

Changing land use in an uncertain climate: impacts on surface water and groundwater in the Goulburn River, NSW

by

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Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Julia Imrie

Date:

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your inspiration and vision guides all my ventures.*

Abstract

As a key contribution to the United Nations (UN) sustainable development goals, the UN high-level panel on water (HLPW) in 2018 identified as a priority the prevention of degradation and pollution of rivers, lakes and aquifers, and the restoration and maintenance of acceptable environmental conditions and water quality at the local, national and regional scale. The HLPW report recognised water crises are exacerbated by climate change. Three of the ten objectives of the Australian National Water Initiative were: transparent, statutory-based water planning; statutory provision for environmental and other public benefit outcomes and improved environmental management practices; and recognition of the connectivity between surface and groundwater resources with connected systems managed as a single resource. This work has applied the HLPW's Foundation for Action to a river water quality issue, salinity, at the local scale, where natural processes are added to or altered by land-use change and climate variability. The focus is to better inform the planning process in a surface-groundwater connected river subject to variable climate. While the 7,800 km² catchment is of local concern, it has national economic and environmental significance.

The Goulburn is the largest tributary of the Hunter River, a highly connected surface-groundwater system with diverse hydrogeology, land use and vegetation, multiple regulations and a spatially and temporally varying climate. Land-use across the Goulburn catchment, once dominated by agriculture and national parks, has been changing with expansion of coal mining. Salinity is a major issue in the Hunter and the Hunter River Salinity Trading Scheme (HRSTS) was introduced to control mine discharge. The Goulburn is not part of HRSTS.

The aim of this work is to assess the impacts of changing land use on trends in stream flow, catchment yield, surface and groundwater interaction, and stream salinity in the Goulburn River system, and to separate them from the impacts of climate change, natural climate variability and regulatory changes. Analysis of seasonal and annual rainfall data since 1920 found the only significant trend in rainfall was in warm season, October to March, rainfall. The trend was +10 mm/decade. Climate change model projections suggest cooler season rainfall will decrease. Significant decreases and increases in rainfall trends over 30-year periods were found with a frequency similar to the Pacific Decadal Oscillation. Reliable pan evaporation (Epan) data since 1970 has no significant annual or seasonal trends despite published reports of general declines in Epan globally.

Previously recognised decadal flood and drought dominated periods were evident in stream discharge. A change in response of the catchment to recent droughts was found, including a loss of low flows over the past 30 years. Catchment water losses have increased by about 10 mm/year since the 1970s. Current water allocation licences are equivalent to about one third to one half of mean catchment specific discharge. Vegetation changes in response to regulation and altered farm practice may have contributed as well as mine dewatering. Stream discharge

elasticity to rainfall shows an additional non-rainfall source of water in the upper catchment in the last 20 years. Discharge of mine make water has occurred over this period.

Salinity profiles of the river during dry periods shows an array of sources of salinity, particularly below an elevation of 280 m AHD. These were associated with tributaries incising into geologies with higher salinity aquifers, such as the Permian Coal Measures and Jurassic shales. Importantly, tributaries draining lower salinity geologies such as the Tertiary volcanics or Triassic sandstones mitigate salinity in the Goulburn. The inverse relationship between stream salinity and stream discharge leads to an important conclusion. Extracting more fresh water from catchments will increase the salinity of Goulburn discharged into the Hunter. Estimates of annual specific catchment salt yield of the Goulburn range from 5.3 to 6.3 tonnes/km²/year, consistent with previous estimates, and much lower than projected by the Salinity Audit in 2000.

Pre-mining spot EC data in the upstream section of the Goulburn showed a mean EC that was only 55% of the currently regulated upper salinity discharge limit for mine discharge of 900µS/cm. Adopting this higher limit automatically ensured that salinity in the upper Goulburn River would always exceed pre-mining levels during mine discharge especially in drier times when almost all river flow is due to mine discharge. The impacts of changing mine discharge and salinity regulations are evident in the river salinity record. The specific salt yield of mined areas discharging into the river is eleven times that of the catchment. Regulations and monitoring have only focused on EC as the key determinant of water quality. This assumes that only the total salt concentration rather than the composition of salt is environmentally important.

Major ion geochemistry of surface and groundwater was useful in “fingerprinting” groundwater sources. Groundwater from the Permian coal measures had unusually high concentrations of potassium and sulfate, perhaps an indication of the longer groundwater residence time and pyrite oxidation. These species are also evident in mine discharge. Potassium concentrations in lower Triassic-Upper Permian strata were elevated suggesting vertical exchange between the Permian and Triassic. Tertiary volcanics sources in the northern sub-catchments were identified by elevated concentrations of calcium, magnesium and bicarbonate in surface and groundwater.

The previously largely unstudied Merriwa River is the Goulburn’s major tributary, a predominantly cleared, agricultural catchment intersecting Tertiary basalts, Jurassic sediments, Triassic strata and Permian Coal measures. Loss of flow is evident downstream, but the cleared catchment has a larger runoff coefficient than the more forested upper Goulburn. The EC and stream discharge relationship points to a baseflow source of high salinity, probably from the Purlewaugh-Comialla siltstone strata. The catchment’s specific salt yield was 20 tonnes/km²/year, which is 3 to 4 times the annual specific salt yield of the Goulburn. The

Merriwa is a significant source of salinity, so water licencing and catchment management are especially important.

Groundwater-dependent ecosystems (GDEs) have not been mapped in the Goulburn. The Drip formation GDE is a unique and protected feature in the upper Goulburn but underground and open cut mining is occurring relatively close by. It is shown here that contrary to claims by the mining industry, The Drip is fed from basalt geology to the north and the regional Triassic groundwater system. Further lowering of Triassic groundwater pressures by an approved, adjacent future mine will decrease groundwater discharge at The Drip. This was demonstrated using a two-dimensional groundwater model. The model showed that hydraulic properties assumed by the mining industry lead to physically implausible boundary conditions.

Suggestions for future research and improved regulations are given. The key to controlling saline discharge in the catchment is controlling sub-catchment geology-specific water abstraction in tune with the large swings in climate generated by large-scale ocean-atmosphere interactions. It is also important that regulations governing groundwater interception and mine water-make and discharge recognise surface-groundwater interactions and pre-mining stream geochemistry.

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List of acronyms and abbreviations

$\mu\text{S/cm}$	micro Siemens per centimetre (EC)
A	Area of rainwater catchment (km^2)
AHD	Australian Height Datum (metres) relative to sea level
BIS	Bobadeen Irrigation Scheme (UCML)
BLR	Basic Landholder Rights
BoM	Australian bureau of meteorology
CCC	Community Consultative Committee
COAG	Council of Australian Government
CSG	Coal Seam Gas
CV	Coefficient of variation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DPI Water	NSW Department Primary Industries - Water
EC	Electrical Conductivity ($\mu\text{S/cm}$)
EL	Exploration Licence
ENSO	El Nino Southern Oscillation
EPA	Environmental Protection Authority
Epan	Pan evaporation (mm/year)
EPBC Act	Commonwealth Environment Protection and Biodiversity Conservation Act 999
EPL	Environment Protection Licence
GDE	Groundwater Dependent Ecosystem
GL	Ground Level
GR	Goulburn River
GRNP	Goulburn River National Park
GW	Groundwater
GS	Gauging station (river or stream)
GEMU	Goulburn Extraction Management Unit
ha	hectares ($10,000 \text{ m}^2$)
HRSTS	Hunter River Salinity Trading Scheme
IOD	Indian Ocean Dipole
KL/day	Kilolitres per day
kms	Kilometres
km^2	Square kilometre
L	Litre
m	metre
mm	millimetre
ML/time	Catchment yield Q (ML/year or ML/day)
$\text{mm/km}^2/\text{year}$	Specific discharge per square kilometre
month	month
m^3/s	Cubic metres per second. A measure of groundwater flux
mbgl	Groundwater depth as metres below ground level
MCC	Moolarben Mine Complex -Stage 1 + 2
MCM	Moolarben Coal Mine

MCO	Moolarben Coal Operation
meq/L	Milliequivalents per litre concentration
mg/L	Milligrams per litre
ML/year	Megalitres per year
MT/year	Million tonnes per year
NOW	NSW Office of Water (to 2016)
NPWS	National Parks & Wildlife Service
OEH	Office of Environment and Heritage
P	Precipitation or rainfall - annual (mm/year) daily (mm/day)
PEL	Petroleum Exploration Licence for CSG
PDO	Pacific Decadal Oscillation
Q	Stream discharge (volume/time)
Q/A/time	Specific discharge (volume/unit area/time)
RO	Rainfall runoff co-efficient
SBNCGS	Sydney Basin -North Coast Groundwater Source
SL	Salt load (tonnes/ML)
SW	Surface water
SWL	Standing Water Level as mAHD
TDS	Total dissolved solids
TOC	Top of collar - groundwater bore
tonnes/km ² /year	tonnes per square kilometres per year
UCML	Ulan Coal Mine Limited
WAL	NSW Water Access Licence units (ML/Year)
WCM	Wilpinjong Coal Mine
WSP	Water Sharing Plan

Glossary and Terms

Baseflow	The portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system
Basic Landholder Rights	Water rights that relate to domestic and stock rights, harvestable rights and Native Title rights
Bobadeen Irrigation Scheme (BIS)	UCML scheme to use excess untreated groundwater for irrigation of pasture for stock
<i>Bord and pillar</i> mining	Underground coal mining using pit props as opposed to longwall mining where extraction results in massive subsidence
Catchment yield or stream discharge (Q)	The total quantity of surface water in millions of litres measured at the outlet of a catchment in a given period (year or day) from a stream. (ML/year, or ML/day)
Coefficient of variation (CV)	A measure of relative variability. It is the ratio of the standard deviation to the mean (average).
Community Consultative Committee	Department of Planning committee operated by mining companies to ensure proponents engage with and inform the community and stakeholder groups on State significant projects.
Dewatering	The process of controlling groundwater flow within and around mining operations that occur below the water table by direct pumping of water from within a mine and installation of dewatering bores.
Geometric mean discharge	A mean or average, which indicates the central tendency or typical value of a set of numbers by using the product of their values (as opposed to the arithmetic mean which uses their sum).
Groundwater Dependent Ecosystem	A GDE or ecosystems that requires access to groundwater to meet all or some of its water requirements and species composition
Groundwater depressurisation	The extraction of groundwater which decreases aquifer pressures in a confined aquifer and lowers groundwater levels in unconfined.
Groundwater recharge	Defined as the volume of water per unit area contributing to aquifer storage over a given period of time (mm/year or mm/day)

Hunter River Salinity Trading Scheme	A state operated economic instrument designed to minimise the impact of saline water discharges by the mining and energy industry on other Hunter River water users and the environment using a system of tradeable credits that allow saline water discharge at high river flow whilst maintaining the Hunter River under 900 μ S/cm below Denman.
Hyporheic zone	Area of sediment and porous space beneath and alongside a stream bed where stream water and groundwater intermix
Lethality	The capacity to cause death or serious harm or damage
Longwall mining	underground coal mining where a panel of coal is mined in a series of slices (typically 1-2 m thick) from a broad coal face that results in the collapse of the roof and overlying rock into the void behind (causing subsidence)
Meteoric salts	Cyclic marine salts of meteoric origin are salts that have been carried through the atmosphere in rainfall and deposited on the land surface
Mine subsidence	The fall in land surface and geological strata when underground mined voids collapse post mining compressing and fracturing overlying strata, changing groundwater pressure
Non-parametric	Does not assume that the data follows a specific distribution e.g. normally distributed
Orographic rainfall	rain produced from the lifting of moist air over a mountain or high elevations
Pan evaporation	The amount of water which evaporates from an open pan due to the effects of several climate elements: temperature, humidity, rain fall, drought dispersion, solar radiation, and wind (Epan)
Percentile rank	The percentage of observations in a frequency distribution that is equal to or lower than that percentile. Median = 0.5
Phreatic groundwater	Groundwater in the saturated zone below the water table. It defines the lower edge of the overlying vadose zone
Ratings Tables	Tables which translate streamflow data such as height and flow rate into volumes of water, used to estimate discharge rates (e.g. ML/day).
Residual catchment	The ‘ungauged’ catchment area downstream of a stream gauge

Riparian zone	The area that borders intermittent or permanent streams and rivers. The interface or transition zone between the terrestrial environment and the aquatic environment.
Salinity (EC)	A measure of all the salts dissolved in water. Units used are EC unless where stated converted to TDS mg/L (Appendix E1)
Salt Load	Total weight of salt carried by a stream over time (tonnes/day, tonnes/year)
Specific discharge	Discharge per unit area per unit time measured as Q/A ($ML/km^2/time$ or $mm/time$)
Specific salt discharge	Amount of salt produced from a given area over time, catchment salt yield ($tonnes/km^2/time$, SL/A $mg/time$)
Stream discharge	Is the product of stream velocity (V - length of travel per unit of time such as metres/second) x depth of the water (D - unit of length) x width (W of the water - units of length). Lengths expressed in the same unit. $Discharge = V \times D \times W$.
Vadose	Underground water that lies above the water table and below the top of the ground surface
Water-make (mining)	Surface and groundwater inflows to mine void, pit or underground
Water-take (mining)	Reported amount of water extracted during underground mining

Chapter 1: Introduction

This chapter provides an overview of the main themes and principal concepts examined in this thesis, and reasons for selecting the area of study. It contains the hypothesis, aims and objectives, key questions to be answered and an outline of the subsequent chapters.

1.1 *Global challenges in water*

The United Nations (UN) Sustainable Development Goals (SDGs) address global challenges such as poverty, inequality, climate, environmental degradation, prosperity, and peace and justice. One goal, SDG 6, is focused on water and sanitation. Access to appropriate quantities of clean water underpins almost all other SDGs. A key target within SDG6 is to protect and restore water-related ecosystems including rivers and aquifers. In April 2016, the Secretary General of the UN and the President of the World Bank convened the high-level panel on water (HLPW), to provide leadership in tackling one of the world's most pressing challenges – an approaching global water crisis. The HLPW was challenged to identify ways in which the world could accelerate progress towards SDG 6 as well as to contribute to the achievement of the multiple SDGs that depend on the development and adequate management of water resources. Australia and 10 other countries were represented on HLPW by their Prime Ministers or Presidents.

The HLPW issued its final report, *Making Every Drop Count*, in March 2018 (UNHLPW, 2018). The report sets out a Foundation for Action at three levels:

1. Understand Water
2. Value Water
3. Manage Water

It proposed an integrated agenda at local, national and regional levels specifically targeting water and the environment and recommended as a priority the prevention of degradation and pollution of rivers, lakes and aquifers, and where necessary, the restoration and maintenance of acceptable environmental conditions and water quality.

1.2 *Australian Water Reforms*

The National Water Initiative (NWI) initiated by the Council of Australian Governments (COAG) in 2004 was one of the most significant water reforms in Australia, since federation. Under the NWI, governments, made several commitments that included preventing degradation and pollution of rivers, lakes and aquifers, and where necessary, restoring and maintaining acceptable environmental conditions and water quality. Three of the ten objectives of the NWI were: transparent, statutory-based water planning; statutory provision for environmental and other public benefit outcomes and improved environmental management practices; and recognition of the connectivity between surface and groundwater resources with connected

systems managed as a single resource. Surface and groundwater systems in Australia have long been viewed and managed by regulators as separate resources (Kalbus *et al.*, 2006) (NSW Government, 2000).

1.3 **Challenges to water reforms and water planning**

One difficulty in carrying through water reforms and developing water plans in Australia is the extreme variability of climate and stream flow in Australia (McMahon *et al.*, 1992). A second difficulty is the competing and changing uses for water between different sectors of the economy while a third difficulty is the impact of those land uses on water quality. A final long-term challenge is planning for and managing the impact of climate change.

Australia's highly variable climate, conflicting changes in land use and ensuing effects on water resources requires an integrated approach to catchment management and planning - one that recognises the importance of surface and groundwater connectivity in sustaining resilient river and groundwater dependent ecosystems (Boulton *et al.*, 2010). The need for evidence-based understanding of river system flow and health is clear, given the history of over-extraction, declining water quality, stream flows and climate change (Foster *et al.*, 2003; Richardson *et al.*, 2011a; Boulton *et al.*, 2010; Schramm, 1980; Wilford *et al.*, 2010; Sophocleous, 2002). Recognising the fundamental role of a functioning and resilient riparian ecosystem involving vital interactions between surface and groundwater and climate is a key challenge to sustainable and integrated resource management (Kalbus *et al.*, 2006).

Phreatic groundwater systems play a fundamental role in maintaining baseflow in Australian streams and are essential for sustaining aquatic ecosystems. Land use and water management changes that result in a significant drop in the water table or depressurisation of an aquifer can alter the flow regime from connected to disconnected in transitional stages over varying degrees and time, affecting sensitive groundwater dependent ecosystems, wetlands, lakes and rivers (Brownbill *et al.*, 2011).

Strategies for understanding surface and groundwater interaction and their impact on ecology under changing land use and climate have to deal with inherent uncertainties and constraints including inadequate baseline data. Numerical groundwater modelling often fails to capture the relevant processes applicable to stream-aquifer interaction (Acworth, 2009). Improved management requires the measurement, conceptualisation and understanding of river-groundwater connectivity and the impacts of land use and climate change (Beale *et al.*, 2000; Krogh *et al.*, 2013; Creelman, 1994; Brownbill *et al.*, 2011; Berhane, 2014).

In line with the UN's HLPW recommendations, this thesis concentrates on understanding water and aspects of managing water at the local scale. It is concerned with the interaction of climate and land use change in maintaining acceptable environmental conditions and water quality in catchments with connected surface and groundwater conditions, where maintenance

of base flow under varying climate and land use as well as preserving appropriate water quality is crucial to protecting water-dependent ecosystems and developing transparent water planning processes.

1.4 ***Local scale, choice of study catchment***

The Hunter River catchment in eastern Australia is of national economic, environmental and social importance. It is the source for major international coal exports, provides electricity generation for much of south-eastern Australia, produces high quality wines and horticultural crops, and supports grazing for cattle, sheep and horse studs. Stream salinity is a significant challenge facing the Hunter, both from natural discharge and due to mining. The Hunter River Salinity Trading Scheme (HRSTS) was introduced in 1994 to manage this problem in the lower valley. The HRSTS was designed to minimise the impact of saline water discharges by the mining and energy industry on other Hunter River water users and on the environment. HRSTS is based on a system of tradeable salinity discharge credits and permits the discharge of saline water when there is high river discharge provided stream salinity in the Hunter does not exceed an electrical conductivity (EC) of 900 $\mu\text{S}/\text{cm}$ below the town of Denman (Krogh *et al.*, 2013; DEC, 2006).

The Goulburn catchment, the largest upstream tributary discharging into the Hunter near Denman, is experiencing increasing pressure from land use change with the expansion of coal mining and also has the potential for coal seam gas production (CSG). Stream salt discharges from the Goulburn River have long been a concern and can affect the functioning and viability of the HRSTS (Krogh *et al.*, 2013). The Goulburn River is, however, not included in the HRSTS despite its impacts on downstream water quality.

The main arm of the Goulburn River and its southern tributaries are highly connected, groundwater-dominated systems (Macdonald *et al.*, 2009a; Biswas, 2010; NSW Department of Water and Energy, 2009). Despite its impact on salinity, the Goulburn is one of the least studied and understood river catchments in New South Wales (Krogh *et al.*, 2013; Somerville *et al.*, 2006). Monitoring both spatially and temporally has been discontinuous and there is limited, readily accessible information on surface and groundwater resources for this catchment (Krogh *et al.*, 2013; Creelman, 1994). While environmental impact assessments, annual reports and modelling of water impacts have been carried out by the mining industry for a number of specific sites, there is no comprehensive, independently verified, publically accessible database of this information, nor any integrated assessment of this information (Ward and Kelly, 2013; Macdonald *et al.*, 2009a).

The significant natural temporal variability of rainfall on an annual and decadal basis, and its spatial non-uniformity across the region, combined with highly non-linear hydrological processes makes the long term impacts of climate change on the Goulburn system difficult to

predict with certainty. In addition to land use change the climate of south-eastern Australia is in a process of change (CSIRO, 2015). Together, these present particular challenges for water resource managers and planners (CSIRO, 2012).

This study examines the current trends in rainfall, streamflow and catchment yield for the Goulburn River and some major tributaries and seeks to disentangle those trends from changes caused by land use change due to mining and agriculture. Trends in stream salinity and salt loads, and catchment salt yields are also analysed. In addition, groundwater contributions to a significant groundwater-dependent ecosystem, adjacent to a mine site and the salt yield of a wholly agricultural tributary are investigated.

1.5 *Hypothesis, aims and key questions*

The central hypotheses examined in this thesis are

- 1) *The impacts of natural processes, land use change, and changing climate on stream discharge and salinity can be separately identified in highly variable catchments with multiple land uses.*
- 2) *Regulations can significantly alter stream salinity in catchments with existing natural salinity.*

1.5.1 Aim and Objectives

The overall aim of this work is to assess the impacts of changing land use on trends in stream flow, catchment yield, surface and groundwater interaction, and stream salinity in the Goulburn River system, and to separate them from the impacts of climate change, natural climate variability and regulatory changes. To accomplish this, the work has the following objectives:

1. Assess the region's climatic characteristics, rainfall variability and trends and their influence on catchment yield and trends in catchment yield (*Chapter 4*)
2. Investigate at catchment scale: the sources, drivers and trends in stream salinity and salt loads (*Chapter 5*).
3. Quantify the impacts of mining discharge on flow and salinity in the upper Goulburn (*Chapter 6*).
4. Identify and characterise the dominant hydrogeological systems in the upper Goulburn catchment contributing to river baseflow and surface-groundwater interaction (*Chapter 7, 8 & 9*)
5. Investigate stream discharge and salinity, and surface-groundwater interactions of the main predominantly cleared, agricultural sub-catchment of the Goulburn River (*Chapter 8*).
6. Identify groundwater sources feeding an important groundwater-dependent ecosystem (GDE) in the upper Goulburn and investigate potential impacts of

groundwater extraction and aquifer depressurisation due to an approved, future mine development on the GDE and river baseflow (*Chapter 9*).

7. Summarise the main findings of this work, identify areas for future research and suggest options to improve the sustainable management and use of water resources under changing climate and land use (*Chapter 10*).

1.6 **Key questions:**

1. *What is the influence of climate variability on catchment yield and water quality?*
2. *How is land use change affecting catchment yield and water quality in the Goulburn River?*
3. *What are the hydrochemical characteristics of the fractured and porous rock groundwater systems in the Goulburn catchment and their influence on water quality and stream flow?*
4. *What effect is coal mine discharge on downstream flows and salinity in the upper Goulburn River?*

1.7 **Thesis outline**

Chapter 1: Introduction

This chapter introduces the main themes and principal concepts examined in this thesis, and reasons for selecting this area of study. It provides the central hypotheses, aims and key questions to be addressed by this thesis.

Chapter 2: Climate, land use and water quality

The development of soundly-based catchment water plans relies on information on water availability and the impacts of changing climate, trends in water use and trends in water quality. In this chapter information on trends in climate in south eastern Australia are reviewed. The projections of global climate models on future changes to climate and implications for hydrology in the region are discussed as well as the differing theories on salt production in catchments from export of evapotranspiration concentrated meteoric salts, to mineral weathering. In addition, methods of determining groundwater recharge, discharge and baseflow and disentangling climate variability, climate change and land use change at the catchment scale are considered. Previous research investigating the hydrochemical signatures of surface and groundwater in the upper Hunter Valley NSW are reviewed. Groundwater dependent ecosystems and their role in surface-groundwater interaction are also discussed.

Chapter 3: The Goulburn River catchment

The Goulburn River catchment chosen for analysis is described in this chapter. Its geography, geomorphology, climate, vegetation, current land uses, geology, hydrogeology and salinity sources are considered and the results of previous research discussed. Current

government policy legislation and regulations relating to licensed water extraction and water sharing plans relevant to the study area are also summarised.

Chapter 4: Changing climate and catchment yield

The aim of this chapter is to assess the region's climatic characteristics, rainfall variability and trends and their influence on catchment yield and trends in catchment yield. This chapter examines the prevailing climate, stream discharge and catchment yield of the Goulburn catchment using data from 1920 to 2014. In order to investigate long term changes monthly or annual data is used. Spatially interpolated monthly rainfall data is analysed to examine mean behaviour, variability and temporal trends in precipitation as well as identifying catchment-wide extreme dry periods. Because of the limited reliable data, pan evaporation trends since 1970 are analysed. The response of the Goulburn River to climate drivers and long term changes are explored.

Chapter 5: Stream salinity

The aim of this chapter is to investigate at the catchment-scale the sources, drivers and trends in stream salinity and salt loads using spot measurements and analysis of available government and industry data supplemented with surface and groundwater sampling. Electrical conductivity (EC) is used as a general surrogate for salinity.

Stream salinity and site information collected from longitudinal field surveys and sampling of the Goulburn River and major tributaries are used to identify the potential source of saline inputs. There is limited salinity data prior to the commencement of mining in the catchment. What is available is analysed in an attempt to identify trends.

The relatively short records of continuously monitored electrical conductivity (EC) between 2012 and 2016 in the Goulburn catchment are used to look the spatial distribution of salt loads and specific salt yields in the catchment. The intimate relationships between salt load and discharge at gauging sites are evaluated.

Chapters 6: Mining impacts on the upper Goulburn

The aim of this chapter is to quantify the impacts of mining discharge on flow and salinity in the upper Goulburn. The influence of mine water discharge on downstream salinity and salt load between 2012 and 2016 are assessed and compared to pre-mining archival stream data. The interception and extraction of surface and groundwater by mining are described and quantified. This Chapter relies on industry reported data, supplemented by departmental monitoring data and measurements carried out in this work.

Chapters 6: Hydrochemistry: surface-groundwater interaction

The aim of this chapter is to identify and characterise the dominant hydrogeological systems in the upper Goulburn catchment contributing to river baseflow. Both the regulations underpinning the HRSTS and the analyses to date in this work have regarded salt generically,

represented by EC, in this chapter examination of the major ion chemistry making up that salt is undertaken to explore contributions from different geologies in the catchment.

Wide spread sampling of the chemical characteristics of water samples from accessible river reaches, springs, seeps and bores in the Goulburn catchment was undertaken and results combined with available industry and online government monitoring data. Site location, elevation and hydrochemical characteristics of surface and groundwater samples are statistically analysed and grouped accordingly into general water types. This is used to infer the source or parent hydrogeological unit and probable connectivity between surface and groundwater sources in the Goulburn catchment.

The following chapters cover two case studies targeting the Merriwa River sub-catchment and The Drip gorge GDE, Upper Goulburn River.

Chapter 7: Merriwa River, an agricultural tributary

The aim of this chapter is to investigate the catchment yield, salinity, and surface-groundwater interactions of a major, agricultural sub-catchment of the Goulburn River and its sensitivity to future land use change. The Merriwa catchment is identified as a significant source of salinity in the Goulburn River with no history of coal mining. Changes in downstream surface water chemistry relative to the catchment's three dominant geologies are examined. The results are used to estimate the catchment contribution of salts to the lower Goulburn River. Key groundwater sources are also characterised and their interaction with surface river water chemistry is examined.

Chapter 8: The Drip Gorge GDE - window into groundwater

The aims of this chapter are to identify sources of groundwater feeding an important groundwater-dependent ecosystem (GDE) in the upper Goulburn and to investigate the impact of groundwater extraction and aquifer depressurisation due to current and planned mining on the GDE and river baseflow.

Chapter 9: Conclusion and Recommendations

This chapter summarises the main findings of this work and provides recommendations on options for future management and research.

Chapter 2: Climate, land use and water quality review

The development of soundly-based catchment water plans relies on information on water availability and the impacts of changing climate, trends in water use and trends in water quality. In this chapter information on trends in climate in south eastern Australia are reviewed. The projections of global climate models on future changes to climate and implications for hydrology in the region are discussed as well as the differing theories on salt production in catchments from export of evapotranspiration concentrated salts of meteoric origin to mineral weathering. In addition, methods of determining groundwater recharge, discharge and baseflow and disentangling climate variability, climate change and land use change at the catchment scale are considered. Previous research investigating the hydrochemical signatures of surface and groundwater in the upper Hunter Valley NSW are reviewed. Groundwater dependent ecosystems and their role in surface-groundwater interaction are also discussed.

2.1 *Climate change ocean-atmosphere interaction and rainfall variability*

The climate in south eastern Australia is in a process of change. There has been a doubling in the annual number of record hot days across Australia since 1960 with heatwaves becoming hotter, starting earlier in the season and lasting longer (Steffen, 2015). Seven of Australia's ten warmest years on record have occurred since 2005, including 2013, 2014, 2015 and 2016; with 2018 being the warmest year on record in NSW, and third warmest for Australia (BoM, 2018b). Eastern Australia is experiencing warming across all seasons with a mean temperature rise of around 0.9 ° Celsius since 1910. During the summer of 2012-13 Australia experienced the longest and most spatially extensive heatwave along with the hottest month, hottest week and hottest day on record (CSIRO, 2015; BoM, 2018b).

Rainfall in Australia is characterised by seasonal, interannual, and multidecadal variability with substantial impacts from El Niño-Southern Oscillation (ENSO), Interdecadal Pacific Oscillation (IPO) and India Ocean dipole (IOD) (CSIRO, 2015; Gallant *et al.*, 2012; Risbey *et al.*, 2013; Verdon-Kidd *et al.*, 2014; CSIRO, 2012). Modelling projections for mean annual rainfall change in eastern Australia indicate a wide range of scenarios - from a substantial decrease in annual rainfall to a substantial increase. Generally south-eastern Australia is expected to experience decreasing winter and spring rainfall and more frequent intense hot days with increasing evapotranspiration driving harsher fire-weather and more extreme rainfall events. The average number of temperature days above 35° is predicted to increase by a factor of two to three times before end of the century (Steffen *et al.*, 2014; CSIRO, 2015). The projected increases in evapotranspiration, however, contrast with observed global decreases in

pan evaporation observed over the past 50 years and attributed to increases in cloudiness and aerosol concentrations (Roderick and Farquhar, 2002).

The report into Climate Change in Australia (CSIRO, 2015) places the Hunter Valley within the Eastern Australia Super-cluster climate zone and NRM East Coast (south) cluster (Figure 2:1) in an ecoregion dominated by temperate mixed forests and woodlands. The Goulburn River catchment extends to the central slopes cluster and so is influenced by both inland and coastal climatic factors. A mid-latitude position exposes the region to fluctuations in the latitudinal position of the subtropical high-pressure ridge.

Seasonal rainfall characteristics are determined by complex interactions of rain-bearing systems from the east, southwest and sub-tropical north. Year to year variability is thought to be strongly influenced by the El Niño (and La Niña) Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) while decadal variability is the result of the Interdecadal Pacific Oscillation (IPO) and Pacific Decadal Oscillation (PDO). PDO is a recurring pattern of ocean-atmosphere climate variability over the mid-latitude Pacific Ocean, detected as warm or cool surface waters, north of 20°N. Large scale ocean-atmosphere interactions are linked to both variability and short term trends in rainfall (Krishnan and Sugi, 2003; Power *et al.*, 1998). A positive Southern Annular Mode (SAM) produces lower autumn rainfall due to a reduction in frontal weather systems and may act to block La Niña rainfall (CSIRO, 2012). A positive IOD pattern can strengthen an El Niño influence increasing drying effects across south-eastern Australia (CSIRO, 2015; Verdon-Kidd and Kiem, 2009). Typically the IOD pattern starts around June and breaks down about November with the occurrence of the sub-tropical north monsoon.

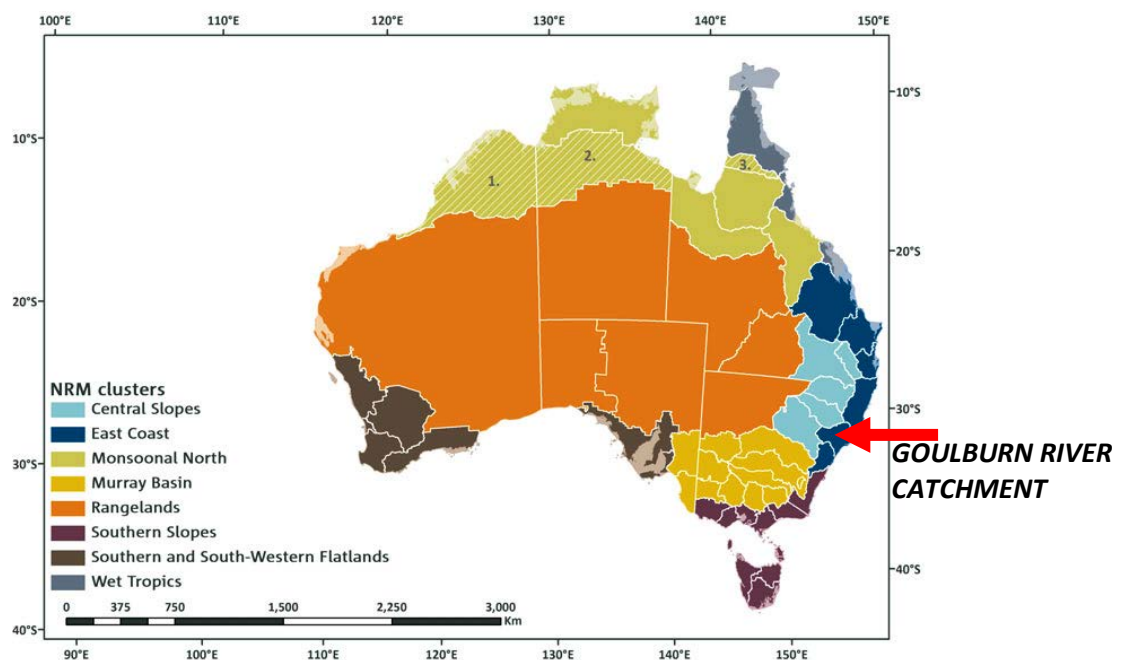


Figure 2:1 NRM regions – from Climate Change in Australia (CSIRO, 2015)

While changes in rainfall trends across southern Australia have broad similarities there are clear differences between subregions. Bureau of Meteorology maps (BoM, 2017) show an increase in annual rainfall since 1910 in the general area of the Goulburn River catchment, particularly for the warm summer season December – February (Figure 2:2, Figure 2:3). Climate trend maps for 1970-2016 show an increasing rainfall trend in the coastal region with a decreasing trend inland from the coast, bisecting the Goulburn River catchment (Figure 2:4).

The Federation (~1885-1902), World War II (~1937-1945) and the Millennium drought (~1997-2007) are considered the three most protracted droughts in southeast Australia. However they exhibited very dissimilar spatial signatures, severity and seasonal rainfall make up with each drought driven by a different combination of climate processes related to the Pacific, Indian and Southern Oceans (Verdon-Kidd and Kiem, 2009). BoM rainfall records for the Goulburn River catchment indicate the drought years 1982-83, 1993-94, 2001-2, and 2005-6 coincide with periods when a positive IOD was in phase with El Niño. The short but intense 1982-1983 drought, considered the worst on record for lack of short-term rainfall occurred when El Nino, IOD, IPO, Southern Angular Mode (SAM) were all in a positive dry phase (Verdon-Kidd and Kiem, 2009). The 1982-83 drought was also associated with a dramatic shift in the position of the South Pacific Convergence Zone (Cai *et al.*, 2012). Similar El Nino Southern Oscillation and Inter-decadal Pacific Oscillation events influencing climate variability have been observed in the Murray-Darling Basin (Rancic *et al.*, 2009)

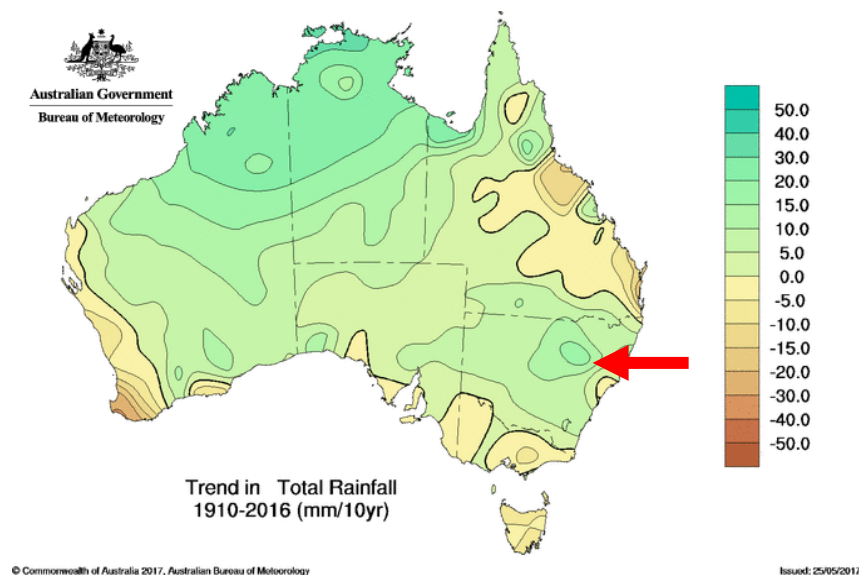


Figure 2:2 Trend in Australian annual rainfall 1910-2016
(red arrow indicates location of Goulburn catchment)

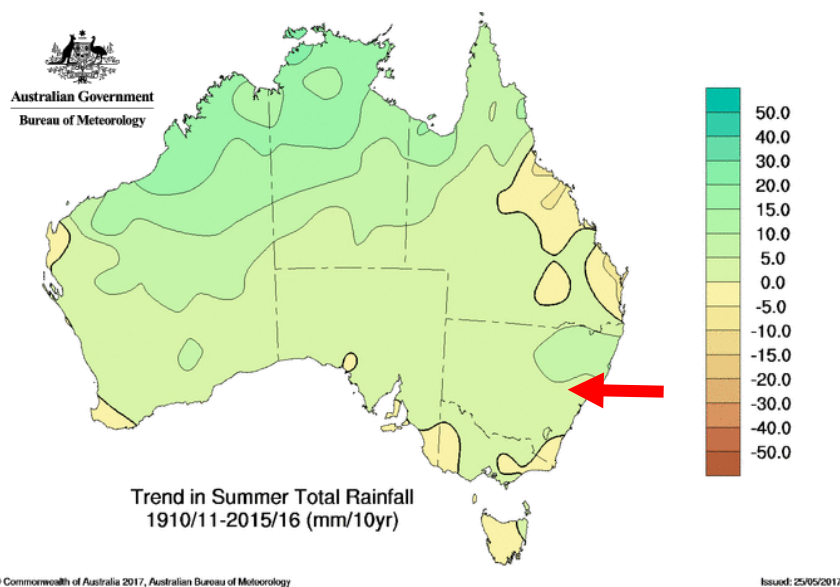


Figure 2:3 Trend in Australian summer (Dec-Feb) rainfall 1910-2016

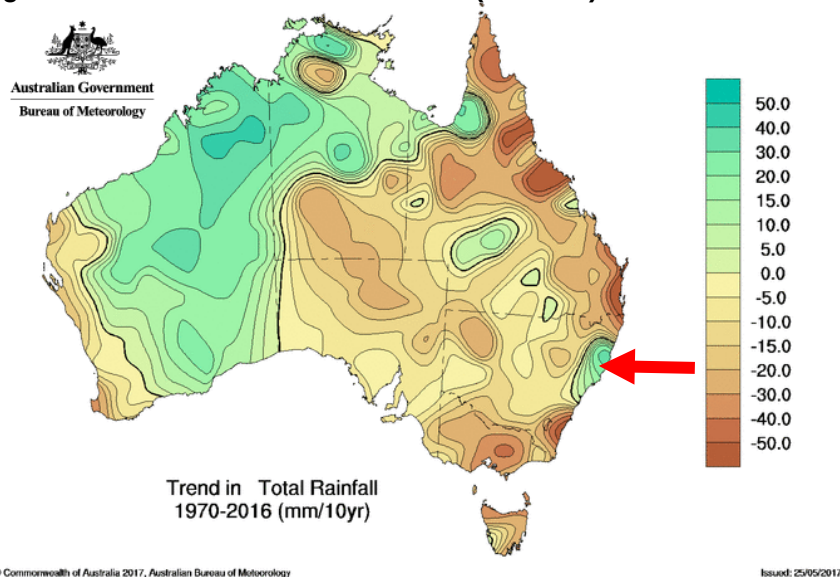
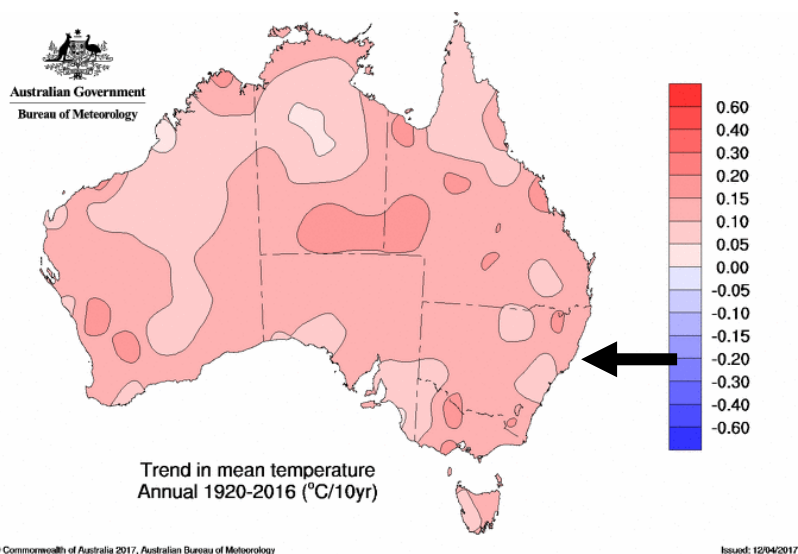


Figure 2:4 Trend in Australian annual rainfall 1970-2016



**Figure 2:5 Trend in annual mean temperature 1920-2016
(black arrow indicates Goulburn catchment)**

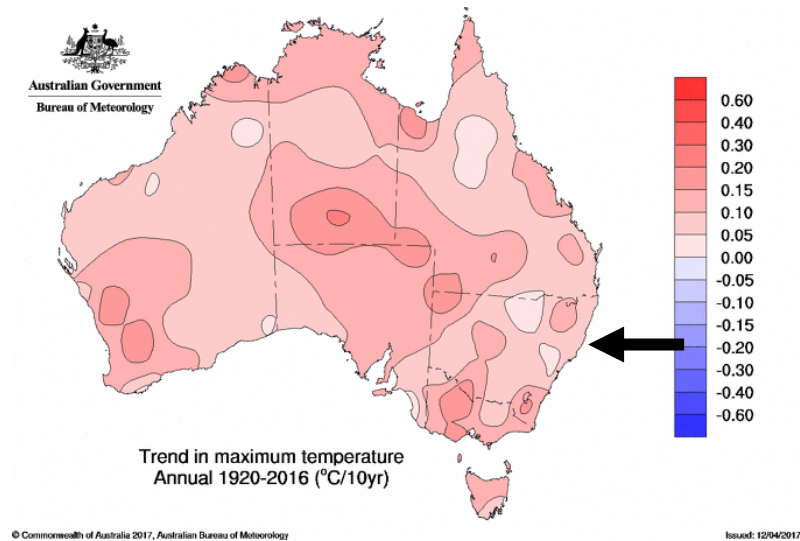


Figure 2:6 Trend in maximum temperature 1920-2016

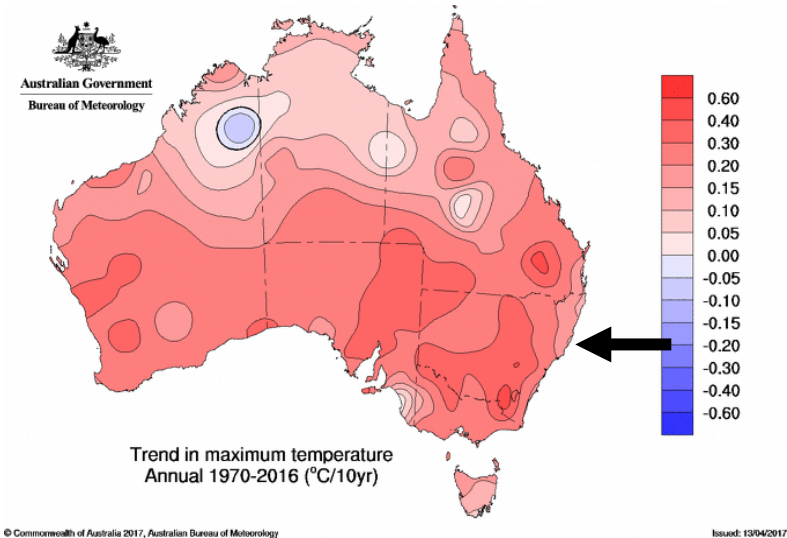


Figure 2:7 Trend in maximum temperature 1970-2016

The Pacific Decadal Oscillation is known to influence long-term trends in rainfall in eastern Australia and elsewhere (Mantua and Hare, 2002). Figure 2:8 shows the 29-point moving average of the annual, warmer and cooler season averages of the PDO index. Positive values of the PDO are associated with lower rainfall periods while negative values are associated with higher rainfall in eastern Australia.

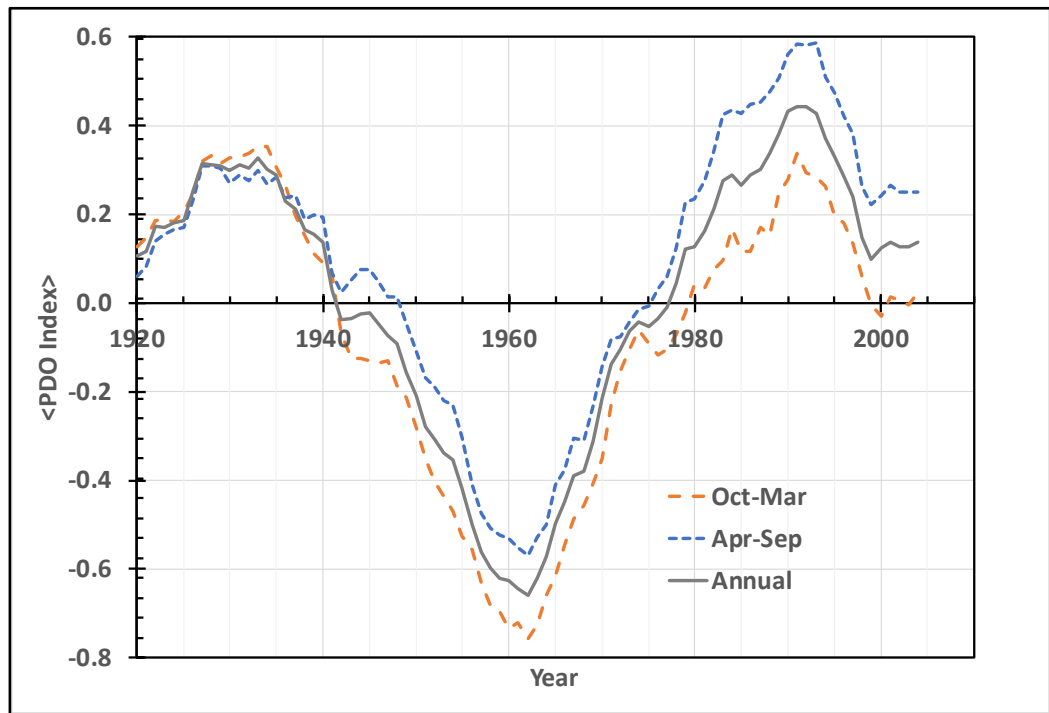


Figure 2:8 Comparison of the 29-point running average PDO Index for annual and seasonal October to March and April to September (six monthly) averages of the Pacific Decadal Oscillation Index

Powerful east coast lows have resulted in some of the most extreme rain events experienced across the Hunter catchment (Pook *et al.*, 2013). An example was the intense extra-tropical low pressure system on the 7-8 June 2007 that occurred off the central New South Wales coast near Newcastle, previous similar events occurred in 1950 and 1974 (Mills *et al.*, 2010; Verdon-Kidd *et al.*, 2010) and most recently in 2016. BoM records since the 1970s, and even more so since 2010, point toward high intensity extreme rainfall episodes with an increase in heavy one-day rainfall events (greater than 0.9 percentile for 24 hour rainfall). This has been accompanied with a statistically significant rise of $0.5 - 1^{\circ}$ Celsius in the average temperature in the general region (Figure 2:5) (HCCREMS, 2010). The recent period from 1970 shows the greatest rise in the maximum temperature of 0.2 to 0.25°C per decade in the Goulburn catchment (Figure 2:7).

Changes over time are highly dependent on the period of analysis, indices and thresholds being monitored; with the extent of influence due to natural variability being difficult to discern.

One potential effect of recent decreasing winter rainfall and lower soil moisture levels in the warmer months is a reduction in surface runoff, aquifer recharge, stream discharge and resulting catchment yields. Declining groundwater levels reduce aquifer discharge and thus baseflows in creeks and rivers. Climate predictions suggest future catchment runoff is strongly influenced by rainfall with a percentage fall in annual rainfall reducing annual runoff by a factor of 2-3 times (Chiew *et al.*, 2006). A one degree temperature rise can reduce annual runoff by 2-5% (although some studies report bigger reductions) (Chiew, 2006; Cai and Cowan, 2008;

Potter *et al.*, 2008; CSIRO, 2015). Dwindling and increasingly unreliable water resources threaten biodiversity, particularly highly cleared and fragmented forests, woodlands and sensitive groundwater dependent ecosystems (GDEs). Regionally significant agricultural industries such as viticulture and intensive livestock are adversely affected by temperature extremes and restricted water use (HCCREMS, 2010). The potential impact of changing climate on stream salinity appears not to have been explored. Decreased surface runoff could lead to less dilution of the saline groundwater discharge to rivers, increasing salinity. Conversely lower recharge to groundwater could decrease groundwater levels decreasing groundwater discharge to streams (Winter, 2001).

Pan evaporation (Epan) is affected by the transmission of solar radiation through the atmosphere which can be attenuated by increasing cloudiness, aerosols, and dust (Roderick *et al.*, 2014). It has been suggested that a rise in temperature may increase evaporation however observations in Australia 1975-2004 indicate an overall decrease in measured Epan. This fall in evaporation rates is related to decreasing winds or global ‘stilling’ (Roderick and Farquhar, 2002; Roderick *et al.*, 2007) or decreasing solar radiation global “dimming”. Whether the cause of the ‘stilling’ was due to local effects (e.g. more tree cover) or regional phenomena is unclear though widespread nature of the stilling suggests a more robust regional effect due perhaps to slowing in the overall circulation rate that is predicted in some climate models (Roderick *et al.*, 2007).

Long term, large swings in flood and drought-dominated regimes in south-eastern Australia were identified by Erskine and Warner (1988) in catchments in the Hunter. These periods correspond to negative and positive phases of the PDO. Underestimating the effect of spatial rainfall variability on stream flow has been shown to decrease the accuracy of water balance modelling (Zhao *et al.*, 2013).

There are currently 23 climate stations recording rainfall in the Goulburn catchment, the oldest recording dates back to 1870 at Cassilis (062005). The spatial distribution of these stations does not reflect the natural variability in topography and influence of orographic rainfall. Only two stations are situated above 550 metres, Nullo Mountain (06210) in the south and Mount Palmer in the north. Records for these stations only commenced in 1994 and 2010 respectively. Access to spatially interpolated rainfall statistics for the upper and lower Goulburn and Merriwa catchments tied to a grid digital elevation model will be necessary to overcome spatial limitations and gaps in the climate data.

2.2 *Coping with spatial variability of rainfall*

In examining the response of a whole catchment to temporally variable and changing climate a method has to be used which copes with the spatial variability of rainfall and to a lesser extent evaporation across a catchment of greater than 6,000 km². This study concentrates

on monthly data to reduce spatial variability. Hutchinson (1995) developed a spatial interpolation method based on point rainfall records that incorporates the impact of elevation, particularly important in remote high elevation areas that are often poorly sampled by rain gauges. The incorporation of a suitably scaled elevation dependence can reduce bias towards the lower rainfalls commonly recorded at lower elevations. A grid of interpolated rainfall values over the catchment using elevation dependent thin plate spline surfaces is fitted to Bureau of Meteorology monthly precipitation data using the ANUSPLIN 4.4 package ([Hutchinson and Xu, 2013](#)) and a regular grid digital elevation model (DEM) with resolution of around one square km ([Hutchinson *et al.*, 2014](#)).

2.3 Long-term meteorological and hydrological droughts

Meteorological drought has been defined as an acute water shortage due to lack of rainfall over one or more seasons resulting in a water shortage for key water users and sectors (CSIRO, 2015; Gibbs, 1975). Since European settlement droughts have been a major challenge to agriculture and water management in Australia ([Verdon *et al.*, 2004](#)). A method that allows the comparison of drought conditions relevant to agriculture, groundwater systems and major water storage reservoirs was developed by Gibbs and Maher (1967). This is a non-parametric method based on rainfall deciles or percentiles that does not require the transformation of data to normal distributions. By varying the period of rainfall summed it can be used as drought indicator for comparing rainfall conditions relevant to different water management issues ([White *et al.*, 1999](#); [Smith *et al.*, 1992](#)). To examine changes in long-term meteorological and hydrological droughts in the Goulburn catchment, percentiles for monthly precipitation and stream discharge were summed over running 5-year, 10-year and one year periods. The longer time periods allow for the Goulburn River's extensive groundwater systems and the decadal long flood- and drought-dominated periods experienced in eastern Australia ([Erskine and Warner, 1988](#); [Erskine and Warner, 1998](#)). Stream discharge or rainfall totals that fall below a percentile of 0.3 are classed as below average, those falling below a percentile of 0.1 as very much below average and a percentile of zero is the lowest on record ([Gibbs, 1975](#))(Table 2:1).

Table 2:1 The BoM Percentile classification scheme of rainfall or stream discharge

Decile	Percentile Range	Rainfall Classification
	1	Highest of record
10	0.9 to <1.0	Very much above average
8	>0.7 to <0.9	Above average
4	>0.3 to <0.7	Average
2	>0.1 to <0.3	Below average
1	>0 to <0.1	Very much below average
	0	Lowest on record

2.4 Precipitation elasticity of river discharge

The concept of precipitation elasticity of river discharge was introduced in hydrology as a measure of the sensitivity of stream discharge to changes in climate (Schaafe, 1990). The precipitation elasticity, ε_Q , of Q is the ratio of the proportional change of Q to the proportional change in P (Sankarasubramanian *et al.*, 2001).

$$\varepsilon_Q = \frac{\partial Q}{\partial P} \cdot \frac{P}{Q} \quad [2:1]$$

The dependence of ε_Q on spatially varying climates has been a focus of study where the humidity index, Φ , of catchments has been used as a gross measure of influence of geographically distributed climates on ε_Q . Here $\Phi = \mu_P / \mu_{PET}$, with μ_P and μ_{PET} the mean precipitation and mean potential evapotranspiration, PET. To a first approximation, it is assumed $PET = 0.7 \cdot E_{pan}$ for annual E_{pan} (Linacre, 1993). For drier regions where $\Phi < 1$, generally $\varepsilon_P > 2.5$ while for wetter regions where $\Phi > 2$, or those with significant snowpacks, $\varepsilon_P \rightarrow 1$ (Sankarasubramanian *et al.*, 2001; Chiew, 2006). For discrete discharge data, a nonparametric form of equation [2.1] has been used to estimate ε_Q (Sankarasubramanian *et al.*, 2001):

$$\varepsilon_Q = \text{median} \left(\frac{Q - \mu_Q}{P - \mu_P} \cdot \frac{\mu_P}{\mu_Q} \right) \quad [2:2]$$

where μ_P and μ_Q are the long term means of precipitation and discharge. Equation [2.2] has been used in addition to hydrological discharge models to estimate the precipitation elasticity of stream flows in Australia (Chiew, 2006)

Equation [2.1] can be rewritten as:

$$\varepsilon_Q = \frac{\partial \ln Q}{\partial \ln P} \quad [2:3]$$

which permits an alternate, nonparametric estimate of elasticity for discrete data:

$$\varepsilon_Q = \text{median} \left(\frac{\ln Q - \mu_{\ln Q}}{\ln P - \mu_{\ln P}} \right) \quad [2:4]$$

where $\mu_{\ln Q}$ and $\mu_{\ln P}$ are the long-term means of the log transformed variables. Problems arise with equation [2.4] when $P = 0$ and, for that reason, equation [2.4] is applied here to annual average precipitation and discharge data over 20-year running periods.

The most common use of precipitation elasticity of stream discharge has been to explore geographic or climatic influences on stream discharge or for elucidating the influence of climate change on stream discharge (Nash and Gleick, 1991; Dooge, 1992; Sankarasubramanian *et al.*, 2001; Chiew, 2006). It has been recognised, however, that land use change can also influence elasticity of discharge (Dooge, 1992). This could include groundwater extractions from connected systems or alternatively regular mine water discharges.

2.5 Differing models of salinity and land use

Rising salinity levels in streams have long been recognised as a major environmental and water management issue in the Murray-Darling Basin (White *et al.*, 2009; Morton and Cunningham, 1985; Collett, 1978). Models using the ratio of chloride inputs estimated in catchment rainfall, to stream outputs in the lower river revealed that subsurface stores of salt were being mobilised in the catchment (Simpson and Herczeg, 1994; Blackburn and McLeod, 1983). Dryland salinity was identified by Jolly *et al.* (2001) as a significant contributor to increasing stream salinities in catchments draining the slopes of the Great Dividing Range. Jolly *et al.* (2001) using a salt balance model compared the input of airborne oceanic salt aerosols (cyclic salts) deposited in rainfall to an estimate of salt load exported by streams. Marine based aeolian salt deposits were assumed to be the main salt source embodied in groundwater and a key driver in dry-land salinity. This is where stored salts of meteoric origin that have been evapo-concentrated in soils over time are discharged into the catchment as a consequence of land use change. In this model the clearing of deep rooted vegetation and planting of shallow rooted annual crops leads to increase in recharge and a rise in groundwater pressures, mobilising and subsequently discharging stored salts embodied in groundwater onto the surface and into waterways (Alison and Hughes, 1983).

The National Salinity Audit applied this catchment salt balances model using assumed rates of groundwater rise and estimates for stream salt load output/input ratios. (Beale *et al.*, 2000; Murray-Darling Basin Ministerial Council, 1999). The results predicted a disturbing rate of land and river salinisation over the next century. However problems emerged with the methodology in relatively undisturbed, higher rainfall catchments. Salt output/input ratios were shown to be considerably greater than the equilibrium value of one (White *et al.*, 2009; Jolly *et al.*, 2001). An alternate hypothesis for the origin of salts was put forward by Gunn and Richardson (1979) (Gunn, 1985). Salts derived from deeply weathered Palaeozoic rocks, not cyclic marine salts of meteoric origin, were identified as the main source of saline groundwater in the southern tablelands, NSW. The assumption that the origin of salt stores and increasing

stream salinities was due to rainfall-deposited cyclic salts of marine-aerosol origin, concentrated by evapotranspiration required a reassessment (White *et al.*, 2009). Mineral weathering as a result of water–rock interactions including acid induced weathering of carbonates in the regolith was identified an equally important source contributing dissolved solutes to stream salt loads as those from cyclic salt (White *et al.*, 2009).

2.6 ***Hydrochemistry and groundwater signatures***

The composition of natural waters are the nett result of chemical dissolution, alteration and precipitation of geological and organic material influenced by biological and physical processes (Hem, 1989; Brunke and Gonser, 1997). The ratios of major ions concentrations in water provide a hydrochemical signature that can be used to investigate the interaction and connectivity of surface and groundwater sources. Analysis of the major ions of regional hydrogeological units in combination with the relative elevation of the groundwater systems allows the characterisation and grouping of aquifers that can be used to establish possible connections between water sources, discharge points and flow lines .

Previous research into the chemical signatures of ground and surface water in the upper Hunter Valley NSW indicated a strong influence of geology on water chemistry (Kellett *et al.*, 1989; Biswas, 2010; Jasonsmith, 2011; Somerville *et al.*, 2006; Golab *et al.*, 2006). Groundwater flow systems can vary in scale from localised to regional (Tóth, 1970; Sophocleous, 2002) and fracture networks play an important role in transferring water and pressure through the earth (Ward and Kelly, 2013).

Cation and anion ratios and multivariate statistical analysis of surface and groundwater samples have been used to indicate active hydrological processes and to group water sources with similar chemical signature within a catchment area. Ionic ratios such as the ratio of HCO_3^- : Cl may differentiate water emanating from saline groundwater intrusion, aeolian deposition of cyclic salts or weathered igneous rocks. Kellett *et al.* (1989) identified eight major geochemical groundwater provinces in the upper Hunter Valley based on 684 surface and groundwater samples – 340 collected during drought conditions when groundwater would have been the dominant factor as baseflow. The geochemical major ionic constituents of provinces applicable to the Goulburn catchment were Na, Mg, Cl for the Triassic (TRIAS) Narrabeen Group; for Wollombi (WO) – Na, Mg, Cl, HCO_3^- and for Upper Wittingham Coal Measures (W11) – Na, Cl, HCO_3^- . Mackie (2009) researching the hydrogeological characterisation of coal measures and impacts on groundwater in the upper Hunter Valley, attempted to group groundwater hydrochemical provinces. The results varied from Kellett *et al.* (1989). Mackie questioned the belief that regional groundwater qualities can be grouped into ‘provinces’ that reflect stratigraphy considering the immense complexity and time dependent interaction and mixing of flow systems in the upper Hunter region.

Kellett *et al.* (1989) analysis of the hydrochemistry of stream flows in the upper Hunter system revealed a longitudinal variation in the concentration of ‘conservative ions’ that suggested interaction between baseflow and groundwater. Their study indicated that saline groundwater upwelling, was caused by structural discontinuities associated with the Hunter Thrust Fault. Signs of deep aquifer upwelling were also apparent in the baseflow chemistry of other tributaries. They found an increasing trend in concentration of Cl^- , Na^+ and SO_4^{2-} downstream from where streams crossed faults lines and discontinuities in geology.

A study by Green *et al.* (2010) in the Sydney Basin developed a model of the aquifer framework of multilayered Triassic Hawkesbury sandstone porous rock aquifers. Their assessment indicated shallow and intermediate aquifers were critical to springs, groundwater-dependent ecosystems (GDEs) and stream baseflow particularly in upper plateau riverine areas. The Hawkesbury sandstones were predominantly medium to coarse grained with secondary porosity characteristics evident in the deeper intermediate aquifers due to structural movements and faulting. The hydrogeochemistry of the shallow groundwater systems was generally NaCl type with pH increasing with depth (from 4.6 to 5.8). The presence of HCO_3^- , Mg and ferrous iron indicated increasing water-rock interaction. The deepest intermediate aquifers tending towards CaHCO_3 type groundwater signature. Stable water isotopes for the shallower groundwater indicated a modern post-1950 recharge and dominantly meteoric origin.

Macdonald *et al.* (2009b) geochemical survey of Wollombi Brook investigated the relationship between surface and groundwater and the floodplain aquifer. This catchment, with its mixture of National Park, agriculture, and coal mines is part of the upper Hunter and has many similarities to the southern tributaries of the Goulburn. The stream drains from incised Triassic Narrabeen Group sandstones with Permian sediments exposed on the valley floor along with infill from Quaternary floodplain deposit. The geochemical and isotopic data indicated groundwater interactions between the Permian and unconfined alluvial aquifers in the lower reaches (elevated sodium ions) while Triassic aquifers provided much lower salinity inputs as baseflows in the upper catchment. The report concluded that Wollombi Brook is a highly connected stream whose quality and quantity are influenced significantly by groundwater discharges.

2.7 ***Environmental tracers***

2.7.1 **Conservative ions**

Chloride ion has been regarded as the ideal ion to use as a conservative tracer in the Hunter system and assumed to be a cyclic salt of meteoric and marine origin (Kellett *et al.*, 1989; White *et al.*, 2009; Lamontagne *et al.*, 2003b; Herczeg and Love, 2007). Chloride is not normally absorbed by sediments and it is not normally weathered from a rock host although an increase of chloride levels in stream water may indicate input from the dissolution of evaporite sedimentary

rocks (Hem, 1989). A NaCl molar ratio greater than one can indicate sodium released from silicate weathering (Meybeck, 1987) in (McNeil *et al.*, 2005). Chloride is used as a tracer in mass balance calculations concerning the proportional mixing of surface water and groundwater. The concentration of chloride in river water and groundwater (as a component of baseflow), together with the rate of river flow has been used to determine the rate of baseflow discharge to the stream using a simple mass balance (Richardson *et al.*, 2011b; Macdonald *et al.*, 2009a; Herczeg and Love, 2007; White *et al.*, 2009).

While sulfate (SO_4^{2-}) can behave as a conservative ion, Kellett *et al.* (1989) did not regard it as a conservative element because of its tendency to be absorbed down the flow line through forming ion pairs and surface adsorption on aluminosilicate gels. Residual sulfate concentrations can be due to a combination of flushing, oxidation of sulfates, and dissolution of sulfate minerals minus sulfate reduction, adsorption and precipitation (Hem, 1989). Bicarbonate ions are contributed to groundwater via mineral dissolution and their concentration can be an indicator of the time span after recharge (Golab *et al.*, 2006). Carbonate minerals normally precipitate from groundwater before reaching the surface resulting in the concentration of Na^+ , Cl^- and SO_4^{2-} in groundwater in the upper alluvial/unsaturated zone (Kellett *et al.*, 1989; Hem, 1989). These characteristics limit the use of sulfate and carbonate ions as reliable tracers. Elevated levels of metals and sulfates from pyrite oxidation have also been used as indicators of groundwater or mine water discharge from disturbed Permian coal measures. (McNally and Evans, 2007; Mackie, 2009; NSW Department of Planning, 2005; Sracek *et al.*, 2010).

2.7.2 Ion ratios as hydrochemical indicators

Analysis of major ions in surface and groundwater provides important information on the source of solutes and whether contributions come from mineral weathering or cyclic salts of meteoric or marine-aerosol origin (White *et al.*, 2009; McNeil *et al.*, 2005; Herczeg *et al.*, 2001). Relationships between the anion HCO_3^- and major cations, Ca, Mg and Na are indicative of the mineral weathering and dissolution of a silicate dominated Tertiary basalt host (Biswas, 2010; Jasonsmith, 2011). Biswas (2010) found that in the Wybong catchment basalt-sandstone fractured rock aquifers in the upper catchment were HCO_3^- dominated, and water samples with elevated HCO_3^-/Cl , $(\text{Ca}+\text{Mg})/(\text{Cl})$ and $(\text{Na}+\text{K})/(\text{Cl})$ were due to mineral weathering. That is when groundwater ratios are compared to rainwater and sea water ratios, levels > 1 supported the likelihood that mineral weathering was contributing solute to the stream sample water rather coming from meteoric aeolian accumulation or marine evaporite stores. A transition in the ion signature from bicarbonate dominance to chloride, along a mixing line coincided with increasing downstream salinity. This reflected basalt weathering in the upper Wybong catchment and marine origin groundwater discharge in the lower catchment. Further differentiation between the water samples with solutes derived from rainwater as opposed to a

marine origin could be made by plotting these solutes against the reciprocal of chloride ($1/[Cl]$) on the same graph (Biswas, 2010).

2.8 ***Salinity and stream ecology***

Water quality is considered an important determinant of biodiversity for inland waterways, and its degradation can be directly correlated to biodiversity loss (Carr and Rickwood, 2008). Regular monitoring of physical and chemical makeup is essential for the early detection of change so appropriate measures can be implemented to mitigate or avoid a worsening situation (UNEP/CBD, 2002). It is common in Australia to use EC or total dissolved solids (TDS) as an indicator of stream or groundwater salinity, such as in the HRSTS. However there is significant variability in the ionic composition making up TDS in natural surface and groundwater and discharges from industry.

Kefford *et al.* (2013) assessed the effect of salinity on macroinvertebrate in the Hunter Valley and made the interim conclusion that increases in EC from less than 600 to 900 $\mu S/cm$ are likely to cause large scale changes in macroinvertebrate community structure in the upper and mid/lower Hunter River. Farag and Harper (2012) found levels of bicarbonate above 1500 mg/L had a toxic effect on early life-stage fish while common ions in different combinations can be toxic to zooplankton and flathead minnows (*Pimephales promelas*). A major finding by Mount *et al.* (1997) demonstrated that the toxicity of a mixture of salts can equal the additive toxicity of individual salts. Horrigan *et al.* (2005) investigated the relationship between macroinvertebrate taxa and EC in Queensland stream systems. The most dramatic changes in invertebrate communities were observed at relatively low salinities, when EC reached 800-1000 $\mu S/cm$, lower than the 1500 EC generally accepted. The paper refers to findings by Bayley (1969) that monovalent ions (Na & K) were more toxic than divalent (Ca). Importantly, McNeil *et al.* (2005) found higher proportions of sensitive taxa could be found in calcium bicarbonate dominated water than in sodium chloride dominated water under equal salinity levels.

A case study on the risk to aquatic biota from salinity in the Hunter (Muschal, 2006) indicated biota in Hunter tributaries were at greater risk from elevated salinity than those in the Hunter River. The study recommended that in addition to studies examining lethality (capability to cause death) of salt levels to instream biota there should also be a risk assessment of 'multiple stressors', such as river regulation, loss of riparian vegetation, erosion, increased suspended solids and eutrophication, on instream ecological function.

2.9 ***Groundwater recharge and discharge as stream baseflow***

Groundwater recharge is predominantly influenced by climate, soil hydrology and underlying geology, topography and vegetative cover. Only a fraction of rainfall infiltrates

down to the saturated zone. Groundwater recharge can be defined as the volume of water per unit area contributing to aquifer storage over a given period of time (Units LT^{-1}) resulting from diffuse infiltration rainwater and surface water into the water table or underlying aquifer (Herczeg and Love, 2007; Brownbill *et al.*, 2011) and can include seepage from losing streams or stream induced recharge (Berhane, 2014). Because of the wide diversity of coastal landscapes and the inadequacy of detailed studies, NSW DPI Water has set a “default value” in NSW for annual recharge into coastal porous rock aquifers. (Pearse – Hawkins *et al.*, 2015). The accepted estimated recharge rate adopted for the Sydney Basin – North Coast Groundwater Source is 1% for Permian exposed areas 5-7% for Triassic strata, and 6% for exposed basalt (Ross and Webb, 2015; DPI Water, 2016).

Baseflow, groundwater discharge to streams, is particularly important in Australia, as it maintains flows in gaining streams especially during dry times (Arnold *et al.*, 1995; Zhang *et al.*, 2017). Quantifying recharge to groundwater and the baseflow groundwater component in streams present challenges (Crosbie *et al.*, 2015). These challenges are exacerbated by spatial and temporal variations in rainfall patterns and surface flows across catchments. Numerous methods have been applied to measure the baseflow component of streamflow with varying advantages, limitations and levels of accuracy (Zhang *et al.*, 2017). The base flow index for the Goulburn River is estimated to be 0.51 using digital filtering of daily hydrographs. This suggests that more than 50% of river flow is base flow groundwater discharge (McVicar *et al.*, 2015). Some of the methods used to calculate baseflow include:

Hydrograph-baseflow and Recession Analysis which uses time series streamflow records from gauging stations. It separates streamflow into two major components, surface runoff or quick flow and baseflow and it analyses the decay in streamflow using a recession constant. When surface runoff is considered to be negligible, stream discharge is assumed to be baseflow, the groundwater discharge emanating from the catchment upstream of the gauging station. Automated and manual hydrograph baseflow separation and recession analysis can provide an efficient and objective assessment method for assessing low flow characteristics of streams (Arnold *et al.*, 1995). This technique relies on the availability of accurate, long term time series of stream discharge data. There is a general paucity of reliable long term stream gauge records available for the Goulburn catchment, due to the nature of the control structures at gauging sites and limited number of gauging stations (Krogh *et al.*, 2013).

Tracer-based Separation techniques – This technique involves the comparison of groundwater and surface water chemistry using a mass balance approach to estimate downstream changes in water chemistry. Longitudinal variations in streamflow chemistry and tracer concentrations such as electrical conductivity, chlorine mass balance and isotopic ratios, are compared to spatial and temporal trends in groundwater inflows (Kennedy *et al.*, 1986; White *et al.*, 2009). The mass balance equation that applies at any point of time is:

$$Q_g/Q_l = (C - C_r)/(C_g - C_r) \quad [2:5]$$

Where C , C_r and C_g are the tracer concentrations in the river, in runoff and groundwater respectively Q_g = groundwater inflow, and Q_l = total river flow.

Tracer based separation method is considered most accurate at low flows, when rainfall runoff and water extraction are not affecting streamflow measurements. Electrical conductivity is a sensitive tracer when there are large differences in salinity between surface water flows and groundwater but can be affected by ongoing chemical reactions. The chloride ion is assumed to be a conservative tracer so a net increase in chloride is taken to indicate inflows of groundwaters containing higher concentrations (Richardson *et al.*, 2011b; Macdonald *et al.*, 2009a; Herczeg and Love, 2007). Evapotranspiration can also concentrate and increase the concentration of chloride.

Environmental tracer methodology for determining baseflow relies on the ability to accurately identify, sample and differentiate source water chemistry and to measure streamflow and end-member concentrations (CSIRO *et al.*, 2009). It also requires monitoring of precipitation as rainfall events can affect relative proportions of surface runoff and groundwater inflow. The spatial variability of rainfall across the Goulburn catchment and the general paucity of reliable river gauges, as well as intermittent mine water discharge make the use of this method problematic in the Goulburn catchment.

Hydraulic Gradient Analysis is based on Darcy's Law for a saturated medium. Estimating groundwater discharge by a comparison of river and groundwater levels using hydraulic gradient analysis is independent of river flow data and any complications resulting from unmeasured water extraction. Groundwater discharge rates are estimated as a product of head gradient (between aquifer and river water level) multiplied by likely aquifer transmissivity. The quantity of ground-water recharge and discharge flux to and from surface-water bodies can be determined for a known cross section of aquifer by multiplying the hydraulic gradient by the hydraulic conductivity of the aquifer materials. This methodology uses Darcy's flux for groundwater flow. This technique requires detailed knowledge of the dimensions, the hydraulic gradient and hydraulic conductivity of the aquifer resource which are difficult to determine. This method is useful for recharge analysis of specific aquifers but generally unsuitable for extrapolation across a complex hydrogeological landscape. There is very limited spatial and temporal groundwater data available for the Goulburn catchment.

Mass Balance Analysis applied as basic hydrological budget to estimate groundwater recharge that can be extrapolated to approximate catchment wide recharge (Macdonald *et al.*, 2009a). The Mass Balance method for estimating base flow is based on a mass balance of all known inflows to and outflows from a given stream reach, with the equation being solved for groundwater flow into or out of the reach. A positive mass balance indicates a gaining reach (base flow) and a negative balance indicates a losing reach.

Inflow = Outflow $\pm$ change in storage

$$R = P - ET - RO \quad [2:6]$$

Where R = recharge, P = precipitation, ET = evapotranspiration and RO = runoff.

This technique relies on accurate long term streamflow data and in high evaporation areas can produce significant errors particularly when using average annual values. Some recharge may also report to deeper groundwater so is problematic for estimating baseflow.

2.9.1 Numerical groundwater modelling

Numerical models provide a relatively transparent method to explore interactions between key variables influencing complex groundwater systems. Their role is to assess likelihood within uncertainty limits based on reliable data. Models using site-specific inputs and parameters are useful tools for exploring various scenarios and potential outcomes but should not be mistaken as a tool to predict the future (Doherty, 2011).

Groundwater modelling relies on a range of measured and assumed input parameters and boundary conditions. Parameters such as hydraulic conductivity can vary by several orders of magnitude due to the natural complexity of geological strata across a landscape and modeller preference. Numerical groundwater models are primarily calibrated by comparing modelled changes in hydraulic heads, with measured change over a specific time. Once verified using groundwater monitoring data they are used to predict further changes in hydraulic head over different time periods and management conditions. This necessitates a network of piezometers, accurate spatial and temporal data over sufficient length of time to incorporate long time lags inherent in the dynamic response of groundwater to development common in catchment-scale groundwater systems.

The mining industry and governments rely on complex modelling to predict mining impacts on groundwater sources and stream baseflow at various spatial and temporal scales. Calibration of mining impact assessment models is considered by some modellers to be insensitive to changes in recharge values below 10% (Pearse – Hawkins *et al.*, 2015). However small changes can significantly alter recharge volumes for regional water sources. Herczeg and Love (2007) identified recharge rates as critical input to numerical models when developing groundwater management policies over time and space along with predicting the impact of groundwater extraction on head pressures and lagged discharge to streams. Herczeg and Love (2007) highlighted the many uncertainties in numerical modelling and warn against using it to predict recharge citing it as ‘*an inverse approach to back calculate recharge*’.

Mining drawdown and depressurisation of groundwater can change the natural groundwater flow pattern and discharge location. Figure 2:9 compares potential changes in groundwater flow between porous rock, alluvium and surface streams - pre-mining and during mining (Ross and Webb, 2015).

Numerical groundwater modelling simulating long term coal mining impacts in the Ulan Wollar area predicts that it will be over 300 years before regional groundwater level substantially rebound to pre-mining levels (MER, 2015; Middlemis and Fulton, 2011). These numerical models rely on a range of assumptions, boundary conditions and estimated hydraulic conductivities of the main hydrogeological units or strata layers. They involve the adjustment of strata hydraulic properties and regional rainfall recharge rates until a plausible match is achieved between the observed groundwater levels and the predicted groundwater levels at the same location. The mining industry maintain their models can be validated over time by calibrating observed changes to groundwater levels with predicted depressurisation of the strata, and re-adjusting the model when necessary. It is also argued that groundwater modelling cannot be verified and is therefore of dubious value, alternatively it is also said that without some form of modelling it is impossible to foresee the future behaviour of groundwater systems (Barnett *et al.*, 2012).

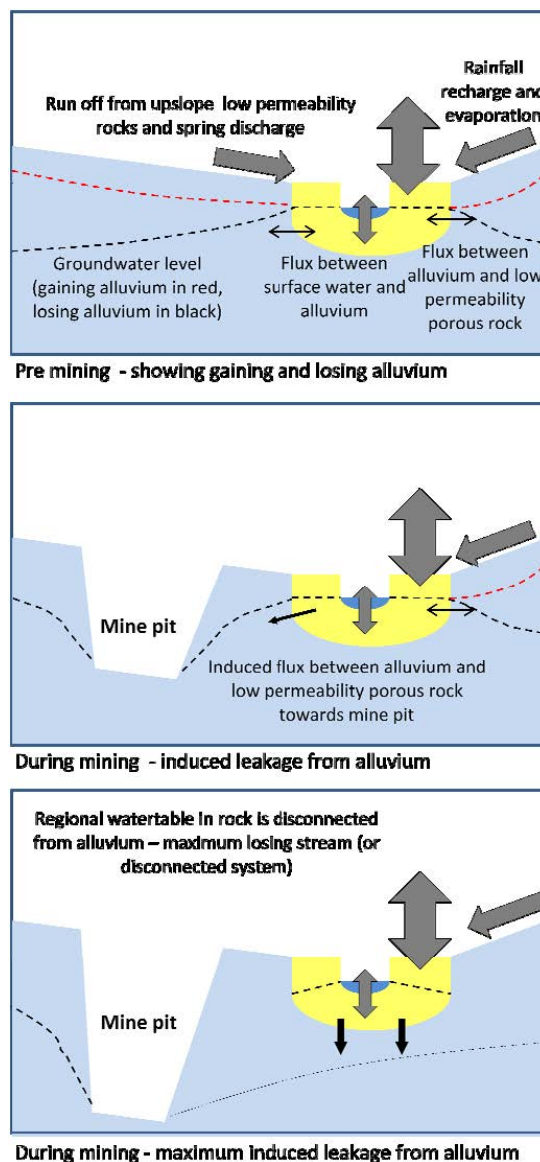


Figure 2:9 Potential groundwater induced leakage and interception due to mining (Ross and Webb, 2015)

2.10 Groundwater Dependent Ecosystems

Groundwater dependent ecosystems (GDEs) along with water quality, are regarded by the international community as an important determinant of biodiversity for inland waterways (Carr and Rickwood, 2008; Murray *et al.*, 2003). GDEs while often geographically limited in scale are a valuable part of Australian biodiversity providing essential ecosystem services (Tomlinson, 2008; Murray *et al.*, 2003; Brunke and Gonser, 1997; Sophocleous, 2002; Nevill *et al.*, 2015). GDEs include any ecosystem that depends on groundwater at any time or for any duration in order to maintain its composition and condition (Serov *et al.*, 2012). This may vary from highly specialised species and communities sensitive to any change in the groundwater regime (quality, level, direction flow etc.) to more opportunistic dependence during extreme conditions such as droughts. GDEs are grouped into three main types: ecosystems dependent on surface expression of groundwater such as springs, seeps, wetlands and river baseflows; ecosystems dependent on subsurface presence of groundwater including terrestrial vegetation where groundwater is within the root zone of the plants and lastly ecosystems that reside in alluvial and fractured rocks aquifers, karsts and the hyporheic zones of rivers supporting unique microorganisms such as stygofauna (Richardson *et al.*, 2004).

GDEs can be good indicators of the presence of groundwater, as well as its depletion. An interruption in groundwater discharge, water quality or distribution will disrupt a GDEs flora communities and fauna assemblage (Serov *et al.*, 2012; Boulton and Hancock, 2006; Murray *et al.*, 2003). Changes to terrestrial vegetation will be observable, though may at first be limited. If impacts are continued the ecosystem becomes progressively degraded, loses resilience and becomes susceptible to cumulative pressures that threaten survival. However the full impact of changes to groundwater can take several years to be fully apparent, at which time the impacts are usually irreversible (Hancock *et al.*, 2005b; Nevill *et al.*, 2015).

The evolution, persistence and resilience of GDEs are affected by the physical, biological and chemical characteristics of groundwater. These include hydrological and geomorphological linkages such as the temporal and spatial aspects of flow paths as well as hydrogeological variables such as rock matrix structure, geo-chemistry and soluble minerals. Microbial biological processes can have a major influence on groundwater quality and connectivity. Biogeochemical processes in the hyporheic zone influence the chemistry of surface and groundwater interaction (Sophocleous, 2002). For example subsurface GDEs fauna or 'stygofauna' consume biofilms, maintain interstitial pore openings and flow paths and physically transport material through the groundwater environment (Hancock *et al.*, 2005b; Serov *et al.*, 2012; Boulton *et al.*, 2010). Lamontagne *et al.* (2003a) investigated the significance of nutrient cycles in groundwater-surface water interactions in sand-bed streams of Wollombi Brook. The study found elevated nutrient levels in the alluvial groundwater interfered with

hyporheic exchange of surface and groundwater that affected GDEs biogeochemistry, salinity levels, density stratification and anoxia of stream flows.

The critical role of hydrological connections for sustaining river landscapes particularly small streams during drought was studied in the Widden catchment, a southern tributary of the Goulburn, by Keene *et al.* (2007). They concluded that a sustained stream baseflow over dry periods supported the ecological function of the hyporheic zone (saturated sediments below and adjacent to river channels) by directly linking surface water to alluvial aquifers underlying the riparian zones and the regional groundwater system.

Different stakeholders attribute different values to GDEs. Murray *et al.* (2003) suggests an assessment of 'value' requires a multidisciplinary triple bottom line approach linking environmental, economic and social/cultural aspects. It is important that groundwater policy and management considers the needs of GDEs, including subterranean, as the role of groundwater in maintaining the health of rivers, streams and associated vegetation is often underestimated or ignored (Nevill *et al.*, 2015).

2.11 Conclusion

This review identified the large-scale ocean-atmosphere interactions that drive climate variability in eastern Australia and details the projections of global climate models on future changes to climate in the general Hunter and Goulburn River region. Seasonal rainfall characteristics and year to year variability is strongly influenced by the El Niño (and La Niña) Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) with decadal variability the result of the Pacific Decadal Oscillation (PDO). Long term, large swings in flood and drought-dominated regimes identified in the Hunter have been shown to correspond to negative and positive phases of the PDO. The influence of large scale climate systems on the Goulburn catchment are further examined in Chapter 4.

In the general area of the Goulburn River catchment climate trend maps show an increase in annual warm season rainfall since 1920, most noticeable during the warm season, with a more recent decrease since 1970 in annual cool season rainfall. The projected increases in evapotranspiration differ from observed global decreases in pan evaporation.

The generation of spatially interpolated monthly rainfall and pan evaporation using ANUSPLIN allows the analysis of the long term trends in the regions climate and impacts on catchment yield and water use. This method overcomes bias from spatial and temporal data gaps in climate records. Monthly interpolated rainfall and stream discharge data can be ranked as percentiles for different time periods to provide the range of normalised departures from average conditions. Longer 5-year running periods are suitable for analysing decadal flood and drought periods and capturing delayed inflow from groundwater systems. Another hydrological model that can be used to assess the elasticity of stream flow measures the sensitivity of stream

discharge to changes in precipitation. Annual average precipitation and discharge data over 20-year running periods are used to explore the influence of climate change on stream discharge. This method can also be used to indicate changes in land use such as increased groundwater extractions from connected systems or regular mine water discharges.

Models investigating increasing stream salinities and dryland salinity in the Murray Darling Basin have used the ratio of chloride inputs in catchment rainfall, to stream outputs. The assumption that rainfall-deposited cyclic salts of marine-aerosol origin were the main source were questioned when chloride ratios greater than one were detected in upland catchments. Mineral weathering and water–rock interactions in the regolith were found to also contribute solutes to stream salt loads.

Analysis of major ion concentrations ratios in surface and groundwater provide hydrochemical signatures that are useful for characterising and grouping aquifers, identifying parent geology and investigating surface and groundwater interactions. Environmental tracers including the conservative chloride ion sulfate and carbonate ions are indicators of weathering of specific geological strata and groundwater contributions to streams as baseflow.

This review revealed surface and groundwater chemistry is influenced by parent geology in the Goulburn catchment, which is the principal driver of salinity. Fault lines and fractures linking saline groundwater to the surface flows are a possible mechanism contributing to elevated levels of stream salinity. Monitoring of water quality in the Goulburn and Hunter Rivers has generally concentrated on EC and pH; however the chemical composition of saline discharge water from mining can differ significantly to what naturally occurs in surface waters. The relative proportion of ions in saline waters as well as other co-occurring environmental stressors can have a combined greater effect on ecosystem health than total salinity and requires further research. Changes in hydrological connections and water quality can affect GDEs that form an important part of the catchment's biodiversity as well as providing important ecosystem services within riparian and hyporheic zones.

More than 50% of river flow in the Goulburn River is estimated to be baseflow groundwater discharge. Numerous methods have been applied to measure the baseflow component of streamflow with varying advantages, limitations and levels of accuracy. Methods rely on the availability of accurate, long term stream discharge and groundwater data. There is a general paucity of reliable long term stream gauge records available for the Goulburn catchment, partly due to the nature of the control structures and limited number of gauging sites. Monitoring data will need to be augmented with a targeted investigation of key surface and groundwater sites along the river and its tributaries and supplemented with available industry reported data where possible.

Numerical groundwater modelling can provide a relatively transparent method to explore interactions between key variables influencing complex groundwater systems. This relies on a

range of measured and assumed input parameters and set boundary conditions plus access to reliable site-specific hydrogeological data. Government and industry data from groundwater monitoring in the Ulan area may be able to provide sufficient input information.

The following chapter describes the study area in detail.

Chapter 3: The Goulburn River catchment

The Goulburn River catchment chosen for analysis is described in this chapter. Its geography, geomorphology, climate, vegetation, current land uses, geology, hydrogeology and salinity sources are considered and the results of previous research discussed. Current government policy legislation and regulations relating to licensed water extraction and water sharing plans relevant to the study area are also summarised.

3.1 Geography and geomorphology

The Goulburn River catchment is located in the western part of the Hunter Valley, NSW in eastern Australia. It overlaps the northwestern region of the Sydney Basin with a latitude extending 31°46'S to 32°51'S and longitude 149°40'E to 150°36'E) (Figure 3:1) (Rudiger *et al.*, 2007). The river is a right bank tributary of the Hunter River and its largest tributary.

