AGL Upstream Investments Pty Ltd

Water Balance for the Gloucester Basin

12 July 2013

PARSONS BRINCKERHOFF

Document information
Client: AGL Upstream Investments Pty Ltd Title: Water Balance for the Gloucester Basin Document No: 2162406A PR_7296 Date: 12 July 2013

Rev	Date	Details
A	28/06/2013	Final DRAFT
B	12/07/2013	Final Report

Author, Reviewer and Approver details			
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A GRI Rating: Sustainability Report 2011

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Executive summary

This report presents an updated quantitative water balance for the Gloucester Basin within which the Stage 1 Gas Field Development Area (GFDA) of the Gloucester Gas Project is located. The report provides additional technical information on the importance of the surface and groundwater components of the water cycle to further assess the proposed CSG development and impacts on water resources and aquatic ecosystems. It also provides a basis for developing numerical models to assess those potential impacts in more detail.

A water balance is an estimate of the storage and flow of groundwater and surface water in a defined area, during a given timeframe. Under natural long term conditions (or steady state conditions), the Gloucester Basin water balance is assumed to be in equilibrium, where inflows equal outflows and the change in storage is (approximately) zero. This and several other assumptions underpinned the development of an initial water budget for the northern Gloucester Basin in 2012. The water balance was developed by focussing on elements derived from data of high reliability such as rainfall and stream records. Other components were estimated using a simple numerical model of the basin, or through applying the water balance equations.

Of the ~322 gigalitres (GL) of rainfall that falls on the Gloucester Basin each year, approximately 150 GL (47 %) flows overland, bypassing the groundwater system, and is discharged via the Avon River and Wards River systems; a further 159 GL (49 %) is returned to the atmosphere via evapotranspiration (ET) or otherwise lost from the system. Surface water flows and ET losses therefore dominate the hydrological system, together accounting for 96% of rainfall.

On a basin scale, approximately 3.5% of rainfall (~11 GL per year) infiltrates the unsaturated zone to recharge the water table. Recharge rates are spatially variably however, being highest in the more permeable alluvial deposits (4% to 13% of rainfall) and significantly lower in areas where the less permeable shallow fractured rock unit outcrops (~0.5% to 1% of rainfall). Current groundwater and surface water use is estimated to be a small component of the basin water balance (~0.5%).

The Avon and Karuah Rivers flow all year round except in very dry conditions (the rivers flow 96% and 98% of the time respectively). Of the total flow in these systems, approximately 6% (Avon River) and 11% (Karuah River) is baseflow derived from groundwater discharge. Most of this is derived from the alluvial deposits with a relatively minor discharge directly from the shallow rock. Groundwater discharge therefore represents a small component of the total surface water balance.

There is substantial groundwater storage within the basin. The main unconfined aquifer unit (shallow fractured rock) has an unconfined storage of approximately 294 GL. By comparison, the alluvial aquifer has less storage (approximately 53 GL). The deeper coal measures unit (comprising coal seams and low-permeability interburden) is a large but tight groundwater reservoir, containing approximately 1505 GL of total groundwater storage, of which approximately 1.5 GL is held in elastic (confined) storage.

It is evident from the water balance, that most groundwater flow in the basin occurs in the uppermost aquifer units; the alluvium and to a lesser extent, the shallow fractured rock where it is permeable. Numerical modelling indicates that leakage between the shallow fractured rock unit and the deeper coal measures is very low and amounts to less than 0.02 GL per year.

The Stage 1 GFDA development may result in a net consumptive dewatering volume of approximately 730 megalitres (ML) per year in the initial years of the project. This consumptive use is expected to diminish substantially with time because of the low permeability strata overlying the targeted coal seams. The maximum groundwater use of 730 ML (0.7 GL) per year represents approximately 6% of the estimated 11.4 GL that is recharged annually to the groundwater system in the basin. It is also a very small proportion (~0.2 %) of the groundwater storage in the shallow fractured rock unit (~294 GL).

1. Introduction

This report is the updated water balance for the groundwater systems of the Gloucester Basin. It builds on the latest hydrogeological conceptual model (Parsons Brinckerhoff, 2013b) and the previous water balance (Parsons Brinckerhoff, 2012c), and is an appreciation of all of the hydrogeological processes happening across the whole of the basin.

1.1 Proposed development

AGL Upstream Infrastructure Investments Pty Ltd (AGL) is proposing to build the Gloucester Gas Project (GGP) which comprises several stages of development facilitating the extraction of coal seam gas (CSG) from the Gloucester Basin. Concept Plan and Project Approval (Part 3A Approval) for the Stage 1 Gas Field Development Area (GFDA) was granted on 22 February 2011 under Part 3A of the *Environmental Planning and Assessment Act (1979) (EP&A Act)*. In addition the project received approval under the *Environment Protection and Biodiversity Conservation Act (1999) (EPBC Act)* (EPBC Approval) on 11 February 2013.

AGL also holds Petroleum Exploration Licence (PEL) 285, under the *Petroleum (Onshore) Act 1991*, covering the whole of the Gloucester Basin, approximately 100 km north of Newcastle, NSW. AGL has also applied for a Petroleum Production Lease (PPL) for the Stage 1 area subject of the planning approvals. The Stage 1 GFDA in relation to the PEL boundary is shown in Figure 1.1.

The GGP will involve the dewatering of deep groundwater and the extraction of gas from multiple coal seams within the Gloucester Coal Measures. Target coal seam depths will vary from site to site but are expected to range between 200 and 1,000 metres below ground level (mbgl). The current GGP includes the construction, operation and decommissioning of not more than 110 coal seam gas wells and associated infrastructure, including gas and water gathering lines, within the Stage 1 GFDA.

The field based groundwater studies commenced with a comprehensive groundwater investigation, the Phase 2 Groundwater Investigations, which was completed in 2012 (Parsons Brinckerhoff, 2012a). The investigation established a dedicated water monitoring network, and enabled the collection of baseline water level, water quality and hydraulic conductivity data for each of the hydrogeological units represented across the different groundwater systems and the surface water systems.

An initial water balance for the Stage 1 GFDA and the northern Gloucester Basin was developed in 2012 (Parsons Brinckerhoff, 2012c). This report significantly updates the previous water balance to include the whole of the Gloucester Basin. EPBC Approval (condition 17) requires that the water balance is revised to:

1. Take into account the following inputs:
    a) Field-based investigation of the spatial distribution of strata and structures within the project area and the role of faulting and its influence on migration of groundwater and/or gas into surface water systems (see Sections 3.3 to 3.8).
    b) Investigation of the age, depth and location of groundwater including proximity to known faults and fractures (see Section 3.7.2).
    c) A baseline investigation of gas occurrence in surface and groundwater (see Section 3.9).
    d) Results of pilot testing of the Stratford and Waukivory pilot wells (see Section 3.7.4).
    e) Baseline data associated with Phase 1 and Phase 2 studies (see Sections 3.3 to 3.7).
    f) Information of the assessment of a representative site for fault testing (See Section 3.8.2).
2. Extend to 1000 metres (m) below ground level.

3. Ensure that all hydrological inputs and outputs are accounted for (sum to zero).
4. Include a list of information sources and statements on confidence, accuracy and precision.

Most of these specific issues are dealt with in Chapters 3 and 4 in the nominated sections. Further detail is provided in other technical studies as listed in Chapter 6 References.

This report primarily draws on the Hydrogeological Conceptual Model of the Gloucester Basin (Parsons Brinckerhoff, 2013b), in which the input information listed in parts 1) and 2) above are presented.

1.2 Scope

The scope of works included the following:

- Review of report table of contents and report scope to align with EPBC Approval and Part 3A Approval conditions.
- Review of additional information and summary of existing studies in accordance with EPBC Approval and Part 3A Approval conditions.
- Development of a simple numerical model to derive key groundwater fluxes.
- Update of water balance calculations to incorporate the entire Gloucester Basin to 1000 m depth.
- Update of the initial water balance report, as appropriate.

1.3 Report structure

This document provides a concise report outlining the methodology and results of the water balance study for the whole Gloucester Basin. The structure of the report is as follows:

- Chapter 2: Summarises the sources of information and data used in this report.
- Chapter 3: Provides a contextual overview of the Gloucester Basin including topography, drainage and geology.
- Chapter 4: Develops the groundwater balance for the Gloucester Basin.
- Chapter 5: Presents the conclusions of the study.
- Chapter 6: Lists the references

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WATER BALANCE FOR THE GLOUCESTER BASIN
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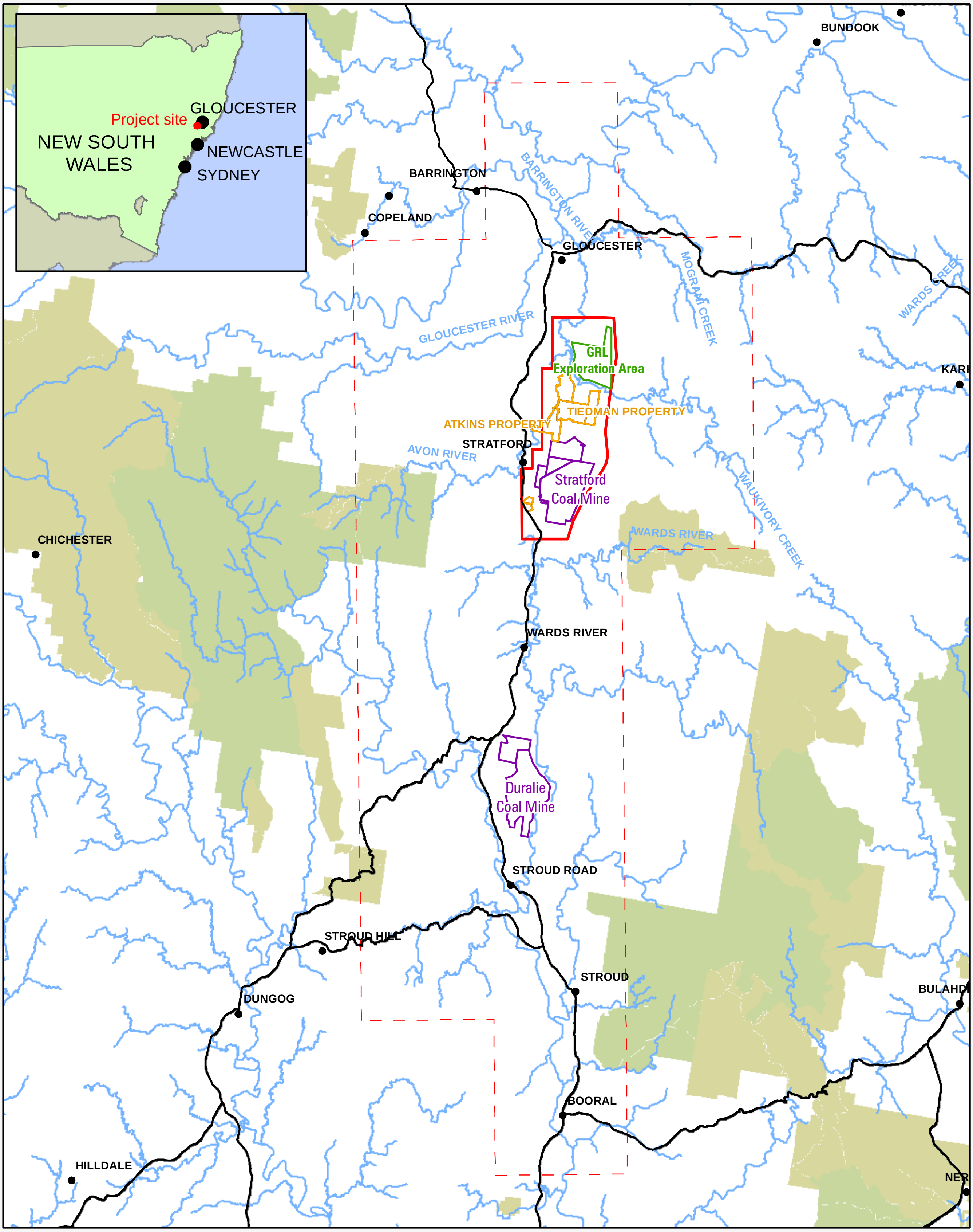

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- Stage 1 GFDA boundary
- PEL 285 boundary
- AGL owned properties
- Mining Lease Boundary
- GRL exploration area boundary
- Towns
- Rivers and streams
- Major roads
- NSW State Forest
- National Park, Nature Reserve or State Conservation Area

N
0 10
Kilometres

Figure 1.1
Regional Location

2. Data sources

This chapter provides information on previously published reports that are relevant to this revised water balance report. Previous studies carried out for the GGP and within the Gloucester Basin are outlined in Table 2.1. The Water Balance for the Gloucester Basin is based on the data collated and reviewed in the Hydrogeological Conceptual Model of the Gloucester Basin (Parsons Brinckerhoff, 2013c).

