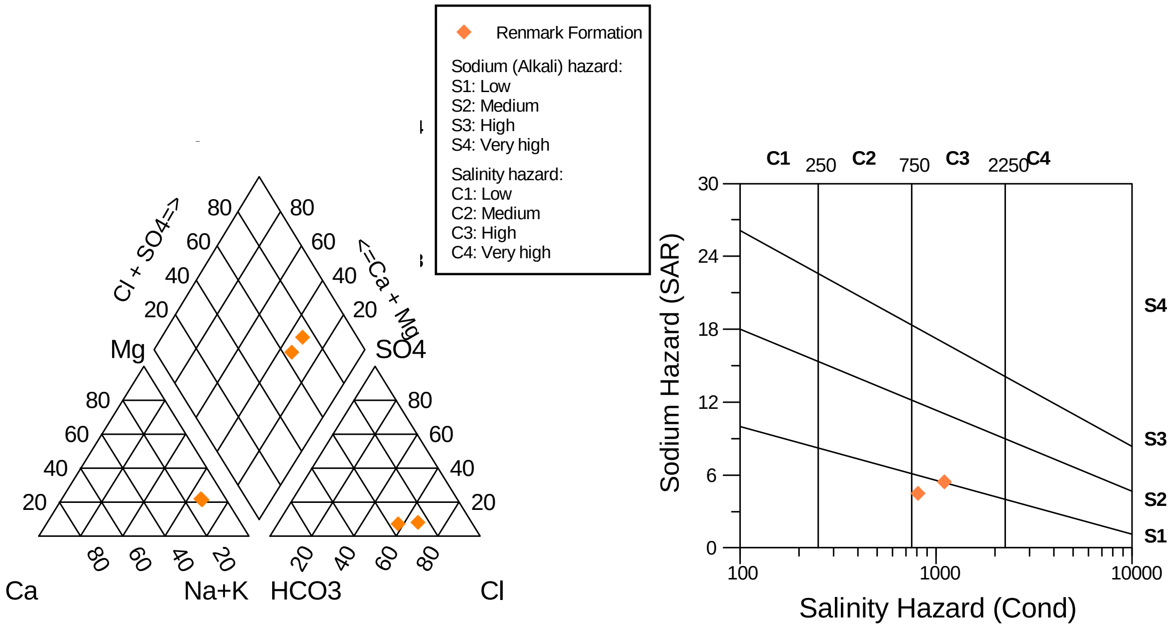
b. Wilcox plot showing medium salinity and low to medium SAR ratings



c. Electrical conductivity from August 1972 to August 2011

Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

Figure H-19 Chemistry Summary GW404126



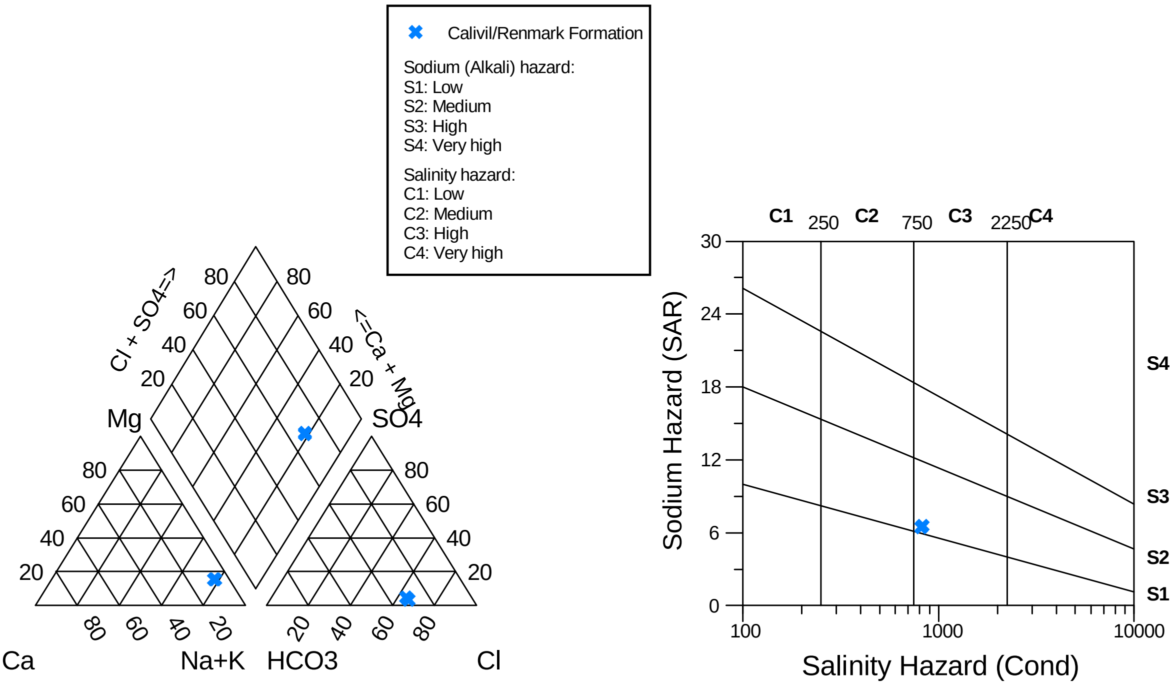
a. Piper plot showing water type: Na-Mg-Cl-HCO3 (Renmark Formation)

b. Wilcox plot showing high salinity and low to medium SAR ratings

Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Figure H-20 Chemistry Summary GW500972



a. Piper plot showing water type: Na-Cl-HCO3 (Calivil/Renmark Formation)

b. Wilcox plot showing high salinity and medium SAR ratings

Client: NSW Office of Water
Location: Lower Murrumbidgee GMA
Project: Characterisation of hydrogeochemistry and risks to groundwater quality

PARSONS BRINCKERHOFF

Appendix

I

Lower Murrumbidgee GMA – Numerical Modelling

CD – NSW Office of Water – Lower Murrumbidgee GMA numerical modelling

Contents

Numerical modelling spreadsheet – LMB_Water_and_Salt_Flux_Calculations3b

PARSONS
BRINCKERHOFF