At its western point the Goulburn River flows from the Great Dividing Range near Ulan¹ (600mAHD) generally east for 225 kilometres before discharging into with the Hunter River at Denman (80m AHD). Its journey begins in a relatively open alluvial valley with Permian sedimentary and Carboniferous granite geology where the tributaries Moolarben Creek and Sportsman Hollow converge, 40 kms north of Mudgee.

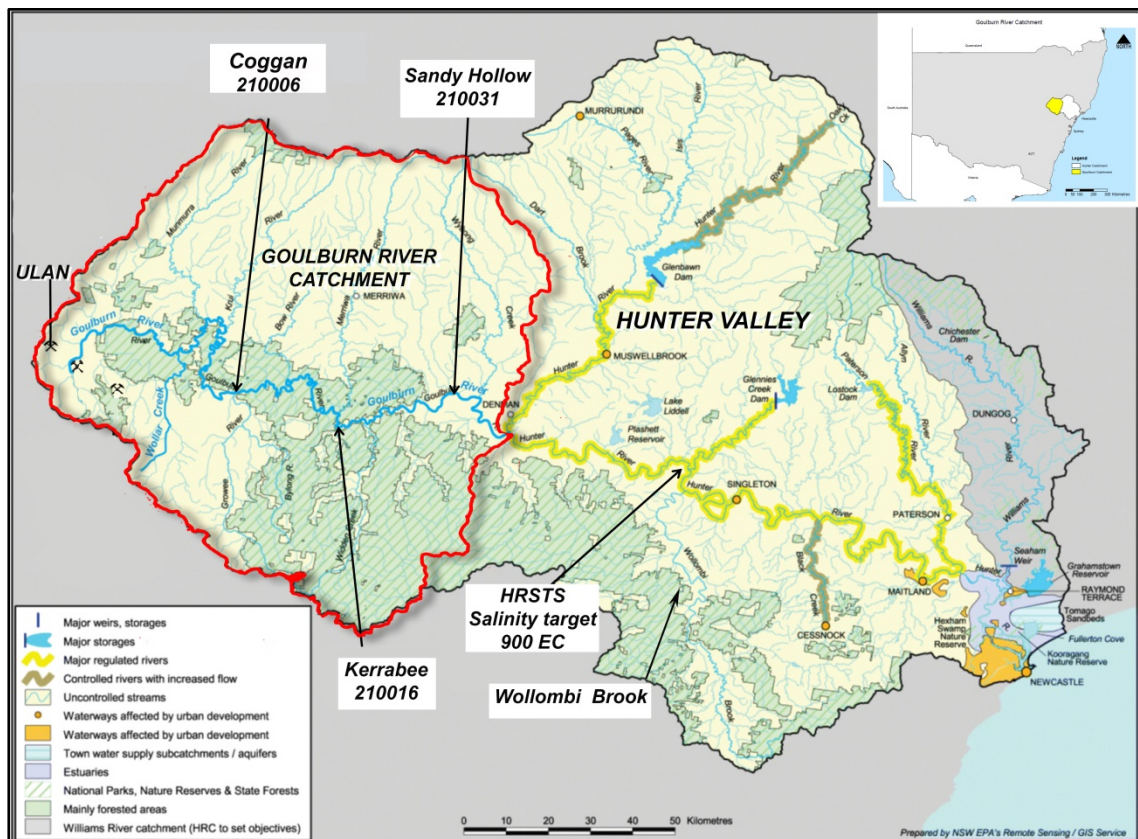


Figure 3:1 Goulburn River and Hunter River catchments (EPA remote sensing/GIS)

¹ Latitude -32.426/Longitude 150.686



Figure 3:2 Goulburn River - sand dominated sediment charged system

The Goulburn River (Figure 3:2) has a wide, mainly sand dominated channel, highly sensitive to changes in the extent and condition of riparian vegetation (Cook and Schneider, 2006). The river begins at Ulan as a laterally unconfined valley infill stream in poor geomorphic condition modified by agriculture and mining (Cook and Schneider, 2006). About 8 kilometres downstream the river enters a confined valley with intact riparian vegetation and the sandstone cliffs and gorges of Narrabeen Group Triassic sedimentary geology (Figure 3:3). Zig-zagging in an easterly direction through the dramatic landscape of the Goulburn River National Park it loops north briefly exploiting paleo-channels until it meets the hard basalt rocks of the Merriwa plateau. Swinging south it encounters softer alluvial sediments, spilling out as a broad sandy river within a laterally unconfined valley in the locality of the Coggan gauging station (Figure 3:4). This marks the extent of the upper Goulburn system. The lower reaches of the Goulburn River continues as a wide sandy channel meandering through alluvial flats for another 110 kilometres until it discharges into the Hunter River near Denman.

The Goulburn River is the largest unregulated tributary of the Hunter river system with a catchment area of 7,840 km². It drains 36% of the total catchment but contributes 23 % of the average flow. The upper Goulburn River catchment area above Coggan gauging station (210006) is approximately 3,500 km², 45% of the Goulburn catchment, while the total

catchment above Sandy Hollow (210031), the last gauging station before the confluence with the Hunter, is approximately 7,000 km².



Figure 3:3 Upper Goulburn Triassic Sandstone cliffs - Goulburn River National Park



Figure 3:4 Lower Goulburn River alluvial flats near Coggan Stream Gauge (210006)

The Goulburn has six major northern, left bank tributaries, Munmurra, Krui, Bow and Merriwa Rivers, Halls Creek and Wybong Creek; and five southern, right bank tributaries, Wollar Creek, Bylong River, Widden Brook and Baerami Creek (Figure 3:5). The western extent of upper Goulburn also includes the minor ephemeral creeks of Moolarben, Ulan, Murrumbline and Wilpinjong Creek, an arm of the Greater Wollar catchment.

The Liverpool Ranges at a height of 1,200 mAHD² forms the northern boundary of the catchment. To the south are the peaks of Coricudgy³ and Nullo Mountain⁴. The most western extremity is near Ulan, at 600 mAHD⁵ falling to 80 mAHD in the east where the Goulburn River joins the Hunter River.

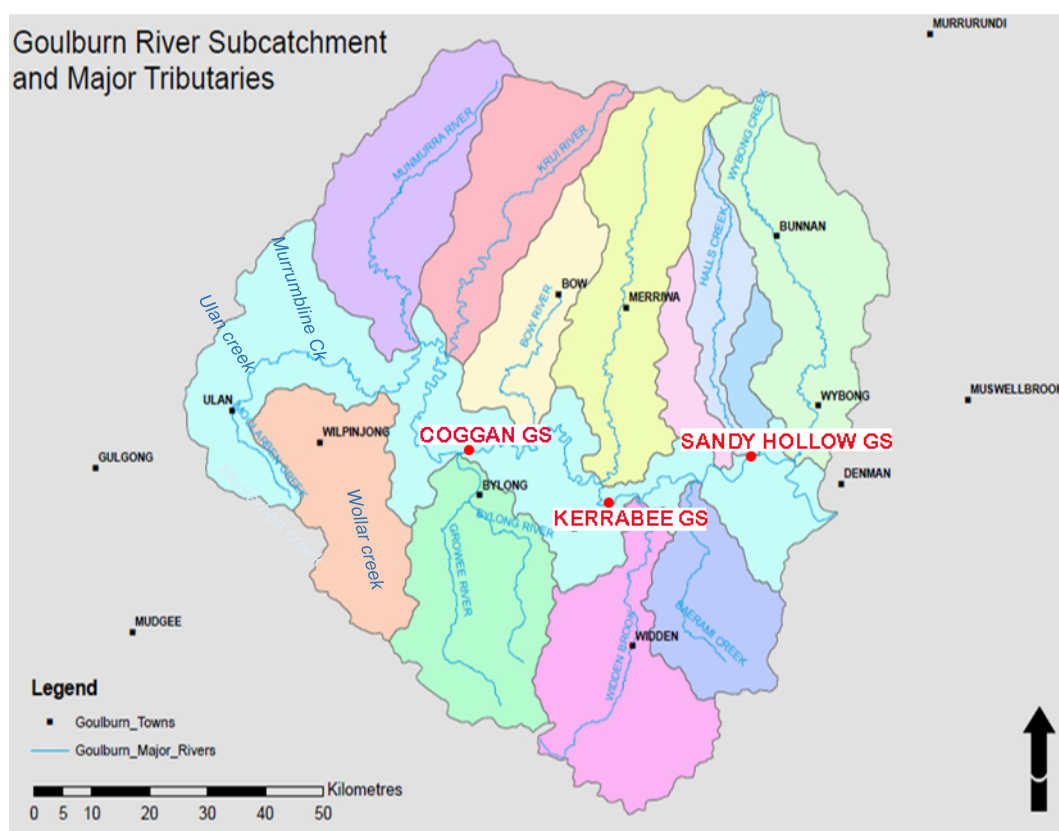


Figure 3:5 Goulburn River sub-catchments, stream gauges (NSW office of Water)

² Latitude -31.78/ Longitude 150.147

³ Latitude -32.85/Longitude 150.36; height 1,200 mAHD

⁴ Latitude -32.76/Longitude 150.22; height 1,100 mAHD

⁵ Latitude -32.25/Longitude 149.68

3.2 Geology of the catchment

Kellett *et al.* (1989) described the geology of the area as follows:

The Southern Mountains region consists of rugged Triassic sandstone mountains up to 1000m and deeply incised valleys; soils are generally shallow because the Triassic sandstones are resistant to chemical weathering. At the junction of the Southern Mountains with the Central Lowlands, discontinuous sheets of quartzose sand fan out from the foothills for 1–2 km. To the west, the Central Goulburn valley region is similar to the Southern Mountains; it is underlain by Triassic sandstones and shales, and consists of irregular steep-sided hills and plateaus, and deeply incised rivers. The Merriwa Plateau region in the north-west consists of rolling to hilly terrain, developed as a planation surface on extensive Tertiary basalt flows. Lavas have partially filled pre-existing valleys, and post-volcanic streams have incised on either side of the flows, forming sub-parallel valleys that reflect the pre-basalt drainage. The degree of incision has been controlled by uplift and by marked variations in relative sea level during the Cainozoic.

The Goulburn River exposes a complex geological history as it flows east cutting through massively faulted sandstone escarpments, following paleo-channels and meandering across broad alluvial valleys. The western and southern catchment forms part of the Sydney Sedimentary Basin, dominated by the Narrabeen Group Triassic sandstones and conglomerates underlain by Permian Coal Measures and shale (Figure 3:6). The geology in the northern catchment, predominantly the Merriwa plateau, is composed of Tertiary basalts underlain by Jurassic shales, siltstones and sandstones that outcrop as a halo, around the elevated basalt plateau. Volcanic activity in the Mesozoic period is thought to have also contributed some volcanogenic material to the Permian and Triassic sedimentary sequences (Mackie, 2009; Gamble, 1984; Watkins *et al.*, 1999).

The valley is constrained in the west by the Lachlan Fold belt, where Carboniferous basement granites outcrop. Sometimes referred to as the bones of the earth they are crisscrossed with lineaments that influences fractures and faulting in the upper layers (Kellett *et al.*, 1989). The major geological units outcropping within the study area from youngest to oldest are listed in Figure 3:6.

Illawarra Coal Measures were deposited during the Permian in a deltaic fluvial system from Gondwana forests and swamps (286 – 245 million years ago). Sediments accumulated within a subsiding basin, followed in later periods by rifting and major uplift. The area was periodically inundated by the sea and strewn with volcanic debris and intrusions from Mesozoic volcanic activity. The mass extinction event – known as the great dying - marks the boundary between the Permian and subsequent Triassic periods. Carbon-rich deposits of the Permian period were buried during the Triassic beneath a series of evolving fans and deltaic river

systems. Sediment sourced from the north east and west were deposited as thick layers forming the massive sandstone strata typical of the Narrabeen Group sedimentary rocks (Ward and Kelly, 2013).

Outcrops of Jurassic geology comprised of Pilliga sandstones and conglomerates underlain by Purlewaugh shales are limited to the north-west of the catchment sandwiched between the Tertiary basalts and Narrabeen Group of Triassic sandstones. The Jurassic Period (208-144 million years ago) was part of the tectonic rifting that formed the basis for Australia's current shape and many of its topographic and geological features (White, 1994) including the Great Artesian Basin – an area of spreading lakes and rivers that accumulated vast quantities of alluvial sands, and intermittently marine sediments during inundation in the Cretaceous. Rainwater recharge areas are thought to occur predominantly along the basins uplifted eastern lip where it meets the Great Dividing Range – which coincides with the north and western areas of the Goulburn catchment (edge of the Oxley Basin). Outcropping fluvio-lacustrine quartzose sediments of the Purlewaugh Formation and Pilliga Sandstone were deposited after a major period of erosion during the Jurassic. Sandstone strata are medium to very coarse grained, well sorted, angular to sub-angular quartzose sandstone and conglomerate with interbeds of mudstone and coal. They form part of the southern tip of the Oxley Basin (a south-eastern unit of the Surat Basin) overlapping the Sydney Basin (Realica-Turner, 2003).

During the Tertiary period tectonic activity and rifting uplifted the landscape and covered it with fluid lava flows of basalt; filling the valleys and capping the sandstone ridges. Accelerating weathering and erosion subsequently carved through the veneer of basalt and underlying alluvial valleys exposing the multi-layered geological history. Buried beneath layers of basalt, that have been warped by Tertiary volcanic intrusions and twisted by faulting lie paleo-drainage systems frozen in time. The Triassic sedimentary ridges subjected to ever accelerating erosion, were carved into deeply incised valleys, exposing the softer Permian shales and coal deposits. Over time the vertical joints and fractures within the massive sandstone strata, juxtaposed with hardened layers of precipitated ironstone formed the sculptured cliff faces, pagodas and escarpments, creating the dramatic landscape of the Goulburn River.

The Tertiary volcanics of basic olivine basalts are centred on the Liverpool Ranges and form the Merriwa Plateau. Scattered volcanic necks, plugs and sills intrude through the deeply weathered and incised sedimentary valleys of the southern catchment.

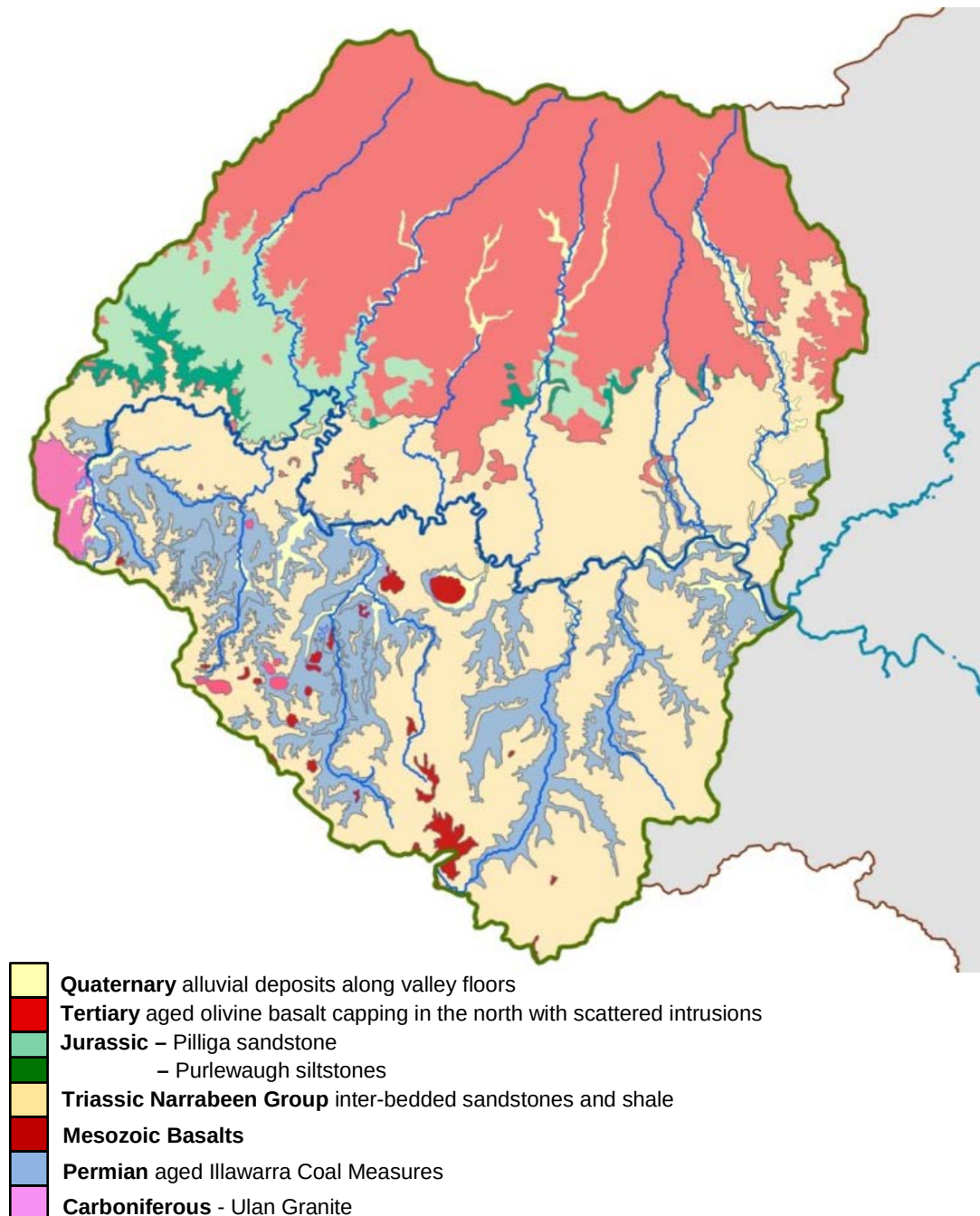


Figure 3:6 Geological Surface Map of Goulburn Catchment. Adapted from (Geoscience-Australia, 2013; Rasmus et al., 1969; Watkins et al., 1999), (NSW Office of Water, 2015).

3.3 Hydrogeology

The Goulburn River acts as a regional drainage sink. Groundwater mounding reflects the elevated sandstone topography and basalt hills, and drains towards topographical lows discharging as baseflows to streams. Secondary permeability through connected bedding planes, faults, fractures and joints, augmented by igneous intrusions, form conduits for vertical and horizontal groundwater flow paths. The Narrabeen Triassic sandstones have been found to be both porous and highly conductive and an integral part of surface-groundwater connectivity that

supports baseflows and groundwater dependent ecosystems (McVicar *et al.*, 2015; Kellett *et al.*, 1989). The regional and local groundwater systems are sustained by rainfall recharge infiltrating over time through the porous sandstone matrix, faults, rock fractures, micro-cracks and bedding planes. The following sections describe the main groundwater bearing hydrological units (Yoo *et al.*, 1995; Nicholson *et al.*, 2014; Kellett *et al.*, 1989).

3.3.1 Alluvial aquifers

Tertiary to Quaternary unconsolidated alluvial sediments are intermittently distributed along watercourses and along the main bed of the Goulburn River. They include infilled paleo-channels of interbedded clays, sandy clays and gravels. Alluvium is the most productive of groundwater sources with hydraulic conductivities reported from 0.5 – 10 m/day with effective porosity 1-10% (MER, 2015; Zhang *et al.*, 2016). Water quality can vary considerably and in some areas is significantly higher in salinity than Permian groundwater (>3,000 $\mu\text{S}/\text{cm}$) (Realica-Turner, 2003). Alluvial groundwater can contain elevated levels of chlorides and sulfates from the oxidation of sulfates present in coal measures and the evapoconcentration and storage of these salts in the alluvium (Kellett *et al.*, 1989).

3.3.2 Fractured and porous rock aquifers

A dominant characteristic of fractured rock aquifers is the inherent spatial variability in hydraulic conductivity and groundwater flow rate (Cook, 2003). Hydraulic properties can be highly anisotropic with various degrees of strata matrix porosity and secondary permeability in the form of conduit fractures and joints.

Tertiary Basalt geology exhibits high hydraulic conductivity where gas cavities are interconnected with joints, fractures and faults. It can be relatively productive, with good quality groundwater relatively low in salinity, though it often exhibits hardness with elevated pH, due to calcium and magnesium carbonates and iron. Bore yield in the Tertiary aquifer has been measured at 5 L/sec though storage capacity may be limited (Biswas, 2010) (NSW Department of Planning, 2005).

There is little hydrogeological information currently available for the **Jurassic Sedimentary Strata** of Pilliga sandstones and Purlewaugh siltstones. The Pilliga unit consists of well sorted medium to coarse grained sediments, angular to sub-angular quartz sandstone with some finer inter-beds of siltstone and mudstone. Generally Pilliga sandstones are regarded as recharge beds for the Great Artesian Basin and a good source of quality, low salinity water with a sodium and bicarbonate chemical composition (Herczeg and Love, 2007). Groundwater monitoring by Ulan Coal Mines indicates the Purlewaugh formation has low porosity and even higher salinity than Permian groundwater (UCML, 2014). Strata consist of anisotropic inter-beds of mudstone, siltstone, fine grained sandstone and coal, with carbonaceous fragments and iron staining.

The **Triassic Narrabeen Group** of Sedimentary rocks underlying the Jurassic geology are regarded as a significant regional groundwater store (MER, 2015) of low to moderate salinity. They are the mostly porous and permeable exhibiting horizontal bedding planes with vertical jointing and fracturing, interspersed with hard ironstone layers. Groundwater throughflow is generally rapid, producing good quality water with a pH 5-7 and salinity ranging from 80-800 $\mu\text{S}/\text{cm}$ and mean total dissolved solids (TDS) of 600mg/L (Creelman, 1994). The dominant major ions are sodium, magnesium and chlorine with elevated ferrous iron.

Bicarbonate ions (HCO_3^{2-}) may dominate Triassic groundwater associated with Tertiary basalt (Creelman, 1994). The principle mechanism producing HCO_3^{2-} enrichment is dissolution of silicate and carbonate minerals including tuffaceous material. Bores yields are reported to range from 0.2 to 2.5 L/sec with higher yields up to 20L/s associated with fracture zones (NSW Department of Planning, 2005; Biswas, 2010; DPI Water, 2016; McNally and Evans, 2007). Triassic sandstone strata are composed of porous friable sandstone, with horizontal groundwater flow along bedding planes and vertical water movement apparent where dense fracture networks form pipes or conduits (Ward and Kelly, 2013). Vertical flow is thought to decrease with depth with increasing pressure and stresses constricting pores and openings (Tammetta and Hawkes, 2009). Triassic rocks can be intruded by basaltic plugs, sills and dykes and depending on the degree and intensity of fracturing, bedding plane partings and the network of joints, may act as conduits for surface water down to coal seam level, form leakage paths and increase secondary permeability and storativity (McNally and Evans, 2007; McVicar *et al.*, 2015).

Permian Illawarra Coal Measures, due to their fine-grained texture and consolidated nature have low primary porosity. Joints and cleats within the coal seam can enhance secondary permeability and increase storage. Elevated salinity levels limits the use of groundwater found in Permian formations. This has been attributed to their marine origin and limited flushing due to low permeability. However salinity levels may be lower where groundwater recharge is via rainfall infiltration or downward migration from Triassic and Carboniferous units in topographically highs as observed in the Ulan area. Dominant ions are sodium, magnesium and bicarbonates and chloride. Elevated carbonates are thought to be due to the presence of volcanic intrusives and tuffaceous interseams. The siltstones, clays and sandstones of the upper non-coal Permian strata appear increasingly impermeable with depth. Vertical faulting can provide hydraulic connectivity between alluvial aquifers and deep highly saline strata (Jasonsmith, 2011; Biswas, 2010; Kellett *et al.*, 1989; Creelman, 1994).

A small localised area of productive good quality groundwater associated with the **Lachlan Fold Belt** granites occurs at the top of the Great Dividing Range in the south west and discharges to local creek-lines to the south of Ulan.

3.3.3 Influence of faults, fractures, sills and plugs

The permeability of fault zones may vary and can either aid transmissivity or form a barrier to flow. Volcanic sills, dykes and plugs can increase the potential for groundwater flux and storage through fracturing networks or alternatively impede and force groundwater flows up dip (Jasonsmith, 2011; McVicar *et al.*, 2015) (Macdonald *et al.*, 2009a; McNally and Evans, 2007). The basement granites of the region contain lineaments interpreted as NE to NW trending faults or zones of weakness that have the potential to effect the direction of watercourses and paleo-channels. Vertical faulting through to the surface could provide connectivity with underlying strata and groundwater bodies facilitating recharge and vertical mixing of groundwater (Kellett *et al.*, 1989; Biswas *et al.*, 2009).

Coal oil slicks have been detected in bores in the Wybong catchment and also observed in bores near Denman (Yarraman GW080947 and Frenchies GW040960). These oily deposits most likely originated from the Permian Wittingham Coal Measures and support the theory that deep fractures and faulting may act as a barrier forcing saline groundwater and associated chemicals from coal bearing strata up dip to the surface (Jasonsmith, 2011). High salinity alluvial groundwater in the Greater Wollar Creek catchment and in Widden Brook was also thought to be due to saline Permian artesian groundwater, springs and seepages discharging along fractures and faults into drainage lines (Realica-Turner, 2003; Somerville *et al.*, 2006).

According to Kellett *et al.* (1989) the major hydrogeological structures of importance in the Hunter region are a series of meridional faults with numerous associated cross-faults. He considered on a regional scale, fractured-rock aquifers constituted a minor proportion of groundwater storage in comparison to the floodplain alluvium. However the reserves were most important during periods of low flow in the Hunter River and its tributaries. Vertical tension fractures and jointing that formed in the Permo –Triassic rocks during regional uplift have the potential to store and transmit considerable quantities of water. The highest groundwater velocities were found in the fractured-rock aquifers of Narrabeen Group and Carboniferous rocks with elevated hydraulic gradients overcoming any limiting factors in their permeability.

3.4 Sources of Salinity in the Goulburn

Potential sources of salinity in the Hunter Valley include atmospheric and aeolian dust deposition, geological weathering and groundwater discharge. Elevated levels of salinity occur naturally in many of the soils and streams across the Hunter Valley (Kellett *et al.*, 1989). The chemical signatures of ground and surface water indicate hydro-geology and groundwater chemistry is the principal driver of salinity in this region (Creelman, 1994). Increasing salinity in some Hunter tributaries has been attributed to a combination of naturally saline geologies, modification of the landscape increasing salt discharge, accumulation of salts on the surface and reduced freshwater inputs due to drought conditions. (Kellett *et al.*, 1989; Creelman, 1994)

(Muschal, 2006; Jasonsmith *et al.*, 2011b). Kellett *et al.* (1989) concluded saline groundwater emanating from Permian Coal Measures was the dominant source of salinity in the Upper Hunter while silicate and carbonate weathering of upland Tertiary basalt geology contributed bicarbonate salts. Creelman (1994) concluded the main contributors to salinity in the Hunter Valley were solutes mobilised by the physical and chemical weathering of rocks, deposited on the surface by groundwater seepage, evapo-concentrated and flushed by rainfall into streams and rivers, in combination with saline discharge from regional groundwater systems via major fault lines. He estimated salts released from the marine interburden sediments of the Wittingham Coal Measures contribute an estimated 40 tonnes/km²/year and Wollombi Coal Measures 4-5 tonnes/km²/year. While salt output from Triassic Narrabeen Group, including overlying Tertiary basalt, averaged 5 tonnes/km²/year (Creelman, 1994).

3.4.1 Salinity trends

The Coastal Rivers Salinity Audit (Beale *et al.*, 2000) analysed stream data in the Goulburn River system from the Sandy Hollow gauging station (210031) (Figure 3:1) representing downstream outcome of processes operating in the twelve upstream sub-catchments. Using predictive modelling, it estimated future 'dryland salinity risk' at strategic locations in the Hunter Valley. Modelling was based on usually two-point estimates of trends in groundwater pressures and in-stream salinity (1975 to 1998) which were assumed to continue for the next century. The report stressed that the general paucity of data; variable catchment size and vegetative cover combined with significant changes in land use made accurate predictions of stream salinity problematic.

The period 1975-1998 included a very wet period in the 1970s, a major drought in the early 1980s and another dry in the mid-1990s. This predicted increase in stream salt discharge was assumed to result from an increase in water table levels. The source of salinity trends was attributed to the influence of tributary and residual⁶ catchments. Potential salt loads from groundwater discharge were based on geology and location (provinces). The western Triassic sediments were allocated the highest potential salt load at 31 tonnes /km²/year with an overall average for all provinces and geologies of 12.7 tonnes /km²/year. Estimated potential tonnes of salt mobilised over time were calculated on an 'area wetness' factor (FLAG⁷ model) using groundwater standing water levels. An intrinsic weakness in the methodology behind these predictions were reliance on a dryland salinity model driving steadily rising groundwater levels which increased salt discharges from the western Triassic sediments. Flaws in the dryland salinity model, also used in the Murray-Darling Basin have been highlighted (White *et al.*, 2009). The predicted trends in the 2000 Audit therefore require further appraisal.

⁶ Residual catchment is the 'ungauged' catchment area downstream of a stream gauge

⁷ FLAG or Fuzzy Logical Analysis GIS

Assessment of the Goulburn River system was based on measured flow at the Sandy Hollow stream gauge whose accuracy was deemed poor due to the shifting geometry of the sandy streambed control. The Audit estimated the annual mean stream discharge for the Goulburn at 150,500 ML/year or approximately 40% of the flow in the Hunter River at Liddell with an annual salt output of 50,600 tonnes. The median EC was 995 μ S/cm and the 80th percentile salinity 1375 μ S/cm, which is significantly higher than the Hunter River at Denman.

A more recent desktop assessment (Krogh *et al.*, 2013) evaluating the Hunter River Salinity Trading Scheme (HRSTS) estimated the specific salt discharge from the Goulburn catchment (including Wybong) over the period 2007-2013 averaged 52,000 tonnes per year - ranging from 24,200 tonnes in 2008-9 to 93,400 tonnes in 2010-11. These are equivalent to specific salt discharges of 3-12 tonnes/km²/year. Median EC from limited early spot measurements and later continuous monitoring over the period 1970-2013 was estimated at 1007 μ S/cm at Coggan and 837.5 μ S/cm at Sandy Hollow, the latter moderated by discharge from the southern catchments draining the lower Triassic sediments.

The salt load entering the Hunter River from the Goulburn tributary measured at the Sandy Hollow gauging station (excluding Wybong) was on average 50% of the total load and at times significantly greater than the Hunter River at Denman (130% in 2010-2011). Between 2002 and 2012 the coal mining industry discharged under the HRSTS regulations approximately 112,500 tonnes of salt into the Hunter River or 10 % of the salt load, with 59,035 tonnes discharged during 2012. The report concluded that salts discharged from the Goulburn River posed a risk to downstream water quality and the HRSTS, reducing the capacity for opportunistic saline mine water discharge into the Hunter River. (Krogh *et al.*, 2013). There are currently three coal mines holding mine water discharge licenses into the upper Goulburn, along with further potential coal mining developments proposed in the Bylong Valley and CSG exploration proposed for the area. In contrast to the Coastal Salinity Audit, Krogh *et al.* (2013) concluded there was minimal evidence supporting a rising trend in groundwater levels or increasing groundwater salinity given the limited available data. It recommended a more comprehensive and representative groundwater monitoring program was required to detect future trends and concluded further work was necessary to better understand existing salinity impacts on the stream biota in the Hunter. The report recommended further strategic real-time monitoring of flow and salinity in the both the upper and lower sections of the Goulburn River catchment and experimental studies to understand the environmental effects of the different components of saline water on the stream biota in the Hunter (e.g. ionic composition, metals/metalloid contamination). Salt inputs from Wollar, Merriwa and Wybong sub-catchments were identified as significant salt contributors.

3.4.2 Sub-catchment salinity

Dryland salinity in a south-western sub-catchment of the Goulburn River in the Greater Wollar Catchment (Figure 3:7) was investigated in 2001 as a priority catchment contributing high salt loads to the Goulburn River (Realica-Turner, 2003). The headwaters of Wollar and Wilpinjong creeks drain from the Triassic sandstone ridges and gullies (Narrabeen Group) that flank the Great Dividing Range including Munghorn Gap Nature Reserve and Goulburn River National Park. The report noted that numerous fresh springs discharge in the upper reaches of the catchment within the Triassic sandstone foot-slopes.

Drainage lines incised through saline Permian geology in lower creek sections through Shoalhaven and Illawarra Coal Measures produced more brackish water within the Quaternary alluvium. This was thought due to a hydraulic connection via faults or fractures to underlying saline Permian aquifers. The mixing of fresher Triassic spring water EC $\sim 150 \mu\text{S}/\text{cm}$, with highly saline Permian discharge 2500- 7500 $\mu\text{S}/\text{cm}$, was a significant factor for reducing stream salinity. Creek salinity profiles indicated an increasing downstream trend in EC indicating continuous input from saline groundwater into fresher surface flows. The report concluded that the NaCl dominant saline water seeping into sodic soils was most likely producing secondary 'dryland' salinity and that further studies were necessary to determine the changes necessary to maintain or decrease salt loads discharging into the Hunter system.

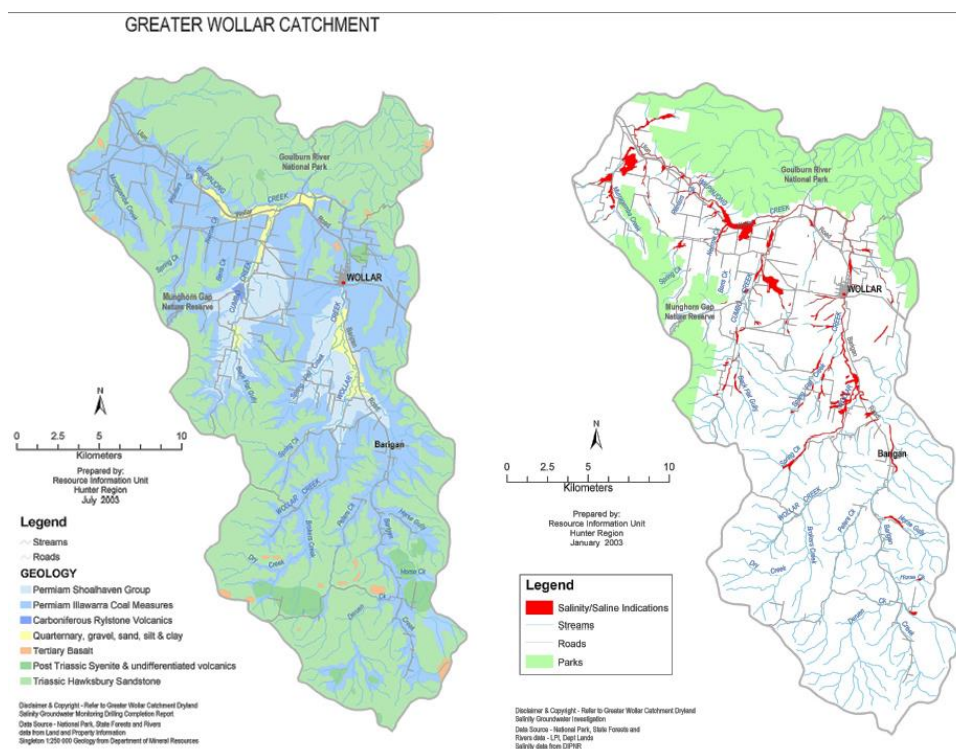


Figure 3:7 Greater Wollar catchment highlighting salinity hotspots in Permian geology (Realica-Turner, 2003)

Macdonald *et al.* (2009a) investigated temporal and spatial changes and hydrochemical interactions in surface and groundwater in the Goulburn River and two tributaries, Widden

Brook and Wybong Creek, using available government streamflow data⁸ and industry water chemistry data augmented with longitudinal ‘snap shot’ sampling of surface waters from the headwaters at Ulan downstream to Sandy Hollow. The Goulburn River catchment was defined as the total area above Sandy Hollow (210031) and Wybong Gauges (210040). Stream salinity was found to be strongly influenced by the regional geology and the ground waters which are hosted in the coal and inter-burden aquifers. An analysis of major ions and strontium isotopes from sampling along the Goulburn River comparing $([Ca] + [Mg])/[Cl]$ to elevation (mAHD), also supported the theory of fresher baseflow inputs from the Narrabeen Group (Triassic) sandstone geological units in the upper and southern catchments.

The influence of climate cycles was investigated using residual mass plots of monthly streamflow and rainfall records (1913-2007)(Macdonald *et al.*, 2009b). These suggested an increasing trend in rainfall since 1950 in contrast to a notable decline in average streamflow with a greater than expected fall in flows and catchment yield in the period 2000-2007 during the millennium drought. The decreasing trend in average catchment yield was reasoned to be due to factors related to alternate flood, and drought-dominated regimes (Erskine and Warner, 1998) driven by El Nino Southern Oscillation and the Inter-decadal Pacific Oscillation. Factors suggested included possible declines in soil moisture and or rising evapotranspiration along with the increased water abstraction from alluvial aquifers. The estimated contribution of salt from the Goulburn River catchment was based on stream EC (1990-2009) and stream discharge at Sandy Hollow (210031). It showed a doubling in specific salt export during drought years from 0.9 tonnes/km²/year (2000-2009) compared to 1.7 tonnes/km²/year in wet years (1990-2000). Salt export from the Wybong catchment also doubled 2.5 tonnes/km²/year in the dry period to 4.5 tonnes/km²/year in wet years. This fluctuation in specific salt yield could have major implications under changing climates.

Interestingly total salt loads appeared to decline between the two lower catchment gauging stations, Kerrabee (GS-210016) and downstream Sandy Hollow (GS-210031). This was presumed to be due to transmission losses of the more saline surface waters to the alluvial aquifers in combination with fresher groundwater inflows emanating from southern catchments such as Widden Brook. Persistent baseflows may explain the greater relative permanence of upstream surface flows measured at the mid catchment gauging station at Coggan (210006) which has the most reliable and longest stream flow data. The report recommended further study on temporal and spatial connectivity in the hydrological and elemental ‘climate’ cycles and emphasised the need to protect freshwater aquifer systems associated with the Triassic sandstones and Tertiary volcanics.

⁸ Government water data was extracted from PINNEENA v9.2 data DVD (daily time step).

3.5 Vegetation of the catchment

The Goulburn River catchment falls within the Central Western Slopes botanical district and the Sydney Basin and Brigalow Belt South bioregions (Harden, 1991; Sahukar *et al.*, 2003). The catchment generally experiences drier and warmer conditions than adjacent tablelands and coastal areas and supports a diverse mix of eastern and western plant species reflecting the east-west orientation and the low elevation of the Great Dividing Range at the western limit of the catchment. The distribution of vegetation communities is influenced by a nexus of elevation, geology, soils, aspect and available moisture levels. The alluvial valleys and richer basalt peaks and plateaus were traditionally cleared for agriculture. Catchment report cards indicate approximately 23% forest cover remains in the northern, predominantly basalt, sub-catchments. The southern and upper Goulburn sub-catchments retain around 65% forest cover. Overall, 44% of the catchment is covered by woody vegetation (Table 3:1) centred on areas with poorer soils, steep slopes or in National Parks.

Table 3:1 Percent and area of woody vegetation (forested) catchment from Water Sharing Plans Report Cards (NSW Department of Water and Energy, 2009)

Catchment - tributary	Sub-catchment Size (km ²)	Woody Veg. %	% Catchment Area	Woody Veg. (km ²)	Woody Veg. cover % Catchment
Southern Catchments (SC)					
Upper Goulburn	994.5	51%	30%	507.20	15%
Wollar	532	59%	16%	313.88	9%
Bylong	697.5	63%	21%	439.43	13%
Widden Brook	708.1	83%	21%	587.72	18%
Baerami	422.8	80%	13%	338.24	10%
Subtotal	3354.9			2186.46	65%
Northern catchments (NC)					
Munmurra	694.1	14%	19%	97.17	3%
Krui (210037)	585.2	16%	16%	93.63	3%
Bow	392.4	12%	11%	47.09	1%
Merriwa	809	21%	22%	169.89	5%
Halls (Gungal 210065)	374.4	19%	10%	71.14	2%
Lower Goulburn above Sandy Hollow (210031)	786.6	46%	22%	361.84	10%
Subtotal	3641.7			840.76	23%
Goulburn River Total	6996.6				44%

The dominant broad vegetation units present across the Goulburn catchment are dry open sclerophyll forests and woodlands from the sandstone ridges, escarpments and basalt peaks to incised alluvial valleys, foot-slopes and watercourses. Vegetation types and growth patterns can provide valuable insight into potential groundwater interaction (Dowsley *et al.*, 2012). The vegetation community known as Apple Alluvial Open Forest (Hill, 2000) is the dominant

terrestrial GDE on the Goulburn River down to the confluence with Wollar Creek. These riparian forests are composed of an over-storey of Rough-barked Apple (*Angophora floribunda*), interspersed with Blakely's Red Gum (*Eucalyptus blakelyi*), Yellow Box (*Eucalyptus melliodora*) and Apple-Top Box (*Eucalyptus bridgesiana*) along wider alluvial flats. The under-storey is composed of native tree-violet (*Melicactus dentatus*) and Tautoon tea-tree (*Leptospermum polygalifolium subsp. transmontanum*). Riparian forests dominated by River Oaks (*Casuarina cunninghamiana*) grow in the northern tributaries and downstream from the confluence of Wollar Creek (Hill, 2000). Dry rainforest communities have also been recorded in sheltered moist sandstone gorges tucked into river canyons and at elevated southern facing sites. Tall moist sclerophyll forests of Silver-top Stringybark (*Eucalyptus leavopinea*), Mountain and Manna Gum (*Eucalyptus dalrympleana*, *E. viminalis*) Eurabbie and Monkey Grey Gum (*Eucalyptus bicostata*, *E. cypellocarpa*) dominate the elevated high rainfall areas along the Liverpool Ranges in the north and around Nullo and Coricudgy Mountains in the south.

The study area contains important remnant vegetation and Threatened Ecological Communities including Ecological Endangered Communities (NSW Government, 1995) and Critically Endangered Ecological Communities (Australian Government, 1999). These include White Box, Yellow Box, Blakely's Red Gum Woodlands and Derived Grasslands, Grey Box Grassy Woodlands, Central Hunter Valley Eucalypt forest and Hunter Valley Weeping Myall Woodlands. To date there has been no comprehensive mapping of vegetation across the Goulburn catchment. The Great Eastern Ranges Conservation Initiative (HCRCMA, 2013) identified the Goulburn catchment as an important east-west vegetation corridor and critical biodiversity link connecting inland and coastal ecosystems that provide adaptation and landscape resilience against changing climatic conditions. Numerous range extensions include remnant forests of coastal Spotted Gum (*Corymbia maculata*) identified inland in the extreme north-west of the catchment between Turill and Cassilis. Three range extensions were identified in the upper Goulburn riparian corridor near The Drip Gorge - large weeping sedge species *Cladium procerum*, bottlebrush *Callistemon rigidus*⁹ and wattle *Acacia floribunda*¹⁰. These finds highlight the importance of the location and role of this catchment in maintaining landscape connectivity and resilience.

3.5.1 Groundwater Dependent Ecosystems (GDEs)

GDEs are particularly vulnerable to changes in groundwater levels and water quality. NSW government policy recognises that the water requirements of GDEs need to be integrated into the water planning process (NSW Office Of Water, 2012). However the allocation of water for environmental health requires more than allocating water for the maintenance of river flows

⁹ Identification confirmed The Royal Botanical Gardens, Sydney Dr P.G. Wilson, 25/11/2014

¹⁰ Ibid., atypical form det. Dr Phillip Kodela, Feb 2015

(Murray *et al.*, 2003). The protection of GDEs in NSW are restricted to those considered as high priority that are listed and mapped in WSPs¹¹ with the demands on groundwater by licensed users also taken into account.

There are significant knowledge gaps in the understanding, identification and mapping of GDEs in the Goulburn catchment. This is due to large gaps in spatial layers due to limited groundwater monitoring and vegetation survey data (Dowsley *et al.*, 2012; BoM, 2016). Hence there are no classified national or regional GDEs listed on the Groundwater Dependent Atlas for the Goulburn River catchment. However a range exist, from terrestrial ecosystems that rely seasonally or episodically on subsurface access to elevated groundwater; seeps or springs where groundwater discharges to the surface or alternatively aquifers and riparian baseflow systems that lie in or adjacent to streams and rivers (Murray *et al.*, 2003). The elevated hydraulic gradient of fractured and porous rock groundwater indicates discharge towards the river in the upper Goulburn (Middlemis and Fulton, 2011) and potential surface-groundwater interaction and connectivity with riparian ecosystems. The Drip gorge located on the Goulburn River north of Ulan is an example of a GDE that is explored in Chapter 9.

In addition a number of perennial springs discharge from high points along the Great Dividing Range at Munghorn Gap into the Moolarben, Wollar, Bylong and Widden Valleys (Realica-Turner, 2003; Somerville *et al.*, 2006). They provide high quality, low yielding groundwater flows to surface waters that act cumulatively diluting the saline water from the Permian alluvium in the valley floor (Realica-Turner, 2003; Macdonald *et al.*, 2009a). These fresh pristine springs are considered drought proof by local landholders and often tapped for domestic water supplies (*pers. Comm. K. Mayberry, D. Stokes – Moolarben Valley*)¹² (Figure 8:5). They support a range of GDE and riparian communities including remnant dry rainforest species that extend down the gullies and creek lines. Dry rainforest communities of the Upper Hunter have a high correlation to sandstone or conglomerate lithology, occasionally occurring on or adjacent to acid volcanics (Curran *et al.*, 2008). Species include the Port Jackson or Rusty Fig (*Ficus rubiginosa*), Native Olive (*Notelaea macrocarpa*), Grey Myrtle or Ironwood (*Backhousia myrtifolia*), Native Cherry (*Exocarpos cupressiformis*), Northern Sandalwood (*Santalum lanceolatum*) and Native tree Violet (*Melicytus dentatus*) and a range of ferns including from the Tree-fern family (*Cyathea australis*, *Calochlaena dubia*), Maidenhair (*Adiantum aethiopicum*), Coral fern (*Gleichenia microphylla*) and *Blechnum* species.

To date there has been no published studies on stygofauna in the Goulburn catchment. The NSW State Groundwater Dependent Ecosystems Policy (DLWC, 2002) refers to work in the Hunter and Goulburn Rivers on fauna and microbes within the sediments of the hyporheic zone and their role in transforming nutrients and maintaining water quality.

¹¹ <https://www.industry.nsw.gov.au/water/science/groundwater/ecosystems>

¹² Spring sampling sites identified as SP on maps

3.6 Land use

Land use in the Goulburn River catchment includes sheep and cattle grazing, viticulture, horse breeding, cropping, irrigation and coal mining with over 50 % of the southern catchment reserved for conservation in national parks, nature reserves and various state conservation areas. The tree and shrub cover, including conservation areas covers 46.7% of the Goulburn catchment (Table 3:2, Figure 3:8). This is a 2.7% higher than provided in the 2009 WSPs (NSW Department of Water and Energy, 2009) that estimated 44% forest cover in the Water Sharing Plans Report Cards (Table 3:1). It may indicate an increase in vegetation regrowth between when the data-sets were collected, 1998-2000 and 2005-2013.

Table 3:2 Percentage land-uses for the Goulburn catchment - NSW Spatial Data (NSW-Office Water - 2014)

LAND USE	% Catchment
Grazing	47.3%
Conservation Area	30.3%
Tree & Shrub Cover	16.4%
Cropping & Horticulture	4.25%
Natural waters & Wetlands	0.75%
Mining & Quarrying	0.22%
Transport and other Corridors	0.34%
Urban	0.25%
Intensive Animal Production	0.19%

Land use is strongly influenced by land capability, soils and geology. The Goulburn River National Park borders a 90 km stretch of the Goulburn River and covers approximately 723 km² of dissected sandstone country with the occasional basalt outcrop. The adjoining Munghorn Gap Nature Reserve covers 68 km² also sedimentary sandstone and basalt geology. The catchment includes a small section of Coolah Tops National Park in the Liverpool ranges in the north-west and a portion of World Heritage listed Wollemi National Park in the southeast encompassing part of the catchments of Baerami, Widden and Bylong.

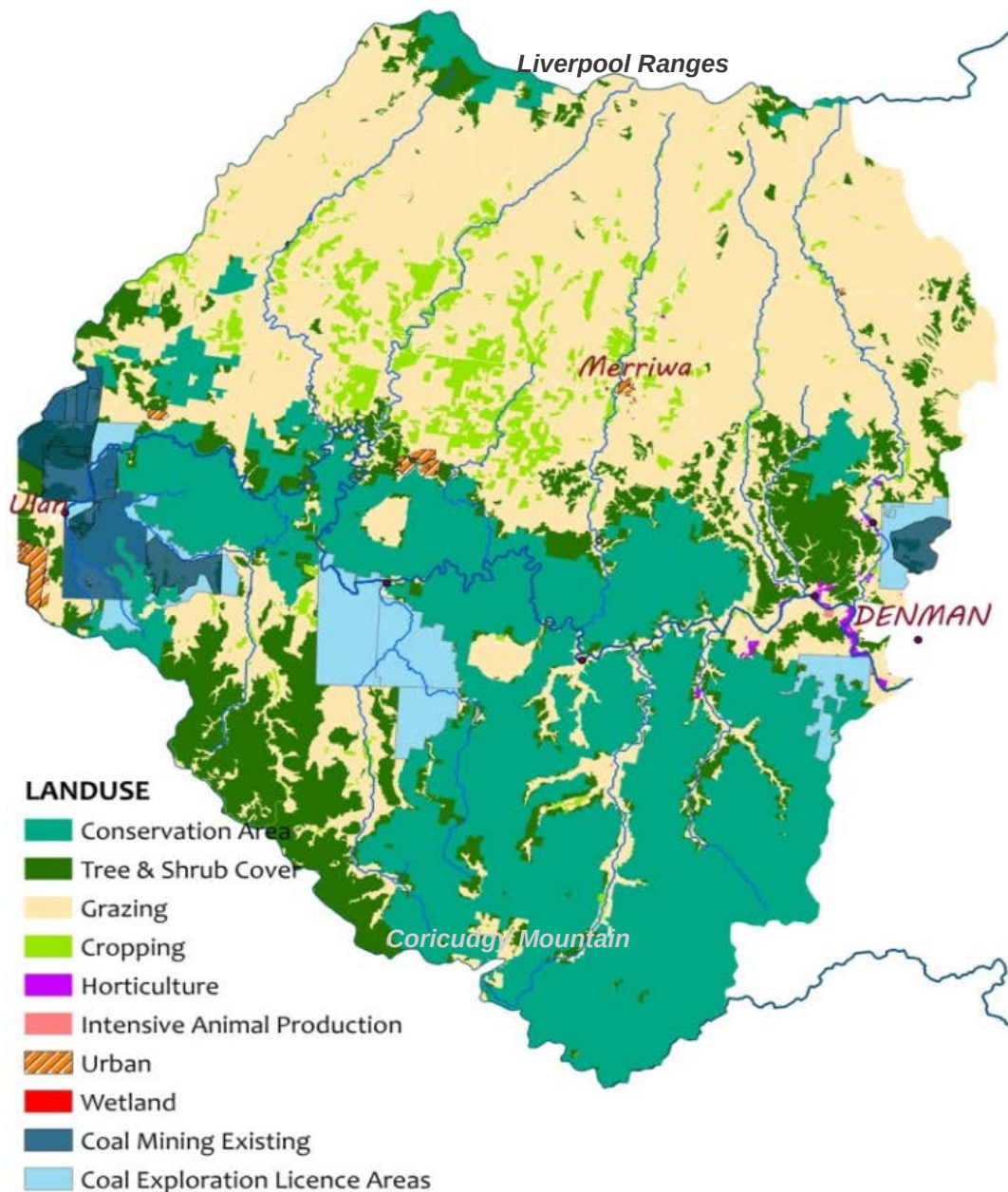


Figure 3:8 Land use map of Goulburn River catchment.
Data: Land use version 53 (NSW Office of Water, 2015)

A pervasive problem in the upper Hunter Region is the extensive deposits of salt linked to the marine sediments associated with the Permian strata (Kellett *et al.*, 1989). Saline runoff and diffuse saline groundwater seepage contributes to elevated stream salinity levels (Kellett *et al.*, 1989; Macdonald *et al.*, 2009a). In addition the mining of Permian coal measures produces substantial volumes of saline wastewater (Zhang *et al.*, 2016). The salinity of surface and groundwater quality and the impacts of both point-source and diffuse salinity discharge is of major concern to the region's communities, dry land farmers and irrigators (Walters, 2016; Campbell, 2014; Hydrocology Consulting, 2014).

3.6.1 Agriculture

Approximately 48% of the Goulburn catchment has been cleared for grazing sheep and cattle, concentrated on the productive basalt soils of the Merriwa plateau in the north, along alluvial flats in the lower Goulburn and within incised valleys in Permian strata to the south (Figure 3:7). Less than 5% of the Goulburn catchment is used for cropping, including irrigation and intensive agriculture.

The Hunter Valley Conservation Trust¹³ was established after the devastating 1950s floods that caused substantial flooding, erosion and sedimentation of the Hunter River. The Trust implemented a mitigation strategy for the Hunter Valley to prevent soil loss and reduce future flooding. This involved generous grants and subsidies to establish dams and contour banks across cleared agricultural areas in the upper catchments in the 1960s to the early 1980s. Increased interception and capture of rainfall runoff by additional on-farm water infrastructure can affect catchment yield. Unfortunately data on the volume of water potentially stored in farm dams across the Goulburn catchment is not reported (Zhang *et al.*, 2016).

Changing wool and beef markets and the collapse of livestock prices in the mid-1970s saw destocking and a shift from sheep to cattle grazing in the upper Hunter. Removal or a reduction in grazing pressure can result in increased native vegetation regrowth (Harris-Adams *et al.*, 2012). Woody forested catchments are known to have higher evapotranspiration rates than grassed catchments and thus have a greater impact on catchment water yield and groundwater recharge (Zhang *et al.*, 2001). Native vegetation regrowth after logging in Victorian ash forests resulted in a significant reduction in catchment yield and land use conflict (Taylor *et al.*, 2018). In 2003 the NSW Native Vegetation Act (NV Act) was introduced to end broadscale clearing of native vegetation in NSW and to improve the revegetation of land in regional areas. Data suggests this legislation led to some increase in woody vegetation retention and regrowth across farming areas 1998-2008 (DECCW, 2009). Agricultural water usage is covered in section 3.5.2

3.6.2 Mining

Small scale *bord and pillar* underground coal mining started at Ulan in the early 1920s for the supply of coal to local markets but ceased due to the distance to major markets. Mining recommenced in 1942 and continued operations until 1950 supplying coal to a small power station built to the north of the Ulan Village, this closed in 1969. Mining using a pit pony continued on a small scale supplying domestic markets.

An exploration program undertaken in 1976 in the Ulan area proved the existence of extensive coal reserves, heralding a major expansion of mining operations by Ulan Coal Mine

¹³ The Hunter Valley Conservation Trust was established after 1950 floods. The name was changed to Hunter Catchment Management Trust in 1989 (<http://search.records.nsw.gov.au/agencies/4850>)

Limited (UCML). Large open-cut coal mining was developed in the headwaters of the Goulburn River in the mid-1980s. In 1984 Ulan Coal Mine (UCML) permanently diverted a 4 km section of the Goulburn River for over 5kms around the open cut mine area to allow for mining of the river bed and alluvial flats (see Appendix G- Figure G2).

Underground longwall mining was developed north-west of the river diversion and open cut area in the 1990s. Further modifications and approvals saw a widening of long wall panels from 250 metres to 400 metres in 2005 and the approval and development of an additional underground mine, Ulan West, in 2014, extending workings over the Great Dividing Range (GDR) into the Talbragar River catchment (Murray Darling Basin).

Two additional large open cut and underground mining projects were approved in 2004 Wilpinjong Coal Mine (WCM) and Moolarben Coal Operations (MCO) in 2007. Numerous subsequent staged extensions and modifications to all three mines have increased total approved coal production from 6 to over 52.5 million tonnes per annum. The total area of underground mine leases at Ulan is over 124 km² and open cut 65 km². The combined mining lease footprint is 2.7% of the Goulburn catchment above Sandy Hollow (Figure 6:2). The combined annual surface and groundwater inflows for the three mines including incidental take, is predicted to exceed 19,000ML by 2025 (See Section 6 Table 6:2).

Mining operations in the Goulburn catchment are currently located in the west around the villages of Ulan and Wollar and in the east near Denman (Glencore - Mangoola Coal Mine). There are a number of active exploration licenses and new mine applications in green-field sites throughout the catchment. A development application has been submitted by KEPCO-Bylong Coal for open cut and underground mining in the Bylong Valley, a green-field site. There are current though non-active Coal Exploration Leases south west of Denman around Yarrawa and Martindale (Figure 3:9). CSG petroleum exploration licenses (PELs) and drilling operations are currently held over a large part of the Goulburn catchment and Upper Hunter including the Merriwa plateau and Ulan Wollar area [PEL456 Hunter Gas Pty Ltd. Area 5019 km²] and around Cassilis [PEL433 Santos NSW Pty Ltd. Area 5759 km²].

Mining subsidence, dewatering and depressurisation of aquifers, disruption of groundwater systems and discharge of mine waste are significant management issues in the Hunter Valley (Mackie, 2009; Walters, 2016; Herron *et al.*, 2018) and of growing concern to the community (Hydrocology Consulting, 2014; Walters, 2016). The scale and cumulative impact of expanded mining operations has implications for the groundwater and river system and the resilience of riverine and groundwater dependent ecosystems (IESC, 2017; Advisian, 2016)

A large number of mine reports, site specific hydrological studies and groundwater modelling of impacts have been conducted by the mining industry. The interception of surface and groundwater by mining operations produces substantial volumes of saline waste water requiring treatment and storage onsite or disposal offsite (MER, 2009; Hancock *et al.*, 2005a).

Overburden material and remaining final voids have the potential to increase saline runoff, seepage and contamination of the groundwater system increasing the overall salt discharge from the catchment (Hancock *et al.*, 2005a). The groundwater drawdown of the fractured rock systems due to mine dewatering and subsidence intercepts both poor and good quality groundwater from surrounding alluvial and upper aquifers that normally contribute flow to the river system (Macdonald *et al.*, 2009a). A key finding (6) in the Bioregional Assessment of the impact of mining on water resources in the Hunter subregion states “*Modelled changes in ecologically important flows indicate a higher risk to the condition of riverine forested wetlands along the Goulburn River compared to other riverine forested wetlands in the subregion*” (Herron *et al.*, 2018). The impact of coal mining on the Goulburn catchment is further discussed in Chapter 6.

3.6.3 Coal Mining and salinity

Hancock *et al.* (2005a) modelled the hydrological and salt balance of mining voids in the Hunter Valley over a 500-year period in order to estimate the long term risks. The study used a mass balance approach combined with modelling to allow for the complex hydrological and hydrogeological processes and salt components within the greatly disturbed open-cut mining environment. The estimate of salt stored in mine spoil was based on leach test on overburden material and mine spoil data together with an estimate of spoil volume and salt concentration. Groundwater salt input was based on a simplified annual inflow system and the estimated total dissolved solids (TDS). Only saturated water flow was considered. Salt derived from rainfall was estimated to be 7.5 tonnes/km²/year for the upper Hunter (Creelman, 1994) and was assumed to fall over the catchment area for the mine voids and to drain into the void. Interception losses from vegetation were taken as the first 2 mm of every rainfall event. Annual average evaporation from the voids was assumed to be 763 mm/year. The modelled contribution of groundwater to salt load from both regional groundwater and spoil seepage in the pit lake was estimated to be 98.5% and 97.5% at years 50 and 500 years respectively reaching 1 million tonnes after 500 years from all mining voids in the Hunter. Other sources such as rainfall were considered negligible.

The study found that the two major influences on EC in the void were groundwater inflow and evaporation from the void water body surface with a steady increase in salinity over time. The modelled salt concentrations were found to be significantly greater than observed in the Hunter River. The potential for stratification in the void was thought to be reduced by the many different aquifers contributing groundwater input and the small depth to surface area ratio (8%). Stratification of the void water body is important due to the redox status at the bottom of the water body and the consequent impact on chemical reactions. The formation of a chemocline and permanently anoxic bottom layer if depth to surface ratio is greater than 10% may produce a

relatively permanent bottom layer of highly saline water provided no leakage or groundwater throughflow occurs.

The study acknowledged that the many variables, unknowns and data limitations increased the model's potential error range. It drew attention to the potential of mining to liberate sequestered salt stores in mine voids and goafs through the interaction of groundwater with spoil, overburden and fractured rock. It also raised the question of the potential use of low quality mine void water and pointed out the long term environmental risk to surface streams and groundwater resources should the scale and rate of liberated salt stores be increased.

The potential extent of coal and coal seam gas resources were mapped in 2011 as part of a draft Upper Hunter Strategic Land Use Plan (NSW Department of Planning, 2011) (Figure 3:9). These maps indicate that the mining potential for coal resources and CSG encompasses almost all of the Goulburn catchment, excluding only National Parks and areas previously mined.

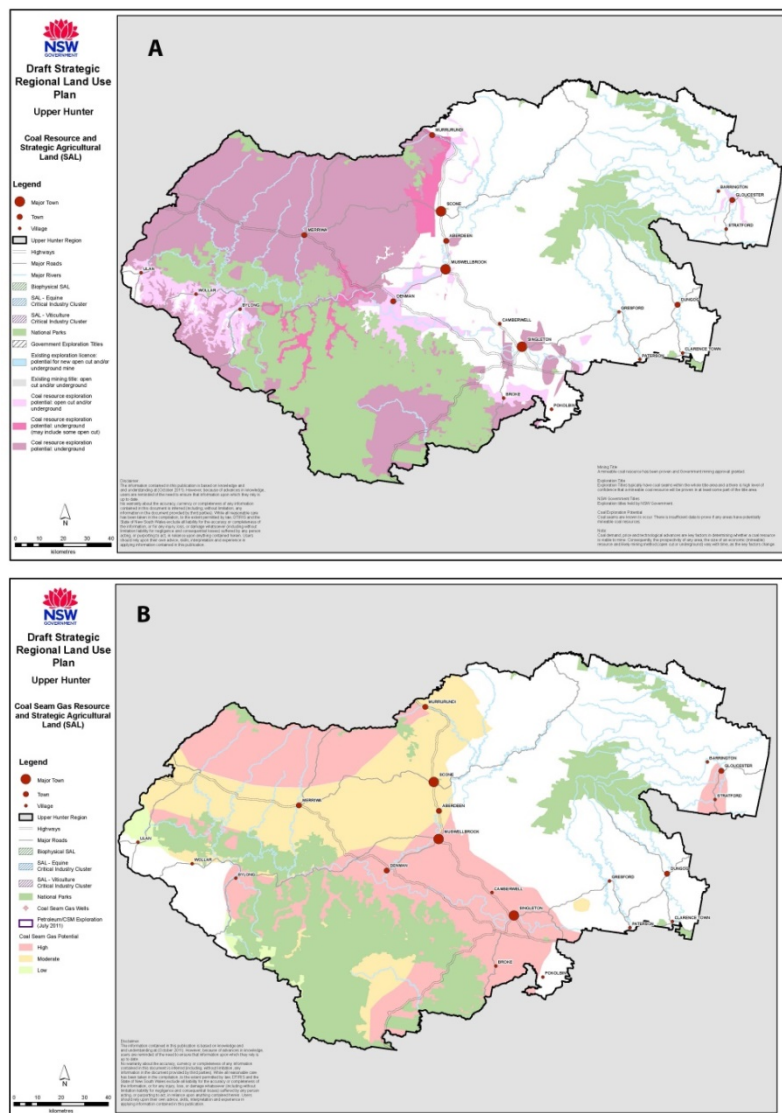


Figure 3:9 Upper Hunter draft strategic land use plan 2011 A) Coal resource potential (crimson = potential underground; light pink = open-cut ; mid pink = both B) CSG resource potential, pink=high potential; yellow=mod (NSW Department of Planning, 2011)

3.7 Water policy, legislation and plans

NSW Water Management Act (NSW Government, 2000) requires that the extraction of water under licensed rights must not prejudice the protection of a water source and its dependent ecosystems or basic landholder rights. The Act provides for the *‘sustainable and integrated management of the water sources of the state for the benefit of both present and future generations’*.

The vision for Water Sharing Plans (WSPs) in NSW is to provide for *“healthy and enhanced water sources and water-dependent ecosystems and for equitable water sharing among users in these groundwater sources”*. An important objective is to protect, preserve, maintain and enhance the important high priority groundwater-dependent ecosystems of these groundwater sources. However groundwater dependent ecosystems across the majority of the Goulburn catchment are not surveyed or mapped (BoM, 2016).

Allocations under WSPs do not include Basic Landholders (Water) Rights (BLR). BLR are made up of domestic and stock rights, harvestable rights and Native Title rights. Harvestable water rights in eastern and central NSW allow farm dams and mining operations to capture up to 10% of the average annual rainfall run-off from a catchment¹⁴ (Zhang *et al.*, 2016).

WSPs for the Hunter unregulated and alluvial water source commenced in 2009. Trading rules restrict the transfer of water licences in the Goulburn Extraction Management Unit (GEMU) to within that water source. Trading can be downstream but not upstream, so theoretically after 2009 there should be no net increase in the total amount extracted from the GEMU water sources, apart from any increases in basic water rights. However according to local landholder¹⁵ and irrigator groups’ water sources prior to commencement of the WSPs were over-allocated in the Bylong Valley (Table 3:4).

The *NSW Aquifer Interference Policy* (AIP) (NSW Office Of Water, 2012) provides considerations for impacts on groundwater associated with alluvial and porous-fractured rock aquifers. The AIP requires that aquifer interference activities do not induce a decline of greater than 2 metres in the cumulative pressure head or standing water level of a bore or well located nearby in highly or less productive groundwater sources. Also no extractive activity is to be within 200 metres from a highly connected surface water source that is defined as a reliable water supply or vertically 100 metres beneath the three dimensional extent of the alluvial water source. To protect surface water the AIP requires *“no increase of more than 1% per activity in the long term average salinity in a highly connected surface water source at the nearest point to the activity”*.

¹⁴ <http://www.water.nsw.gov.au/water-licensing/basic-water-rights/harvesting-runoff>

¹⁵ Bylong Valley Protection Alliance submission to Bylong Coal Project

Current regulations for Water sharing Plans exempt the mining industry in the Hunter Region from ‘cease-to-pump rules (CtP)’ if licences have been purchased as offsets to aquifer interference (groundwater that seeps into the mine and voids) on the grounds that they cannot feasibly be implemented. Groundwater take through mine aquifer interference require a water licence under the WMA 2000, unless an exemption applies in Water Management (General) Regulation 2011(DPI Water, 2016).

3.7.1 Water Sharing Plans and licences in the Goulburn catchment

The Goulburn River surface waters and alluvial aquifers are covered by the *Water Management Act 2000*, *Hunter Unregulated and Alluvial Water Sharing Plan* (2009) and the *Wybong Water Sharing Plan* (NSW Department of Water and Energy, 2009; NSW Government, 2000). Table 3:3 provides a summary of the sub-catchment water sources and applicable WSPs in the Goulburn catchment. As mentioned basic water rights including harvestable rights are not included in WSPs allocations and water may be extracted under these rights without the need for a water access licence. Groundwater bores for stock and domestic use require a water supply work approval license from DPI Water (Zhang *et al.*, 2016).

Table 3:3 Upper and Lower Goulburn River 10 sub-catchment water sources area, forest cover and annual rainfall in WSP report cards (NSW Department of Water and Energy, 2009; NSW Government, 2000)

Goulburn Water Sources Sub-catchments	Total Area km ²	Forested Area %	Annual Rain (mm)
Upper Goulburn River above Coggan (210006)	995	51	613
Wollar Creek	532	59	658
Munmurra River	694	14	634
Krui River	585	16	648
Bylong River	698	63	682
3503			
Bow Creek	392	12	574
Merriwa River	809	21	634
Widden Brook	708	83	746
Baerami Creek	423	80	665
Halls Creek	374	19	632
Lower Goulburn River above Sandy Hollow (210031)	787	46	601
3493			
TOTAL	6997		
Wybong Creek	793		

Extraction licences for fractured and porous rock groundwater in the Goulburn catchment are now part of the *Sydney Basin – North Coast Groundwater Source WSP* (SBNCGS) (DPI Water, 2016). Prior to 2016 fractured and porous rock groundwater were under *Part 5 Water Act*

1912 (NSW Government, 1912). The SBNCGS WSP applies to the deeper, non-alluvial groundwater sources in the Goulburn River. The licensed entitlement in the Hunter Management Zone, Sydney Basin - North Coast Groundwater Source is 33,471 MLs spread across 179 accounts with an additional 3,175 allocated to BLR (Ross and Webb, 2015). An estimated 69% of the entitlement volume is associated with a mining purpose including dewatering. The next largest licensed purpose is water for irrigation, which represents 17% of the total licensed volume (Ross and Webb, 2015). There is currently an embargo on the granting of water licenses in this WSP (NSW Government, 2016). However consideration is given to the release of a percentage of the volume of water in storage in porous rock groundwater systems in the Sydney Basin water source under *NSW Policy for Managing Access to Buried Water Sources* (NSW Office of Water, 2011).

Coal and coal seam gas projects in the Goulburn catchment have been referred under the Commonwealth water trigger for comment to The Independent Expert Scientific Committee (IESC, 2017) under the provisions of the Environment Protection and Biodiversity Conservation Act 1999 - EPBC Act). Coal mining operations in the Goulburn also influence the capacity of the NSW Hunter River Salinity Trading Scheme (Section 1.1) to manage and control salinity in the Hunter River. The IESC have expressed concern over the potential for increased salinity and heavy metals concentrations as a result of multiple mines discharging into the Goulburn River and eventually reaching the Hunter River.

The Coal mining industry groups water usage into three categories;

- Mining process (e.g. dust suppression),
- Industrial use (e.g. coal washing) and
- Incidental take resulting from intercepted aquifers and runoff (e.g. dewatering).

Accounting and reporting can be complicated with several purposes attributed to a single licence. Annual mine water balances reporting also use a mixed combination of measured, modelled and estimated “inflows (inputs) and outflows (outputs).

3.7.2 Estimating water allocation in the Goulburn catchment

Water use data records are not available in the Hunter due to the lack of comprehensive monitoring of surface and groundwater extraction. This means it is not possible to quantify the actual water use relating to agriculture, industry, or stock and domestic licences in the Goulburn catchment. Estimates can be made based on licensed volumes, patterns of use in metered areas and assumptions about basic water rights for landholders (Zhang *et al.*, 2016). Table 3:4 shows the number of water licenses entitlements and volumes (ML/year) applicable to each sub-catchment under *Hunter Unregulated and Alluvial Water Sharing Plan (2009) and the Wybong Water Sharing Plan (2003 merged with HUAWSP in 2016)*. One water unit allocation equates to one ML/year.

The total volume of surface and alluvial water licences entitlements allocated to the Goulburn catchment is 60,296¹⁶ ML/year. If all licences were used on a catchment basis this corresponds to 8 mm/year, an appreciable fraction of the catchment yield. However this does not include water licenses granted for fractured-porous rock groundwater sources in the Sydney Basin. In 2015 Coal Mines in the upper Goulburn had fractured-porous rock groundwater licenses totalling 13,351 ML/year (Chapter 6: Mining Impacts on the Upper Goulburn). The proposed Bylong Coal Mine holds another 1,596 ML/year of entitlements and is seeking an additional 2,093 ML for its mining development (AGE, 2018).

It is noted that water allocations are on a volumetric basis. No consideration is made of the salinity of the water in the sub-catchments. Given the significance of the Triassic fractured-porous rock water source and stream flow from these catchments in mitigating the salinity in the Goulburn, water quality should be an important consideration in water licencing in these areas.

Table 3:4 Summary Goulburn catchment water entitlements according to WSP sub-catchments for Hunter Unregulated and Alluvial Water source (NSW Department of Water and Energy, 2009)

Catchment Water Source	SW No. Lic. Shares	SW Entitlements ML/y	GW No. Lic. Shares	GW Entitlements ML/y	Stock & Domestic No. Lic. Shares	Stock & Domestic ML/y	Total ML/y	GE MU %
Upper Goulburn	15	1770	2	102	1	8	1880	3.1
Wollar Creek	7	103	7	1,222	5	20	1345	2.2
Munmurra			2	24	1	6	30	0.0
Krui River	14	1449	1	5	1		1454	2.4
Bylong	2	89	29	7,719			7808	12.9
Upper Goulburn							12,517	20.8
Bow	4	201	1	5	1	1	207	0.3
Merriwa	50	4451	12	1901	3	6.5	6358	10.5
Widden Brook	4	2022	6	1,206	1	5	3233	5.4
Baerami	11	1556	16	2,524			4080	6.8
Halls Creek	55	3250	11	691			3941	6.5
Lower Goulburn	85	14974	27	3,086	18	82.5	18143	30.1
Wybong	109	9157	26	2560	21	100	11817	19.6
Lower Goulburn							47,779	79.2
TOTAL	356	39,022	140	21,045	50	229	60,296	100

Blanks denote missing values. SW=Surface water

GW=Groundwater GEMU – Goulburn Extraction Management Unit

Source: Additional data supplied by DPIWater Nov. 2017 . Note: This table does not include water licences granted for the Sydney Basin-North Coast Fractured and Porous Rock Groundwater source or basic water rights

¹⁶ Other estimates of the total volume of surface and alluvial water licence entitlements in the Goulburn catchment are 58,909 (Zhang *et al.*, 2016) and 57,554 ML/day (Harris and Bird, 2018)

3.8 Conclusion

This chapter has described the Goulburn River study catchment which occupies 40% of the Hunter catchment. Its complex geology ranges from Narrabeen Group of Triassic sedimentary rocks underlain by Permian Coal Measures in the Sydney Sedimentary Basin in the south and west to the elevated Tertiary basaltic plateau, underlain by Jurassic sedimentary and Triassic sandstone topography in the north. Aquifers within those formations as well as alluvial aquifers play a significant role in providing base flow to the Goulburn and in supporting as yet unmapped groundwater-dependent ecosystems. Groundwater from the Permian Coal measures is the principal source of salinity in the catchment.

Early work, based on a rising groundwater model due to land clearing, and measurements of stream salinity spanning wet and dry periods predicted increasing stream salinity in the catchment to the year 2100. Later work shows that salinity discharge waxes and wanes with increasing and decreasing rainfall suggesting that changing climate could change the salt dynamics of the catchment. Results from sub-catchments of the Goulburn show that discharge from the southern and western Triassic sandstones mitigates salinity in the Goulburn.

The region supports a diverse mix of eastern and western plant species reflecting the east-west orientation and the low elevation of the Great Dividing Range at the western limit of the catchment. Approximately 44% of the catchment is covered by woody vegetation centred on areas with poorer soils, steep slopes or in National Parks. Approximately 48 % of the region is cleared for grazing and around 4-5% for cropping concentrated on the better soils in the Merriwa basaltic plateau in the north and within incised Permian valleys in the south. Devastating floods and soil erosion in the 1950s led to major construction of farm dams and contour banks across agricultural regions in the upper catchment in the 1960s to early 1990s. Changing farming practices due to changes in regulations over recent decades may have resulted in an, at present, unquantified increase in woody vegetation.

Open cut and underground coal mining in the upper catchment expanded greatly in the 1980s and more recently from 2004. Coal mining leases (MLs) now cover over 180 km² across the headwaters of the Goulburn River, or 5.5% of the upper catchment. Mining follows the Permian coal measures that dip to the northeast along incised valleys and under sandstone escarpments. The mines in the Goulburn catchment are not covered by the HRSTS. Since 2003 they have been required to desalinate mine water prior to discharge into the Goulburn with the maximum EC set at 900. Further expansions of mining are currently under assessment.

Hunter unregulated and alluvial water source Water Sharing Plans (WSP) commenced in 2009 under the NSW Water Management Act (NSW Government, 2000). The Sydney Basin Fractured and Porous Rock Groundwater source WSP was declared in 2016 (NSW Department of Primary Industries, 2016). Previously deeper, non-alluvial groundwater sources were licensed under Part 5 - 1912 Water Act. Water extraction licences do not include domestic and stock

rights, or harvestable water rights. The latter allow farm dams and mining operations to capture up to 10% of the average annual rainfall run-off from a catchment. There is no comprehensive monitoring or reporting of surface and groundwater extraction in the Goulburn. It is estimated here that the total licenced water allocation for alluvial and surface water sources in the Goulburn catchment is just under 60,300 ML/y. If all licenced allocations were used this translates into 8 mm/y over the entire catchment, a substantial fraction of the annual yield. This does not include Sydney Basin Fractured and Porous Rock sources, in which over 13,000 ML of groundwater licences are held by Coal Mines in the Ulan area.

It is clear that these allocations of water licences are based on the assumption that there will not be major changes in climate or catchment yield. These are examined in the next chapter.

Chapter 4: Changing climate and catchment yield

Chapter 2 summarised projections for changing climate in south eastern Australia and Chapter 3 identified land use changes in the Goulburn catchment. The aim of this chapter is to assess the region's climatic characteristics, rainfall variability and trends and their influence on catchment yield and trends in catchment yield. This chapter examines the prevailing climate, stream discharge and catchment yield of the Goulburn catchment using data from 1920 to 2014. In order to investigate long term changes monthly or annual data is used. Spatially interpolated monthly rainfall data are analysed to examine mean behaviour, variability and temporal trends in precipitation as well as identifying catchment-wide extreme dry periods. Because of the limited reliable data, pan evaporation trends since 1970 are analysed. The response of the Goulburn River to climate drivers and long term changes are explored.

4.1 *Climate characteristics*

The Goulburn catchment has a temperate to subhumid climate with hot summers, though there is no distinct dry season (Stern *et al.*, 2000). The mean monthly temperature (1970-2016) can reach a maximum of 31 °C in summer and fall to a minimum of around 2 °C in winter (BoM, 2018b). Rainfall is spatially variable across the catchment due to the wide range of topography. Mean annual precipitation ranges from 590mm at Denman to over 1130 mm at higher altitudes in the Liverpool Ranges in the north and 940 mm at Nullo Mountain (Station No.062100) in the south. The mean annual rainfall based on data collected by the Bureau of Meteorology (BoM) climate monitoring station at Ulan Post Office (Station No. 062036) between 1906 and 2015 was 644 mm; at Gulgong (Station No.062013) between 1881 and 1915 was 651 mm; and at Merriwa (Station No.062013) between 1890 and 2014 was 590 mm.

The average rainfall 1920-2014 for the Goulburn catchment based on spatially interpolated data was 675 mm (Hutchinson *et al.*, 2014; Hutchinson and Xu, 2013). Average monthly rainfall varied from 42 mm during May to 88 mm in January. The average spatially interpolated annual class A pan evaporation for the whole catchment was 1496 mm (1920-2014), ranging from a minimum of 44 mm in June to a maximum of 219 mm in January.

4.1.1 Rainfall

Interpolated rainfall grids for the period 1920-2014 were generated for the upper Goulburn (catchment above Coggan) and lower Goulburn (catchment above Sandy Hollow) and the Merriwa sub-catchment (Appendix A). These grids were calculated from elevation dependent thin plate spline surfaces fitted to Bureau of Meteorology monthly precipitation data using the

ANUSPLIN¹⁷ package (Hutchinson and Xu, 2013) and a regular grid digital elevation model (DEM) with resolution of around one square km (see 2.2) (Hutchinson *et al.*, 2014)

Interpolated catchment rainfall records over the period 1920-2014 for above Coggan gauging station (upper) and above Sandy Hollow gauging station are closely similar. The mean annual precipitation in the Goulburn catchment over the period was 675 mm/year with coefficient of variation (CV) 0.27 (Table 4:1). The average annual rainfall for the 30 years 1985-2014 increased to 699 mm (CV=0.23) in the upper catchment and 695mm (CV = 0.22) across the whole catchment above Sandy Hollow. Monthly rainfall shows some seasonality with higher rainfall in the warmer October to March period and lower rainfall in the cooler April to September season (Figure 4:1).

Table 4:1 Temporal trends in annual; warm and cool season rainfall, for the upper (above Coggan) and whole Goulburn catchment (above Sandy Hollow) based on spatially interpolated monthly precipitation.

Catchment	Property	Period	Mean Value (mm) [CV]	Non Parametric*		Linear Regression		
				Trend (mm/decade)	Significance	Trend (mm/decade)	Standard Error (mm/decade)	Significance
Upper Goulburn above or at Coggan gauge	Precipitation 1920-2014	Annual	675 [0.267]	10.1	ns	9.7	6.7	ns
		Oct-Mar	400 [0.323]	11	p > 0.95	9.7	4.8	p > 0.95
		Apr-Sep	276 [0.365]	1.2	ns	-0.1	3.8	ns
	Precipitation 1985-2014	Annual	699 [0.231]	-28.1	ns	-14.6	34.7	ns
		Oct-Mar	414 [0.237]	-32.2	ns	32.3	20.1	ns
		Apr-Sep	283 [0.372]	-41.8	p>0.95	-39.8	21.3	p>0.90
Lower Goulburn above Sandy Hollow	Precipitation 1920-2014	Annual	675 [0.257]			9.3	6.5	ns
		Oct-Mar	399 [0.322]			9.4	4.9	p > 0.95
		Apr-Sep	272 [0.361]			-0.38	3.7	ns
	Precipitation 1985-2014	Annual	695 [0.216]			-13.3	32.3	ns
		Oct-Mar	413 [0.246]			0.14	21	ns
		Apr-Sep	280 [0.361]			-36.5	20.9	p>0.90

* non-parametric Theil-Sen slope estimator (Theil, 1950).

¹⁷ <http://fennergchool.anu.edu.au/research/publications/software-datasets/anusplin>

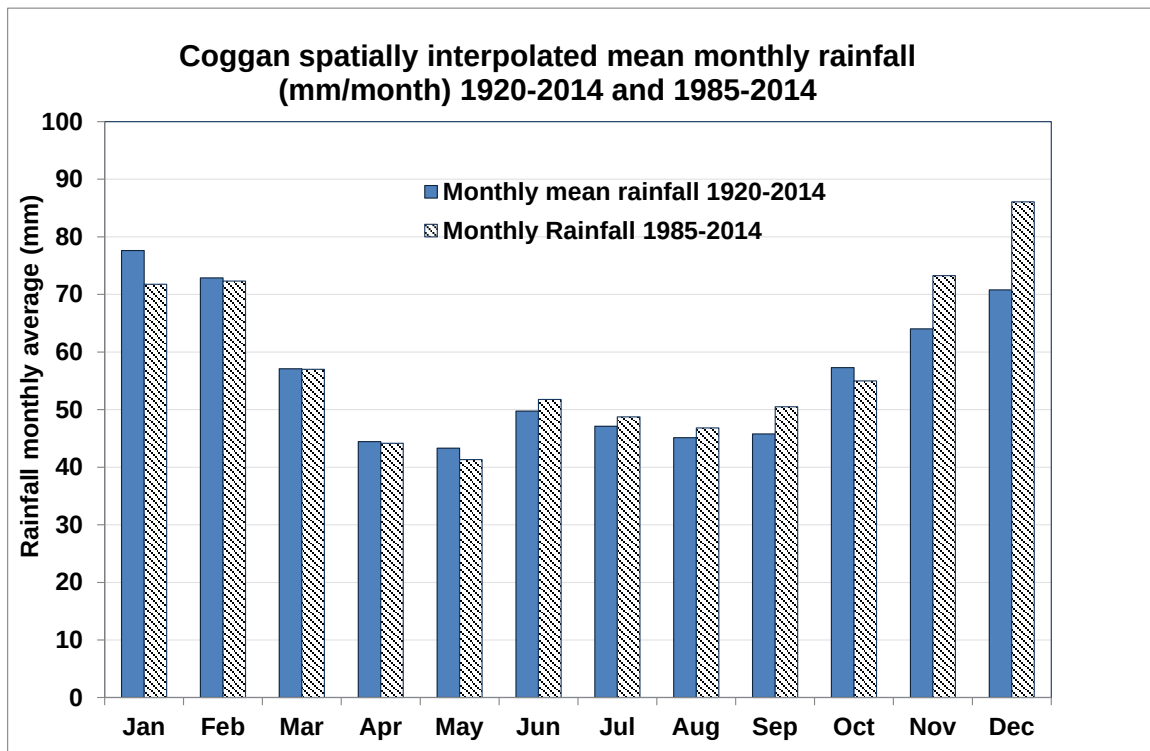


Figure 4:1 Upper Goulburn Catchment (Coggan) mean monthly rainfall (mm) 1920-2014 (95 years) and 1985–2014 (30 years)

4.1.2 Pan evaporation

Interpolated monthly grids of pan evaporation (Epan) for the upper Goulburn catchment based on BOM regional Epan data sets were generated using ANUSPLIN program (Hutchinson and Xu, 2013; Hutchinson *et al.*, 2014). Data prior to 1970 were discarded as they were both limited and unreliable due to the absence of animal guards. Epan is inherently less variable than precipitation. Mean annual interpolated Epan for the catchment above Coggan for 1970 to 2014 was 1574 mm (CV = 0.093) while for the period 1985 to 2014 it was essentially identical, 1563 mm (CV = 0.85) (Table 4:2). The monthly distribution of Epan in Figure 4:2 follows the seasonal distribution of solar radiation. The dryness index for the Goulburn catchment, $E_{pan}/P = 2.3$, shows that the catchment is generally water limited.

Table 4:2: Temporal trends in annual; warm and cool season Epan, for the upper (above Coggan) based on spatially interpolated monthly Epan

Catchment	Property	Period	Mean Value (mm) [CV]	Non Parametric*		Linear Regression		
				Trend (mm/decade)	Signific	Trend (mm/decade)	Standard Error (mm/decade)	Signific
Goulburn above or at Coggan gauge	Pan Evaporati on 1970-2014	Annual	1574 [0.093]	-3.8	ns	-6.5	17	ns
		Oct-Mar	1118 [0.132]	-6.3	ns	-7	17	ns
		Apr-Sep	449 [0.112]	-0.6	ns	-1.5	5.9	ns
	Pan Evaporati on 1985-2014	Annual	1564 [0.085]			-4.4	29	ns
		Oct-Mar	1111 [0.133]			-25.2	31	ns
		Apr-Sep	451 [0.095]			7.2	9.2	ns

* non-parametric Theil-Sen slope estimator (Theil, 1950).

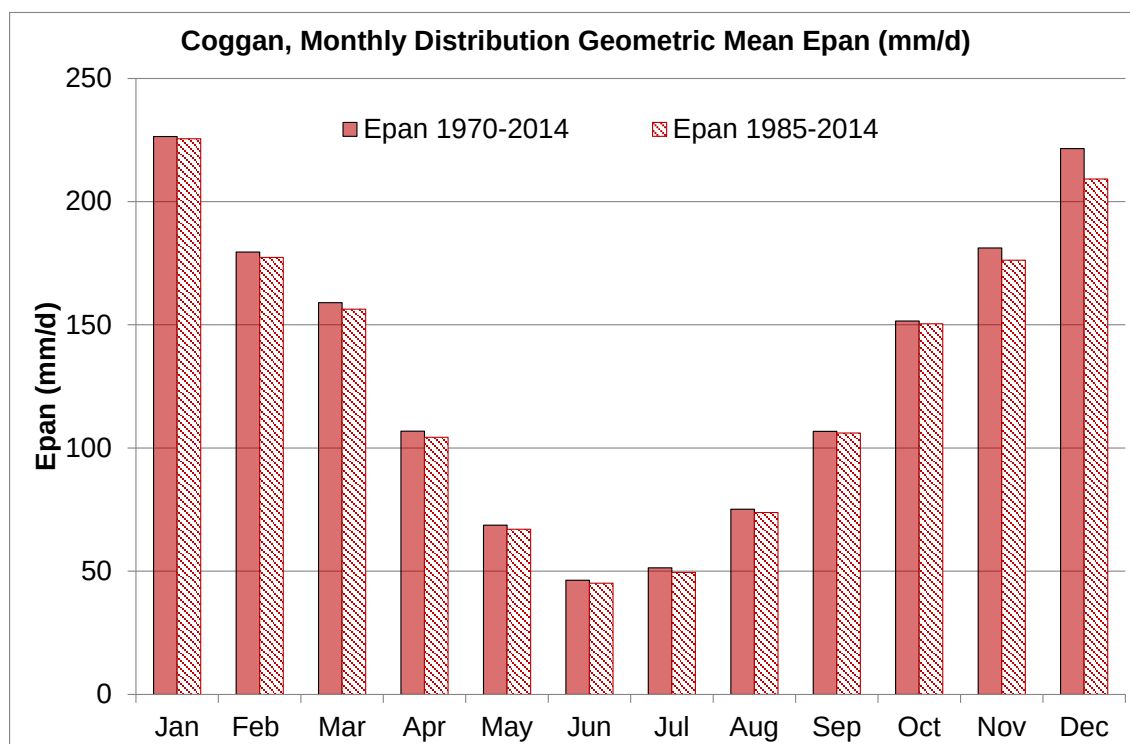


Figure 4:2 Spatially interpolated mean monthly Epan (mm/d) 1970-2014 and 1985 to 2014 Coggan, upper Goulburn

4.2 Climate Trends

Overall trends in the region's climate are discussed in 2.1 Climate change, ocean-atmosphere interaction and rainfall variability.