Table 2.1 Previous reports

Report	Area covered	Summary
Geology of the Camberwell, Dungog and Bulahdelah 1:100,000 Geological Sheets, Roberts (1991)	Gloucester Basin	Geology of the Camberwell, Dungog and Bulahdelah 1:100,000 Geological Sheets
Gloucester Basin Geological Review, SRK (2005)	Gloucester Basin	Lucas Energy Pty Ltd, the PEL holder prior to AGL, commissioned SRK Consulting to undertake a desktop geological review of the Gloucester Basin to identify areas that have been least disturbed by faulting and contain thick sequences for coal, for the purposes of CSG exploration.
Hydrogeological Review of the Gloucester-Stroud Basin, URS (2007)	Gloucester Basin	Lucas Energy Pty Ltd, the PEL holder prior to AGL, commissioned URS Australia Pty Ltd to undertake a desktop review of the hydrogeological conditions at three CSG exploration areas within the Gloucester-Stroud Basin.
CSG pilot/flow testing programs, AGL (2012)	Stage 1 GFDA	Nine gas wells were flow tested by Lucas/AGL as part of the Stratford pilot testing program between 2006 and December 2009. Produced water volumes, water levels and water quality were assessed as part of the study.
Stroud Gloucester Trough: Review of the Geology and Coal Development, Lennox (2009)	Gloucester Basin	Summary of the work carried out in the period 1980-1985, including mapped geology at a scale of 1:10,000, photogeological studies, logged core, review of electric bore logs and measured sections at several locations within the Gloucester Basin.
Seismic Surveys, AGL (2009, 2010 and 2012)	Stage 1 GFDA (2009 & 2010) Gloucester Basin (2012)	Seismic data collected by AGL mapped a number of north-south striking thrust faults, and east-west striking sub-vertical normal faults across the Stage 1 GFDA.
Gloucester Basin Stage 1 Gas Field Development Project: Preliminary Groundwater Assessment and Initial Conceptual Hydrogeological Model, SRK (2010)	Stage 1 GFDA	Hydrogeological assessment of the Gloucester Basin, in particular the Stage 1 GFDA, including a desktop review, initial site visit, data collection and initial conceptual hydrogeological model.
A Hydrogeological Assessment of the Duralie Extension Project: Environmental Assessment, Heritage Computing (2009)	Duralie Mine Lease	Hydrogeological assessment of the Gloucester Basin, in particular the Duralie Mining Complex, including characterisation of the existing groundwater regime, collation and review of baseline geological and groundwater data; and development of conceptual and numerical groundwater models
A Hydrogeological Assessment in Support of the Stratford Coal Project: Environmental Impact Statement, Heritage Computing (2012)	Stratford Mine Lease	Hydrogeological assessment of the Gloucester Basin, in particular the Stratford Mining Complex, including characterisation of the existing groundwater regime, collation and review of baseline geological and groundwater data; and development of conceptual and numerical groundwater models

Report	Area covered	Summary
Phase 2 Groundwater Investigations – Stage 1 Gas Field Development Area, Parsons Brinckerhoff (2012a)	Stage 1 GFDA	Comprehensive groundwater investigations to confirm the conceptual model and connectivity of different groundwater systems across the Stage 1 GFDA, establishment of a dedicated monitoring network across the area; and collection of baseline water level and water quality attributes for each of these groundwater systems
Gloucester Groundwater and Surface Water Monitoring – Annual Status Report, Parsons Brinckerhoff (2012b)	Stage 1 GFDA	Annual review of the monitoring network established across the Stage 1 GFDA, detailing groundwater and surface water level and water quality trends for the period January 2011 to June 2012
Water Balance for the Gloucester Stage 1 GFDA, Parsons Brinckerhoff (2012c)	Northern Gloucester Basin	Updated conceptual model and water balance for the Gloucester Basin, with a focus on the northern Gloucester Basin within which the Stage 1 GFDA is located. Estimation of the storage and flow of water within a defined area, within a given timeframe.
Hydrogeological Investigation of a strike-slip fault in the Northern Gloucester Basin, Parsons Brinckerhoff (2013a)	Stage 1 GFDA	Following GGP referral to SEWPaC under the EPBC Act, an extension of the baseline Phase 2 Groundwater Investigations for the Stage 1 GFDA was carried out, assessing the connectivity between a strike-slip fault and shallow and deep groundwater systems.
Hydrogeological Conceptual Model of the Gloucester Basin (2013b)	Gloucester Basin	Development and update of a conceptual hydrogeological model to be used as a basis for the development of a water balance and numerical groundwater model. Including review of baseline geological, surface water and groundwater data, and characterisation of the groundwater systems of the Gloucester Basin.
Gloucester Resources Groundwater Investigation, Annual Monitoring Report Parsons Brinckerhoff (2012d)	Rocky Hill Coal Project Exploration Area	Hydrogeological investigation at the Gloucester Resources Ltd (GRL) proposed Rocky Hill Coal Project open cut coal mine. Annual review of the monitoring network detailing groundwater level and quality trends for the period March 2011 to March 2012

3. Review of Gloucester Basin hydrology and hydrogeology

This chapter provides an overview of the physical characteristics of the Gloucester Basin including topography, drainage, climate, geology and geological structure.

3.1 Topography and drainage

The Gloucester Basin is a narrow, north-south trending, elongated basin approximately 40km long and 10km wide, extending from Gloucester in the north to Stroud in the south. A major surface water divide, just north of Wards River, separates the Basin into two major catchment areas (Figure 3.1).

The Gloucester Basin is located high in the Manning River and Karuah River coastal catchments. The area occupied by the Permian Coal Measures (about 217 km^2) is small in comparison to the size of these catchments.

In the southern catchment area, surface water flow is generally to the south, and is part of the Karuah River catchment. In the northern catchment area, surface water flow is generally to the north, and is part of the Manning River catchment. Figure 3.2 illustrates the surface water catchments, and the surface water divide between the Wards River catchment (part of the Karuah River catchment) and the Avon River catchment (part of the Manning River catchment).

The Gloucester Basin is topographically enclosed to the west by the Gloucester and Barrington Tops, and to the east by the Mograni Range.

3.2 Rainfall and evapotranspiration

There are four Bureau of Meteorology (BoM) weather stations within the Gloucester Basin (Figure 3.2), and an additional AGL weather station on the Tiedman property (Figure 1.1). Average rainfall and the period of monitoring for the BoM stations are presented in Table 3.1.

Table 3.1 BoM stations in the Gloucester Basin

BoM station number	Name	Monitoring period	Long term average annual rainfall (mm) *
BoM 60015	Gloucester Post Office	1888 to present	982.4
BoM 60112	Gloucester Hiawatha	1976 to present	1023.2
BoM 60042	Craven (Longview)	1961 to present	1061.6
BoM 61071	Stroud Post Office	1889 to present	1145.8

* Long term average annual rainfall (mm) over the monitoring period

Long term (1888–2013) cumulative deviation from the annual mean rainfall at Gloucester Post Office (BoM station 60015) is presented in Figure 3.3. Historically, the period between July and September records the lowest monthly rainfall, while the period between January and March typically has the highest monthly rainfall.

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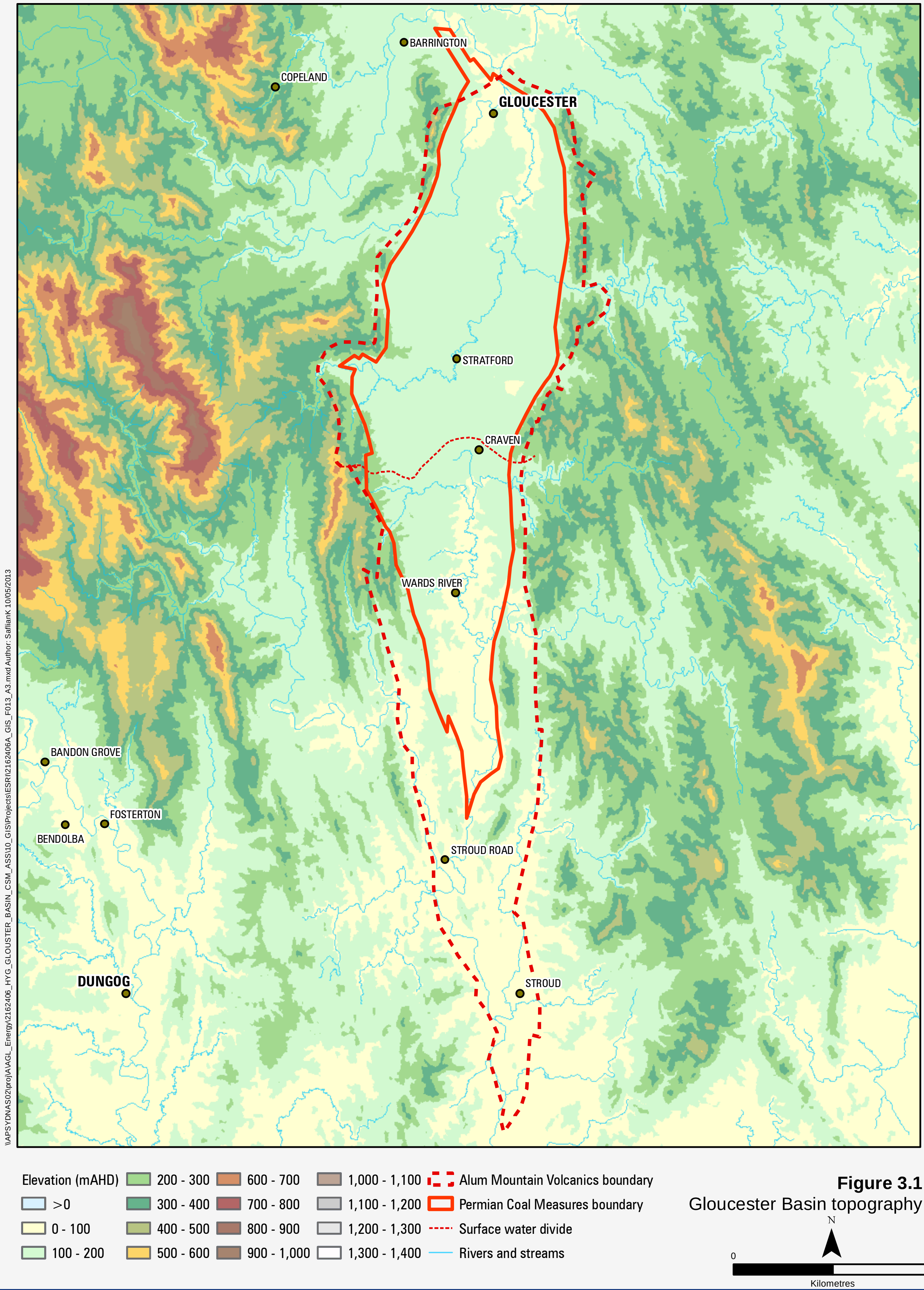
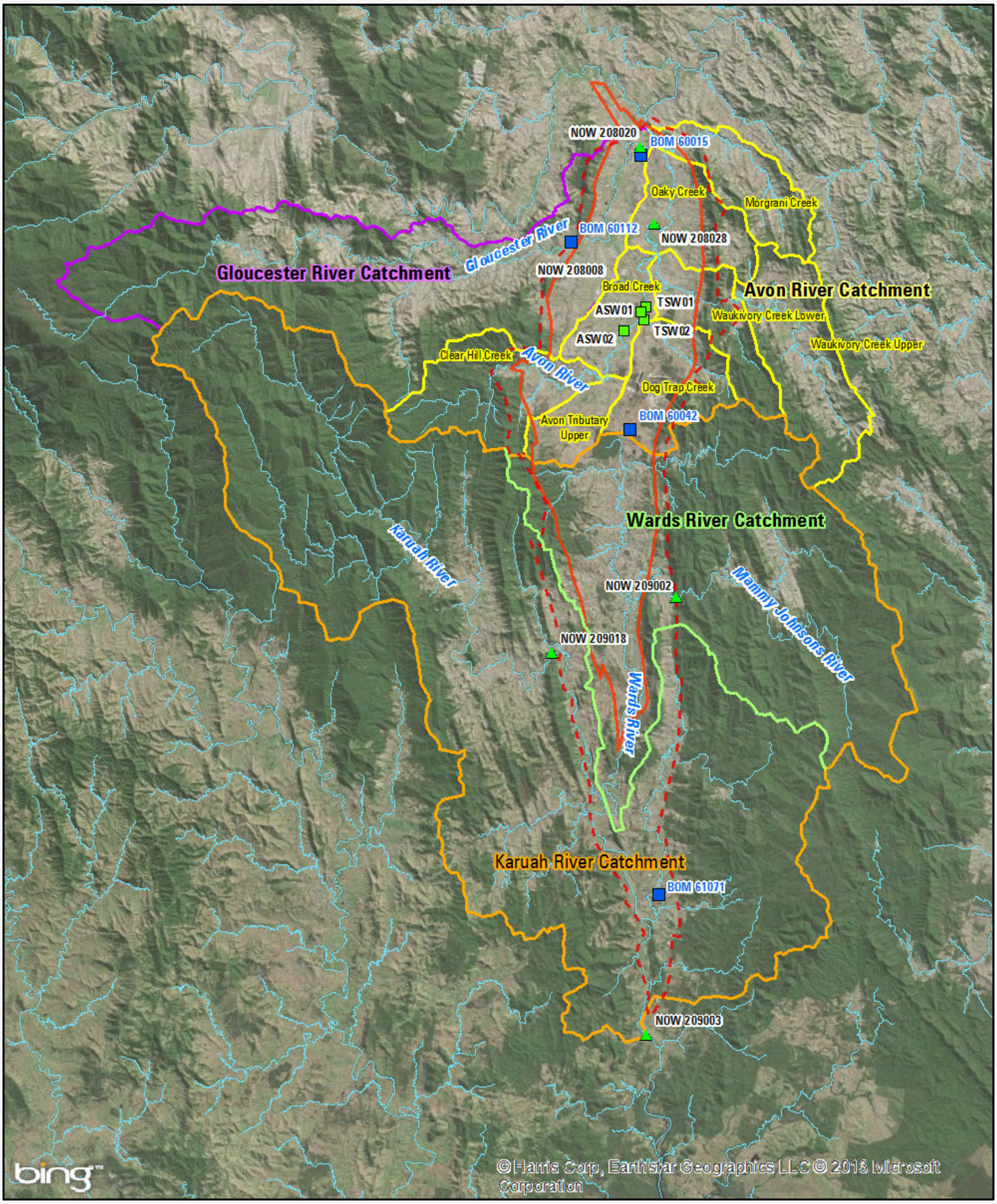


Figure 3.1
Gloucester Basin topography



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Surface water catchments

- Avon River
- Gloucester River
- Karuah River (to NOW 209003)
- Wards River

- Alum Mountain Volcanics boundary
- Permian Coal Measures boundary
- Rivers and streams
- Project gauging station
- NOW gauging station
- BOM Weather Station