4.2.1 Trends in rainfall

Despite the variability in seasonal rainfall there was a statistically significant ($p > 0.95$) increasing trend for the period 1920-2014 warm October to March season rainfall of 10mm/decade (Table 4:1, Figure 4:3). The increase in warm season rainfall is possibly linked to the rise in ocean temperatures in the Pacific and Indian Oceans over the last century of about

1°C (CSIRO, 2015). The long term trends in annual or cooler April to September season precipitation were not significant ($p < 0.9$).

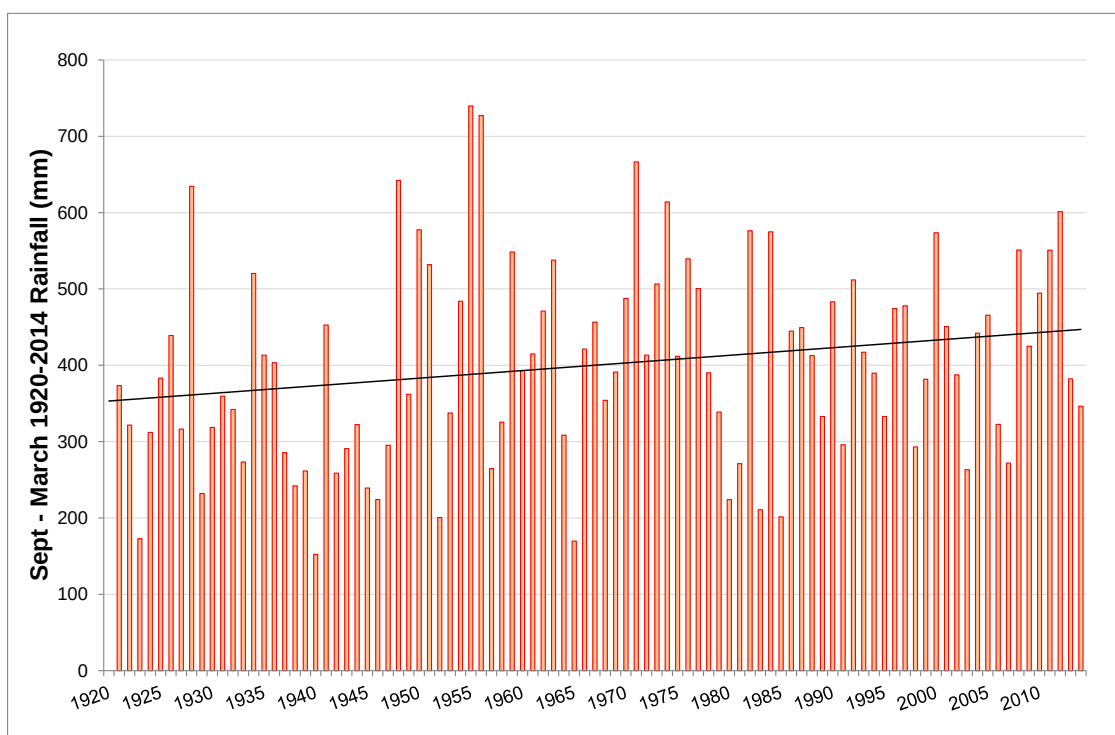


Figure 4:3 Interpolated rainfall 1920 to 2014, for the upper Goulburn catchment (Coggan). Warm season, October to March shows a significant trend

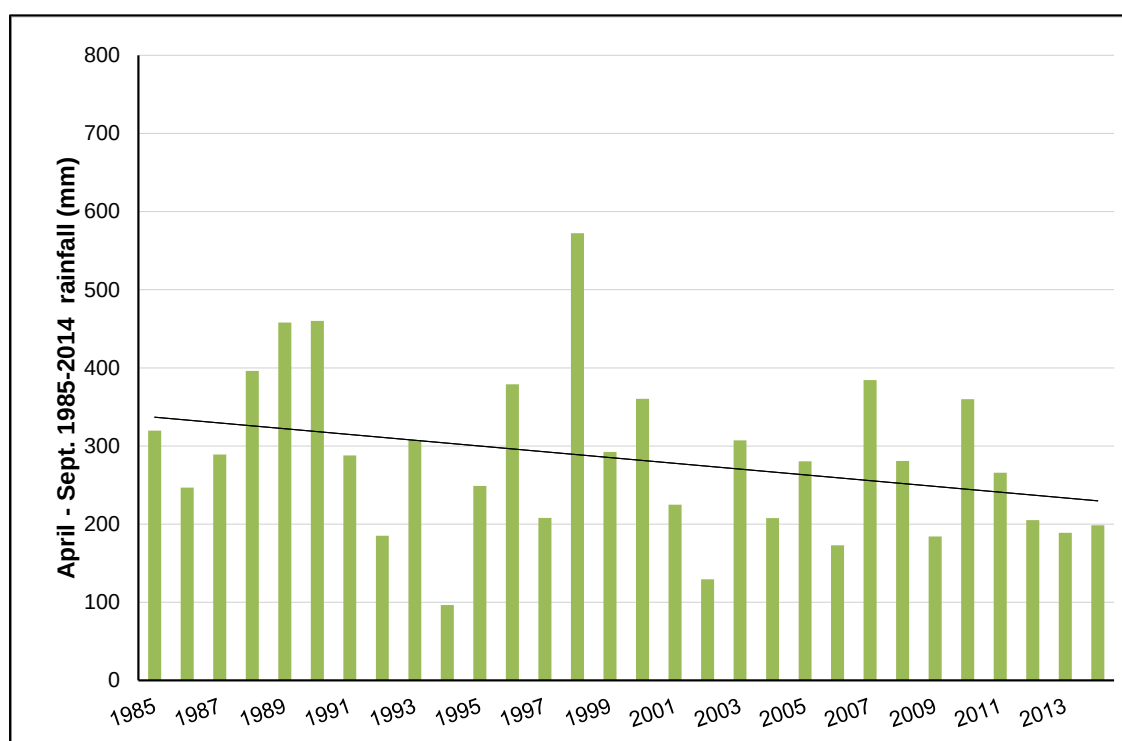


Figure 4:4 Interpolated rainfall trends 1985-2014 (30 Years) Goulburn above Coggan GS cool season trend (Apr–Sept) shows a weakly significant linear regression (Table 4.2).

However the shorter 30 year rainfall period 1985-2014 had a weakly significant negative trend in rainfall of magnitude 40 mm/decade (Table 4:1, Figure 4:4). A decreasing trend in cooler season rainfall could have significant impacts on both stream discharge and groundwater recharge and a drying trend in cool season rainfall is consistent with the broad climate change predictions for changing frontal patterns projected for winter (CSIRO, 2015). However the short term fluctuation in cool season rainfall since 1985 could be due to natural variability from alternating drought-dominated and flood-dominated regimes (Erskine and Warner, 1988; Erskine and Warner, 1998) tied to long term ocean-atmosphere oscillations such as the Pacific Decadal Oscillation (PDO) (Figure 2:8) (Krishnan and Sugi, 2003).

To test the significance of the 30-year trend in cooler season rainfall in the context of the long-term behaviour of the catchment, the most significant of the successive 30-year trends (Table 4:3) were compared to the long-term trend of annual cooler season rainfall 1920-2014. Figure 4:5 illustrates the fluctuating nature of precipitation in the Goulburn. There have been two significant decreasing trends beginning around 1948 and 1983, with swings from negative to positive starting in the 1920s and 1960s in cooler season precipitation. Over the period of interest for catchment there are no significant trends in cooler season precipitation. This means catchment management water sharing plans would need to be sufficiently flexible to accommodate such large scale swings over 30 year periods in catchment precipitation.

Table 4:3 Cool season 30 year trends, with significance

Period	Trend (mm/decade)	Significance
1923-1952	45	>0.96
1948-1977	-41	>0.94
1961-1990	35	>0.93
1983-2012	-37	>0.90

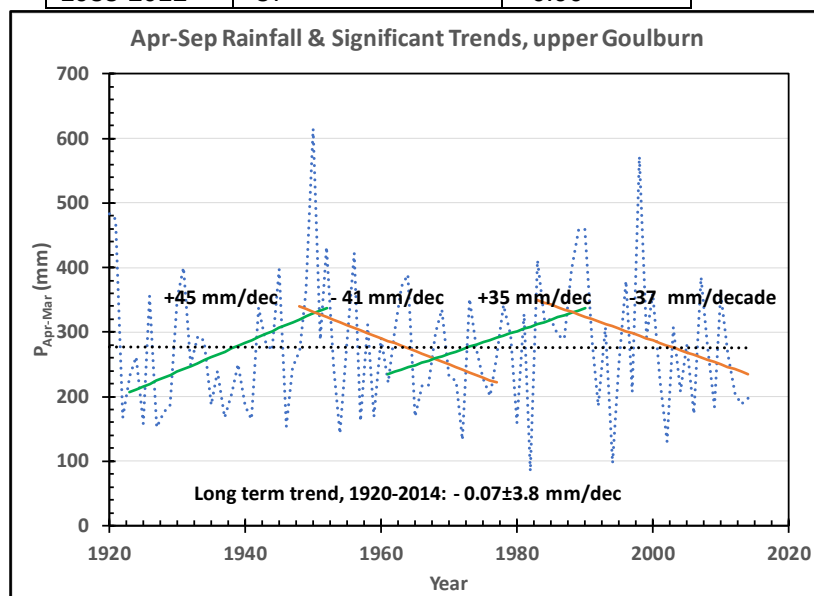


Figure 4:5 Annual April to September precipitation in the upper Goulburn catchment and the significant 30-year regression trends. Also shown is the nonsignificant long-term trend in cooler season precipitation for the period 1920 to 2014.

4.2.2 Trends in pan evaporation

The results summarised in Table 4:2 show the trend in Epan from 1970 – 2014 and 1985-2014 for the upper Goulburn (above Coggan) with the mean monthly distribution for Epan shown in Figure 4:6. None of the trends for annual and or seasonal Epan for either period were statistically significant ($p > 0.9$). This differs from the results of Roderick and Farquhar, 2002; Roderick *et al.*, 2007 who found general decreasing trends in Epan, although there were marked spatial variations in fitted trends. Bureau of Meteorology trend maps show a close to zero trend in annual pan evaporation in the Goulburn catchment region from the 1970s to the present (BoM, 2017).

4.2.3 Extreme climatic events

4.2.3.1 Meteorological Droughts

Assessing changes in the behaviour of droughts over time depends on the drought indicators used and time scale applied (refer 2.3). For agriculture cumulative rainfall totals and soil moisture levels over three month periods are normally considered as this relates to the formal agricultural drought declaration criteria. That is when the rolling three monthly rainfall is below the 0.01 percentile (CSIRO, 2015). In this work we are concerned with long term changes and will examine longer periods.

For assessing water deficit conditions likely to affect large hydrological systems dependent on groundwater recharge over longer timescales, cumulative monthly rainfall data for 12 month, 2, 5 and 10 years periods are often appropriate (CSIRO, 2015; Erskine and Warner, 1988; Erskine and Warner, 1998). These longer periods capture an extended lag times between rain events, stream flow and groundwater discharge response and minimizes the influence of seasonal variability.

To identify periods of long-term meteorological drought, percentile rankings for the previous 12 month, 5 year and 10 year rainfalls were calculated based on spatially interpolated rainfall data for the catchment above Coggan (1920-2014) (Figure 4:6; Figure 4:7; Figure 4:8). Rainfall rankings that drop below 0.3 percentile (red line) represent extended dry periods of below average rainfall (Gibbs, 1975). During these low rainfall periods, groundwater baseflow can be the main component of baseflow and subsurface flow that support groundwater dependent ecosystems.

Figure 4:6, Figure 4:7, and Figure 4:8 (12 month, 5 year and 10 year percentiles rankings) all show that the incidence of extended dry periods occurred more frequently prior to 1950. For 5 year percentile rankings (Figure 4:7) only the 1940s fell below the 0.05 percentile, while the 1960s, 1980s and millennium drought all fell below 0.3. For 10 year rainfall percentile rankings (Figure 4:8) post 1950s, the main years that the rankings fell well below the 0.3 percentile line was during 1983-1988 - apart from a brief period in 1966. This analysis shows that the World

War II drought meteorological period was more severe than the much discussed millennium drought (2001-2009) while the 1980-1983 drought was more severe than the millennium drought in terms of 12 month and 10 year decadal percentiles

If the catchment is relatively unchanged in its response to rainfall, then it is expected that long term catchment yield in the Goulburn should be at its lowest during the World War II drought.

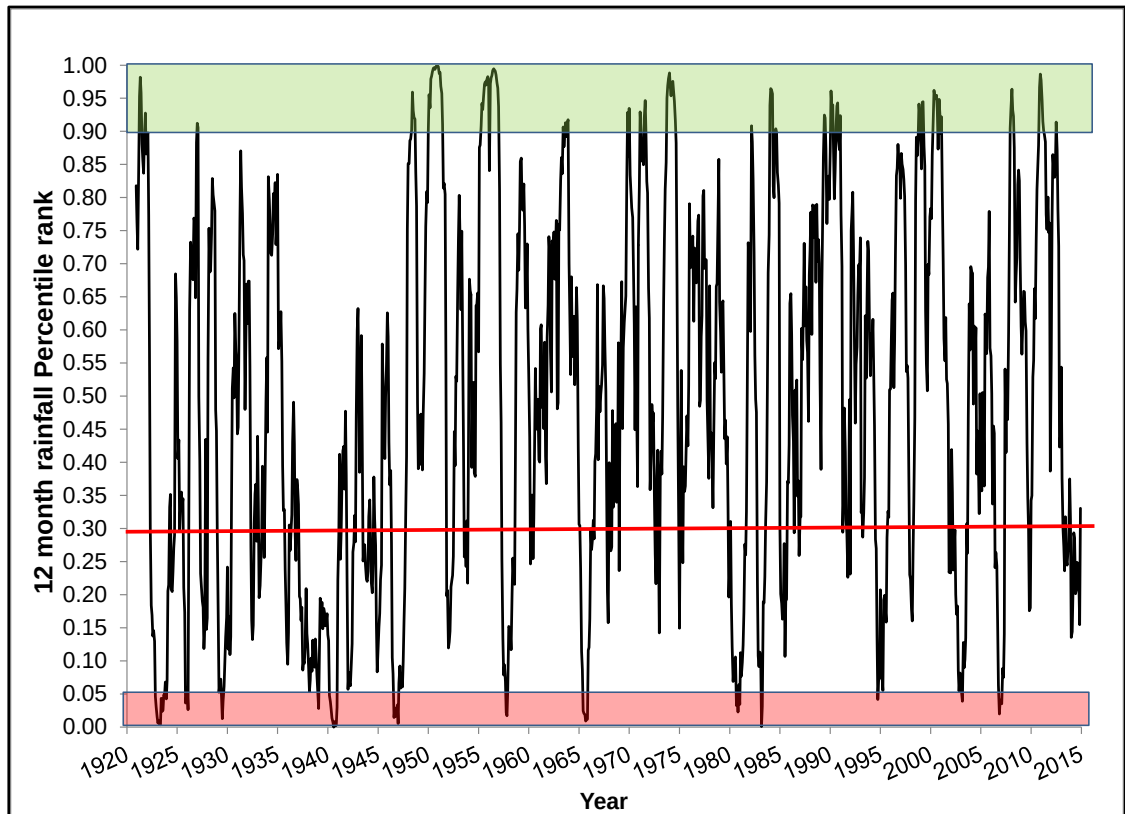


Figure 4:6 Percentile ranking rainfall - upper Goulburn 12 month rainfall percentiles 1920-2014

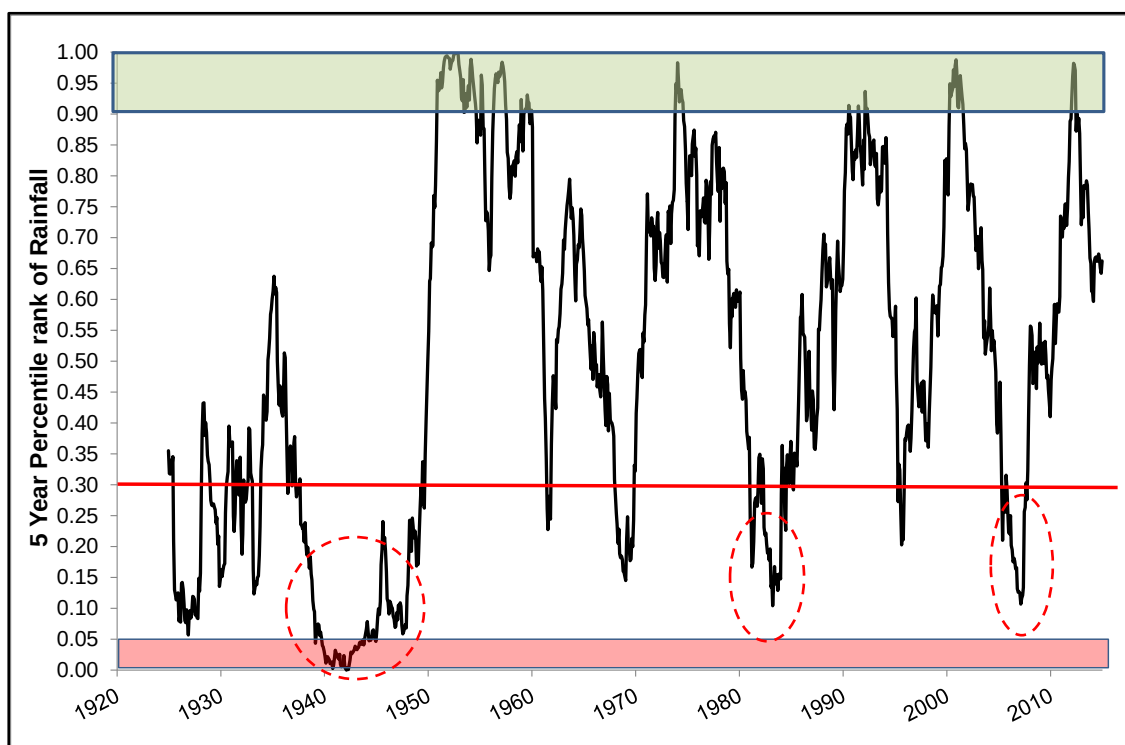


Figure 4:7 Five year rainfall percentile Upper Goulburn 1920-2014

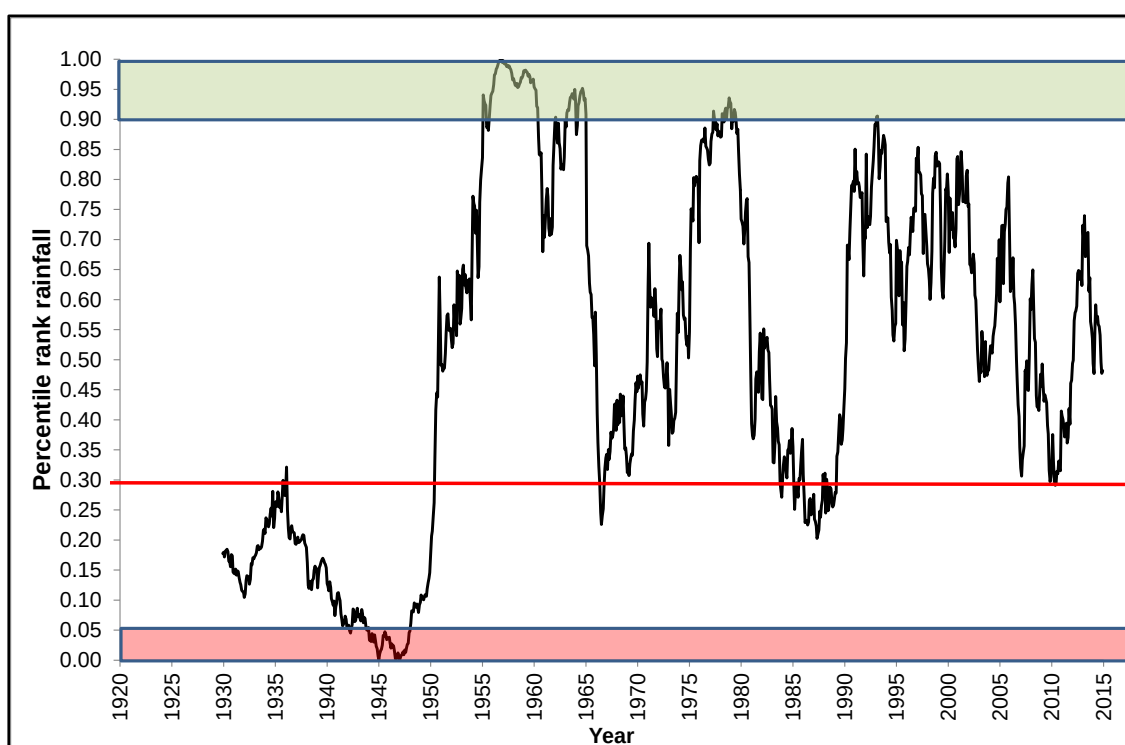


Figure 4:8 Decadal - 10 year rainfall percentiles Upper Goulburn 1920-2014

4.3 Catchment water yield

NSW Government DPI-Water¹⁸ operates three active stream gauging stations on the Goulburn River - Coggan (GS 210006); Kerrabee (GS 210016); Sandy Hollow (GS 210031); two on the Merriwa River – Merriwa Town (GS 210019) and U/S Vallance (GS 210066); and one on Wybong Creek (GS210040) (Figure 4:9). The other stream gauge sites shown have been inactive for many years and only cover a limited range of years (Table 4:4, Figure 4:9)

Table 4:4 Stream Gauges details - Goulburn River, Merriwa River and Wybong Ck

LOCATION	Site Number	Lat:	Long:	Area km ²	Elevation mAHD	Monitoring Period	Salinity data
GOULBURN RIVER							
Ulan (US)	210046	-32.2822	149.7438	159	403	1968-82	Monthly grab
Coggan	210006	-32.3444	150.1013	3340	221.333	1913-present	May-12
Kerrabee	210016	-32.4166	150.3201	4950	162.841	1960-Present	Jul-02
Sandy Hollow	210031	-32.3452	150.5743	6810	126.655	1955-present	Feb-92
MERRIWA RIVER							
Merriwa Town	210091	-32.1401	150.3539	465	238.955	1972- present	n/a
U/S Vallance Ck	210066	-32.2963	150.3343	684	189.575	1963-present	Jun-02
WYBONG CREEK							
Wybong Ck@bridge	210040	-32.2693	150.6360	676	144.92	1955-present	Jul-93

Goulburn stream gauge records contain significant temporal data gaps in streamflow and water quality records caused by non-continuous and interrupted monitoring, terminated programs, and systemic technical difficulties related to stream sand bed controls. Where identified anomalous zero values for flow and negative salinity EC readings were removed. Data gaps were infilled using the highest correlated relationship between monthly stream discharge and previous rainfall (Appendix B).

The station at Sandy Hollow (GS210031) is the last gauging site before the Goulburn's confluence with the Hunter River and a key site where trends due to either climate or land use change may be discernible. Unfortunately, the sand sediment control structure at the Sandy Hollow gauging station is highly mobile and subject to by-pass flow and EC probe failure when exposed to air, as indicated by the many data gaps and spurious readings. The monthly stream records for Sandy Hollow contain 25 data gaps and 40 zero or anomalous negative readings, with zero flows recorded on 996 days or 12% of all daily records. Quality control records indicate over 75% of the daily stream flow data 1954-2016 has not been quality coded and is subject to change, ratings were applied up to 2004 (DPI Water, 2018; BoM, 2018a; SKM, 2010). Stream data for 2010-2016 were most complete with no gaps, or anomalous negative readings for Q or EC data. Sandy Hollow has a shorter flow record than at Coggan (GS210006) commencing in 1954 but a longer salinity record for electrical conductivity (EC) – starting in 1992).

¹⁸ previously NOW - NSW Office Water

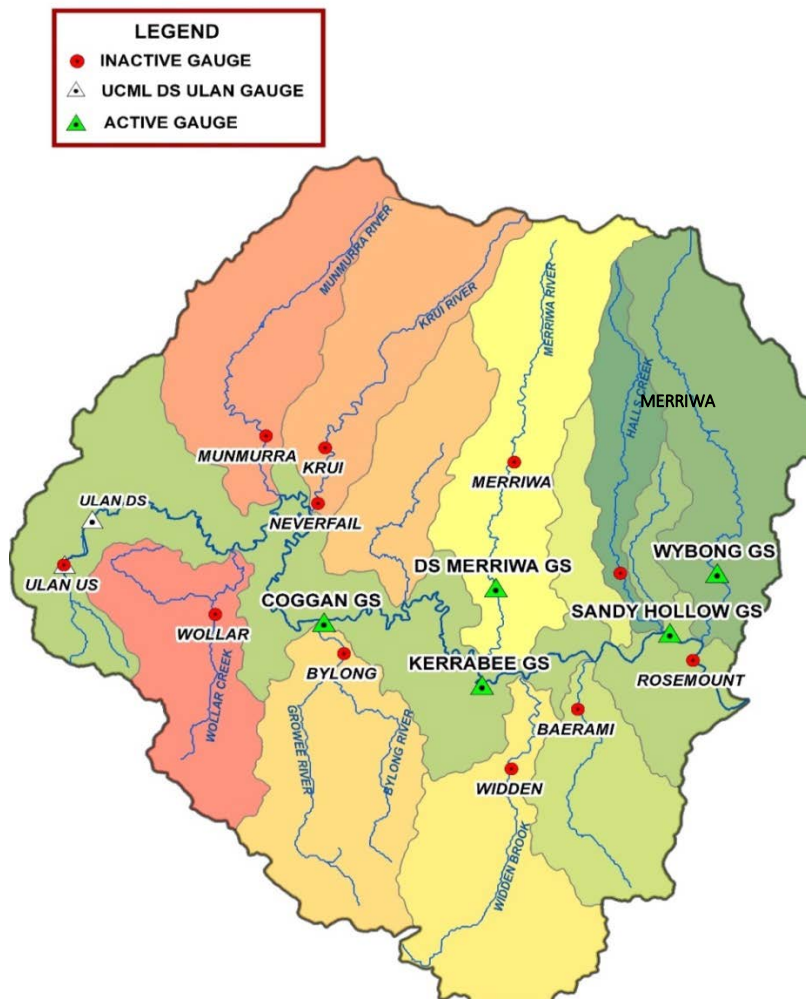


Figure 4:9 Goulburn River active (green) and inactive (red) catchment stream gauging stations (GS), locations, and tributary sub-catchments (DPI Water, 2018)

The Coggan Stream Gauge (GS210006) monthly discharge dataset for the upper Goulburn catchment contained the longest discharge records from 1913 to 2016. There were 62 months of missing monthly stream discharge data out of a total of 1248 months between 1913 and 2016 representing 5% of the total recorded data. The daily stream discharge flow ratings were investigated for the Coggan gauge. This indicated ratings curve had been adjusted at critical periods (Appendix B2). The Coggan gauging station was considered the most reliable stream flow data source, as well as having the longest flow records.

The period December 1943 to April 1944 was found to contain anomalous data. This period and gaps in monthly stream discharge were infilled with correlated streamflow data (Appendix B). Monitoring data for daily EC commenced in May 2012 and comprises a complete dataset to 2016.

4.3.1 Characteristics of stream discharge

This study has concentrated on the Coggan gauge record of stream discharge because of the uncertainties and the shorter record of stream flow at Sandy Hollow. Table 4:5 shows the mean annual specific discharge Q/A at Coggan between 1920 and 2014 was 23.4 mm (CV = 1.37) while between 1985 and 2014 the mean annual Q/A was 20.5 (CV = 1.09). Table 4:5 also shows the median specific discharge is much lower than the mean indicating that the distribution of Q/A is positively skewed. The minimum annual specific discharge for the period 1920 to 2014 was 0.15 mm/year in 2006 while the maximum was 206 mm/year in 1950.

Table 4:5 Mean and median annual and seasonal specific discharge and analysis of trends for the Goulburn River at Coggan for the periods 1920 to 2014 and 1985 to 2014 (not significant = ns<0.9)

Years	Period	Mean Q/A (mm) [CV]	Median Q/A (mm)	Non Parametric		Linear Regression		
				Trend (mm/ decade)	Signif	Trend (mm/ decade)	Standard Error (mm/ decade)	Signif
1920- 2014	Annual	23.4 [1.37]	13.4	0.17	ns	-0.03	1.2	ns
	Oct-Mar	12.6 [1.43]	6.2	-0.09	ns	0.005	0.7	ns
	Apr-Sep	10.9 [1.68]	5.6	0.02	ns	-0.04	0.7	ns
1985- 2014	Annual	20.5 [1.63]	11.2			0.51	4.8	ns
	Oct-Mar	9.2 [2.06]	5.3			2.9	2.7	ns
	Apr-Sep	11.6 [1.62]	5.2			-2.1	3.9	ns

Figure 4:10 shows the response of mean and median monthly stream flow to median monthly rainfall at Coggan for the period 1920 to 2014. Two peaks in mean monthly stream flow occur, one in July in response to higher rainfall in June and much lower evaporation (Figure 4:2) and one in February in response to peak rainfall in January. Two things are noticeable about this mean behaviour. The first is the one month lag in stream response to peak rainfall, indicating a slower groundwater response, and the second is that despite the much larger evaporation during warmer season months, significant stream flow is still generated by the peak warmer season rainfall. The main peak in median monthly stream flow is during August in response to winter rainfall followed by a second peak in October coinciding with spring rainfall. The third somewhat subdued peak in March for median monthly stream flow follows peak warm season rainfall in January and February suggesting a delayed groundwater response.

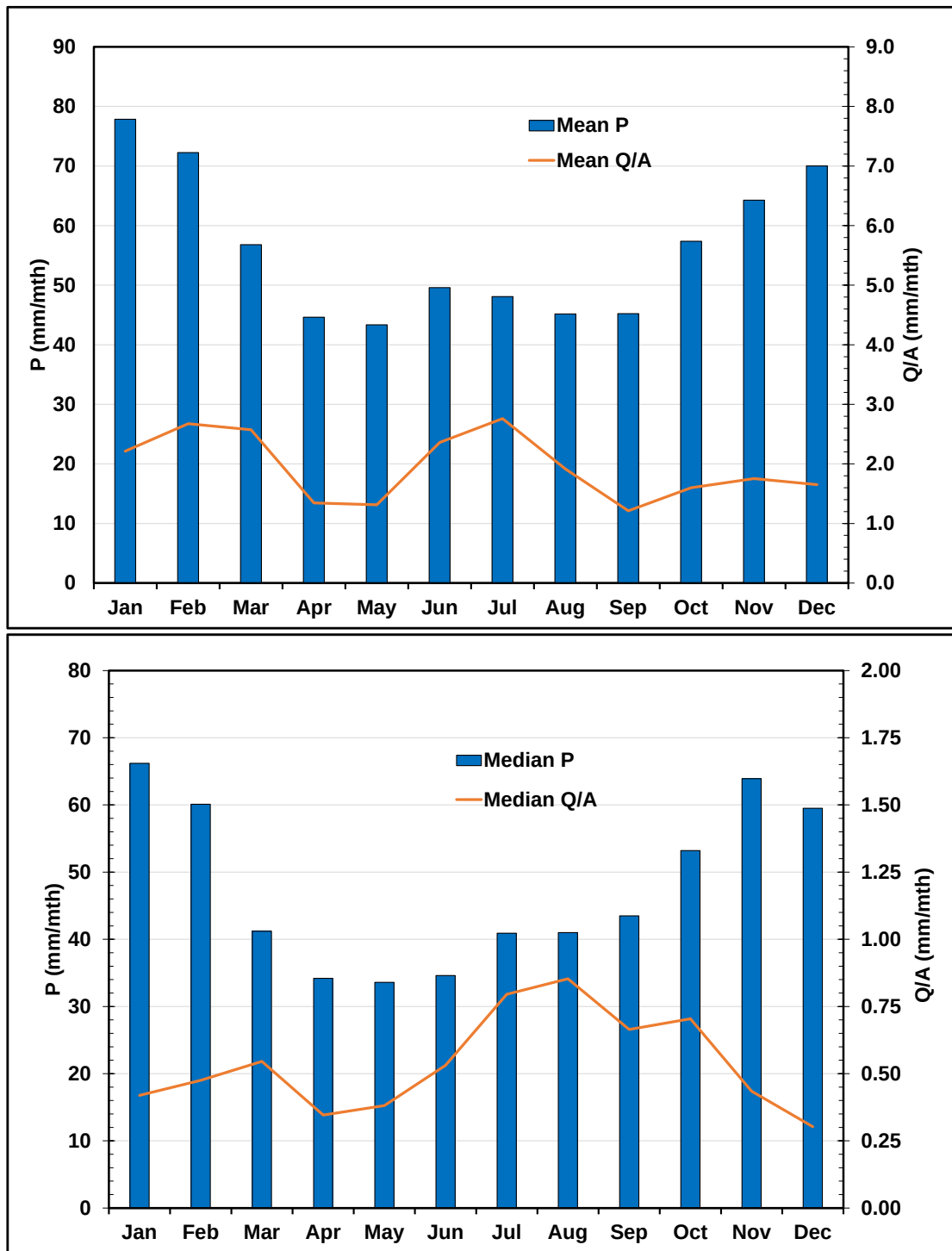


Figure 4:10 Upper Goulburn Catchment (Coggan) mean and median monthly precipitation P and monthly specific discharge Q/A (mm/mth) 1920-2014

The long-term mean runoff coefficient, RO, is a key characteristic of any catchment, fundamental to planning water allocations. Figure 4:11 shows the cumulative monthly specific yield, (Q/A) (mm) plotted against cumulative monthly rainfall, P (mm). From this a mean RO over the full period can be estimated from;

$$RO = \frac{\sum Q/A}{\sum P} \quad [4:1]$$

Here Q is monthly discharge (ML); A is area of catchment (km^2) and P is monthly rainfall (mm)

Figure 4:11 shows that the mean runoff coefficient for the full period is 0.036. Significantly lower slopes can be seen during the 1930-1950, 1975 to 1985, 1990 to 1994 and 2000 to 2006 corresponding to protracted dry periods in the catchment.

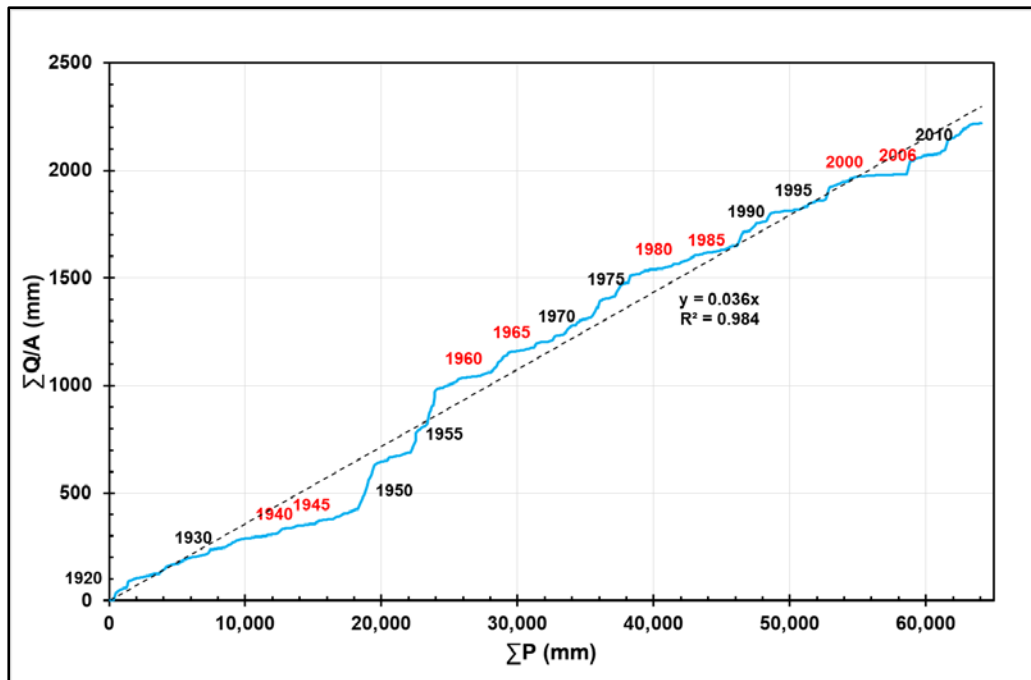


Figure 4:11 Upper Goulburn catchment cumulative monthly specific yield as a response to cumulative monthly rainfall 1920 – 2016

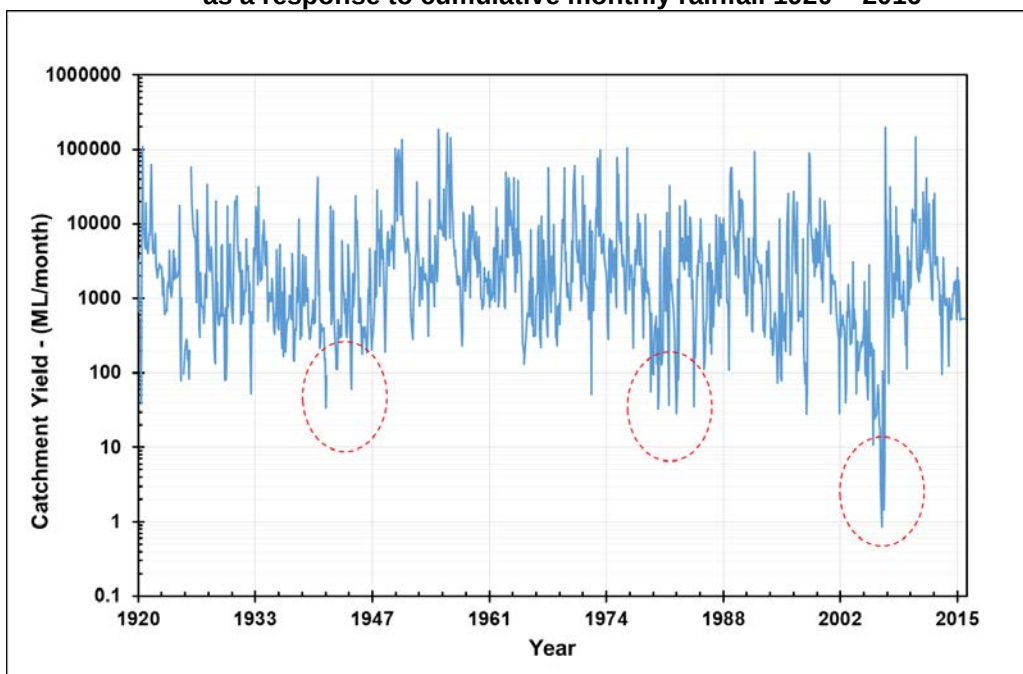


Figure 4:12 Monthly stream discharge (ML/month) Coggan 1920 - 2016 upper Goulburn catchment

Figure 4:12 shows the monthly stream discharge for Coggan for the period 1920-2016. Low monthly occurred during the 1940s, 1980s, briefly in the mid-1990s and the lowest flows on

record are during the millennium drought period (2001-2007). Stream discharge during the millennium drought was an order of magnitude lower than during the 1940s WWII drought, despite the latter being a more severe drought over 12 months, 5 years or 10 years.

4.3.1 Trends in stream discharge

Table 4:5 shows that because of the large variability of annual and seasonal Q/A there are no significant trends in stream discharge. This is still the case when variability is reduced by taking the log transform of Q/A. Figure 4:13 compares the five year run-off (RO) co-efficient 1920-2016 to the five year rainfall percentile for the catchment above Coggan (210006) for the period 1920 to 2014. Five years was selected to lessen the influence of any lags in groundwater discharges, which may be apparent in annual runoff coefficients.

In terms of rainfall percentiles, the 1940s were clearly the longest and most severe dry period over the period (Figure 4:6, Figure 4:7, Figure 4:8). The minimum five-year runoff coefficient for Coggan, however, is at least five times lower during the millennium drought than that during the 1940s record meteorological drought. The stream discharge records at the other two active gauging sites are too short to show the full comparison between the 1940s and millennium droughts. Comparing the millennium drought with the 1980s drought shows that while the 5 year rainfall percentiles for both droughts were similar, the minimum 5 year runoff coefficient for the millennium drought was an order of magnitude lower than that in the early 1980s.

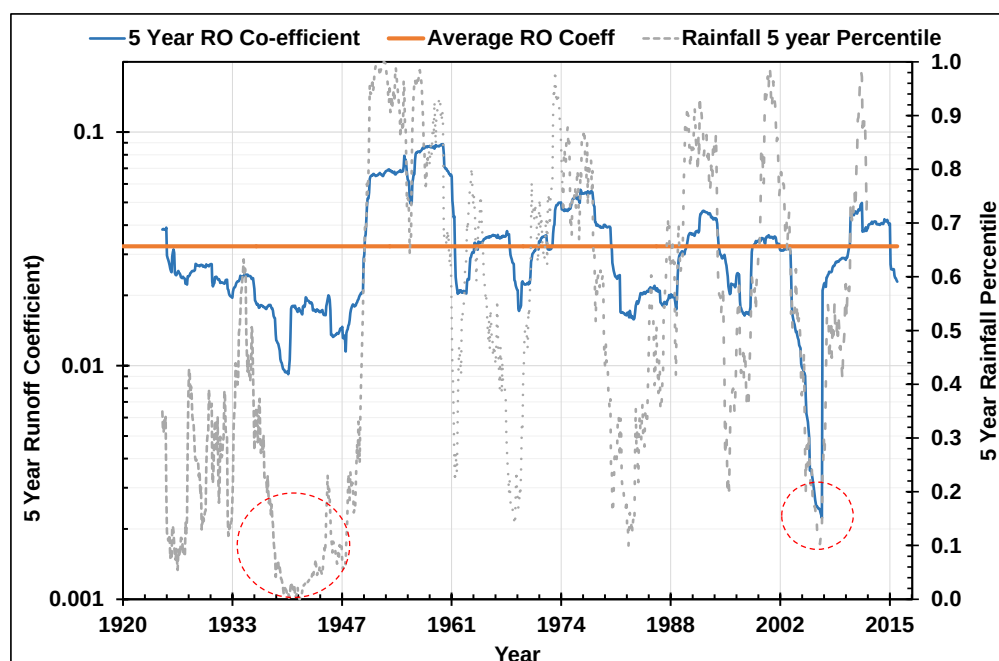


Figure 4:13 Five year run-off co-efficient compared with the 5 year rainfall percentile Upper Goulburn 1920-2014 (Coggan GS210006)

Figure 4:13 shows a change in the long-term response of the upper catchment to rainfall. The response of the catchment during the 1940s and 1980s was consistent but differed markedly to that in the millennium drought which showed a much lower catchment yield. Since it has been shown that Epan has not changed significantly over the period 1970 to 2016, it appears that there has been a change in catchment yield during dry times since the early 1980s. One possible explanation for this could be a loss of baseflow in the catchment that could have been generated by a change in the distribution of rainfall in the catchment. This is examined in the following section.

4.3.2 Changes in rainfall and stream flow regime 1913-2014

To examine the possible loss of baseflow in the catchment was due to a change in the rainfall regime in the catchment was tested, the percentile distributions of both monthly spatially interpolated rainfall (P) and specific discharge (Q/A) over the same 20 year periods, 1913-1932, 1933-1952; 1953-1972; 1973-1992 and 1993-2012 were examined for Coggan GS (210006)

A summary of the characteristics of the percentile distributions of monthly rainfall, P are provided in Table 4:6 and the characteristics of the percentile distributions of specific discharge Q/A in Table 4:7 for the period 1913-2014 and for the five, 20 year periods from 1913 to 2012. These are also plotted in Figure 4:14 and Figure 4:17 with expanded views provided in Figure 4:15, and in Figure 4:18 for percentiles less than or equal to the 0.3 percentile.

In Table 4:6 and Table 4:7 the relative spread is $(X_{0.95} - X_{0.05})/X_{0.5}$ where $X_{0.95}$ is the 0.95 percentile value for P or Q/A respectively; with $X_{0.05}$ is the 0.05 percentile, and $X_{0.5}$ is the median value. In Table 4:6 the relative spread of the percentile distributions for all 20 year periods are similar, with the period 1993-2012 having the lowest relative spread of monthly rainfall. The monthly rainfalls for the period 1993-2012 lie above those of all other 20-year periods in the percentile range 0.3 to 0.7. Examination of the plot of the percentile distributions of P in Figure 4:14 and Figure 4:15 revealed that monthly rainfall distribution for the period 1994-2012 lies above those for all other periods in the percentile range 0.19 to 0.7 percentiles (equivalent to rainfalls in the range 18.8 to 74.7 mm/month over the period 1913-2014). The distribution for 'P' for 1993-2012 falls below some other periods under the 0.2 percentile, Figure 4:16 and only for the percentile ranges 0.05 to 0.13 does the distribution for the period 1993-2012 drop below all other 20-year periods. The lower percentile range is equivalent to rainfalls of about 6 and 14 mm/month, which are not hydrologically significant in terms of groundwater recharge or stream discharge generation.

Table 4:6 Characteristics of the percentile distributions of monthly rainfall P (mm/month) for the full record and five 20 year periods

	Full Record	20 Year Periods				
	1913-2014*	1913-1932	1933-1952	1953-1972	1973-1992	1993-2012
Median Ann. Rainfall (mm)	551	486	505	580	572	609
Percentile						
0.05 (mm/mth)	5.72	7.08	7.49	6.48	5.20	4.98
0.3 (mm/mth)	27.9	23.1	28.2	29.9	29.1	30.7
Median [0.5] (mm/mth)	45.9	40.5	42.1	48.4	47.6	50.8
0.7 (mm/mth)	69.9	64.3	66.2	72.1	73.1	74.7
0.95 (mm/mth)	137	135	126	142	151	130
Relative Spread	2.9	3.1	2.8	2.8	3.1	2.5

In contrast the results for specific discharge (Q/A) in Table 4:7 reveal the period 1993 to 2012 has the lowest specific discharges of any 20-year period in the percentile range 0.05 to 0.7, while Figure 4:18 and Figure 4:19 indicate that the distribution of Q/A for all percentiles lower than about 0.77 lie below those of all other 20-year periods, equivalent to monthly Q/A of between 0.002 and 1.2 mm/month.

Table 4:7 Characteristics of the percentile distributions of monthly specific discharge, Q/A (mm/mth), for the full record and five 20 year periods

	Full Record	20 Year Periods				
	1913-2014	1913-1932	1933-1952	1953-1972	1973-1992	1993-2012
Percentile						
0.05 (mm/mth)	0.029	0.040	0.045	0.094	0.032	0.009
0.3 (mm/mth)	0.219	0.231	0.140	0.372	0.348	0.112
Median [0.5] (mm/mth)	0.505	0.446	0.348	0.686	0.773	0.286
0.7 (mm/th)	1.16	0.88	1.19	1.56	1.42	0.84
0.95 (mm/mth)	7.13	5.28	6.86	12.69	8.41	5.84
Relative Spread	14	12	20	18	11	20

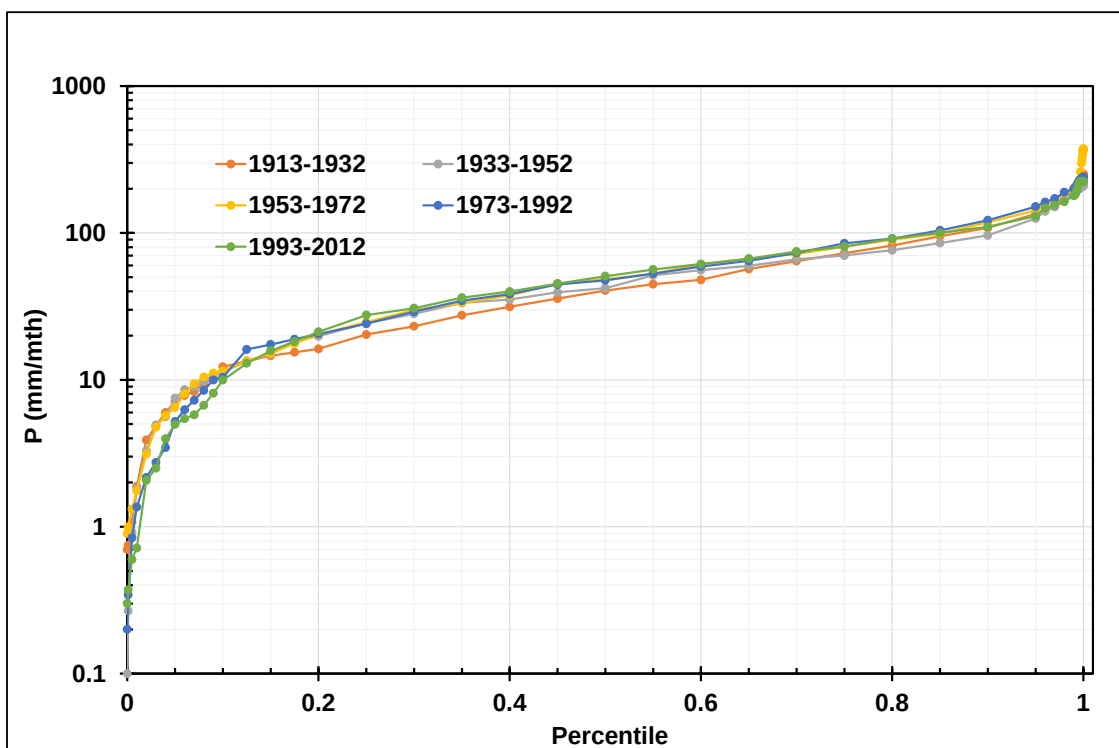


Figure 4:14 Percentile distributions of interpolated monthly rainfalls for five 20 year periods covering the time span 1913-2012 (monthly P in log scale).

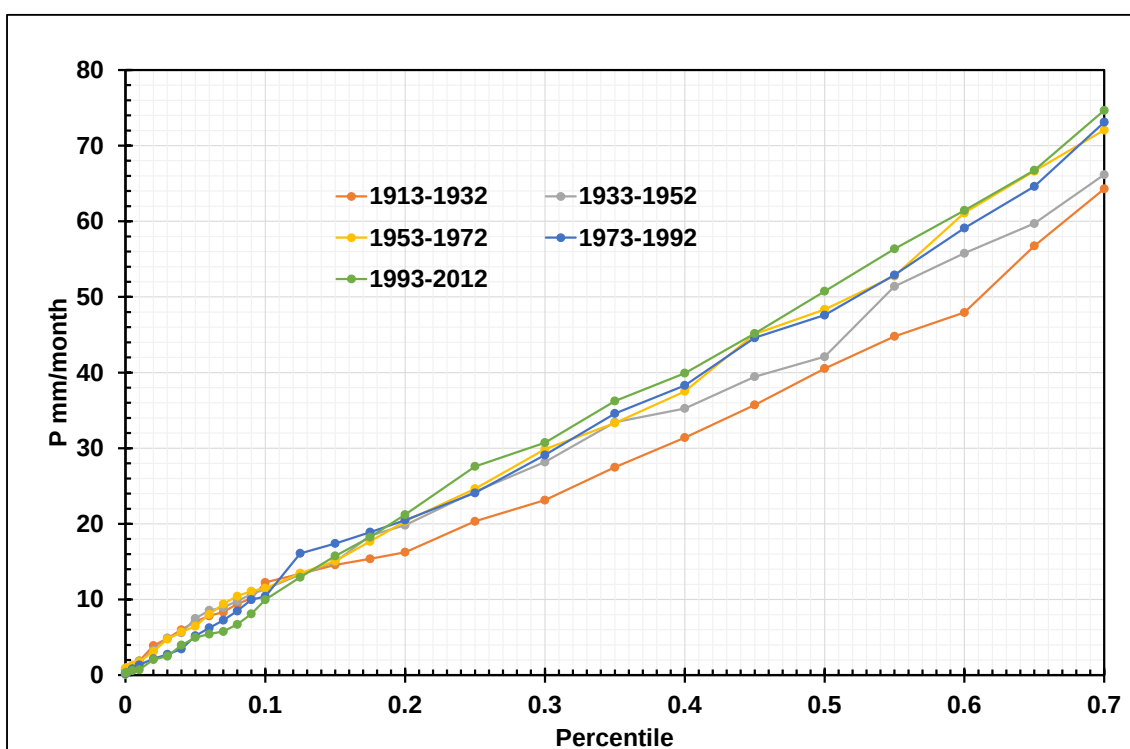


Figure 4:15 Expanded view of Figure 4:14 for less than 0.7 percentile (rainfall monthly P in linear scale)

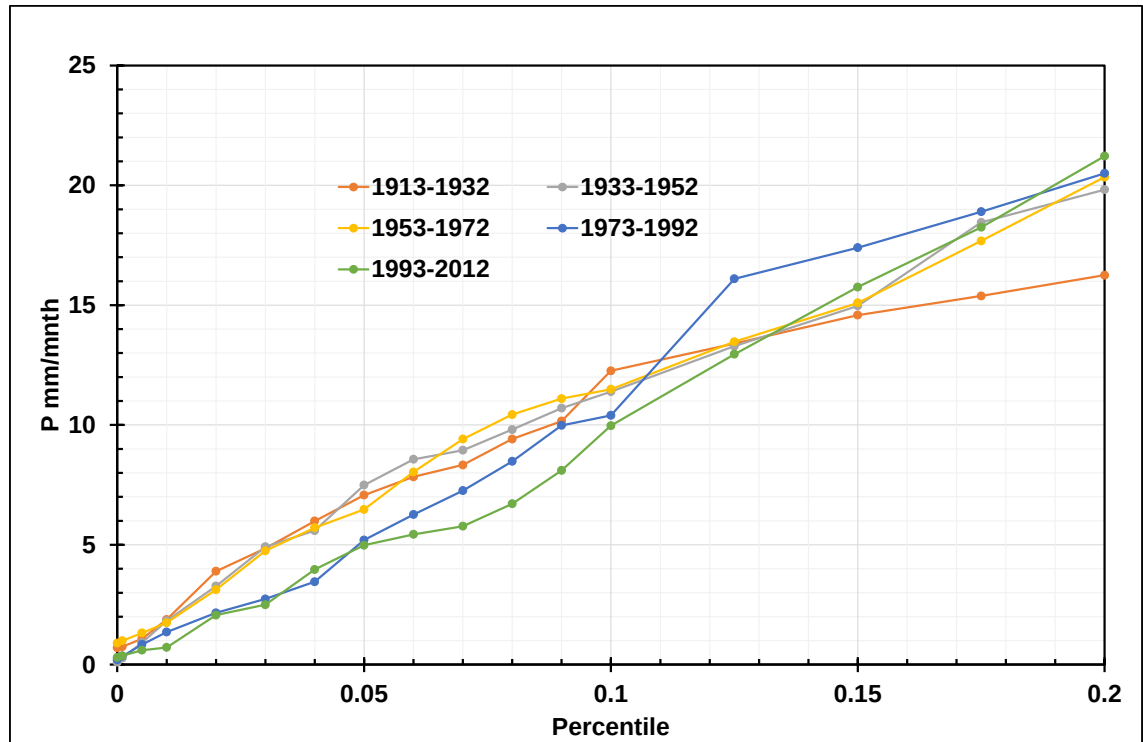


Figure 4:16 Expanded view of Figure 4:14 for less than 0.2 percentile (rainfall P in linear scale)

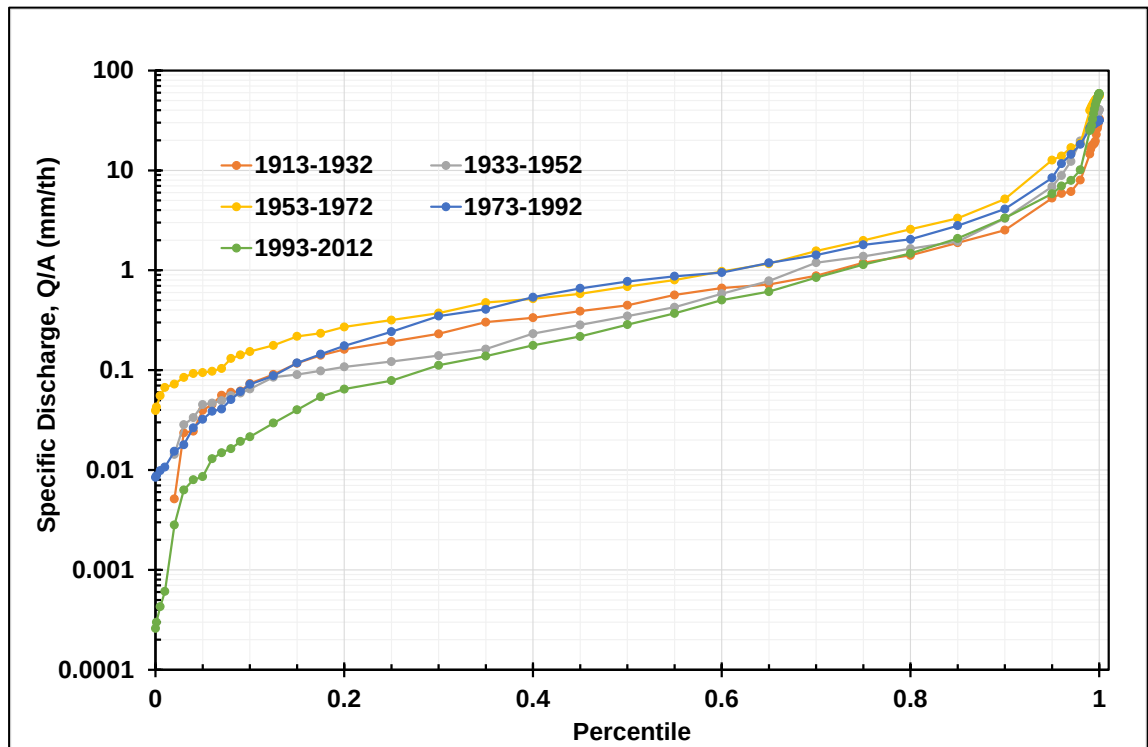


Figure 4:16 Percentile distributions of monthly specific discharge Q/A (in log scale) at Coggan for five 20 year periods covering the time span 1913-2012

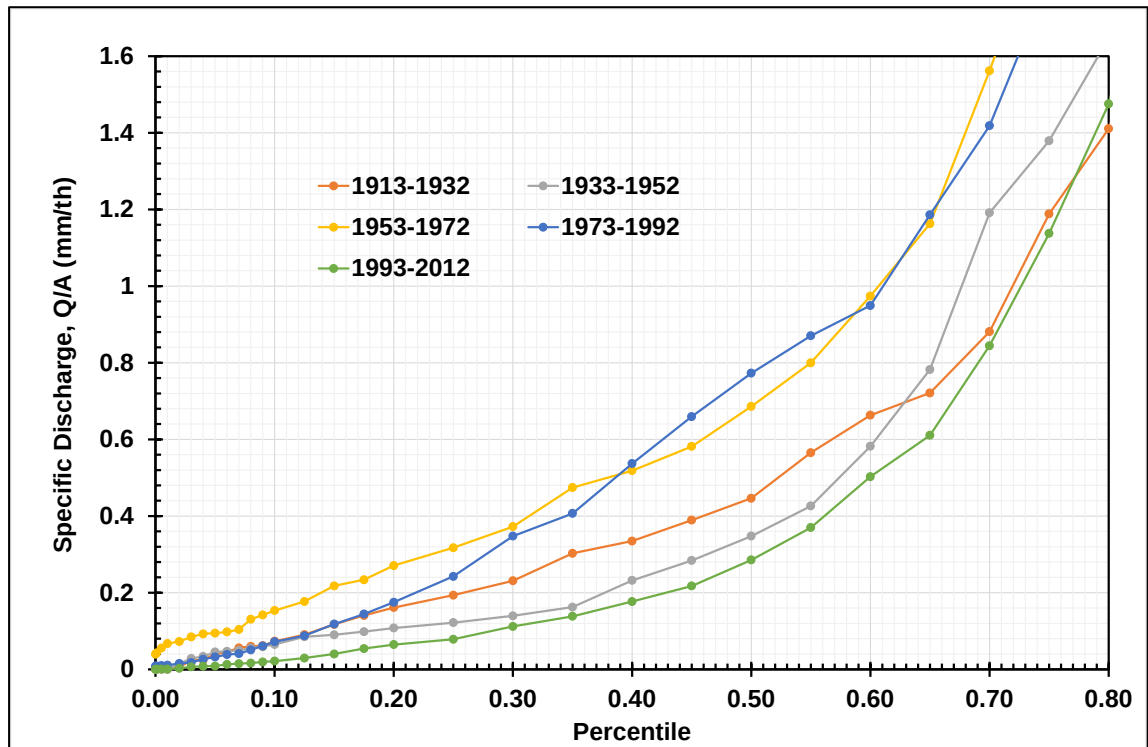


Figure 4:17 Expanded view of Figure 4:17 for percentiles less than or equal to 0.8 (monthly specific discharge in linear scale).

The above results demonstrate that the low stream specific discharges for the period 1993 to 2012 in the percentile range 0 to 0.7 are lower than any other 20 year period, but cannot be attributed to unusually low rainfalls over the period 1991 to 2012. Over the 100 years of rainfall records, monthly rainfalls over the period 1993 to 2012 are the highest of any 20-year period in the percentile range 0.19 to 0.7. It only drops below the distributions of all other 20-year period rainfalls in the hydrologically less important percentile range 0.05 to 0.13. Thus differences in rainfall regime do not explain the unusually low stream discharges in the period 1993-2012, which appear to indicate a loss of baseflow and median flows.

4.3.3 Stream discharge elasticity to rainfall

The rainfall elasticity of streamflow (ϵ_P) is a normalised measure of the response of the ratio of catchment discharge to rainfall over a specified time (Chiew et al., 2006). For observed streamflow and rainfall data over a specific period, a non-parametric estimator of ϵ_P is defined as (Sankarasubramanian et al., 2001). This equation has been used to estimate the precipitation elasticity of stream flows in Australia (Chiew, 2006). The log formula described in equation [2.4] applied to annual average precipitation and discharge data over 20-year running periods has been used in this analysis.

Typically, elasticity has been used to assess the impact of a changing climate on stream flow (Chiew, 2006). Values close to or less than 1.0 indicate additional sources of stream

discharge other than direct rainfall (Sankarasubramanian *et al.*, 2001). When elasticity equals one a 10% change in rainfall produces a 10% change in discharge. The stream elasticity may be reduced in drier periods when stream flow is sourced from groundwater discharge which is less responsive to rainfall.

The long term elasticity of stream discharge at Coggan for the period 1913-2012 based on annual local rainfall data, using the above equation was estimated to be 2.04. The elasticities for the shorter periods of 20 years are shown in Table 4:8.

Table 4:8 Elasticity of Coggan stream discharge 1913-1914, calculated using mean Q/A and P for 20 year periods.

20 Year Periods	Mean P (mm)	Elasticity
1913-1932	613	2.997
1933-1952	635	1.568
1953-1972	704	2.112
1973-1992	710	1.909
1993-2012	694	0.450
Overall Elasticity 1913-2014		2.04

It is clear that the 20 year period 1993-2012 is anomalous with an elasticity of less than 0.5, over 3 times less than the next lowest elasticity for the period 1933 to 1952. This indicates that streamflow had less sensitivity to changes in rainfall for this period than for any other period. During the early 1990s Ulan Coal Mine commenced discharging increasing volumes of mine water excess to the operational needs. Increasing mine water discharge in the upper catchment may have contributed to this loss of sensitivity of stream discharge to annual rainfall. This is discussed further in section 4.4

4.3.4 Trends in baseflow

Baseflow Index (BFI) is defined as the proportion of streamflow that is baseflow over a long period of streamflow records. The baseflow index for the Goulburn River has been estimated to be 0.51 (McVicar *et al.*, 2015) indicating that slightly more than 50% of recorded river flow at Sandy Hollow is baseflow discharge. Salinity can also be used to estimate the baseflow index however in the Goulburn this becomes quite problematic due to the generally unknown EC of alluvial and fractured rock groundwater inflows and the complicating factor of mine water discharge (see section 6.6).

Mining operations through the interception and depressurisation of the groundwater system can intercept groundwater that contributes to stream baseflows. This alters the direction and magnitude of water exchange between the river, alluvial aquifers and fractured rock aquifers (Ross and Webb, 2015). There was a significant expansion of mining in the upper Goulburn post 1980s (see section 3.5.2 and Chapter 6).

The percentile distributions of spatially interpolated rainfall and stream discharge at Coggan were examined in two 32 year periods to examine any change in the distribution of stream flow pre-and post-mining upstream at Ulan (1951-1982 & 1983-2014). The rainfall distributions for the two periods are very similar with only a slight increase in rainfall post mining up to 0.8 percentile. However the stream specific discharge post-1983 is *less* than the pre-mining discharge up to the 0.8 percentile range, despite the higher rainfall. The median specific discharge dropped from 0.70 mm/month for the period 1951 to 1982 to 0.50 mm/month for 1983-2014 (Table 4:9).

Growns and Marsh (2000) suggest that if the percentile distributions are normalised between the 0.2 and 0.8 percentile using the median specific discharge to normalise discharge, streams with a shallow slope of the normalised distribution have higher baseflow than streams with a steeper slope. For the period 1983-2014 (Table 4:9) the slope for the normalised percentile distributions of specific discharge between 0.2 - 0.8 is 6.1 or 30% greater than the normalised slope of 4.9 during 1951 to 1982 period, suggesting a loss of baseflow over the period 1983 to 2014. In contrast the normalised slope of the rainfall distributions over the percentile range 0.2 to 0.8 are very similar for both periods, indicating no major shift in the monthly rainfall distributions.

Table 4:9 Coggan summary pre and post-mining distributions of interpolated rainfall and specific discharge over 32 years

Property	Monthly Specific Discharge, Q/A		Monthly Rainfall, P	
	Pre-Mining 1951-1982	Post-Mining 1983-2014	Pre-Mining 1951-1982	Post-Mining 1983-2014
Minimum (mm/mth)	0.0085	0.0003	0.10	0.30
Percentile 0.2 (mm/mth)	0.224	0.086	20.1	21.6
Median (mm/mth)	0.704	0.496	47.0	50.9
Percentile 0.8 (mm/th)	2.22	1.91	88.6	91.4
Maximum (mm/mth)	55.9	58.8	374.0	240.0
Normalised 0.2 Percentile	0.319	0.173	0.427	0.425
Normalised 0.8 Percentile	3.2	3.9	1.9	1.8
Slope Normalised Distrib 0.2 to	4.7	6.1	2.4	2.3

In support of this, when the runoff coefficients at Coggan for 32-year periods pre-1982 to post 1982 are compared (see Table 4:10). There is an average of 9 mm per year less runoff in the post mining period, equal to a volume of 28,785 ML/year or 79 ML/day, despite the post mining period having a similar aggregate rainfall.

Table 4:10 Coggan runoff coefficient pre-mining and post mining at Coggan over 32 year periods

Period	Full Period	Pre-mining	Post - mining
	1920-2014	1951-1982	1983-2014
Aggregate Discharge (mm)	2217	935	652
Aggregate Rainfall (mm)	63504	22101	21915
Runoff Coefficient	0.0349	0.0423	0.0297

Difference between periods if pre-mining RO Coefficient still held 276 mm
 Difference per year 9 mm

At the downstream Sandy Hollow gauging stations we find the average runoff for 27 year period 1955-2010 and 1983-2010 was reduced by 11 mm/year (Table 4:11). However the aggregate rainfall of the catchment for the post mining period was 4% less than in the pre-mining period, so the 11 mm/year reduction could be roughly equivalent to the 9 mm/year reduction at Coggan (Table 4:10). The comparison between the reduction in specific discharge between the full Goulburn catchment at Sandy Hollow and the upper catchment at Coggan suggests a generalised loss of runoff from all the catchment which includes a loss of baseflow. This could be due to a combination of factors including an overall increase in water extraction and retention of surface runoff in farm dams, interception of surface and groundwater by mining and regrowth of native vegetation (see Section 4.3.6).

Table 4:11 Sandy Hollow aggregate runoff coefficient pre-mining and post mining at Coggan over 27 years

Period	Full Period	Pre-mining	Post mining
	1954-2014	1955-1982	1983-2010
Aggregate Discharge (mm)	1281	752	429
Aggregate Rainfall (mm)	40858	19515	18752
Runoff Coefficient	0.0314	0.0385	0.0229

Difference between periods if pre-mining RO Coefficient still held 294 mm
 Difference per year 11 mm

4.3.5 Effect of land use change on catchment yield

The cumulative effect of increased surface and groundwater abstraction due to changing land use across the Goulburn catchment coupled with decreasing groundwater recharge is a possible explanation for the significant change in the relationship between rainfall and observed catchment yields since the 1980s, particularly evident during the millennium drought. Land use changes that may cumulatively be affecting catchment yield include:

- An increase in total catchment vegetative cover, particularly perennial woody regrowth. This can decrease catchment water yield through the interception losses and increased evapotranspiration (ET) with a consequent fall in the water table (Christy *et al.*, 2011; Zhang *et al.*, 2001; Taylor *et al.*, 2018; Cornish, 1993). Changes include the retention and increase in vegetative cover due to legislation

restricting broad scale land-clearing (NSW Native Vegetation Act 2003); decrease in sheep numbers in preference to cattle grazing resulting in increased native vegetation regrowth (see 3.4.1); and elevated carbon dioxide levels in the atmosphere due to climate change stimulating plant growth and increasing ET losses (Bond *et al.*, 2003; Kgope *et al.*, 2010; Ukkola *et al.*, 2015).

- Increased number of on-farm dams and soil conservation works from the 1970s increasing the interception of runoff as part of a flood mitigation and erosion-control strategy implemented by the Hunter Valley Conservation Trust (see 3.5.1). The impact of these would be most evident during low flows;
- Increasing consumptive use and interception of surface and groundwater by agriculture such as crop irrigation and extractive industries such as mining.

Recent long-term water balance ET measurements in sub humid river basins in Australia show a “greening” effect presumably due to increasing atmospheric CO₂ concentration is consuming more water producing a 24-28% reduction in stream flow over the past three decades (Ukkola *et al.*, 2015).

According to the 2009 catchment report cards the southern and upper Goulburn sub-catchments retain around 65% forest cover, and 23% in the northern. The total catchment retains 44% of woody vegetation (Table 3:1). Unfortunately vegetation mapping and satellite data for the Goulburn catchment were not available for this study preventing a comparison of the relative catchment area of vegetation cover and woody regrowth prior to 2000 (Rudiger *et al.*, 2007). Vegetation generally is identified using the infra-red band, but distinguishing between woody and non-woody vegetation requires multispectral images, which were not available until post 1999 (*personal communication* Narelle Irvine OEH). It is possible that the Native Vegetation legislation in 2003 restricting land clearing may have resulted in the greater retention of native woody regrowth; affecting stream discharge post 2003. Periods of high rainfall also stimulate regrowth when coinciding with low stocking rates, particular for sheep. If the scale of woody regrowth was of sufficient area it could increase ET affecting groundwater levels and total catchment yield (Zhang *et al.*, 2001). The effects of increased ET would be most noticeable during extended dry periods as vegetation becomes more reliant on groundwater sources. Quantifying increases to vegetative cover since the 1990s requires further investigation and access to temporal vegetative cover maps based on satellite data¹⁹.

¹⁹ Communication with Narelle Irvine (OEH), Herbert Hemakumara (DPI Water)

4.3.6 Long term water losses from the upper Goulburn

The long-term catchment water balance can be written as.

$$\bar{Q}/A = \bar{P} - \bar{ET} \quad [4:2]$$

With $\bar{Q}/A$ the long term average specific discharge from catchment of area A, and $\bar{ET}$ and $\bar{P}$ the average rainfall and evapotranspiration as well as other losses over the same time period. This assumes that the change of soil and groundwater storage in the catchment is negligible over longer periods. Running 15 year averages of specific discharge (Q/A) and monthly interpolated rainfall (P) for Coggan stream gauge for the period 1913-2014 were analysed to estimate long-term ET losses for the upper Goulburn catchment. Figure 4:19 compares the ratio $\bar{ET}/\bar{P}$, the so-called evaporative index, with the 15 year averaged precipitation. The record period in the mid-1930s to 1940s has the largest evaporative indices, while the record wet period during the 1950s to late 1960s has the lowest evaporative indices, as expected.

Figure 4:20 shows the estimated average in the running evapotranspiration over 15 years as a function of the 15 year running averaged rainfall. The graph appears to show at least two main clusters, one from 1913-1970 and the other from 1970 to 2014. The data fits the simple linear relationship for the period 1913-1970:

$$\bar{ET} = (0.800 \pm 0.002) \times \bar{P} + (105 \pm 1) \quad R^2 = 0.998^{20} \quad [4:3]$$

and for 1970 to 2014

$$\bar{ET} = (0.891 \pm 0.009) \times \bar{P} + (54 \pm 6) \quad R^2 = 0.945 \quad [4:4]$$

The relationship in equation [4.3] can be used to find the difference, $\Delta\bar{ET}$ between the long-term ET calculated from the water balance equation [4.4] for the period 1970 to 2014 and that estimated from equation [4.3] for the period 1913 to 1970 using the 15 year running average rainfall over the full period 1913 to 2014.

These differences in estimated evapotranspiration $\Delta\bar{ET}$ are plotted in Figure 4:21. For the period 1913-1970 the average $\Delta\bar{ET}$ is 0.0 ± 2.4 mm/year, while for 1970-2014 the average difference is 12.1 ± 3.7 mm/year.

²⁰ Note: values following $\pm$ are standard errors

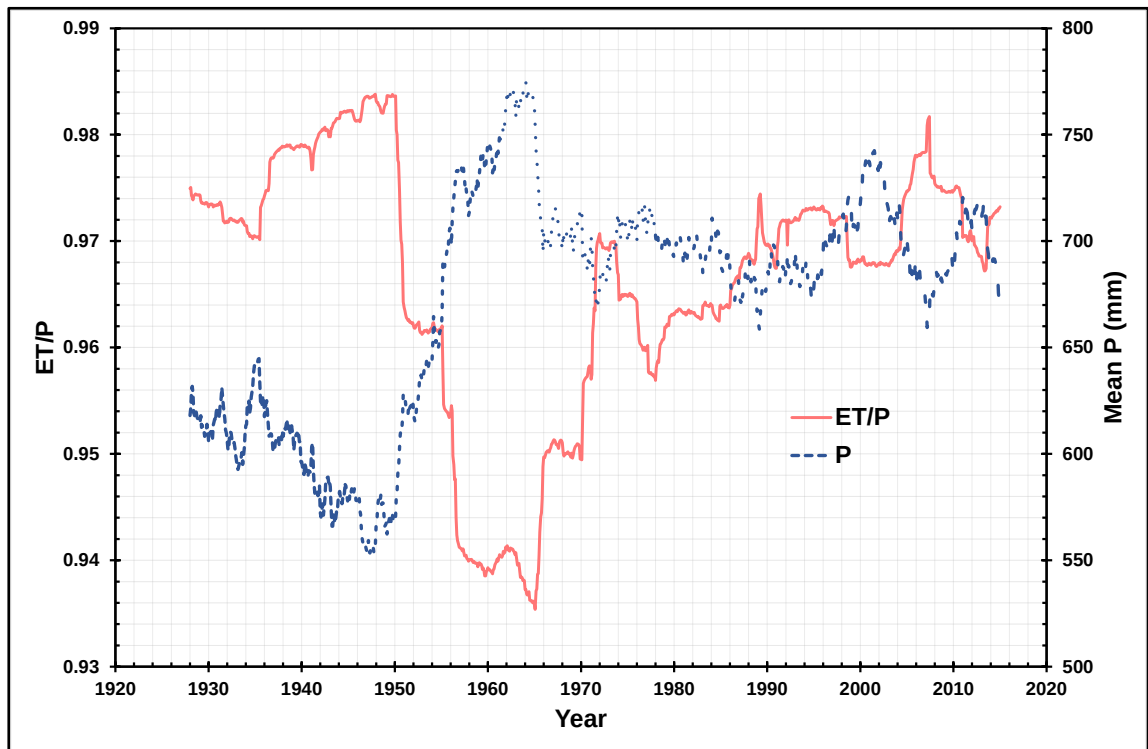


Figure 4:18 Estimated running 15 year averages $\overline{ET}/\overline{P}$ compared with the 15 year averaged mean annual precipitation, estimated using monthly values of interpolated P and measured Q/A at the Coggan gauge

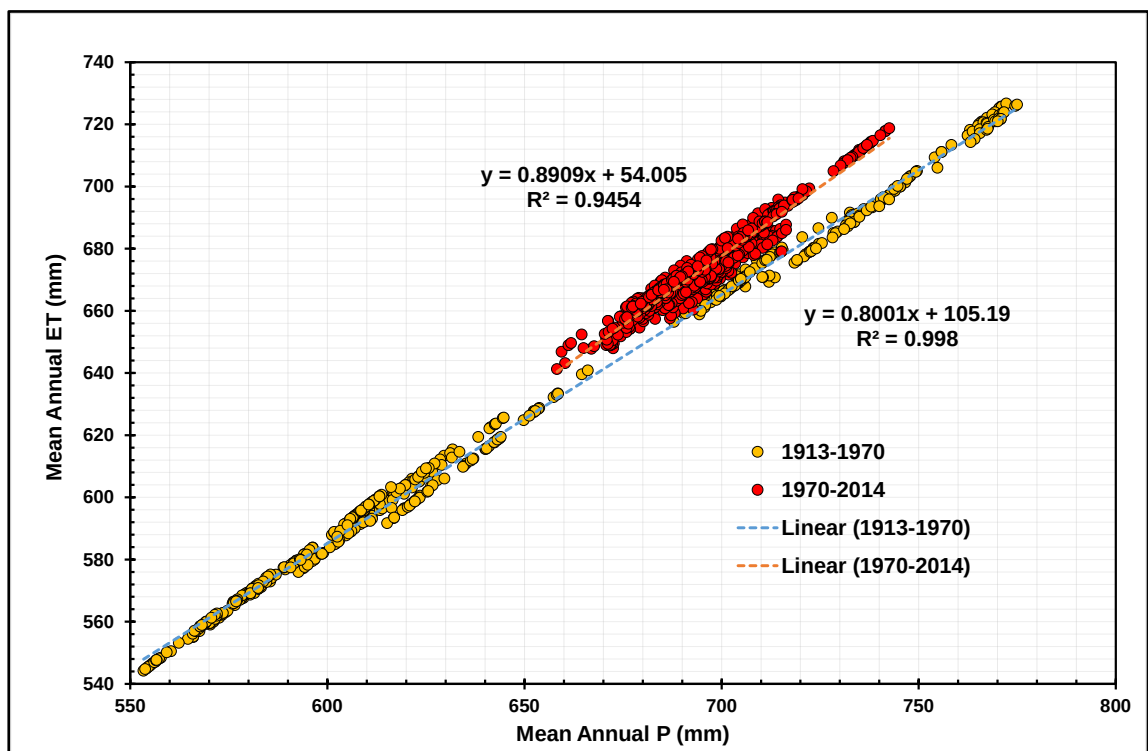


Figure 4:19 Average annual ET estimated over 15 year running periods using the long-term water balance starting in 1913 and using specific discharge and interpolated rainfall data for Coggan.

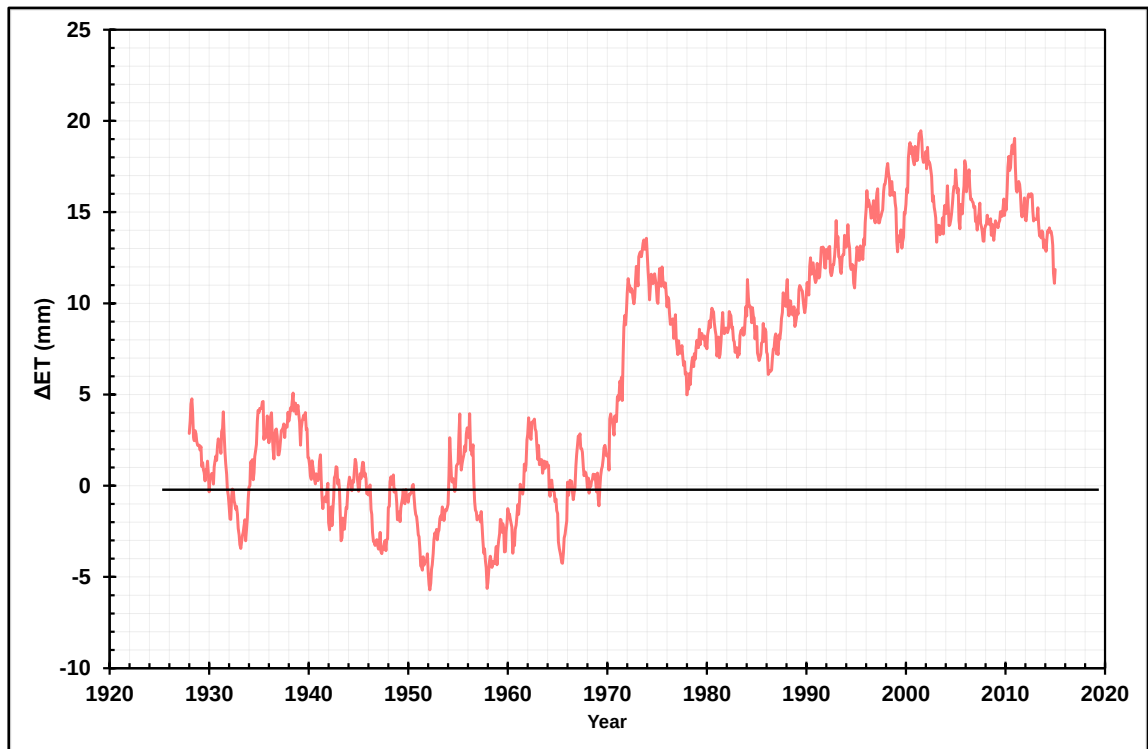


Figure 4:20 Coggan, difference in estimated 15 year running mean ET from that predicted for the same mean annual rainfall from the relationships between average ET and average P, relations [4.4] and [4.3] fitted to the period 1913-1970

It is noted here than in equation [4.2] the ET term incorporates all catchment losses. This analysis supports an apparent change in catchment behaviour post 1970s marked by increasing water losses of an average 12 mm/year in the upper Goulburn. This is consistent with the 9 mm loss in runoff observed in the post 1983 in Table 4:10.

4.4 *Changes in agricultural and mine water use*

Metering of groundwater extractions is minimal in the region so it is difficult to quantify total surface and groundwater extracted in the Goulburn River for crop irrigation, stock, or domestic use (Zhang *et al.*, 2016). A condition of alluvial and surface water licences for landowners is that they keep a log book of water use; however, there is no requirement to report total volumes extracted (comment DPI-Water 2016). One method applied to ascertain a licensed irrigator's water usage is from an assessment of cropping area and crop type extracted from satellite imagery. Surface and alluvial groundwater extraction licences in the Goulburn total over 60,000 ML/year or 8 mm/year over the entire catchment. Most of these are for agricultural purposes. Over 95% of groundwater license allocated in the Sydney Basin porous and fractured rock groundwater source are for mining extraction (Ross and Webb, 2015). This does not include water use under basic water rights, or extraction from fractured and porous rock groundwater sources (3.7.1). The NSW harvestable rights online calculator estimates the maximum permissible farm dam storage for the Goulburn catchment is approximately 27,000

ML/year, excluding the 44% forested Goulburn catchment and conservation areas (see section 3.5). If this is added to the 60,000 ML/year it is equivalent to about 11.5mm/year over the entire catchment. It is however not certain that all licenced allocations are used.

One source of quantifiable data of water use and groundwater extraction in the Goulburn is contained in the annual water balances supplied by the mining industry post 2004. The reporting of each coal mines water balance is based on measured, modelled and estimated water inputs and outputs. Mining industry annual management reports (AMRs) 2004-2016 show a substantial increase in fractured rock groundwater licences granted for consumption and dewatering purposes as a direct result of the expansion of the mining industry (Table 6:2, Table 6:4). In 2015 water licence caps (maximum extraction rates) for surface and groundwater abstraction for the three coal mines operating in the upper Goulburn catchment totalled over 14,000 ML/year (Table 6:2) most sourced from fractured and porous rock groundwater source – with over 1,300 ML from the Hunter unregulated and alluvial water sources. Mines are also eligible under landholder harvestable rights to intercept over 1,330 ML/year in storage dams based on their total area of land ownership.

4.5 *Conclusions*

The aim of this chapter was to assess the region's climatic characteristics, rainfall variability and trends and their influence on catchment yield. The impact of mine water use on catchment yield is further considered in a separate chapter on mining (Chapter 6: Mining Impacts on the Upper Goulburn)

4.5.1 *Climate trends*

Analysis of spatially interpolated rainfall of the Goulburn catchment above Sandy Hollow over the period 1920 to 2014 showed that during the warmer October to March period rainfall significantly increased ($p > 0.95$) by around 9 ± 5 mm/decade and for the upper catchment the rainfall increase was around 10 ± 5 mm/decade ($P > 0.95$). This increase in warmer season rainfall is not predicted by climate models. Both annual and colder season rainfall trends for the full and upper catchment were not significant despite climate models suggesting a decrease in cooler season rainfall of 10 mm/decade. When the rainfall trends were analysed over a more recent shorter 30-year time span, both significant positive and negative trends in rainfall have occurred of magnitude ± 40 mm/decade with similar periods to the oscillations of the Pacific Decadal Oscillation. This illustrates the need for catchment management water sharing plans to be sufficiently flexible to accommodate large scale swings in precipitation.

The trend in Epan was examined over the period 1970 to 2014 and 1985-2014. It was found that over both periods there was no significant ($p < 0.9$) trend in either annual or seasonal Epan. This is in contrast to studies which have reported generally decreasing trends in Epan due

to global “dimming” or “stilling”(Stanhill and Cohen, 2001; Roderick and Farquhar, 2002; Roderick *et al.*, 2007).

The most severe meteorological droughts in eastern Australia occurred during 1940s, 1960s, 1980s and 2000s coinciding with periods when a positive IOD was in phase with El Niño. In the Goulburn catchment the five year cumulative rainfall percentiles shows annual rainfall below the 0.10 percentile occurred in the 1920s, 1940s, 1980s and millennium period. The 1940s drought was both the most extended and severest meteorological drought, much more than the widely discussed millennium drought.

4.5.2 Trends in catchment yield

Trends in catchment yield in the upper Goulburn between 1920 and 2014 were investigated and stream discharge rates recorded at the more reliable and longer record Coggan stream gauge. Stream discharge was found to be significantly less during the millennium drought than during the 1940s drought – despite the latter being a much lower period of rainfall. Despite this, the shorter and less intense millennium drought had 5 year runoff coefficients 5-times lower than those of the World War II drought. Since annual rainfall and pan evaporation haven’t changed significantly over this period, this suggests a change in catchment characteristics between the 1940s and 2000s.