N

0 10 Kilometres

Figure 3.2
Surface water catchments

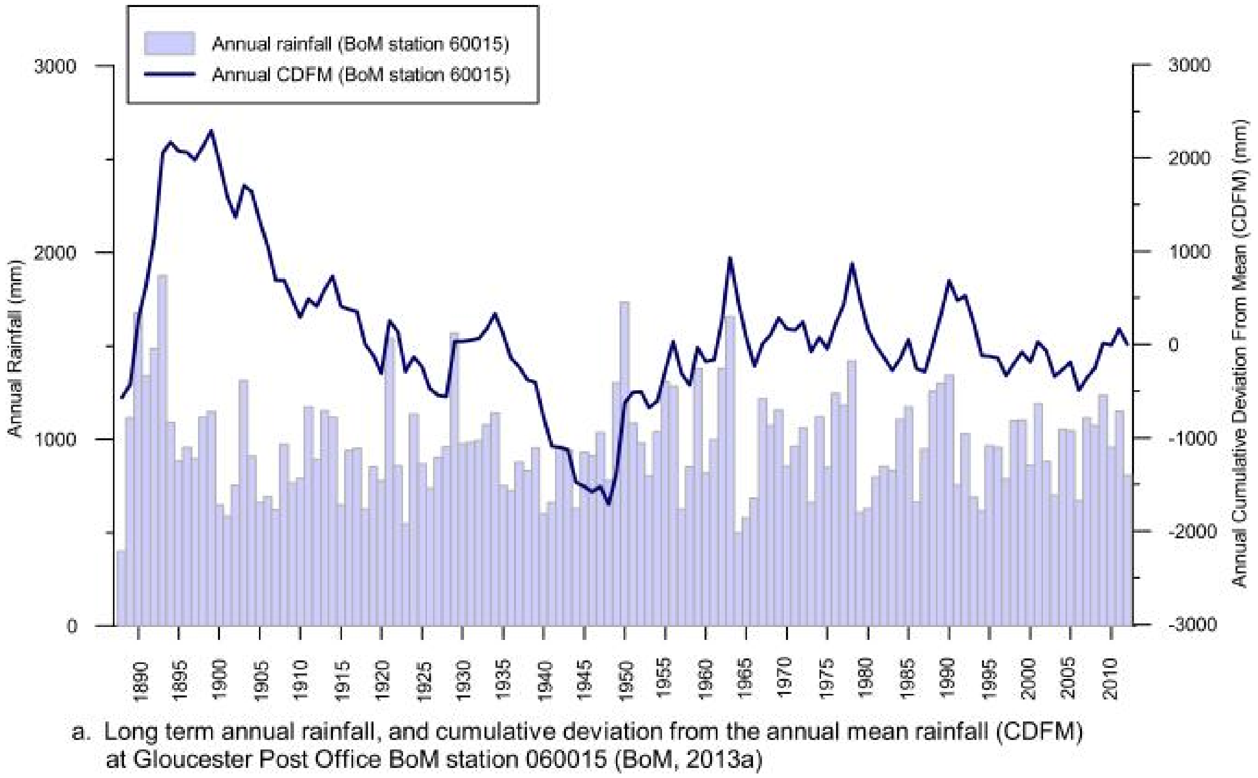

Figure 3.3 Long term annual rainfall, and cumulative deviation from the annual mean rainfall (CDFM) at Gloucester Post Office BoM station 060015 (BoM, 2013a)

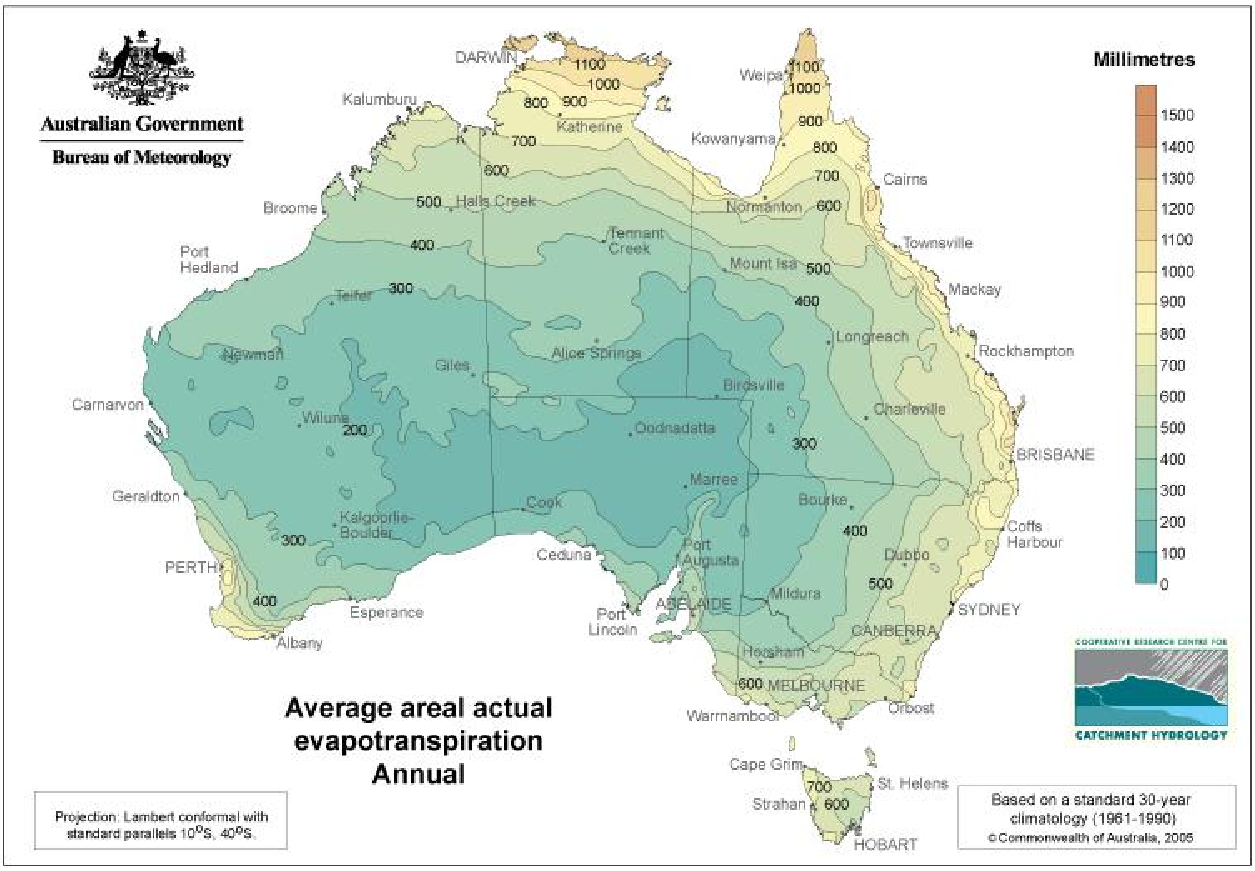

Figure 3.4 Average, areal, actual evapotranspiration (BoM, 2013b)

Evapotranspiration (ET) is the collective term encompassing the transfer of water, as water vapour, to the atmosphere from both vegetated and clear land surfaces (BoM, 2013b). Evapotranspiration rates are affected by climate and the availability of water and vegetation.

The average, annual evapotranspiration for the whole Gloucester Basin is approximately 750mm; this was obtained from the average, areal, actual evapotranspiration maps created by the BoM from data collected between 1961 and 1990 (Figure 3.4) (B0M, 2013b).

3.3 Geological setting

3.3.1 Overview

The Gloucester Basin represents a complex geological system formed by the interplay of extensional tectonic faulting and high rates of sedimentation. The Basin stratigraphy comprises a thick succession of Permian sedimentary rocks representing deposition in both terrestrial and marine environments during a complex period of subsidence, uplift and relative sea level change (marine transgression and regression).

The Basin is a synclinal intermontane structure formed in part of the New England Fold Belt between a major Permian plate margin and the Sydney-Gunnedah Basin (Lennox, 2009). The north – south trending synclinal nature of the Gloucester Basin resulted from the collision between the East Australian and Pacific Plates.

Following a period of extension during the Early Permian the Gloucester Basin has undergone periods of normal and reverse faulting, with large scale tilting associated with late stage compressional movements towards the end of the Permian (Hughes 1995). Reverse faults dominate present day structure. A comparison with the contemporary horizontal stress field map (Hillis *et al* 1998) indicates the Basin is likely to be under compression in an east-west orientation.

The stratigraphy dips steeply (up to 90°) on the flanks of the Basin, dipping towards the north-south trending synclinal basin axis and flattening toward the centre of the Basin. Early Permian and Carboniferous hard resistive volcanics form the ridgelines of the Basin: the Mograni Range to the east; and the Gloucester and Barrington Tops to the west.

Overlying the Permian stratigraphy is a thin sequence of surficial Quaternary sediments. The Quaternary sediments are non-uniform in thickness, and comprise unconsolidated alluvial sediments (sand, gravel, silt and clay) along the drainage channels and colluvial deposits across the rest of the plain sourced from the surrounding outcropping Permian deposits.

3.3.2 Stratigraphy of the investigation area

The Gloucester Basin is divided into three major Permian stratigraphic units each representing a distinct depositional setting: the Gloucester Coal Measures, the Dewrang Group, and the Alum Mountain Volcanics. The generalised stratigraphy of the basin is summarised in Table 3.2. A geological map of the basin is shown in Figure 3.5, and regional geological cross-section through the Gloucester Basin is shown in Figure 3.6.

The CSG development in the Stage 1 GFDA is targeting the intermediate and deep coal seams in the Gloucester Coal Measures generally below depths of 200m to around 1000m.

Table 3.2 Stratigraphy of the Gloucester Basin

Period	Group	Sub-group	Formation	Approx. thickness (m)	Coal seam	Depositional Environment	Tectonic Events
Upper Permian	Gloucester Coal Measures	Craven	Crowthers Road Conglomerate	350		Marine regression, pro-gradation of alluvial fans	Uplift to west of Gloucester Basin
			Leloma	585	Linden		
					JD		
					Bindaboo		
					Deards		
			Jilleon	175	Cloverdale		
					Roseville		
					Tereel/Fairbairns		
			Wards River Conglomerate	Variable			
			Wenham	23.9	Bowens Road		
					Bowens Road Lower		
		Speldon Formation				Marine transgression but also some progradation of alluvial fans in the west related to uplift	Extension (normal fault development) and regional subsidence. Uplift to west of Basin
		Avon	Dog Trap Creek	126	Glenview		
			Waukivory Creek	326	Avon		
					Triple		
					Rombo		
					Glen Road		
					Valley View		
					Parkers Road		
	Dewrang	Mammy Johnsons		300	Mammy Johnsons	Marine transgression, regression and further marine transgression	Extension (normal fault development) and regional subsidence
		Weismantel		20	Weismantel		
		Duralie Road		250			
Lower Permian	Alum Mountain Volcanics				Clareval	Arc-related rift	Rift?
					Basal		

Modified from AECOM (2009) and SRK (2005)

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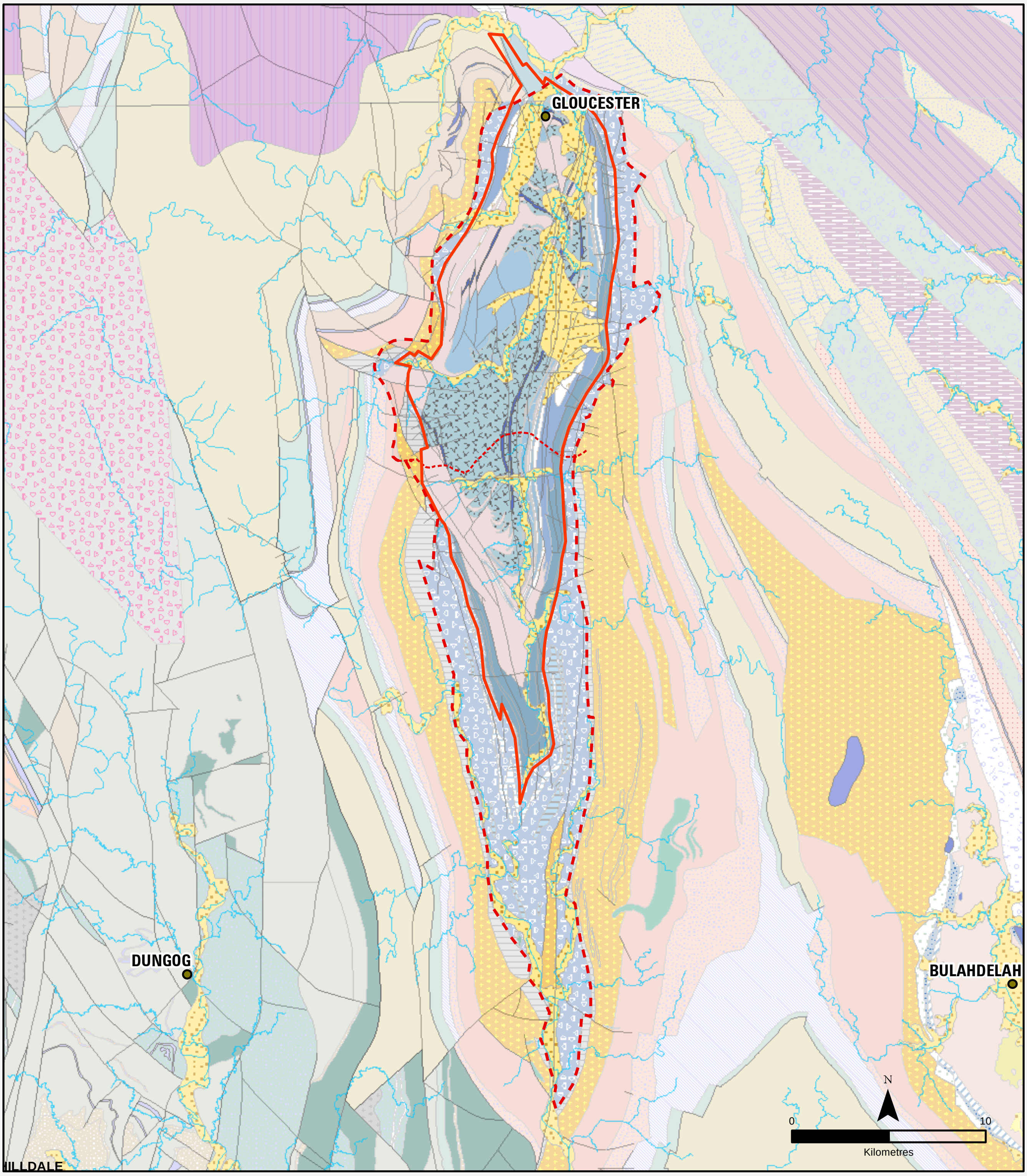