The possibility that the lower flows were due to a difference in rainfall regimes was investigated using percentile distributions of monthly rainfall and specific discharge over five, 20 year periods from 1913 to 2012. The results demonstrated that the extremely low stream discharges could not be attributed to unusually low rainfalls. The overall results indicate a decrease in catchment yield at some stage post 1970s.

The long term stream elasticity examined 20 year periods from 1913 to 2012 in the upper Goulburn revealed an average elasticity of 0.5 in the 20 year period from 1993 to 2012 which was three times smaller than the lowest of other 20 year periods. An elasticity index less than one indicates a general decoupling of stream discharge from rainfall due to a source of water not dependent on rainfall.

The percentile distributions of spatially interpolated rainfall and stream discharge at Coggan were examined in two 32 year periods, 1951-1982 and 1983-2014, to examine any change in the distribution of stream flow pre-and post-mining upstream at Ulan. It was found that the rainfall distributions for the two periods are very similar with only slight increases in rainfall post mining up to 0.8 percentile. However the stream specific discharge post-mining is less than the pre-mining discharge by up to the 0.8 percentile.

The slope of the normalised percentile distribution of stream flow between percentiles 0.2 and 0.8 has been used to assess the contribution of baseflow. A comparison of the 32 year periods pre and post mining (1982) percentile distributions of monthly interpolated rainfall and

specific discharge showed that while the slope for the pre- and post-mining rainfall were essentially identical, the slope for the post-mining period was 30% higher than the pre-mining period indicating a loss of base flow since 1983.

An examination of runoff coefficients over these two periods showed a generalised loss in catchment runoff post 1983 of 9 mm/year in the upper catchment and 11mm/year at Sandy Hollow at the bottom of the catchment. Long term cyclical fluctuations in the rainfall regime did not explain these losses. Reduced yields could be due to a combination of factors such as an overall increase in water extraction; greater retention of surface runoff in new dams; increased ET by widespread native vegetation regrowth or increased groundwater extraction and consumption.

A simple water balance model to assess average ET combined with other losses in the upper Goulburn indicates an apparent change in catchment behaviour from 1970s marked by increasing water loss of around 12 mm/year. This requires further assessment and investigation of satellite vegetation mapping data to quantify the extent and relative change in forest cover over time and the increase in farm dams.

Current estimated licenced water abstraction allocations in the Goulburn catchment amounts to about 11.5 mm/year spread over the entire catchment. This is a minimum estimate since it does not include licences for water abstracted from deeper aquifers. While not all allocations are used, this is a substantial fraction of the estimated median catchment yield of 13.4 mm/year.

Land use changes are further examined in Chapter 6: Mining impacts on the upper Goulburn and in Chapter 9: Merriwa an agricultural sub-catchment. The impact of mine discharge on salinity levels is examined in section 6.5. The impact of changing flow on stream salinity is examined in the next chapter.

Chapter 5: Stream salinity

In chapter 4 it was shown that significant changes have occurred in the response of stream discharge to rainfall in the Goulburn. In this chapter the aim is to investigate at the catchment-scale the sources, drivers and trends in stream salinity and salt loads using spot measurements and analysis of available government and industry data supplemented with surface and groundwater sampling. Electrical conductivity (EC) is used as a general surrogate for salinity. The salinity of stream discharge from the Goulburn has a significant impact on water quality in the Hunter with the potential to affect downstream water users and the operation of the Hunter River Salinity Trading Scheme (HRSTS). Critical issues for catchment management in the Goulburn and the downstream Hunter River are the impacts of natural processes, land use change and climate change on the discharge of salinity.

Stream salinity and site information collected from longitudinal field surveys and sampling of the Goulburn River and major tributaries are used to examine the influence of catchment hydrogeology on stream salinity. There is limited salinity data prior to the commencement of mining in the catchment. What is available is analysed in an attempt to identify trends.

The relatively short records of continuously monitored electrical conductivity (EC) between 2012 and 2016 in the Goulburn catchment are used to look at the spatial distribution of salt loads and specific salt yields in the catchment. The intimate relationships between salt load and discharge at gauging sites are evaluated.

5.1 *Sources of salinity in the Goulburn*

A longitudinal stream survey of the Goulburn River and its major tributaries was conducted at 24 sites, 16-26 October, 2012. The surveys occurred following an extended low rainfall period when there was limited surface runoff into the creeks and streams. Table 5:1 shows the percentile ranking of rainfall (1920-2014) was 0.04 for 3 monthly and 0.1 for 6 monthly rainfall totals prior to October 2012. The 12 monthly rainfall percentile for October was 0.73, while not low, could indicate the contribution of a delayed groundwater component. The survey was designed to assess the influence of major tributaries, and identify the potential source of saline inputs. The location is shown in Figure 5:1 and details of each sampling site are listed in Table 5:2. Spot measurements of EC were recorded and flow data was estimated wherever feasible. Water samples were collected for analysis of major ions and tested at NSW Office of Water laboratory in Wolli Park, Sydney. The methodology used in the longitudinal transect survey is provided in Appendix F.

[illegible]

Changing land use in an uncertain climate; surface water and groundwater, Goulburn River 4 October 2019

**Table 5:2 Surface water sampling locations, dates, EC and pH values
Goulburn River Oct 2012**

ID	Goulburn River Sample Sites	EC	Elev. mAHD	pH	Easting	Northing	Date
SW01	Goulburn R @ US Ulan GS - 210046	709	417	7.7	758502	6425051	17-Oct-12
SW02	Goulburn R @ DS Ulan LP18	854	393	7.7	762046	6431246	17-Oct-12
SW23	Goulburn R @ The Drip	828	380	8	763778	6432555	17-Oct-12
SW03	Goulburn R @ Gleniston 21010017	790	372	8	765271	6432000	16-Oct-12
SW11	Goulburn River US confluence Murrumbline	807	363	7.9	768621	6433612	22-Oct-12
SW29	Goulburn R US confluence Munmurra Rr	1141	275	7.8	220546	6434606	07-Dec-12
SW09	Goulburn R Upstream confluence Krui	992	261	8.6	224452	6433131	16-Oct-12
SW19	Goulburn R @ O'Brien's Crossing	956	246	8.5	221249	6419362	16-Oct-12
SW-COG	Goulburn River @ Coggan	1170	221		227180	6417694	16-Oct-12
SW17	Goulburn R Upstream confluence Merriwa	1063	157	8.6	247589	6413722	16-Oct-12
SW-KER	Goulburn River US Kerrabee GS	1201	163		247981	6410225	16-Oct-12
SW-SH	Goulburn River @ Sandy Hollow GS	1089	127		271713	6418714	16-Oct-12
SW-RM	Goulburn River @ Rosemount	1138	106	8.6	274905	6415090	16-Oct-12
ID	Tributary Samples 2012	EC	mAHD	pH	Easting	Northing	Date
SW21	Bobadeen-Curra Ck @ Goulburn Riverr	294	397	7.4	763072	6432579	17-Oct-12
SW20	Wollar Ck @ Mogo Causeway	1590	356	8.1	777759	6418952	17-Oct-12
SW27	Wollar Creek @ Goulburn River	1944	304	7.9	779735	6425840	26-Oct-12
SW04	Murrumbline Ck @Causeway	798	374	7.4	769242	6435765	17-Oct-12
SW07	Murrumbline Ck @ Goulburn Rr	749	369	7.3	768525	6434032	22-Oct-12
SW05	Munmurra River @ Bridge	719	376	8.4	780162	6453479	16-Oct-12
SW30	Munmurra River @ Goulburn Rr	856	279	8.4	220361	6434856	07-Dec-12
SW06	Krui River@ Golden HWY	775	322	8.4	228045	6445279	16-Oct-12
SW08	Krui River @ Goulburn River	876	268	8.6	225220	6433826	16-Oct-12
SW10	Merriwa R @Merriwa Town	1027	244	8.4	250192	6441397	16-Oct-12
SW16	Merriwa R Upstream confl Goulburn	1185	161	8.4	247730	6413797	16-Oct-12
SW-WB	Widden at Bylong Way Bridge	522	149	8.3	252964	6411574	16-Oct-12
SW-WC	Wybong @ Golden Hwy	1645	145	8.4	277335	642760	16-Oct-12

5.1.1 Salinity in the Goulburn River and tributaries

The longitudinal profile of stream EC in the Goulburn River as a function of elevation (mAHD) for the Goulburn River is shown in Figure 5:2. At elevations below about 280 mAHD, all river ECs during the survey were above the HRSTS limit of 900 $\mu\text{S}/\text{cm}$. Generally EC increases with decreasing elevation; however, there are swings in EC due to discharge from various sources.

Discharges from Ulan Coal mine, Wollar Creek, the Merriwa River and Wybong Creek all increase EC in the Goulburn River. There was also an increase between SW19 and Coggan (SW-COG). This appears due to the influence of Bylong Creek, although there was no surface flow in the Creek itself. Wollar and Bylong Creeks are both southern tributaries that flow through incised saline Permian geology in their mid and lower reaches. One arm of the Wollar catchment is affected by active open cut mining at the Wilpinjong Coal Mine which commenced operations in 2005. Between SW17 and SW Kerr there is an increase in salinity due to the Merriwa River, a northern tributary that flows through Tertiary basalt, Jurassic siltstones and Triassic sandstones.

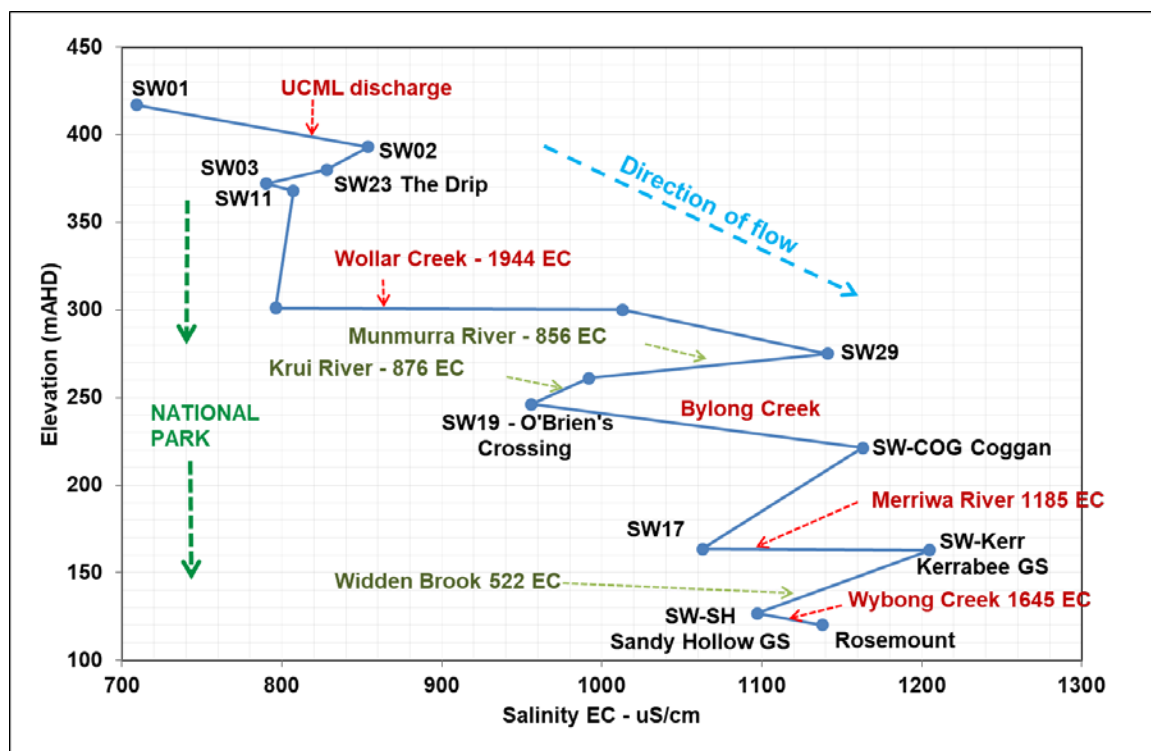


Figure 5:2 Longitudinal transect of salinity as a function of elevation (mAHD) in Goulburn River also showing the salinity of tributaries - October 2012

Significant decreases in mainstream EC are seen downstream from The Drip gorge, and following inflows from the Munmurra and Krui Rivers and Widden Brook. In addition, a significant decrease in salinity occurs between Coggan and immediately upstream of the

confluence with the Merriwa River. Widden Brook is a southern tributary that flows through Triassic sandstones and is very important for mitigating the impact of salinity in the Goulburn at Sandy Hollow.

The general relation between EC of water samples in the catchment and the underlying geology is shown in Figure 5:3. This shows that generally streams which intersect the Permian Coal Measures and Jurassic sedimentary strata are associated with higher salinity water. In contrast, streams sourced from the Tertiary volcanics and Triassic sedimentary strata are associated with the lowest salinity water.

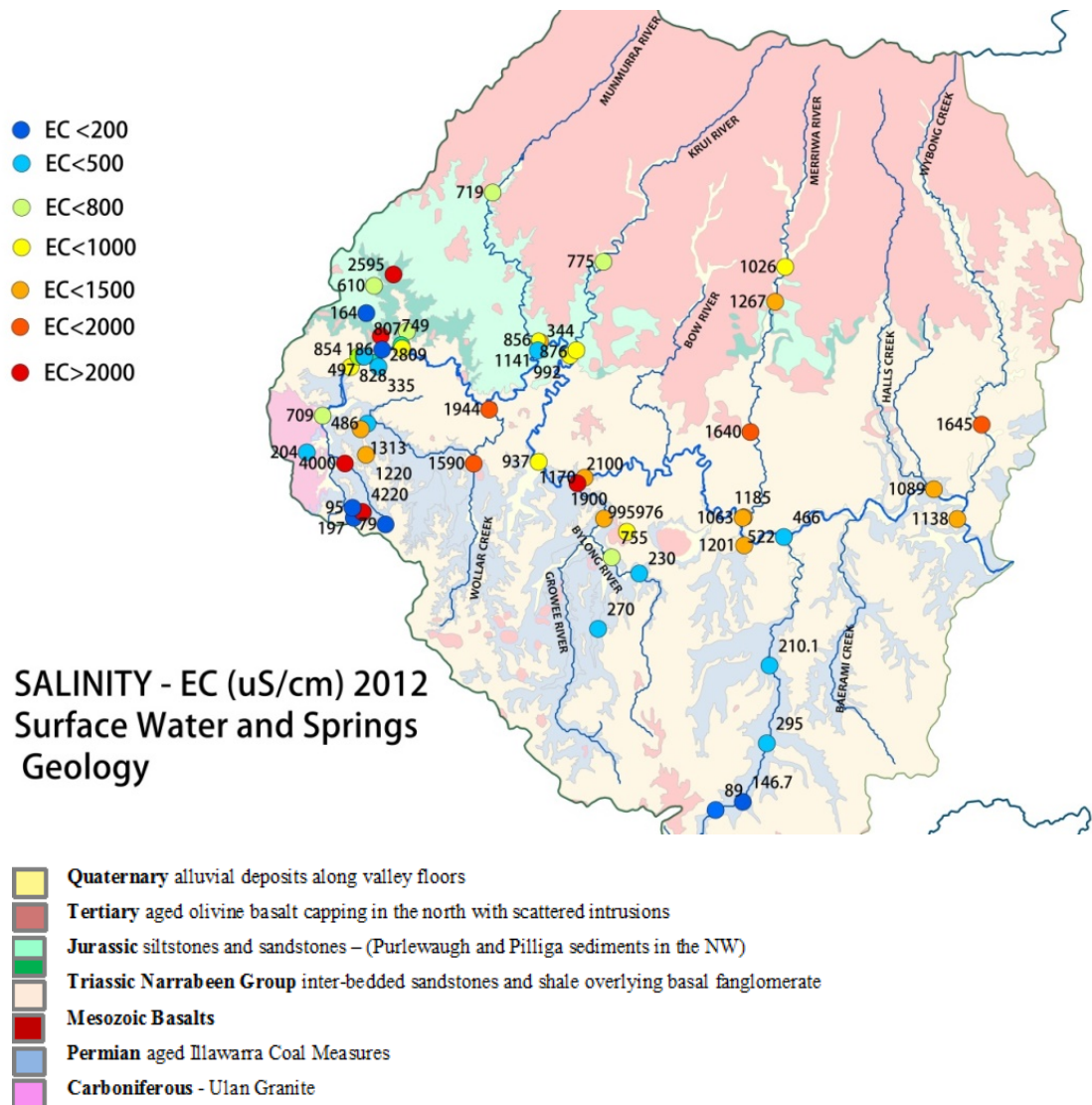


Figure 5:3 The association of stream salinity (EC) and geology at survey sampling sites in the Goulburn catchment (Geoscience-Australia, 2013; Rasmus *et al.*, 1969; Watkins *et al.*, 1999)

5.1.2 Longer term temporal change in river salinity

In Sections 4.3.4 and 4.3.6 it was shown that in the 1970s-1980s the long-term specific annual water losses from the catchment above Coggan increased by between 9 to 12 mm per year, a major change in catchment specific discharge. The intimate connection between

discharge and stream EC suggests that the decrease in catchment discharge should be accompanied by a general increase in stream EC.

Unfortunately, grab measurements of EC, together with spot measurements of Q are only available from 1969 to 2007 for the Goulburn at Coggan. In addition, no regular measurements of EC were collected during the late 1980s – early 1990s when significant discharge from mines in the upper Goulburn commenced. Figure 5:4 compares the 1969-1982 pre-mining percentile distribution of spot EC measurements at Coggan with the distribution of continuous EC measurements from 2012 to 2016. It can be seen, for the percentile range below 0.9, that the 1969-1982 measurements fall below those for 2012-2016 as they do again for the percentile range greater than 0.98.

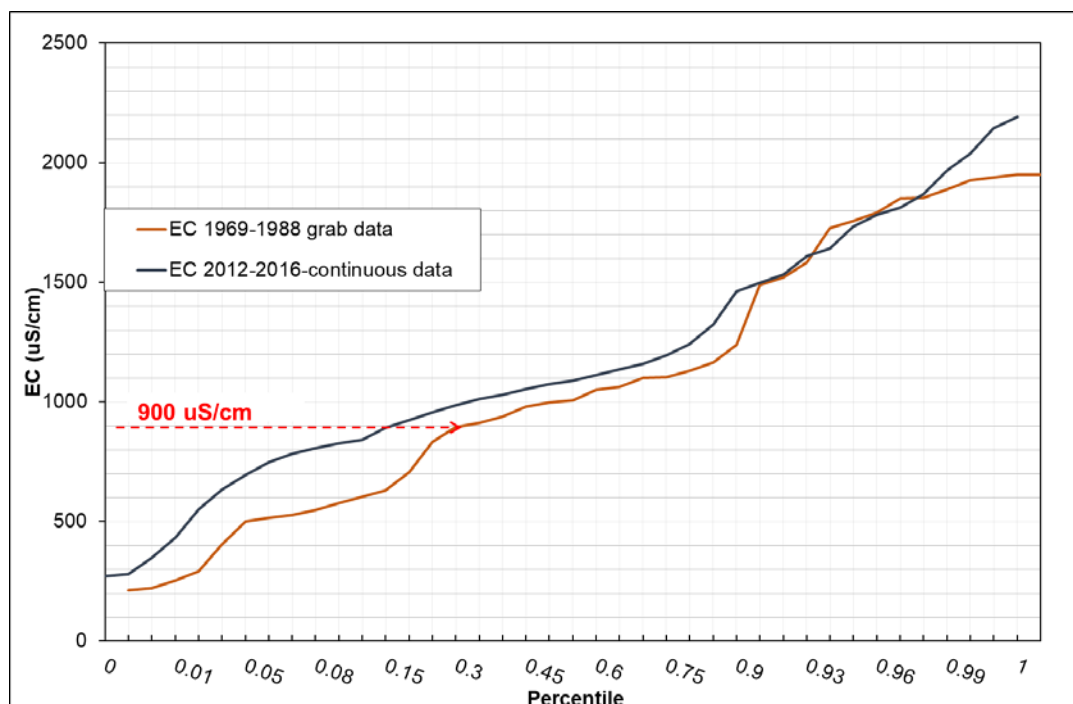


Figure 5:4 Comparison percentile range of salinity at Coggan pre-mining (1969-1982) and during mining (2012-2016)

Table 5:3 shows the mean and median ECs at Coggan for 1969 to 1982 are well below that for 2012-2016. The fact that median and mean at each period are similar suggests EC here is approximately normally distributed.

To examine if the increase in EC is caused by a decrease in stream discharge, Figure 5:5 compares the percentile distribution of Q at Coggan for the period 1969-1982 with that for 2012-2016. Both spot and continuous stream discharge measurements were available for 1969-1982.

Table 5:3 Comparison percentile range EC & Q (ML/day) pre-mining (1969-1982) to during mining (2012-2016) at Coggan

Property	1969-1982	2012-2016
Measurements	72	1688
Median EC ($\mu\text{S/cm}$)	681	1091
Mean EC ($\mu\text{S/cm}$)	690 $\pm$ 220	1140 $\pm$ 270
Median stream discharge (ML/day)	40	38
Geometric mean stream discharge (ML/day)	34	43
Percentile salinity (when EC=900)	0.26	0.16
Equivalent Q (ML/day)	63	107
Q Percentile	0.53	0.64

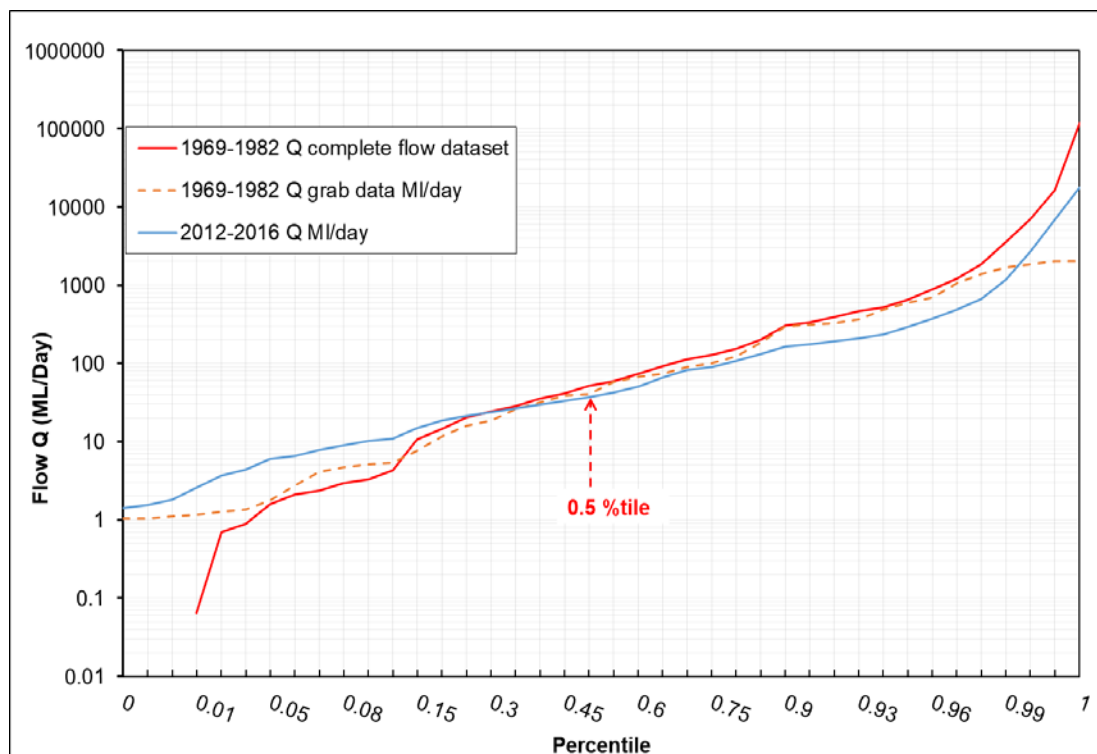


Figure 5:5 Comparison of the percentile distribution of stream discharge Q, for Coggan for pre-mining (1969-1982) and during mining (2012-2016) daily discharge Q (ML/Day). The distribution for grab samples is also compared with that for continuous samples for the period 1969 to 1982

At low flows, below percentile 0.2, the 2012 - 2016 flow distribution is higher than those for 1969-82, perhaps reflecting the impact of mine discharges at low flows. For flows above percentile 0.45, the flow distribution for 2012-2016 drops below that of 1969-1982. The similarity between the distributions of spot and continuous Q measurements for 1969 to 1982 in the percentile range 0.02 to 0.97 suggests that the spot measurements were reasonably representative of the river flow regime over this period.

Table 5:3 also shows the median and geometric mean Q for the two periods, the geometric mean reflecting the approximately log normal distribution of daily stream flow. While the median Q for both periods is similar, the geometric mean Q for 2012-16 is larger than that for

1969-1982. The lower mean EC during 1969 to 1982 cannot therefore be attributed to a higher geometric mean stream discharge during this period.

In terms of the HRSTS limit of EC $900\mu\text{S}/\text{cm}$, for the 1969-82 data this EC limit corresponds to an EC percentile of 0.26 (Table 5:3), while for 2012-16 data this is as low as 0.16. By using the relationship between EC and Q it is estimated that for the 1969-82 period discharges at or below 63 ML/day were equal to or exceeded the 900 EC limit while for 2012 to 2016 flows as high as 107 ML/day exceeded the limit. The results suggest that at Coggan, the task of achieving the catchment target EC of $900\mu\text{S}/\text{cm}$ has become more difficult.

5.2 *Salinity, discharge and salt load sites down the Goulburn River*

There are three currently active principal gauging stations on the Goulburn before it enters the Hunter River. These are Coggan (GS210006), Kerrabee (GS 2100016) and Sandy Hollow (GS210031) (Table 4:4). The Coggan gauge has salinity records from May 2012; Kerrabee gauge from 2002; and Sandy Hollow from 1992 (Table 4.4). Data from the Coggan gauging site characterises discharge from the upper Goulburn which includes the tributaries Munmurra, Krui and Bylong Rivers. Kerrabee gauging station, in addition, captures tributary flows from Merriwa and Bow Rivers. Sandy Hollow, the last gauging site on the Goulburn River, captures all the above plus additional inflows from the southern tributaries of Widden and Baerami Creeks. Wybong Creek discharges into the Goulburn below Sandy Hollow GS approximately 17 kilometres above the confluence with the Hunter River.

The contiguous period of quality salinity data for Coggan, Kerrabee and Sandy Hollow is May 2012 to June 2016. Table 5:4 presents the results of analyses of EC and stream discharge over this four-year period. The mean and median ECs of approximately $1100\mu\text{S}/\text{cm}$ at all gauges appear to be a consequence of the lower geometric mean flows for the period 2012 to 2016. The percentile distributions of EC at each gauging station are plotted in Figure 5:6

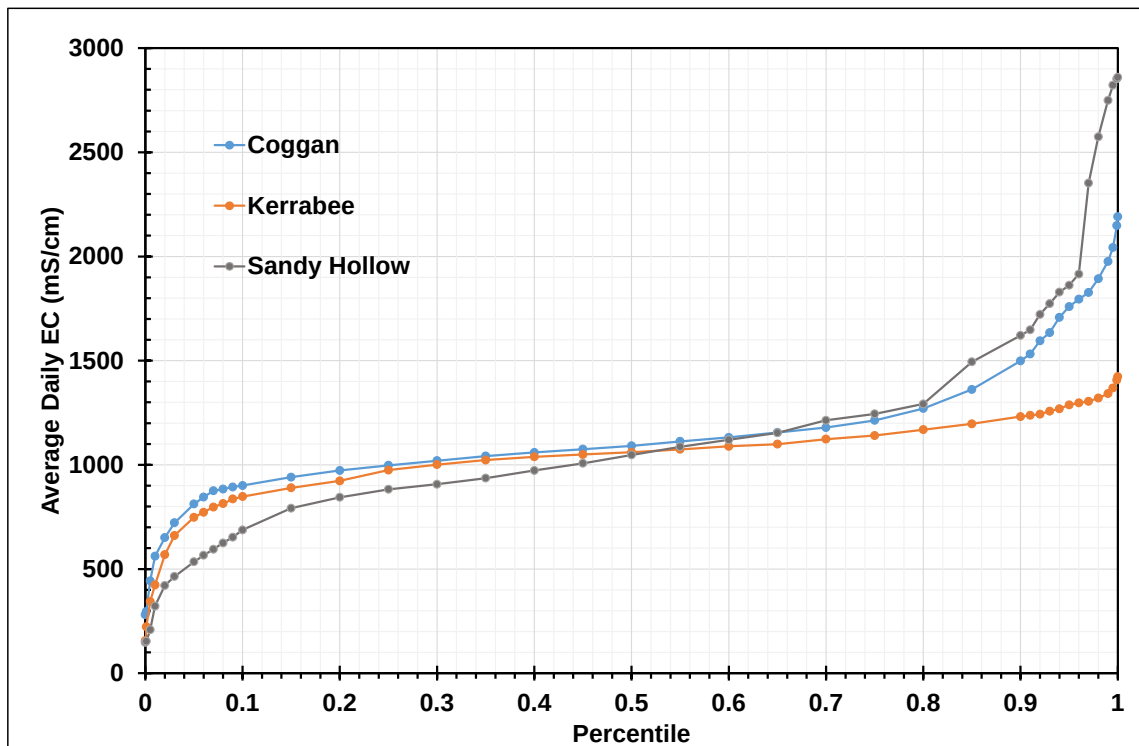


Figure 5:6 Comparison percentile distributions of daily salinity EC for three gauges on the Goulburn River 2012-16

Below the 0.5 percentile Sandy Hollow has lower EC than both Kerrabee and Coggan. This reflects the mitigating impact of lower salinity inflows from the southern tributaries draining the Triassic sediments, particularly Widden Brook. Between percentiles 0.5 and 0.8 the percentile distributions of EC for Sandy Hollow and Coggan are similar. Above the 0.8 percentile Sandy Hollow has much higher salinity than Coggan. This suggests an additional source of salinity in the lower Goulburn catchment due to groundwater discharge perhaps from the Wittingham Coal Measures or salt accumulating and concentrating in alluvial sandy bed during very low flows that are mobilised and spike during the first flush of high flows.

The EC distribution at Kerrabee is problematic, considering its central position between the two other stations. Between the zero percentile and 0.6 percentile Coggan and Kerrabee have similar EC distributions at high flows. After 0.6 percentile the EC values for Kerrabee increasing fall well below those for Coggan and Sandy Hollow. These results suggest some inherent monitoring problems at Kerrabee which could be due to transmission losses of more saline lower discharge flows into alluvial sand aquifer in the river bed or the influence of fresher flows from Kerrabee Creek located immediately upstream from the gauge.

Table 5:4 shows that the mean daily discharge at each gauging site is much larger than either the geometric mean or median flow, both of which are identical within error. This reflects the skewed distribution of daily discharge close to a log normal distribution.

Normalising the discharges with above gauge catchment area shows in Table 5:4 that the geometric mean specific discharges at all three stations were identical within error. This

suggests a surprisingly uniform catchment, despite the topographic, geologic and land use heterogeneity across the catchment.

The percentile distributions of specific discharges Figure 5:7 at the three gauging stations were similar between percentiles 0.4 and 0.9. Below percentile 0.4, Coggan had a higher specific discharge than Sandy Hollow or Kerrabee, which were similar in this range. There appear to be two possible explanations for this. The first is the higher specific discharges below percentile 0.4 are due to the discharge of mine water of up to 28 ML/day during low flows. The second is that gauge by-pass flow is occurring in the sandy stream bed controls at Kerrabee and Sandy Hollow.

Sandy Hollow has the largest specific discharge above percentile 0.9. This appears to be due to stream discharge from the higher yielding southern tributaries of Widden and Baerami draining from the higher elevations of Nullo and Coricudgy Mountains. These have the highest annual rainfalls in the catchment.

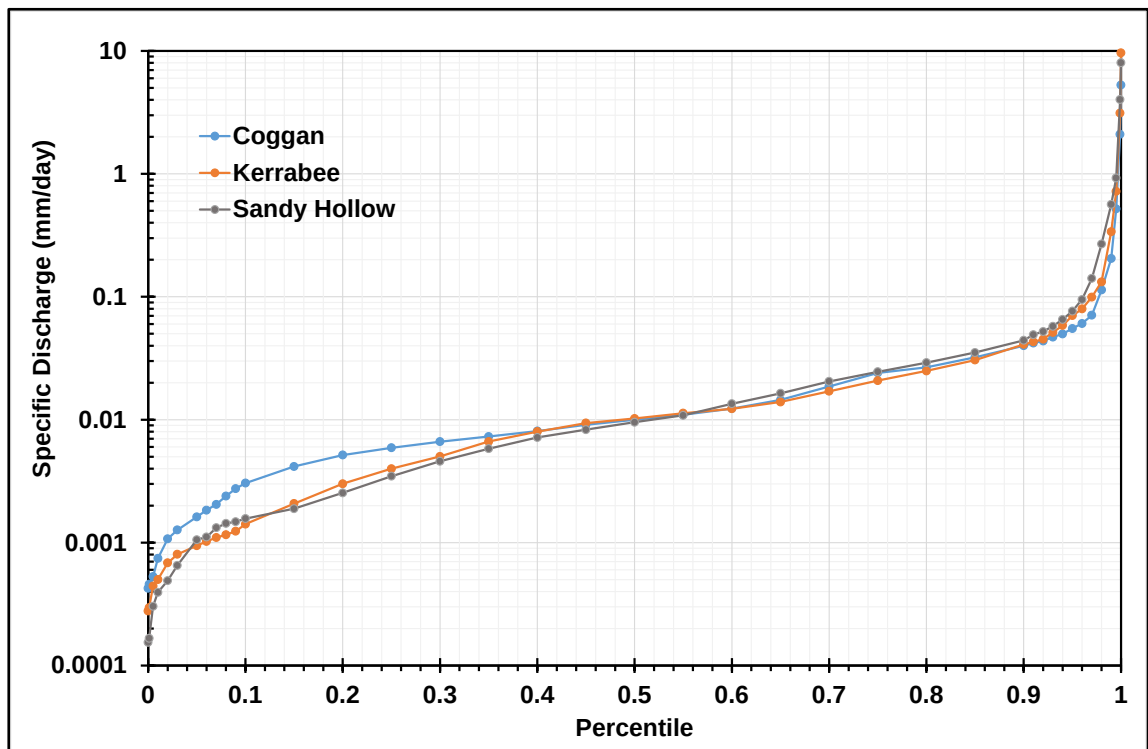


Figure 5:7 Comparison of the percentile distributions of specific discharges for three gauges on the Goulburn River over the period 2012-16

The average annual specific salt production for each of the gauging stations for the period 2012-16 in Table 5:4 were estimated in two ways. In the first the slope of the linear regression between the cumulative specific salt load, $\Sigma(SL/A)$ versus time was determined. In the second the aggregate salt load over the period was calculated ($\Sigma(SL/A)/\Sigma t$). These gave values of about 6.3 and 5.3 tonnes/km²/year respectively, similar to earlier estimates (Krogh *et al.*, 2013)

and with the salt yields at Kerrabee and Coggan identical. This indicates a remarkably uniform salt yield from the catchment despite the different sources in Figure 5:2.

Table 5:4 Comparison of stream discharge and salinity for three stream gauges on the Goulburn River 2012-2016

Property	Sandy Hollow	Kerrabee	Coggan
Catchment Area (km ²)	6810	4950	3340
Elevation (m AHD)	126.655	162.841	221.333
EC (µS/cm)			
Mean	1115	1042	1142
St Dev	428	169	266
CV	0.383	0.162	0.233
Geometric Mean	1040	1024	1112
Minimum	148	156	280
Median	1047	1061	1091
Maximum	2856 ²¹	1423	2191
Discharge, Q (ML/day)			
Mean	284	174	95
St Dev	1926	1443	576
CV	6.79	8.30	6.06
Geometric Mean	63.8 ±4.2	45.3 ±3.8	36.2±3.0
Minimum	1.0	1.4	1.4
Median	64.9	50.6	33.3
Maximum	54538	47775	17665
Specific Discharge, Q/A (mm/day)			
Mean	0.042	0.035	0.028
St Dev	0.283	0.292	0.172
CV	6.79	8.30	6.06
Geometric Mean	0.0094±0.0006	0.0092±0.0008	0.0108±0.0009
Minimum	0.00015	0.00028	0.00042
Median	0.0095	0.0102	0.0100
Maximum	8.01	9.65	5.29
Annual Catchment Yield (ML/year)			
Average (from regression)	130,281	82,732	44,724
St Error	855	594	314
Average (from final ΣQ)	103,622	63,489	34,709
Annual Catchment Specific Yield (mm/year)			
Average (from regression)	19.1	16.7	13.4
St Error	0.13	0.12	0.09
Average (from final ΣQ/A)	15.2	12.8	10.4
Annual Specific Salt Yield (tonnes/km²/year)			
From Regression ΣSL/A vs time	6.18±0.03	6.43±0.04	6.40±0.04
From (ΣSL/A/Σt)	5.35	5.24	5.22

5.2.1 Salt loads in the Goulburn River

Daily salt loads (SL, tonnes/day) have been estimated here from Total Dissolved Solids (TDS mg/l) and the daily discharge rate Q, (ML/day). Salt loads (SL) have been estimated from Total Dissolved Solids (TDS mg/l) and the daily discharge rate (Q, ML/day)

$$SL = TDS \times Q = 0.68 \times EC \times Q \times 10^{-3} \quad [5:1]$$

TDS was determined from the empirical relationship between measured EC and known TDS, using best fit linear proportionality representative water quality samples for the Goulburn, $TDS = 0.68 \times EC$. Typically the proportionality constant can vary from 0.56 for high chloride water type to 0.75 for high bicarbonate (McNeil *et al.*, 2005; Hem, 1989). The value for surface and groundwater in the Goulburn was estimated to be 0.68 (Appendix E).

Table 5:5 shows that the mean, geometric mean and median daily salt loads increased down-stream with increasing catchment area. The similarity of the median and geometric mean salt loads at a particular site suggests salt load is approximately log normally distributed.

When the catchment yield of salt is examined through the daily specific salt load at each of the three gauging stations, it is seen in Table 5:5 that the geometric mean salt loads in the lower catchment at Kerrabee and Sandy Hollow are equal but lower than that at Coggan. The higher geometric mean specific salt load at Coggan may represent an additional source of salinity in the upper Goulburn.

Table 5:5 Comparison of salt load results for three Goulburn stream gauges, for the period 2012-16

Property	Sandy Hollow	Kerrabee	Coggan
Salt Load (tonnes/day)			
Mean	99.7	71.0	47.7
St Dev	286.3	263.0	137.9
CV	2.9	3.7	2.9
Geometric Mean	45.1	31.5	27.4
Minimum	0.87	1.17	1.67
Median	46.3	36.3	24.4
Maximum	7528	7625	3369
Specific Salt Load (tonnes/km²/day)			
Mean	0.015	0.014	0.014
St Dev	0.042	0.053	0.041
CV	2.87	3.71	2.89
Geometric Mean	0.0066	0.0064	0.0082
St Dev	±1.04	±1.05	±1.04
Minimum	0.00013	0.00024	0.00050
Median	0.0068	0.0073	0.0073
Maximum	1.106	1.540	1.009
Correlations			
Correlation EC-Q	-0.206	-0.315	-0.251
Correlation EC-ln(Q)	-0.516	-0.746	-0.821

Figure 5:8 plots the percentile distributions of daily SL/A for the three gauging sites for the period 2012-16. Coggan has a notably higher specific salt load than the other two stations below percentile 0.4. This reflects the higher stream discharge at Coggan in this percentile range (Figure 5:7). The higher geometric mean SL/A for Coggan in Table 5:5 reflects the higher SL/A values below percentile 0.4 at Coggan gauge. This could indicate the influence of mine water discharges or groundwater discharge during low flows. The magnitude of this extra salinity source can be estimated if it is assumed that the geometric mean daily specific salt load at Sandy Hollow and Kerrabee 0.0065 tonnes/km²/day is the natural salt load at Coggan. If so the geometric mean daily salt load would be 21.7tonnes/day. Using the actual geometric mean specific salt load at Coggan shows the geometric mean daily salt is 27.4tonnes/day. This suggests an additional source of salt in the upper catchment of 5.7 tonnes/day, or 2,080 tonnes/year. Salt export in the upper Goulburn contained in UCML discharge water averaged 2,758tonnes/year in 2012-2016; a total 12,871 tonnes over 4.7 years (see section 6.5).

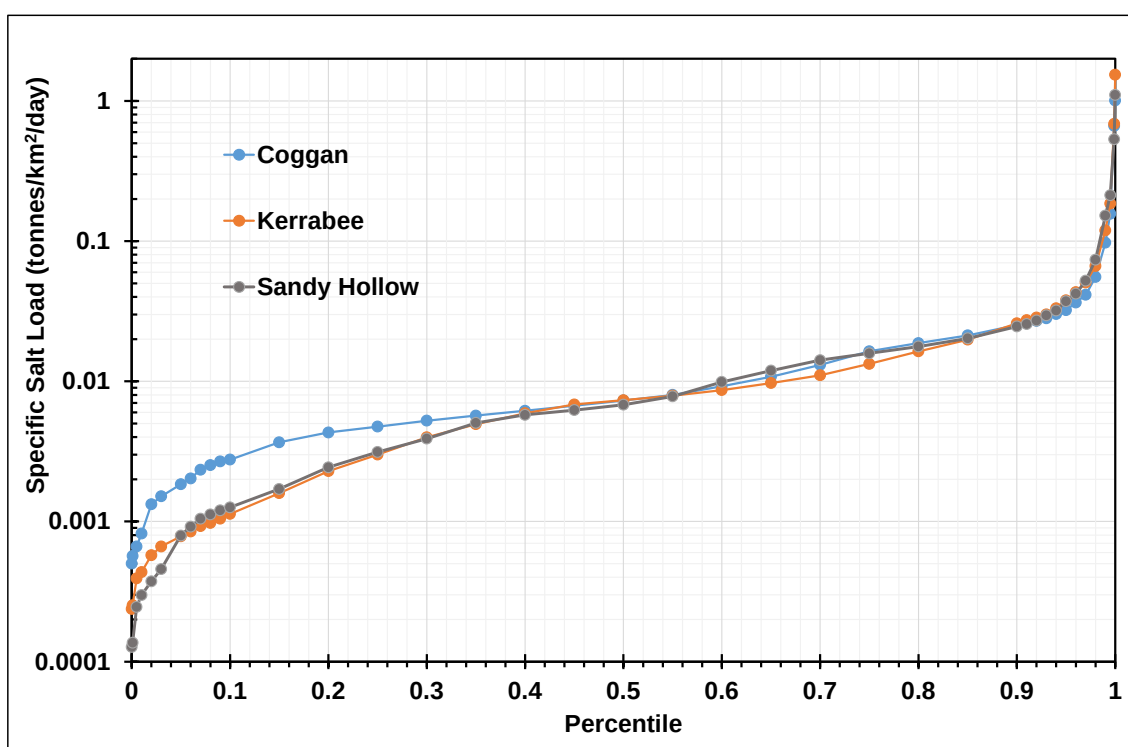


Figure 5:8 Percentile distribution of daily specific salt load at three gauging sites on the Goulburn River for the period 2012-2016.

5.3 Salt Load, EC and stream discharge

In chapter 4 a decrease in catchment specific discharge was identified starting in the 1970s. A simple two component mixing model of stream salinity in which more saline groundwater discharge mixed with fresher surface runoff, predicts that any decrease in surface runoff could result in higher stream salinity. Figure 5:9 explores the relationship between stream EC and stream discharge and Figure 5:10 explores the relationship between salt load and Q.

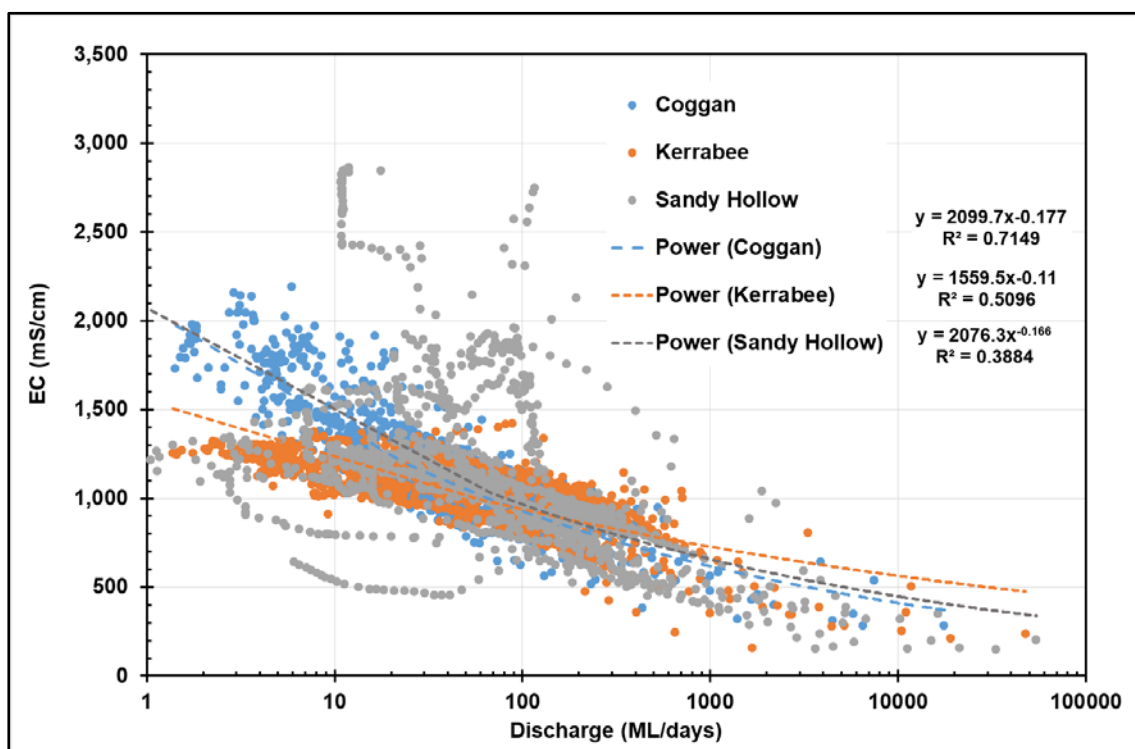


Figure 5:9 Relationships between log daily EC and log daily discharge for all three gauging sites on the Goulburn River for the period 2012-16.

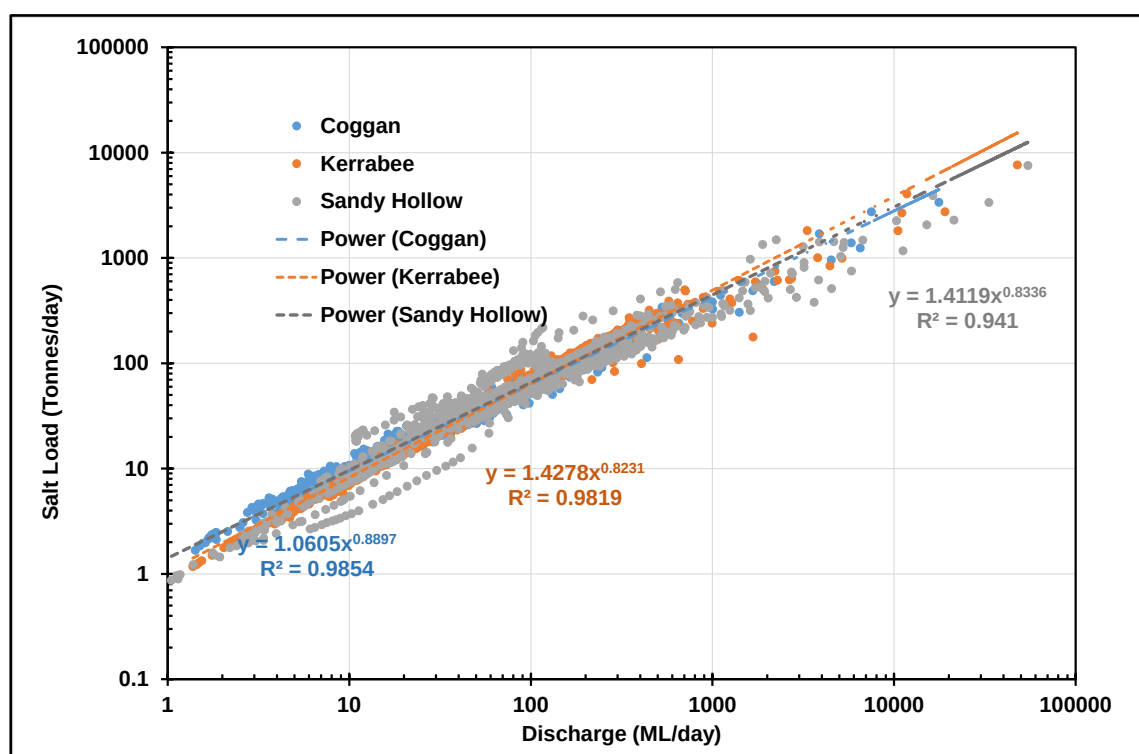


Figure 5:10 Relationship between log daily salt load and log daily stream discharge for the period 2012-16

Both EC and salt load were fitted to relationships $\log(X) = a \cdot \log(Q) + b$ with X either EC or SL. Table 5:6 displays the relationships between salt load, EC and discharge. The

relationships are plotted in Figure 5:9 and Figure 5:10. Stream salt load plotted against Q is a common method used to reduce the scatter in the EC versus Q plot (Jolly *et al.*, 1997).

The relationships between EC and Q in Figure 5:9 show considerable scatter but the relationships are significant. The relationships between EC and Q at Sandy Hollow and Coggan are similar, although Sandy Hollow shows much more scatter and with systematic departures. This appears due to difficulties in the stream rating tables at Sandy Hollow related to the highly mobile sand bed control there. The slope of the EC-Q relationship for Kerrabee is lower than that for the other two sites. This is a consequence of lower salinity distribution above percentile 0.6 at Kerrabee in Figure 5:6. These differences are also reflected in the lower slope for log (SL) versus log (Q) at Kerrabee.

What is clear from these relationships is that any decrease in log mean discharge in the catchment will result in an increase in stream salinity.

Table 5:6 Relationships between Salt load, EC and stream discharge (Q) at the three gauges for the period 2012-2016

Property	Sandy Hollow	Kerrabee	Coggan
Relation Between Salt Load & Discharge $\ln(SL) = m \cdot \ln(Q) + b$			
m	0.834	0.890	0.823
st error m	0.0054	0.0028	0.0029
b	0.345	0.059	0.356
st error b	0.024	0.011	0.011
R²	0.941	0.985	0.982
Relation Between EC & Discharge $\ln(EC) = m \cdot \ln(Q) + b$			
m	-0.166	-0.110	-0.177
st error m	0.0054	0.0028	0.0029
b	7.638	7.352	7.650
st error b	0.024	0.011	0.011
R²	0.388	0.510	0.715

The cause of the wide variability of EC data at Sandy Hollow is uncertain. The systematic departure trends appear to suggest instrumental or calibration problems. This raises concerns over the reliability of the site, particularly as it is the last downstream site before the Goulburn's confluence with the Hunter River.

5.4 **Conclusions**

The aim of this chapter was to investigate at the catchment-scale the sources, drivers and trends in stream salinity and salt loads using spot measurements and analysis of available government and industry data supplemented with surface and groundwater sampling.

The spot survey of EC in the Goulburn River and tributaries revealed a wide array of sources of salinity, particularly below an elevation of about 280 m AHD. These were associated with tributaries incising into geologies of higher salinity, such as the Permian Coal Measures. Discharges from mines at Ulan, from Wollar Creek, the Merriwa River, Wybong and Bylong Creek all increase EC in the Goulburn River. Importantly, in terms of downstream discharge into the Hunter River, tributaries draining from lower salinity geologies or higher yielding and lower salinity geologies mitigate salinity in the Goulburn. These include catchments with Triassic sandstone geology like Widden Brook; baseflows, seeps and springs like The Drip, or tributaries such as the Munmurra and Krui Rivers dominated by Tertiary volcanics and Triassic geology.

A critically important conclusion here is that extracting more water for other uses from these lower salinity catchments will increase the salinity of Goulburn discharge into the Hunter. Equally important, any decrease in rainfall with climate change, particularly that predicted in the cooler season, will also decrease discharge and increase salinity.

It was shown in Chapter 4 that there has been a significant decrease in catchment yield starting in the 1970s. The intimate relationship between salinity and discharge means that a decrease in discharge means an increase in salinity. Although full examination of this is not possible due to the absence of early salinity data, spot measurements of EC from 1969 revealed a shift in the percentile distribution of EC between 1969 to 1982 and 2012 to 2016. The mean EC in the period 1969 to 1982 was significantly lower than that for the period 2012 to 2016 despite the latter period having a higher geometric mean discharge.

This shows that in the period 2012-16 the frequency of exceedance of the HRSTS limit of EC 900 $\mu\text{S}/\text{cm}$ has increased. Further increases in surface and groundwater abstraction from the catchment will lead to additional increases in stream salinity over time.

Mean salinities over the period 2012 to 2016 were identical at all three gauging sites although the percentile distributions of salinity differed with Sandy Hollow showing lower salinity flows below a percentile of 0.5. This could be due lower salinity discharge from streams draining the Triassic sandstones such as the Widden.

Two estimates of the annual specific catchment salt yield at the gauging sites gave values ranging from about 5.2 to 6.4 tonnes/ km^2 /year, were consistent with previous estimates. The yields from the catchments above Coggan and Kerrabee were identical.

Analysis of continuous salinity data at all three active gauging stations in the Goulburn revealed problems in the gauging stations. The intermediate Kerrabee had much lower maximum ECs than at the upstream Coggan and the downstream Sandy Hollow. This appears due to loss of low flows which are more saline below the stream sand bed control. At Sandy Hollow, the relationship between EC and Q showed major systematic departures which appear to be due to changes in rating tables of the highly mobile sand bed control and means that the Sandy Hollow site is unreliable.

The relationships between $\log(\text{EC})$ and $\log(Q)$ were all significant and the slopes of the relations for Sandy Hollow and Coggan were identical as they were for the relationships between $\log(\text{SL})$ and $\log(Q)$. Kerrabee, with its loss of higher salinity flows differed. These relationships demonstrate that any decrease in catchment water yield through changing climate, land use or water extraction will result in an increase in stream salinity. When the catchment yield of salt is examined through the daily specific salt load at each of the three gauging stations, the geometric mean salt loads in the lower catchment at Kerrabee and Sandy Hollow are equal but lower than that at Coggan. The higher geometric mean specific salt load at Coggan may represent an additional source of salinity in the upper Goulburn.

The influence on mine discharge on flow and salinity in the Goulburn is considered in Chapter 6:.

Chapter 6: Mining impacts on the upper Goulburn

The aim of this chapter is to quantify the impacts of mining discharge on flow and salinity in the upper Goulburn River. The interception and extraction of surface and groundwater by mining are described and quantified here and the effect of groundwater depressurisation further discussed in Chapter 9. This Chapter relies on industry reported data, supplemented by departmental monitoring data and measurements carried out in this work.

6.1 *Pre-mining salinity in the upper Goulburn River*

An important question in the Goulburn is what was the pre-mining stream salinity in the upstream catchment? While pre-mining EC data is limited the pre-mining archival grab salinity and discharge records 1968-1982 for the discontinued Ulan and still active Coggan sites are sufficient to give an indication of pre-mining conditions. These are shown in Table 6:1. Pre-mining water quality data indicates the mean EC at Ulan was over 30% lower than that at the downstream Coggan gauge. The annual average specific salt yield for the catchment upstream at Ulan, in the period 1969 to 1982, however was about 45% higher than at Coggan.

Table 6:1 Archival grab sample records Ulan 210046 & Coggan 210006 for the period prior to 1982 (NSW Department Water Resources, 1994; NSW Department of Water and Energy, 2008)

Property/Site	Ulan 210046	Coggan 210006
Period	Jun 1968 - July 1982	Oct 1969 - July 1982
Geometric Mean Annual Specific Yield (mm/year)	6.7	4.8
Mean EC ($\mu\text{S}/\text{cm}$)	490 $\pm$ 200	690 $\pm$ 220
Minimum EC ($\mu\text{S}/\text{cm}$)	200	145
Median EC ($\mu\text{S}/\text{cm}$)	432	681
Maximum EC ($\mu\text{S}/\text{cm}$)	1230	1306
Mean Annual Catchment Salt Yield (tonne/km ² /year)	10.0	6.9

The geology of the catchment above the Ulan gauge is dominated by incised, often saline, Permian and alluvial sediments of the Moolarben Valley, with Ulan granites (Lachlan fold belt) in the west and vegetated Triassic sandstones in higher elevations to the south east. Further downstream Triassic sandstones dominate the landscape through the Goulburn River National park (Figure 3:6, Figure 6:2)

The geometric mean annual specific catchment yield at Ulan was nearly 40% higher than that for the Coggan catchment (Table 6:1). Figure 6:1 shows that the percentile distributions of the specific discharge at Coggan and Ulan were similar above percentile 0.4. Below this, Ulan had higher specific discharge than Coggan, which may indicate groundwater spring discharge in the Ulan region is contributing baseflows.

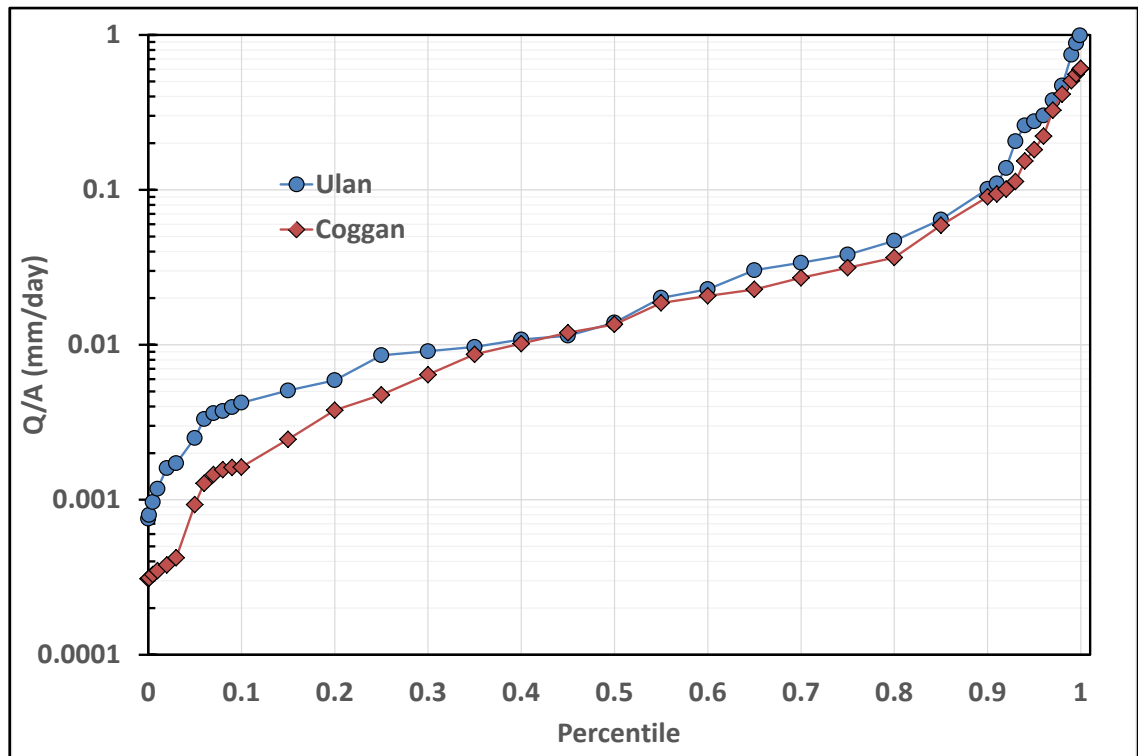


Figure 6:1 Percentile distribution of specific yield (Q/A) for the grab samples at Ulan (210046) & Coggan (210006) for the period 1968-1982

6.2 ***Groundwater and surface water interception by mines***

There are currently three approved mines operating in the upper Goulburn River catchment (Figure 6:2, Table 6:2).

- Ulan Coal Mine Ltd (UCML - Glencore): underground and open cut mining
- Moolarben Coal Complex (MCC- Yancoal): underground and open cut mining in the Moolarben valley
- Wilpinjong Coal Mine (WCM - Peabody's): an open cut mine in the Greater Wollar valley

The total approved mining footprint for all three mines in 2016 was over 180 km²; with 65 km² of open cut mines and 124 km² of underground longwall mines (Table 6:2). The open cut mining footprint is concentrated predominantly within the valley floor in natural recharge, discharge and alluvial areas (Figure 6:2)

Mining operations can alter the direction and magnitude of water exchange between the river, alluvial aquifers and fractured rock aquifers through the drawdown and depressurisation of the groundwater system (McVicar *et al.*, 2015). Underground longwall mining causes subsidence that intercepts and depressurises the overlying porous and fractured rock regional Permian -Triassic groundwater system (MER, 2009; MER, 2011; MER, 2015; Hodgkinson *et al.*, 2015). The hydrological units associated with the Triassic Narrabeen Group and upper

Permian strata at higher elevations have hydraulic gradients towards the Goulburn River contributing to the river's baseflow (Middlemis and Fulton, 2011). Intercepted groundwater and surface runoff that is excess to mining operations is regularly discharged to streams under licenced conditions (UCML, 2011; WCM, 2015c). During extreme rain events licences have been varied to allow high volume discharges with minimal conditions on water quality (UCML, 2011; MCO, 2011).

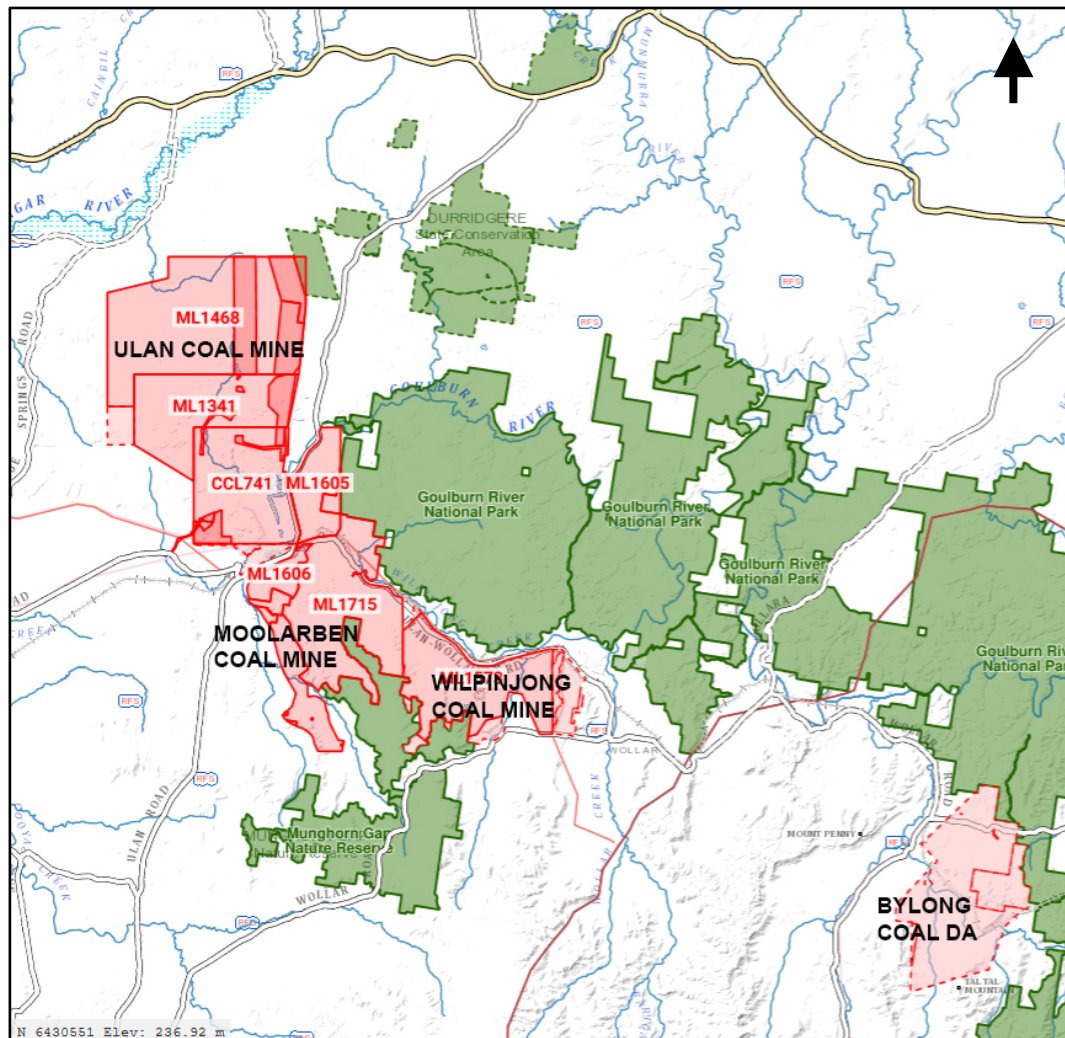


Figure 6:2 Current coal mine leases in the upper Goulburn at Ulan, Moolarben and Wilpinjong Coal mines, and proposed Bylong coal development Mapping (GSNSW, 2018)

Since the development of open cut and underground mining at UCML in the mid-1980s the groundwater ingress to longwall operations and subsided areas has risen significantly above predicted levels. Between 1985-1990 groundwater levels in the alluvial flats adjacent to the first open cut mine dropped 40 m from 3 mbgl to 43 mbgl, with aquifer yields reduced from 10L/s to less than 1L/s (Coffey-Partners-International, 1991; Middlemis and Fulton, 2011). These groundwater levels have never recovered and remain disconnected to the river system.

In 1998 a regional groundwater model developed by the National Centre for Groundwater Management at the University of Technology Sydney predicted total mine inflows ranging from 4 ML/day to 11 ML/day by 2017 (Kinhill, 1998a). However average daily groundwater inflows by 2011 had exceeded 11 ML/day and 18.6 ML/day by 2014 (MER, 2011; MER, 2015). The unpredicted increase in mine water make resulted in an increasing volume of mine water discharge to the Goulburn River (Section 6.3)

Groundwater modelling by Mackie Environmental Research (MER, 2011) estimated hydraulic conductivity data was based on a combination of core sample rock porosity and pump tests with recharge rates from less than 1 to 2 % of annual rainfall. Groundwater associated with secondary permeability from faults, fracturing or jointing and perched aquifers were not included in the modelling. Predicting the occurrence of these structures was regarded as too complex to be incorporated. Given the occurrence of faulting in the region, and the predisposition of the Triassic geology to vertical jointing and tension cracks as visible in the sandstone escarpments (Kellett *et al.*, 1989) groundwater modelling could significantly underestimate mine inflows.

UCML modelling (MER, 2011; MER, 2015) has indicated complete dewatering of the Triassic strata above mined panels with the cone of depressurisation extending 4-6 kms with a 2 metre decline in hydraulic head. Within the Permian coal seam the effects are predicted to be regional, extending 10-20 kms beyond the longwall panels with a long term decline in the water table by around 5 metres in the 105 km² UCML footprint for over 300 years.

Total annual surface and groundwater interception is predicted to reach 10,220 ML by 2023 (Table 6:2). The associated decrease in groundwater inflow to nearby streams due to mine depressurisation include almost complete loss of baseflows in the minor tributaries, Ulan and Bobadeen Creeks by 2020 (Figure 6:4), with losses in the Goulburn River to be 0.039 ML/day at the close of mining in 2029 (MER, 2015).

MCC modelling in 2011 predicted cumulative losses of baseflow in the Goulburn River due to all the mines to reach about 7 ML/day by the end of mining (Middlemis and Fulton, 2011). Groundwater impacts will extend further to the east and south of UCML due to MCC underground operations (MER, 2015).

Table 6:2 Coal Mine approvals summary to 2016; footprint, predicted water usage, inputs-outputs (UCML, 2015b; UCML, 2016; MCC, 2017; WCM, 2015c)

MINE DETAILS	UCML	MCC	WCM	Total
Mine Approval to Year.	2033	2039*	2027**	
Approved Production Capacity (MT)	20	20*	12.5**	52.5
GW Extraction Licence Part 5 WA1912^{^^} (ML/year)	7,060	2,950	3,341	13,351
Upper Goulburn unregulated WMA 2000 (ML/year)	600	227	474	1,317
Predicted GW inflows/ intercepted ML/day [Year]	27.7 [2023]^	17.3 [2025]	3.3 [2019]	48
EPL. Max. licensed Discharge ML/day [EC μS/cm]	30 [900]	10* [900]	5** [500]	45
Maximum combined GW and SW Inflows ML/year [predicted in year]	10,220 [2023]	6,780 [2025]	2,823 [2024]	19,823
Approved U/G Mine Area [2014 mined km²]	102.3 [32.5]	21.7 [0]	0	123.7
Approved Open Cut Area + disturbed footprint (km²)	15.59	29.1	19.9	64.59

GW – Groundwater, GR – Goulburn River, Ext – Extraction (ML/year)

[^] GW inflow attributed to Goulburn catchment estimated to be 18 ML/day (6570 ML/a)

^{^^} Converted to North Coast Sydney Basin Fractured & Porous rock Groundwater source in 2016

* MCC modification lodged 2017 to increase licensed discharge to 20 ML/day

**WCM extension granted May 2017 - water discharge 15 ML/day, ext. mining to 2033 & coal production 13mtpa

Moolarben Coal (MCC) Stage one first commenced open cut operations in May 2010. Stage One and Stage Two (approved in 2014) include three underground mines with a footprint of 21.7 km² and four open cut mines with a disturbance footprint of 32.9 km² (Figure 6:2). MCC was approved with an EPL allowing restricted discharge up to 400 KL/day. In March 2013 the licensed volume was increased to allow the discharge of up to 10 ML/day of mine water, maximum EC 900 μ S/cm.

MCC underground mine, UG4 is bounded on two sides by the Goulburn River which comes within 200m to the west and around 500m to the north of the longwall footprint. MCC current exploration license extends to the north of the Goulburn River another 4 kms above The Drip gorge GDE (Chapter 8:). It has been proposed that a future expansion of underground mining to the north would involve connecting tunnels under the Goulburn River.

When the Moolarben Coal mine was approved in 2007 the modelling predicted groundwater inflows to the underground mine would peak at 6.6 ML/day with an overall volume of 15,655 ML groundwater inflows over the 16 years of mining (Table 6.4). Subsequent

recalibration of the water model in 2011 predicted maximum inflows would reach 5.5 ML/day, totalling 17,930 over 10 years. When MCC commenced underground operations in late 2016 the modelled groundwater inflows predicted to be under 1 ML/day exceeded 5 ML/day in the first few months (MCC, 2017). This triggered a major re-calibration in 2017 including a change of numerical model but using the same assumed permeability's for the geological strata (HydroSimulations, 2017). The predicted maximum daily inflows were increased to 17.3 ML/day with total water make over the 6 years of production reaching 30,189 ML. This is nearly double the total inflows that were originally predicted in the 2007 model (MCC, 2017; HydroSimulations, 2017).

Table 6.4 Increase in predicted inflows to Moolarben Coal UG4 based on mine modelling carried out in 2007, 2011, 2017 (HydroSimulations, 2017; EMM, 2013)

Moolarben Coal Mine UG4	MC1.6	RPS Aquaterra	Hydrosimulations
Model year	2007	2011	2017
Daily Max. (ML/day)	6.6	5.5	17.3
GW inflows (ML)	15,650	8,000	28,770
Borefield (ML)		9,930	1,419
Total inflows (ML)	15,655	17,930	30,189
Mining (Years)	16	10	6

WCM commenced in 2006 with open cut operations located within the Greater Wollar catchment. WCM was initially a no discharge mine but was granted a licence in 2012, with a maximum discharge of 5 ML/day, EC not to exceed 500µS/cm (Table 6:2). WCM discharge licence was increased to 15 ML/day in 2017 (WCM, 2017). WCM surface and groundwater interception is predicted to exceed 2,800ML in 2024 (Table 6.2).

The combined annual surface and groundwater inflows for the three mines are predicted to exceed 19,800 ML by 2025 (Table 6:2). The total reported groundwater inflows and surface water interception for all three mines in 2014, exceeded 12,400 ML with the net mine water usage exceeding 7,800 ML (Table 6:3). The balance excess to mine operations is discharged into the Goulburn River and lost through evaporation.

It is apparent that mine groundwater modelling has failed to predict the scale of impacts on groundwater resources and volume of excess mine water requiring disposal at the headwaters of the catchment.

Table 6:3 Combined water use, input/output 2014/15 for UCML, MCC & WCM (UCML, 2015b; UCML, 2016; MCC, 2017; MCO, 2014; WCM, 2015a)

2014 COMBINED MINE WATER USAGE	UCML	MCC	WCM	Total
Est. Groundwater inflow ML/year ¹	6,800	1,019	571	8,390
Est. Surface Interception (Rain runoff) ML/year	1,792	906	1,517	4,215
Total Mine Water USAGE ML/year ²	3,962	2,014	1,830	7,806
Mine Water Discharge ML/year	5,655	0	147	5,802
Total Est. Water Loss/ Output ³ ML/year	9,617	2,014	1,977	13,608

1 Includes groundwater seepage, borefield, ROM

2 Includes washery, dust suppression, CHPP, underground, ablutions, irrigation

3 Includes licensed mine water discharges.

6.3 Mine water use and off-site discharge

Groundwater extraction and dewatering to accommodate underground mining at UCML increased from over 1,000 ML in 1995 to 6,800 ML in 2014 (Table 6:4). Water-make excess to needs was discharged offsite. All three mines have been granted discharge licences that permit the discharge of treated excess mine water into the upper Goulburn River in varying quantities and quality (UCML-EPL394; MCC-EPL13932; WCM-EPL12425²²). Mine water discharged into the headwaters of the Goulburn catchment has the potential to affect salinity levels and salt loads over the 225 kilometres length of the Goulburn River and on to the Hunter River below Denman.

From 1984 UCML discharged untreated mine water into the Goulburn River with no limit on salinity up until the mid-1990s. In 1994 the discharge of mine water was changed to limit volume, but not salt levels under EPL394. Post 2000 in response to a Pollution Reduction Program condition aiming at 'nil' discharge, UCML trialled a evaporation water cannon over an open pit and a pasture irrigation scheme²³ as the prime means of waste water disposal (UCML, 2004b; MCO, 2014). From November 2003 a "nil discharge" requirement was introduced, that exempted 1 in 20 year daily rainfall event (UCML, 2004b).

During the millennium drought, 2004 - June 2007, UCML was able to restrict offsite discharge using the irrigation scheme and water cannon. UCML was granted a permanent offsite discharge license following an extreme rainfall event in June 2007. The licence set a 900 EC water quality limit on salinity (UCML, 2007). This was to assist in the management of the increasing water make in the underground (Table 6:4) and involved the use of a reverse osmosis plant to treat contaminated mine water, with the disposal of brine into disused pits. The downstream Goulburn River gauging station - Ulan DS (LP18) was installed to monitor

²² <https://apps.epa.nsw.gov.au/prpoeoapp/default.aspx>

²³ Bobadeen Irrigation Scheme (BIS),

streamflow and EC in the Goulburn River below UCML²⁴ licensed discharge points (LP6 & LP19).

The annual reporting of a Site Water Balance (SWB) at UCML commenced in 2004. The SWB estimates surface and groundwater use; input and outputs including groundwater seepage, washery and site evaporation.

Table 6:4 Annual UCML groundwater extraction, mine water discharge, irrigation and total water use vs Coggan (GS210006) annual discharge (KinHill, 1998b; Woodward-Clyde, 1995; UCML, 2004b; UCML, 2007; UCML, 2012; UCML, 2013; UCML, 2014; UCML, 2015b; UCML, 2016; UCML, 2017; Kinhill, 1998a)

UCML Annual Water balance (July to June)	Total groundwater make (ML/year) ¹	Mine water discharged to Goulburn River (ML/year) ²	Irrigation (BIS) (ML/year)	Total Mine Water output ³ (ML/year)	Coggan Annual Discharge July-June (ML/year)
1988	480	NR	0	NR	59900
1995	1020	~700	0	NR	16050
2004	2870	3.5	1320	3560	6680
2006	3250	1000	NR	6460	4090
Jan-Jun 2007	2200	130	550	NR	160
2009	3470	620	2200	NR	39600
2011	4250	5400		9410	232100
2012	5150	4300	1400	6310	124150
2013	4550	4000	1400	8430	91400
2014	6800	3850	1750	9980	16850
2015	5940	6100	1260	9620	10100
2016	6400	8020	710	10440	14950
2017	6450	5600	1800	8080	69500

The reporting year is July to June exception 2007.

NR = Not Reported

¹ Includes groundwater inflow from dewatering bores and seepage

² includes water discharged from LDP6 + LDP 19 (+ pasture irrigation at BIS)

³ total annual water use - licensed discharge, irrigation, shared to other mines, evaporation, CHPP, dust suppression, tailings, seepage to spoil

Extended periods of low rainfall are when groundwater inflows are most crucial for maintaining stream flow. In the six month period during the Millennium drought, January -June 2007, UCML reported a groundwater make in the underground mine of 2,200 ML (Table 6:4). A limited release of 130 ML was discharged to the Goulburn system and irrigation consumed 550 ML (UCML, 2007). Over the same period the total annual stream discharge downstream at Coggan was a low 160 ML. The total groundwater extraction at UCML reported in 2014, 2015 and 2016 annual reports equalled 45% the total stream flows at Coggan, while mine discharge

²⁴ Stream gauge DS Ulan LP18 is 3 kilometres downstream from UCML licensed discharge point LDP19 and 12 kilometres from Licensed discharge point LDP6 (via Ulan Creek).

including irrigation, equalled 51% of stream flow measured at Coggan over the same three year period (Table 6:4).

6.4 Impact of changing regulations on river salinity

The section above documented the range of changing regulations imposed between 1990 and the present on mine discharge to the upper Goulburn ranging from no conditions on salinity discharge prior to March 2003 through nil discharge during the Millennium drought to the current EC 900 $\mu\text{S}/\text{cm}$ upper limit.

Monthly grab samples at Gleniston site (21010017), seven kilometres downstream of mine discharge into Ulan Creek, have been taken between 1993 and 2016 (Figure 6:3, Figure 6:4). These clearly demonstrate the effect of the changing regulations on EC. The impact of earlier untreated mine discharge on downstream water quality is clear with EC spiking over 2000 EC. In 2003 mine discharge was temporarily halted under a 'nil discharge' condition with only an occasional release permitted. The conditions were altered after June 2007 to allow up to 30 ML/day excess mine water discharge, not to exceed 900 EC. While the extreme fluctuations have been damped post 2007, the mean EC is above the mean pre-mine river EC in the upper Goulburn (Table 6:1).

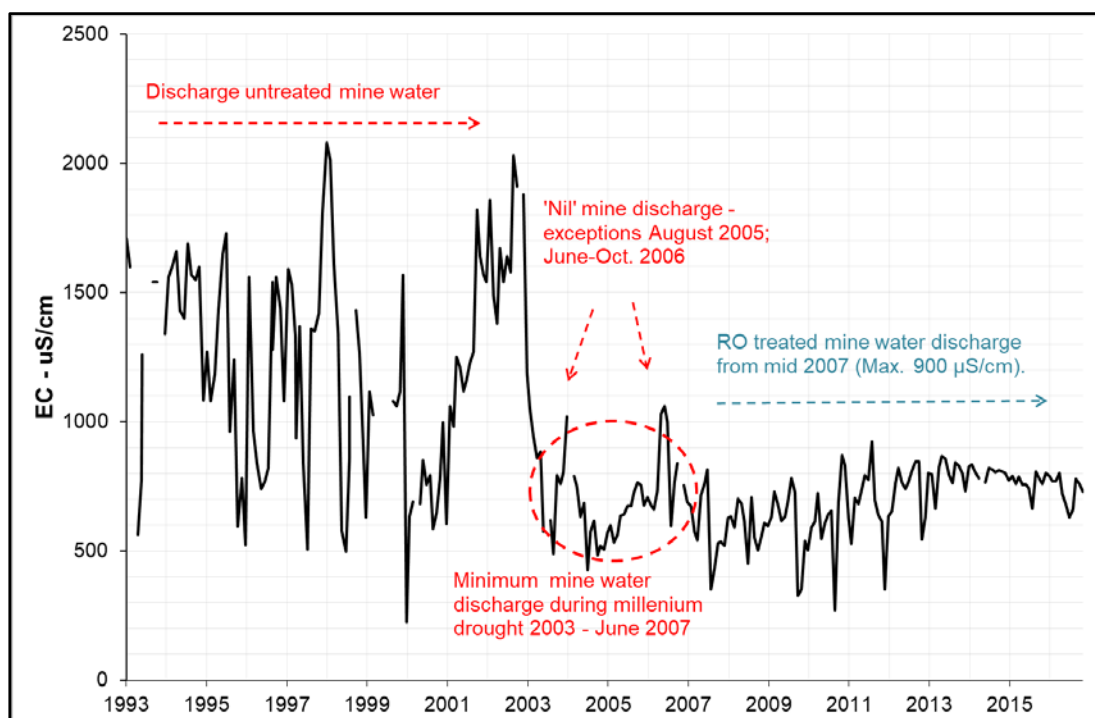


Figure 6:3: Salinity (EC) in the Goulburn River @ Gleniston (Site 21010017) from monthly grab data for the period 1993-2017 (NSW Environmental Water Laboratory, Sydney)

UCML operates up to three reverse osmosis (RO) plants to treat saline waste water. The treated mine water is mixed with surplus intercepted groundwater and discharged into the upper Goulburn catchment. The reject brine 6,000- 12,000 $\mu\text{S}/\text{cm}$ EC is disposed into open cut pits or

used as a dust suppressant. Current planning approval for all three mines allows for five open cut pits to remain in the landscape. Over time these open pits will hold increasingly saline water requiring management and security post mine for many decades (Hancock *et al.*, 2005a). Water quality in some is predicted to eventually exceed the salinity of sea water (WCM, 2015b). There are a range of pollutants including petroleum products that can be present in the Sydney Basin Permian coal measures such as BTEX, Phenols, Total petroleum hydrocarbon –TPH and other polycyclic hydrocarbons (Volk *et al.*, 2011).

Mine EPL discharge limits have been suspended during extreme rainfall events under emergency conditions. In December 2010 the mines in the Ulan Wollar area were granted emergency discharge licences for up to three months to allow for the dewatering of flooded underground and open-cut workings following a period of high rainfall (>95th percentile). The total amount of salt exported over this period exceeded 3,600 tonnes. UCML discharged 2,254 ML, median 2030 EC, with an estimated salt exported 3,000 tonnes. MCC reported a discharge of about 465 ML/day, of approximate EC 900, with an estimated salt export of 275 tonnes (MCO, 2011). Wilpinjong Coal Mine reported a discharge total of 241 ML, EC of approximate 2,500, with an estimated salt export 400 tonnes (WCM, 2010).

6.5 Mine water discharge salinity and specific salt yield

The three active mines in the Upper Goulburn contribute to river salinity via direct and diffuse mine discharge. A possible source of diffuse salt is the Goulburn River diversion (GRD) constructed in 1983-4 around the UCML open cut mine (see Appendix E). Elevated levels of salinity have been recorded in the sediments along the base of the diversion channel²⁵.

The reported water discharges from UCML can be used to estimate the minimum impact this mine is having on ambient EC and salt export into the Goulburn River. Under licence UCML discharges a maximum 30 ML/day of treated mine water with an EC < 900 µS/cm into the Goulburn River via Ulan Creek. The total volume of groundwater and surface water intercepted and extracted from its mining sites, allocated to various operations plus loss from evaporation is modelled and reported in the annual water balance (UCML, 2013; UCML, 2014; UCML, 2015b; UCML, 2016). While the total salt mass balance for the whole mining operation is not supplied in annual reporting, the amount of salt exported to the Goulburn River can be estimated using the reported daily licenced discharge.

Spot daily EC, Q and continuous EC were also available in the upper reaches of the Goulburn from industry monitoring data for the US Ulan²⁶, DS Ulan gauging station (LP18/SW02) and licensed mine discharge points (LDP6 + LDP19), plus archival state

²⁵ UCML March CCC & December 2018 Community Consultation Committee meeting, UCML Environment Manager comments, 33,000 EC in soils associated with the GRD

²⁶ no flow Q data at US Ulan since 198

government data from the discontinued Ulan gauging station (210046) and monthly grab data for a water quality monitoring site on the upper Goulburn River at Gleniston (21010017). Both active gauging stations in the upper Goulburn, US and DS Ulan are operated by UCML. US Ulan is located on the Goulburn at the village of Ulan approximately 7.1 kilometres upstream from the Ulan Creek junction (mine discharge point), and DS Ulan (LP18) is a further 2.4 kilometres downstream (see location Figure 6:4).

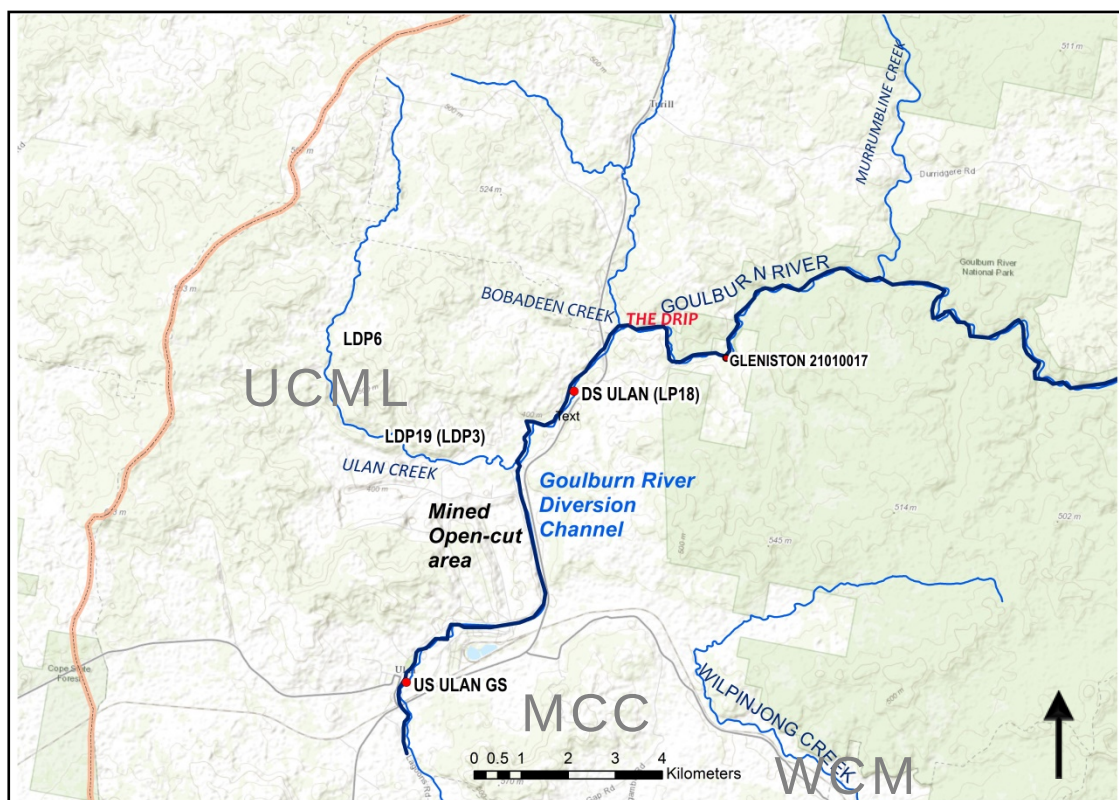


Figure 6:4 Location Map - surface monitoring points US Ulan (210046 & SW01), DS Ulan (LP18/SW02), mine discharge points (LDP19; LDP6), Goulburn River @ Gleniston (21010017) and GR diversion channel

The US Ulan gauging station has continuous daily salinity (EC) data covering the period 2012-2016, plus archival daily flow 1957-1982 and 49 salinity grab samples over the period 1968-1982²⁷ (NSW Department Water Resources, 1994). Records for daily discharge ML/day, EC, pH and turbidity 2012-2016 are available for the mine licensed discharge points on Ulan Creek and mine operated stream gauge on the Goulburn River downstream. Monthly grab data (1993-2016) are also available from the NSW Office Water site at Gleniston (Figure 6:3).