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Alum Mountain Volcanics boundary
Permian Coal Measures boundary
Rivers and streams

Gloucester Basin Geology

Qa Quaternary Alluvium
G Unnamed microgranite

Permian Geology

Plc Crowthers Rd Conglomerate
Pll Leloma Formation
Pllj Jo Doth Tuff Member
Plo Jilleon Formation
Plw Wards River Conglomerate
Pla Wards River Conglomerate
Plgx Gloucester Coal Measures
Plh Wenham Formation
Plp Speldon Formation
Plt Dog Trap Creek Formation
Pli Waukivory Creek Formation
Pldy Mammy Johnsons Formation
Plde Weismantels Formation
Pldd Duralie Road Formation
Pea Alum Mountain Volcanics
Pear Unnamed Rhyolite Member
Peat Unnamed Welded Tuff Member
Peac Unnamed Basal Sequence

Carboniferous geology

Clo1 Johnsons Creek Conglomerate
Clkm McInnes Formation
Clr Booral Formation
Fault

Figure 3.5
Regional Geology

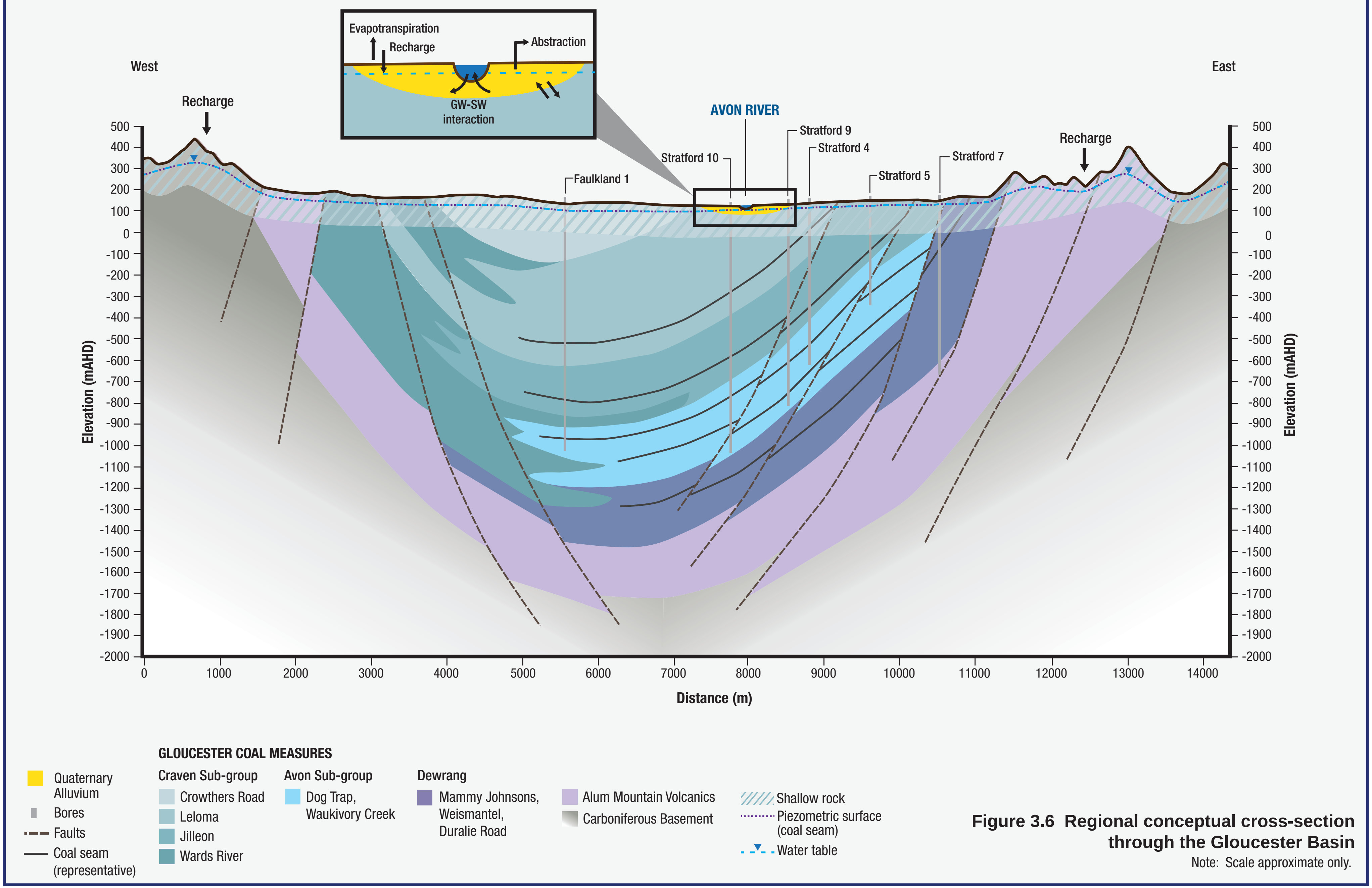


Figure 3.6 Regional conceptual cross-section through the Gloucester Basin

Note: Scale approximate only.

3.3.3 Structural development

The tectonic development and structural setting of the Gloucester-Stroud Syncline is discussed by Roberts et al. (1991) based on regional geological mapping and seismic profile interpretation. Subsequent structural interpretations have been carried out by SRK (2005) and Lennox (2009). The following summary is based on those reports.

The Gloucester-Stroud Syncline is the largest structure in the surrounding region, being more than 55 km long and 24 km wide with steeply dipping limbs containing a stratigraphic section up to 8 km thick (Roberts et al, 1991). The syncline has a sinuous axial trace that trends generally northerly (355°) but that swings eastwards (022°) between Stratford and Gloucester. The syncline is doubly plunging, closing at both ends forming a tight canoe-like structure. The axial plane is inclined slightly to the east; bedding in the limbs of the syncline tends to dip steeply toward the axis at more than 60°, with some bedding sub-vertical or slightly overturned.

The syncline is a fault bounded trough, active during the Permian. Roberts et al (1991) identify up to six deformation events that were important in the depositional and structural development of the Basin. SRK (2005) simplified the structural development into two main stages:

1. Early – Middle Permian dextral tectonic margin, resulting in reactivation of NNW-striking faults as strike-slip dextral and formation of NE and EW striking normal faults, particularly around the margins of a circular basement feature (suspected deep intrusion) in the northern part of the Basin. The majority of the Coal Measures were deposited during this complex phase.
2. Late Permian NE shortening during the early stages of the Hunter Bowen Orogeny, resulting in reverse and thrust faulting on NNW faults and some NNE faults.

Combining structural domains with the known distribution of stratigraphy, SRK (2005) divides the Basin into three structure/stratigraphic domains:

1. An eastern domain containing a number of coal seams in the Avon and Craven Sub-Groups.
2. A western domain where the surface mapping indicates sequences of Waukivory Formation and Wards River Conglomerate that mark periods of prograding fluvial systems that have significantly reduced the thickness of coal seams.
3. Major fault zones that separate the eastern and western domains.

In addition, SRK (2005) identifies a possible basement structure or intrusion overlapping with the northern part of the Basin that appears to have influenced the structural development of the Basin. The margin of that structure coincides with arcuate and east-west faulting in the mid part of the basin (e.g. west of Stratford) and may account for the contrasting deformation styles in the Carboniferous basement rocks to the north and south of this approximate line.

3.3.4 Faulting

Faulting in the Gloucester Basin is discussed by Roberts et al. (1991) who identify five distinct types or styles of faulting based on mapping and seismic interpretations:

1. Low-angle, west-dipping broadly meridional (N–S) thrust faults.

2. Sinistral shear zones striking between 300° and 350°.

3. Meridional reverse faults.

4. East-west striking normal faults.

5. Shears or normal faults striking between 040° and 060°.

These contrasting fault types reflect different episodes of deformation throughout the complex structural history of the Basin (Roberts et al. 1991), and the possible influence of basement structures (SRK, 2005). Lennox (2009) provided a spatial analysis of faults and other linear features based on air photo and seismic interpretations which follows a broadly similar classification (Figure 3.7).

Geological mapping of the Basin (Roberts et al. 1991) shows that, in the vicinity of the Stage 1 GFDA, the geological structure is dominated by moderately to steeply west-dipping strata intersected by near-vertical sinistral strike-slip faults with significant vertical components (Style 2, Figure 3.7) and westerly-dipping thrust faults (Style 1, Figure 3.7). Similar faulting and folding styles extend to the southern part of the basin. A geological cross-section through the Gloucester Basin with representative faulting is shown in shown in Figure 3.6.

Recent (deep, high resolution) seismic data acquired by AGL in the period from 2009 to 2012 identify a number of westerly dipping thrust faults striking north-south, and north-south striking high angle oblique faults. The resolution of the vertical seismic profiles is good to depths of approximately 1000 m; however the technique returns poor resolution in the top 200 m. This inhibits the ability to map these fault structures through the shallow surface rock and currently lineament traces can only be inferred. The resolution of the seismic data allows for identification of faults when displacement is greater than approximately 10 m.

The seismic section presented in Figure 3.8 shows the subsurface bedding and structure to depths of 1,900 mbgl beneath the Tiedman property in the centre of the Stage 1 GFDA. This seismic section has been interpreted to identify four major westerly dipping thrust faults and two easterly dipping north-south trending strike-slip faults with minimal vertical offset (Figure 3.8).

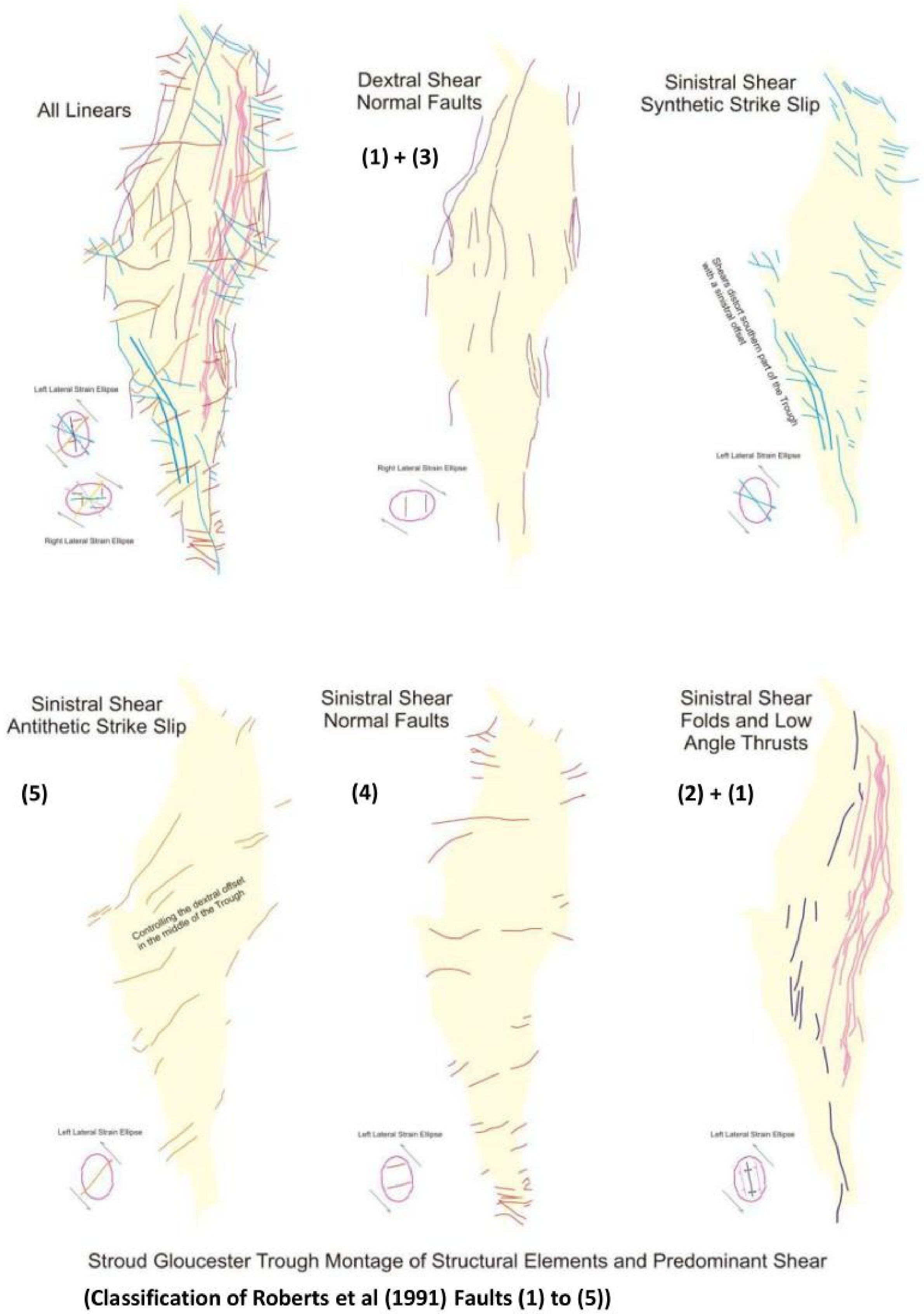


Figure 3.7 Major sets and styles of faulting in the Gloucester Basin (after Lennox, 2009)