Analysis of the mine discharge data for the period May 2012 to the end of December 2016 (4.666 years) gives the following results which can be compared with the salt discharge at the Coggan and Ulan gauges:

²⁷ Stream monitoring station 210046 was discontinued in 1982 prior to commencement of open-cut mining at Ulan

Comparison of Mine and Catchment Total Salt Discharge 2012-2016

Total salt discharged by Ulan mine = $\Sigma SL_{UCML} = 12,871$ tonnes

Total salt discharge at Coggan gauge = $\Sigma SL_{CG} = 97,054$ tonnes

Ratio = $\Sigma SL_{UCML} / \Sigma SL_{CG} = 0.133$

Salt discharged naturally by the catchment at Coggan gauge

= $\Sigma SL_{CG} - \Sigma SL_{UCML} = 97,054 - 12,871 = 84,183$ tonnes.

Salt discharged naturally by the catchment at Sandy Hollow gauge

= $\Sigma SL_{SH} - \Sigma SL_{UCML} = 195,276 - 12,871 = 182,405$ tonnes.

Ratio = $\Sigma SL_{UCML} / \Sigma SL_{SH} = 0.066$

The value of ΣSL_{UCML} can now be used to estimate the salt yield from the mined area over this period.

Salt Yield of Mined Area compared with Natural Salt Yield

Area of open cut mine and infrastructure = 13 km^2

Area of underground mine = 32 km^2

Total UCML mining footprint $A_m = 45 \text{ km}^2$

Fraction of total catchment area @ Coggan = $A_m / A_{CG} = 45/3340 = 0.0135$

Fraction of total catchment area @ Sandy Hollow = $A_m / A_{SH} = 45/6810 = 0.0066$

Average annual salt yield from mine discharge = $12,871 / (45 \times 4.666)$

= $61.3 \text{ tonnes/km}^2/\text{year}$

Natural annual salt yield at Coggan = $5.22 \text{ tonnes/km}^2/\text{year}$ (Table 5:4)

Natural annual salt yield at Sandy Hollow = $5.35 \text{ tonnes/km}^2/\text{year}$

In section 5.2.1 using the geometric mean specific salt loads in the Goulburn, it was noted there appeared to be an extra salinity source in the upper Goulburn of 2,080 tonnes/yr, or 9,700 tonnes over the 4.7 year period, which is of the same order of magnitude as this estimate of salt exported by mining operations, 12,900 tonnes. These calculations show that UCML mining footprint occupies less than 1.4% of the area of the Goulburn catchment above Coggan gauge. In the period May 2012 to December 2016 mine discharge was at least 13.3% of the total salt load at Coggan and 6.6% of the total salt load at Sandy Hollow. In terms of average annual salt yields, UCML discharged approximately 61 tonnes/km²/year. This was over eleven times greater than the average natural annual salt export per km² at Coggan and at Sandy Hollow. While the discharge volumes of water exported from the whole catchment are several orders of magnitude higher than those from the upstream mines, at low flows mine discharge can be a significant fraction of the upstream river flow.

6.6 Mine discharge impacts during dry conditions

Annual rainfall during 2014 was in the below normal, less than 0.3 percentile range for the year 2014. The reported annual water extracted and intercepted in 2014 by the three coal mines operating across the upper Goulburn catchment was reported as over 12,500 ML (Table 6:3). This was a combination of groundwater (incidental take) and intercepted surface water (rainfall runoff). This amount equates to more than 70% of the annual stream discharge measured at Coggan during 2014 (Table 6:4).

During 2014 UCML discharged approximately 3,850 ML of their mine water take into the Goulburn River. Figure 6:5 compares the daily volume of mine water discharged by UCML to the daily flow volume recorded in the Goulburn River at DS Ulan stream gauge approximately 2.4 km from Ulan Creek junction. For the full year of data, total mine discharge was 3,834 ML while the measured stream discharge 2.8 km downstream was 3,824 ML. This demonstrates that streamflow at the Ulan DS gauge in the upper Goulburn during the dry year of 2014 was essentially mine discharge. In Figure 6:5 total daily mine discharges exceeded the downstream daily total stream discharge measured at the DS Ulan on 178 occasions or 49% of daily flows. On some days water discharged by the mine did not reach the DS Ulan gauge. This river reach was regarded as a perennial ‘gaining’ stream in early mine reports (KinHill, 1998b) and anecdotal observations, but now appears to be a losing stream. The mine discharge could explain the exceptional low stream elasticity of 0.5 for the period 1993 to 2012 (Table 4:7).

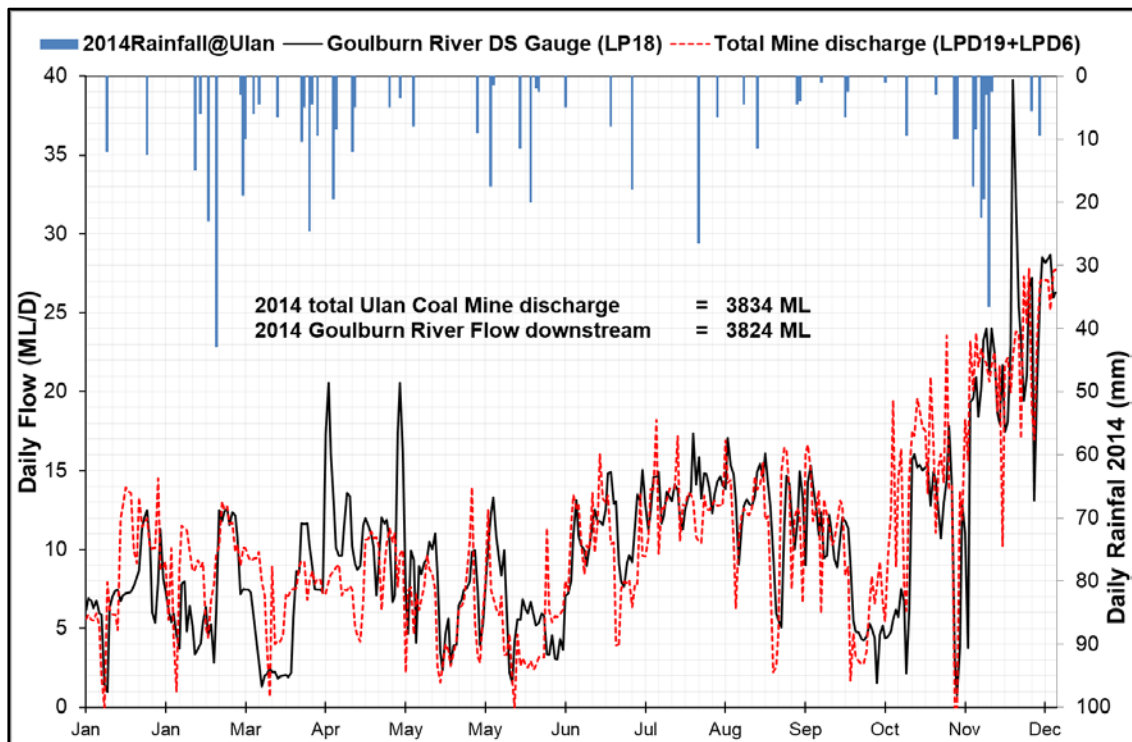


Figure 6:5 Comparison UCML daily mine water discharge with Goulburn River daily stream flow at Ulan DS gauge in 2014

Surface flow in the upper Goulburn River also ceased for four months in late December 2017 to late April 2018. The cease to flow directly coincided with an extended pause in mine discharge from mid-December 2017. While annual rainfall at Ulan (062036) for 2017 was 497.8 mm - below the 0.2 percentile of yearly rainfalls for the station (BoM, 2018b), storm activity during this period produced monthly rainfall totals for Ulan of 118 mm in November, 70mm in December; and over 120mm between late February and early March 2018. A comparison of interpolated 12 monthly rainfalls for the upper Goulburn catchment (1920 - 2014) also places it between 0.15-0.2 percentile range of annual rainfalls (Figure 4:7). Statistically this period had a higher annual rainfall than the 1980-81 (pre-mining) and 2006-7 millennium drought declared periods. This sudden loss of flow in the upper Goulburn again demonstrates the close coupling of mine discharge and loss of river base flow in the upstream region.

This suggests that mine discharge salt loads should be a significant determinant of nearby downstream river salt loads in the Goulburn. Figure 6:6 shows the daily salt load 2012-2016 exported by UCML in mine discharge water compared with the salt load recorded in stream flow at the DS Ulan gauge. It reveals a similar close coupling of mine salt export with the salt loads measured in the Goulburn River downstream during low rainfall periods. The spikes in salt loads evident in 2012 and March 2013 reflect high stream flows following significant rainfall events (Figure 6:6).

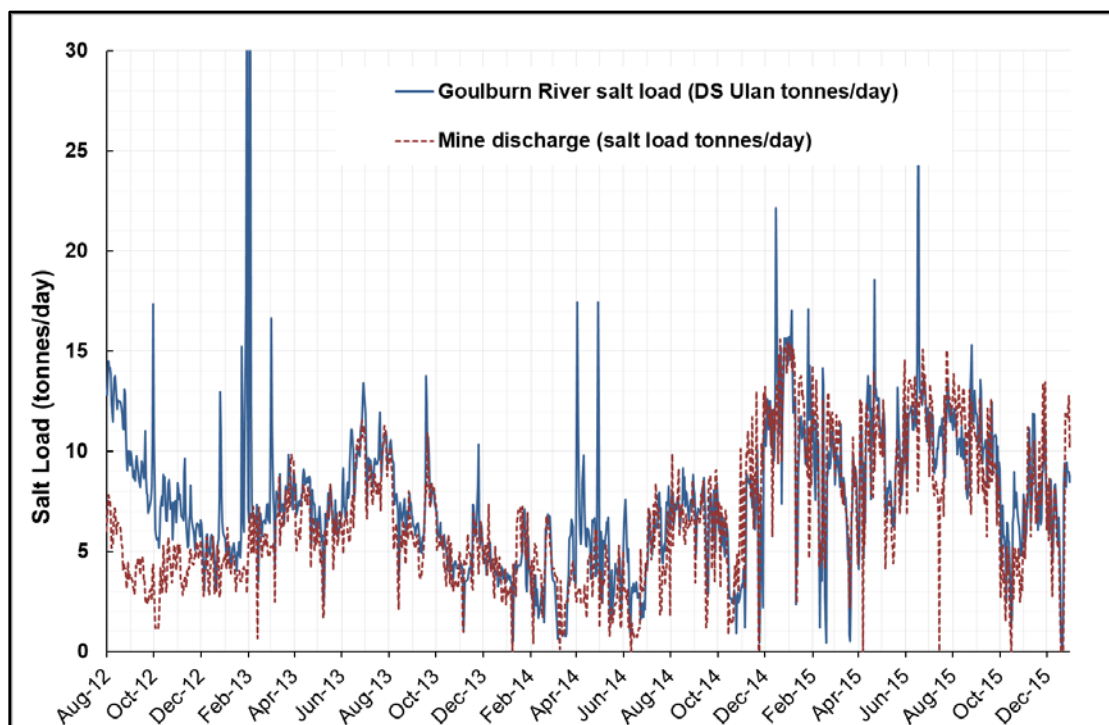


Figure 6:6 Daily salt load (tonnes) in the upper Goulburn River (DS Ulan - LP18) compared to mine discharge (UCML - LDP19+6)

During the drier months salt deposits have been observed along reaches of the Goulburn River in the sandy river bed and on stream banks due to evaporation and capillary action. This was recorded in the upper Goulburn River at Gleniston site (2101017 Appendix E- Figure E2). The embedded evaporated salts within river sediments once mobilised during high stream flows would contribute to elevated EC levels and elevated salt loads. Pulses or spikes of increased salinity immediately following rainfall runoff events are considered quite common in the Hunter system (Kefford *et al.*, 2013; DEC, 2006).

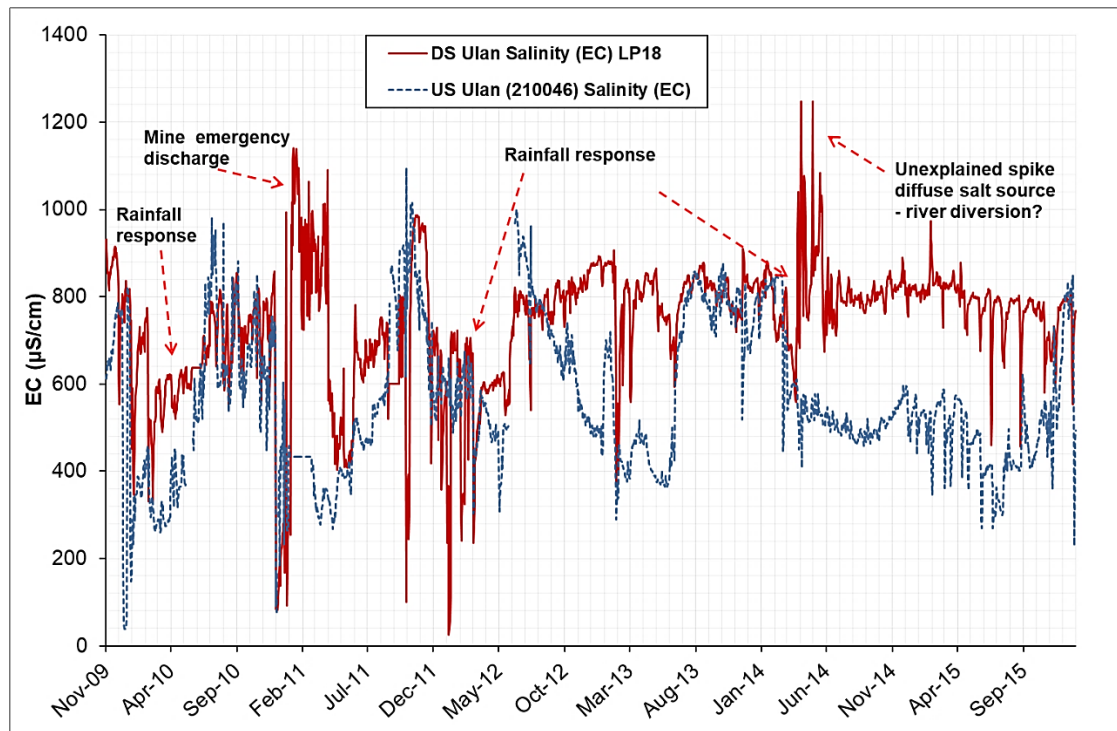


Figure 6:7 Daily salinity (EC) in the Goulburn River upstream (Ulan) and downstream (LP18) of mine discharge point in the period 2009 – 2014

Figure 6:7 shows salinity (EC) spike in the daily records for DS Ulan coinciding with the mine discharge between December 2010 and March 2011 and another unexplained salinity spike between March 2014 and May 2014. The latter salinity is not evident at the upstream monitoring site or due to rainfall runoff or direct mine water discharge. It is speculated that salts accumulating in alluvial sediments and or diffuse seepage from exposed Permian coal measure strata along the Goulburn River diversion could be a possible source. This requires further investigation.

6.7 Conclusions

The aim of this chapter was to quantify the impacts of mining discharge on flow and salinity in the upper Goulburn. Pre-mining spot data shows that prior to mining the upstream section had a mean EC < 500 $\mu\text{S}/\text{cm}$, which is 55% of the regulated upper salinity limit of 900 EC for mine water discharge. Adopting this higher limit automatically ensured that salinity in the upper Goulburn River would always exceed pre-mining levels during drier times.

Since the development of open cut and underground mining at Ulan in the late 1980s the groundwater ingress to longwall operations and subsided areas has exceeded modelled predictions. Groundwater extraction by UCML increased from over 1,000 ML in 1995 to 6,800 ML in 2014. Intercepted groundwater included the complete dewatering of the Triassic strata above mined panels and a cone of depressurisation extending 4-6 kms with a 2 metre decline in hydraulic head. With the impact on the Permian coal seam predicted to extend 10-20 kms beyond the longwall panels. Groundwater modelling predicts the decline in the water table will persist for more than 300 years over the 105 km² underground footprint. The intercepted surface and groundwater excess to mine requirements, needs to be disposed of for mining operations to continue. Surface and groundwater interception for all three mines in 2014, exceeded 12,400 ML with the net mine water usage exceeding 7,800 ML (Table 6:3). The balance excess to mine operations is discharged into the Goulburn River, EC < 900. It is apparent that mine groundwater modelling has failed to predict the scale of impacts on groundwater resources and mine water discharge at the headwaters of the catchment.

Historic monitoring of the salinity of the Goulburn River 7 km below the discharge point has tracked the changing regulations applied to mining post 1990 until 2003, when discharge volume was regulated but discharge salinity was unregulated. This resulted in major fluctuations in stream salinity with EC exceeding 2000 $\mu\text{S}/\text{cm}$. After June 2007 the maximum EC of discharge dramatically reduced but mean EC was still higher than the pre-mining ambient EC.

Estimation of the specific salt yields from UCML for the period 2012 to 2016 found it to be 11 times greater than that of the Goulburn catchment. It was shown that over this period mine salt discharge was over 13% of the total salt discharge at Coggan and nearly 7% of the salt discharge at Sandy Hollow while the ratio of mined area to catchment area was only 1.4 and 0.7% respectively at both sites. The elasticity of stream flow at Coggan had suggested an extra source of water in the catchment uncorrelated with rainfall. Mobilisation of diffuse salts accumulating in alluvial sediments within the river diversion and within the alluvium along the 225 kilometres of river bed are other potential stores of salt affecting the salinity of the river that requires investigation.

During dry periods almost all the flow and the salt load in the upper Goulburn is now due to mine discharge. Salinity concentration has up to now been a key consideration of both monitoring and regulation. This however assumes that only the total salt concentration rather

than the composition of salt is environmentally important (Chapter 5:). It also does not consider the intimate connection between stream flow and salinity and the impact of groundwater interference and extraction on stream salinity.

Chapter 7 examines the hydrogeochemistry of the region's waters while Chapter 9 examines the effect of mine depressurisation on groundwater levels and discharge to the river as baseflow.

Chapter 7: Hydrochemistry: surface-groundwater interactions

The aim of this chapter is to identify and characterise the dominant hydrogeological systems in the upper Goulburn catchment contributing to river baseflow. Both the regulations underpinning the HRSTS and the analyses to date in this work have regarded salt generically, represented by EC, in this chapter examination of the major ion chemistry making up that salt is undertaken to explore contributions from different geologies in the catchment.

Wide spread sampling of the chemical characteristics of water samples from accessible river reaches, springs, seeps and bores in the Goulburn catchment was undertaken and the results are combined with available industry and online government monitoring data. Hydrochemical characteristics of surface and groundwater samples are statistically analysed and grouped into general water types. This is used to infer the source or parent hydrogeological unit and probable connectivity between surface and groundwater sources in the Goulburn catchment. The underlying assumption here is that samples with similar chemical characteristics are likely to have similar hydrologic histories in relation to recharge areas, flow paths, mineralogy and residence time (Güler *et al.*, 2002; Hem, 1989)

7.1 *Sample sites*

Most sampling sites selected were located in the upper catchment (Figure 5:1, Figure 7:1). Information on areas that were not sampled have been compiled from government databases, industry and earlier ANU research projects (2004-2009)(Macdonald *et al.*, 2009a; Biswas *et al.*, 2009; Jasonsmith *et al.*, 2011a; White *et al.*, 2004; NSW Department of Water and Energy, 2008; Realica-Turner, 2003; WCM, 2015b; WCM, 2015c; UCML, 2012; Middlemis and Fulton, 2011). Sites ranged from the headwaters of Great Dividing Range and Moolarben Valley, west and south of Ulan down to Rosemount stream gauge (Station 210003 - inactive). The major streams and sub-catchments investigated were Merriwa River, Munmurra River, Krui River, Murrumbline and Wollar Creek. The gauging stations sampled in the lower Goulburn were Kerrabee (GS210066), Wybong (GS210040), Sandy Hollow (GS210031) and Rosemount (GS210003). One site was sampled in the lower Widden catchment above the confluence with the Goulburn River.

A total of 77 surface and groundwater samples were collected from sites shown in Figure 6.4 between January 2012 and December 2014 and sent to the NSW DPI Water Laboratory for analysis. Hydrochemistry datasets from an additional 73 sites were sourced from mine reports, NSW DPI Water PINEENA database and previous ANU research. The major ion analyses of surface water samples in the Goulburn are listed in Table 7:1 and groundwater samples are listed in Table 7:2.

Table 7:1 Major Ion composition of water samples (mg/L) - Goulburn River and Tributaries

Code	<i>Upper Goulburn (GR)</i>	DATE	Ca	Mg	Na	K	CO ₂	HCO ₃	Cl	SO ₄	TDS	EC	pH
SW01	US Ulan-210046	17/10/12	16	17	87	4.3	<1	95	140	53	412	709	7.4
SW02	DS Ulan-LP18	17/10/12	33	30	90	9.8	<1	90	92	200	545	854	7.7
SW23	GR nr The Drip	17/10/12	30	27	86	9	<1	92	92	190	526	828	8
SW03	GR @Gleniston-21010017	16/10/12	31	24	75	9.1	<1	99	87	170	495	790	8
SW11	GR above Murrumbline	7/12/12	29	28	84	9	<1	97	86	180	513	809	7.9
SW29	GR below Wollar	7/12/12	43	37	130	10	<1	150	160	230	760	1141	7.8
Mid to Lower Goulburn (GR)													
SW09	GR above Krui/ below Munmurra	16/10/12	50	52	81	5.6	13	250	120	110	682	992	8.6
SW19	GR @O'Brien's X, below Krui	16/10/12	50	55	67	4.5	14	310	110	74	685	956	8.5
SW17	GR above Merriwa below Bylong	16/10/12	45	56	84	5.5	16	290	140	84	721	1063	8.6
SW_RM	GR @ Rosemount below Wybong	16/10/12	53	59	90	5.1	15	310	170	48	750	1138	8.6
West Tributaries													
SW21	Curra Creek	17/10/12	4.6	11	33	1.5	<1	50	62	3.9	166	294	7.4
SW24	Saddlers Ck	5/03/13	0.31	7.3	51	2.1	<1	2.6	91	3.8	158	335	5
SW33	Curryall Ck	2/05/13	5.4	19	76	1.5	<1	47	160	4.3	169	610	7
SW34	US Murrumbline @ Turill	31/05/13	20	73	370	4.6	<1	65	760	62	1355	2595	7.3
SW04	US Murrumbline CW	17/10/12	11	28	100	3.3	<1	130	180	0.9	453	798	7.4
SW07	DS Murrumbline	22/10/12	11	27	94	3.3	<1	130	170	4	439	749	7.3
SW27	DS Wollar Creek	30/10/12	86	85	210	11	<1	260	260	430	1342	1944	7.9
Northern tributaries													
SW05	US Munmurra Rr	16/10/12	43	51	32	1.6	5.9	370	55	5.5	564	719	8.4
SW30	DS Munmurra	7/12/12	49	48	50	3.6	4.6	380	92	4	631	856	8.4
SW06	US Krui Rr	16/10/12	45	58	36	1.5	6.5	410	58	5.2	620	775	8.4
SW08	DS Krui River	16/10/12	51	63	46	2.5	22	400	82	6.6	673	876	8.6
SW10	US Merriwa (210091)	16/10/12	51	76	58	2.3	7	510	92	9.6	806	1027	8.4
SW16	DS Merriwa River	16/10/12	51	79	84	6.3	9.7	490	150	11	881	1185	8.4
South and North East													
SW_WB	DS Widden Brook (South)	16/10/12	15	20	57	4.3	<1	150	82	11	339	522	8.3
SW_WC	Wybong (210040) (NE)	16/10/12	71	85	130	3.4	10	410	340	21	1070	1645	8.4
2006 Goulburn River													
SW-RC	Goulburn @ Cottage	2/02/06	21	17	92	8	<1	79	100	120	420	800	6.4
SW-GG	Goulburn @Gleniston gate	1/02/06	21	16	90	8	<1	90	99	95	400	780	6.6

Table 7:2 Hydrogeology & groundwater hydrochemistry (mg/L) Goulburn catchment

BASALT	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
W34	44	51	33	1.7	0.5	370	57	6	563	754	8.3
PZ752 (2013)	38	46	86	1	0	331	21	40	606	760	8
PZ752 (2014)	53	75	88	1.0	0.1	385	187	47	880	1300	7.7
PZ752 (2015)	29	40	64	3.0	0.1	325	15	45	500	742	7.9
PZ752 (2001)	25	21	27	1.0	<1	220	14	5	313	390	7.4
JURASSIC	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
SP26A	50	170	290	3	<1	690	740	13	1956	2809	7.1
PZ10B	32	81	259	11	<1	227	507	56	1173	2130	10.1
PZ14C	13	20	109	10	<1	102	213	<1	467	725	7.52
PZ28B	100	108	434	27	<1	422	801	179	2071	3395	7.00
TRIASSIC	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
MCM_SP60	6.9	4.3	20.0	2.3	<1	7.0	32.0	<1	117	150	5.50
MCM-SP141	1.5	2.2	15.0	1.9	<1	<1	28.0	4.0	80	145	4.60
SP01	4.1	11.0	13.0	0.8	<1	59.0	27.0	2.0	117	197	5.38
SP04	2.1	1.4	8.5	2.5	<1	9.1	13.0	<1	37	79	6.4
SP05	0.3	1.5	11.0	1.0	<1	<1	21.0	1.3	36	95	7.4
SP24	0.3	7.3	51.0	2.1	<1	2.6	91.0	3.8	158	335	6.4
SP29	4.2	5.5	22.0	1.0	<1	15.0	36.0	11.0	95	186	8.7
SP31	3.1	5.9	49.0	2.3	<1	17.0	93.0	5.2	234	344	6.6
PZ105C	6.8	4.5	30.0	2.5	<1	27.8	53.3	5.0	130	373	6.4
PZ103c	11.0	12.0	28.0	7.4	<1	13.0	74.0	21.0	166	310	7.3
SW21	4.6	9.4	30.0	1.1	<1	42.0	57.0	3.2	147	271	8
B7	3.6	5.9	22.0	3.7	<1	39.0	38.0	8.4	121	227	7.00
PZ04A	9.3	4.5	29.0	1.8	<1	37.0	57.0	<1	139	245	8.5
PZ105C	4.0	3.0	34.0	2.0	<1	15.0	45.0	4.0	100	193	6.2
PZ105B	7.0	5.0	34.0	2.0	<1	24.0	59.0	0.1	140	239	5.71
B5	17.7	24.0	78.6	4.5	<1	84.0	178.4	13.7	472	768	8.2
GW195	3.8	7.2	23.0	0.7	<1	27.0	49.0	<1	111	215	6.9
B6	27.0	41.0	110.0	2.5	<1	170.0	240.0	22.0	613	1051	5.6

TRIAS-BASALT	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
SP22E	9.6	16.0	36.0	1.3	<1	110.0	54.0	2.9	230	432	8.2
SP22W	18.0	35.0	55.0	1.5	<1	230.0	74.0	5.2	393	591	8.2
R755A	18.0	23.0	39.0	2.7	<1	153.0	67.0	4.0	306	450	5.7
PZ24B	9.6	11.0	49.0	4.4	0.1	132.0	64.0	<1	270	360	6.9
PZ08C	9.1	37.0	53.0	4.4	<1	151.0	142.0	<1	397	600	9.2
PZ01	41.0	8.0	46.0	1.6	<1	90.0	85.0	20.0	292	500	9
PZ01A	43.0	16.0	47.0	26.0	<1	185.0	92.0	5.0	414	485	8.9
B1	21.0	44.0	72.0	2.3	<1	320.0	63.0	12.0	534	780	7.4
PZ10A	7.6	3.9	37.0	17.0	5.4	101.0	36.0	<1	208	260	8.9
PZ07C	6.7	19.0	42.0	4.8	2.4	122.0	64.0	<1	261	415	10.6
B2	2.8	3.4	26.0	1.1	<1	58.0	18.0	1.8	111	164	5.0

Lower TRIAS- Upper PERM	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
B8	54.0	44.0	120.0	77.0	<1	590.0	130.0	6.7	1022	1323	6.80
BMT-1	29.0	17.0	95.0	50.0	<1	380.0	82.0	0.3	653	883	7.30
BMT-2	31.0	16.0	96.0	52.0	<1	380.0	80.0	1.5	657	861	6.70
PZ101C	44.0	10.0	50.0	13.0	75.0	267.0	60.0	5.0	524		6
PZ101C	31.0	16.0	62.0	12.0	<1	175.0	68.0	8.0	319	579	7.15
PZ108R	22.0	18.0	38.0	3.0	<1	116.0	64.0	7.0	242	420	6.10
PZ103B	20.0	15.0	29.0	8.2	0.1	76.0	78.0	7.0	340	375	5.80
PZ28A	4.4	28.0	58.0	13.0	13.2	242.0	53.0	3.0	414	510	6.43
PZ105A	12.0	5.0	27.0	2.9	<1	17.0	81.0	<1	151	220	5.60
PERMIAN - COAL	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
PZ103A	21.0	11.0	34.0	11.0	0.1	110.0	70.0	9.0	266	437	6.43
PZ24A	3.0	2.2	162.0	63.0	72.0	342.0	74.0	<1	718	970	6.8
PZ25A	35.0	0.2	153.0	37.0	60.0	110.0	149.0	46.0	590	1100	6.9
PZ07A	2.6	1.5	114.0	50.0	105.0	140.0	60.0	<1	473	1090	11.3/8.7
PZ07B	3.8	1.7	148.0	23.0	30.0	287.0	74.0	<1	567	730	8.6
PZ08B	2.5	0.7	108.0	26.0	66.0	171.0	57.0	<1	431	580	8.2/10.1
PZ107	40.0	23.0	77.0	13.0	<1	163.0	132.0	57.0	505	838	6.13
PZ108	8.0	17.0	42.0	2.0	<1	100.0	60.0	6.0	235	376	6.11
PZ109	7.0	0.0	65.0	26.0	12.0	42.0	44.0	7.0	330	650	7.87
B4	36.0	26.0	170.0	8.8	<1	620.0	53.0	<1	914	1088	8.1
BY14	35.0	20.0	210.0	11.0	<1	470.0	84.0	1.0	831	987	7.6
BY16	31.0	19.0	640.0	17.0	<1	1100.0	173.0	4.0	1984	2325	7
AGE08	35.0	28.0	241.0	14.0	<1	581.0	84.0	1.0	984	1256	7
PZ104	312.0	5.0	93.0	226.0	314	76.0	53.0	12.0	1091	5584	11
WM-01	39.1	30.0	177.9	10.2	<1	463.7	40.1	139.8	665	1020	8
WM-02	43.9	27.5	307.6	15.6	<1	781.0	209.9	32.2	1021	1550	7.5
WM-03	72.5	85.3	350.1	27.0	<1	449.7	340.0	419.8	1516	2330	7.4
WM-04	28.6	56.5	219.8	15.6	<1	295.3	181.9	249.8	897	1380	6.6
WM-05	53.3	35.5	560.0	23.1	<1	1246.6	162.0	264.6	1712	2630	7.6
WM-06	100.0	70.0	565.0	31.0	<1	825.0	330.0	685.0	2200	3390	6.6
WMc1	104.0	73.0	620.0	33.0	<1	726.0	342.0	565.0	2052	3420	7.2
WMc2	34.0	14.0	159.0	22.0	<1	398.0	66.0	<1	564	940	7.8
WMc3	106.0	100.0	554.0	35.0	<1	588.0	487.0	468.0	2082	3470	6.9
WMc4	175.0	84.0	228.0	52.0	<1	619.0	305.0	230.0	1482	2470	6.5
SW-seawater(Hem)	410	1350	10500	390	0	142	19000	2700	40000		
RW-Merriwa	0.33	0.12	0.58	0.28	0.85	0.38	1.10	1.58	5.44	12.11	8.80
RW1- rainwater	1.1	0.23	0.82	0	0	3.8	0.5	0	6.80	10.00	6.90

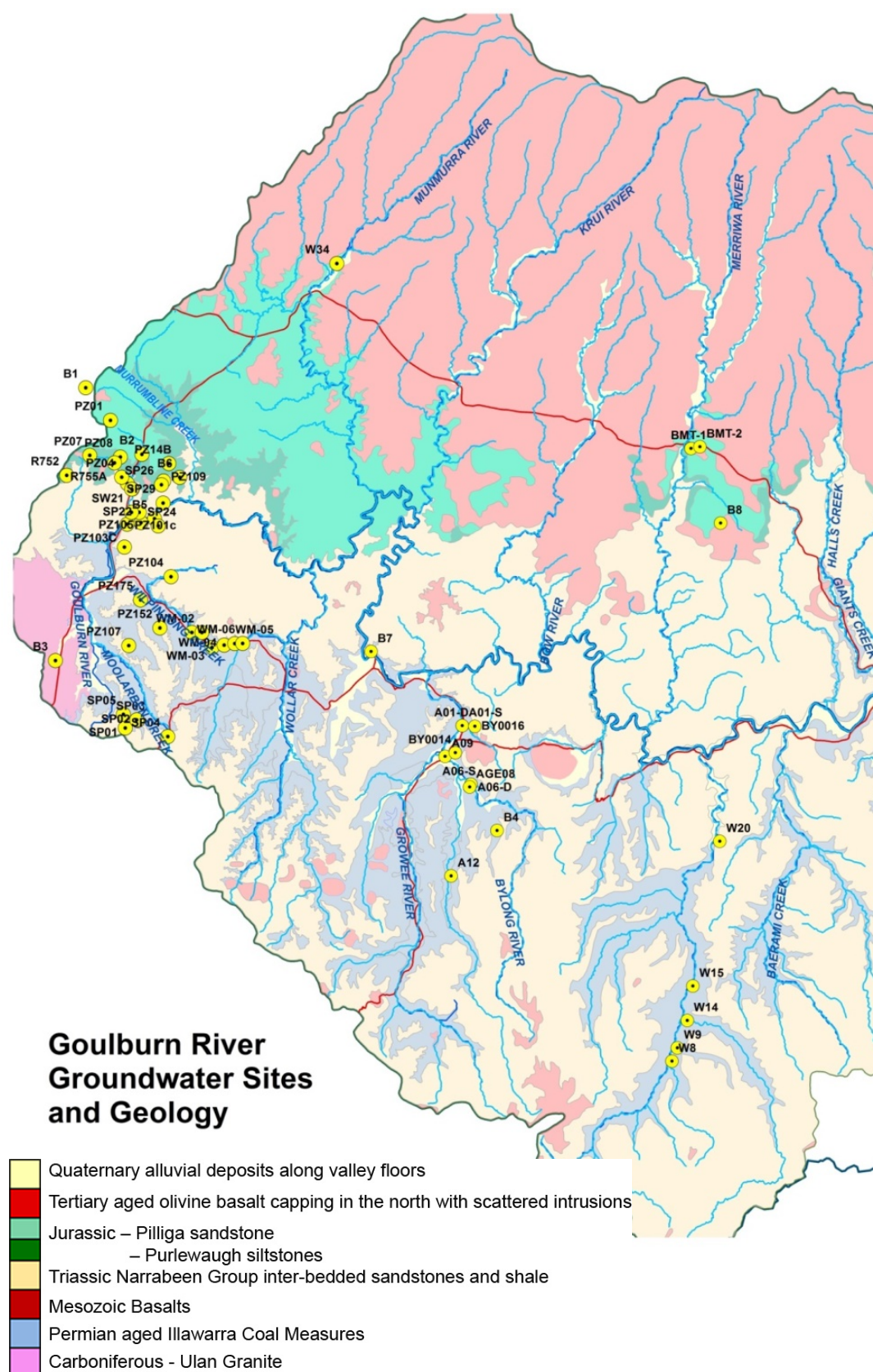


Figure 7:1 Groundwater sample locations and catchment geology.
NSW Office Water 2014 (Rasmus *et al.*, 1969; Watkins *et al.*, 1999; WCM, 2015b; Umwelt, 2014; UCML, 2013; Geoscience-Australia, 2013).

7.2 Data quality

To test the accuracy of laboratory major ion analyses for this work, the charge balances were calculated for negative and positive ion with concentrations were in Milliequivalents per litre (meq/L). An acceptable charge imbalance was set at a maximum of 5% (Appendix E2).

For the groundwater analyses from other information sources, contamination of results can occur with relatively high potassium concentrations or pH the resulting from potassium rich drilling fluids or bentonite packing. Mine data that had unexplained, unusually high or low pH readings were rejected (i.e. pH >10; pH<4). Private bores can be screened into multiple water bearing strata resulting in the samples with a mixture of chemistries. Bore logs, where available, were checked and screened strata noted.

7.3 Hydrochemistry

7.3.1 Goulburn River transect

The composition of water samples collected on a transect down the Goulburn River in October 2012 are plotted in Figure 7:2 and Figure 7:3 against stream elevation.

The profiles in Figure 7:2 show a sudden steep increase in the concentration of SO_4 in the upper catchment corresponding to mine discharge plus discharge from Wollar creek followed by a decrease after the confluence with the Munmurra River. Alternatively HCO_3^- dramatically increases at around 280 mAHD, in conjunction with Ca and Mg ions (Figure 7:3), indicative of inputs from Wollar Creek and the northern rivers that drain the tertiary basalts, Munmurra, Krui and Merriwa rivers.

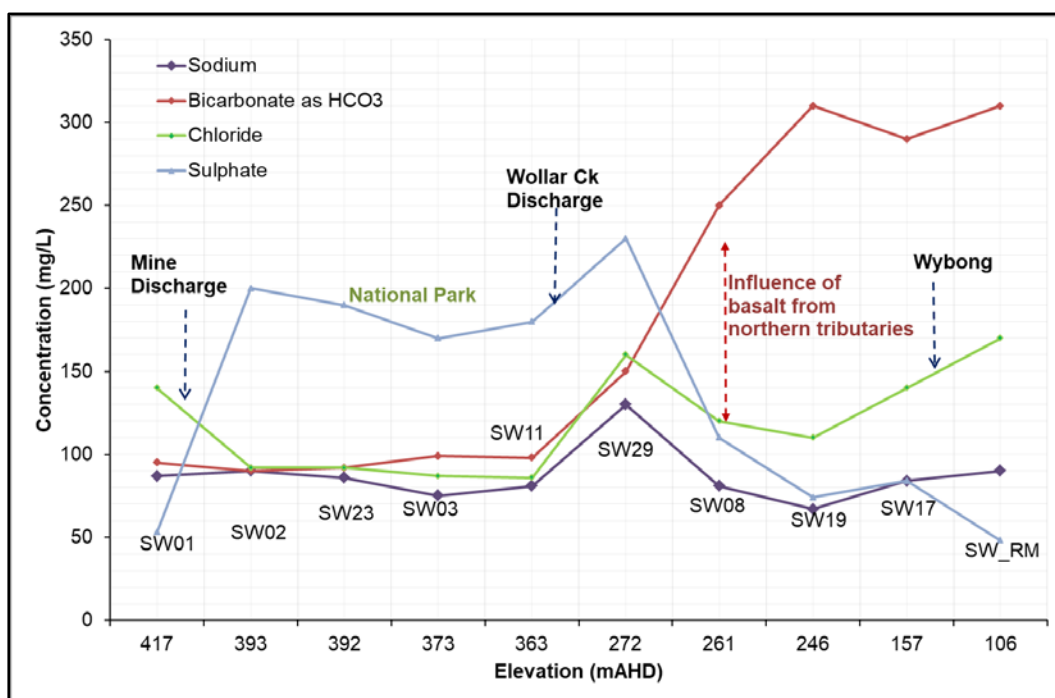


Figure 7:2 Sample site major ion hydrochemistry (Na, HCO_3^- , Cl, SO_4) as a function of elevation (mAHD) Goulburn River, October 2012

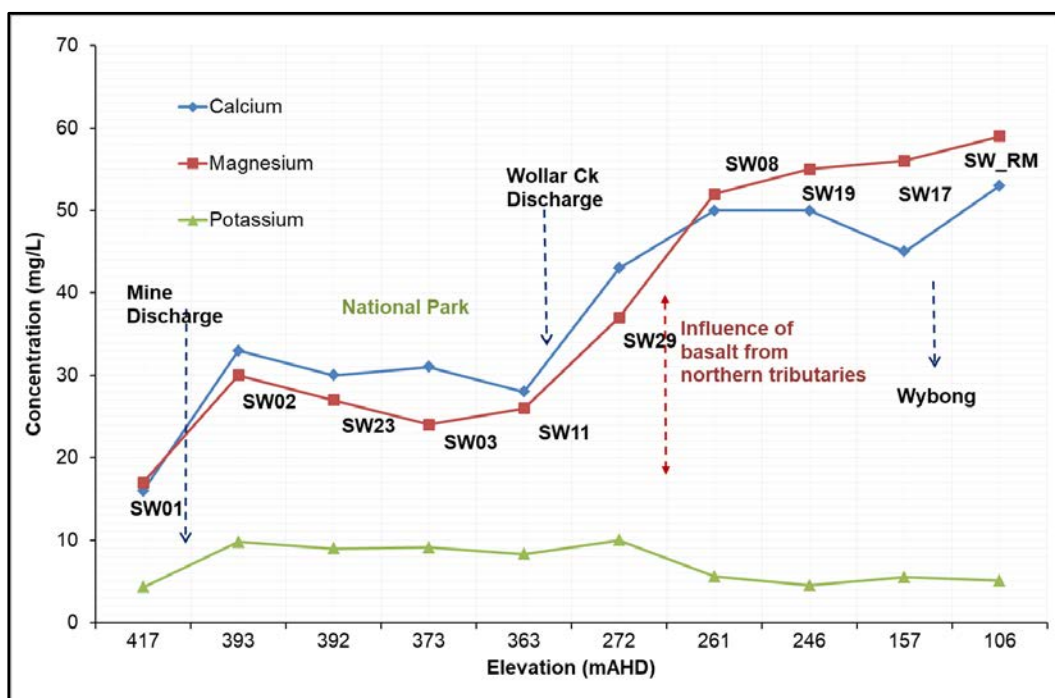


Figure 7:3 Sample site major ion hydrochemistry (Ca, Mg, K) as a function of elevation (mAHD) Goulburn River, October 2012

Na and Cl also peak below Wollar but then decline due to the influences of the northern rivers. In Figure 7:4 stream pH also increase abruptly at the 280 mAHD point from 7.8 to 8.6 and remains constant downstream (Table 7:1). The pH also illustrates the dramatic change in the chemical characteristics of the River that occur below elevation 280 m due to the influence of firstly Wollar, then Krui, Munmurra, Bylong and Merriwa sub-catchments reflecting the rise in HCO_3^- concentration.

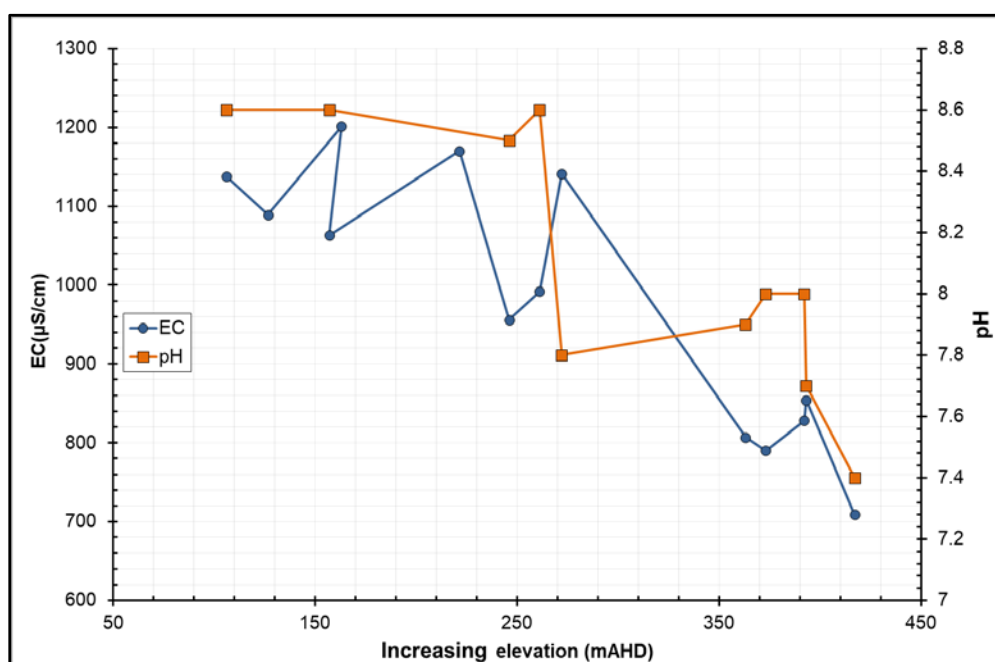


Figure 7:4 Transect EC and pH with increasing elevation Goulburn River, includes real-time EC data from Coggan and Sandy Hollow stream gauges, October 2012

The impact of mine effluent is evident at the higher elevation with increased SO_4 river concentrations and to a lesser extent Mg, Ca and K. Sulfate peaks again in concentration below Wollar. Mine discharge also elevates potassium and chloride. Discharge from the northern rivers lowers SO_4 , K and Cl concentrations downstream, although Cl increases further downstream due to discharge from Wybong Creek. This lowering of SO_4 concentration may be due to precipitation of sulfates from interaction with higher Ca from the northern catchments.

7.3.2 Goulburn River tributaries

The major ion analyses of the Goulburn River tributaries (Table 7:1) are plotted Figure 7:5

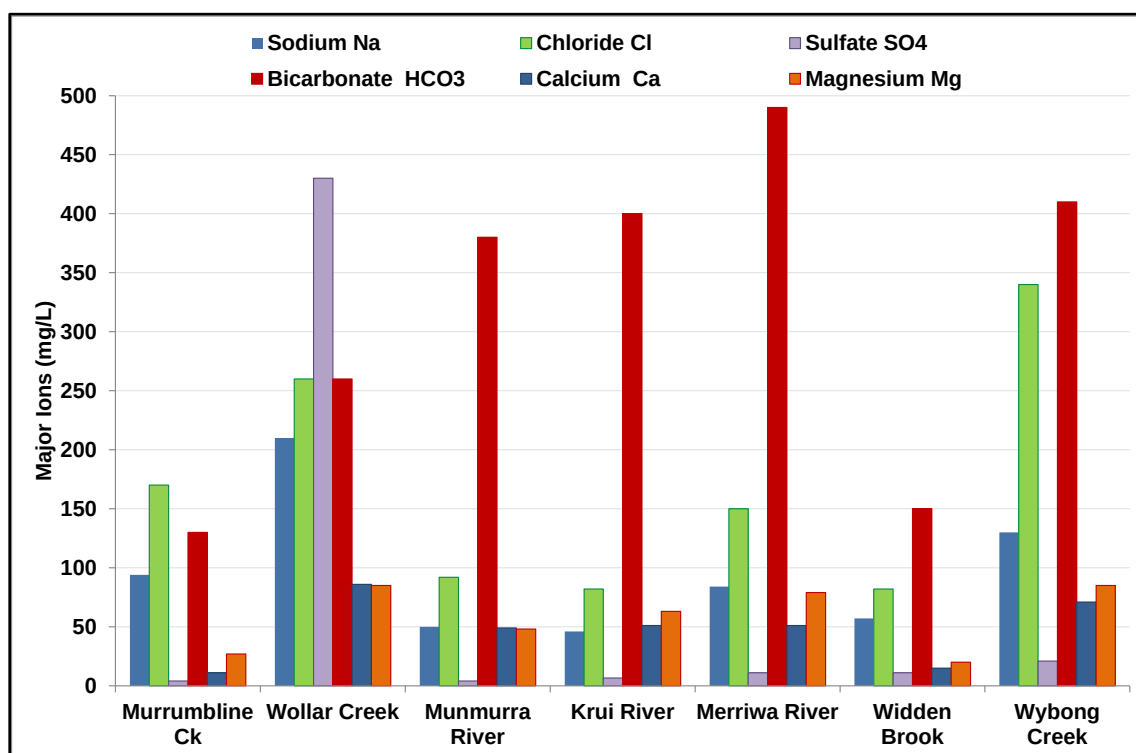


Figure 7:5 Major ions in tributaries, October 2012

A feature of the analyses of tributaries in Figure 7:5 is the high sulfate, sodium and chloride concentrations in Wollar creek whose impacts on the Goulburn River composition are clear in Figure 7:2. This southern tributary flows through incised Permian Coal Measures, and includes Wilpinjong Coal Mine discharge. High levels of SO_4 and higher concentrations of K in groundwater associated with the Permian Coal Measures and alluvium are a characteristic of this catchment (Realica-Turner, 2003; WCM, 2015b; WCM, 2015c). Inputs of SO_4 were also evident below Ulan in treated mine discharge.

The large inputs of HCO_3 from Wollar and the northern tributaries, Munmurra, Krui, and Merriwa Rivers as well as Wybong Creek are evident in Figure 7:2 and reflected in Figure 7:3 and Figure 7:4. The high HCO_3 shows the influence of the Tertiary basalt geology in the

northern catchments. Elevated HCO_3 and Mg levels can also be a feature of Permian-coal based groundwater where carbonates form the cement and replacement minerals in the source rock. They typically exhibit elevated Cl and SO_4 concentrations (Kellett *et al.*, 1989; Creelman, 1994; AGC, 1984) as in Wollar Creek. Wybong Creek also has elevated HCO_3 , Cl, and Mg indicative of interaction with Permian coal measures. Both the Merriwa River and Murrumbline Creek are incised into Jurassic geology which tends to have higher salinity associated with it. Both catchments do not directly incise or connect with the underlying Permian coal measures (Figure 7:1). The northern catchments are in sharp contrast with the southern catchment, Widden, is characterised by lower total salinity and bicarbonate reflecting its Triassic sources.

7.3.3 Surface water types

The Piper diagram Figure 7:6 shows the distribution of major ion water types for data from the Goulburn and its tributaries in Table 7:1 collected during surveys in October and December 2012, March and May 2013 plus two surface water monitoring samples collected during drought conditions in February 2006 from the upper Goulburn River (Gleniston 2101017) by Moolarben Coal when there was nil mine water discharge to the river. The hydrochemistry of the main flow in the Goulburn is complicated by the presence of treated mine discharge water, as evidenced by the SO_4 in Figure 6.2 so a period of nil mine discharge in 2006 was included for comparison. The hydrochemistry of baseflow water in the upper Goulburn River has been reported to be generally consistent with a water dominated by Triassic groundwater (MER, 2009; MER, 2015).

The Piper diagram in Figure 7:6 indicates sodium chloride (NaCl) dominance (P-type water) for the western tributaries and surface flows in the upper Goulburn River including the samples collected in 2006. This signature is indicative of Triassic groundwater in that region. Water from the mid to lower Goulburn River, after the confluence with the Munmurra River, shows increasing bicarbonate dominance (M - type water - Ca (Mg) HCO_3) due to inflows from the northern tributaries, which are characteristically M-type. This is attributable to the mineral weathering and dissociation of Tertiary basalts in the upper reaches of the northern catchment. Surface water samples from the lower reaches of these tributaries indicate a proportional decrease in bicarbonate to chloride ratio (a shift towards the middle of the trilinear plot). This may result from precipitation of CaCO_3 , with ion exchange and evaporative concentration enhancing NaCl dominance (Mackie, 2009).

The tributary Murrumbline Creek at the upstream site at Turill (SW34 – green star) has both the highest salinity, EC 2,600 $\mu\text{S/cm}$, and the greatest relative concentrations of chloride and sodium. The sample was taken at Turill, from the upper reaches of the Murrumbline creek where it flows through incised Jurassic Purlewaugh siltstone strata Figure 7:1. Wollar Creek also had high EC (1944 $\mu\text{S/cm}$) associated with elevated SO_4 , Na, Cl and HCO_3 from Permian geology (Figure 7:1).

Trilinear Plot - Major Ions Goulburn River & Tributaries Surface Water (%meq/l)

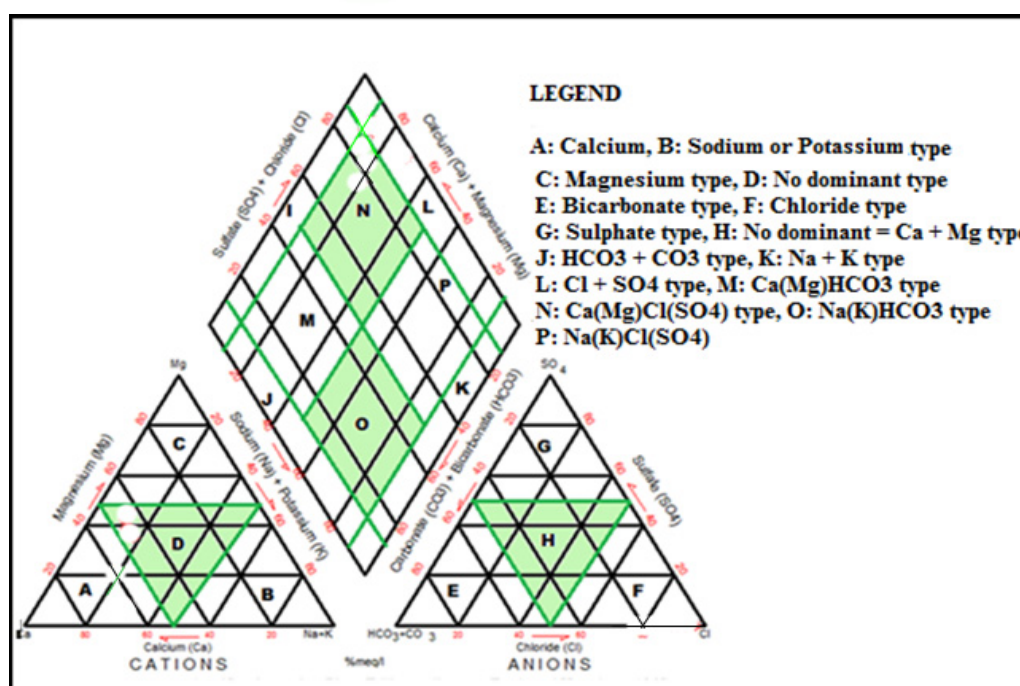
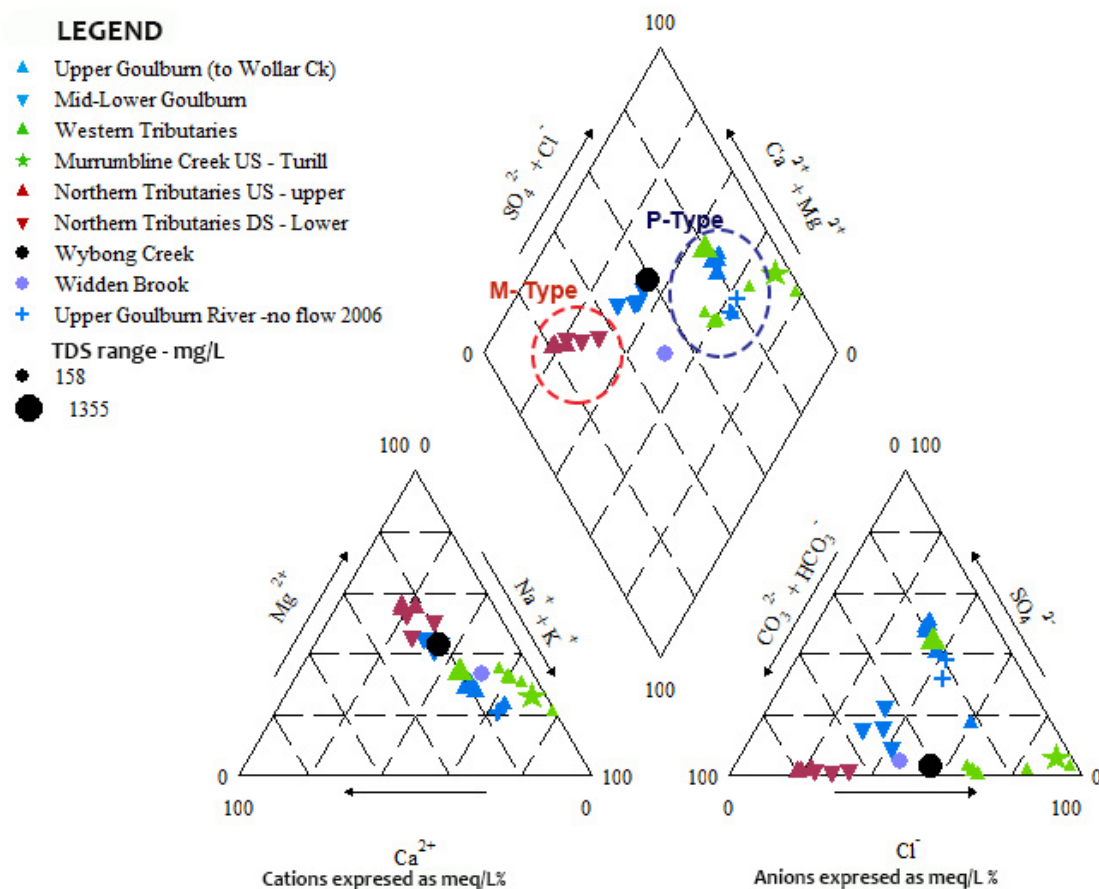


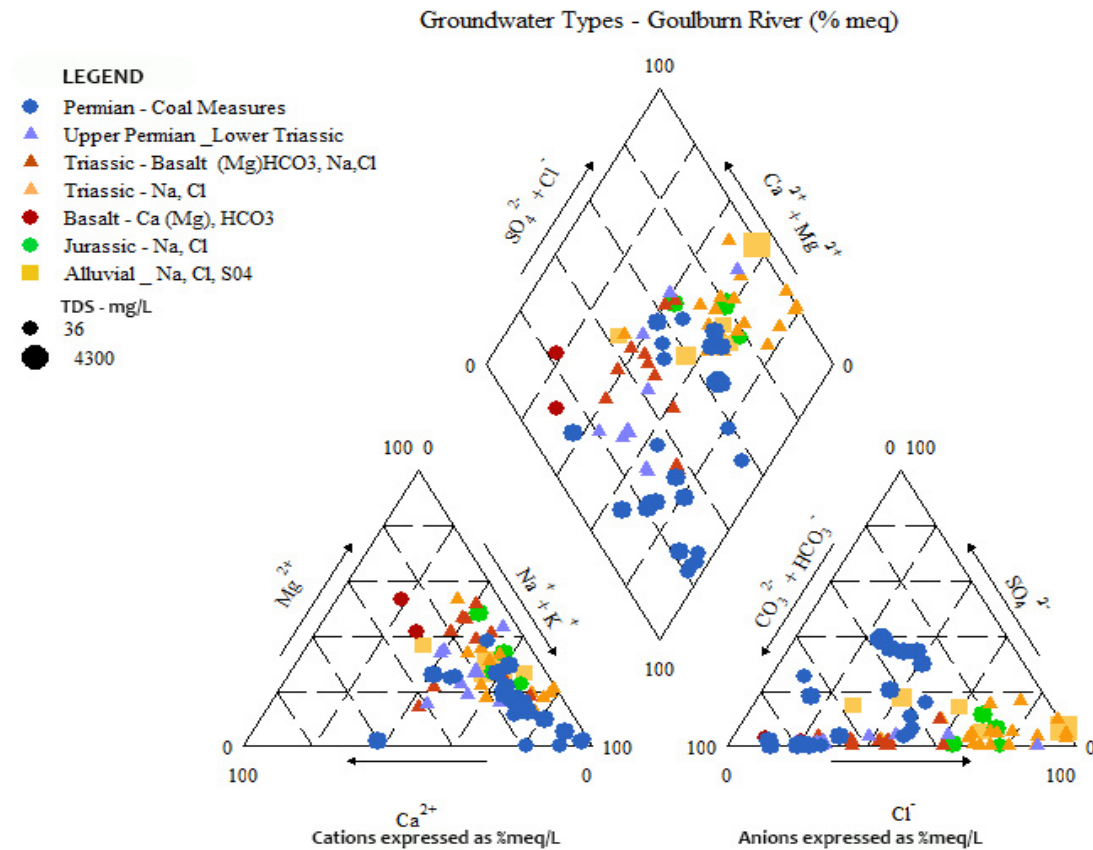
Figure 7:6 Trilinear Piper diagram surface water Goulburn River and tributaries (meq/l %). The sizes of the points indicate samples TDS.

7.3.4 Groundwater hydrochemistry

The groundwater analyses in Table 7:2 are plotted in the Piper diagram Figure 7:7. Groundwater associated with Triassic Narrabeen sandstones demonstrates NaCl dominance (P Type). The hydrochemistry of Triassic groundwater shows a close association with surface water during low flows and no mine discharge in the upper Goulburn catchment indicating surface-groundwater interaction as baseflow. Triassic groundwater associated with volcanic intrusion and basalt caps displays a bicarbonate mixing influence lying between Type M and P.

There are only three Jurassic groundwater samples for Purlewaugh siltstone strata which outcrop in the northwest of the catchment). Jurassic groundwater is NaCl ($>\text{HCO}_3$) dominant (Type P & F) but also exhibit elevated levels of bicarbonate and magnesium possibly reflecting the overlying basalt geology. Groundwater associated with Jurassic Purlewaugh siltstone strata shows some of the highest salinity levels suggesting a legacy of marine inundation and evapo-concentration. Salinity associated with Jurassic siltstone can exceed the underlying Permian coal measures in the upper Goulburn and are up to five times higher than the underlying Triassic groundwater (MER, 2011). Surface water salinity levels for Murrumbline Creek, incised into Jurassic Purlewaugh Siltstone were measured at 2,500-4,000 $\mu\text{S}/\text{cm}$ at the village of Turill as discussed above.

Groundwater samples associated with Tertiary basalt geology have elevated magnesium levels $\text{Mg} > \text{Ca}$ and HCO_3 dominance (M Type). The Triassic-Basalt group and upper Permian-lower Triassic group display similar transitional hydrochemical characteristics with elevated bicarbonate HCO_3 , Na and minor K (O Type). The Triassic-Basalt group contains proportionally more magnesium (M Type) while the upper Permian-lower Triassic has proportionally more sodium levels. The bicarbonate signal may be related to up gradient groundwater sourced from overlying Tertiary-basalts or alternatively *in situ* residual interbedded tuff from Mesozoic volcanics (Mackie, 2009). The trilinear Piper diagram places them into two general groups, both separate and above the Permian coal measures.



**Figure 7:7 Trilinear Piper diagram - Groundwater types Goulburn River (meq/l %).
The sizes of the points indicate sample TDS.**

Groundwater associated with Permian coal measures are sodium plus potassium (Na+K) dominant (Type P & K) with elevated bicarbonate Na (K)HCO₃ (O Type). Alluvial groundwater incised or hydraulically connected to Permian coal measures can display a high chloride and sulfate component (P & L Type). Alluvial groundwater associated with incised Permian coal measures and mine discharge water can also exhibit a strong sulfate signal and elevated salinity from the oxidation of pyrites. Mine monitoring data of the alluvial aquifers along Wilpinjong Creek reveal higher than average K, along with some of the highest salinity levels recorded in the catchment (WCM, 2015b). Potassium concentrations greater than 10 mg/L in the Permian units may provide a distinguishing characteristic for some Permian coal measures. The trilinear piper plot does not distinguish between potassium and sodium levels; this is examined in the following using ion ratios.

7.4 Ion ratios

Multivariate analyses based on major ion ratios were used to investigate hydrochemical characteristics and natural associations between groundwater and geological source. Chloride is usually considered a conservative tracer that has originated from either a cyclic salt deposited by rainfall or marine sources (Biswas, 2010; Jasonsmith, 2011; Hem, 1989; White *et al.*, 2009). Evaporation over time concentrates Cl. The ion ratios HCO_3/Cl , $(\text{Ca}+\text{Mg})/\text{Cl}$ and $(\text{Na}+\text{K})/\text{Cl}$ can provide some insight into the source. If groundwater $\text{HCO}_3:\text{Cl} > 1$, sediment mineral weathering is considered the main contributor of solutes while samples associate with marine origin formations have $\text{HCO}_3/\text{Cl} \ll 1$. For seawater, $\text{Na}/\text{Cl} \approx 0.85$ (Hem, 1989) so $\text{Na}/\text{Cl} > 1$ suggests additional sodium ions have been released from silicate or mineral weathering host.

To investigate mineral weathering component ion ratios (meq/l) for groundwater samples were plotted against the reciprocal of chlorine. The reciprocal is used to incorporate and better display rainwater and seawater on the same graph. Groundwater groups are identified according to the geology in which the bore is screened or that surrounding the water source or spring. The groups used here are Basalt (Tertiary), Jurassic, Triassic, Trias-basalt, Trias- Perm, Alluv-Permian, and Permian-coal.

Figure 7:8 shows the plot of HCO_3/Cl against $1/\text{Cl}$. Groundwater types closer to rainwater tend to fall to the right and those closer to seawater (connate marine origin) to the left. The upper Triassic groundwater is associated with a fresh rainwater source while Jurassic and Alluv-Permian groundwater indicate a marine evaporative influence. Groundwater associated with basalt and some Permian coal measures display an elevated $\text{HCO}_3/\text{Cl} > 1$ on the Y-axis. The close relationship between Trias-basalt and lower Triassic, upper Permian groundwater suggests a possible link with increasing residence and depth of water source (Green *et al.*, 2009).

Figure 7:9 $(\text{Na}+\text{K})/\text{Cl}$ groups Permian and Jurassic groundwater samples indicating a common seawater origin and divide them from the fresher Triassic – basalt groundwater which has meteoric influence.

Figure 7:10 shows the ratio Na/Cl against $\log [\text{Cl}]$ and a transition from rainwater to seawater. Triassic groundwater lies closest to rainwater, with Na and Cl ions derived from accumulated atmospheric aerosols. Alternatively Jurassic groundwater samples lie closer to seawater along with the Alluv-Permian, while Permian and basalt groundwater derive additional sodium from mineral weathering. Trias-basalt and lower Trias-upper Permian groundwater lie along a transitional zone between the fresher Triassic groundwater and seawater. Permian samples show a transition related to silicate weathering which may be due to the age or depth of samples.

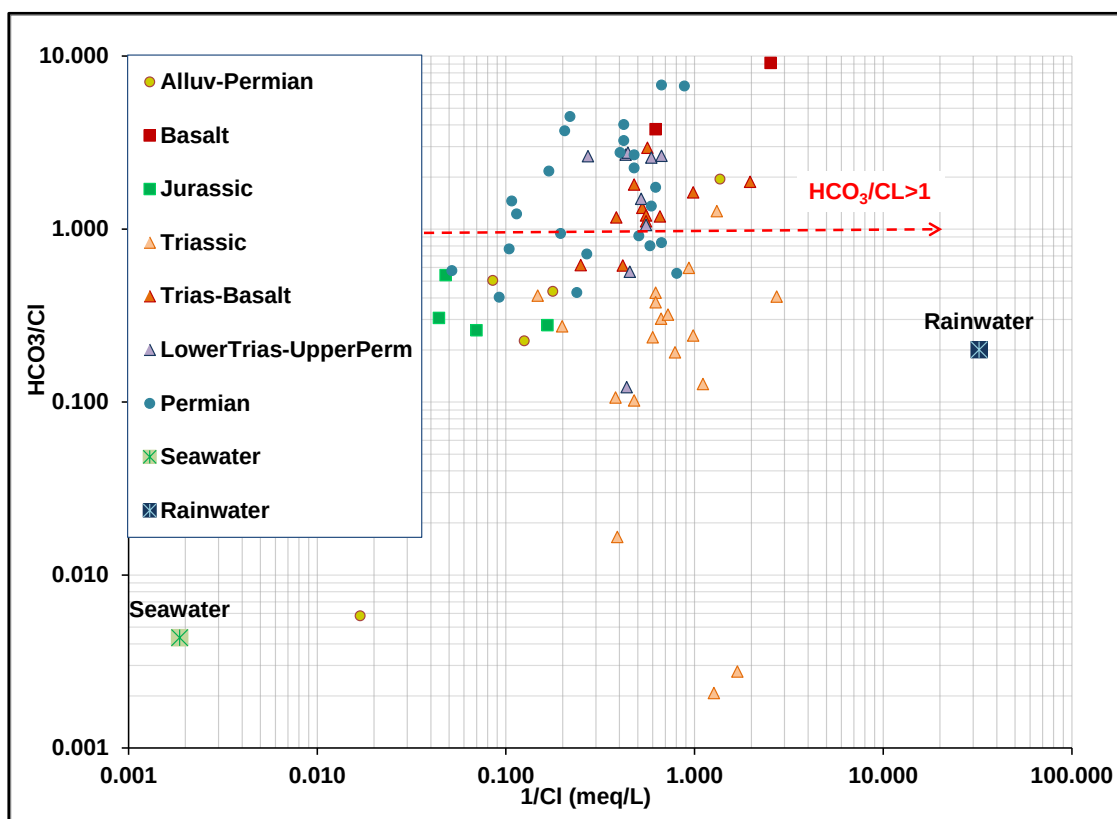


Figure 7:8 Groundwater ratios – $\text{HCO}_3^-/\text{Cl}^-$ vs $1/\text{Cl}$

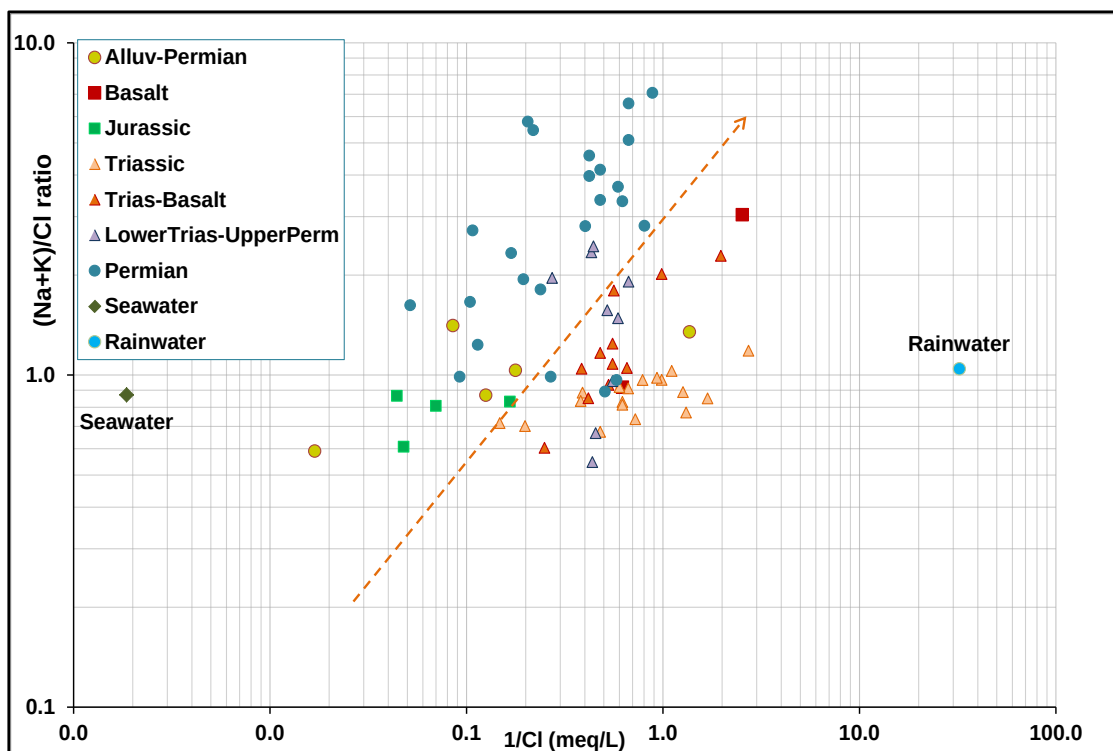


Figure 7:9 Ratio $(\text{Na}+\text{K})/\text{Cl}$ plotted against $1/\text{Cl}$

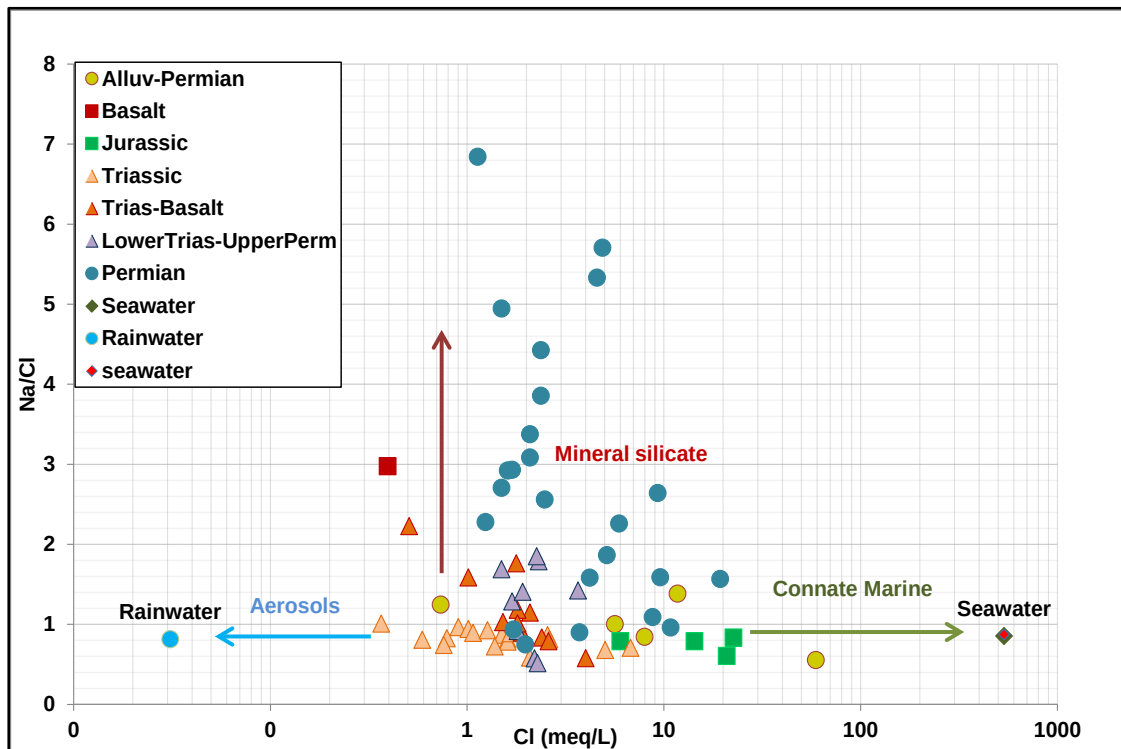


Figure 7:10 Groundwater ratio Na/Cl vs Cl (log)

Figure 7:11 is a bivariate plot of K concentrations vs Cl (log). It indicates a possible association between above average K concentrations in groundwater originating in Permian/Illawarra Coal Measures and deeper Triassic groundwater with a longer residency time. Marine evaporite rocks are a potential source of elevated potassium and sodium in groundwater. Hem (1989) suggests that due to the stability of potassium-bearing aluminosilicate minerals, high potassium concentrations are uncommon in natural water, though deeper groundwater may increase in potassium levels with increasing residence time and dissolution of silicate minerals. Elevated potassium in surficial/ alluvial aquifers may indicate a transitional water type reflecting the discharge of Permian groundwater. This would be a relatively temporary state as potassium has a tendency to readily bind with clay minerals in surface water (Hem, 1989). Elevated potassium may signal a hydraulic connection with Permian groundwater or alternatively the discharge of mine water from a Permian coal source. Surface flows downstream from Ulan Coal Mine discharge (SWO2) in 2012 recorded 9.8 mg/l of potassium as opposed to upstream levels (SWO1) of 4.3 mg/L.

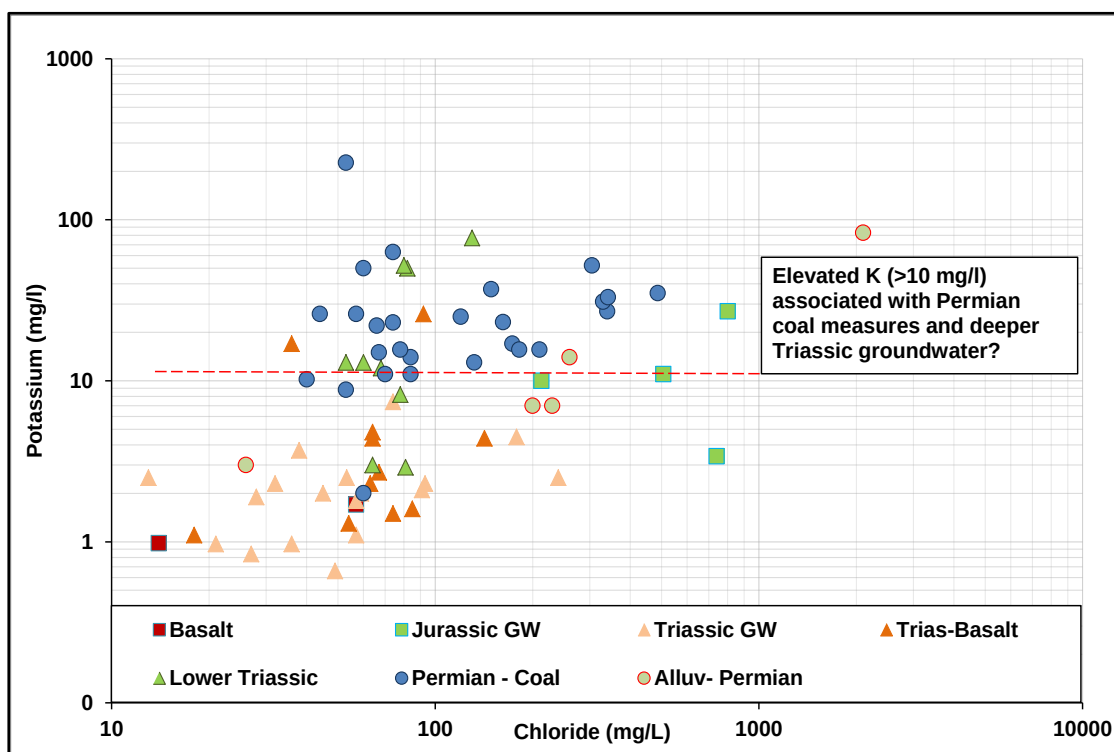


Figure 7:11 Groundwater ratio K/Cl (potassium ions to chloride) (mg/L)

The analysis of the major ions of available groundwater samples representing hydrogeological units of the upper Goulburn can be summarised by the general water types in Table 7:3.

Table 7:3 Summary Characteristics Hydrogeological Units Water Type

HYDROGEOLOGICAL UNIT	Salinity (EC $\mu\text{S/cm}$) Median [Standard Deviation]	pH [Standard Deviation]	Dominant Water Type Anions Cations
Tertiary Basalt	754 [326]	7.8 [0.3]	Ca(Mg) - HCO_3
Jurassic (Purlewaugh Siltstone)	2470 [1149]	7.3 [1.5]	Na - $\text{Cl} > \text{HCO}_3$
Upper Triassic Sandstone	233 [241]	6.4 [1.1]	Na - Cl
Triassic - Basalt	450 [168]	7.8 [1.45]	$\text{Na} > \text{Mg} - \text{HCO}_3 > \text{Cl}$
Lower Triassic-Upper Permian	545 [357]	6.43 [0.6]	Na - $\text{HCO}_3 > \text{Cl}$
Permian Coal Measures (PCM)	1095 [1271]	7.3 [1.0]	Na + K – $\text{Cl}, \text{HCO}_3 > \text{SO}_4$
Note: Alluvial aquifers hydraulically connected to PCM have been recorded > 7,000 $\mu\text{S/cm}$			

Groundwater derived from rainfall recharge with only limited rock interaction produces low salinity water reflective of atmospheric aeolian salts such as the fresh springs and seeps from the higher Triassic strata in the Goulburn catchment. These exhibit low salinity, NaCl type water. Surface and groundwater associated with the basalt dominated northern tributaries of the Goulburn River exhibit elevated HCO_3 and Mg indicative of silicate weathering from a Tertiary basalt source. Towards the end of the flow path and at discharge, evapo-concentration and

precipitation processes dominate, producing an end-member characteristically rich in Na Cl and high in salinity. It has been found here that alluvial groundwater in the Goulburn catchment is typically high in salinity with elevated Cl and SO₄.

A complicating factor to this picture is the marine-origin Jurassic and Permian strata that can produce highly saline water chemistry *in situ* reflecting an evaporative end member signature from the dissociation of a marine origin rock host. In addition, groundwater, with elevated bicarbonate and magnesium, may be due to the dissociation of residual interbedded Mesozoic tuffaceous deposits. This is evident in some deeper Triassic - upper Permian strata and in coal measures. Triassic groundwater in the Goulburn catchment can therefore exhibit a range of hydrochemical signatures reflecting their relative position and depth in the geological landscape and proximity to basalt intrusives, and deeper interbedded Mesozoic tuff.

7.5 Conclusions

The aim of this chapter was to identify and characterise the dominant hydrogeological systems in the upper Goulburn catchment contributing to river baseflow. Surface water samples were taken during a dry period when baseflow is expected to dominate in the Goulburn catchment where over 50% of river discharge comes from baseflow.

River sampling revealed an increase in HCO₃ inputs at elevations below about 280 mAHD, not only from Tertiary basalt in the northern tributaries but starting with discharge from upstream Wollar Creek sourced incised Permian Coal measures and alluvium. Discharge in the lower catchment from Wybong Creek is characterised by inputs from both coal measures, similar to those for Wollar, and basalt geology. In the lower catchment this is mitigated by lower HCO₃ and salinity discharge from the Widden draining from higher elevation Triassic sandstones.

The rise in HCO₃ inputs are accompanied by increasing concentrations of Mg and Ca again sourced mainly from basalt in the northern tributaries. Inputs of SO₄ were characteristic of drainage from the Permian coal measures, possible due to pyrite oxidation. It was also characteristic of the treated mine water discharged into the river at Ulan. This means that much of the upper Goulburn is now dominated by SO₄.

An unusual characteristic of groundwater from the Permian coal measurements was unusually high concentrations of K. This is perhaps an indication of the longer residence time. As well it was found that K concentrations in lower Triassic-Upper Permian strata were elevated suggesting vertical exchange between the Permian and Triassic. The range of K concentrations in the Permian groundwater samples must reflect different groundwater ages, but there was insufficient data in the mining reports to test this. The need for a well-managed accessible source of both government and industry groundwater data is clearly warranted.

This research was able to analyse upper Goulburn river water sampled over a period when there was no mine discharge during a prolonged dry period. These results clearly showed that the source of baseflow in the upper Goulburn was Triassic. Mining companies have disrupted discharge from Triassic strata into the upper Goulburn despite head gradients towards the river (Chapter 6: Mining Impacts on the Upper Goulburn).

A critical point here is that the chemistry of Triassic discharge differs substantially from that of the treated mine waste water particularly in regard to the latter's high SO_4 concentration. Regulations concerning mine discharge only specify a maximum salinity for discharge without regard to chemistry (see Chapter 2:). There is no information on the impact of the change in water chemistry on in-stream ecology of the upper Goulburn.

Two northern catchments, Murrumbidgee Creek and the Merriwa River are both sourced from Tertiary basalt but are incised into more saline Jurassic Purlewaugh Siltstone. Very little is known about these catchments. In the next chapter a survey of the predominantly cleared Merriwa River is carried out.

Chapter 8: Merriwa River, an agricultural tributary

Agriculture is the predominant land use in the Goulburn. The aim of this chapter is to investigate the catchment yield, salinity, and surface-groundwater interactions of a major, agricultural sub-catchment of the Goulburn River. In Chapter 5 the Merriwa River, a major northern sub-catchment was identified as a significant source of salinity in the Goulburn River. In Chapter 7, it was identified that the combination of the upper catchment's Tertiary Basalt and rivers incision into the saline Jurassic Purlewaugh Siltstone underlain by Triassic strata has not been studied. In addition, the Merriwa catchment has no history of coal mining. The area, however, has moderate to high potential for Coal Seam Gas (CSG) extraction (NSW Department of Planning, 2011)

The characteristics of the catchment are described in this chapter. Discharge data from the two gauging stations on the Merriwa River is analysed to determine salt yield. Changes in downstream surface water chemistry relative to the catchment's three dominant geologies are examined. The results are used to estimate the catchment contribution of salts to the lower Goulburn River. Key groundwater sources are also characterised and their interaction with surface river water chemistry is examined. This chapter provides information on the relative influence of this major agricultural area and its sensitivity to future land use change.

8.1 *Characteristics*

The Merriwa River is the largest sub-catchment (809 km²) of the Goulburn River encompassing 12% of the catchment above Sandy Hollow (Figure 8:1). Approximately 78 kilometres in length it rises in the Liverpool Ranges (elevation 1117 mAHD) and flows south passing through the township of Merriwa (250 m AHD) which lies approximately 40 kms upstream from the confluence with the Goulburn River (160 m AHD). Its tributaries include Coulsons Creek, Gummun Creek, Mountain Station Creek and Butchers Swamp to the north of Merriwa; Witneys Creek, Wyndam Springs and Farm Springs Creek, Vallance Creek, Horse Creek and Kittens Creek to the south. Land use is predominately grazing with some cropping and irrigation on the richer basalt soils in the upper catchment. Goulburn River National Park encompasses the lower reaches within the Triassic Narrabeen Group sedimentary geology (Figure 8:2, Figure 8:3).

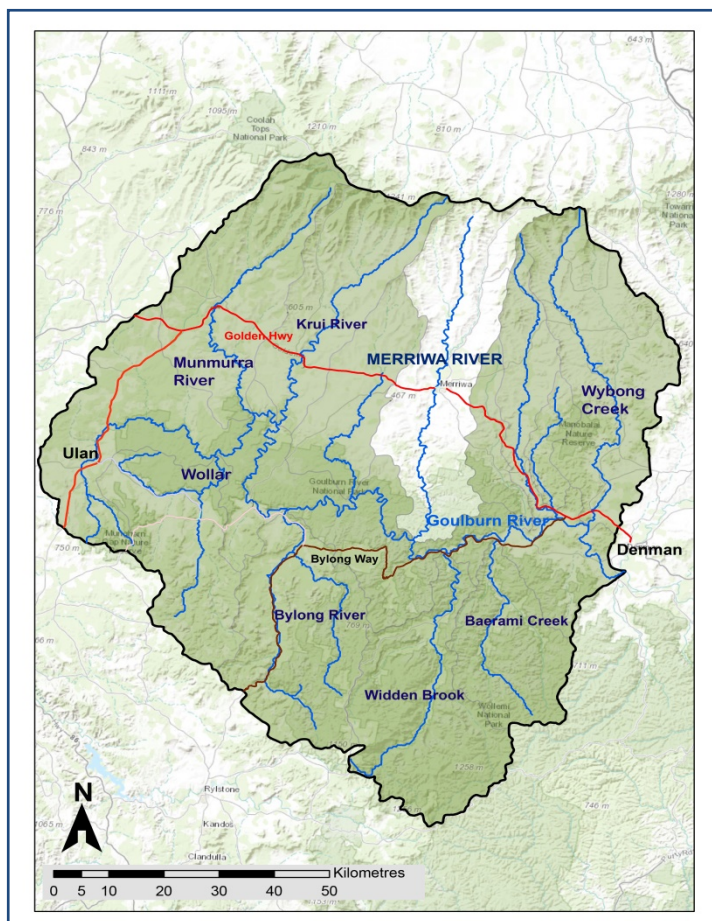


Figure 8:1 Goulburn catchment showing location of Merriwa River catchment

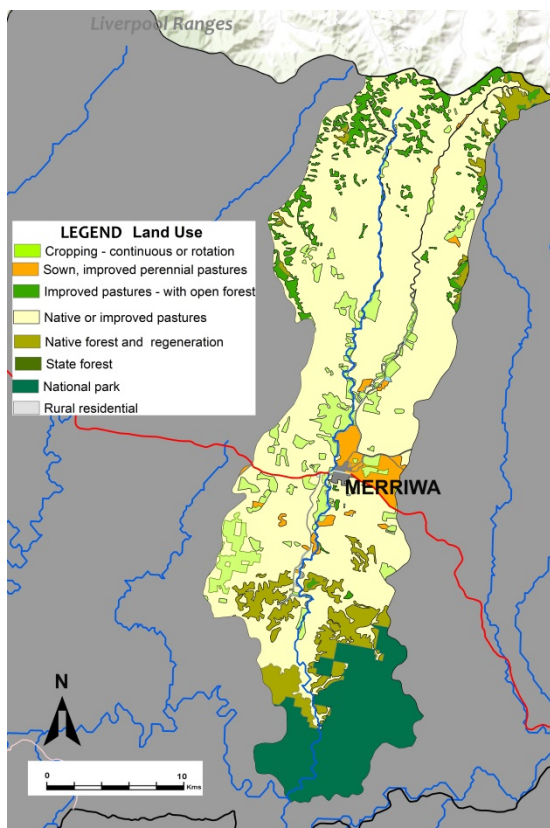


Figure 8:2 Merriwa sub-catchment - land use data supplied NSW Office-of-Water2016, (Geoscience-Australia, 2013)

8.1.1 Geology

Merriwa River traverses Tertiary igneous basalt in the upper catchment and sedimentary Jurassic and Triassic dominated geology in the mid and lower catchment before joining the Goulburn River upstream of Kerrabee gauging station (Figure 8:3). The catchment immediately north of the township of Merriwa is Tertiary olivine basalts classed as Cainozoic mafic volcanics with intrusive volcanic plugs and sills scattered across the catchment. Jurassic strata of Pilliga-Munmurra sandstones and Purlawaugh siltstone/Comialla shale outcrop in township of Merriwa and immediately south. The underlying Triassic Narrabeen Group sedimentary strata are exposed about 1 kilometre south of the Golden Highway at Merriwa, continuing to the confluence with the Goulburn River. Quaternary alluvial deposits and Permian strata outcrop at the Goulburn River, Kerrabee gauging station and Kerrabee Creek. There is currently no mining in the Merriwa catchment.