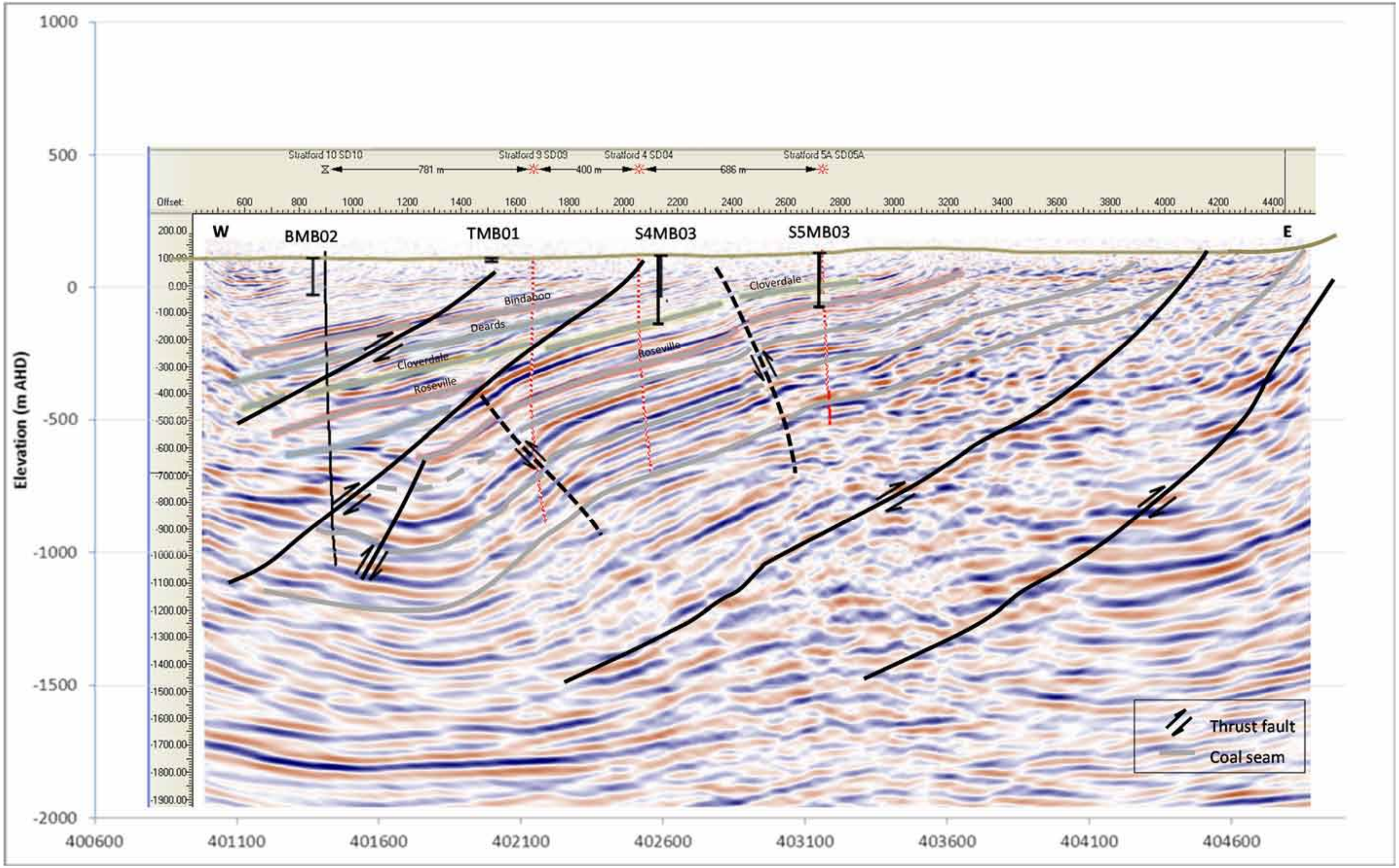


Figure 3.8 Interpreted seismic cross-section through the eastern Gloucester Basin

3.4 Monitoring network

A groundwater and surface water monitoring network for the Stage 1 GFDA was established as part of the Phase 2 Groundwater Investigations (Parsons Brinckerhoff, 2012a). Additional monitoring has been installed as part of the Hydrogeological Investigation of a strike-slip fault in the Northern Gloucester Basin (Parsons Brinckerhoff, 2013a).

A review of the monitoring network detailing baseline groundwater and surface water level data and water quality trends is presented in the Hydrogeological Conceptual Model of the Gloucester Basin (Parsons Brinckerhoff, 2013b).

The groundwater and surface water monitoring network is presented in Figure 3.9. Groundwater and surface water hydrographs for the Stage 1 GFDA are presented in Appendix A.

3.5 Hydrogeological units

Four broad hydrogeological units have been identified within the Gloucester Basin (Table 3.3). The permeability and groundwater flow characteristics of rocks within the Gloucester Basin are controlled by several factors including lithology, depth and the degree of fracturing and faulting. In this sense hydrogeological units and flow systems do not always correspond with defined geological boundaries. The hydrogeological conceptual model for the Gloucester Basin is presented in Figure 3.6.

Table 3.3 Four key hydrogeological units

Unit	Aquifer type	Formation name	General lithology	Hydraulic characteristics
Alluvium	Semi-confined, clay capped, porous, granular	Quaternary alluvium	Clay/mixed gravels	Heterogeneous, highly variable permeability associated with varying lithology
Shallow Rock (<150m)	Semi-confined, fractured rock	Upper Permian Coal Measures, Alum Mountain Volcanics	Interbedded sandstone/siltstone with bedding plane fractures	Heterogeneous, high and low permeability domains associated with fault zones and fracturing
Interburden	Confined, fractured rock	Upper Permian Coal Measures	Interbedded indurated sandstone/siltstone and claystone	Low permeability associated with sparse fractures, permeability decreases with depth
Coal Seams	Confined, fractured rock	Upper Permian Coal Measures	Coal/shale	Low permeability associated with cleating and fractures in coal seams, permeability decreases with depth

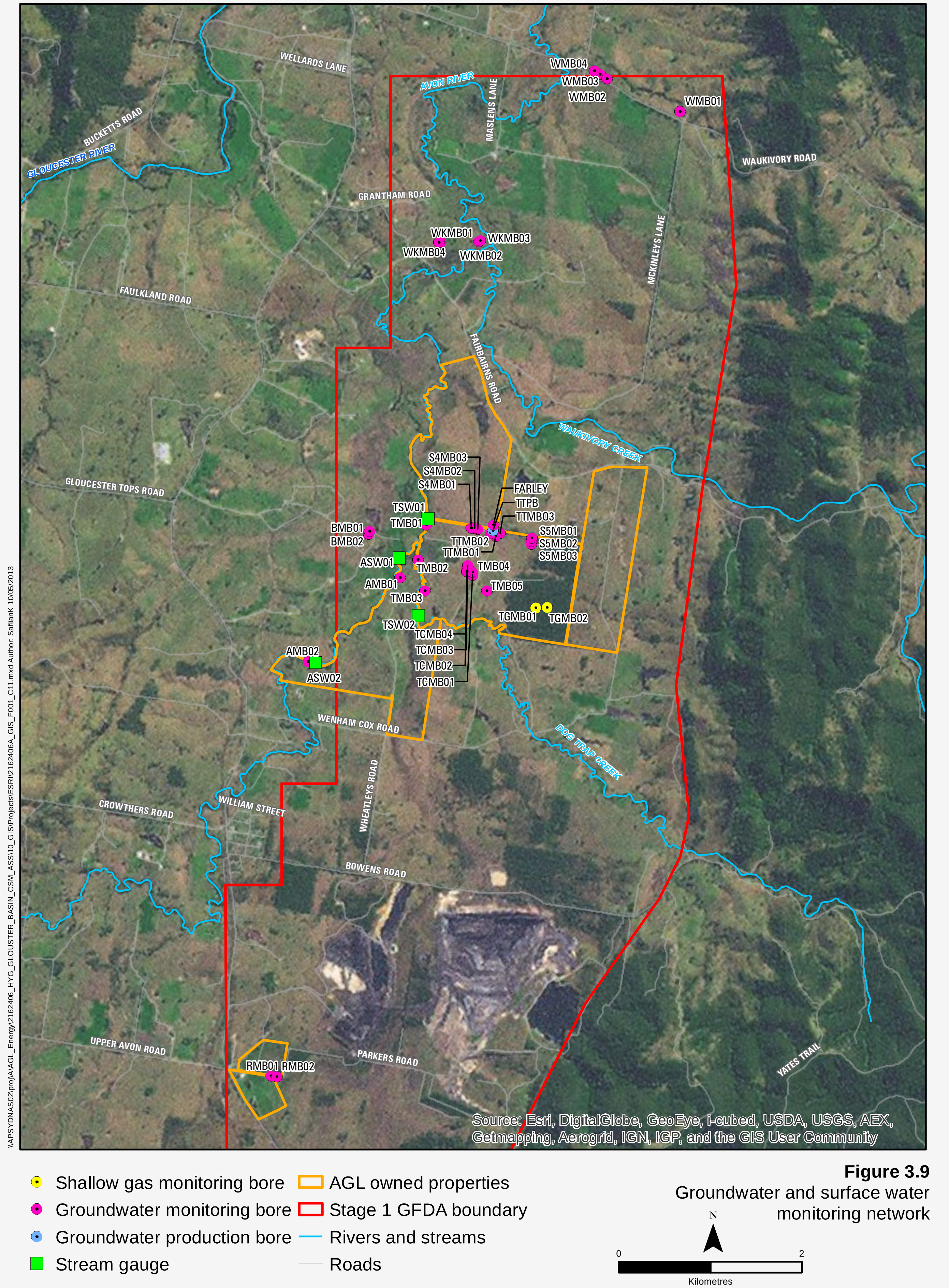
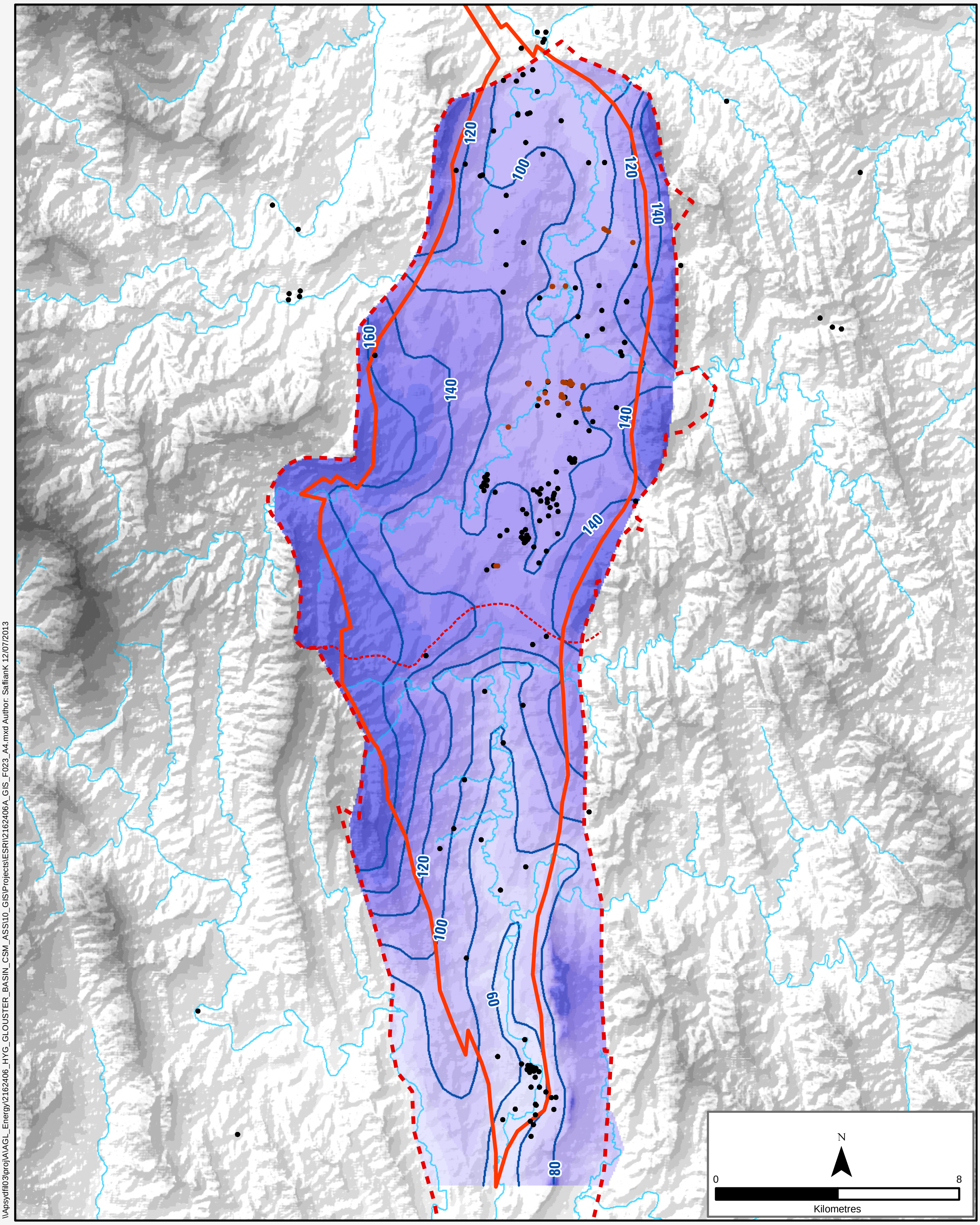


Figure 3.9
Groundwater and surface water monitoring network



Water levels m(AHD)
41 - 60
60 - 70
70 - 80
80 - 90
90 - 100
100 - 110
110 - 120
120 - 130
130 - 140
140 - 150
150 - 160
Alum Mountain Volcanics boundary
Permian Coal Measures boundary
Surface water divide
Rivers and streams
AGL bores
All other bores

Figure 3.10
Interpreted regional groundwater contours

The four hydrogeological units are summarised as follows:

1. **Alluvial deposits** adjacent to major creeks and rivers comprising unconsolidated sand, gravel and clay. These systems are heterogeneous but generally permeable with rapid recharge, through-flow and discharge associated with interactions with streams, and to a lesser extent with the underlying less permeable shallow rock. Hydraulic conductivity measurements range from 0.3 to 300 metres per day (m/d), averaging around 10 m/d.

2. **Shallow rock** comprising variably weathered and fractured Permian rocks extending to approximately 150 m below the surface, across all sub-cropping Permian units. The shallow rock zone is highly heterogeneous with relatively impermeable domains separated by more permeable domains, but on the whole it is more permeable that the deeper coal measures. The domains of higher permeability domains are due to a higher density of fracturing associated with an irregular weathering profile and the near-surface expression of faulting. Groundwater flow within this zone is more strongly controlled by weathering and fracturing than the attitude of geological strata. Hydraulic conductivity of the shallow rock ranges from 10 m/d to $1x10^{-6}$ m/d at a depth of 150 m, but is typically in the order of 10^{-3} to 10^{-4} m/d.

3. **Deep Coal Measures interburden**. Sandstone and siltstone units that form interburden to coal seams are indurated and typically of very low permeability, forming aquitards and confining layers. Permeability of interburden decreases with depth such that, at the maximum depth of CSG production is likely to be in the order of 10^{-5} to 10^{-7} m/d, or less.

4. **Coal seams**. Coal seams tend to be slightly more permeable than interburden and commonly form weak water bearing zones. Permeability and storage are provided by small fractures and cleats in the coal. As with interburden, drill-stem tests clearly show that the permeability of coal seams generally decreases with depth. At the maximum depth of CSG production, the permeability of coal seams is very low (10^{-4} – 10^{-6} m/d), but may be an order of magnitude higher than the interburden.

The Alum Mountain Volcanics underlie the Permian Coal Measures, and form the impermeable base of the Gloucester Basin. The Alum Mountain Volcanics outcrop in the eastern and western boundaries of the basin, forming the elevated topography of the Gloucester and Barrington Tops to the west, and the Mograni Range to the east.

3.6 Groundwater recharge

Rainfall is the primary recharge source to the aquifers and water bearing zones within the Gloucester Basin. Recharge from streams may occur during periods of high rainfall/surface flow and flooding. Recharge of the alluvium aquifers from high stream flow events and associated ponding is implied by bore hydrographs from piezometers screened within alluvium. Direct recharge rates to the rock aquifers and water bearing zones are low based on water level responses, and water quality indicators such as chloride and age dating (Parsons Brinckerhoff, 2012c). Recharge to deeper rock layers through vertical leakage from overlying hydrogeological units is possible but lateral flow appears to dominate. Observations of vertical head gradients indicate that recharge is highest towards the margins of the basin due to surface runoff from the adjacent elevated areas and more rocky outcrop/thinner soils in these areas.

3.7 Groundwater flow

3.7.1 Lateral flow

The groundwater flow pattern is controlled by topography, and recharge and discharge locations. The regional groundwater flow in the northern part of the basin is predominantly from south to north. The regional groundwater flow in the southern basin is predominantly from north to south (Figure 3.10). At the margins of the basin, groundwater will flow away from elevated areas of outcrop where recharge occurs and towards the centre of the basin where discharge occurs as stream baseflow and evapotranspiration.

The largest groundwater flows (in terms of through-flow per year) are likely to occur within the shallow rock unit which forms a thick and relatively permeable mantle of weathered and fractured rock over the low permeability Permian Coal Measures and basement rocks. Groundwater flow is likely to be relatively rapid within the alluvial deposits that underlie the main drainage systems. However these deposits tend to be thin (i.e. less than 15 m) and of relatively limited storage volume (compared to the deeper hydrogeological units). In the underlying Permian deposits, age dating of the groundwater indicates very slow groundwater movement and very long residence times, consistent with the very low measured permeability of those rocks.

3.7.2 Groundwater age and residence time

Radiocarbon analysis of groundwater samples from monitoring bores was carried out as part of the Phase 2 Groundwater Investigations (Parsons Brinckerhoff, 2012a). All these bores are located in shallow aquifers and water bearing zones in the eastern portions of the basin relatively close to recharge areas. This analysis identified that the alluvial aquifers contain modern and sub-modern water, <1000 years before present (BP) on average. Groundwater in the shallow rock system was found to contain water that was on average 12,000 years BP. Groundwater in the interburden units was on average 10,500 years BP, and groundwater in the shallow coal seams was on average 13,600 years BP. Groundwater in the deeper interburden and coal seams (below 300 m) is expected to be much older but has not been dated. Groundwater age was found to increase with depth at the nested monitoring bore sites.

Further investigation of groundwater age, based on radiocarbon and tritium analysis, was carried out as part of the Hydrogeological Investigation of a strike-slip fault in the Northern Gloucester Basin (Parsons Brinckerhoff, 2013a). Radiocarbon ages within the Tiedman fault zone were generally older (25,000 to >30,000 years BP) than in monitoring bores at equivalent depths/formations outside of the high permeability zone (5,000 to 22,000 years BP), suggesting there may be some contribution of deeper, older waters within the shallow fault zone.

3.7.3 Vertical connectivity

Vertical gradients in groundwater head have been observed in sedimentary rock aquifers within the Stage 1 GFDA, based on information from multiple piezometer installations. Although there is no systematic spatial pattern of upward and downward gradients across the Stage 1 GFDA, it is expected that downward gradients will prevail in topographically elevated areas towards the basin margin (recharge areas) and upward gradients in topographically lower parts of the Basin, towards the primary drainage lines (discharge areas).

Connection between the shallow and deep groundwater systems will be limited by the permeability of the rock strata which is known to be very low. This does not mean total isolation between the shallow and deep groundwater systems, but it implies that rainfall recharge to the deeper hydrogeological units via vertical or lateral seepage is very slow (Parsons Brinckerhoff, 2012a). This is further supported by bore hydrographs which show rapid groundwater responses to rainfall events in shallow bores and alluvium, but negligible, delayed or subdued responses in deeper monitoring bores.

3.7.4 Groundwater response to gas well flow testing

3.7.4.1 Stratford flow tests

Nine (9) gas wells were flow tested as part of the Stratford flow testing program between 2006 and December 2009 (AGL, 2012). This testing program was centred on the Tiedman property and all wells, apart from the Stratford 1 well, were fracture stimulated. There was monitoring of produced water volumes and water quality from the tested gas wells but there was only limited monitoring of beneficial aquifers in the local area. Produced water volumes from the gas production wells at the start were generally low (instantaneous rates of less than 0.35 L/s). In all cases the final dewatering volumes from each well were less than 0.11 L/s. Some 25 ML of produced water was pumped into lined storages from these wells for the duration of the flow testing program for later reuse. Water production (dewatering) volumes at all gas well sites reduced during the period of the flow testing program (AGL, 2012).

A 29 day flow test was conducted at gas production well Stratford 4 from 11 September to 9 October 2012 as part of the Hydrogeological Investigation of a strike-slip fault in the Northern Gloucester Basin (Parsons Brinckerhoff, 2013a). Stratford 4 has a total depth of 846.3 m and has 10 sections that are open (perforated) against coal seams; the shallowest being the Bowens Road seam (515 mbgl) which is stratigraphically below the intervals screened by the monitoring bores. A total volume of 0.292 ML was pumped during this period from the deep coal seams below 500 m depth.

Groundwater hydrographs at the S4MB, S5MB, TCMB and TTMB nested monitoring bores (Appendix A) were assessed to determine whether depressurisation of the coal seams at depth resulted in measurable drawdown of groundwater levels in the shallow groundwater system in the vicinity of Stratford 4. Table 3.4 contains a summary of hydrograph observations, and two trends were identified:

1. Eight out of the 15 monitored bores (S5MB bores, TCMB02, TCMB03, TCMB04, TTMB03 and Farley) show relatively stable groundwater levels with no consistent trend during or after the flow test. These bores tend to be relatively distant from the Stratford 4 well and have screened intervals that are relatively deep compared with other monitoring bores.

2. Seven out of the 15 monitored bores (S4MB bores, TTPB, TTMB01, TTMB02 and TCMB01) show relatively stable groundwater levels prior to the flow test, with a gradual decline in groundwater levels from early October.

It is not possible from the existing data to determine unequivocally the cause of the observed slight declining trend in groundwater levels in seven of the shallow monitoring bores that appears to start in early October. However it appears to be more consistent with the regional decline in groundwater levels due to the very low rainfall conditions in late 2012, than due to possible depressurisation effects.

The main findings of the water quality analysis undertaken as part of the Stratford 4 flow testing are summarised as follows:

- Groundwater chemistry at Stratford 4 gas well showed no significant change during the 29 day flow testing with the exception of dissolved methane. Variability in dissolved methane is expected and related to variability in methane present in the gas phase and flow volumes.
- Salinity and major ion chemistry of the shallow monitoring bores did not vary between pre and post flowing testing. Changes in trace metal concentrations occurred at some monitoring bores; however, these are not likely to be associated with flow testing as water levels remained mostly constant throughout the flow testing period. Dissolved methane concentrations showed a significant reduction in monitoring bores within the inferred fault zone.

3.7.4.2 Waukivory flow test

AGL plans to conduct a further flow testing program at Waukivory in 2013. This program involves four vertical gas wells that are to be fracture simulated and then flow tested. This program is yet to commence, although the WKMB nested monitoring bores for this testing program have been installed (Figure 3.9).

Table 3.4 Stratford 4 flow test groundwater level observations

Monitoring bore	Distance from Stratford 4	Screen depth	Formation screened	Groundwater level observations
TTPB	212	76–88	Leloma Fm; interburden	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.15 m)
TTMB01	258	76–88	Deards Coal Seam, Leloma Fm	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.1 m)
TTMB02	189	76–88	Deards Coal Seam, Leloma Fm	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.2 m)
TTMB03	296	186–199	Leloma Fm; interburden	Stable water level prior to and following flow test; No apparent trend
S4MB01	62	58–64	Leloma Fm; interburden	Stable but fluctuating water level prior to flow test; very slight declining trend from early October to mid-December <0.1 m)
S4MB02	67	89–95	Leloma Fm; interburden	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.15 m)
S4MB03	73	162–168	Leloma Fm; interburden	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.1 m)
S5MB01	658	52–58	Leloma Fm; interburden	Continued slow recovery after sampling events; No apparent trend
S5MB02	657	110–102	Leloma Fm; interburden	Stable water level prior to and following flow test; No apparent trend
S5MB03	656	158–164	Jilleon Fm: Roseville Coal Seam	Stable water level prior to and following flow test; No apparent trend
TCMB01	520	87–93	Leloma Fm; interburden	Stable water level prior to flow test; gradual declining trend from early October to mid-December (~0.1 m)
TCMB02	515	175–181	Leloma Fm; interburden	Slow recovery evident after sampling event in October; No apparent trend
TCMB03	510	260–266	Jilleon Fm: Cloverdale Coal	Stable but fluctuating water level prior to and following flow test; No apparent trend
TCMB04	505	327–333	Jilleon Fm: Roseville Coal Seam	Stable water level prior to and following flow test; No apparent trend
Farley bore	217	unknown	unknown	Continuing declining trend from before the flow test (early September); No apparent change in trend.

3.8 Influence of faulting on groundwater flow

3.8.1 Role of faults

Numerous faults occur throughout the basin and these have been divided into several types according to their orientation and past movement. On the eastern side of the basin (and in the vicinity of the Stage 1 GFDA) the structure is dominated by west-dipping thrust faults and near-vertical sinistral strike-slip faults.

Folding and faulting of sedimentary rocks can give rise to complex hydrogeological systems. Fault zones can act as either barriers to groundwater flow or as groundwater conduits, or have negligible influence, depending on the nature of the fault zone and the material within it (Fetter, 2001). If the fault zone consists of finely ground rock and clay (fault gouge), the material may have very low hydraulic conductivity compared with the host rock and form a barrier to flow. Such low-permeability faults may be apparent from significant differences in groundwater level across the fault, or appear as hydraulic boundaries in aquifer (pumping) tests.

Conversely, if a fault zone consists of one or more continuous open fractures, then it may act as a conduit. Under natural conditions, evidence for such conduit faults may be seen in geophysical surveys (contrasting conductivity), perturbations in groundwater levels, or the occurrence of fault related springs and discharge zones. When the groundwater system is pumped, such as in an aquifer test or extended flow test, a conduit fault may manifest as an apparent recharge boundary (source of recharge) and/or cause anomalous drawdown in monitoring bores connected to the fault. Any enhanced permeability of a fault zone is likely to apply to the migration of gasses as well as water.

3.8.2 Fault investigations

3.8.2.1 Tiedman property

A field based hydrogeological investigation was carried out to assess the hydraulic characteristics of a strike-slip fault within the Stage 1 GFDA on the Tiedman property (Parsons Brinckerhoff, 2013a). The investigation included a TEM geophysical survey, the 29-day Stratford 4 flow testing program and a 3-day pumping test. The TTMB nested bores were installed as part of this investigation, with TTPB installed as the test pumping bore (Figure 3.9). Water level trends were used as the primary proof of any enhanced connectivity within the fault zone. Water samples were collected and analysed for groundwater quality, dissolved methane content, isotopic composition and age to place further constraints on groundwater processes.

Results of the pumping test indicate that the fault zone is a broad and heterogeneous zone of enhanced hydraulic conductivity within the shallow rock aquifer. The fault zone does not form a barrier to flow, and does not cause strong preferred longitudinal flow in the direction of the surface trace. However there is evidence that at depth, these fault zones decrease in permeability due to increasing clay content and increasing lithostatic pressure which causes fractures to close and may even form barriers to flow where water bearing zones are truncated or offset.

Distinct hydrochemistry and (older) radiocarbon ages within the fault zone may indicate discharge of deeper groundwater under natural conditions. However, this appears to contrast with groundwater level data from multiple nested piezometers which indicate a generally downward hydraulic gradient at this site, consistent with recharge. Therefore there is no clear indication as to whether the fault zone is a net recharge or net discharge feature based on the current data.

Monitoring of groundwater levels and dissolved methane during the Stratford 4 flow test provided no clear evidence of enhanced connections between the deeper coal seams and shallow groundwater system over the timescale of the tests.

3.8.2.2 Waukivory

AGL plans to conduct a further hydrogeological investigation into faulting in association with the proposed Waukivory flow testing program. This is an equally (if not more important) fault investigation program than the Tiedman study as the thrust fault in this area is typical of many such features across the eastern portion of the basin (Figure 4.6).

The WKMB nested monitoring bores for this testing program have been installed (Figure 3.9). There were no noticeable increases in fracturing and water inflows when constructing those monitoring bores that were drilled through the thrust fault zone. In particular at the WKMB03 site that targeted the trust fault at depth, there were very clayey returns in the cuttings, there were no increases in water volumes, and the slug testing program suggested a hydraulic conductivity of 2×10^{-4} m/d.