The township of Merriwa and some farms within the catchment rely on groundwater sourced from various aquifers, particularly during dry periods. The catchment has been identified by the Upper Hunter Coal Seam Gas (CSG) Strategic Plan as having moderate CSG potential within the underlying Permian strata (NSW Department of Planning, 2011).

8.1.2 Hydrogeology and water use

There are no publicly available hydrogeological maps of the Goulburn or Merriwa River catchments. Geological information has been sourced from the Singleton Map Sheet 1:250 000 (Rasmus *et al.*, 1969). Alluvial, porous and fractured rock aquifers have been identified within the Tertiary Liverpool Ranges volcanics, Jurassic Pilliga sandstones and Triassic Narrabeen Group sandstone and Permian Coal Measures (Creelman, 1994; Kellett *et al.*, 1989; Macdonald *et al.*, 2009a). Regional groundwater of varying quality and quantity is associated with Triassic and Permian strata. Potable surface and ground water is extracted for irrigation, stock and domestic use.

A relatively deep productive groundwater source, thought to be Jurassic Pilliga sandstones from the Oxley Basin, is used by Merriwa and Cassilis townships for town water supplies and the local farming community for irrigation, stock and domestic use. The most productive bores, located predominantly in the mid-catchment (Figure 8:4) have a depth of greater than 99 metres below ground level and have yields of 4-17 L/s (DPI Water, 2018).

Merriwa town water supply draws up to 2 ML/day from three bores 167-201 m below ground level. Treated town effluent is intermittently discharged into the river via trickle overflow from treatment ponds immediately downstream of Merriwa. The volume varies, dependent on public water usage which includes house tank supplies (pers.comm. S. Walmsley Officer upper Hunter town water supply, Dec. 2014).

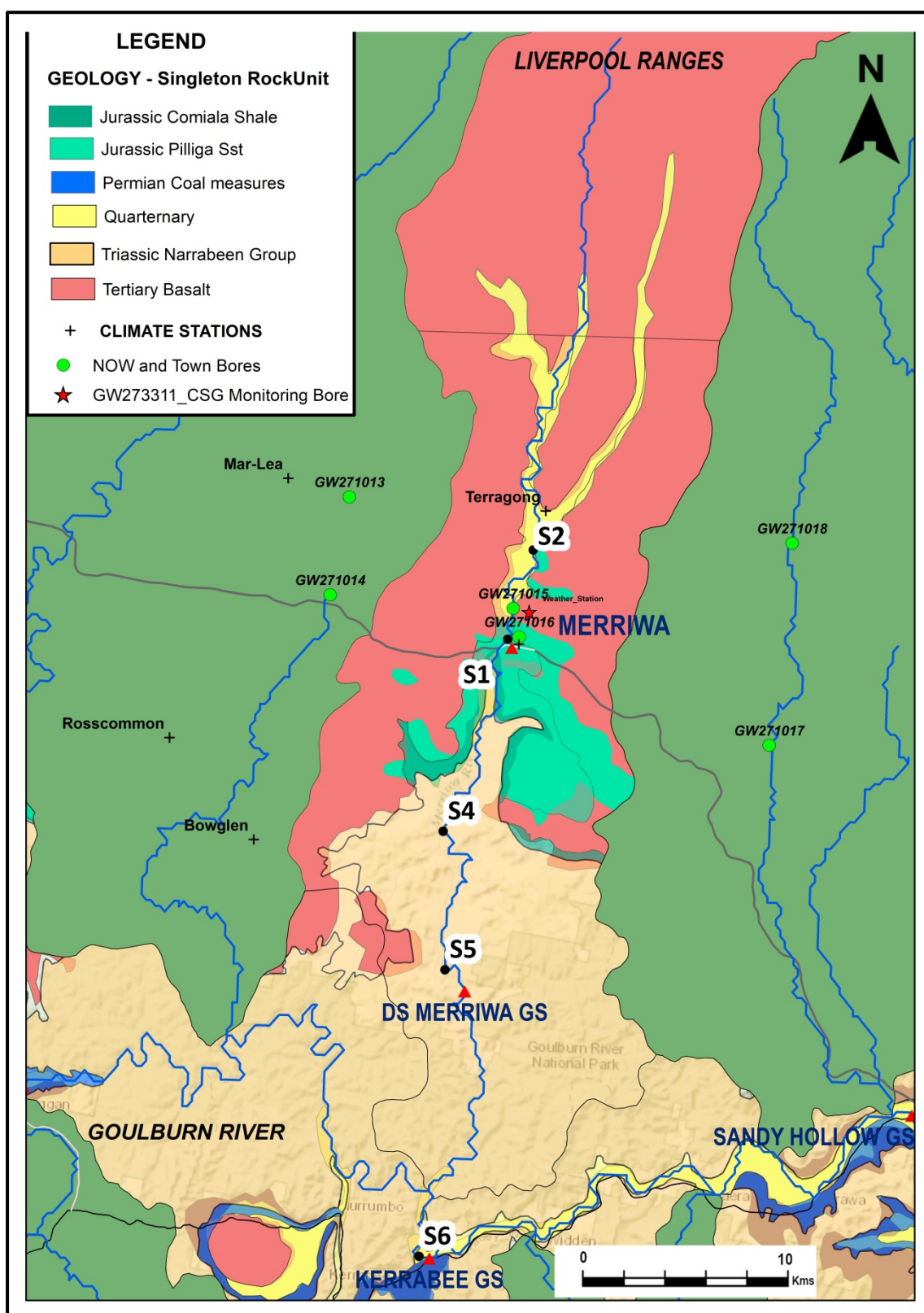


Figure 8:3 Geology map of the Merriwa catchment and location of monitoring sites (Source: data supplied (Geoscience-Australia, 2013))



Figure 8:4 Location registered bores in Merriwa catchment (DPI Water, 2018)

Land-use maps and satellite imagery (SPOT 5) indicates most irrigation occurs on the agriculturally productive alluvial and basalt soils to the north of Merriwa (comments NSW DPI Water, Dec 2016). The total licensed water entitlements for Merriwa within the Hunter Unregulated and Alluvial Water Source is 6,358 ML/year, equivalent to 8 mm/year, or 10.5 % of the Goulburn Extraction Management Unit (see Table 3:4 for details).

The total groundwater allocation under the Sydney Basin Porous and Fractured Rock Water source for Merriwa catchment is unknown. The general recharge rates as reported earlier in section 2.9 for porous and fractured rock groundwater sources in the Hunter is estimated to be 5-7 % of annual precipitation, 30-50 mm/year of annual rainfall.

Farm dams in the catchment are permitted to intercept 10% of annual runoff for domestic and stock use. The storage capacities of farm dams across the region are, however, not known. There is no accurate data as for the whole catchment on the amount of water stored, consumed or lost through evaporation (Zhang *et al.*, 2016). A lack of comprehensive monitoring of take means accurate estimation of water use is not possible. Estimates can be made based on licensed volumes, patterns of use in metered areas and assumptions about basic water rights use.

8.1.3 Salt sources

Soil and rock weathering is considered the primary source of salts in surface and groundwater in the upper Hunter region, with deposition and evapo-concentration of aeolian cyclic salts secondary (Creelman, 1994; Kellett *et al.*, 1989; Biswas, 2010). The hydrogeological units and associated water types are summarised in Table 7:3 in Chapter 6.

8.2 *Field survey*

A field survey was carried out at the end of an extended dry period on 2 December 2014. The annual rainfall November 2013 - November 2014 was below the 0.3 percentile (Figure 4:6). Field salinity (EC) and pH levels were measured on the day and on a previous reconnaissance trip on 27 November 2014. Eight surface water samples were collected from monitoring sites along the Merriwa River and Goulburn River plus two groundwater samples from Merriwa town water supply bores (MT1, MT2). A groundwater sample was also collected on 21 November 2014 from a private bore (B8) located south-east of Merriwa town (Figure 8:6). Water samples were analysed for major ions by the NSW DPI-Water laboratory²⁸ Surface and groundwater monitoring site details are shown in (see Appendix H – Merriwa).

²⁸

previously NSW Office of Water - NOW

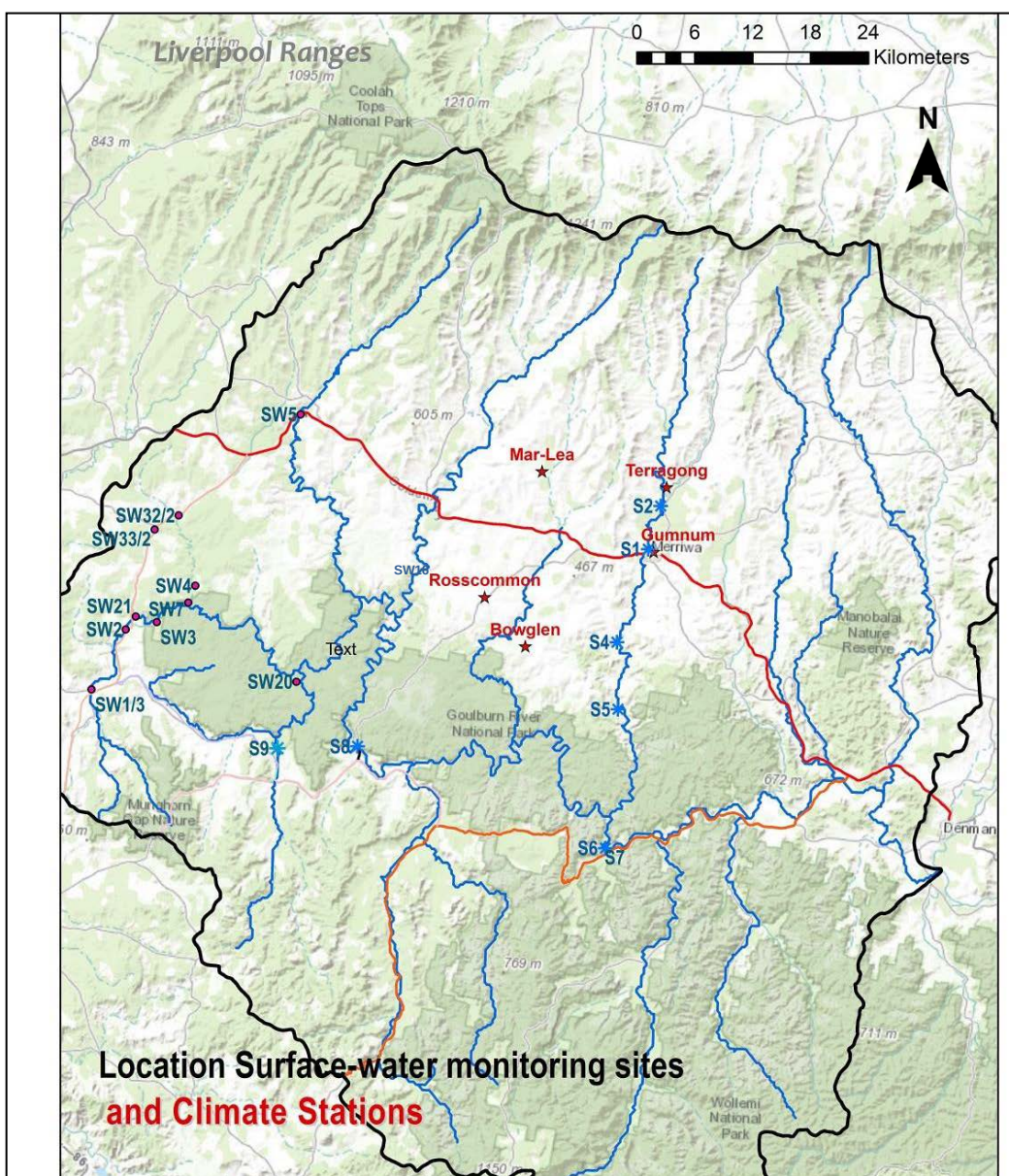


Figure 8:5 Location of surface monitoring sites and rainfall stations in the Merriwa catchment

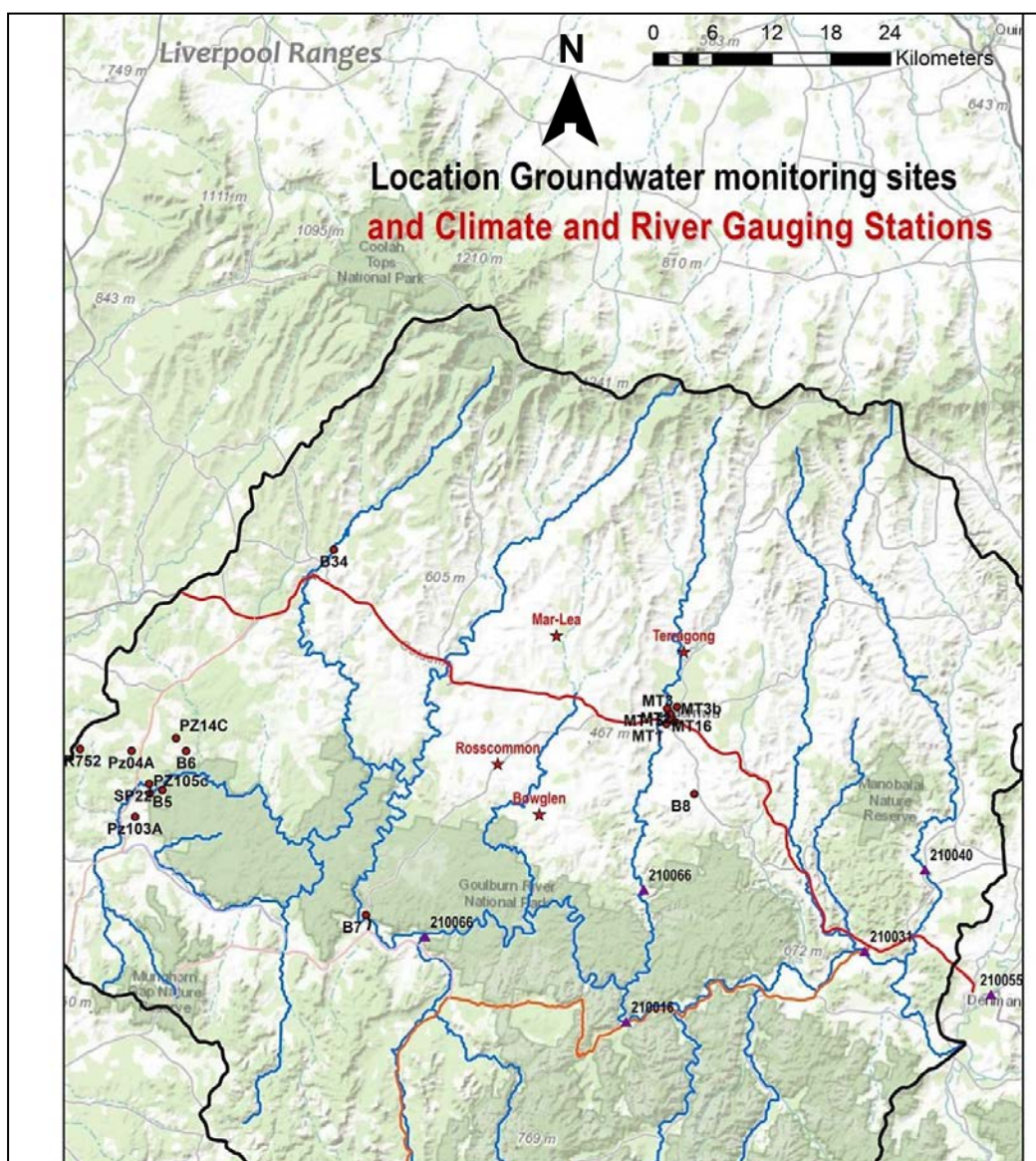


Figure 8:6 Location groundwater sampling sites, river gauges & rainfall stations in the Merriwa catchment

8.3 River gauging sites

There are two river gauging stations on the Merriwa River (Fig 8.2) in addition the station at Kerrabee on the Goulburn River which is 5 kms below the confluence with the Merriwa. Their location is shown in Figure 8:3 and their details are listed in Table 8:1 (and Table 4:4). The two gauging stations on the Merriwa River have major gaps in their records. Site 210091 has missing annual flow data from 1992 to 2010, covering the dry period during the mid-1990s and the whole of the millennium drought. Site 210061 has a major gap from 1991 to 2001 together with other smaller gaps.

Table 8:1 Details of gauging stations relevant to the Merriwa catchments

LOCATION	Site Number	Lat:	Long:	Area km ²	Elevation mAHD	Monitoring Period	Salinity data
MERRIWA RIVER							
Merriwa Town	210091	-32.1401	150.3539	465	238.955	1972- present	n/a
U/S Vallance Ck	210066	-32.2963	150.3343	684	189.575	1963-present	Jun-02
GOULBURN RIVER							
Kerrabee	210016	-32.4166	150.3201	4950	162.841	1960-Present	Jul-02

8.4 Catchment rainfall and pan evaporation

Spatial interpolation of monthly rainfall for the Merriwa catchment (Hutchinson *et al.*, 2014) over the period 1920 to 2014 showed both the distribution of monthly rainfall and the characteristic of rainfall were very similar to those in the whole Goulburn catchment (see section 4.1.1 and Appendix G) giving a mean annual rainfall of 672 ± 169 mm/year, with a minimum of 370 mm/year in 1946 and a maximum of 1281 mm/year in 1950. There was also no significant trend in annual rainfall. Spatially interpolated pan evaporation for the Merriwa catchment was essentially identical to that for the whole Goulburn catchment (See section 4.2.2).

8.5 Annual specific yield and runoff

The significant gaps in annual stream discharge in the Merriwa catchment and the correspondence between annual specific yields at each gauging station and between them and annual precipitation are shown in Figure 8:7. The correlation for Q/A between the two gauging sites was high, 0.989. Correlation between $\log(Q/A)$ at the upstream site, 210066, and P was lower, 0.555, while for the larger catchment area downstream site the correlation was 0.588. Curiously, for the upstream the correlation between $\log(Q/A)$ and the previous years' rainfall was higher, 0.603, while that at downstream site was 0.388. This may suggest significant delayed discharge of groundwater in the catchment upstream.

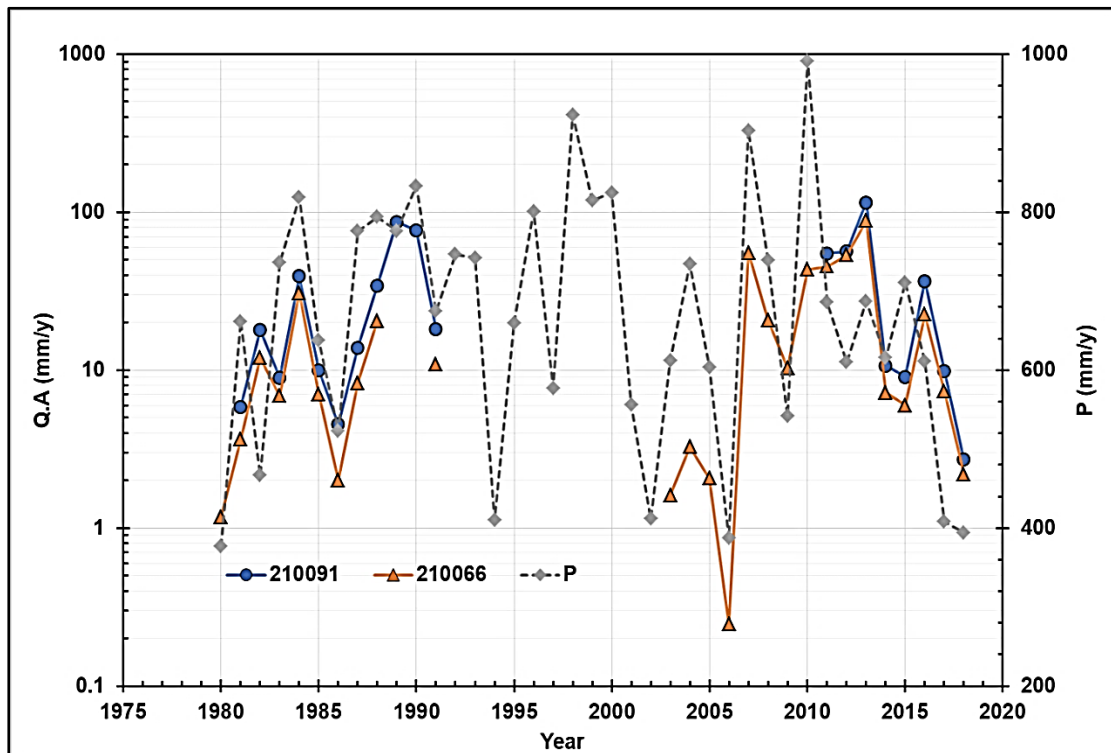


Figure 8:7 Correlation of annual specific yield between the two gauging sites in the Merriwa River (Table 8.4) and between those yields and annual interpolated catchment rainfall. Large gaps in stream monitoring are obvious.

A summary of the annual specific yield and the runoff coefficients at the two gauging stations is presented in Table 8:2. The mean annual rainfalls for the two different periods for which stream discharge measurements were available for the two sites were identical. The geometric mean Q/A at the lower site with larger contributing area was, however, just under 60% of that of the upstream site. While median annual runoff coefficients for both sites were similar, the aggregate runoff coefficient ($\Sigma(Q/A)/\Sigma P$) of the downstream site was 90% of that upstream. Comparison of annual Q/A for contiguous measurements at the two sites (Figure 8:8) shows that annual flows downstream are just less than 78% of upstream flows. This sustained loss of flow on an annual basis suggests significant transmission losses in the River downstream of Merriwa.

The aggregate runoff coefficient for both sites in this cleared agricultural catchment is greater than for the larger, but more forested Goulburn catchment at Coggan. While pastured catchments have lower evapotranspiration losses than forested catchment, catchment size and slopes are also relevant in runoff generation (Christy *et al.*, 2011).

Table 8:2 Characteristics of the annual specific discharge and the runoff coefficients for the two gauging station in the Merriwa River

Site	210091	210066
Area (km ²)	464	685
Period	1981-2018	1963-2018
Annual Rainfall* (mm/y)	654±131	654±147
Q/A (mm/y)		
Mean	32±32	29±32
Minimum	2.7	0.25
Median	18.0	12.0
Maximum	115.6	126.0
Geometric Mean	19.5	13.6
Runoff Coefficient		
Mean	0.047±0.044	0.042±0.045
Minimum	0.007	0.00064
Median	0.027	0.026
Maximum	0.168	0.191
Geometric Mean	0.031	0.021
Aggregate	0.049	0.044

*Average annual precipitation over the period of available discharge measurements

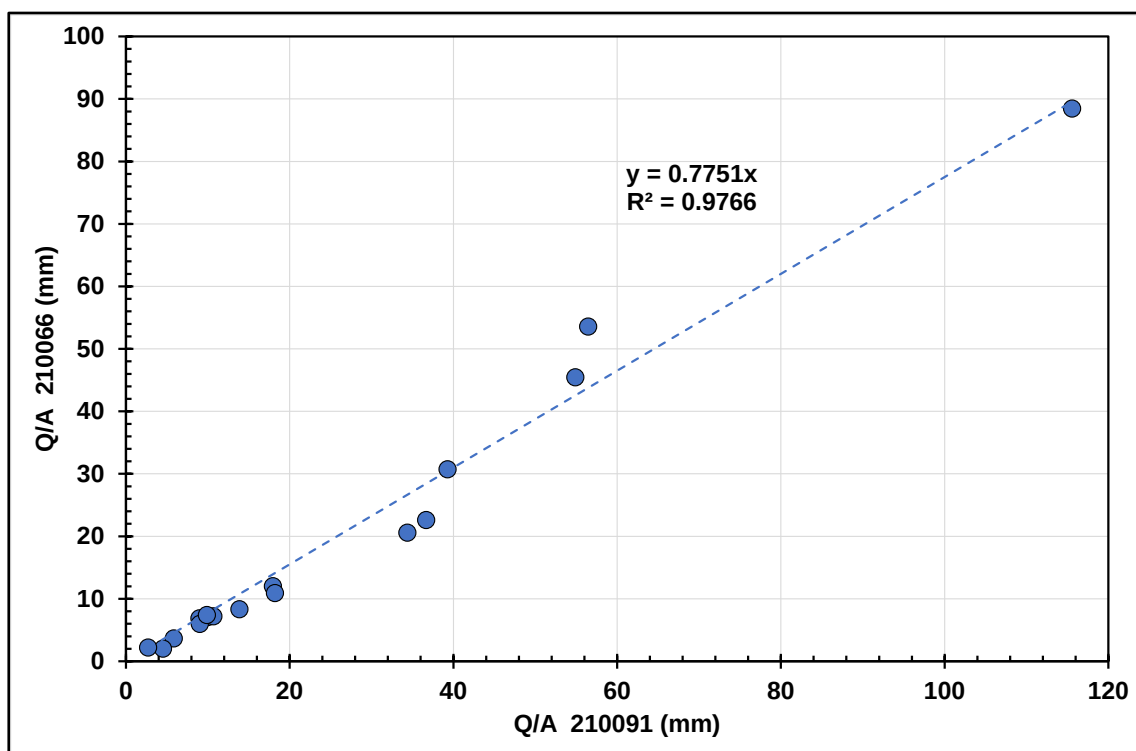


Figure 8:8 Comparison of contiguous annual specific discharges at the two gauging sites in the Merriwa River.

8.6 Merriwa River salinity, salt load and catchment salt yield

Daily real-time stream salinity and flow data has been measured intermittently at the downstream Merriwa River gauging station (GS210066) from June 2002, a period which includes the millennium drought. Average annual EC is 1574 $\mu\text{S}/\text{cm}$ and annual stream discharge was 20,178 ML/year equivalent to Q/A of 0.0295 for the period (DPI Water, 2018). Figure 8:9 shows the strong negative correlation, $R = -0.853$, between average stream EC and $\log(Q)$ for annual data.

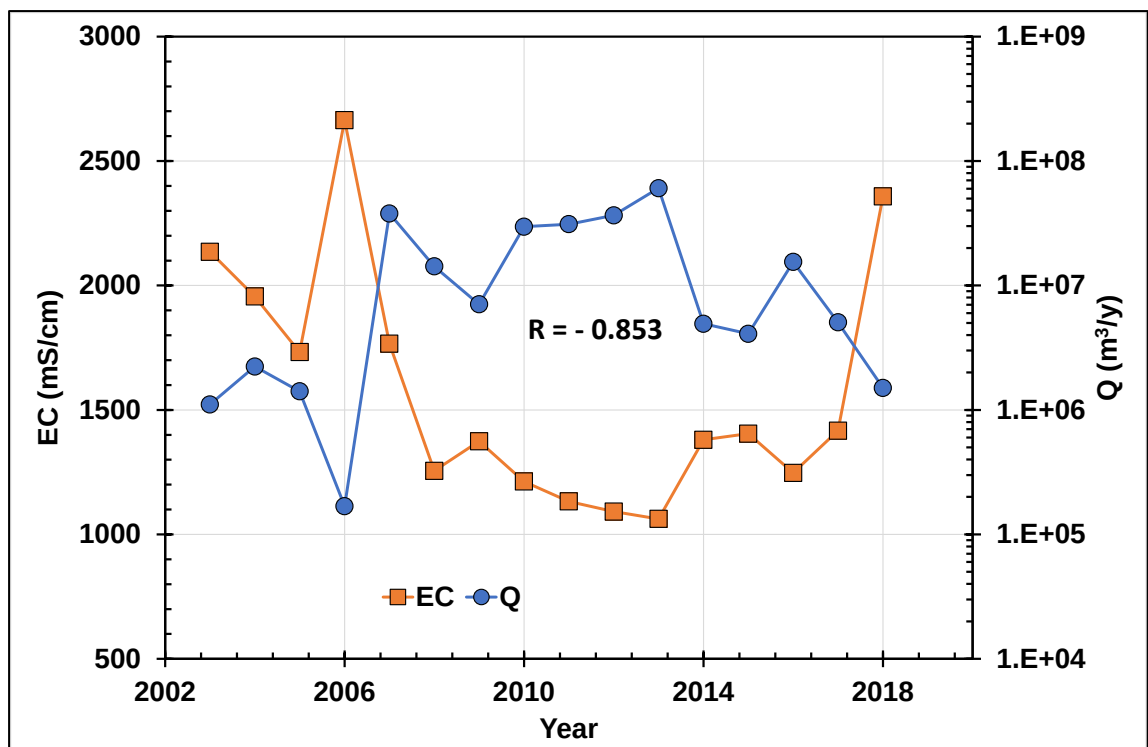


Figure 8:9 The strong negative correlation between stream EC and log discharge for annual data, Merriwa River gauging site 210066.

The highly significant relation between annual average EC and $\log(Q)$ is:

$$EC = (5542 \pm 652) - (582 \pm 92) \cdot \ln(Q) \quad [8:1]$$

Equation [8.1] suggests a strong source of salinity at low flows. During the period of record, the highest annual EC was in 2006 during the millennium drought when the lowest recorded flow occurred. All mean annual EC in the period of the record were larger than the specified maximum for the HRSTS of 900 $\mu\text{S}/\text{cm}$.

Table 8:3 summarises the available annual data for the period 2003 to 2018 and provides estimates of stream TDS, annual salt loads and annual catchment specific salt yield.

Table 8:3 Annual stream discharge, mean EC and estimate mean TDS and annual salt load for the Merriwa River at gauging site 210066 for the period 2003 to 2018.

Year	P (mm/year)	Q (10 ⁶ .m ³ /year)	EC (µS/cm)	TDS (mg/L)	SL (tonnes/year)
2003	612.4	1.11	2135	1452	1,608
2004	734.2	2.23	1956	1330	2,967
2005	603.9	1.41	1732	1178	1,662
2006	387.3	0.17	2664	1811	305
2007	903.3	37.91	1766	1201	45,534
2008	739.6	14.23	1255	854	12,144
2009	542	7.06	1374	934	6,593
2010	991.6	29.67	1213	825	24,462
2011	685.8	31.08	1132	770	23,935
2012	609.8	36.63	1092	742	27,190
2013	687.3	60.50	1062	722	43,697
2014	615.8	4.92	1380	938	4,622
2015	711	4.09	1405	955	3,904
2016	611	15.46	1247	848	13,110
2017	408	5.05	1417	963	4,869
2018	394.2	1.50	2358	1603	2,412
Annual Salt Yield		20.0	tonnes/km²/year	Σ(SL)	219,014

Over the period 2003 to 2018, Table 8:3 shows that the average annual specific salt yield was 20 tonnes/km²/year, comparable with yield from Wybong Creek, which has been identified as a salinity hot-spot in the Goulburn (HCRCMA, 2013). The specific salt yield for the Merriwa is three to four times more than the salt loads estimated for the Goulburn above the confluence with Wybong. The influence of discharge from the Merriwa on salinity in the Goulburn is clearly evident in the transect in Figure 5:2

8.6.1 Salinity transect of the Merriwa River

The results for the EC and pH transect taken on 2 December 2014 are given in Table 8:4 and the EC and pH profile is plotted in Figure 8:10. There was no flow in the River above sampling site S2 (Figure 8:3).

Table 8:4 Merriwa River surface water survey – 2 December 2014

Location	Site	Elevation mAHD	EC $\mu\text{S/cm}$	pH
Merriwa River @ Mountain Station	S2	258	1026	8.6
US Merriwa Rr @ Merriwa GS210091	S1	238.96	1267	8.5
Merriwa River @ Glandore	S4	219	1646	8.4
DS Merriwa Rr - US Vallance GS 210066	S5	183.24	1593	8.6
Kerrabee Creek @Kerrabee	S6	163	1281	7.8
Goulburn River @Kerrabee 210016	S7	162.8	1307	8.2

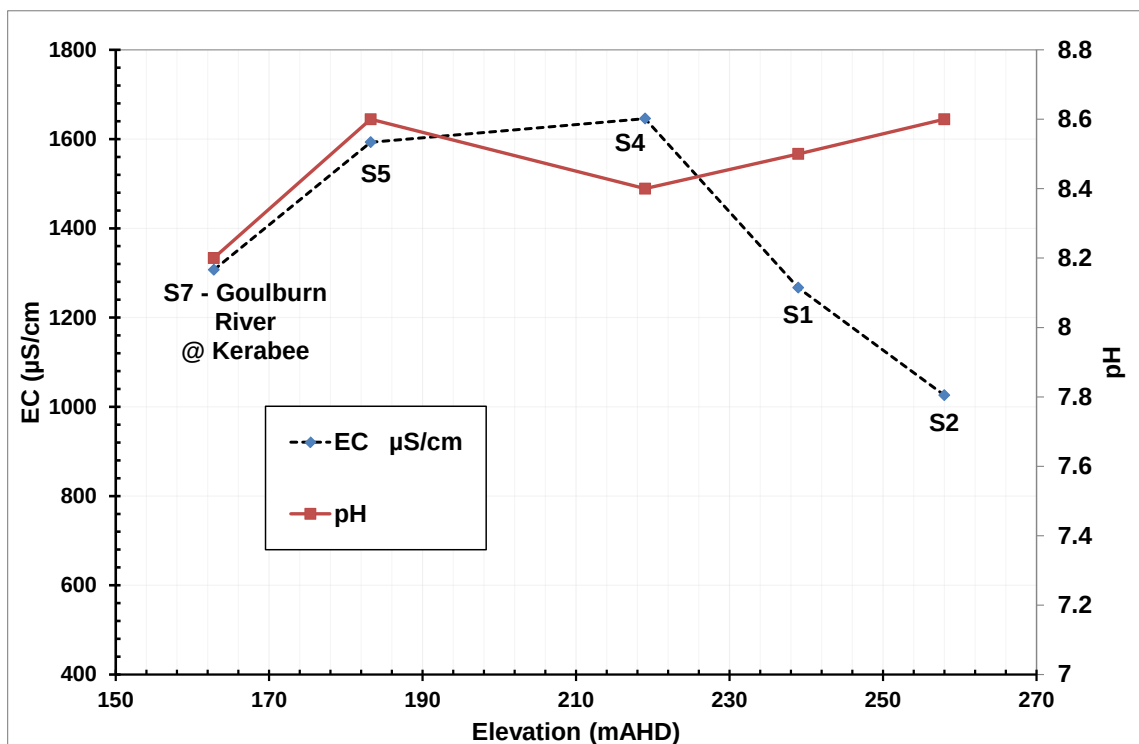


Figure 8:10 Salinity and pH profile down the Merriwa River measured during a dry period on 2 December 2014

Figure 8:10 shows that salinity increased between Mountain Station Bridge, site S2 located on surficial Tertiary basalt and downstream Merriwa Town, site S1 on Jurassic strata (Figure 8:3). The apparent geological discontinuity between the two sites may represent saline discharge due to the stream incision into the Jurassic siltstones and shales (Figure 8:3) or possibly discharge from a fracture as in the Wybong Creek (Kellett *et al.*, 1989; Creelman, 1994; Biswas, 2010; Jasonsmith, 2011). The salinity increases downstream to Glandore, site S4 but then

remains constant to site S5. Both sites S6 and S5 are located on the Triassic Narrabeen Group (Figure 8:3).

The pH transect in Figure 8:10 shows no abrupt changes. The upstream pH appears dominated by upstream basalts.

8.7 Hydrochemistry

8.7.1 Transect of surface water hydrochemistry

The results of analyses of water samples taken during the December transect of the Merriwa River are shown in Table 8:5, and Figure 8:11.

Table 8:5 Major ions (meq/L) Merriwa transect December 2014

Surface Water (meq/L)	Code	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄
Merriwa Rr @ Mt Station Rd Bridge	S2	1.32	3.13	2.35	0.06	0.28	7.87	2.51	0.07
Merriwa Rr @ Merriwa	S1	1.42	3.50	3.52	0.12	0.23	8.19	4.80	0.08
Merriwa River @Glandore	S4	1.77	3.95	5.22	0.25	0.14	9.01	7.62	0.07
Merriwa River @US Vallance	S5	1.67	3.91	5.22	0.26	0.32	8.19	8.18	0.07
Goulburn River @Kerrabee	S7	1.00	1.93	6.09	0.28	0.01	5.90	6.21	0.37

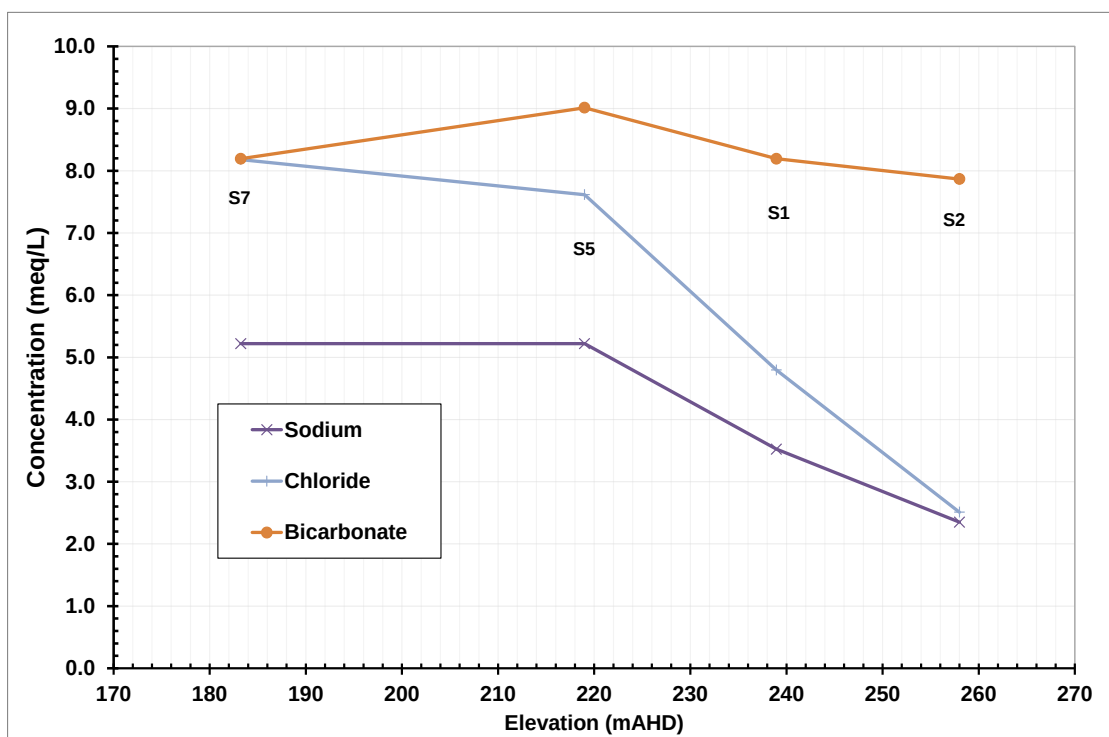


Figure 8:11 Transect of major ions Na, Cl, and HCO_3 in surface water samples from the Merriwa River in the December 2014 survey

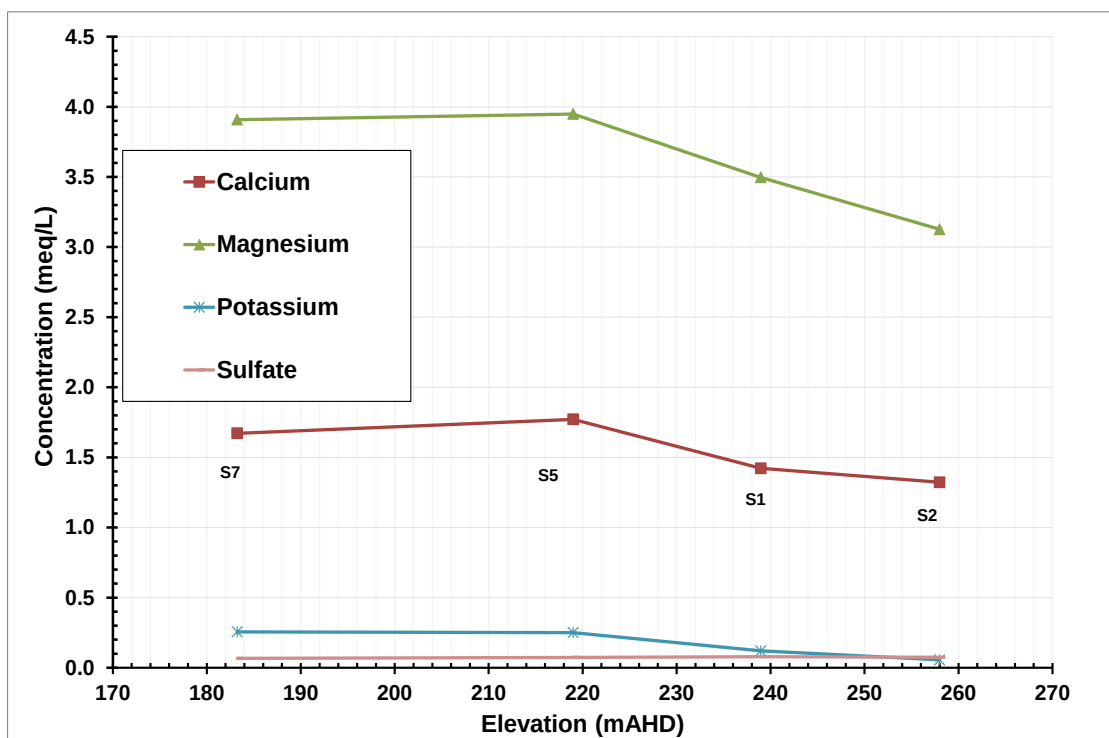


Figure 8:12 Transect of major ions Ca, Mg, K, and SO_4 for surface water samples from the Merriwa River in December 2014 survey

Figure 8:11 shows that increase in salinity in Figure 8:10 is associated with an increase in Cl and Na stream concentration between sites S2 and S1. This coincides with the geological discontinuity at Merriwa with outcropping Jurassic Purlewaugh-Comialla siltstone sedimentary strata displacing the basalt geology (Figure 8:3). Treated town sewage trickle discharged below Merriwa could not have affected stream hydrochemistry at S2 or S1 as the sewage outflow point is further downstream.

There were no major concentrations of SO_4 or K in the Merriwa River transect samples. In the Goulburn, higher concentrations of SO_4 and K were associated with Permian coal measures.

8.7.2 Ion ratios and stream transect

Figure 8:13 plots the ion ratios Na/Cl , $(\text{Na}+\text{K})/\text{Cl}$, $(\text{Ca}+\text{Mg})/\text{Cl}$ and HCO_3/Cl (concentrations in meq/L) of surface waters as a function of elevation in the catchment from the December 2014 transect. The figure shows upstream flows dominated by bicarbonate, magnesium and calcium ions and downstream by sodium and chloride ions. The significance of ion ratios is discussed in section 7.4. Ratios of $\text{Na}/\text{Cl} > 1$ in the upper catchment are normally associated with silicate weathering. The higher ratios of $(\text{Ca}+\text{Mg})/\text{Cl}$ also indicate mineral weathering, particularly in basalts. Na/Cl ratios approaching 1 in the lower catchment suggest that groundwater discharge from Jurassic and Triassic sources are influencing surface water chemistry below Merriwa. It is very clear from these results that mineral weathering and not evapo-concentrated meteoric salt are the source of salinity in the upper catchment.

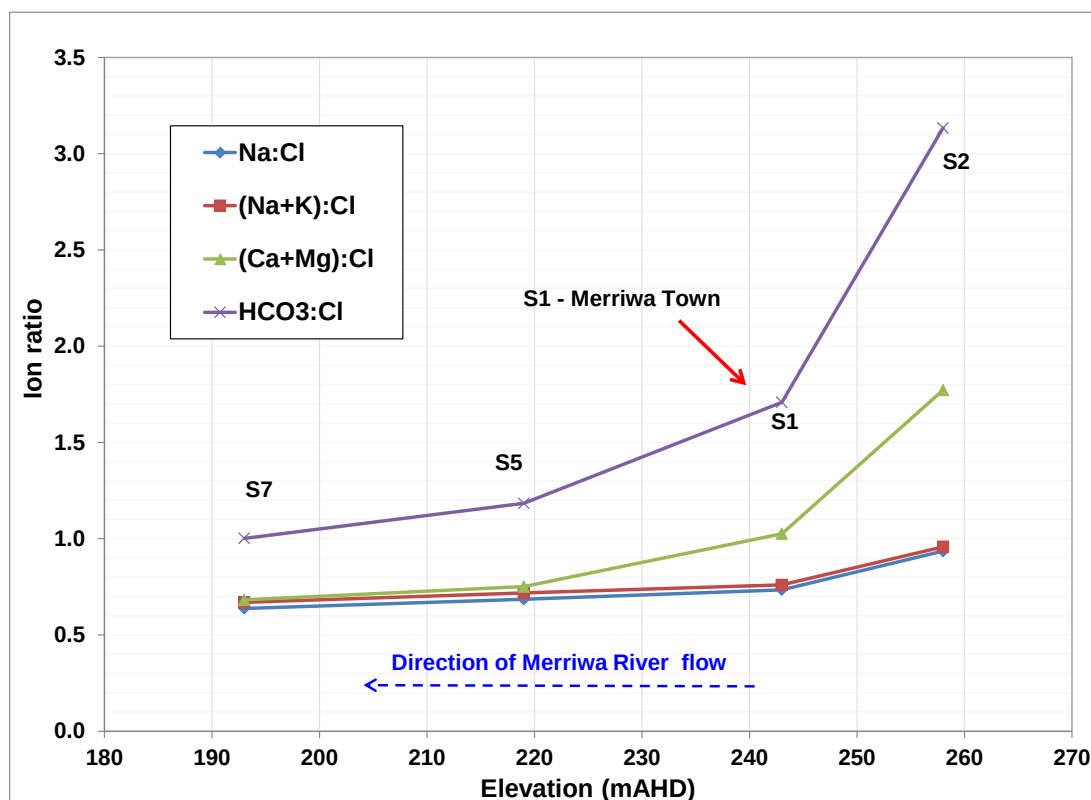


Figure 8:13 Merriwa transect ion ratios Na/Cl , $(\text{Na}+\text{K})/\text{Cl}$, $(\text{Ca}+\text{Mg})/\text{Cl}$, HCO_3/Cl with ion concentrations in meq/L.

8.7.1 Surface water hydrochemistry water types

Hydrochemical characteristics for a total of 24 surface water sites from the upper and lower Goulburn River, Merriwa River and other northern and southern tributaries (see Appendix H Table 1 for details) including 12 samples collected in November-December 2014 were analysed using a trilinear piper plot (Figure 8:15 - % meq/L). Table 8:6 shows hydrochemical data (meq/L) for the 12 samples collected in 2014. The other 12 samples collected in 2012 are in Table 7:1. The relative position of the samples collected in the upper Merriwa River reflects elevated bicarbonate ions (Type M) and magnesium dominance (Type C) associated with the basalt dominated plateau and Liverpool Ranges. These are similar to northern Goulburn River tributaries of Munmurra and Krui. Downstream Merriwa samples plot to-wards the right (Type F) reflecting increasing dominance of chloride ions. Lower Wybong Creek and Wollar Creek flow through incised Permian geology influenced by saline water emanating from the Coal Measures (Jasonsmith, 2011; Biswas, 2010). Permian coal measures are not exposed along the Merriwa River until the confluence with the Goulburn River at Wombat Station (SW16).

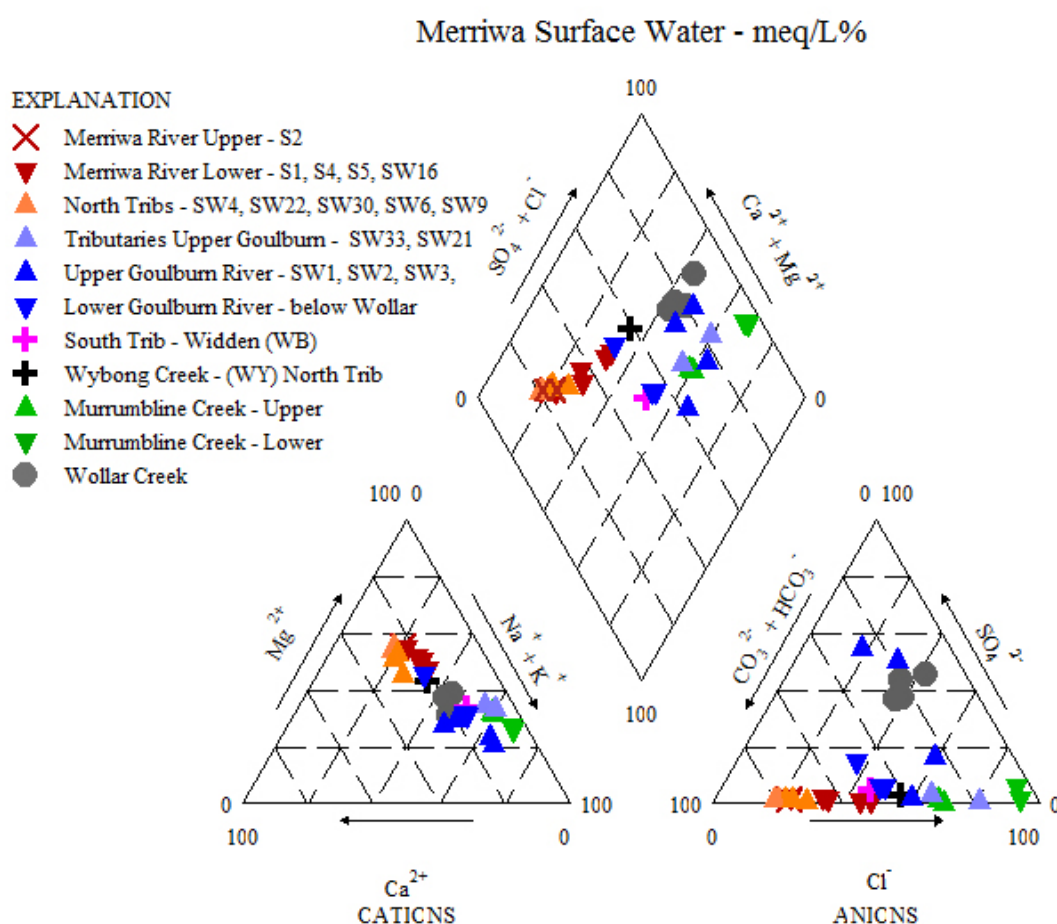


Figure 8:14 Trilinear Piper diagram - surface water samples Merriwa River (meq/L%)

Table 8:6 Surface Water Hydrochemistry (meq/L) sampled 27 November - 2 December 2014, (for previous samples see Table 7:1)

Surface water (mg/L)	Code	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	EC uS/cm	pH	Date 2014
Merriwa Rr @ Mt Station Rd Bridge	S2	1.3	3.1	2.3	0.1	0.3	7.9	2.5	0.1	1026	8.6	2-Dec
Merriwa Rr @ Merriwa (SW10/2)	S1	1.4	3.5	3.5	0.1	0.2	8.2	4.8	0.1	1267	8.5	2-Dec
Merriwa River @Glandore	S4	1.8	3.9	5.2	0.3	0.1	9.0	7.6	0.1	1646	8.4	2-Dec
Merriwa River @US Vallance	S5	1.7	3.9	5.2	0.3	0.3	8.2	8.2	0.1	1640	8.6	2-Dec
Goulburn River @Kerrabee	S7	1.0	1.9	6.1	0.3	0.0	5.9	6.2	0.4	1271	8.2	2-Dec
Kerrabee Creek @Kerrabee	S6	0.9	1.9	6.1	0.3	0.0	5.6	6.2	0.4	1266	7.8	2-Dec
Goulburn Rr @ OBriens X (SW19/2)	S8	1.1	2.4	3.3	0.2	0.1	5.1	3.9	0.8	1030	8.4	2-Dec
Wollar Creek Mogo (SW27/3)	S9	3.0	7.0	16.1	0.2	0.0	4.4	15.5	8.3	3234	7.8	2-Dec
Murrumbidgee Ck @ Turill	SW 32/2	0.7	4.9	24.8	0.2	0.0	2.0	33.9	0.2	3900	7.7	27-Nov
Goulburn River@ Ulan	SW 1/3	0.3	0.5	3.3	0.1	0.0	2.1	3.4	0.0	619	7.7	29-Nov
Curryall Ck @ Ulan Rd Bridge	SW 33/2	0.2	0.9	3.2	0.1	0.0	1.1	4.8	0.0	671	7.3	27-Nov
Goulburn Rr @ Gleniston	SW 3/2	0.9	1.1	3.3	0.3	0.0	2.1	1.5	2.2	807	8.2	1-Dec

8.7.1 Groundwater hydrochemistry

In order to investigate possible groundwater sources of surface water in the Merriwa River a comparative analysis of groundwater chemistry from 20 bores and springs were used in this study (site details see Appendix H –Table 2). This included two additional water samples collected on the 2 December 2014 from Merriwa town water bores (MT1, MT2) (Table 8:7). The following groundwater sample data from Table 7:1 were also used - private Bore (B8 - 27 November 2014) located south east of Merriwa town on a basalt knoll, bore and springs collected previously from the upper catchment - B6 located near Turill (50kms west- probably screened into lower Triassic strata); W34 an alluvial basalt well on the Munmurra River at Cassilis; B7 private well at O'Brien's Crossing on alluvial river flats on the Goulburn River; B5 private bore on the upper Goulburn River at Gleniston and two natural springs (The Drip GDE

SP22 and Comialla Spring SP24). Data from six groundwater monitoring bores representing specific geological strata contained in UCML and Moolarben Coal Mines environmental reports were also included. The total dataset comprised 20 samples with hydrochemistry for 15 sites. Four DPI Water monitoring sites situated in Merriwa provided online data of standing water levels, temperature and salinity since October 2014 but no water chemistry was available at the time of the study.

The Trilinear piper diagram (Figure 8:16) displays the distribution of major ions. Merriwa town groundwater bores MT1, MT2 and B8 lie remote from Jurassic groundwater samples (on the right side of the graph Type O/B – Na(K)HCO₃ dominance. This supports the likelihood that this high value groundwater resource may be associated more closely with lower Triassic and Upper Permian than Jurassic Purlewaugh-Comialla siltstones or Pilliga sandstones.

Table 8:7 Groundwater hydrochemistry Merriwa Sites (meq/L) 2 December 2014

Groundwater (meq/L)	Site	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	EC uS/cm	pH
Merriwa Town GW062053	MT2	0.77	0.66	4.18	1.33	0.01	6.23	2.26	0.02	861	6.7
Merriwa Town GW042918	MT1	0.72	0.70	4.13	1.28	0.01	6.23	2.31	0.00	883	7.3

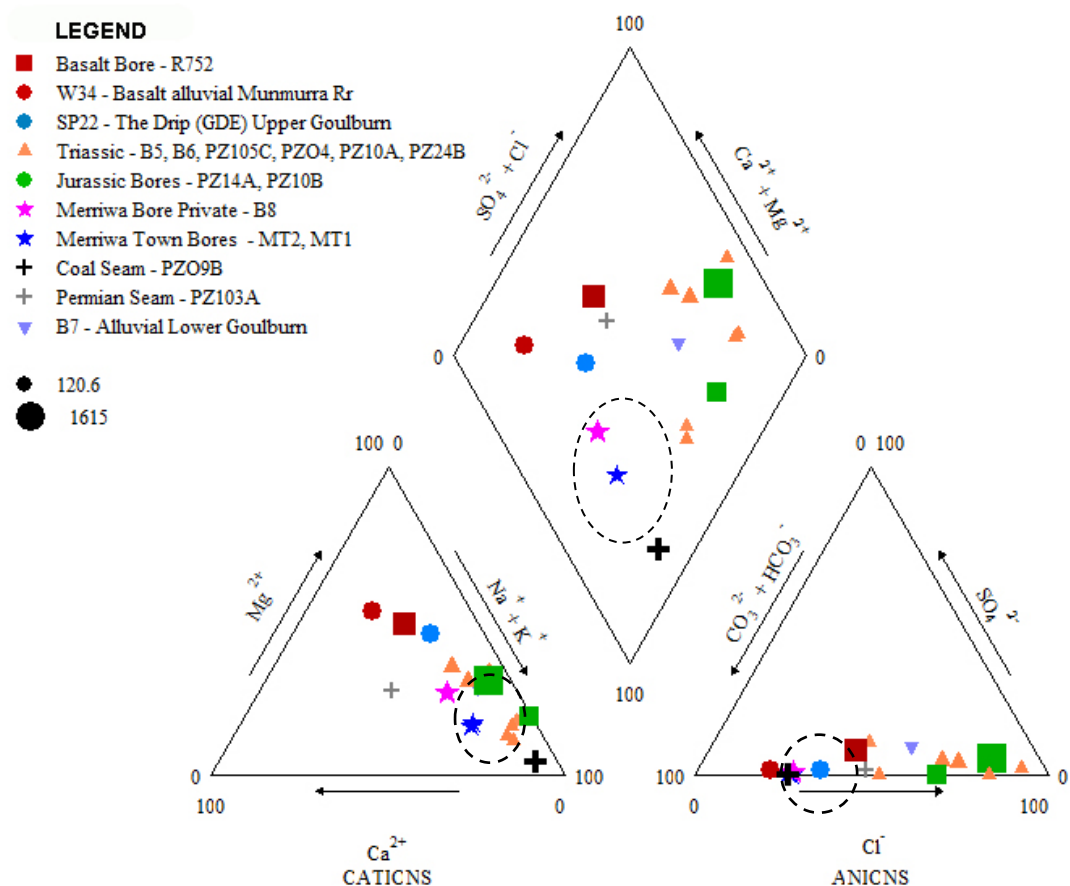


Figure 8:15 Trilinear Piper diagram of groundwater (meq/L%) comparing Merriwa groundwater samples with other groundwater sites in the Goulburn

8.8 Groundwater hydraulic gradient

Figure 8:16 represents a conceptual geological cross-section with relative depths of the Merriwa Town bores MT3, MT16 and the bore B8 overlaid on the Singleton Map Sheet (Rasmus et al., 1969). The transect passes from the north-west to south-east approximately 3.8 kilometres south of Merriwa. The Tertiary basalt and Jurassic sedimentary geology is shown as relatively narrow, underlain by significant Triassic Narrabeen Group sedimentary strata. The relative dip of Permian and Triassic strata according to coal exploration data at Ulan indicate the Permian Illawarra coal reserves (and associated regional groundwater system) has a 1-2 degree dip to-towards the north-east from the Ulan-Wollar Coal fields. The relative depth of these bores locates them within the Triassic sandstone water bearing zone, at a much deeper stratigraphic position than the Jurassic strata from the Oxley Basin.

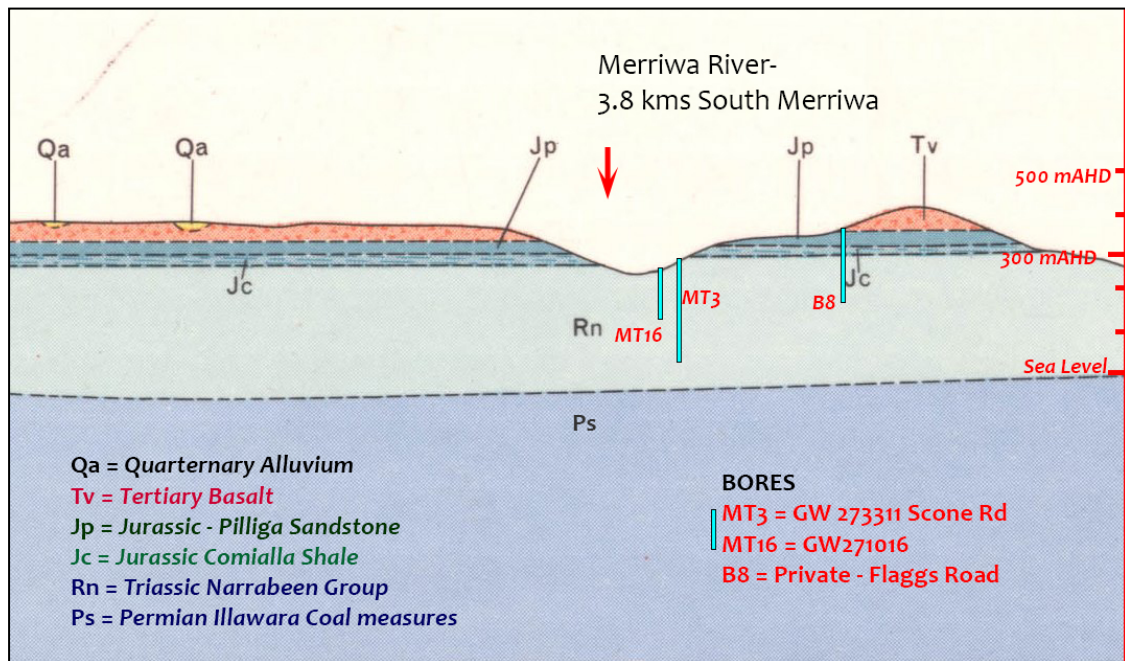


Figure 8:16 Conceptual geological CS – 3.8 kms south of Merriwa (Rasmus et al., 1969)

Appendix H (Table 2) provides details for the monitoring bores at Merriwa. Continuous data for standing water levels (SWL), salinity (EC) and temperature were accessible online for two DPI Water monitoring bores located on the Scone Road, Merriwa. Bore GW273311 (MT3) and GW080930 (MT3b). These were drilled through Tertiary basalt into underlining sedimentary strata and screened at different depths. The drillers log for MT3 indicates a basalt top layer greater than 100 metres thick (to 175 mAHD); a mudstone layer 48 metres thick (175-127 mAHD); a sandstone-shale band of 6 metres (127-120 mAHD); and a sandstone bottom layer of 89 metres (120-38 mAHD) (Figure 8:18). The main water bearing zone was screened into this bottom sandstone layer at a depth of 213-235m below the surface (55-40 mAHD). This is within the lower Triassic strata overlying the Permian and well below the Purlewaugh-Comialla shales. The standing water level (SWL) for MT3 was closer to the surface at a depth of 40-51 metres (220-235 mAHD). The standing water level of the shallower MT3b was 21 metres from the surface (252 mAHD). Two other DPI Water monitoring bores located in Merriwa Town MT15 and MT16 (GW271015, GW271016) provide additional information. The drillers log for GW271015 had the water bearing zone at depth 128-129 m (123 mAHD) within banded sandstone-shale.

Figure 8:18 illustrates stratigraphic logs, water bearing zones (WBZ), screen height and standing water levels (SWLs) for the five bores at Merriwa compared to the Merriwa River GS210091 (base 239.14-240.03 mAHD). Bores are screened at various levels; the most productive lower groundwater source (14-17 L/s) lies at a depth placing it within the Triassic sandstone water bearing zone. MT1, MT2, MT15 and MT16 coincide with Merriwa river levels (above 239 mAHD). This suggests a hydraulic gradient direction towards the river and possible

interaction with surface flows – recharge or discharge, though SWLs could be co-incidental with other factors related to overburden confining pressure.

The elevated hydraulic head of the groundwater sourced by these bores indicate a semi-confined aquifer. Lithostatic pressure of the overburden would also increase aquifer pore pressure. The significant reduction in downstream flow in the lower reaches of the Merriwa River below Merriwa town on an annual basis suggests active stream bed leakage or water extraction. The River could be a losing river with surface-groundwater interaction. It is possible the river is contributing to underlying groundwater storage via fractures or faulting.

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8.8.1 Groundwater levels and rainfall

The time lag between rainfall events and groundwater recharge was investigated by comparing groundwater levels in monitoring bores to nearby rainfall records at Terragong (Table 8:9). Data from DPI monitoring bores MT16 and MT15 (Table 8:8) were used to estimate the most likely time lag between rainfall and resulting groundwater recharge.

Table 8:8 Climate Stations Details (Rainfall) near Merriwa

Station	Site No.	Kms - Merriwa	Elevation mAHD	Period	Lat.	Lon:
Terragong	61073	6.1	274	1890-2015	-32.08	150.37
Mar-lea	61316	13	396	1972-2014	-32.07	150.23°
Roscommon	61287	17.6	375	1969-2014	-32.19	150.17°
Gumnum (closed)	61040	1.2	260	1882-2011	-32.138	150.37°

Figure 8:19 for monitoring bore MT16 compares six years of average monthly water level data from April 2010 to February 2016 against cumulative rainfall over different periods. The correlation R^2 coefficients were calculated by comparing the average monthly groundwater levels to 3, 12, 24, 30, 36 and 40 cumulative monthly rainfall totals. The 24 and 36 month recharge lag time shows the greatest correlation with changes to groundwater levels with R^2 equal to 0.68 and 0.77 respectively. Figure 8:20 shows the close correlation between the average monthly SWLs and cumulative monthly rainfalls over 24 and 36 months.

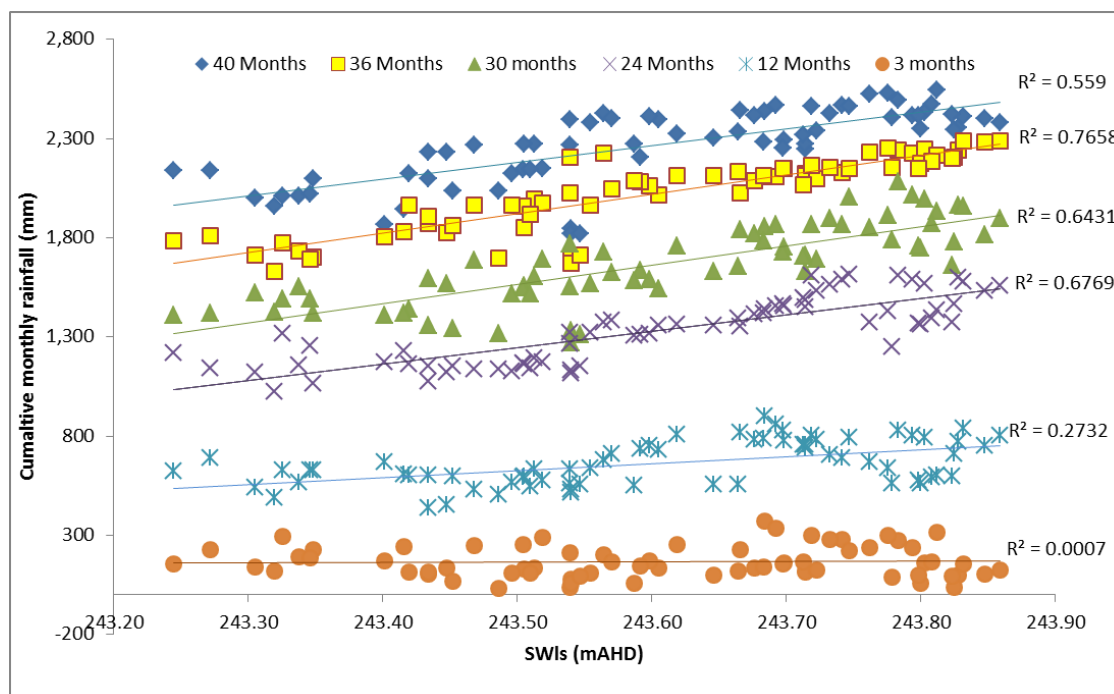


Figure 8:18 Correlation MT16 groundwater levels and cumulative rainfall (3 – 40 months) for the period 2010-2016

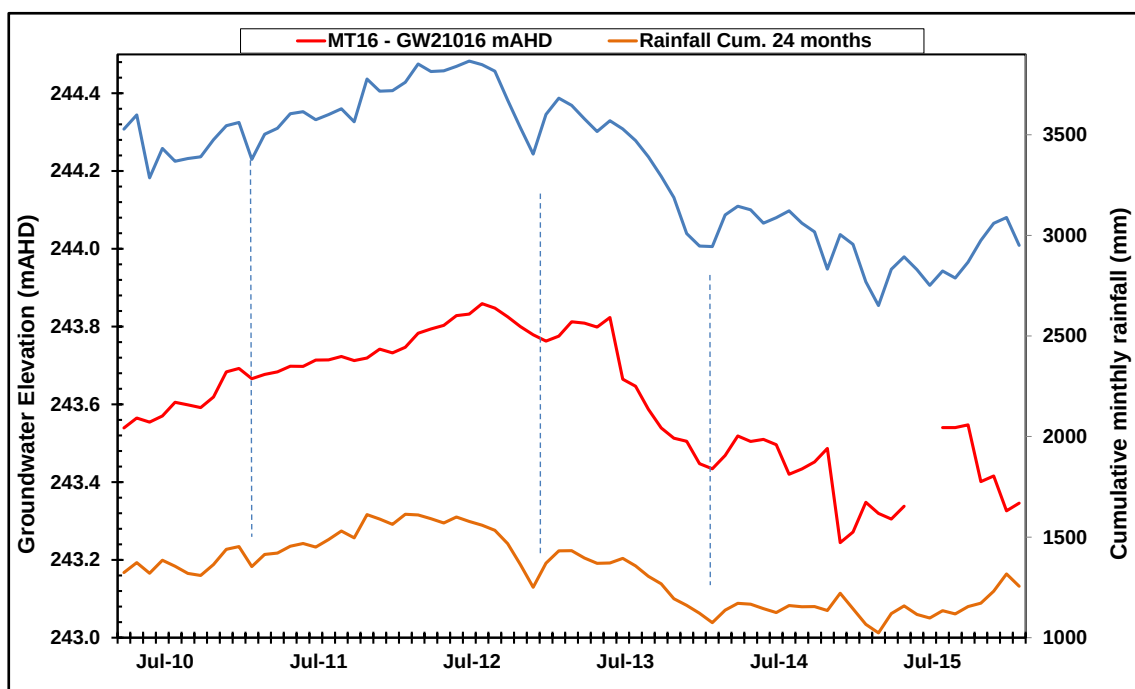


Figure 8:19 MT16 groundwater hydrograph (mAHD) with 24 month and 36 cumulative monthly rainfall (mm) 2010-2016

Figure 8:20 indicates an active recharge regime and an interaction between surface and deep groundwater sources with a rainfall-recharge response for deep groundwater bores of around 24-36 months. Ongoing monitoring and investigation of groundwater sites and further hydrochemical analysis is recommended to confirm these observations and improve our understanding of the interaction between surface and deeper groundwater sources in the Merriwa catchment.

8.9 Conclusion

The aim of this chapter was to investigate the catchment yield, salinity, and surface-groundwater interactions of a cleared, agricultural sub-catchment of the Goulburn River. The Merriwa River is a major tributary of the Goulburn River. It has not been studied in any detail despite its significant impact on the Goulburn River (see 5.1.1 and 7.3.2). The geology of the catchment reveals that the River is sourced in Tertiary basalts and then intersects Jurassic sediments and cuts across Triassic strata before being exposed to Permian Coal measures as it enters the Goulburn.

The basalt-derived soils support cropping, irrigation and grazing and groundwater is extensively used for both agriculture and townships in addition to abstraction of surface water. While there are two river gauging stations in the catchment their relatively sparse and shorter stream discharge records together with wide flow variability make identifying trends impossible. The data is sufficient, however, to show that the long-term runoff from the catchment is about 4.5% of mean annual rainfall, higher than the more forested whole Goulburn catchment.

Comparison of the two gauging stations for annual stream flow showed strong correlation between the two stations; however the lower station had annual flows that were consistently only 78% of the upstream gauging station flows. This suggests possible transmission or extraction losses below the town of Merriwa.

For the Goulburn catchment, the salinity record is relatively long, dating back to 2003, during the millennium drought. Annual average stream salinities have always exceeded the HRSTS 900 EC limit and the intimate relationship between EC and stream discharge points to a high baseflow source of salinity, at low flows. This means that maintaining River surface flow ensures lower stream salinity. The salinity data revealed that the Merriwa catchments specific salt yield was 20 tonnes/km²/year. This shows that the Merriwa is a more important significant source of salt than Wybong Creek. The abstraction of higher quality water through water allocation licences therefore has a significant effect on water quality in the Goulburn River. Since the estimated allocation in the Merriwa catchment, about 8 mm/year, is the same as in the Goulburn catchment, no allowance has been made in water allocation for the higher salinity yield of the Merriwa catchment.

A transect of the Merriwa River during a dry period revealed increasing salinity downstream. The water geochemistry revealed a transition between the Tertiary basalt derived bicarbonate water in the upper catchment and NaCl dominant water in the lower catchment. This transition occurred where the River incised into Jurassic sediments most likely derived from Purlewaugh-Comialla siltstone strata which produce NaCl dominant waters. The main contributor of solutes to streamflow and groundwater in the Merriwa River is from mineral weathering.

Important potable groundwater sources appear to have a closer association with the underlying Triassic regional groundwater system than the previously thought Jurassic hydrological units. The prevailing assumption that accessible high-quality groundwater is derived from the Jurassic geology or the Oxley Basin is not supported by evidence, rather it is more likely to be from a lower Triassic - upper Permian hydrogeological source. In addition, the hydraulic gradient towards the river and the significant change in hydrochemistry at Merriwa suggests the possibility of surface-groundwater interaction and or connectivity via faults or fractures requiring further research.

The Merriwa town water supply, irrigators and an unquantified number of private household and stock bores depend on alluvial and deep groundwater resources to sustain water supplies throughout the year. The research based on analysis of flow gauging, hydraulic head and water quality indicates an active recharge regime and interaction between surface and deep groundwater sources with a rainfall-recharge response for deep groundwater bores of 24-36 months. Ongoing monitoring and investigation of groundwater sites and further hydrochemical

analysis is recommended to confirm these observations and improve our understanding of the interaction between surface and groundwater sources.

Water management is the key to managing salinity in this catchment. The intimate relation between stream salinity and stream discharge means that granting additional water licences, failing to regulate water use in the catchment, or decreasing rainfall or increasing evaporation will increase salinity discharged into the Goulburn from the Merriwa River.

Chapter 9: The Drip gorge - groundwater dependent ecosystem

Groundwater-dependent ecosystems have not been mapped in the Goulburn River (section 3.4.1). The aims of this chapter are to identify sources of groundwater feeding an important groundwater-dependent ecosystem (GDE) in the upper Goulburn and to investigate the impact of groundwater extraction and aquifer depressurisation due to mining on the GDE and river baseflow.

In Chapter 2 the importance of GDEs to river health and management (Kalbus *et al.*, 2006) was discussed and in Chapter 6, the extraction of groundwater to enable mining was examined. The Drip gorge is an important GDE in the upper Goulburn which lies less than 2 km from the closest mined area. This chapter provides information on the GDE and surrounding area and investigates the potential groundwater sources that support The Drip GDE. An analysis of hydrochemical characteristics and hydraulic properties of neighbouring creeks, groundwater bores, local springs and GDEs with The Drip groundwater hydrochemical signature is carried out to identify potential hydrogeological sources.

A conceptual model and a two-dimensional (2D) numerical model are used to demonstrate surface and groundwater interactions. The conceptual model uses a known geological cross-section to illustrate groundwater gradient and flow direction based on topographical and hydrogeological data sourced from bore log and industry piezometric records. The 2D model is used to investigate the potential groundwater impacts from an approved but not commenced underground mine 500 metres to the south of The Drip gorge over a 40 year period using a range of assumed hydraulic parameters for the geologic strata. A comparison is made with model predictions using hydraulic properties assumed by the mining industry.

9.1 *Characteristics*

The Drip gorge is an extensive perennial spring that seeps from a multilayered sandstone cliff abutting the upper Goulburn River north-east of Ulan, Hunter Valley New South Wales (Figure 9:1). The seeping cliff face forms a potential window into the relationship between the groundwater system and source of baseflows to the river.

The study area covers approximately 135 square kilometres in the upper reaches of the Goulburn River on the eastern side of the Great Dividing Range (altitude 370 - 560 m AHD) (Figure 9:2). The Drip gorge GDE is 12 kilometres downstream from the confluence of the Moolarben and Sportsman Hollow Creeks at Ulan - where the Goulburn River begins (Latitude 32.21260, Longitude 149.798817). The area is located at the most north-western lip of the Sydney Sedimentary basin where the Tertiary basalt intrusions of the Liverpool ranges overlap Jurassic and Triassic strata and the underlying Permian Illawarra Coal Measures. The Goulburn

River in the vicinity of The Drip is regarded as a ‘gaining’ river section (Middlemis and Fulton, 2011; MER, 2015).

The Drip, Corner gorge and associated escarpments of the Goulburn River were listed by the National Trust (NSW) as a significant heritage and conservation landscape in August 2013. The Drip gorge and surrounding 20 hectares were incorporated into the Goulburn River National Park in March 2015. The area, including the nearby “Hands on Rock” aboriginal art site is regarded as culturally significant by the Wiradjuri people with relics dated to 5800 BC (Moore, 1970). Its European heritage is demonstrated in historic photos taken in the early 1900s of a group of picnickers at The Drip – (Raisin Collection - Figure 9:3) (Burge *et al.*, 2013). The Drip gorge is not currently listed on the National Atlas of GDEs (section 3.4.1).

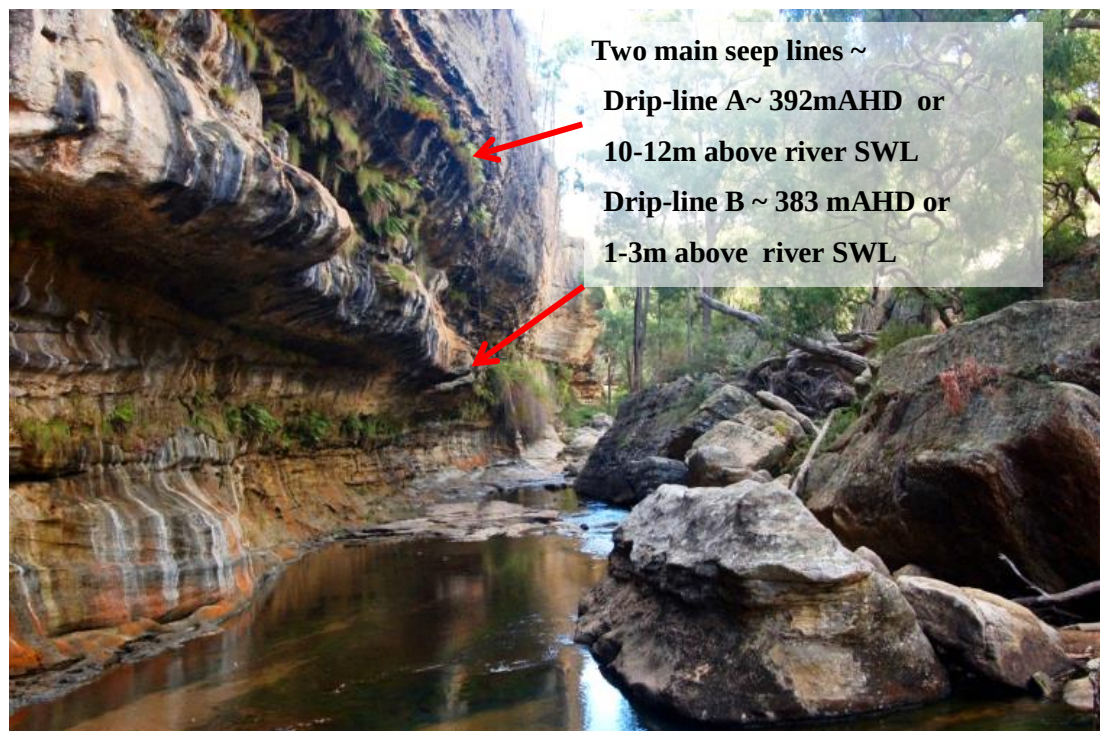


Figure 9:1 The Drip gorge – looking east

9.2 Climate, rainfall and recharge

The upper Goulburn has an inland temperate climate. The closest Bureau of Meteorology (BoM) climate monitoring station is at Ulan Post Office (Station No. 062036) 12 kilometres to the south-west (BoM, 2018b). Mean annual rainfall for Ulan is 672mm (1961 to 1990) (BoM, 2018b) and the interpolated spatially averaged catchment rainfall is 675mm for the upper Goulburn (1920-2014) while the annual interpolated Epan for the upper Goulburn catchment 1970 to 2014 was estimated at 1574 mm (Table 4:1, Table 4:2). The general groundwater recharge rate for porous and fractured rock groundwater sources in the Hunter is estimated to be 5-7% for Triassic and 1% for Permian groundwater (Ross and Webb, 2015; Pearse – Hawkins *et al.*, 2015).

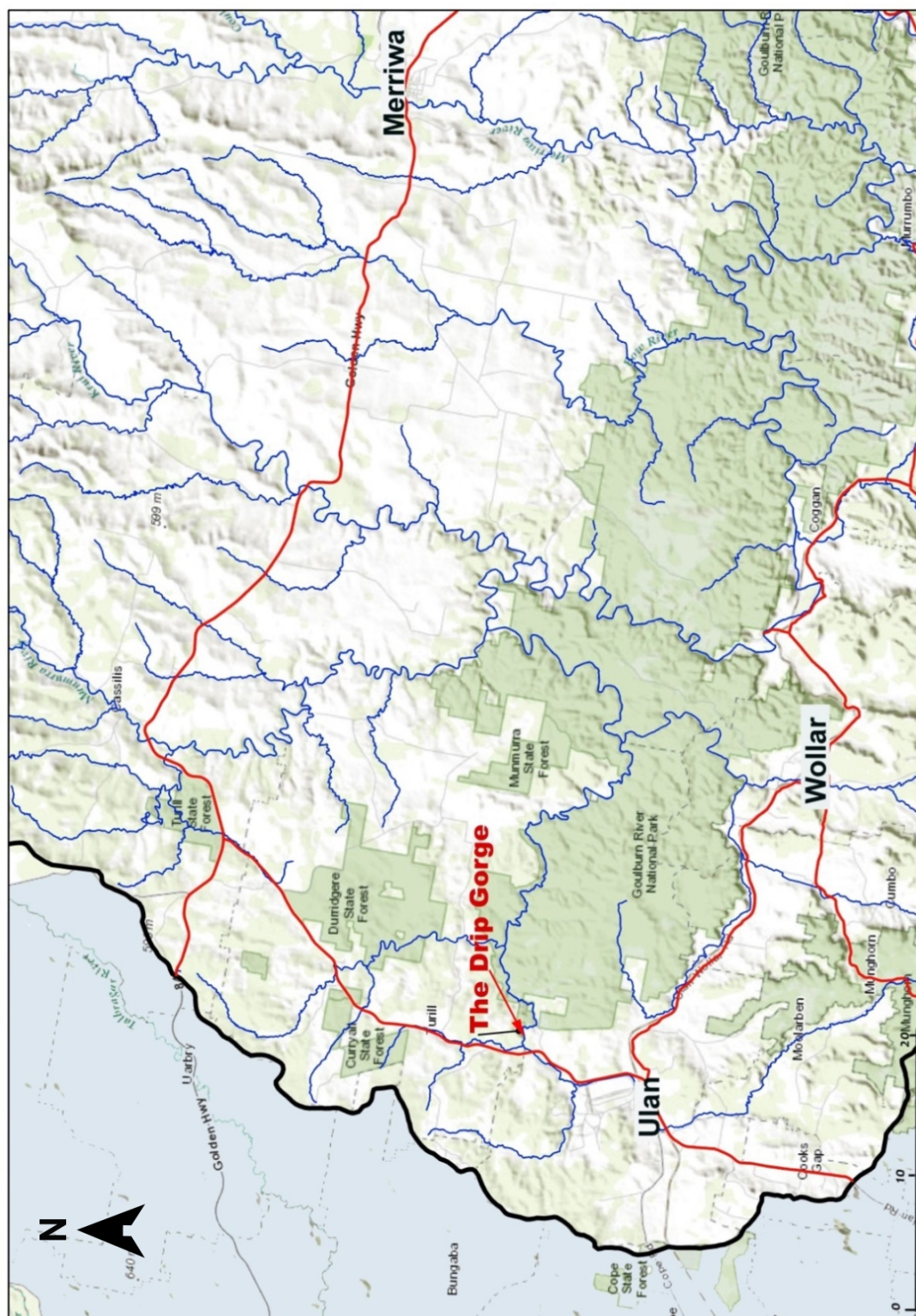


Figure 9:2 Location of 'The Drip Gorge' - Goulburn River Catchment Map
 Source: adapted from datasets Geoscience-Australia (2013)

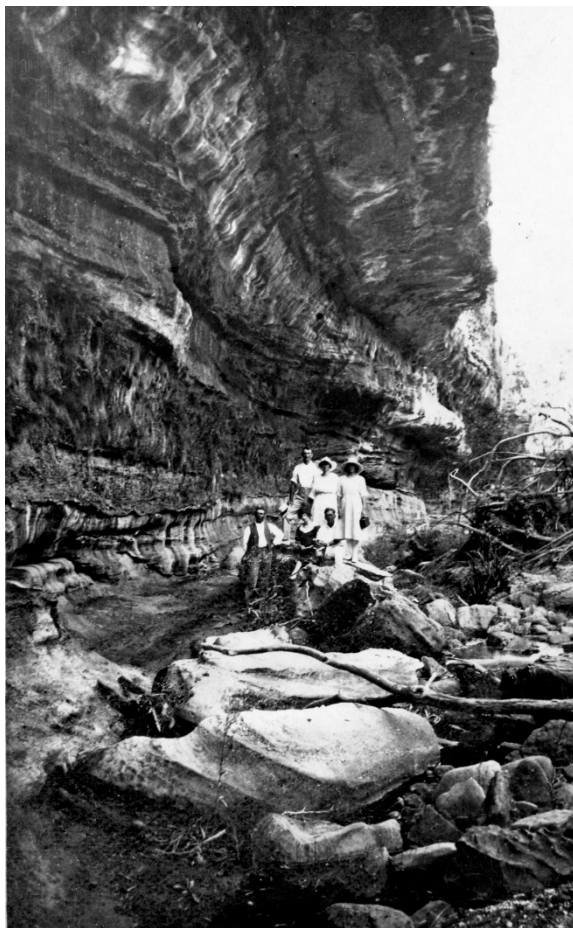


Figure 9:3 Historic photos of The Drip (western end) - Raisin Collection courtesy: Gulgong Pioneers Museum (early 20thC~1915). Illustrate the presence of tree ferns in the foreground and the range extension water dependent species *Cladium procerum* on the cliff face

9.2.1 Water sampling and rainfall

Water samples from The Drip seep were collected after an extended period of dry weather to minimise the influence of surface rainfall runoff and shallow vadose seepage on the hydrochemical characteristics of the groundwater. The annual rainfall at a local surface water monitoring site Gleniston²⁹ (21010017) three kilometres downstream from The Drip Gorge was 642mm in 2011; 618mm in 2012; 488 mm in 2013 and 577 mm in 2014, all below the long term mean annual spatially interpolated rainfall 675mm in the upper Goulburn (Section 4.1). Table 9:1 shows prior rainfall recorded at Gleniston 10 and 30 days prior to sampling plus 3 month and 12 month percentiles of interpolated rainfall for the upper Goulburn confirming sampling was during a predominantly low rainfall period.