3.9 Occurrence of gas in groundwater and surface water

Dissolved gas sampling of groundwater was carried out as part of the Phase 2 Groundwater Investigations (Parsons Brinckerhoff, 2012a). Dissolved methane concentrations tend to increase with depth and are highest in coal seams; results for the different hydrogeological units are shown in Figure 3.11.

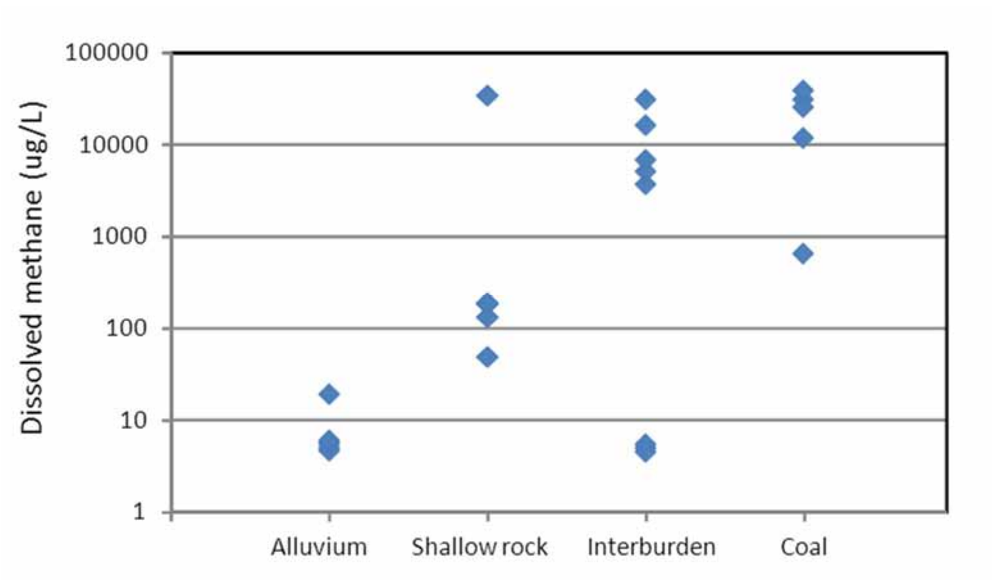


Figure 3.11 Dissolved methane in groundwater

Dissolved methane concentrations from the three surface water monitoring locations on the Avon River near the Tiedman property were negligible and ranged from <10 ug/L (LOR) to 14 ug/L.

3.10 Groundwater discharge

Groundwater outflow predominantly occurs as discharge to gaining streams (baseflow) and, to a lesser extent, direct evapotranspiration losses from the water table where the groundwater is shallow (i.e. close to the creeks and towards the northern and southern Basin outflow points). It is expected that most baseflow to the perennial streams is derived from groundwater discharge from the alluvium via relatively short flow paths. By contrast groundwater discharge from the shallow rock and underlying coal measures via longer flow paths is expected to be a minor component of stream baseflow.

Groundwater may also exit the Basin via aquifer through-flow in the alluvium and deeper hydrogeological units beneath the Avon and Wards Rivers, although this is assumed to be a minor component of the total outflow. The basin is a closed groundwater system in that negligible groundwater enters from outside the basin and most groundwater exits the basin via stream baseflow or evapotranspiration from the shallow water table.

Groundwater pumping for mining, and stock and domestic purposes also results in consumptive use from the Gloucester Basin. New CSG extractions will slightly increase the future consumptive uses. The cumulative impact of these consumptive uses is small based on the overall basin water balance (Parsons Brinckerhoff, 2012c). The net effect is there will be slightly less saline water discharging to the alluvium and discharging to the streams as baseflow. This will have a negligible impact on total river flows but may improve the stream water quality (especially during low flows).

3.11 Groundwater use

3.11.1 Mining

Groundwater modelling carried out as part of the Hydrogeological Assessment of the Duralie Extension Project (Heritage Computing, 2009) predicts that pit inflows to the Duralie Mine open cuts are expected to vary between approximately 0.2 and 1 ML/day during mining operations.

Groundwater modelling carried out as part of the Hydrogeological Assessment in Support of the Stratford Coal Project (Heritage Computing, 2012) predicts that total pit inflows will peak at 1.35 ML/day in Year 2 of mining, for all of the open cuts at the Stratford Mining Complex. Minimum pit inflows are predicted to be 0.74 ML/day at the end of mining (Year 11). Pit inflows are predicted to be reduced by a maximum of 0.5 ML/day if CSG dewatering in the Stage 1 GFDA are coincident with mining at the Stratford Mining Complex.

3.11.2 Coal Seam Gas

Coal seam gas dewatering is deemed to be industrial and irrigation use as water that is pumped as part of exploration (appraisal) programs and production programs is mostly reused for drilling, fracture stimulation, industrial recycling and irrigation reuse purposes. The long term reuse of produced waters at Gloucester will mostly be for irrigation purposes.

The GGP will involve the dewatering of deep groundwater and the extraction of gas from multiple coal seams within the Gloucester Coal Measures. Target coal seam depths will vary from site to site but are expected to range between 200 and 1,000 mbgl. The GGP includes the construction, operation and decommissioning of not more than 110 coal seam gas wells and associated infrastructure, including gas and water gathering lines, within the Stage 1 GFDA. The volumetric rate of groundwater extraction will not exceed 2 ML/day (averaged over a 12 month period), as specified in the Part 3A Approval (condition 3.11) and EPBC Approval (condition 22).

3.11.3 Stock and domestic use

A search of the NSW Office of Water (NOW) groundwater database indicates that there are 188 registered bores in the Gloucester Basin, within the Alum Mountain Volcanics boundary. Of the 188 registered bores, 24 are registered for stock and domestic use. A further 4 are registered for irrigation, 5 bores are registered for commercial and industrial use, 4 are registered for mining use, 121 for test and monitoring associated with mining across the area, and 30 are registered with unknown use. All those bores registered for industrial, mining, test and monitoring purposes are associated with either coal mining or coal seam gas developments.

The depth of the 24 private bores registered for stock and domestic use ranges from 4 and 66 mbgl, and therefore these bores are assumed to intersect the alluvium and shallow rock within the Gloucester Basin. Beneficial aquifers are not expected to exceed a depth of 75 m across the basin. It is assumed that annual stock and domestic bore use is approximately 1 ML/bore, therefore the total groundwater use is not expected to exceed 24 ML per year from the 24 privately registered bores.

4. Regional water balance

A water balance (or budget) involves estimation of the storage and flow of water in a defined area, during a given timeframe. A mass balance equation is used in which the change of water stored within an open (natural) hydrological system, is equal to the inputs to the system minus the outputs from the system (Todd and Mays 2005):

$$\text{Change in storage } (\Delta S) = \text{Inflows} - \text{Outflows}$$

Or:

$$\Delta S = (Q_{in} - Q_{out}) + (G_{in} - G_{out}) + P - ET$$

ΔS = change in the volume of water stored within the system.

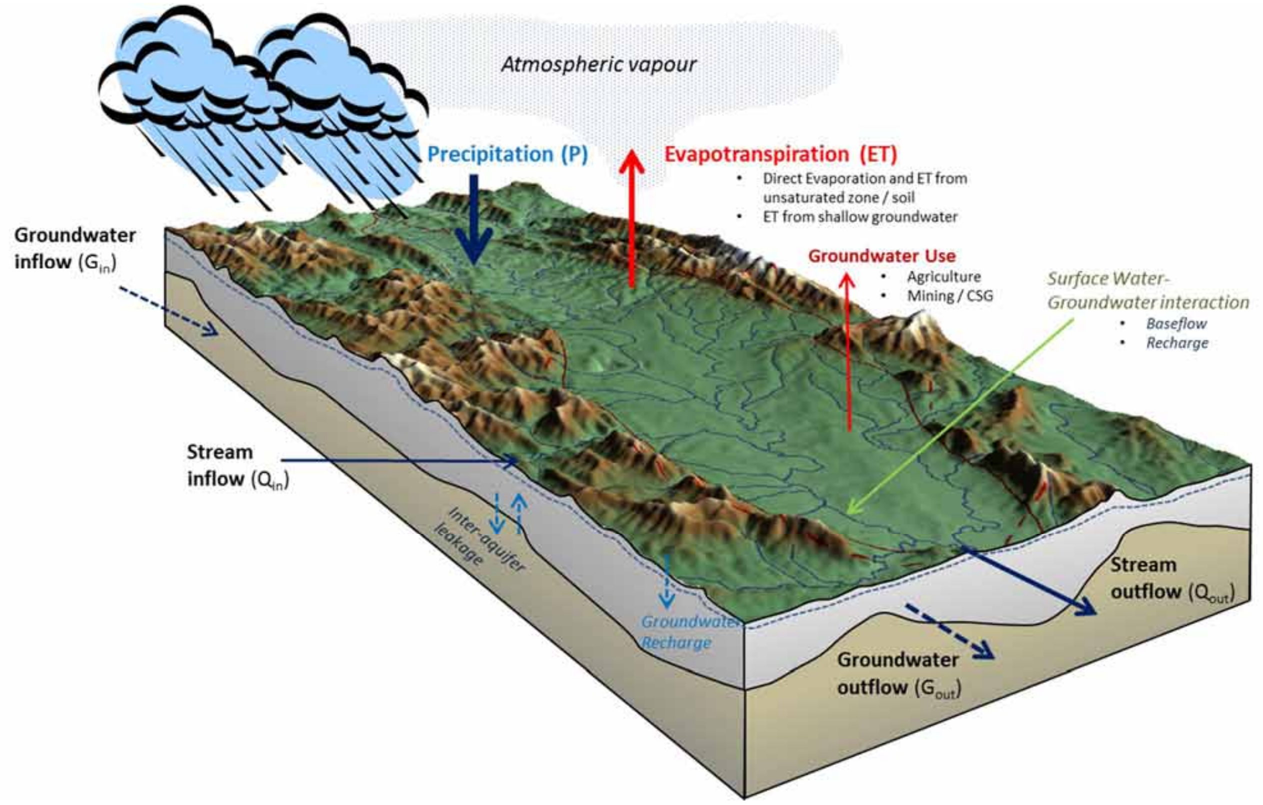


Figure 4.1 Conceptual water balance model

Inflows:

- Q_{in} = surface water flow into the system.
- G_{in} = groundwater flow into the system.
- P = total precipitation (a portion of which recharges the groundwater system).

Outflows:

- Q_{out} = surface water flow out of the system (or abstracted from the system).
- G_{out} = groundwater flow out of the system (or abstracted from the system).
- ET = evapotranspiration (comprising two components: ET from intercepted rainfall and the unsaturated zone and ET directly from the water table in areas of shallow groundwater).

Under natural long term conditions (or steady state conditions), the Gloucester Basin water balance can be assumed to be in a state of equilibrium, in which inflows equal outflows and the change in storage is (approximately) zero, as follows:

Total inflows = Total outflows

Or, including specific water balance components:

$$P + Q_{in} + G_{in} = ET + Q_{out} + G_{out}$$

This assumption underpins the development of a water budget for the Gloucester Basin under the current conditions. Given the current low level of groundwater use in the Basin, this assumption is considered valid.

Additional assumptions that have been required in the development of the water balance are as follows:

1. The Basin is essentially closed with respect to groundwater and surface water inputs, and the main water source is derived from rainfall recharge. This assumption is justified because the Basin is bounded to the east and west by elevated areas and geological units of very low permeability. Groundwater exits the basin mainly as base flow to streams, particularly in the lower reaches. It is assumed that a relatively minor component exits the basin as groundwater flow in the alluvium. This small component has been estimated using a numerical model.
2. Aquifer storage is not relevant to the calculation of long term groundwater fluxes when the Basin is assumed to be in natural equilibrium (or steady state). However, aquifer storage becomes relevant when assessing the effects of increased groundwater use that may temporarily change equilibrium conditions. Therefore estimates are made of the groundwater storage in each of the identified hydrogeological units to provide a basis for that assessment.
3. Structural complexities, such as faults, discussed in the model conceptualisation section were not included in this regional-scale water balance calculation. Investigations are ongoing to further assess the influence of faulting on the hydrogeological regime at the Stage 1 GFDA and these are presented in separate reports.
4. Surface water systems have not been explicitly modelled in this study; components of surface water flow are approximate only and based on the outflow characteristics of river catchments that overlap or are adjacent to the Gloucester Basin.

The key water balance components for the Gloucester Basin are summarised in Figure 4.2 and Table 4.1.