Table 9:1 Prior rainfall 10 days, 30 days & total of 3 months at Gleniston (21010017) plus upper Goulburn interpolated rainfall percentiles for prior 3 & 12 month periods

Drip SP22 Sample Date	Prior rainfall (mm)			Long Term 3 monthly mean (mm)	Upper Goulburn rainfall percentile (interpolated)	
	10 days	30 days	3 month		3 month	12 month
17-Oct-12	4	30.0	54.5	143.8	0.04	0.7
06-Nov-12	0	7.5	52.5	156.8	0.07	0.4
30-Apr-13	0	5.5	121	161.5	0.6	0.3
15-Sep-13	0	2.0	35.5	136.4	0.1	0.3
16-Jan-14	12	34.5	98.5	70.2	0.4	0.2

9.3 Landscape of the study site

The landscape around the GDE ranges from sandstone escarpments along the river corridor, interspersed with ironstone capped pagodas and sandstone ridges supporting dry sclerophyll vegetation grading to grassy box woodlands on remnant basalt hills dominating the top of the range. There are numerous springs and seeps slowly discharging good quality groundwater to surface streams in this catchment. Springs commonly discharge from rocky sandstone outcrops into the headwaters of minor creeks and gullies as well as directly into the sandy bed of the Goulburn River as evidenced by the indicative iron staining (Macdonald *et al.*, 2009a; Realica-Turner, 2003). While many are ephemeral and directly rainfall driven, some are permanent drought resilient water sources. These groundwater sources support a range of ferns, remnant dry rainforest, and a range of other riparian species including range extensions. The springs also provide a permanent freshwater source for domestic farm use in the Moolarben Valley (SP01, SP04, SP05) and in the uplands of Wollar Creek and the Turill area (Figure 7:1, Figure 9:5, Appendix C).

The main focus of this study is the catchment to the north of the river above The Drip, and immediately to the south, from the river bed to the top of the Great Dividing Range (560

²⁹ Goulburn River @ Gleniston - Site 21010017 (DPI Water, 2018) collected by Author

mAHD). The Drip GDE feature is a south facing, 300m wide monumental undercut sandstone cliff towering approximately 35 metres above an ironstone platform forming the bed of the Goulburn River. Horizontal bedding planes interspersed with impermeable ironstone layers seep groundwater that support weeping grasses, ferns, bottlebrushes, mat-rushes and sedges. Including the weeping sedge species *Cladium procerum* a significant range extension found normally in coastal wetlands (Wilson, July 2009).

9.3.1 Geology

Five main geological strata outcrop in a predominantly north-south pattern in the Goulburn River catchment (Figure 3:6) (Kellett *et al.*, 1989; Rasmus *et al.*, 1969; Yoo *et al.*, 1995; Watkins *et al.*, 1999; Meakin and Morgan, 1999; Johnstone, 2008; Creelman, 1994; Geoscience-Australia, 2013) (see section 3.2 and Figure 3:6).

- Tertiary volcanic basic olivine basalts cap the topographic highs immediately to the north of The Drip, including a series of volcanic intrusions.
- Jurassic sediments underlay the basalts, outcropping in the north and west. Pilliga sandstone strata are well sorted medium to very coarse grained, Purlewaugh siltstone form interbeds of mudstone and coal.
- Triassic Wollar Narrabeen Group quartz and lithic sandstones and conglomerates form the dramatic sandstone escarpments, cliffs and gorges of the Goulburn River. The massive sandstone strata have strong vertical jointing and sub-horizontal bedding planes interspersed with hard ironstone layers and occasional pagodas. Both the Triassic and Permian strata underlay the northern catchment dipping 1-2° in a north-easterly direction.
- Permian strata which include the Illawarra Coal Measures are exposed in the deeply incised weathered valleys and alluvial flats of the southern catchment dipping to the north-east situated at about 190 m below the river channel and The Drip gorge.
- Carboniferous granites form the basement rocks with only a minor outcrop on the south western lip of the catchment outside this study area.

The stratigraphy and land forms surrounding The Drip gorge are influenced by these geological components. Remnant Tertiary basalt flows cap the hills approximately two kilometres to the north of the Drip, including a series of plugs and sill intrusions and fault lines (Figure 9:4). Underlying Jurassic strata outcrop in a halo around the edge of the basalt extending to the Triassic sandstones that form the cliff-lines and escarpments closer to the river, hedged by iron-capped pagoda formations. There is an ironstone platform over 300 metres long that forms a massive water worn rock layer at the foot of The Drip gorge cliff-face. The Drip sandstone cliff face appears to be due to massive offset of an east west vertical-joint or fracture approximately 26-33 metres in height. Deep alluvial sands interspersed with Quaternary to Holocene peat beds make up the meandering bed of the river. Metamorphic and granitic rocks of

the Lachlan Fold Belt lie to the south-west. Based on their depth below ground level, the underlying Carboniferous and Permian geology are unlikely to have any direct connection with the groundwater seepage at the Drip, though contribute baseflows upstream to the creeks and river in the south and west (MER, 2011; Middlemis and Fulton, 2011) .

9.3.2 Faults and fractures

There are three known faults that dissect the area to the north of Goulburn River; the Spring Gully fault in the north-east, and the Curra and the Curryall fault lines to the north-west (Figure 9:4). Testing carried out by UCML consultants in 2005 concluded that the Spring Gully fault located on the eastern boundary of the underground mine, trending north south with an 8 metre displacement, was not a significant barrier or impediment to groundwater flow. This was supported by declining piezometric levels on both sides of the fault line linked to mine depressurisation (MER, 2011). Information on the other two fault lines is limited. Curra Creek fault is located immediately adjacent to volcanic intrusions that display a high magnetic intensity, thought to be volcanic plug or sill (Johnstone, 2008). These structures can enhance groundwater storage due to fracturing, displacement or coal seam cindering (Middlemis and Fulton, 2011; Kellett *et al.*, 1989; Cook, 2003).

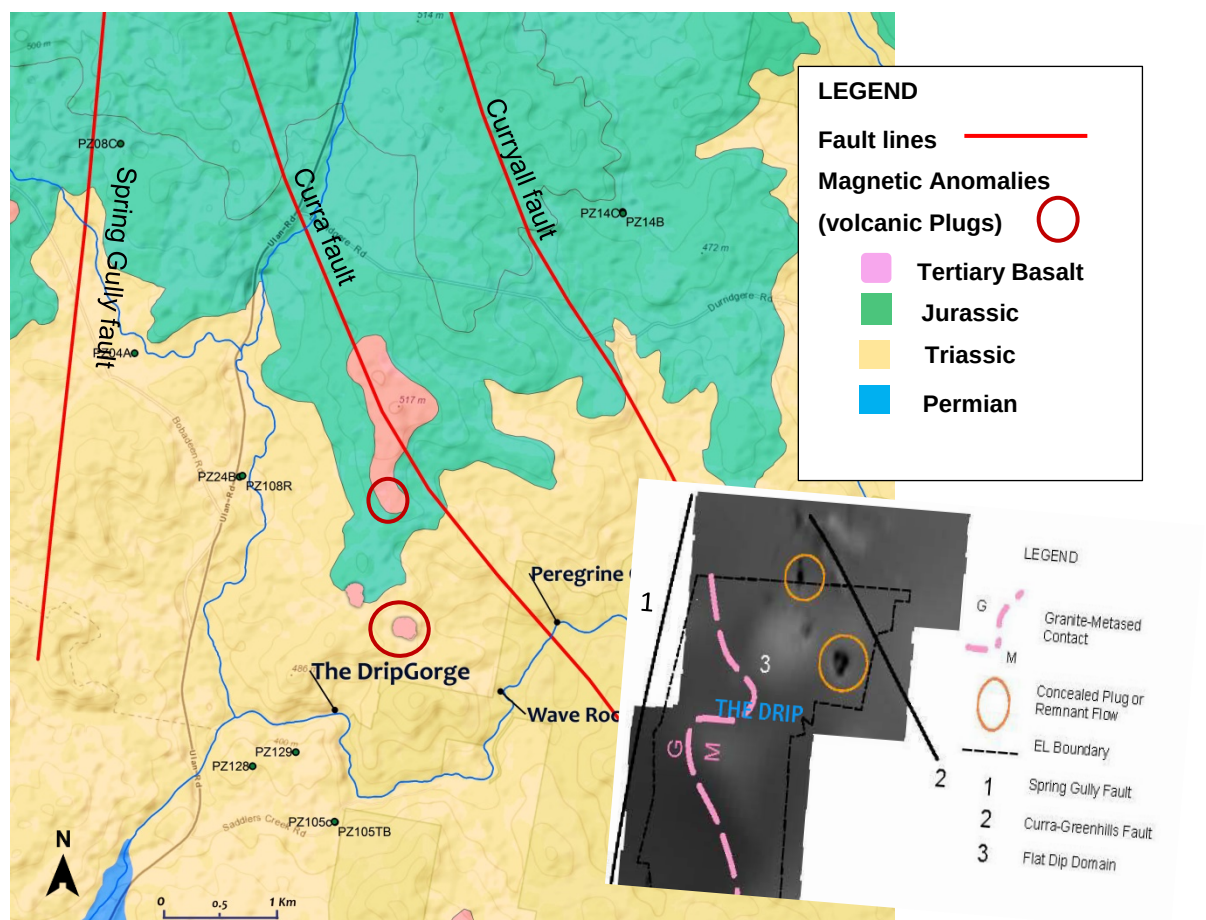


Figure 9:4 Surface geology showing fault lines and magnetic anomalies in the vicinity of The Drip gorge (Geoscience-Australia, 2013; Johnstone, 2008)

Fault zones can either aid transmissivity or form a barrier to flow. Volcanic plugs potentially increase groundwater storage due to fracturing and can also impede and force groundwater flows up dip (Jasonsmith *et al.*, 2011a; White *et al.*, 2009; Cook, 2003). Vertical jointing typical of Triassic Narrabeen Group geology provides potential connectivity between underlying strata and associated aquifers facilitating recharge and vertical mixing of groundwater (Biswas, 2010). The important major hydrogeological structures in the Hunter region include a series of meridional faults with numerous associated cross-faults (Kellett *et al.*, 1989). Kellett *et al.* (1989) concluded that, while on a regional scale the fractured-rock aquifers constituted a minor proportion of groundwater storage, groundwater transmission became of critical importance during periods of low flow in the region. The largest groundwater velocities were found in the fractured-rock aquifers of Narrabeen Group and Carboniferous rocks due to larger hydraulic gradients minimising the limiting effects of lower permeability.

9.3.3 Groundwater sources and potential flow paths

Six main hydro-geological units in the Upper Goulburn Catchment have been identified (see section 3.3) (Kellett *et al.*, 1989; Nicholson *et al.*, 2014; Yoo *et al.*, 1995; Johnstone, 2008; Mackie, 2009)

- Alluvial aquifers composed of quaternary silts, sands and gravels along the main river bed and associated alluvial flats.
- Localised fractured rock aquifers in the Tertiary basalts that cap and intrude through higher topography. They generally form Ca, Mg and HCO₃ Type water.
- Jurassic sediments of the Purlewaugh siltstone and Pilliga sandstones associated with the Oxley Basin. These interbedded layers of mudstone, siltstone and fine grained sandstone with carbonaceous fragments and iron staining produce generally quite saline water. Herczeg and Love (2007) found the chemical composition of the Pilliga sandstone aquifer in the South Eastern portion of the Great Artesian Basin (GAB) a Na,HCO₃, Cl type water.
- Triassic sandstones of the Narrabeen Group include local and regional porous and fractured rock aquifers. Triassic sandstones have not been regarded as a significant groundwater source; however they represent an extensive, good quality regional groundwater store by virtue of their porosity, uniformity and hydraulic conductivity with yields measured by UCML at 5.25 L/s (UCML, 2004a). The upper Triassic strata produces NaCl Type water, pH 5-7; while the lower Triassic groundwater is more Na, HCO₃ type water with a higher pH 7-8. This may indicate interaction with Tertiary basalts or interlayered Mesozoic volcanic deposits (Creelman, 1994; MER, 2015). Groundwater quality in these is generally good with total dissolved solids less than 600 mg/L, though may contain elevated iron levels.

- Groundwater associated with the cleats and fractures within the Permian Illawarra Coal Measures is more saline than the overlying Triassic geology. Permian strata generally have low primary porosity due to the fine grained, consolidated nature. Water storage is associated with secondary faults and fractures in the joints, cleats and bedding planes of coal bearing strata which can form significant but low quality aquifers. The geochemistry of Permian water tends to be highly variable depending on location, depth and disturbance of strata.
- Fractured rock groundwater associated with the underlying basement granites of Central-West Fold belt discharge to the surface in the Cooks Gap, Ulan area at Ryans Creek well to the south-west corner of the catchment.

There are clearly multiple groundwater flow paths discharging and providing baseflows as seeps and springs along the Goulburn River. A characteristic red staining of the sandy river bed due to iron precipitation is evidence of diffuse groundwater discharge (Macdonald *et al.*, 2009a; Somerville *et al.*, 2005). Surficial or perched groundwater bodies are likely to have hydrochemical characteristics closer to rainwater together with solutes accumulated from infiltration through the regolith and local geology (Winter *et al.*, 1998). Intermediate groundwater systems recharge across diverse formations and geologies. Regional groundwater systems recharge from topographic highs on the catchment divide and have long flow paths that discharge toward major topographic lows or valley bottoms. The longer flow path and residency time is likely to produce a high level of mineralisation and ion exchange due to extended contact and interaction with geological strata (Fetter, 2001; Freeze and Cherry, 1979).

Green *et al.* (2010) developed a model of the aquifer framework for the multilayered sandstone aquifers of the neighbouring Sydney Basin, in the Blue Mountains. They indicated shallow and intermediate aquifers were critical to springs, GDEs and stream baseflow particularly in the upper plateau riverine areas. The Hawkesbury sandstones were predominantly medium to coarse grained with secondary porosity characteristics evident in the deeper intermediate aquifers due to structural movements and faulting. Surficial or shallow aquifers had a low pH (~4.6) with the major ions exhibiting NaCl type water with cyclic salt influence. Deeper 'intermediate' groundwater systems were also NaCl type with a higher average pH due to an increasing bicarbonate, magnesium and ferrous iron, consistent with water-rock interaction. The deepest intermediate aquifers tended towards CaHCO₃ type groundwater.

Aquifers can form in the soft relatively porous sandstone from the weathering and water movement within the sandstone mass and bedding planes creating a system of caves and tubes that store and transfer groundwater. "Sandstone karsts" that form multiple water tables with various independent conduit systems and rest levels have been recorded in the Sydney Basin (Young *et al.*, 2009; McNally and Evans, 2007).

The above suggests complex groundwater systems with multiple aquifer sources varying in scale have the potential to discharge at The Drip GDE and Goulburn River.

9.4 ***Aquifer drawdown due to coal mining in the area***

Extraction of groundwater by coal mining activities (Chapter 6) is the only major water use in the area. Mining operations for coal extraction has required the significant depressurisation of regional Permian aquifers, with further impacts on overlying Triassic, Jurassic and Tertiary hydrogeological units. Modelled mine drawdown in porous rocks of the Sydney Basin - North Coast Groundwater Source indicate regional Triassic groundwater drawdown can extend 5 - 7 kilometres from the active mine (Ross and Webb, 2015).

Ulan Coal Mine (UCML) currently operates two underground mines Longwall 3 and Ulan West, the closest mined point approximately two kilometres to the west of The Drip (Figure 9:12). Excess mine water make from the underground workings is used for dust suppression and pivot irrigation of pasture crops and discharged to streams entering the Goulburn River (Table 6:4). Moolarben Coal (MCC) has a number of active underground and open-cut mines seven kilometres to the south. Another underground mine (UG4) has been approved but not developed 500 metres to the south of The Drip Gorge GDE.

Coal mining directly intersects groundwater resources to west, north-west and south of the study site, with a cone of drawdown affecting the Permian and Triassic hydrological units, effectively acting as a regional sink (Umwelt, 2011). Modelling indicates complete dewatering of the Triassic strata above mined panels with the cone of depressurisation extending 4-6 kms with a 2 m decline in hydraulic head. Within the Permian coal seam the effects are predicted to be regional, extending 10 -20 kms beyond the longwall panels (MER, 2011; MER, 2015).

In 2011 UCML was required to monitor The Drip in order to identify possible impacts from their nearby underground mining operations (UCML, 2011). Hydrochemical monitoring of The Drip GDE commenced in 2012 (UCML, 2012). UCML groundwater report predicted that there would be no impact on the Drip as it is sustained by surficial and relatively shallow groundwater storage driven by short term rainfall recharge events (MER, 2011). The report surmised that the shallow perched flows paths that feed The Drip groundwater seepage were relatively short and would show groundwater chemical composition similar to rainwater and different from the deeper regional Triassic sandstone groundwater (UCML, 2012; MER, 2011).

The Moolarben Coal Mine Stage 2 Preferred Project Report states:

“P. 19 ...groundwater derived from the Triassic is believed to be the main baseflow contributor to the Goulburn River. This contribution must originate predominantly from the northern side of the river, as the Triassic is largely unsaturated to the south. Groundwater discharging from the upper Triassic at ‘The Drip’, a local sandstone outcrop, and similar seeps along Goulburn River is derived from perched aquifer zones recharged from local infiltration of

rainfall. Hence groundwater in the upper Triassic probably does not have a significant influence on a regional scale, and only contributes to more localised drainages. Groundwater contours for the Triassic, show groundwater levels within the upper and lower Triassic to typically range between 380mAHD and 400mAHD with the groundwater flow direction generally towards the Goulburn River.” (Middlemis and Fulton, 2011)

9.5 Groundwater sampling

Groundwater geochemical data drawn from 30 monitoring points and groundwater sources in the upper Goulburn catchment, focusing around The Drip GDE were analysed (Figure 9:5, Table 9:2, Table 9:3). The hydrochemistry and hydraulic characteristics of water samples collected from springs, streams and nearby private bores were combined with datasets of groundwater monitoring piezometers sourced from local mine reports and environmental assessments. Details of the methods used are provided in Appendix I.

9.5.1 Groundwater sampling results

The major ion chemical analyses of the groundwater samples collected in this work are listed in Table 9:3, grouped according to geology, with location shown in Figure 9:5.

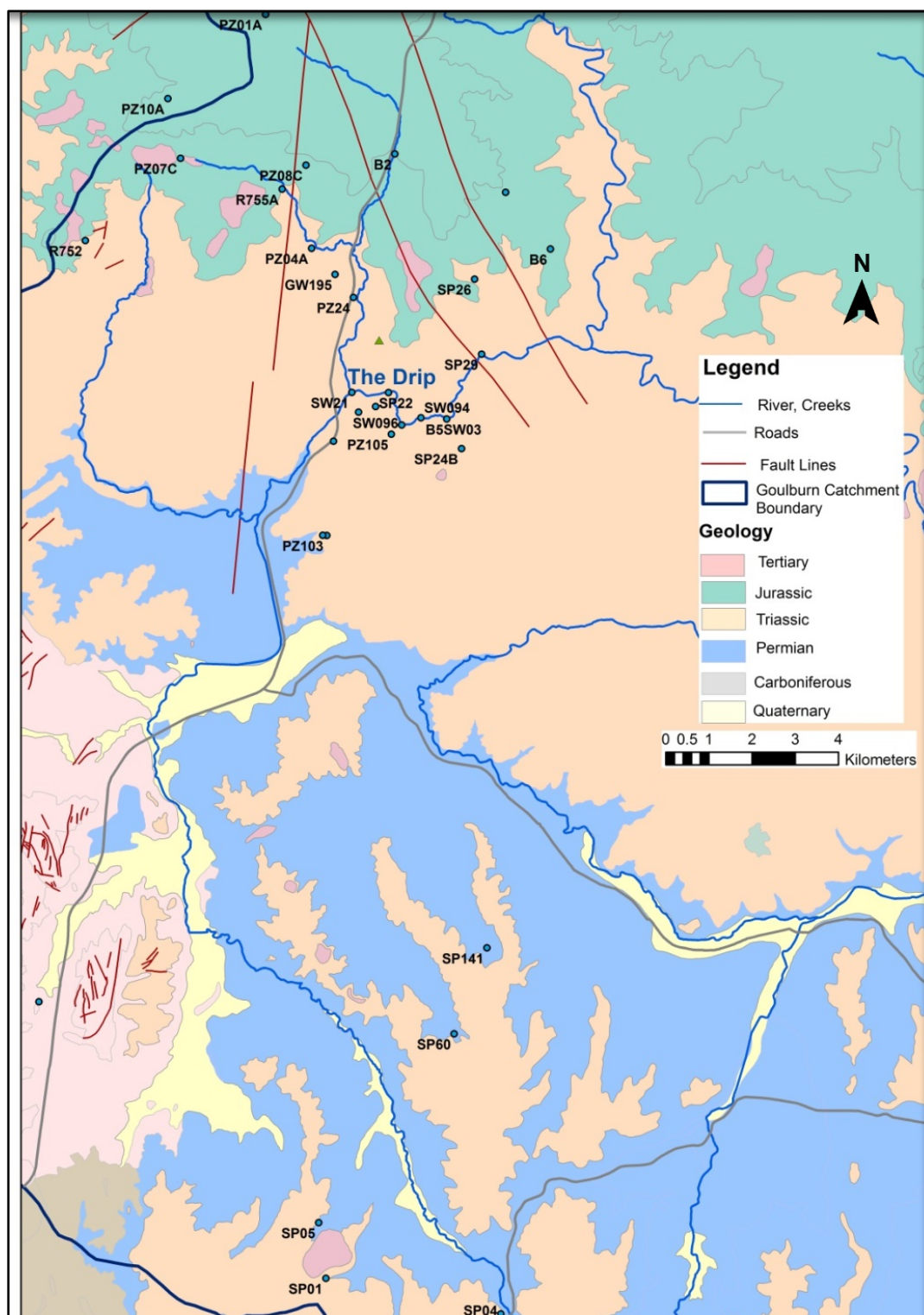


Figure 9:5 Surface and groundwater site location and geology map and Triassic springs SP24B, SP05, SP01, SP04 located to the south and downstream SP29 (see Appendix). Adapted from data supplied by Office-of-Water 2015 (Geoscience-Australia, 2013)

Table 9:2 Sampling site location, geology and salinity (Tammetta, 2014; Umwelt, 2014; UCML, 2014; MER, 2011; MCC, 2017; MCO, 2014; Middlemis and Fulton, 2011)

Code	Easting	Northing	Elevation GL (mAHD)	Site geology	Year	EC μS/cm
R752	756900	6436100	549.1	Basalt	20-03-01	390
PZ10B	758808	6439383	514.1	Jurassic	01-12-05	2130
R755A	761457	6437292	462.42	Trias-Bas	01-03-01	450
PZ01A	761073	6441346	534.25	Trias-Bas	01-06-01	485
PZ04A	762140	6435921	440.74	Trias-Bas	01-06-01	245
PZ07C	759105	6438009	502.19	Trias-Bas	01-07-05	415
PZ08C	762011	6437848	482	Trias-Bas	01-10-05	600
PZ10A	758812	6439393	513.8	Trias-Bas	01-12-05	260
PZ24B	763107	6434783	420.585	Trias-Bas	01-10-06	360
B2	764067	6438109	475	Triassic	02-05-13	164
GW195	762685	6435318	440	Triassic	01-04-79	215
SP24B	765613	6431276	388	Triassic Spring	05-03-13	335
SP60	765442	6417706	560	Triassic Spring	23-04-09	150
SP141	766203	6419696	476	Triassic Spring	19-05-09	145
SP01	762471	6412034	614	Triassic Spring	28-02-13	197
SP04	766523	6411207	607	Triassic Spring	14-03-13	79
SP05	762302	6413326	612	Triassic Spring	13-03-13	95
SP29	766078	6433467	379	Triassic Spring	15-01-14	186
SP26	765915	6435208	407	Jurassic Spring	03-11-12	2809
B5	765268.31	6431962	375.1	Triassic	27-11-95	770
B6	767670	6435905	430	Jurassic-Triassic	06-08-13	1051
PZ103C	762397	6429264	424.85	Triassic	28-11-05	304
PZ105B	763986.59	6431607	389.052	Trias-Permian	28-04-06	210
PZ105C	763986	6431606	389.74	Trias- Permian	29-06-05	193
PZ07A	759136	6438002	502.71	Lower PCM	01-07-05	1090
PZ24A	763109	6434793	421.12	Ulan Seam	01-10-06	970
PZ103A	762490.96	6429261	425.21	Ulan	01-04-13	437
PZ103B	762397.25	6429264	425	Lower Permian	11-04-13	510
PZ105A	763988.15	6431610	388.93	Lower Permian	30-06-05	235
SW094	764674.3	6431992	372.3	River	02-02-06	800
SW096	764227	6431823	371	River	02-02-06	480
MC01	765268	6431962	370	River (21010017)	02-09-05	800
MC02	765268	6431962	370	River (21010017)	02-10-05	780
MC03	765268	6431962	370	River (21010017)	14-03-05	550
SW03	765268	6431962	370	River (21010017)	16-10-12	550
SW21	763072	6432579	397	Curra-Boba Creek	17-10-12	294
SP22P	763761	6432586	380	Drip Pool	17-10-12	410
SP22-1	763920	6432574	383-387	Drip-line AB	06-11-12	561
SP22-2	763920	6432574	383-387	Drip-line AB	30-04-13	556
SP22-3	763806	6432585	386	Drip-line B -east	15-09-13	325
SP22-4	763806	6432585	383	Drip-line B	16-01-14	432
SP22-5	763920	6432574	386	Drip-line A	16-01-14	591

Table 9:3 Hydrochemistry (mg/L) of groundwater north and south of river

Code	Date	Ca	Mg	Na	K	CO ₃	HCO ₃	Cl	SO ₄	TDS	EC	pH
BASALT												
R752	26-09-12	24.0	41.0	50.0	<1	6.0	305.0	12.0	30.0	455	680	7.5
TRIAS-BASALT (north of River)												
R755	24-09-12	10	6	20	20	<1	56	14	3	135	200	6.5
PZ01A	26-06-12	35	15	50	29	<1	168	102	9	410	610	6.8
PZ04A	26-06-12	3	11	36	1	<1	16	94	2	230	340	5.4
PZ07C	24-09-12	17	24	44	2	<1	148	81	1	390	580	6.7
PZ08C	24-09-12	9	32	52	4	<1	59	177	<1	415	620	8.0
PZ10A	25-09-12	6	4	29	13	<1	68	36	<1	175	260	8.5
PZ24B	26-09-12	4	8	34	2	8	23	78	<1	200	300	9.7
B2	02-05-13	3	3	26	1	<1	58	18	2	111.1	164	6
GW195	17-02-02	3.8	7.2	23	0.66	<1	27	49	<1	146.2	215	5.38
TRIAS SPRINGS												
SP24	05-03-13	0.31	7.3	51	2.1	<1	2.6	91	3.8	158	335	6.4
SP60	23-04-09	6.9	4.3	20.0	2.3	<1	7.0	32	<1	116.5	150	5.50
SP141	19-05-09	1.5	2.2	15.0	1.9	<1	<1	28	4.0	80.1	145	4.60
SP01	28-02-13	4.1	11	13	0.84	<1	59	27	2	116.94	197	6.3
SP04	13-03-13	2.1	1.4	8.5	2.5	<1	9.1	13	<0.5	36.6	79	6.2
SP05	13-03-13	0.28	1.5	11	0.97	<1	<1	21	1.3	36.05	95	5
SP29	15-01-14	4.2	5.5	22	0.97	<1	15	36	11	94.67	186	7.1
BORE - Monitoring South of RIVER												
PZ103A	01-04-12	51	23	37	15	<2	196	92	<2	318	630	6.6
PZ103B	01-04-12	20	15	29	8.2	<2	76	78	7.0	204	400	6
PZ103C	01-04-12	11	12	28	7.4	<2	13	74	21	160	310	5.3
PZ105A	01-04-12	12	5	27	2.9	<2	17	81	<2	151	250	5.6
PZ105B	01-04-12	12	6	21	2.0	<2	26	67	<2	139	220	5.5
PZ105C	01-04-12	12	4	17	2.4	<2	22	53	3	116	220	5.9
ALLUVI TRIAS												
B5	04-08-13	16	23	71	4.4	<1	99	160	9.7	383.1	723	6.3
RIVER Pools (no flow or mine discharge)												
SW094	02-02-06	21	17	92	7.9	<1	79	100	120	420	800	6.4
SW096	02-02-06	21	19	60	7.5	<1	90	99	95	400.0	480	6.60
SW03_MC1	01-09-05	19	16	86	7	<1	73	110	84	410	760	7.10
SW03_MC2	01-10-05	24	20	87	8.5	<2	55	110	160	470	740	7.50
SW03_MC3	14-03-05	17	13	60	7.2	<1	69	69	84	330	550	7.60
SW21	17-10-12	4.6	11	33	1.5	<1	50	62	3.9	166	294	7.4
SW03 +discharg	16-10-12	31	24	75	9.1	<1	99	87	170	495.1	790	8
The Drip												
SP22-1	06-11-12	15	32	50	1.4	<1	210	72	4.7	385.1	561	7.7
SP22-2	30-04-13	17	31	48	1	<1	210	67	5	379.26	556	8
SP22-3	15-09-13	8.1	14	28	0.86	<1	99	46	2.1	198.06	325	8.1
SP22-4	16-01-14	9.6	16	36	1.3	<1	110	54	2.9	229.8	432	8.2
SP22-5	16-01-14	18	35	55	1.5	<1	230	74	5.2	418.7	591	8.2

UCML historic groundwater monitoring between 2001 and 2015 to the north of The Drip indicated differences in the groundwater character of the hydrochemical units in sedimentary strata (Table 7:3)(UCML, 2015a) (MER, 2009). The upper Triassic groundwater has the lowest salinity generally EC < 250 μ S/cm, lower Triassic groundwater has an EC > 500 μ S/cm with a higher pH. The EC of Permian sequences are at least double the lower Triassic. The Jurassic groundwater is the most saline at more than double the EC of the Permian. Basalt groundwater character exhibited a dominance of Mg, Ca, HCO₃, Type water and elevated pH. Triassic water can be divided into upper dominated by Na, Cl and lower dominated by Na, Mg, HCO₃ ions. UCML monitoring results for EC and pH at The Drip are shown in Table 9:4. It is noted that the pH is generally greater than 8 and the EC greater than 500 μ S/cm. Neither is characteristic of recently recharged rainwater from upper Triassic strata.

Table 9:4 UCML monitoring of The Drip water quality (Salinity and pH) (UCML, 2015b; UCML, 2014; UCML, 2013; UCML, 2012)

UCML The Drip Hydrochemistry	Drip-East TDS mg/L	Drip-East EC $\mu\text{S/cm}$	pH	Drip-West TDS mg/L	Drip West EC $\mu\text{S/cm}$	pH
Median	362	504	8.4	430.5	604	8.4
Minimum	313	471	7.7	365	529	8
Maximum	409	604	8.6	562	756	8.7
Standard Deviation		28.9	0.23		52.8	0.19

9.6 Groundwater sources

The hydrochemical character of major ions in water samples from the Drip were compared to other groundwater sources in the Goulburn River within 20 km. The Piper diagram shown in Figure 9:6 plots the chemistry of groundwater sources at The Drip as well as sites located immediately to the north and south of the GDE (Figure 9:5).

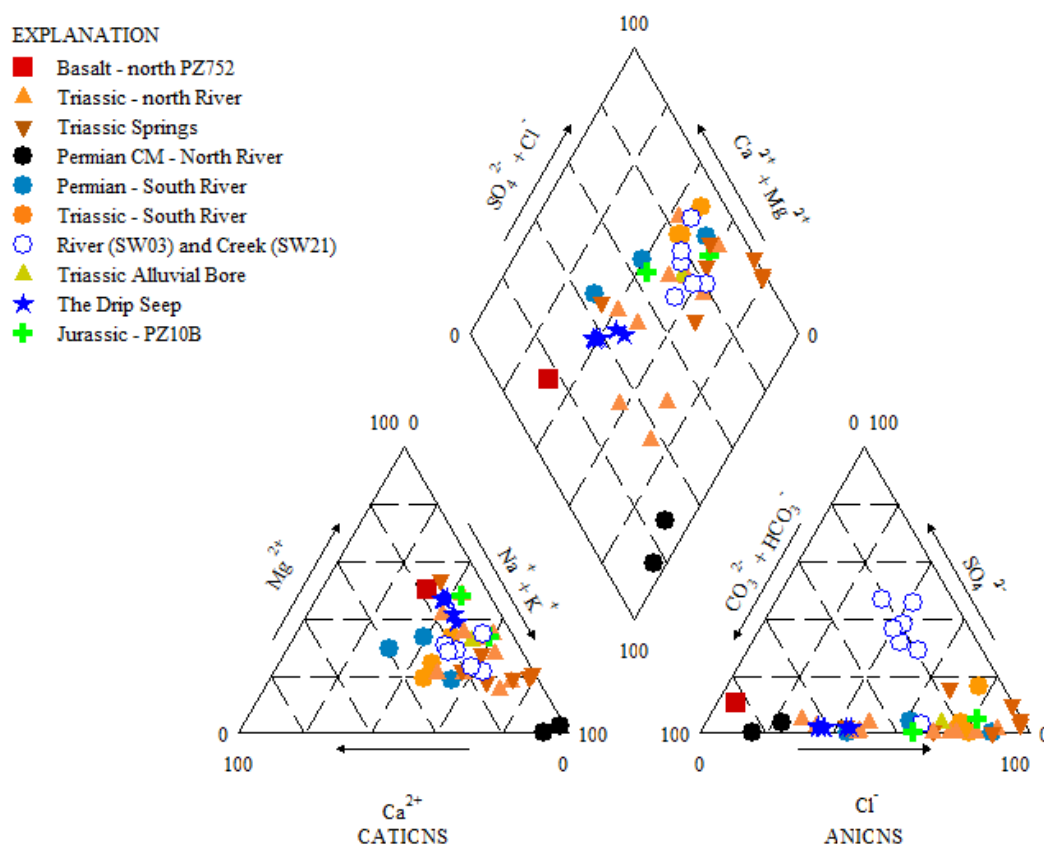


Figure 9:6 Trilinear Piper diagram – The Drip groundwater (meq/L%)

From the Piper diagram (Figure 9:6) the following observations can be made about the features of the surface and groundwater samples

- The Drip groundwater (blue stars) has a distinct bicarbonate water type (blue stars) exhibiting a Na, (Mg) HCO_3 dominance more typical of the lower, regional Triassic groundwater type.
- Groundwater sources that exhibit a similar character to The Drip are Triassic bores north of the River (PZ01, PZ07); Triassic Springs SP01 (located adjacent to a basalt outcrop at the headwaters of Moolarben Creek) and unexpectedly PZ103A in the southern catchment recorded by MCC as screened into the Permian Coal Measure groundwater.
- Permian Coal Measures – north of the River, exhibited a different character type, with Na + K, HCO_3 dominance
- Basalt groundwater has a distinctive Ca, Mg, HCO_3 dominance
- Goulburn River surface flow is Na, Cl, (SO_4) type most similar to Triassic groundwater bores PZ105C, GW195, PZ24B. The elevated sulfate reflects the influence of mine discharge water (Chapter 6: Hydrochemistry).
- Triassic groundwater appears to be divided into two major types; one dominated by Na, Cl ions (e.g. Triassic springs - associated with rainwater and solutes derived from cyclic salts) the other Na, HCO_3 type water with a basalt or volcanic influence.
- There is a possible mixing along a flow path of basalt derived and Triassic groundwater

9.6.1 Ion ratios

Trilinear Piper diagrams provide a general analysis of ion groupings or speciation. The hydrochemical character of water sources were further investigated using ion ratios (White *et al.*, 2009; Biswas, 2010). Carbonic acid is important in the dissolution of basalt minerals. A ratio for $[\text{HCO}_3]/[\text{Cl}]$ (meq/l) > 1 in groundwater is indicative of mineral weathering of a basalt host – conversely a $[\text{HCO}_3]/[\text{Cl}] < 1$ is indicative of both rainwater and marine origin water.

Ratios of major ions were plotted against the reciprocal of chlorine $1/[\text{Cl}]$. The log reciprocal allows rainwater and seawater to be displayed on the same graph for comparison. Figure 9:7 show the ratio $[\text{HCO}_3]/[\text{Cl}]$ against $1/[\text{Cl}]$. The ionic ratio for The Drip, Triassic Spring SP01 and Trias-basalt water samples PZ10A, PZ01A and R755 plus R752 (basalt source) all plot with $[\text{HCO}_3]/[\text{Cl}]$ close or > 1 indicating increased bicarbonate most likely from mineral weathering. The Triassic Spring (SP01) is located approximately 20 kms south of The Drip in similar Triassic geology near a basalt outcrop in Munghorn Gap Nature Reserve. PZ103A, also has $[\text{HCO}_3]/[\text{Cl}] < 1$, is a mine monitoring bore reported to be screened into upper Permian-Ulan Seam groundwater. Bicarbonate may due to interburden calcium carbonate cementation. Most of

the Triassic Springs plot $[\text{HCO}_3]/[\text{Cl}] < 1$, showing rainwater influence. The Jurassic groundwater PZ08 also has $\text{HCO}_3/\text{Cl} < 1$ lies closer to seawater suggesting a marine origin or halite salt.

Figure 9:8 ($[\text{Na}]+[\text{K}])/[\text{Cl}]$ vs $1/[\text{Cl}]$. Here there appears to be a mixing line passing from Triassic springs to The Drip and surface water. The Drip results also lie close to Triassic-Basalt groundwaters.

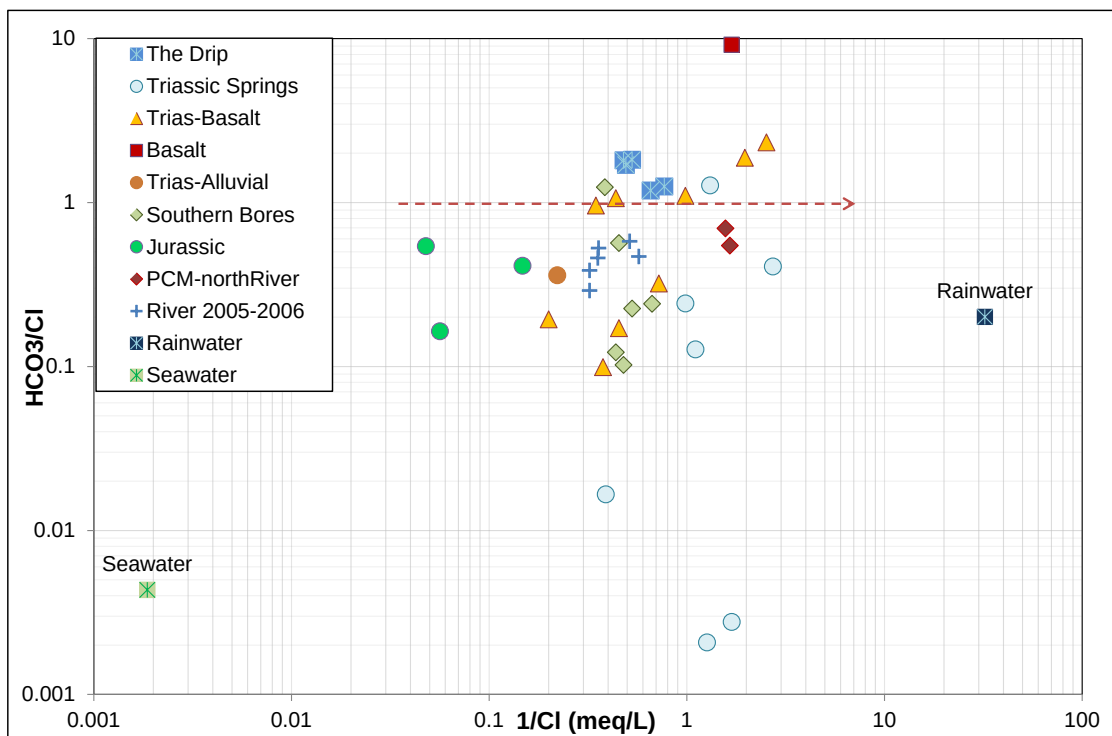


Figure 9:7 The Drip & nearby groundwater – $[\text{HCO}_3]/[\text{Cl}]$ vs reciprocal chlorine $1/[\text{Cl}]$

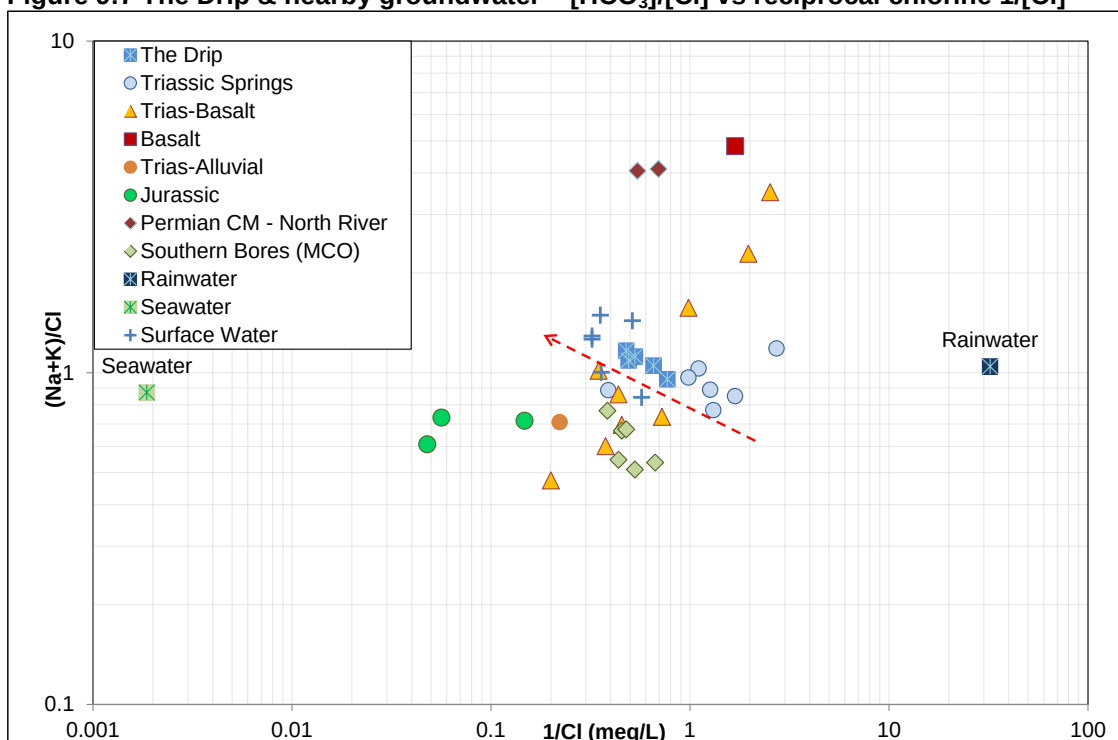


Figure 9:8 The Drip & nearby groundwater – $([\text{Na}]+[\text{K}])/[\text{Cl}]$ vs reciprocal chlorine $1/[\text{Cl}]$

Figure 9:8 shows major ion to chloride ratio ($[\text{Na}]+[\text{K}]/[\text{Cl}]$) has Triassic springs closest to rainwater and Jurassic source to seawater. There appears to be a mixing line passing from Triassic springs to The Drip to surface flows. The ($[\text{Na}]+[\text{K}]/[\text{Cl}]$) and ($[\text{Ca}]+[\text{Mg}]/[\text{Cl}]$), and The Drip seep lie closer to rainwater and basalt groundwater.

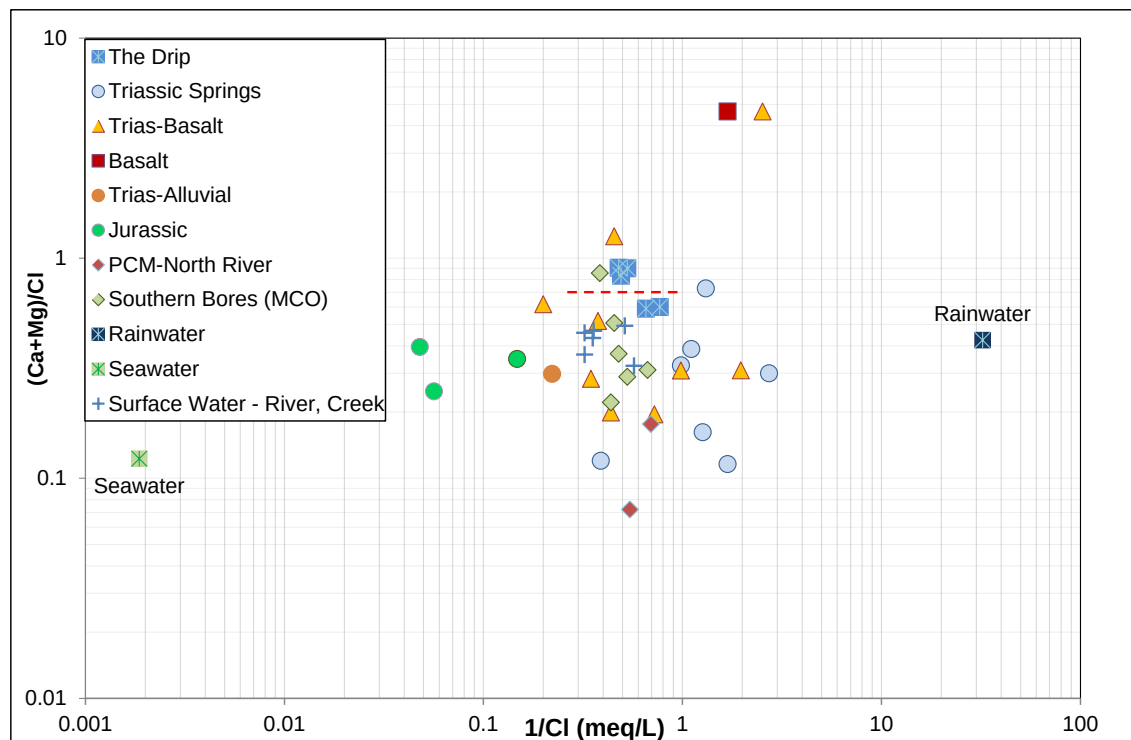


Figure 9:9 The Drip groundwater type – $([\text{Ca}]+[\text{Mg}])/[\text{Cl}]$ vs reciprocal chlorine $1/[\text{Cl}]$

Figure 9:9 plots the ratio $[\text{Ca}]+[\text{Mg}]/[\text{Cl}]$ to the reciprocal of chlorine and shows a separation between Drip-lines A & B. This suggests more than one potential groundwater type may be contributing to discharge at The Drip. The dominant cations mobilized depend on the composition of rock minerals and thus surrounding lithology.

Halite dissolution produces $[\text{Na}]/[\text{Cl}]$ generally in equal concentrations or 1:1 ratio in water (Nur *et al.*, 2012). Na/Cl ratios of ~ 0.8 show a similarity to the oceanic ratio (0.86) and also that of local rainfall (0.83). A high $[\text{Na}]/[\text{Cl}]$ ratios in low salinity groundwater may be explained by Na^+ being derived predominantly from mineral weathering of plagioclase from a volcanic host (Cartwright *et al.*, 2004). Samples with $[\text{HCO}_3]/[\text{Cl}]$ and $([\text{Ca}]+[\text{Mg}])/[\text{Cl}] > 1$ indicates mineral weathering is contributing a comparable higher amount of solutes than cyclic salt (White *et al.*, 2009).

The Piper diagram and the ion ratio results suggest that the major ion chemistry of water collected at The Drip seep is a combination of both rainfall-induced chemical weathering of Triassic strata and the dissolution of rock-forming minerals of volcanic origin. Tertiary basalt capping and intrusions outcrop north of the Drip, with the closest being approximately 1 kilometre to the north. The chemistry is quite different from that of more shallow, perched Triassic groundwater.

9.7 Conceptual model of groundwater flow

To understand the possible impacts of mining drawdown of groundwater a pre-mining conceptual 2D model was developed of a hydrogeological cross-section based on a transect line AB between northern groundwater monitoring bores PZ04A, PZ24B, through The Drip and Goulburn River to the southern bores PZ129 and PZ105C and is shown in Figure 9:10.

The conceptual model is based on geological and hydraulic characteristics provided by monitoring records from nearby groundwater bores and The Drip GDE. It depicts the main hydrogeological units, position and depth of the various geological strata and pre-mining standing groundwater levels showing hydraulic gradient extrapolated from available piezometric monitoring data collected 2001-2006 (MER, 2011; MER, 2015; UCML, 2015a; UCML, 2012; UCML, 2004a). Figure 9:11 shows the location of the profile and surface geology and Figure 8:12 the proximity to the UCML long wall panels and location of monitoring bores (Table 9:5, Table 9:6).

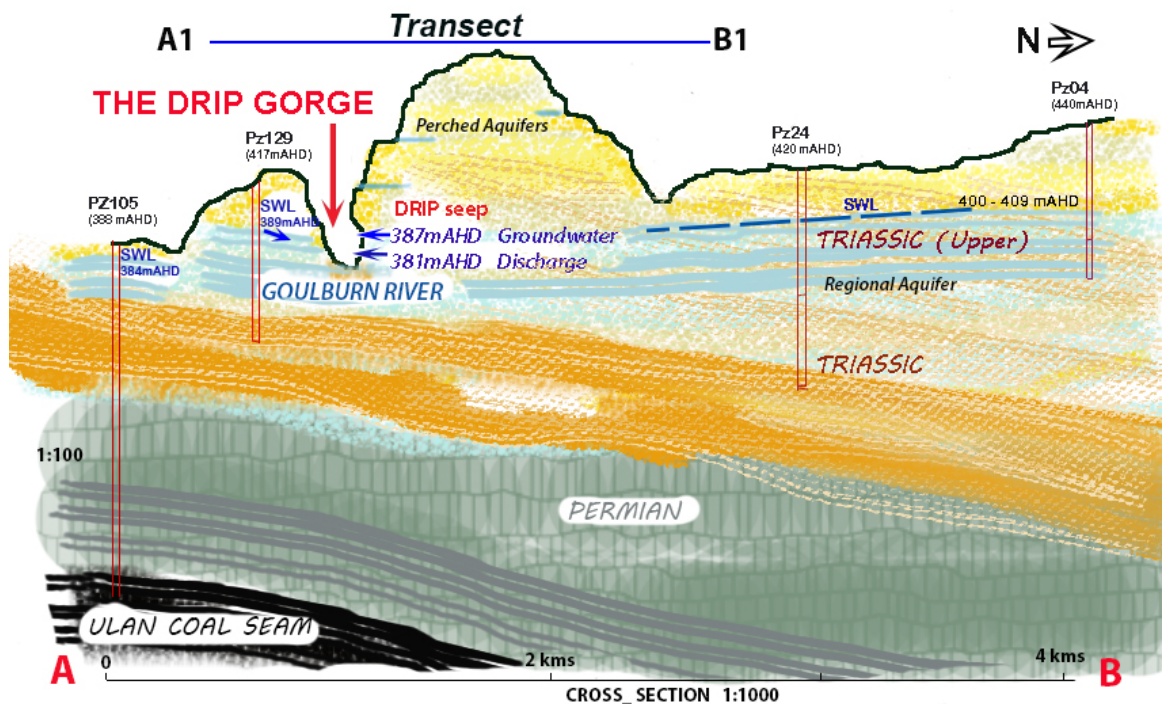


Figure 9:10 Conceptual cross-section A – B through The Drip gorge GDE based on elevations and SWLs from monitoring bores, and local geology. The transect A1 – B1 is the cross-section analysed in numerical modelling see section 9.9 Figure 9:15

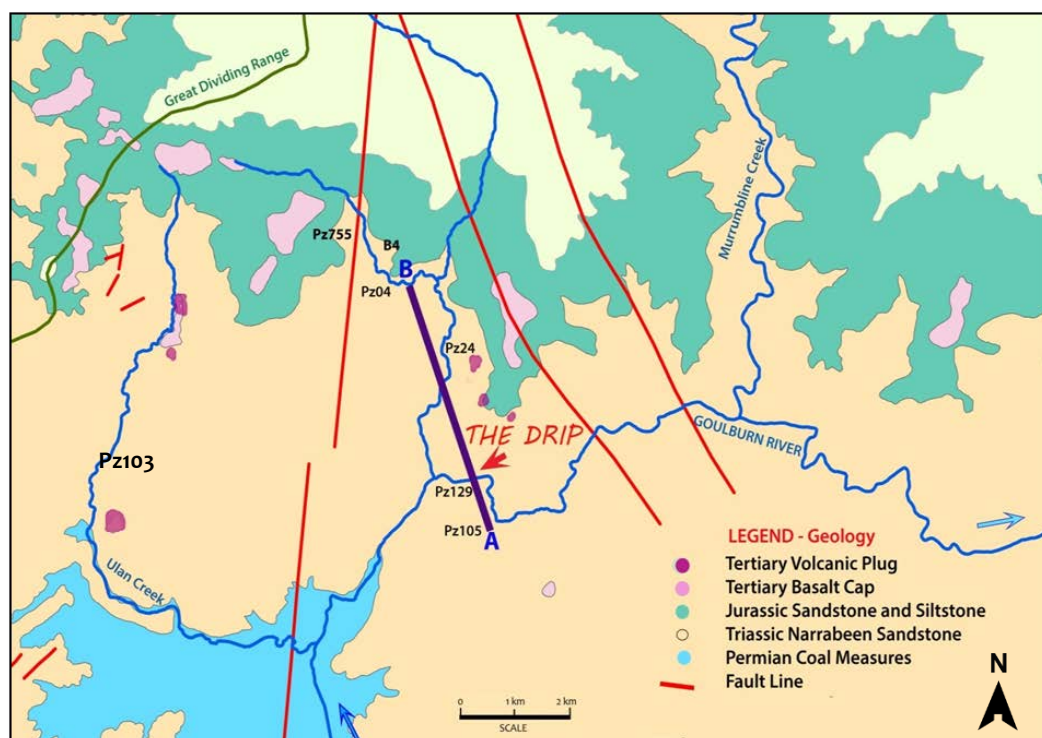


Figure 9:11 Conceptual CS – A- B from PZ105 to PZ04 bisects The Drip and Goulburn River. Compiled from data (Geoscience-Australia, 2013)

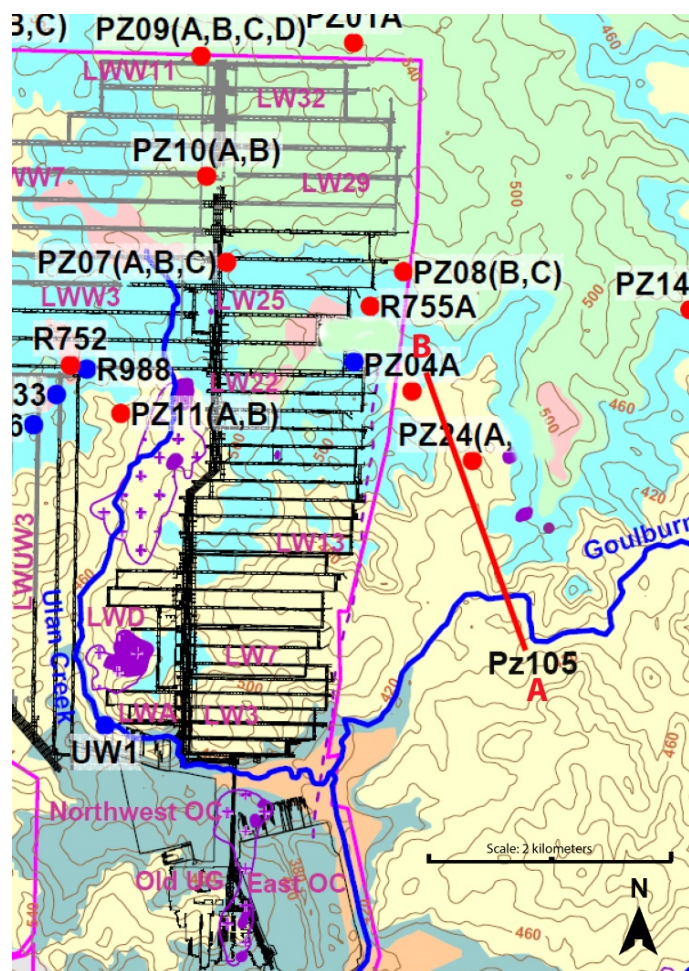


Figure 9:12 Location of conceptual cross-section A- B and proximity to Ulan Coal longwall panels (UCML 2015)

9.8 Standing water levels

The standing water levels (SWL) of The Drip cliff face Seep A and Seep B are approximately 382-385 mAHD and 388-392 mAHD respectively while the surface of the Goulburn River is at 380 mAHD. The northern monitoring piezometers, PZ24B, PZ04C are located 2.3 to 6 km respectively to the north-west of the river at the Drip. PZ24B is the closest monitoring bore to the Goulburn River apart from the most recently installed PZ29³⁰ (Figure 9:14). PZ24B was installed in 2006 to the east of Longwall 19 that was mined in 2003. The hydraulic heads of all the monitoring piezometers were originally above the level of the river. Since 2006 the SWL of the regional Triassic groundwater system has fallen between 2.62 m and 40 m (Table 9:5, Figure 9:13). The SWL of PZ04 installed in 2001 has fallen by over 10 m. The change in SWLs demonstrates in the period 2000 to 2017, the hydraulic gradient has reversed from groundwater flow towards the Goulburn River, to one that is away - and SWLs are continuing to fall. Groundwater levels in the Triassic monitoring bore PZ10 and PZ07 located directly over the mined longwall panels decreased by 30 to 40 metres between 2005 and 2017. (Table 9:5).

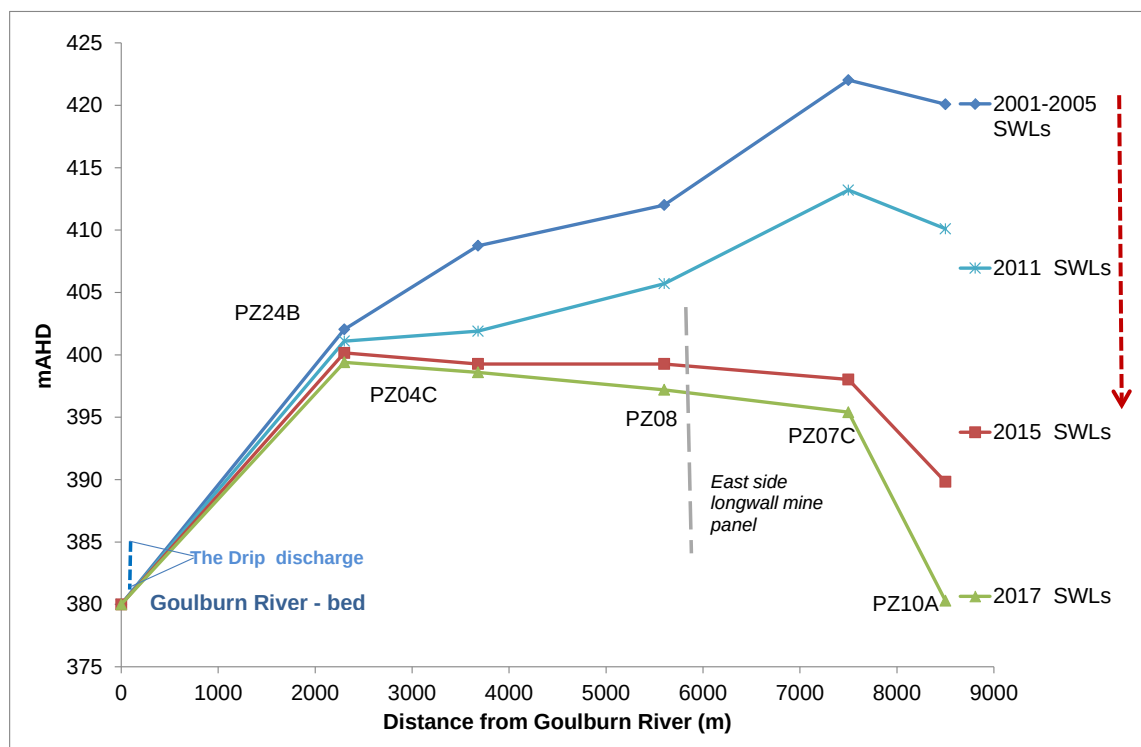


Figure 9:13 Shows the decrease in SWLs (mAHD) of bores monitoring the Triassic groundwater as a function of distance from the Goulburn River over time (2001 – 2017) with the flattening and reversal of the hydraulic gradient away from the river, towards the depressurised underground mine (data Table 9:5, Figure 9:14)

³⁰ PZ29 is a vibrating wire monitoring piezometer installed November 2015, 2018 SWLs for Triassic GW were reported at 399.2 mAHD slightly below PZ24

Table 9:5 Change in SWLs (mAHD) groundwater monitoring bores located between The Drip gorge and UCML underground 2001 - 2017
Sources:(UCML, 2015b; UCML, 2004a; UCML, 2017)

Bore Code	Metres from River	2000-05 SWL (mAHD)	2011 SWL (mAHD)	2015 SWL (mAHD)	2017 SWL (mAHD)	Change SWL (m) to 2017	Ground Level (mAHD)
River	0	380	380	380	380	-	380
PZ24	2300	402.04	401.1	400.15	399.4	-2.64	430
PZ04	3680	408.74	401.9	399.27	398.6	-10.14	441
PZ755	5250	412.5		391.6	390.5	-22	-22
PZ08	5600	412	405.7	399.27	397.2	-14.8	482
PZ07	7500	422.02	413.2	398.02	395.4	-26.62	502
PZ10	8500	420.08	410.1	389.82	380.3	-39.78	514

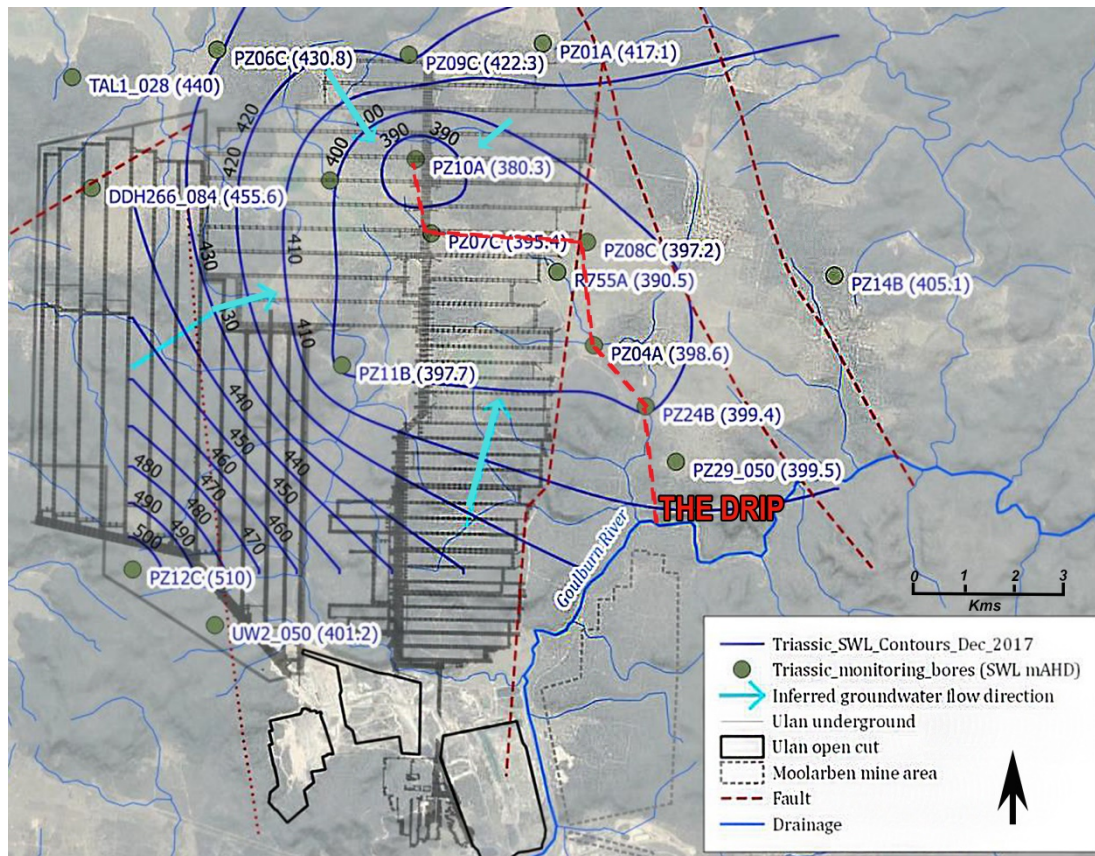


Figure 9:14 UCML 2017 Triassic groundwater SWL contours between the underground mine and The Drip, Goulburn River. (UCML, 2017)
Red arrow is cross-section for Figure 9:13, Table 9:5

The general hydraulic gradient of regional Triassic groundwater pre-mining was originally towards the topographical low of the Goulburn River supporting groundwater discharge as baseflow. Subsidence due to long wall mining which caused fracturing of the Triassic strata and groundwater depressurisation in the vicinity of the mined goaf has altered the hydraulic gradient of the regional groundwater drawing flow towards the active underground mine and away from

the Goulburn River. This lowering of the hydraulic head and reversal of groundwater flow direction must have decreased groundwater discharge to the river (Figure 9:13).

The potential scale of the decrease in groundwater discharge is difficult to determine due to the lack of pre mining baseline data and inherent time lag between drawdown and decrease in seepage and river baseflow. The nearby faults lines, volcanic plugs and sills, vertical and sub-vertical joints, fractures and impermeable ironstone layers have the potential to increase permeability, as well as impede direct groundwater flow. The presence of these geological structures underlines the inherent complexity of the stratigraphy above The Drip GDE. The mines have modelled the groundwater source supporting The Drip seep as an unconnected, perched aquifer. The major ion chemistry of The Drip and the hydraulic gradient of the Triassic show this to be an oversimplification of a complex system.

In the next section a simple two-dimensional (2D) model is developed to examine the potential impacts of the Moolarben Coal Complex (MCC) underground mine, which is approved but not currently active and located 500 metres to the south of The Drip GDE.

9.9 A simple 2D model – recharge discharge

A simple 2D numerical model using the program GEOSTUDIO SEEP/W (Geoslope, 2016) and based on the A2-B2 transect shown in the conceptual model in Figure 9:10 was used to explore the Triassic groundwater system in a 2,200 m north-south cross-section passing through The Drip Gorge and Goulburn River (Figure 9:15). The aim was to model connectivity between Triassic groundwater and the upper Goulburn River and estimate probable rates of groundwater discharge to The Drip Gorge and Goulburn River as baseflow based on pre-mining groundwater levels extrapolated from Table 9:5 and Table 9:6. Groundwater impacts of the approved but not yet developed underground coal mine(UG4)³¹ located 500 metres to the south of The Drip (Middlemis and Fulton, 2011) was also investigated and modelled over 2.14 years and 40 year period (Figure 9:15).

Table 9:6 Triassic monitoring bores SWLs (mAHD) at installation and in 2015 located to the south of The Drip gorge (Middlemis and Fulton, 2011; MCC, 2015)

Piezo	SWL mbgl	Collar Elevations mAHD	Year installed	Triassic SWL mAHD	2015 Triassic SWL mAHD
PZ128 (VW)	20	409.52	2008	dry	389
	36			380.8	379.8
PZ129 (VW)	35	417.95	2008	389.2	392.6
	53			378.5	389.4
PZ105C	12.1	389	2006	376.9	377

VW =vibrating wire piezometer

³¹ Moolarben Coal Operations UG4 – ML1605

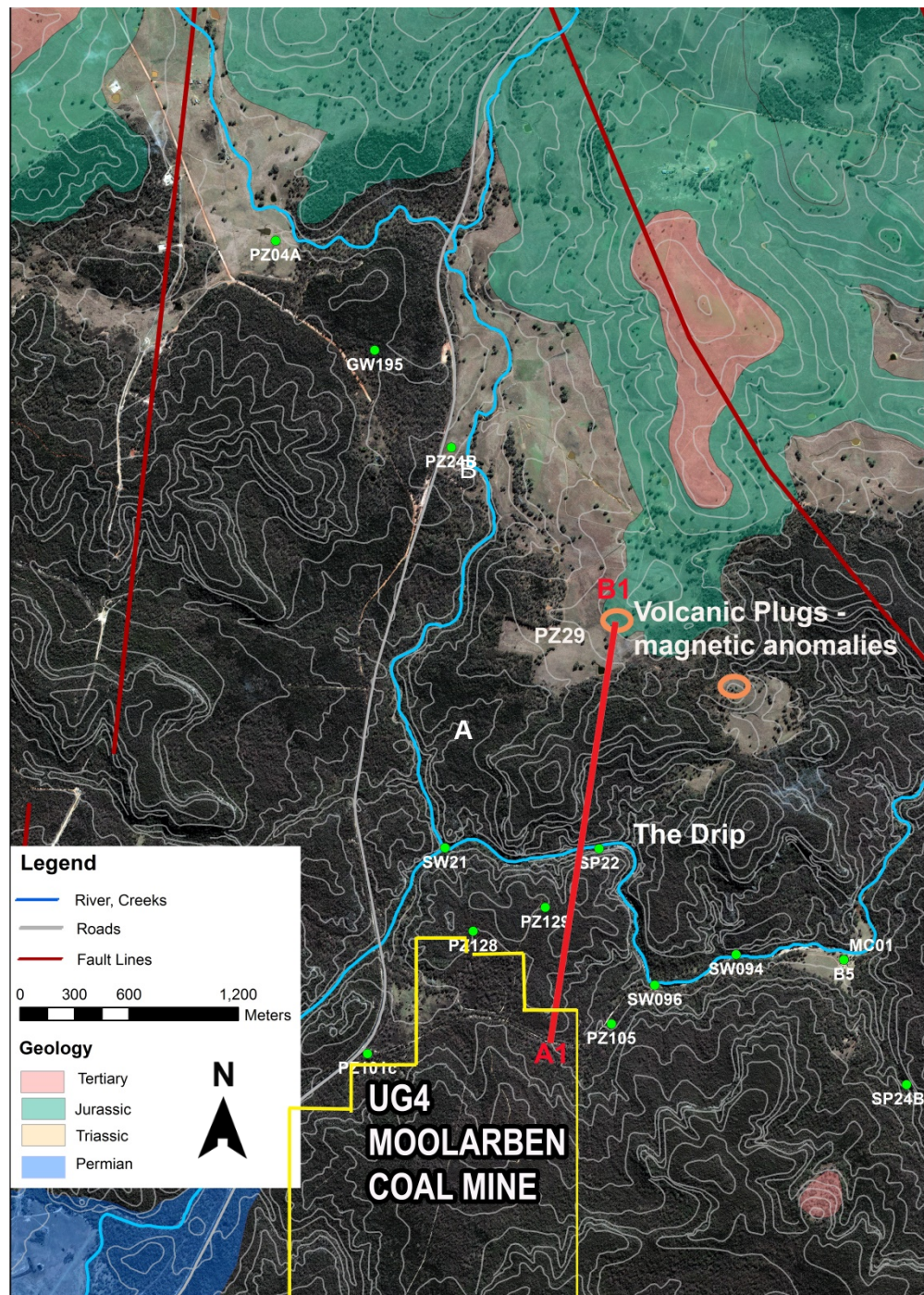


Figure 9:15 Location of numerical model cross-section A2 – B2 through The Drip Gorge, Goulburn River, proximity of UG4 mine overlaid on aerial photograph with geology. Adapted from (Geoscience-Australia, 2013; Johnstone, 2008)

It was assumed that the potential collapsed zone above the mined coal seam in UG4, and all layers immediately above, were depressurised due to mine subsidence and dewatering (pressure head = zero). The height of complete groundwater drainage above subsided longwall panels is dependent on the depth and width of the mined coal seam (Tammetta, 2015). On the basis that the mined seam for UG4 is 4.25m thick and approximately 100-140 metres below

ground level (Middlemis and Fulton, 2011) the area directly above the collapsed zone would be severely disturbed and completely drained of groundwater (Pells, 2006).

Soil moisture pressure and secondary permeability as per fractures, defects, joints and bedding planes are not included in this simple 2D model with the exception of subsidence induced increase in permeability. The model demonstrates a high degree of sensitivity to the assumed horizontal and vertical hydraulic conductivity ratios and estimated permeability's with a significant range of uncertainty equivalent to many orders of magnitude.

The model incorporated 3 layers associated with a basalt plug, weathered basalt, upper basalt, lower basalt, and six layers representative of the main geological strata and hydrological units - upper Triassic, lower Triassic, upper Permian, Ulan Coal Seam, lower Permian, Granite and meta-sediments. Vertical and horizontal permeability and ratios ($K_h:K_v$), were assigned for each unit (Table 9:8), the estimation drawn from number of sources, see discussion below. The hydraulic boundary condition applied for rainfall infiltration or recharge, is generally accepted at around 5% of annual average rainfall (672 mm) or 33.6 mm per year - 1.07×10^{-9} m/s (Pearse – Hawkins *et al.*, 2015). Stratigraphic and groundwater data was drawn from mine monitoring bores located to the north and south of the Goulburn River (Figure 9:15).

The granite plus metasediment basement was considered an impermeable lower boundary for The Drip numerical model (1). Permeability values (K_v) and ratios (K_h/K_v) were adjusted to achieve a total head SWL within the known range of the regional Triassic groundwater table in 2005, which was 412 mAHD (700 metres to the north) and 386 mAHD (40 metres to the south) of The Drip (Table 9:6).

PZ29 was installed 1.3 kms north of the Drip by UCML in 2016 to assess groundwater gradients and trends around the Drip. The Triassic sediments recorded a piezometric groundwater level of 406 mAHD (50m bgl) to 389 mAHD (120m bgl). These corresponded to the levels recorded for PZ128 & PZ129 immediately to the south of The Drip and Goulburn River in the period 2008-2016 (MCO groundwater monitoring program).

Table 9:7 The Drip model (1) parameters – Hydrological unit permeability K_h/K_v

	Permeability (K_v) m/s	Ratio K_h/K_v	Sat. Vol Water Content m^3/m^3	Mv (kPa)
Weathered Basalt	1.16	1	0.05	2.00E-06
Basalt upper	5.00E-06	2	0.2	2.00E-07
Basalt Plug	1.16E-10	50	0.02	8.30E-08
Jurassic	9.00E-07	2	0.15	3.33E-07
Upper Triassic	1.20E-07	4	0.1	1.67E-07
Lower Triassic	7.00E-07	10	0.08	1.43E-07
Upper Permian	5.80E-08	50	0.05	1.00E-07
Ulan Seam Coal Measures	1.16E-06	1	0.15	1.25E-06
Lower Permian	2.30E-08	3.3	0.05	5.00E-08
Granite+meta sediments	1.20E-10	1	0.001	5.00E-08
Extracted Goaf	7.00E-03	1	0.5	0.001

Figure 9:16 shows the conceptual stratigraphical cross-section transposed from bore drilling logs (UCML - PZ24B, PZ04, PZ08, PZ29 and MCO - PZ129, PZ128, and PZ105c). Standing water levels (mAHD) are based on Standing Pipe piezometers (SP) monitored since 2005-2006 plus multi-level vibrating wire piezometers (VW) - PZ129 and PZ128 (MCO). Hydraulic data for VW piezometer PZ29, installed in February 2016, was not available at the time of this modelling exercise.

The pre-mining Drip model (1) estimated discharge rate of $2.28 \times 10^{-6} \text{ m}^3/\text{second}$, equal to a steady state inflow rate of $0.197 \text{ m}^3/\text{day}$ for the one metre wide transect. Extrapolated over a stream length of 10 kilometres this represents a possible baseflow contribution of approximately 2 ML/day. It is worth noting that the volume of annual recharge is significantly smaller than the potential volume of storage in porous rock groundwater sources due to the thickness and large spatial extent of the sedimentary strata (Ross and Webb, 2015).

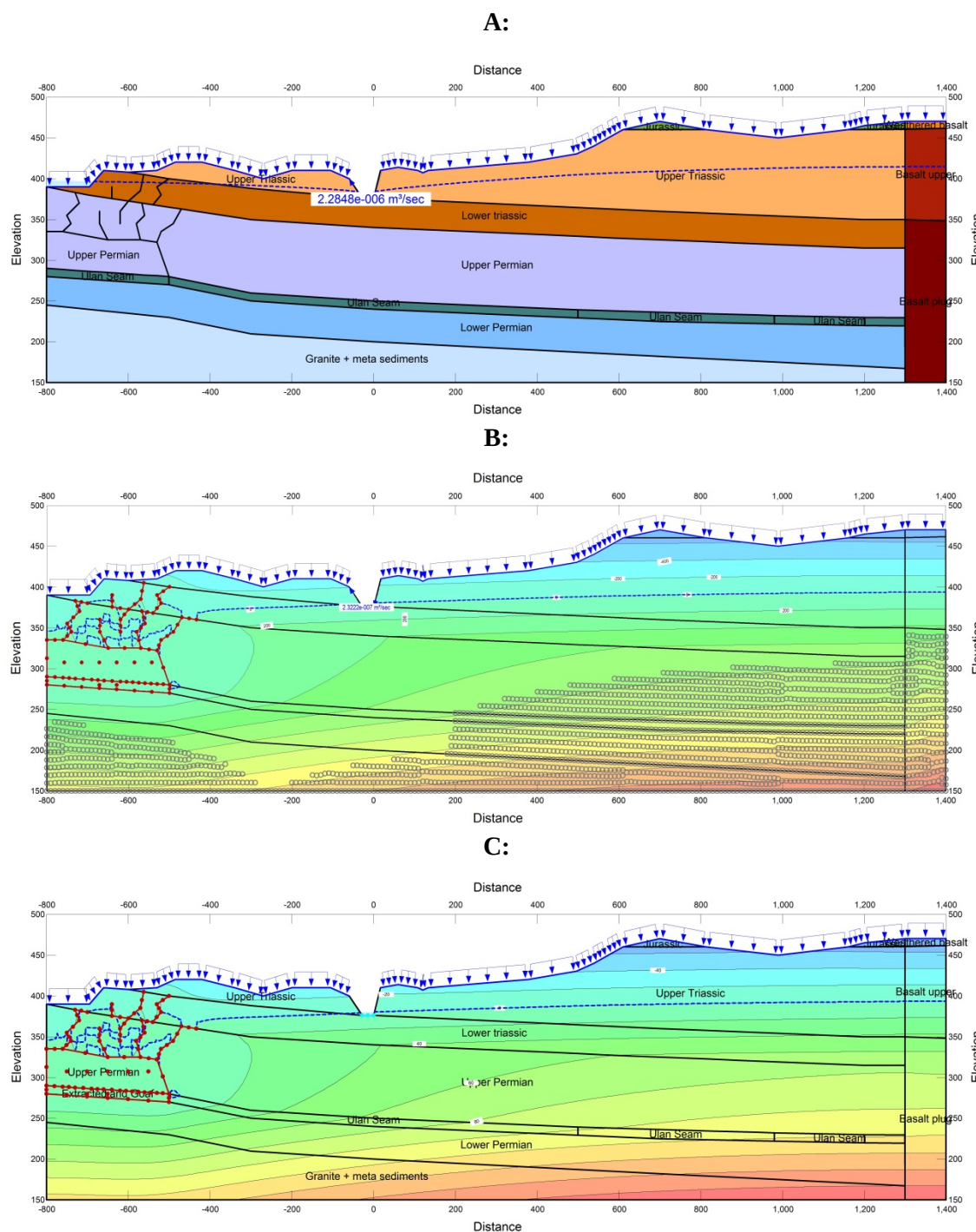


Figure 9:16 The Drip model (1) A) pre-mine stratigraphic version with 5 % rainfall recharge B) 2.14 years after LW mining C) 40 years after LW mining. UG4 mine is shown on the left, 500 m from the Drip. Groundwater flux rate at The Drip are shown in Table 9:9 Note: colours delineate geology in A (Table 9:7) and in B, C pore pressure contours at the modelled time. Scale: Elevation & Distance in metres

The preferential flow pathways in Triassic strata on the left of Figure 9:16 are due to secondary porosity features, such as bedding planes and vertical jointing, with hydraulic conductivity considered to be an order of magnitude greater in the horizontal direction (Ward and Kelly, 2013). These are generated by the mining process.

The hydraulic conductivity applied to these strata are plausible estimates that can vary considerably dependent on modeller preference. There is limited available data regarding the hydraulic conductivity values for fractured and porous rock (Pells and Pells, 2012a; Pells and Pells, 2012b). Kellett *et al.* (1989) considered the average hydraulic conductivity of sandstone aquifers was 1.1×10^{-7} m/s with a porosity of 0.02. Hydraulic conductivity can decrease with depth and can be as small as 1.2×10^{-8} m/s at 400 mbgl (Ward and Kelly, 2013) The depth of the Triassic strata in this example is less than 150 metres below ground level.

Substantially different parameters have been used by the two mines in modelling the impact of mining. Table 9:8 compares permeability (K) and K_h/K_v ratios for numerical modelling used by UCML and MCO. There are many orders of magnitude differences in the assumed permeability, with K_h/K_v ratios varying from 2 to 5000. MCO model assumes very little vertical groundwater flux despite the known secondary porosity features in the Narrabeen Group of sedimentary rocks and shallow depth of the coal seam.

Table 9:8 Comparison of UCML & MCO hydraulic unit permeability ($K_h:K_v$)

UNIT	UCML			MCO		
	K_h	K_v	RATIO	K_h	K_v	RATIO
	m/s	m/sec	K_h/K_v	m/s	m/s	K_h/K_v
Jurassic Sandstones - Siltstones	6.944E-08	9.26E-10	75	5.79E-06	1.16E-10	50000
Triassic upper (quartz)	2.3E-07	1.2E-07	2	5.79E-06	1.16E-09	5000
Triassic lower (lithic)	9.3E-08	2.3E-09	40	1.74E-07	5.79E-10	300
Upper Permian Coal Measures	1.2E-09	5.8E-11	20	1.16E-06	2.89E-10	4000
Permian coal measures	4.6E-09	9.3E-11	50	5.79E-07	1.16E-10	5000
Ulan Seam	6.9E-06	6.9E-06	1	1.16E-05	5.79E-09	2000
Lower Permian coal measures	2.3E-08	6.9E-09	3.3	1.16E-06	1.16E-10	10000
Granite +metasediments	1.2E-10	1.2E-10	1	5.79E-09	1.16E-10	50

Source: (MER, 2015; Middlemis and Fulton, 2011)

The SEEP/W numerical model using UCML (Figure 9:17) and MCC (Figure 9:18) assumed parameters for the various strata. With these parameters to match the measured SWLs for the regional groundwater levels in the Triassic required an assumed recharge rate of 1% annual average rainfall (6.72mm/year) for the UCML parameter values and an absurdly low 0.002% or 0.01 mm /year for MCC. The low recharge has caused the model to produce ponding above ground to 100 metres (blue peaks).

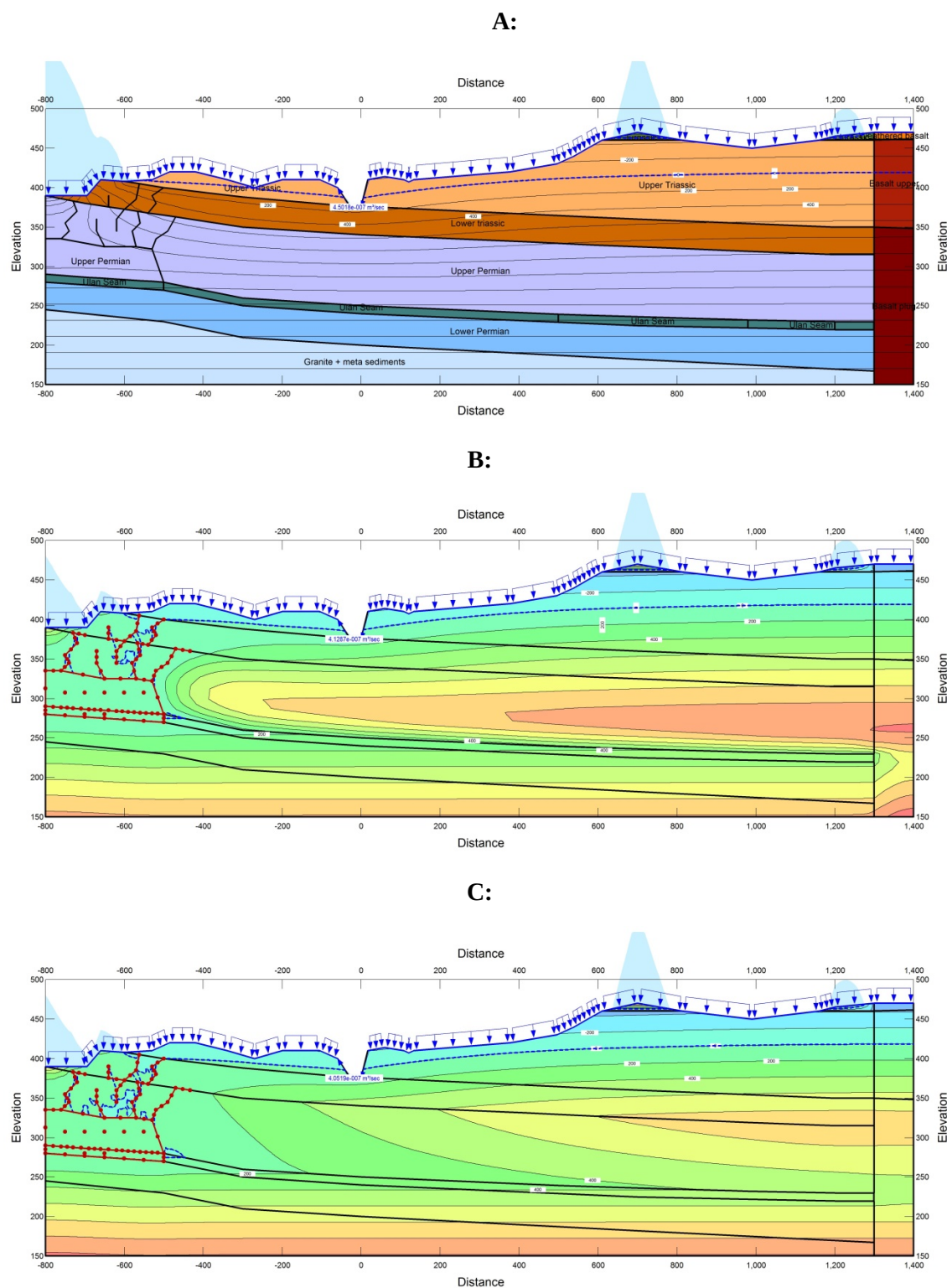


Figure 9:17 UCML model A) pre-mine geological stratigraphy and regional Triassic SWL - 1 % annual rainfall infiltration recharge B) 2.14 years after UG4 mined C) 40 years after mining UG4. Groundwater flux rate at The Drip are shown in Table 9:10. Note: colours delineate geology in A (Table 9:7) and pressure head in B, C at the modelled time. Scale: Elevation & Distance in metres

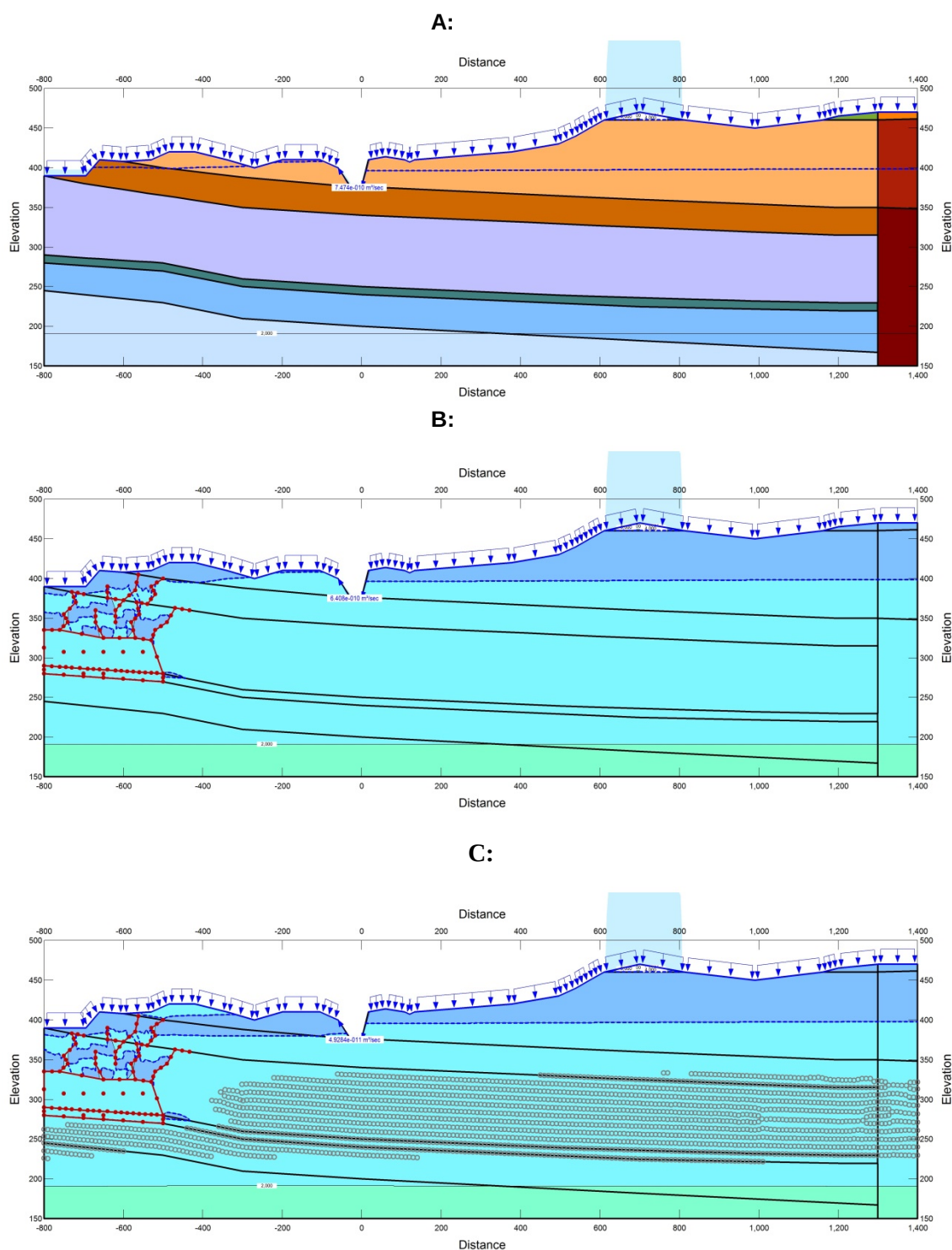


Figure 9:18 MCC model A) pre-mine stratigraphic version 0.01% annual rainfall infiltration recharge B) 2.14 years UG4 mining C) 40 years after UG4 mining. Groundwater flux rate at The Drip are shown in Table 9:10 Note: colours delineate geology in A (Table 9:7) and in B, C pore pressure contours at the modelled time. Scale: Elevation & Distance in metres

9.9.1 Estimated groundwater discharge and hydraulic heads

The pre-mining Drip model estimated groundwater discharge rate at the Drip of 2.3×10^{-6} m³/second, or 0.2m³/day for a one metre wide transect at the Goulburn River (Table 9:9). Extrapolated over a stream length of 10 kilometres this represents a possible baseflow contribution of approximately 2 ML/day from the Triassic hydrological unit. Within 2.14 years after longwall mining commences the modelled groundwater discharge is reduced by almost an order of magnitude down to 2.3×10^{-7} m³/s and 40 years after longwall mining it is still at a low 2.4×10^{-7} m³/s. The hydraulic head 700 m north of the river after 40 years is 18.5 m lower than pre-mining levels while levels at 40 m south of the river are about 6 m lower.

Table 9:9 Results of the Drip model (1) applying parameters in Table 8:8

The Drip Model (1)	Pre-mine	Mined	
Boundary Conditions	0 years	2.14 years	40 years
Rainfall Infiltration mm/year	5% - 33.6 mm		
Flux - m/s	1.07E-09		
Flux Rate m ³ /s (River baseflow)	2.28E-06	2.32E-07	2.42E-07
Flux Rate m ³ /day (River baseflow)	0.197	0.020	0.021
ML/day/10 kms (River baseflow)	1.97	0.20	0.21
Total head mAHD @ 700m north	409.5	390	391
Total Head mAHD@ 40 m South	384	378.4	377.8
Total Head @ The Drip (mAHD)	385	380	380

Table 9:10 Results for the Drip model with parameters assumed by UCML & MCC in Table 7.7 with 1% and 0.002% annual rainfall recharge

	UCML - model			MCC - model		
	Pre-mine	Mined		Pre-mine	Mined	
Boundary Conditions	0 years	2.14 years	40 years	0 years	2.14 years	40 years
Rainfall Infiltration mm/year	1%-6.72mm			0.002%-0.01mm		
Flux - m/s	2.13E-10			3.50E-13		
Flux Rate m ³ /s (River baseflow)	4.50E-07	4.13E-07	4.05E-07	7.47E-10	6.40E-10	4.93E-11
Flux Rate m ³ /day (River baseflow)	0.039	0.036	0.035	6.46E-05	5.53E-05	4.26E-06
ML/day/10 kms (River baseflow)	0.39	0.36	0.35	6.46E-04	5.53E-04	4.26E-05
Total head mAHD @ 700m north	419.5	409.6	409.6	400	400	400
Total Head mAHD@ 40 m Sth	387	385	385	408	407	383.5
Total Head mAHD@ The Drip	387	387	387	397	397	397

Unsaturated flow introduces many unknown variables so these simple numerical models have been run under saturated flow conditions (Pells and Pells, 2012b). The three numerical models indicate quite different baseflow discharges pre-mining, and post UG4 longwall mining impacts on the Triassic groundwater system:

- The Drip model (1) (Figure 9:16, Table 9:9) indicates mining UG4 will lower regional water table on both sides of the river by up to 20 metres at the northern point with the potential for a reduction in groundwater levels and seepage at The Drip cliff face by around 5 metres and an order of magnitude loss into the Goulburn River.
- In contrast UCML parameters (Figure 9:17; Table 9:10) predicts a fall of approximately 10 metres in the regional water table 700 meters to the north, with a slight reduction in baseflows and relatively no change in discharge at The Drip face.
- While MCC model (Figure 9:18; Table 9:10) indicates no change in Triassic SWLs in north, or at The Drip but a significant drop of 15 metres in groundwater levels south of the river.

Any value of groundwater discharge to the Goulburn can be generated by the parameter selection. Those selected for the UCML and MCC models require unrealistically low values for recharge in order to match the head distribution. The findings of models based on the mining company assumed parameters that mining will cause minimal impacts to river baseflow are hardly surprising. None of these models reflect reality; they are a tool to test uncertainty limits or a range of probable outcomes dependent on estimated parameters chosen by the modeller.

Here however, the hydrochemistry has indicated that some of the Triassic groundwater discharges at the Drip so lowering of Triassic groundwater levels due to mine depressurisation will impact on groundwater discharge to the upper Goulburn.

9.10 **Conclusion**

The aim of this chapter was to investigate the groundwater sources supplying an important, groundwater-dependent ecosystem (GDE) in the upper Goulburn, to explore the impact of groundwater extraction due to mining on a groundwater-on groundwater hydraulic heads in the vicinity of the GDE and to explore the potential influence on future mining expansion on river baseflow at the GDE.

As discussed in section 2.10, GDEs are widely recognised as vital indicators of the health of river-groundwater systems. The Drip formation GDE is a unique and protected stratified sandstone and ironstone cliff feature in the upper Goulburn. The permanence of The Drip groundwater discharge is supported by the presence of groundwater dependent vegetation species, remnant of a wetter period, and sustained through the major Federation, World War II, and 1980s droughts. Early 20th century photos confirm abundant growth of large water-dependent plants at The Drip.

Sampling of discharge at the Drip showed elevated relative levels of bicarbonate, sodium and magnesium ions; a slightly alkaline pH ~ 8 and a low EC in the range 380-580 $\mu\text{S}/\text{cm}$. The water character suggests a more complex groundwater source and higher salinity (EC) than fresh localised springs associated with perched water tables in upper Triassic strata that exhibit a simpler Na, Cl dominance. The hydrogeochemistry of The Drip discharge suggests interaction with basalt geology to the north and the regional Triassic groundwater system. The Drip groundwater type is similar to Triassic groundwater in monitoring piezometers located over 2 kilometres to the north of the GDE. Mining companies have assumed the Drip is fed from local perched groundwater with no connectivity to the regional groundwaters systems.

Unfortunately, groundwater monitoring bores were installed after mining commenced in the region and there was no monitoring of the Drip groundwater seep pre-mining. The standing water levels of the closest bores to the north, however, reveal that shortly after mining had commenced there was a hydraulic gradient towards the Drip with groundwater levels 20m above the Goulburn River. After long wall mining in the area, hydraulic heads in the regional Triassic groundwater system have reduced by 2 to over 26 m and the flow gradient in a substantial area has reversed towards the mined area due to the continued groundwater extraction at the mine. This head decline and flow reversal means that the magnitude of groundwater discharge at the Drip will have been reduced.

As underground mining expands, the depressurisation and hydraulic drawdown of Triassic groundwater that currently extends over two kilometres from the mining footprint will continue to spread over time. Groundwater inflow into the UCML underground mine has risen significantly over time (Table 6:4) with the widening of the underground mine footprint and is predicted to exceed 28 ML/day by 2023. Mine modelling predicts it will take 300 years for groundwater levels to return to a steady state (MER, 2015).

A simple two-dimensional numerical model was developed to explore the impact of a future approved underground mine located 500 metres to the south of the Drip, requiring the depressurisation of the regional groundwater system. This used a conceptual model of the known geological strata, and estimated permeabilities and porosities of the strata together with the widely accepted rainfall groundwater recharge rate of 5% average annual rainfall. The strata hydraulic properties were adjusted so that the modelled piezometric heads matched the pre-mining head distribution.

The model predicted pre-mining groundwater discharge to the Goulburn River in the vicinity of the Drip to be about 2 ML/day over a 10 kilometre reach. The model predicted that 40 years post mining the groundwater discharge would be reduced ten-fold to about 0.2 ML/day. The model was also run using hydraulic properties of the geological strata adopted by the mining companies in the area for their estimation of mining impacts. In order to match pre-mining piezometric heads, unrealistic values of groundwater recharge of 1% and 0.002% has to

be assumed. It is unsurprising that with the hydraulic properties assumed by the mining companies, they have predicted no impact on groundwater discharge to the Goulburn River.

Chapter 10: Conclusions

The UN's high level panel on water (UNHLPW, 2018) identified as a priority the prevention of degradation and pollution of rivers, lakes and aquifers, and where necessary, the restoration and maintenance of acceptable environmental conditions and water quality at the local, national and regional scale. Its Foundation for Action was based on three levels: understanding water; valuing water; and managing water. It recognised that many water crises are exacerbated by climate change. Three of the ten objectives of the Australian National Water Initiative were: transparent, statutory-based water planning; statutory provision for environmental and other public benefit outcomes and improved environmental management practices; and recognition of the connectivity between surface and groundwater resources with connected systems managed as a single resource. This work has applied the Foundation for Action to a river water quality issue, salinity, at the local scale, where natural processes are added to or altered by land-use change and climate variability. The focus is to better inform the planning process in a surface-groundwater connected river. While the greater than 7,800 km² catchment is of local concern, it has national economic and environmental significance. This final chapter summarises the main findings of this work, identifies areas for future research and suggests options to improve the sustainable management and use of water resources under changing climates and land uses.

The impacts of global change are particularly severe in coastal catchments. Economic and industrial development, increasing demands, expanding populations, waste disposal, nutrient discharge and the increase in frequency of extreme events impose significant constraints on water security in coastal catchments, especially in drier inland areas. All these are evident in eastern mid coast catchments of New South Wales. Adaptation to change requires understanding and disentangling the key processes driving catchment systems.

The starting hypotheses for this work were:

- 1) *The impacts of natural processes, land use change, and changing climate on stream discharge and stream salinity can be separately identified in highly variable catchments with multiple land uses.*
- 2) *Regulations can significantly alter stream salinity in catchments with existing natural salinity.*

The Goulburn River catchment, chosen for this study, is an economically and environmentally important multi-use catchment encompassing national parks, protected ecosystems, wide-spread grazing, cropping and irrigated agriculture and major open-cut and underground mining, as well as scattered townships. Additionally, it is the largest tributary of the Hunter River, a coastal river of national economic significance, where the Hunter River Salinity Trading Scheme, an economic and regulatory instrument, is used to control salinity

discharge from mining. The HRSTS, however, does not operate in the Goulburn whose salinity discharge to the Hunter challenges operation of the scheme. In order to optimally licence water extraction to provide water security for productive mining and agriculture, sustain settlements and communities, and maintain river health and GDEs it is necessary to understand the impact of variable and changing climate and altering land use on catchment yield, river discharge and its quality as well as identifying the processes operating in the catchment, including the consequences of regulations.

To examine these hypotheses the research was structured around seven aims to:

1. Assess the region's climatic characteristics, rainfall variability and trends and their influence on catchment yield and trends in catchment yield (*Chapter 4*).
2. Investigate at catchment-scale the sources, drivers and trends in stream salinity and salt loads (*Chapter 5*).
3. Quantify the impacts of mining discharge on flow and salinity in the upper Goulburn (*Chapter 6*).
4. Identify and characterise the dominant hydrogeological systems in the upper Goulburn catchment contributing to river baseflow (*Chapter 7*).
5. Investigate stream discharge and salinity, and surface-groundwater interactions of a predominantly cleared, agricultural sub-catchment of the Goulburn River (*Chapter 8*).
6. Identify groundwater sources feeding an important groundwater-dependent ecosystem in the upper Goulburn and investigate potential impacts of groundwater extraction and aquifer depressurisation from an approved mine development on the GDE and river baseflow (*Chapter 9*).
7. Summarise the main findings of this work, identify areas for future research and suggest options to improve the sustainable management and use of water resources under changing climate and land use (*Chapter 10*).

Because the hypotheses and aims involve long term impacts, this work has focused on available monthly and annual climate and river data supplemented where necessary with in-stream and groundwater measurements.

The literature review identified the large-scale ocean-atmosphere interactions that drive climate variability in eastern Australia and detailed the projections of global climate models on future changes to climate and implications for hydrology in the region. It also reviewed the differing theories on salt production in catchments from export of evapotranspiration concentrated meteoric salt to the contributions from the weathering and dissolution of parent geology and source aquifers. In addition, methods of determining baseflow and disentangling climate variability, climate change and land use change at the catchment scale were considered. The review also highlighted the importance in drier areas of groundwater discharge, especially

to GDEs and identified the impacts of not only salinity, but also stream chemistry on in-stream ecology.

The importance, general characteristics and diversity of the Goulburn study catchment as well as its geology and its importance to the Hunter were described in Chapter 3. Sources of information and the availability of data were highlighted. In a catchment with over 50% baseflow index, the interaction between ground and surface water is a key issue, particularly where mining intersects regional aquifers. There is, however, limited publicly available information on this interaction which is a focus of this research. The prevailing regulations and water sharing plans were detailed and previous work in the catchment discussed. If all licenced water allocations are consumed, between about one third and one half of the mean annual specific discharge would be used.

10.1 *Changing Climate*

This work used spatially interpolated monthly and annual rainfall and pan evaporation data for the Goulburn catchment based on a digital elevation model to cope with the considerable spatial variability of climate across the 7,840 km², topographically complex catchment. This showed considerable temporal variability with large departures which appeared linked to major regional ocean-atmosphere interactions, such as ENSO events, or oscillations of the Indian Ocean Dipole or the Pacific Decadal Oscillation (Verdon-Kidd *et al.*, 2010; Krishnan and Sugi, 2003). Since the PDO, in particular, has a 30 to 50-year period, identifying climate trends over shorter 30-year periods is problematic.

Climate change projections suggest that winter season rainfall in the general region will decrease (CSIRO, 2015). Over the last 100 years, cooler season, April to September rainfall in the Goulburn has shown two statistically significant 30-year decreasing linear trends in rainfall of -40 mm/decade that started in 1948 and 1983, in line with projections. These decreases, however, are balanced by two equally statistically significant periods of increasing rainfall of +40 mm/decade starting in the 1920's and in the 1960s. These oscillations have a similar period to the PDO.

When change over the longer period is considered, these large swings make it difficult to identify statistically significant climate trends. It was shown in the Goulburn catchment between 1920 and 2014 there were no significant ($p > 0.9$) trends in annual or cooler season rainfall nor in annual, cool or warm season Epan between 1970 and 2014 using linear regression and non-parametric trend analysis (Theil, 1950). Other studies in Australia and elsewhere have reported decreasing trends in Epan due to global “dimming” or “stilling” (Stanhill and Cohen, 2001; Roderick and Farquhar, 2002; Roderick *et al.*, 2007). A statistically significant ($p > 0.95$) increasing trend in warmer season rainfall of about +10 mm/decade was found between 1920 and 2014, in contrast with the projected trends from global climate models (CSIRO, 2015).

The most severe meteorological droughts in eastern Australia occurred during the 1900s, 1940s, 1980s and 2000s coinciding with periods when a positive IOD was in phase with El Niño. In this work, one, five and 10 year cumulative rainfall percentiles were used to identify prolonged dry periods expected to impact significantly on river discharge. It was found that the so-called World War II drought in the 1940s was both the most extended and severe meteorological drought over all three cumulative rainfall periods, much more than the widely discussed millennium drought in the decade after 2000.

10.2 *Changing Stream Discharge*

Stream discharge records were available over different time periods at three gauging sites in the Goulburn. Two gauging stations have mobile sand bed controls with potential for gauge by-pass flow and are problematic. The most reliable and longest-term record comes from Coggan (GS210006), which measures discharge from the upper 50% of the catchment. These monthly discharge records showed large swings in stream discharge, with zero flows recorded. These large swings coincide with the flood- and drought-dominated periods identified by Erskine and Warner (1998). Between 1920 and 2014, no statistically significant trends in annual, cool or warm season stream discharge were found, despite the finding that warm season rainfall was increasing, but in a season when evapotranspiration is highest.

It was found that stream discharge in the Goulburn was significantly less during the millennium drought than during the record 1940s drought. The shorter and less intense millennium drought had the lowest minimum 5-year runoff coefficients. Since annual rainfall and pan evaporation haven't changed significantly over this period, it suggests a change in catchment characteristics between the 1940s and 2000.

It was found that the extremely low stream discharges post 1970s could not be attributed to unusually low rainfalls or changes in the rainfall distribution. The overall results indicate a decrease in catchment yield post 1970s. Simple mass balance estimations pre- and post-1982 over two 32-year periods suggest a loss in specific discharge of around -10 mm/year from the catchment. Over the same period, an examination of the percentile distributions pre- and post-1982 showed a loss in baseflow post-1982 which could not be attributed to a change in rainfall distributions over the two periods. Reduced yields could be due to a combination of factors such as an overall increase in water extraction; greater retention of surface runoff in farm dams constructed in the 1960s to 1980s for flood mitigation and erosion control; increased ET by native vegetation regrowth or increased groundwater extraction and surface water interception and consumption by mining. The change in catchment yield has significant implications for both regulations and water licencing in the catchment.

An examination of long-term stream elasticity of discharge over 20-year periods from 1913 to 2012 in the upper Goulburn revealed the elasticity over the last 20-year period from 1993 to

2012 was much less than one, three times smaller than the lowest of other 20 year periods. This indicates a general decoupling of stream discharge to rainfall and an extra source of discharge. This period coincides with increasing mine water discharge in the upper Goulburn.

10.3 **Stream Salinity**

A spot survey of EC, used widely as an indicator of salinity, in the Goulburn River and tributaries revealed a wide array of sources of salinity, particularly below an elevation of about 280 mAHD. These were associated with tributaries incising into geologies with higher salinity aquifers, such as the Permian Coal Measures and Jurassic shales. Discharges from Ulan Coal mine, Wollar Creek, the Merriwa River and Wybong and Bylong Creek all increase EC in the Goulburn River. Importantly, in terms of downstream discharge into the Hunter River, tributaries and groundwater flowing from lower salinity geologies and catchments dominated by Triassic sandstones and Tertiary volcanics mitigate salinity in the Goulburn. These include seepage from springs and GDEs such as The Drip, and discharge from the Munmurra and Krui Rivers, and Widden Brook. An important conclusion here is that extracting more water for other uses from these lower salinity catchments will increase the salinity of Goulburn discharge into the Hunter. Equally important, any decrease in rainfall with climate change, particularly that projected in the cooler season, will also decrease discharge and increase salinity.

The significant decrease in catchment yield starting in the 1970s found in this study has important ramifications for trends in stream salinity. An intimate, inverse relation between salinity and stream discharge was found in the Goulburn, as in the Murray-Darling (Jolly *et al.*, 2001). This relation implies a relatively simple two component model of stream salinity with more saline groundwater discharge into fresher surface runoff. This means that a decrease in discharge, particularly by extracting or intercepting fresher groundwater or runoff, will increase stream salinity. Although full exploration of this is not possible due to the absence of pre-1960s salinity data, spot measurements of EC from 1969 revealed a shift in the percentile distribution of EC between 1969 and 1982 and 2012 to 2016. The mean EC in the period 1969 to 1982 was significantly lower than that for the period 2012 to 2016 despite the latter period having a higher geometric mean discharge. Further increases in fresh water abstraction or degradation of fresh groundwater sources will lead to additional salinity increases.

Overlapping, continuous EC and flow records were only available from 2012 at all three gauging stations. This is despite ad hoc mine discharge being permitted from 1984 until 1994 when the discharge of mine water excess to operational needs was changed to limit volume, followed by an upper limit on salinity levels after June 2007. Two estimates of the annual specific catchment salt yield at the gauging sites gave values ranging from about 5.3 - 6.3 tonnes/km²/year consistent with previous estimates.

Analysis of continuous salinity data at all three active gauging stations in the Goulburn revealed problems in the gauging stations at both Kerrabee and the downstream Sandy Hollow, which is the main station for assessing salinity contributions to the Hunter. These appear due to the mobile sand bed controls at the two downstream sites.

10.4 *Mining impacts*

Pre-mining spot EC data prior to the introduction of large scale open cut and long wall mining in the upper Goulburn showed the upstream section had a mean EC that was only 55% of the currently regulated maximum salinity limit for mine discharge of 900 μ S/cm. Adopting this limit automatically ensured that salinity in the upper Goulburn River would always exceed pre-mining levels during mine discharge in drier times.

While volumes of water discharged to the Goulburn are also regulated, the volume of groundwater intercepted by mines has exceeded predicted levels. Mine modelling has proved unable to reliably predict the scale of impacts on groundwater resources and mine water discharge at the headwaters of the catchment. Using historic monitoring of the salinity of the Goulburn River 7 km below the mine discharge point it has been possible to track the changing regulations applied to mining-post 1990 through changing stream EC. Until 2003, discharge volume was regulated but discharge salinity was unregulated. This resulted in major fluctuations in stream salinity with EC exceeding 2000 μ S/cm. After June 2007, when the maximum EC of discharge was limited to 900 EC, the fluctuations dramatically reduced but mean EC remained higher than the pre-mining ambient EC.

Estimation of the specific salt yield from mines in the Goulburn for the period 2012 to 2016 was 11 times greater than that of the Goulburn catchment. It was shown over this period mine salt discharge was over 13% of the total salt discharge at Coggan and nearly 7% of the salt discharge at Sandy Hollow while the ratio of mined area to catchment area was only 1.4%. The elasticity of stream flow at Coggan discussed above suggested an extra source of water in the catchment uncorrelated with rainfall. During dry periods almost all the flow and salt load in the upper Goulburn is due to mine discharge. The accumulation of these salts in alluvial sediments along river reaches during low intermittent flows would contribute to elevated salt loads during wetter periods when flushed downstream during high flows.

Both regulations and monitoring have only focused on salinity concentration or EC as the key determinant of water quality. This however assumes that only the total salt concentration rather than the composition of salt is environmentally important. The literature suggests otherwise.

10.5 Catchment hydrogeochemistry

River sampling revealed increasing inputs of HCO_3 at elevations below about 280 m AHD, not only from Tertiary basalt in the northern tributaries but starting with discharge from upstream Wollar Creek sourced from incised Permian Coal measures and alluvium. Discharge in the lower catchment from Wybong Creek is characterised by inputs from both coal measures, similar to those for Wollar, and basalt geology. In the lower catchment this is mitigated by lower HCO_3 and lower salinity discharge from the Widden draining from higher elevation Triassic sandstones.

The rise in HCO_3 inputs are accompanied by increasing concentrations of Mg and Ca again sourced mainly from basalt in the northern tributaries. Inputs of SO_4 were characteristic of drainage from the Permian coal measures, possibly due to pyrite oxidation. It was also characteristic of the treated mine water discharged into the river at Ulan. This means that much of the flow in the upper Goulburn is now dominated by SO_4 .

Groundwater major ion geochemistry was useful in “fingerprinting” sources. An unusual characteristic of groundwater from the Permian coal measurements was unusually high concentrations of K, perhaps an indication of the longer groundwater residence time. It was found that K concentrations in lower Triassic-Upper Permian strata were elevated suggesting vertical exchange between the Permian and Triassic. The range of K concentrations in the Permian groundwater samples may reflect different groundwater ages, but there was insufficient data in the mining reports to test this. The need for a well-managed accessible source of both government and industry groundwater data is clearly warranted.

Upper Goulburn river water chemistry sampled over a period when there was no mine discharge during a prolonged dry period showed that the source of baseflow in the upper Goulburn was Triassic strata. Mining has decreased discharge from Triassic hydrogeological strata into the upper Goulburn, with mine depressurisation causing some head gradient reversal away from the river.

A critical point is that the chemistry of Triassic discharge shown to occur in the upper Goulburn differs substantially from that of the treated mine waste water regarding the latter's ionic composition and in particular it's high SO_4 concentration. Regulations concerning mine discharge only specify a maximum salinity for discharge without regard to chemistry. There is no information on the impact of the change in water chemistry and toxicity on the in-stream ecology of the upper Goulburn (Krogh, 2018). Further research into the toxic effects of differing ionic composition in this area is urgently required. It is recommended that salinity standards for specific ions and ionic mixtures should be developed for mine discharge water to protect downstream aquatic life (Cañedo-Argüelles *et al.*, 2016).

Two northern catchments, Murrumbidgee Creek and the Merriwa River are both sourced from Tertiary basalt but are incised into more saline Jurassic Purlewaugh Siltstone. Little is known about these catchments.

10.6 *Salinity discharge from an agricultural catchment, the Merriwa River*

This work has carried out the first detailed study of water and salt yield from the Merriwa River, the major tributary of the Goulburn River, and a predominantly cleared, agricultural catchment. Merriwa River is sourced in Tertiary basalts and then intersects Jurassic sediments and cuts across Triassic strata before being exposed to Permian Coal measures as it enters the Goulburn. The basalt-derived soils support cropping, irrigation and grazing and groundwater is extensively used for both agriculture and townships in addition to surface water abstraction. Climate is similar to that in the upper Goulburn.

The sparse stream discharge records together with large flow variability make identifying significant trends in stream flow impossible. The data is sufficient, however, to show that the long-term runoff from the catchment is about 4.5% of mean annual rainfall, higher than the more forested Goulburn catchment. There was a strong correlation between annual stream discharges at the two gauging stations on the Merriwa River; however, there were consistent losses in the region where the river intersects Jurassic sediments below the town of Merriwa.

Compared with the upper Goulburn, the salinity record in the Merriwa is relatively long, dating back to 2003, and covering part of the millennium drought. Average annual stream salinities have always exceeded the HRSTS limit of 900 $\mu\text{S}/\text{cm}$. The relationship between EC and stream discharge points to a baseflow source of high salinity. Maintaining flow in the Merriwa will ensure lower stream salinity. The salinity data revealed that the catchments specific salt yield was 20 tonnes/ km^2 /year, which is 3 to 4 times the annual specific salt yield of the Goulburn. This means that the Merriwa River is a more important source of salt than Wybong Creek so that water licencing and catchment management are especially important.

A transect of the River during a dry period revealed increasing salinity downstream. The chemistry of the waters revealed a transition between the Tertiary basalt derived HCO_3 rich waters in the upper catchment and NaCl dominant water in the lower catchment. This transition occurs where the River incised into Jurassic sediments and salinity is most likely derived from Purlewaugh-Comialla siltstone strata which produce NaCl dominant waters. The main contributor of solutes to streamflow and groundwater in the Merriwa River is from water-weathering rather than evapo-concentration of meteoric salt.

Groundwater geochemistry revealed important, potable groundwater sources in Merriwa catchment have a closer association with the underlying lower Triassic-upper Permian regional groundwater system than the previously thought Jurassic hydrological units of the Oxley Basin.

In addition, the hydraulic gradient towards the river and the significant change in hydrochemistry at Merriwa suggests surface-groundwater interaction and or connectivity via faults or fractures. This requires further research.

Water management is the key to managing salinity in this catchment. The inverse relation between stream salinity and stream discharge means that granting additional water licences, failing to regulate and monitor water use in the catchment, or decreasing rainfall or increasing evaporation will increase salinity discharged into the Goulburn from the Merriwa River. This is a dilemma since the basalt-derived soils in the catchment are highly productive.

10.7 Groundwater-dependent ecosystems and mine dewatering

Groundwater-dependent ecosystems are recognised in Australia and elsewhere as vital indicators of the health of river-groundwater systems. The legal protection of GDEs are restricted to those considered as high priority that are listed and mapped in WSPs with the demands on groundwater by licensed users taken into account. However there are significant gaps in the identification and mapping of GDES in the Goulburn catchment.

The Drip formation GDE is a unique and protected stratified sandstone and ironstone cliff feature in the upper Goulburn. The permanence of The Drip groundwater discharge is supported by the presence of groundwater dependent vegetation communities, and species remnant of a wetter period, that have been sustained through the major Federation, World War II, and 1980s droughts. Early 20th century photos confirm abundant growth of large water-dependent plants at The Drip.

Mining industry reports suggest The Drip is sourced from local, perched groundwater. Sampling of discharge at The Drip showed elevated relative concentrations of HCO_3^- , Na and Mg ions; a slightly alkaline pH ~ 8 and a low EC in the range 380-580 $\mu\text{S}/\text{cm}$. The water character shows a more complex groundwater source and larger EC than fresh localised springs associated with perched water tables in the upper Triassic strata that exhibit a simpler Na, Cl dominance. The hydrogeochemistry of The Drip discharge suggests interaction with basalt geology to the north and the regional Triassic groundwater system. This means that lowering of Triassic groundwater pressures is likely to decrease discharge at The Drip over time.

Groundwater monitoring bores were installed after mining commenced in the region. The standing water levels of the closest bores to the north show that shortly after commencement of mining there was a hydraulic gradient towards The Drip with groundwater levels being 20 m above the Goulburn River. After long wall mining in the area, hydraulic heads reduced by 2 to over 14 m and the flow gradient in a substantial area has reversed towards the mined area due to the continued groundwater extraction at the mine. This head decrease and flow reversal means that the magnitude of groundwater flow towards The Drip has been reduced.

As underground mining expands, the depressurisation and hydraulic drawdown of Triassic groundwater that currently extends over two kilometres from the mining footprint will continue to spread over time. In 2014-2015 groundwater inflow into the UCML underground mine averaged 16.2 ML/day (UCML, 2015b). This is predicted to increase to over 28 ML/day by 2023. Mine modelling predicts it will take 300 years for groundwater levels to achieve a steady state (MER, 2015).

A simple two-dimensional numerical model was developed to examine the potential impact of a proposed underground mine immediately adjacent to the Drip. This was based on a conceptual model of the known geological strata, and the model used estimated permeabilities and porosities of the strata together with the widely accepted rainfall groundwater recharge rate of 5% average annual rainfall. The strata hydraulic properties were adjusted so that the modelled piezometric heads matched the pre-mining head distribution.

The model predicted pre-mining groundwater discharge to the Goulburn in the vicinity of the Drip to be about 2 ML/day. The model projected that even 40 years after mining, groundwater discharge would be reduced ten-fold to about 0.2 ML/day due to mine depressurisation of groundwater. The model was also run using hydraulic properties of the geological strata adopted by the mining companies in the area for their estimation of mining impacts. In order to match pre-mining piezometric heads, unrealistic values of groundwater recharge of 1% and 0.002% of annual rainfall had to be used. Suggesting that the mining company assumed permeabilities are too low. As a consequence, these models showed surface ponding of up to 100 m deep in order to match the head distribution and insignificant groundwater discharge rates at the Drip.

Before mining, flow in the Goulburn below the Drip persisted even in extreme droughts. During a recent 2017-2018 dry period, when mines stopped discharging treated waste water, flow in the Goulburn at the Drip ceased. This suggests that baseflow in the upper river has been greatly diminished and is normally replaced with treated mine water discharge. The long-term consequences of reductions in groundwater discharge on the resilience of the iconic Drip GDE are a major concern.

10.8 *Hypotheses*

Two underlying hypotheses formed the basis for this work:

- 1) *The impacts of natural processes, land use change, and changing climate on stream discharge and stream salinity can be separately identified in highly variable catchments with multiple land uses.*
- 2) *Regulations can significantly alter stream salinity in catchments with existing natural salinity.*

It has been demonstrated that despite the large swings in climate in south eastern Australia due to major ocean-atmosphere interactions over the past 100 years, and catchment heterogeneity in terms of geology, topography, land use and vegetation, that existing techniques were able to show a change in the long-response of the catchment to rainfall is not driven by changing or variable climate. Rather this change results from the loss or abstraction of fresher water from the catchment. The discharge of higher salinity groundwater from particular strata in the catchment means that this loss of fresher water results in increased stream salinity downstream.

The regulations in the study catchment cover many aspects of water use, land use and environmental protection. Water abstraction licences in the catchment amount to a minimum of between one third and one half of mean annual discharge of the Goulburn. The intimate relation between stream salinity and stream discharge mean that fresh water abstraction increases stream salinity which is most evident during drier periods. In addition, mining discharge has been subject to a variety of regulations over the past 30 years whose impacts on stream salinity are clear. Regulations permitting mine dewatering replace baseflow fed by groundwater discharge with mine waste water discharge. The current maximum limit for salinity of waste water discharge was set at almost twice the ambient salinity of the upstream river pre-mining.

10.9 *Areas for future research*

This work has revealed areas in which future research is required;

- 1) The large interdecadal swings in climate in eastern Australia pose a significant problem for water allocation. The setting of more flexible regulations to prevent over allocation in drier times requires additional research.
- 2) In the study region regulations permit farms and mines to intercept 10% of the mean annual runoff. There is no available information on the amount of surface water stored in small dams and ponds or its impact on stream discharge.
- 3) It was not possible in this work to estimate the impact of vegetation change on long-term stream discharge. Separating the impacts of water abstraction, water interception and changes in vegetation would provide useful information for water planners
- 4) Investigation of surface-groundwater interaction and salinity sources in the Merriwa catchment to assist in salinity management in the Hunter catchment is needed.
- 5) Water discharge regulations in mined catchments use easily measured salinity as a gross indicator of water quality. In-stream ecology, however, is sensitive to the composition of that salinity. Research on refining the discharge requirements for salinity in terms of ionic composition and relative toxicity on aquatic biota is needed.

- 6) Groundwater dependent ecosystems are vital to stream health and provide a window in groundwater – surface water connectivity. There is a pressing case for the mapping and assessment of GDEs in the Goulburn catchment.
- 7) A detailed analysis of the accuracy of all gauging stations in the Goulburn River and ratings tables over critical periods such as low and high flows.
- 8) The development of scientifically robust, risk appropriate, site specific triggers is necessary to assist water and land managers maintain the resilience of natural systems and protect them against future extreme climate events.
- 9) A comprehensive independent assessment of the cumulative impacts of mining developments on the Goulburn catchment is clearly needed.

10.10 ***Policy, regulations and River management***

Knowledge gained from this research contributes to the sustainable management of connected surface and groundwater resources as a single resource³² subject to changing land use in an uncertain, highly variable climate.

- 1) Water allocation licences for the Goulburn appear to disregard the varying geology of the catchment and the impact of different geologies on stream salinity. Southern streams draining the Triassic sandstones mitigate salinity in the Goulburn, while some of the northern streams contribute higher salt yields. Regulations on water abstraction need to be developed which have control of stream salinity as a key outcome.
- 2) The regulation permitting the interception of 10% of mean annual runoff should be reviewed in catchments that have salinity challenges.
- 3) Management objectives that permit the discharge of mine water with a maximum 900 EC are inappropriate for the upper Goulburn catchment. The permitted salinity levels of mine discharge water should reflect pre-mining levels.
- 4) Groundwater needs to be mapped in the Goulburn catchment. The management of water resources and surface groundwater interaction requires better understanding of the fractured and porous rock groundwater system
- 5) Accessing information on mine water use, discharge and quality is difficult and is not standardised. A readily accessible centralised data base combining government, industry and research data would greatly assist catchment management and monitoring.
- 6) The complexity of geological strata and multifarious impacts of mining call into question the reliance on groundwater models over time. This work has shown the profound differences between modelled impacts on groundwater due to mining depend

³² National Water Initiative goal

on the choices of hydraulic properties. Verification and validation of the original models should be transparent and subject to ongoing scrutiny and reassessment.

- 7) This work has demonstrated the gaps and uncertainties in catchment monitoring in a mined catchment with very limited pre-mining groundwater and water quality data. There are lessons here that need to be applied in the future.

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Appendix A: Interpolated climate data

Coggan interpolated data 1920-2016 (precipitation and evaporation)

Sandy Hollow interpolated data 1920-2014 (precipitation and evaporation)

Merriwa interpolated data 1920-2014 (precipitation and evaporation)

(**Source:** Prof. Michael Hutchinson ANU – Data as Zipfile can be provided)

Appendix B: Analysis stream data, infilling data gaps and testing daily stream ratings

Historical and current stream gauge discharge (*ML/day*) and conductivity (*EC*) data was downloaded from Department Primary Industries – Office of Water website - Rivers and Streams (DPI Water, 2018)

Calculating catchment yield and infilling data gaps

When records were complete the daily flow data (Q_d) was summed for each month to calculate monthly flow (Q_m ; **MLd**)

$$Q_m = \sum Q_d$$

Monthly catchment yield R_m (mm) = runoff ($Q_m / A - \text{km}^2$ catchment area DEM above stream gauge).

The relationship between Q_m and P_m (monthly precipitation) was used to infill gaps in the monthly flow data. Missing 'x' monthly flow data ' Q_{mx} ' were infilled by multiplying the total monthly rainfall for that month P_{mx} by a correlation factor calculated from the ratio of average monthly yield to mean monthly rainfall (mm) based on spatially interpolated rainfall³³ 1920-2014

$$R_{mx} = P_{mx} * C$$

$C = R_m : P_m$ (dimensionless coefficient relating the amount of runoff to the amount of precipitation received)

Files:

Coggan 210006 infilling Missing Stream Discharge 2016 11.xlsx

Sandy Hollow 210031 Cleaning of EC and Q data.doc

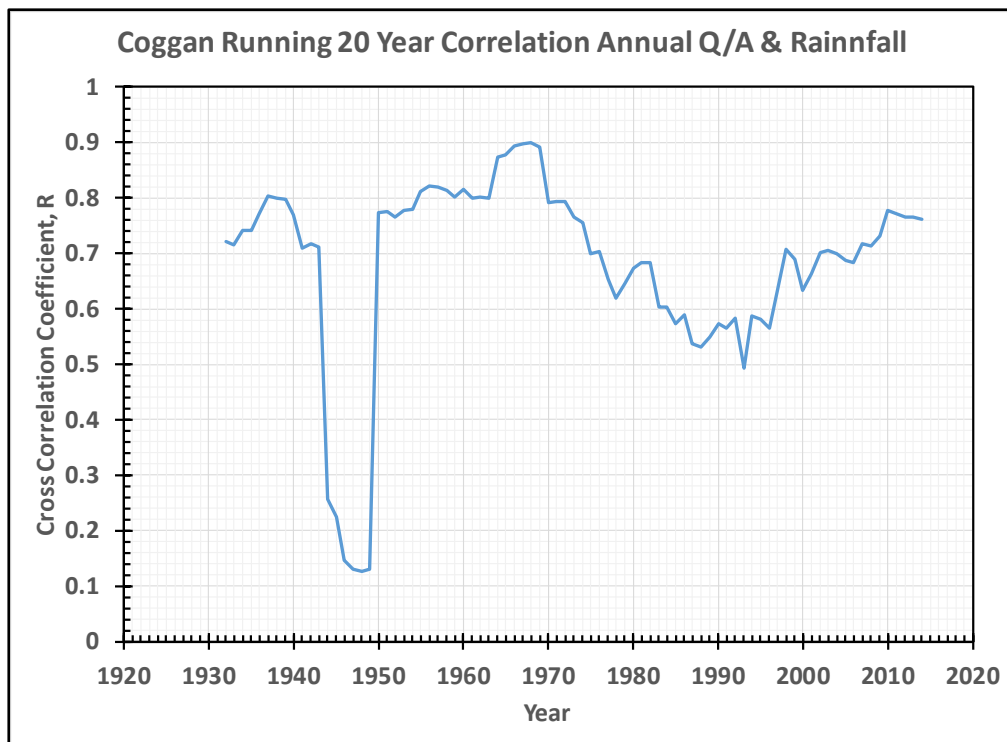
B1: Coggan anomalous stream discharge 1943-1944

Coggan has anomalous discharge in the years 1943-44. The table below shows the total annual specific stream discharge, Q/A, and the total annual rainfall.

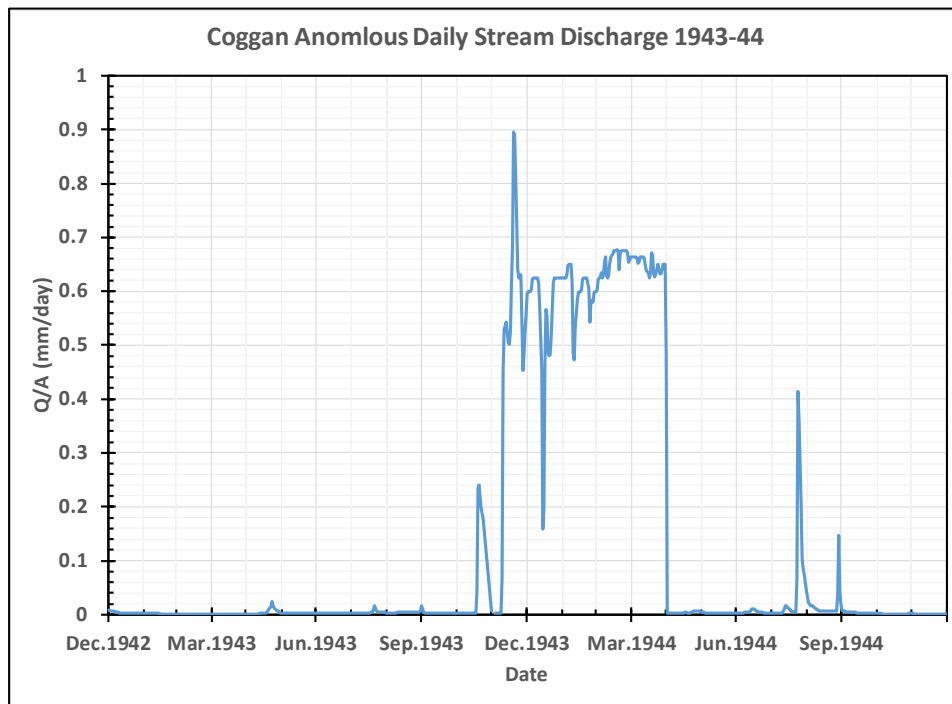
Year	Q/A (mm)	P (mm)
1943	3.31	547
1944	76.90	472

While annual discharge depends on the timing of rainfall events, there is nothing in the rainfall data to show exceptionally large monthly rainfall in 1944.

When we look at a 20 year running cross correlation coefficient between rainfall and stream discharge there is a marked step anomaly after 1943 as shown below.



It appears that there is indeed anomalous data in 1943-44. In order to investigate these further we examine the daily streamflow record for 1942 and 1943 below.



It is clear that the stream discharge data from December 1943 to end April 1944 is anomalous. The discharge peaks in Nov 1943 and August 1944 show the typical rapid rise and gradual decline in stream flow expected as a response to rainfall. The data from December 1943 to end of April 1994 shows an atypical block response typical of a fault at the stream flow gauge.

It is concluded that the record of discharge from December 1943 to April 1944 is an error and should be removed from the record.

B2: Changes in Coggan gauge ratings

The impacts of any changes at the stream flow gauge at the stream flow gauge was analysed in using running average over 30 years of the minimum and average daily gauge height, GH (m), compared to the 30 year running average of the daily stream discharge. Stream discharge, Q (ML/day) is derived from the gauge height via rating curves. It is assumed the average minimum GH is close to the gauge zero for no flow. Significant changes in gauge zero height, GH_0 , indicate major changes in the geometry of the gauging site. The average gauge height, GH_{AV} , gives an indication of average stream height above gauge zero. The difference between average and minimum, $GH_{AV}-GH_0$ indicates the average driving head for flow.

Raw daily water level data and daily discharge were used without infilling missing data. The anomalous gauge heights and discharges found for the period 10 December 1943 to 30 April 1944 were removed as were spurious zero flows at the very start of the record.

Results

Figure 1 shows the 30 year running average minimum GH₀.

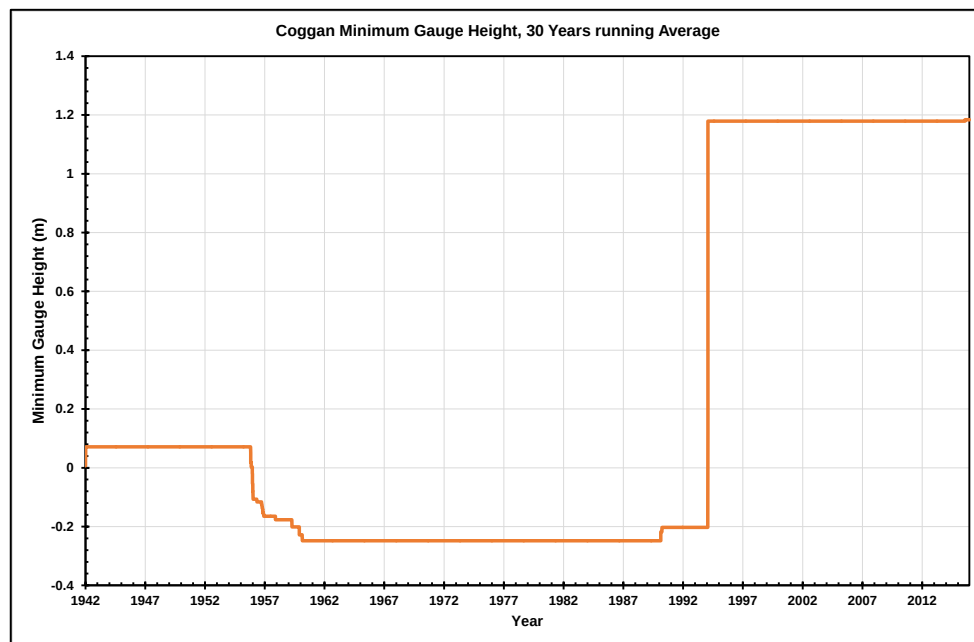


Figure 1. Coggan, 30 year running minimum daily stream gauge height 1913-2016

From Figure 1 there seem to have been approximately three minimum stream gauge heights at the Coggan gauge. These are summarised in Table 1.

Table 1. Minimum daily stream GH over running consecutive 30 year, Coggan

Period	Minimum Daily Gauge Height over 30 years (m)	Comments
10/1/1943 to 25/10/56	0.071	13 Year Period
26/10/1956 to 7/1/1957	0.071 to -0.107	Transition Period
8/01/1957 to 2/5/1957	-0.107	
5/5/1957 to 23/9/1957	-0.116	
24/9/1957 to 29/11/1957	-0.116 to -0.165	Transition Period
30/11/1957 to 21/11/1958	-0.165	
24/11/1958 to 8/4/1960	-0.177	
21/11/1960 to 14/2/1961	-0.228	
21/2/1961 to 16/02/1991	-0.248	30 Year Period
18/2/1991 to 24/3/1991	-0.248 to -0.203	Transition Period
25/3/1991 to 22/1/1995	-0.203	4 Year Period
23/1/1995 to 1/8/2016	1.179	11 Year Period
2/8/2016 to 8/12/2016	1.184	

Table 1 and Figure 1 show there were four major long-term changes to the minimum gauge height: 0.071 m which ended in late October 1956, probably following the record-breaking 1956 floods; a very long period from February 1961 to February 1991 where the minimum gauge height was -0.248 m; a shorter period from March 1991 to January 1995 with GH_0 of -0.203 m; and a period from January 1995 to August 2016 where GH_0 was 1.1179 m. From these it seems safe to conclude that the change in long-term ET estimated over 30 years that commenced in about 1980, was not due to a dramatic change of stream gauge configuration.

We will now examine how the above changes in GH_0 have impacted on the average water level over consecutive running 30 year periods which are plotted in Figure 2. It is immediately obvious in Figure 2 that there are also transition periods in the average gauge height which appear to correspond to the changes in GH_0 . Table 2 lists the dates of the transition points in average gauge heights.

Table 2. Transition points in the average gauge height and the conditions prior to the transition

Date	Prior Conditions
17/12/1956	Prior to this date fluctuating $GH_{AV} \approx 0.35$ m
30/2/1965	Linear decline in GH_{AV} to 0.27 m
25/01/1995	Marked linear increase to $GH_{AV} \approx 1.54$ m
26/11/2000	Relatively constant $GH_{AV} \approx 1.55$ m
12/2016	Approx linear decline in GH_{AV} to 1.46 m

Again there were no marked transitions in GH_{AV} around 1980. It appears that two of the transitions apparent in the average gauge height record correspond to changes in the minimum gauge height in 1956 and in 1995. The marked 30 year linear increase in GH_{AV} from 1965 to 1995 is described by the highly significant relation:

$$GH_{AV} = (1.13702 \pm 0.00053) * 10^{-4} * t - (2.4400 \pm 0.0016) \quad R^2 = 0.998$$

Where t is in days. This shows an increase in average stream gauge height of 41.5 mm/year.

The difference between GH_{AV} and GH_0 gives an indication of the actual river height above cease to flow conditions this difference is shown in Figure 3.

The question is how was this marked difference especially in January 1995 taken into account in the gauge rating curve in order to estimate stream discharge. Figure 4 shows the comparison between stream discharge, Q (ML/day) and the difference between GH_{AV} and GH_0 .

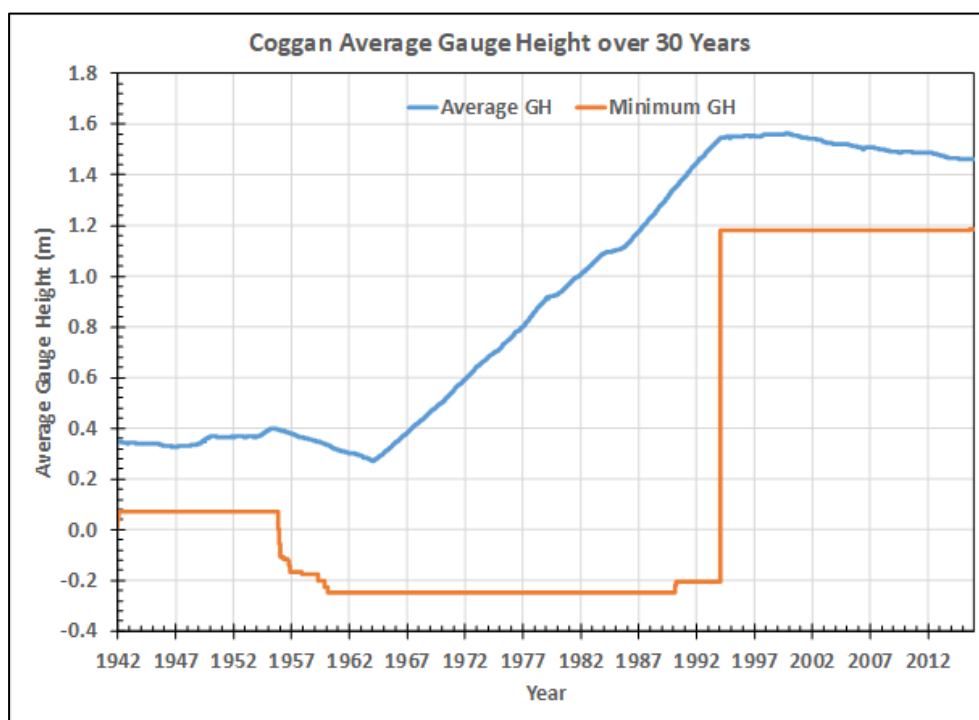


Figure 2. Average stream gauge height over 30 year periods compared with the minimum gauge height over the same period.

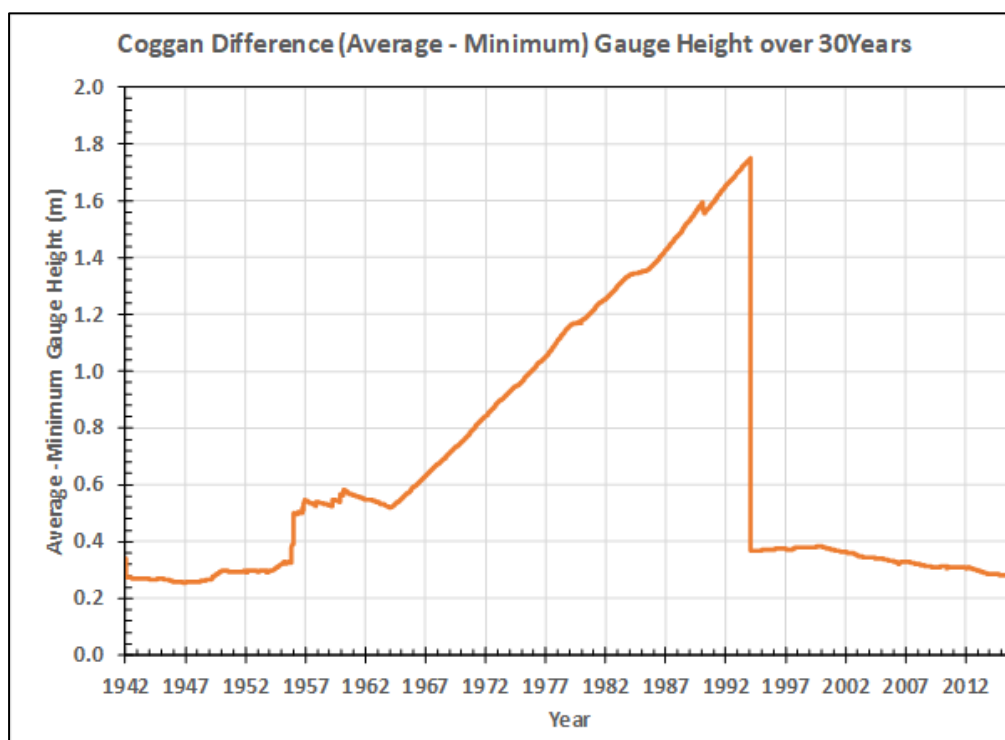


Figure 3. Difference between the 30 year averaged gauge height and the 30 year averaged minimum height

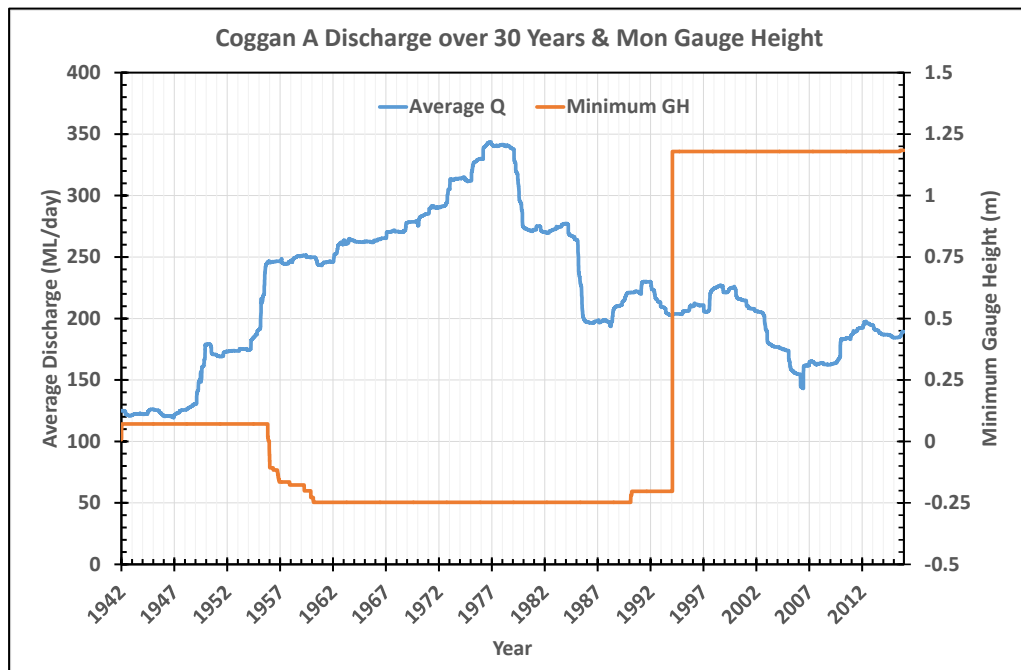


Figure 4. Comparison between the stream discharge averaged over 30 year periods and the difference between the average and minimum GH averaged over the same period.

It appears from Figure 4, that the abrupt change in $GH_{AV} - GH_0$ in January 1995 had no dramatic impact on the estimated stream discharge which suggests that the rating curve has constantly been adjusted over the period from 1965 to 1995 when GH_{AV} increased linearly.

Conclusions

1. The marked linear increase of average stream gauge height from 1965 to 1995 of 41.5 mm/year does not correspond to any shift in the minimum gauge height but is abruptly ended in January 1995 when the minimum stream gauge height was adjusted.
2. This linear increase does not seem to be reflected in the average stream discharge suggesting that the ratings curve was adjusted during this period.
3. The change in minimum gauge height in January 1995 which persisted to Aug 2016 approximately corresponds to the 1993 to 2012 period where the percentile distribution of stream flow over 20 years was the lowest of any 20 year period on record despite the rainfall being amongst the highest for a large part of the percentile range.
4. From June 1990, the daily raw data record provides quality ratings comments on the data. For the period January 1994 to July 1996, the period of the abrupt change in GH_0 , the comments say that “38 - Pre 1 Nov 1996 - RATINGS/TS - Good record processed prior to 1/11/96:

Files: *Coggan changes in reference gauge heights.doc (Dec 2016)*

Coggan Catchment ET estimation long term water balance rev.xlsx

Appendix C: GDEs examples Goulburn catchment

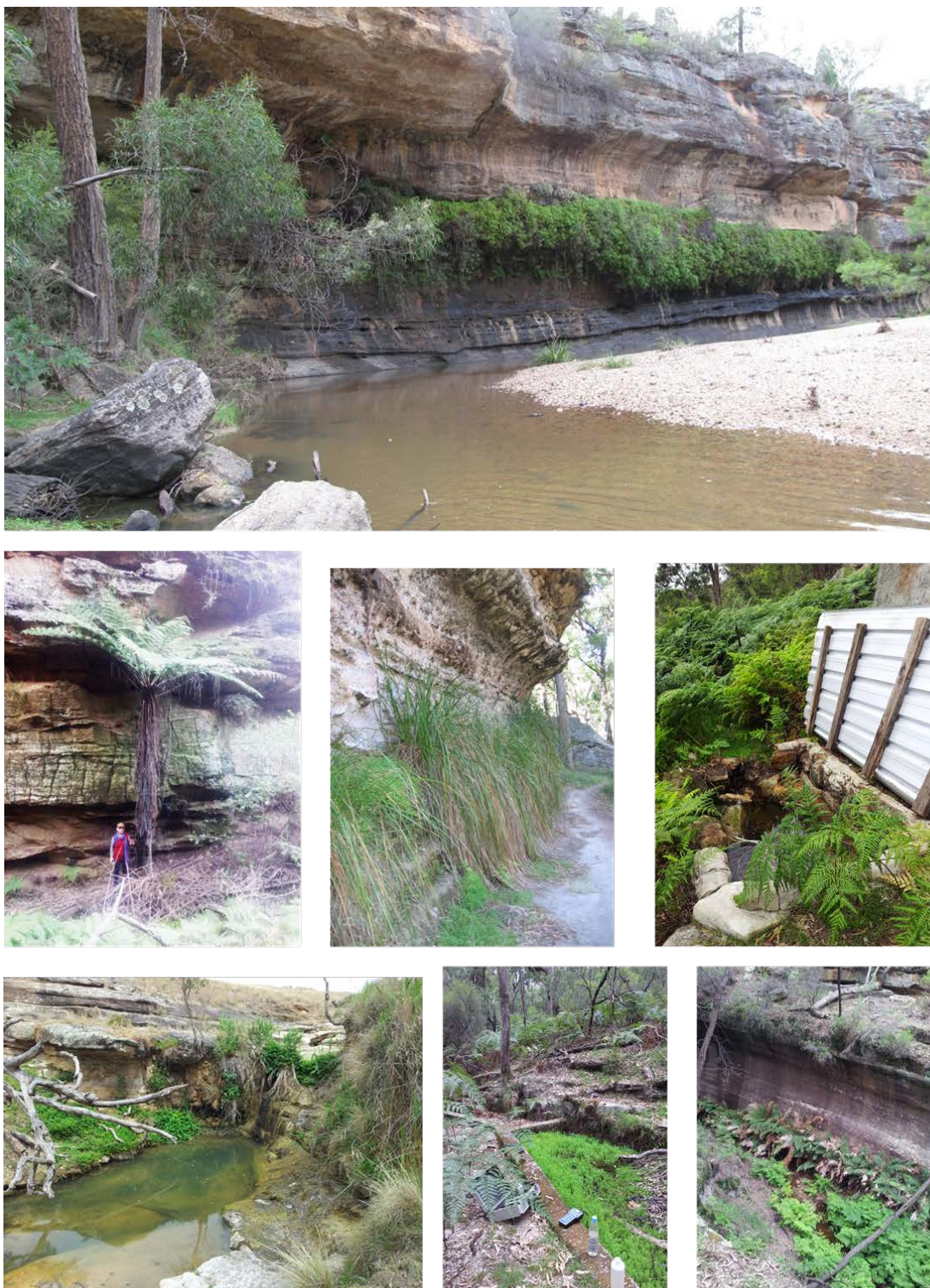


Figure A1: Ferns and a range of plant species dependent on seeps, springs and shallow groundwater in sedimentary geology; Photo 1 – weeping callistemon and ferns downstream from The Drip; Photo 2 – tall tree-ferns in sandstone gorge GRNP; Photo 3 – leafy twig-rush (*Cladium procerum*) inland range extension; Photo 4 – Pinemount (SP05) farm spring-water supply on GDR, Munghorn Gap; Photo 5 – incised spring-fed creek & remnant GDE on cleared basalt outcrop- Old Bobadeen (SP26); Photo 6 (SW04)– Munghorn Gap spring - historic water trough for Cobb & Co coaches; Photo 7 (SP24B)– Saddlers Creek spring-fed watercourse in sandstone gorge. Photos by author



Figure A2 'The Drip' gorge GDE looking east – SP22 (Photo – Amber Hooper)



Figure A3 'The Drip' gorge GDE looking west SP22 (Photo – Kate Smolski)

Appendix D: Data constraints

Quantifying surface and groundwater interaction and the influence of climate variability and land use change requires a range of investigative methodologies and the analysis of key monitoring data from across the catchment over time. A lack of long term, good quality water records has hindered in-depth assessment in the Goulburn catchment (Krogh *et al.*, 2013; Beale *et al.*, 2000). There are significant spatial and temporal data gaps in streamflow, water quality and rainfall records in the Goulburn caused by intermittent and interrupted monitoring, terminated programs, systemic technical difficulties and equipment and power failures (NSW Department of Water and Energy, 2008; DPI Water, 2018).

The typically sand-dominated mobile sediments and shifting bed and bank geometry of streams in the Goulburn catchment creates difficulties achieving accurate and consistent stream discharge measurement, particularly during extremes in high and low flow. There are only three active gauging stations monitoring stream discharge in the Goulburn (GS210006, GS210016, and GS210031) and one operated by UCML downstream from Ulan installed in 2006. Coggan retains the longest continuous records (since 1913) with 33 data gaps in monthly totals (2.7%). The Merriwa River (GS210091, GS210066) and Wybong Creek (GS210040) are the only tributaries with active stream monitoring stations from twelve stations (decommissioned between 1969 and 1997, data range 10-27 years). Merriwa (GS210066) has 130 data gaps over 600 months (1964 – 2014). Data gaps in stream discharge records were filled based on the average monthly runoff co-efficient (RO) calculated using monthly rainfall data for each catchment.

There is a paucity of water quality data for the Goulburn catchment. The longest continuous real-time salinity (EC) data was monitored at Sandy Hollow stream gauge (210031) between 1993 and 2016; however it contains many data gaps and anomalous readings. Coggan stream gauge (210006) salinity monitoring is more reliable but only commenced in 2012.

Obtaining reliable hydraulic and water quality information for groundwater was a particular challenge. Drill logs and water chemistry data for porous and fractured rock systems were extremely limited spatially and temporally. Groundwater data accessible through industry published reports and government websites are concentrated on specific areas of interest – the mine footprint for industry and shallow alluvial bores for government. There are also issues concerning data consistency as related to collection purpose and methodology, laboratory analysis, range of parameters tested, timing and quality control measures (comments from NSW Office of Water staff 2015).

Appendix E: Estimating salt load & data assurance

E1 - Calculating salt load

Empirical relationship used to estimate daily salt load S (tonnes/day) from TDS total dissolved solids (mg/L) and Q (ML/day) based on relationship between measured EC (Electrical Conductivity) and TDS using best fit power law over a wide range of representative data

$$TDS = a \cdot EC^b$$

The linear relation between laboratory EC and TDS (major ions)

$$\text{Surface water} \dots TDS = 0.68 \times EC \quad (R^2 = 0.98)$$

$$\text{Groundwater} \dots TDS = 0.68 \times EC \quad (R^2 = 0.95)$$

The approximate stream salt loads, SL , can then be found by multiplying the stream discharge, Q , by the TDS with appropriate conversion factors.

$$SL \text{ (tonnes/day)} = aEC_m^b (\mu S/cm) * Q_m(ML/d) \times 10^{-3}$$

$$\text{Salt Load (tonnes/day)} = TDS \text{ (mg/L)} \times Q \times 3600 \times 24/1000$$

$$\text{When } TDS \text{ (mg/L)} = 0.68 \times EC \text{ (}\mu S/cm\text{)}$$

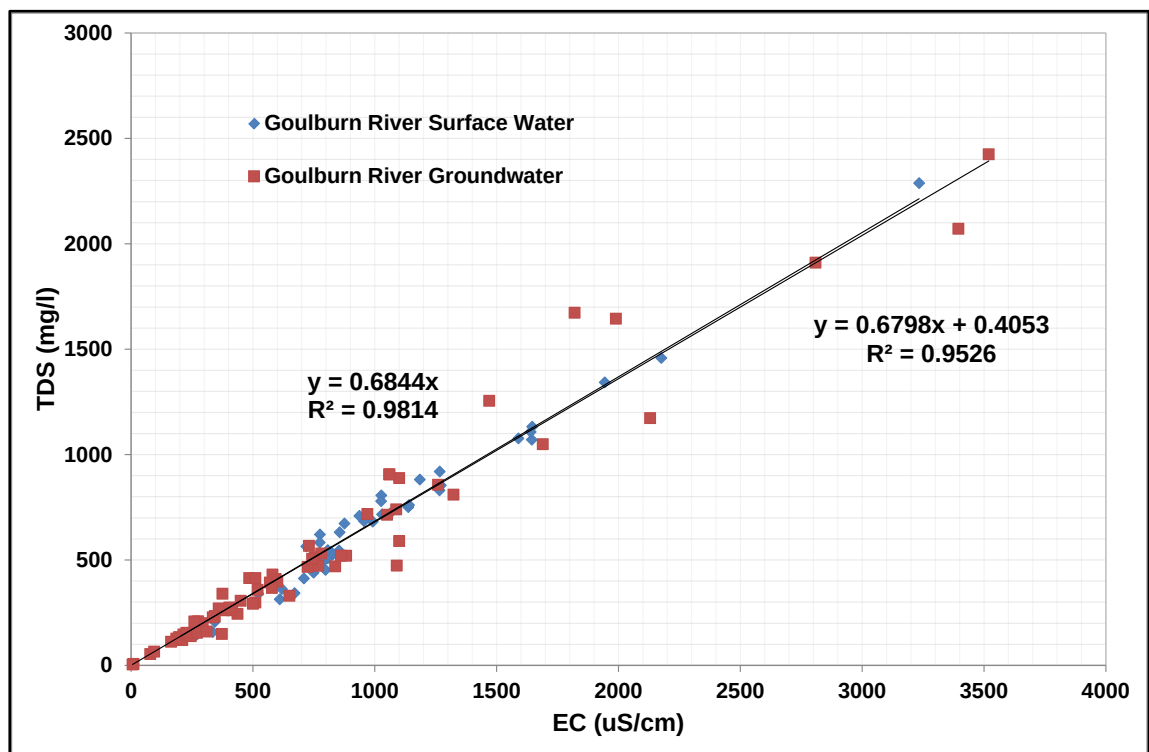


Figure E1 - Empirical relationship used to estimate daily salt load S (tonnes/day) from TDS total dissolved solids (mg/L) and Q (ML/day) using best fit power law over a wide range of representative data

E2: Data quality assurance of hydrochemistry

To test the accuracy of laboratory major ion analyses, charge balances were calculated for each sample analysed by expressing the samples individual ion concentrations in milliequivalents per litre. An acceptable charge imbalance should not exceed 5%.

$$\text{Percent charge imbalance} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100$$

Where $\sum \text{cations (meq/L)} = [\text{Na}^+] + [\text{K}^+] + [\text{Ca}^{2+}]/2 + [\text{Mg}^{2+}]/2$

and

where $\sum \text{anions (meq/L)} = [\text{Cl}^-] + [\text{SO}_4^{2-}]/2 + [\text{HCO}_3^-] + [\text{CO}_3^{2-}]/2$

Appendix F: Methodology - longitudinal survey Goulburn River

A longitudinal stream survey of the Goulburn River and its major tributaries was conducted at 24 sites, 16-26 October, 2012. The surveys occurred following an extended low rainfall period when there was limited surface runoff into the creeks and streams. Table 5:1 shows the percentile ranking <0.02 for 3 monthly and 6 monthly rainfall prior to October 2012. The 12 monthly percentile for October was 0.73, while not low, could indicate the contribution of a delayed groundwater component.

The survey was designed to assess the influence of major tributaries, and identify the potential source of saline inputs. The location and details of the sampling site are listed in Table 5:2 and mapped in Figure 5:1. Spot measurements of EC were recorded for cross referencing and flow data was estimated wherever feasible. Water samples were collected for analysis of major ions and tested at NSW Office of Water laboratory in Wolli Park, Sydney.

The survey followed relatively extended dry period when it was expected that baseflow in tributaries would be a dominant factor³⁴. In the upstream Goulburn River, flow included 8-10 megalitres per day of mine water discharge from Ulan Coal Mine (UCML, 2014). No rain fell during sampling; a total of 28mm rain was recorded over the prior month (September 2012).

In-stream measurements were made and samples collected from the Goulburn and tributary sites upstream and immediately above the confluence with the river or tributary. Site location and approximate elevation was recorded with a GPS, *In situ* water quality measurements of stream EC, pH, temperature were taken. Bicarbonate concentration was determined by titration.

Stream discharge was estimated by the centre-float method over a 10 metre section of stream channel where flow width and depth were relatively constant. The stream width and depth of the flowing stream section were measured, to provide a mean cross-section of streamflow A (m^2). Stream velocity V_s (m/s) was calculated from the average time, $\bar{t}$ (seconds) over three measurements for a just buoyant float to travel the 10 metres in the mid-streamflow (3 samples). Stream discharge using the centre float method required a correction constant K , this was calculated to be 0.84 based on field testing. The stream discharge Q (ML/d) was estimated from:

$$Q = 86.4 \cdot K \cdot A \cdot V_s = 864 \cdot A / \bar{t}$$

Water samples were collected simultaneously at the measurement site, refrigerated and sent by courier to the NSW Department of Primary Industries Water laboratory (Wolli Ck, Sydney) to be analysed for major ions, pH and EC.

³⁴ The Bioregional Assessment Context statement for the Hunter Subregion estimated the baseflow index for the Goulburn River to be 0.51 using digital filtering of daily hydrographs, so that more than 50% of river flow is baseflow groundwater discharge.

Appendix G: Mining



**Figure G1 - Goulburn River Diversion (2004) A) main channel looking north-west
B) undercut bank erosion C) erosion of highly dispersive clays**



Figure G2 Goulburn River @ Gleniston Site (21010017) – encrustations of evaporated salts deposited by capillary action during a period of low rainfall (Photo: 4 August 2013 & 12 September 2017)

Appendix H: Merriwa

Table 1: Surface water site details Merriwa catchment - 24

Surface Water	SITE	Date	UTM		mAHD	EC (Lab)	pH
Merriwa River @ Mt Station Rd Bridge	S2	2/12/2014	56 0251203	6445920	258	1026	8.6
Merriwa River @ Merriwa Town (210091)	S1	2/12/2014	56 0250180	6441390	243	1267	8.5
Merriwa River "Glandore"	S4	2/12/2014	560247482	6431611	219	1646	8.4
Merriwa River US Vallance GS (210066)	S5	2/12/2014	56 0247963	6424690	193	1640	8.6
Kerrabee Creek @Kerrabee	S6	2/12/2014	56 247471	6410295	162.5	1266	7.8
Goulburn River @Kerrabee	S7	2/12/2014	56 247451	6210301	163	1271	8.2
Goulburn River @ OBriens Crossing	S8	2/12/2014	56 22150	6419366	221	1030	8.4
Wollar Creek	S9	2/12/2014	55 77764	6418951	356	3234	7.8
Goulburn River @ Gleniston 21010017	SW3	1/12/2014	55 765271	6432000	372	807	7.3
Curryall Creek	SW33/2	27/11/2014	55 765048	6441588	439	671	7.7
Murrumbline Ck @Turill	SW32/2	27/11/2014	55 767530	6443036	427	3900	7.7
Goulburn R @ Ulan	SW1/3	29/11/2014	55 758502	6425051	417	619	8.2
Krui R @ Golden Hwy Bridge	SW6	16/10/12	56 6445279	228045	322	775	8.4
Krui River @ Goulburn Rr	SW9	16/10/12	56 6433826	225220	268	876	8.6
Merriwa Rr @ Goulburn Rr	SW16	16/10/12	56 6413797	247730	163	1185	8.4
Widden-Bylong Bridge	SW-WD	16/10/12	56 6411574	252964	149	522	8.3
Wybong Ck@ Golden Hwy	SW-WY	16/10/12	56 6427260	277335	144.92	1645	8.4
Munmurra Rr@Ulan Rd Bridge	SW5	16/10/12	55 6453479	780162	376	719	8.4
Munmurra River @ GR	SW30	7/12/13	56 6434856	220361	279	856	8.4
Boba-Curra Ck @ Goulburn Rr	SW21	17/10/2012	55 6432579	763072	397	294	7.4
Murrumbline Creek @ GR	SW7	22/10/2012	55 6434032	768525	369	749	7.3
Murrumbline Ck @Durrigere Rd	SW4	17-Oct-12	55 6435765	769242	374	798	7.4
Wollar Creek @ Goulburn R	SW27	30-Oct-12	55 6418952	777759	304	1944	7.9
Goulburn R at UCML DS Gauge	SW2	17-Oct-12	55 6431246	762046	393	854	7.7

Table 2: Groundwater Sites details - Merriwa – 20 sites

Ground water SITES	SITE No.	Date	Zone	UTM		Elev. mAHD	Screen Depth (mbgl)	SWL (mbgl)	SWL Depth mAHD	EC μ S/cm	Surf. Geol
				E	N						
NOW Scone Rd GW273311	MT3	2/12/14	56	251334	6442271	275	213-231	40-51	235	1312	Basalt
NOW Scone Rd GW080930	MT3b	2/12/14	56	251345	6442299	273	shallow?	21.02	251.98	700.8	Basalt
Merriwa Town GW062053	MT2	2/12/14	56	251227	6440731	265*	201	14*	251	862	Jurassic
Merriwa Town GW042918	MT1	2/12/14	56	250378	6440523	271*	165	32*	239	853.5	Jurassic
Private - Faggs Road	B8	21/11/15	56	253587	6433587	392	183	30-15*	374	1377	Basalt
NOWBore - GW271015	MT15	16/1/08	56	250359	6442050	251.22	42-48 & 120-130	30	221.22	NS	Jurassic
NOWBore - GW271016	MT16	17/1/08	56	250739	6441529	255.86	124-126	8	247.86	NS	Jurassic
Priv-Well @ O'Brien's X	B7	15/10/13	56	221047	6419514	245	242	1.46	243.54	535	Alluvial
Comialla Spg	SP31	17/12/13	56	220377.5	3566470.3	299	NA	surface	299	344	Triassic
Priv. Turill GW078314	B6	6/8/13	55	767670	6435905	440	99	30*	410	1051	Jurassic
Private Well - Cassilis	W34	30/6/14	55	782635	6456282	389	well	3	386	754	Basalt
The Drip Seep GR	SP22	6/11/12	55	763920	6432574	383-387	NA	NA	387	561	TrisBasalt
Priv. GR - GW800279	B5	4/8/13	55	765268.31	6431962.47	375.1	24	4.85	370.25	723	Triassic
Moolarben CM Pz105c	PZ105c	1/4/12	55	763986	6431606	389	22-28	11.07	377.93	220	Triassic
Ulan CML R752	R752	26/9/12	55	756900	6436100	549.1	31	39.495	509.6	680	Basalt
Moolarben CM PZ04A	PZ 04A	26/6/12	55	762140	6435921	440.74	42-54	39.67	401.07	340	Triassic
Moolarben CM PZ14c	PZ14C	1/9/06	55	766637	6437208	454.56	32-56	32.91	421.65	725	Jurassic
Ulan CML PZ10A	PZ10A	25/9/12	55	758812	6439393	513.8	150	103.755	410.045	260	Trias Bas
Ulan CML PZ24A	PZ24A	3/11/12	55	763109	6434793	421.12	208	86.72	334.4	870	Permian
Moolarben CM 103A	Pz103A	1/4/12	55	762490.96	6429260.85	425.21	128	374.51	50.7	630	Ulan Seam

Table 3: Field sampling details

Location	Site	mAHD	Flow ML/day	EC µS/cm	Salt Load T/d*	Comments
Upstream Merriwa River	S3		no flow	n/a	n/a	Dry - no sample
Merriwa River @ Mountain Station	S2	258	NA	1026	-	Overnight rain 7.2 mm (Station 61287) 10.8 mm (Station 61073) 34 mm obs. in Merriwa
US Merriwa Rr @ Merriwa GS210091	S1	238.96	4.289	1267	3.7	Downstream 23 % increase in EC coinciding with Jurassic geology
Merriwa River @ Glandore	S4	219	-	1646	-	60% rise in EC - Merriwa flow est. 2-3 ML/d
DS Merriwa Rr - US Vallance GS 210066	S5	183.24	0.031	1593	0.03	Decreasing flow DS losing stream or extraction? EC - 50% rise from Merriwa
Kerrabee Creek @Kerrabee	S6	163	-	1281	-	Flow est. 1-2 ML/day
Goulburn River @Kerrabee 210016	S7	162.8	3.725	1307	3.31	Flow from NOW online data
Goulburn River @ O'Brien's Crossing	S8	222	NA	1060	-	Upstream of Coggan GS
Wollar creek	S9	356	NA	3305	-	No visible flow
Goulburn R @ Coggan 210006	NS	221.3	13.476	1774.1	16.26	Data- DPIWater online
Goulburn River @ Sandy Hollow 210031	NS	126.7	14.312	1547	15.1	NOW online Data 2/12/14

NS = Not sampled

NA = Not Available

GS = Gauging Station * Conversion mg/L - EC x 0.68

Photographic Record of Merriwa River survey



**Site 2 (S2) Mountain Station road – on left site look south (downstream)
on right – site facing north (upstream)**



Site 1 (S1) Merriwa River @ Merriwa township



Site 4 (S4) Merriwa River @ Glandore



Site 5 (S5) Merriwa River above US Vallance (GS210066)



Site SW16 Merriwa River looking South at confluence Goulburn River



Site SW16 confluence Merriwa and Goulburn River looking east

Appendix I - The Drip gorge GDE

I1 Methodology

This case study compares water data drawn from 30 monitoring points and groundwater sources in the upper Goulburn catchment, focusing around The Drip gorge GDE. The hydrochemistry and hydraulic characteristics of water samples collected from springs, streams and nearby private bores were combined with datasets of groundwater monitoring piezometers sourced from local mine reports and environmental assessments (Tammetta, 2014; Umwelt, 2014; UCML, 2014; MER, 2011; MCC, 2017; MCO, 2014; Middlemis and Fulton, 2011) Tammetta, 2014; Umwelt, 2014; UCML, 2014; MER, 2011; MCO, 2017; MCO, 2015; MCO, 2012)

Water samples (42) were collected in periods of low rainfall during spring, summer and autumn - October 2012 to January 2014. This was to reduce the influence of surface runoff and delayed drainage from the regolith (after rain) on the hydrochemical signature. All data samples were coded and grouped according to geological strata in which they were located along with the spatial and hydraulic context. GPS location, elevation (mAHD) and standing water level (SWL) were recorded and tabulated for each survey site (Table 9:2). The samples were chilled and sent for hydrochemical analysis to the DPI Water laboratory in Sydney and tested for major anions and cations plus bromide, silicate, strontium, electrical conductivity, pH and total alkalinity. ArcView program was used to create maps and GIS layers to illustrate relative site position and geology (Figure 9:5). Major ions signatures were compared to rainwater collected at Merriwa (Jasonsmith, 2011) and Gleniston (2101007) and to seawater (Hem, 1989).

Drip-line A - seepage ~8-12m above river level (388 - 392 mAHD)

Drip-line B - seepage ~2-5 metres above the river level (382 – 385 mAHD)

Water samples were collected by positioning sampling containers with a 100mm diameter funnel under major drips. Of the six water samples collected two were from Drip-line A+ B (SP22-1 & SP22-2); one from Drip-line A (SP22-5); two from Drip-line B (SP22-3 & SP22-4) and one sample from the pool directly underneath (SP22-P). The salinity (EC) for Drip-Line A was 591 μ S/cm and Drip Line B was 325 μ S/cm (pH 7.7 – 8.2).

The Drip groundwater quality was also collected and analysed by Ulan Coal Mines (UCML) December 2012 –2015 (Table 9:4.). The results of 56 data-sets (major ion speciation) were accessed from UCML annual environmental reports (2013, 2014, and 2015). Ulan Coal personnel collected groundwater from two seepage areas approximately 30 metres apart (Drip east and Drip west). Sampling did not differentiate between the higher and lower Drip Lines (Drip A & Drip B). The aim of UCML monitoring was to characterise water quality and determine any relationship between rainfall recharge and variations in salinity that would indicate a shallow perched groundwater source. Resulting hydrochemistry data supported a

sodium chloride (halite Na Cl) and bicarbonate (Ca-MgCO₃)₂ Type water. Changes in salinity (TDS) compared to a rainfall-runoff simulation (cumulative percolation) were relatively inconclusive indicating a quite variable lag-time between rainfall-recharge and groundwater response (dilution TDS).

Ulan Coal Mines (UCML) historical groundwater monitoring between 2001 and 2015 to the north of The Drip indicated differences in the groundwater character of the hydrochemical units in sedimentary strata (UCML, 2015a) (MER, 2009). Upper Triassic groundwater had the lowest salinity ($520 \pm 430 \mu\text{S/cm}$); Permian sequences were double the Triassic; and Jurassic groundwater the most saline at more than double the Permian ($2890 \pm 690 \mu\text{S/cm}$). Between 2001 -2015 Conductivity (EC) levels and sulfate concentrations exhibited an overall rising trend in the Wollar sandstone (Triassic) hydrogeological unit. Minimum SWLs were observed to coincide with droughts conditions and maximum levels following periods of high rainfall due to recharge. Basalt groundwater character was noted to exhibit a dominance of HCO₃, Mg, Ca, Type water. Triassic water was further divided into Upper (quartzose) dominated by Na, Cl and Lower (lithic) dominated by Na, HCO₃ ions

I2 Vegetation

The Goulburn River catchment above The Drip Gorge is part of the Sydney Basin and Brigalow Belt South bioregions (Harden, 1991; Sahukar *et al.*, 2003). The region supports a diverse mix of eastern and western plant species reflecting the east-west orientation of the river valley and the low elevation of the Great Dividing Range west of the Drip Gorge (490 - 560mAHD). The riparian corridor supports open grassy woodland dominated by Rough-barked Apple (*Angorophora floribunda*), Blakely's Red Gum (*Eucalyptus blakelyi*); Yellow Box (*E. mellidora*) and scattered Apple-Top Box (*Eucalyptus bridgesiana*). The under-storey is composed of native tree-violet (*Melicytus dentatus*), Tooton tea- tree (*Leptospermum polygalifolium* subsp. *transmontanum*) and a range of wattles (*Acacia linearfolia*, *Acacia spectabilis*) including an unusual variety of *Acacia floribunda* growing only on the river edge.

The permanent moist seeps support a range of ferns (Rainbow fern - *Calochlaena dubia*, Coral fern- *Gleichenia microphylla*., Maidenhair - *Adiantum aethiopicum*, Rock-felt Fern - *Pyrrosia rupestris*, Sickie fern -*Pellaea falcate*, Water fern - *Doodia aspera*) also two botanical range extensions; the weeping sedge species *Cladium procerum* and an atypical weeping crimson bottlebrush *Callistemon rigidus*³⁵. The skeletal soils on the sandstone pagodas immediately above The Drip support diverse range of heaths and forbs including flannel flowers and vulnerable ROTAP listed plants - Tangled Pseudanthus (*Pseudanthus divaricatissimus*) and wattle *Acacia ausfeldii*. The drier ridges support narrow and broad leaved Ironbark (*E. crebra*, *E. fibrosa*) along with forests of Scribbly gum (*Eucalyptus rossii*), White and red Stringybark

³⁵ Identification confirmed The Royal Botanical Gardens, Sydney det. Dr P.G. Wilson, 25 Nov 2014

(*Eucalyptus sparsifolia* and *E. macrorhynca*), and Dwyer's Red Gum (*Eucalyptus dwyeri*), with dense heaths along moist drainage lines. The more fertile basalt peaks to the north of the river are covered by grassy box woodlands - EPBC listed White Box (*Eucalyptus albens*), Yellow Box (*E. mellidora*), Grey Box (*E. mollucana*) and Red gum woodlands and derived native grasses.