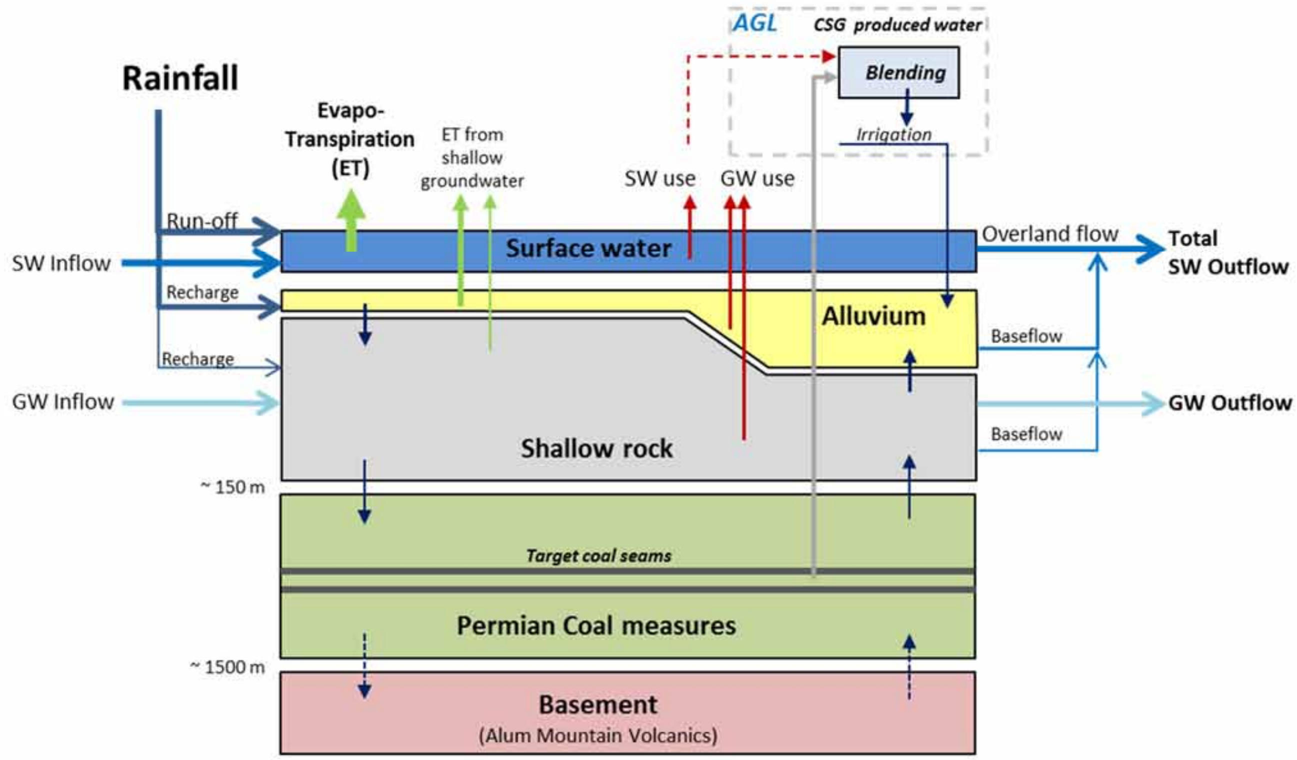


Figure 4.2 Schematic diagram showing components of the Gloucester Basin water balance

4.1 Regional water balance methodology

Many components of a regional model cannot be measured or determined with precision. For example, the total volume of water lost from a system to evapotranspiration cannot be directly measured and must be estimated by indirect means, and yet it forms a significant part of the regional water balance. Some components such as inter-aquifer leakage may be so uncertain as to provide an order-of-magnitude estimate only, while other quantities (e.g. stream flow, rainfall) are accurately measured and known to reasonable precision (± 10%). Therefore a regional water balance provides only an approximation of natural water fluxes in the environment. Given these uncertainties, the following approach and methods were used to derive the Gloucester Basin water balance:

1. A water balance framework was established based on field investigations and the latest conceptual model for the groundwater and surface water systems.
2. Fundamental concepts and assumptions of regional water balance were used to provide the basis for water balance calculations.
3. Elements of the regional water system that are measured and well known, such as surface water flow, rainfall, potential evaporation, groundwater levels and water quality were used to calculate key parts of the water balance such as total rainfall, stream flow, baseflow and groundwater recharge.
4. Estimates for groundwater and surface water use were based on publicly available information, databases and reports.
5. Components that are difficult to measure or calculate such as evapotranspiration from shallow groundwater and inter-aquifer leakage were estimated using a simple numerical model. The model included key elements of the system such as aquifer geometry, permeability, boundary conditions and known fluxes. It was then calibrated to observed conditions and used to derive estimates of groundwater flux.
6. The remaining elements of the water balance (principally evapotranspiration) were then derived or adjusted by difference by applying the water balance equations.

The actual water balance components vary substantially from year to year depending on whether the seasons are wet, dry, or average seasons. For this assessment, average rainfall data has been used together with more recent data sets regarding stream baseflow and groundwater recharge. Elements of the regional water balance, and methods used to assess them are defined in Table 4.1.

Table 4.1 Elements of the Gloucester Basin water balance

Flow	Description	Method of estimation
Inflows		
Total rainfall	The total volume of rain that falls within the basin (average annual).	Average rainfall multiplied by area of basin
Groundwater recharge	The component of rainfall that infiltrates the unsaturated zone and contributes to groundwater storage.	Multiple independent methods
Outflows		
Total surface water flow	The total volume of water that leaves the basin as surface water flow via the Avon River and Wards River systems (average annual river flow). This comprises two components: *baseflow* (groundwater discharge to streams) and *overland flow* which essentially bypasses the groundwater system.	Stream gauging data, (normalised to the basin area)
Stream base-flow	The component of stream flow that represents groundwater discharge (calculated by separating and removing the surface water flow component from stream hydrographs).	Base-flow separation of stream hydrographs (normalised to the basin area)
ET (Unsaturated)	The volume of water that is transferred to the atmosphere as vapour via evaporation of intercepted rainfall at the ground surface and also via evapotranspiration from the unsaturated zone before it reaches the water table. Because this component is calculated by mass balance it may include other losses from the surface water system, including local use and transfer to small dams and evaporation from streams and dams.	Mass balance
ET (shallow groundwater)	The volume of water that is transferred to the atmosphere as vapour via evapotranspiration directly from the water table in areas of shallow groundwater (i.e. riparian zones and any wetland zones).	Numerical model
Groundwater outflow	Groundwater that exits the Basin via seepage through the aquifers beneath the Avon and Wards Rivers in the Basin outflow zone (a minor component).	Numerical model
Groundwater and surface water use	The total annual consumptive use of groundwater and surface water in the Basin.	Estimate from reports and usage data
Inter-aquifer flows	The volume of groundwater that moves from one aquifer to another under a natural or induced hydraulic gradient in one year. In a closed basin, the net inter-aquifer flows are expected to be small. A simple numerical model is used to calculate inflow and outflow volumes for each hydrogeological unit in this study.	Numerical model, using observed values for hydraulic conductivity.
Aquifer Storage (S)	The volume of water that is contained within the pore-space (or fractures) of an aquifer. Aquifer storage comprises two components: elastic storage (confined storage) and total storage (specific yield or drainable porosity).	Saturated aquifer volume multiplied by reasonable storage coefficient

4.2 Inflows

4.2.1 Total rainfall

In a closed hydrogeological basin, the principal water input is rainfall. The total average annual volume of rainfall is simply calculated as the average annual rainfall multiplied by the basin area. For the purpose of a basin wide assessment the average annual rainfall for the four BoM weather stations (Table 3.1) located within the basin have been used (1053 mm):

- Total average annual rainfall volume = annual rainfall x basin area
- = 1053 mm x 305.6 km^2
- = 322 gigalitres (GL)

Note that the basin area of 305.6 km^2 includes the area of shallow rock overlying the Alum Mountain Volcanics (as against 217 km^2 for the Permian sediments) to account for the runoff and recharge directed into the basin from the immediately adjacent slopes.

4.2.2 Aquifer recharge

Only a small proportion of total rainfall actually recharges the aquifers via infiltration through the unsaturated zone. The remainder is lost as surface runoff via rivers and streams, and as evapotranspiration. The rate of recharge to the alluvial sediments differs to the rate of recharge to the shallow rock aquifers because of the difference in the thickness and permeability of the unsaturated zone.

Rainfall recharge has been estimated using three independent methods:

1. Water table fluctuation method (WTF).
2. Chloride mass balance (CMB).
3. Stream baseflow analysis.

4.2.2.1 Water table fluctuation method

The water table fluctuation (WTF) method assumes that the rise in groundwater level, as measured by fluctuations of water level in a monitoring bore (after correction for barometric effects) due to a significant rainfall event, represents the change in aquifer storage due to recharge from that event. The change in groundwater level is influenced by many other factors including the topography, monitoring bore location and local storage characteristics of the aquifer and soil profile. However the method does provide an approximate estimate of recharge.

The amount of rainfall recharge was assessed by analysing the increase in groundwater level in the aquifer following several rainfall events in 2011 using the equation below:

Estimated % recharge = (Δ WL (mm) x S_y x 100)/rainfall (mm)

Where:

- Δ WL = change in water level
- S_y = specific yield.

Monitoring bores, drilled for the Phase 2 Groundwater Investigations, screened within the alluvium commonly show significant and rapid water level increases following rainfall events indicative of rapid recharge (Parsons Brinckerhoff 2012b). Monitoring bores screened within shallow rock units and coal measures show insignificant water level changes immediately after significant rainfall events, but show gradual increases in water level over several months of generally above average rainfall (late 2011) (Parsons Brinkerhoff 2012b). Therefore this gradual groundwater level increase has been used to calculate a minimum recharge estimate for those areas where interburden and/or fractured rock outcrops.

Estimates of recharge as a percentage of rainfall based on the WTF method is shown for six rainfall events at five representative locations in Table 4.2. The results show a wide range in estimates of recharge, reflecting both the uncertainty in such estimates and the spatial variability of recharge fluxes. Groundwater level responses indicate that the rate of recharge as a percentage of rainfall is highest in the alluvium (~4% to ~13%), and significantly lower in the areas where the shallow rock sub-crops (~0.5%).

Table 4.2 Estimated rainfall recharge

Groundwater monitoring bore	Aquifer type	Rainfall event (mm)	Increase in groundwater level (mm)	Specific yield	Estimated recharge as % of rainfall
AMB01	Alluvium	82.4 (July 2011)	110	0.1	13
TMB01	Alluvium	82.4 (July 2011)	92	0.1	11
AMB01	Alluvium	44.8 (Aug 2011)	20	0.1	5
TMB01	Alluvium	44.8 (Aug 2011)	18	0.1	4
S4MB02	Shallow rock	733 mm (7 months: June–Dec 2011	~450	0.01	0.6
WMB04	Shallow rock	733 mm (7 months: June–Dec 2011)	~400	0.01	0.5
BMB02	Shallow rock	871 mm (9 months: April–Dec 2011)	~400	0.01	0.5

4.2.2.2 Chloride mass balance

Recharge rates can be estimated using the steady state chloride mass balance of groundwater method (CMB); this is the most widely used method for estimating recharge in Australia (Crosbie et al. 2010).

The CMB method assumes that the chloride concentration in shallow groundwater originates from chloride in recharging rainfall and that this has been concentrated by evapotranspiration during infiltration. Processes of rock weathering and halite dissolution are assumed not to be significant. For this reason the method has been applied to monitoring bores screened within the shallow rock (fractured interburden), but not the alluvial aquifer where those mineral dissolution processes are likely to be significant.

The CMB method can be described using the following equation:

$$R = \frac{D}{C_{gw}}$$

Where:

- R = recharge (LT^{-1})
- D = chloride deposition rate ($ML^{-2}T^{-1}$)
- C_{gw} (ML^{-3}) = the chloride concentration in groundwater.

The chloride deposition rate (D) is often estimated as the chloride concentration of rainfall multiplied by the average annual rainfall.

As there was no local available data for chloride concentrations in rainfall, the approximate chloride concentration in rainfall was estimated based on the well-established relationship between chloride concentration in rainfall and distance from the ocean (Hutton 1976). Assuming a distance of 50 km from site to the ocean the concentration of chloride in rainwater will be approximately 5 mg/L.

Concentrations of chloride in groundwater within shallow rock from baseline sampling have a median of 693 mg/L, and 25th and 75th percentiles of 100 mg/L and 987 mg/L respectively (Parsons Brinckerhoff, 2012a). An average annual rainfall of 1053 mm is assumed, with a chloride concentration of 5 mg/L. The implied recharge rates as a percentage of rainfall are shown in the Table 4.3 below:

Table 4.3 Estimates of recharge using the chloride (Cl) mass balance

	Units	Median Cl concentration	25th Percentile Cl concentration	75th Percentile Cl concentration
Rainfall [Cl]	mg/L	5	5	5
Groundwater [Cl]	mg/L	693	100	987
Annual Rainfall	mm	1053	1053	1053
Recharge	mm	7.60	52.70	5.30
Recharge	**% Rainfall**	**0.7**	**5.0**	**0.5**

The chloride concentrations in groundwater within the shallow rock aquifer imply an average recharge rate of approximately 0.7%, in line with the estimates from the water table fluctuation method. However given the significant variability in measured chloride concentrations, this estimate is imprecise. Estimates based on the 25th and 75th percentile Cl concentrations imply recharge rates ranging between 0.5% and 5% of rainfall.

Note that it is possible that a small proportion of chloride in groundwater is derived from dissolution of minerals in the sedimentary rocks (e.g. halite) some of which were deposited in marine environments. Therefore, estimates of recharge based on the chloride method should be considered a minimum value.

4.2.2.3 Baseflow analysis

Under long-term, steady state condition a groundwater basin is essentially in equilibrium whereby the aquifer recharge is balanced by the aquifer discharge, and the long term change in storage (groundwater level) is zero. By inference, the total volume of aquifer recharge can be assessed by estimating groundwater discharge.

In an essentially closed geological basin, there are three main sources of groundwater discharge (in order of decreasing magnitude in the Gloucester Basin):

1. Baseflow to streams.
2. Direct evapotranspiration losses from the water table where it is shallow (i.e. riparian zones).
3. Groundwater extraction.

It has been noted by several authors that the assumption that stream base flow approximates groundwater recharge may not be valid when those other balance components are significant or uncertain (Evans, 2007; Healy, 2010). For instance, stream baseflow characteristics can be influenced by many factors such as river bank storage, riparian vegetation, and modifications to the channel system such as diversions and dams. Evans (2007) suggests that baseflow should be considered as an upper bound for groundwater discharge.

Notwithstanding these potential issues, baseflow analysis is considered to be a useful method for assessing the Gloucester Basin because the surface water drainage system is not significantly modified and is considered to be, on the whole, a gaining system. In addition those other components of groundwater discharge (shallow evapotranspiration (ET) and groundwater use) are able to be approximated.

A hydrograph for the NOW stream gauge 208028 on the Avon River including an approximation of the baseflow component from 2005 to early 2013 is shown in Figure 4.3. Stream baseflow is the component of stream flow that is derived from groundwater discharge. Baseflow can be estimated by separating the overland flow component (transient flood peaks) from the stream hydrograph.

Hydrograph data for gauge 208028 indicates that the Avon River at this location flows 96% of the time. Periods of ‘no flow’ or very low flow, when the river is characterised by multiple disconnected pools, correspond to anomalously low rainfall, particularly in the months leading up to summer (Figure 4.3B). It is apparent that periodic and relatively frequent high rainfall events (>80 mm in a week) and associated significant stream flow events (> ~3000 ML/day) are required to recharge the alluvial groundwater system and sustain baseflow recessions over the following months. This suggests that the alluvial system is of limited storage and is rapidly depleted and replenished in response to rainfall variations.

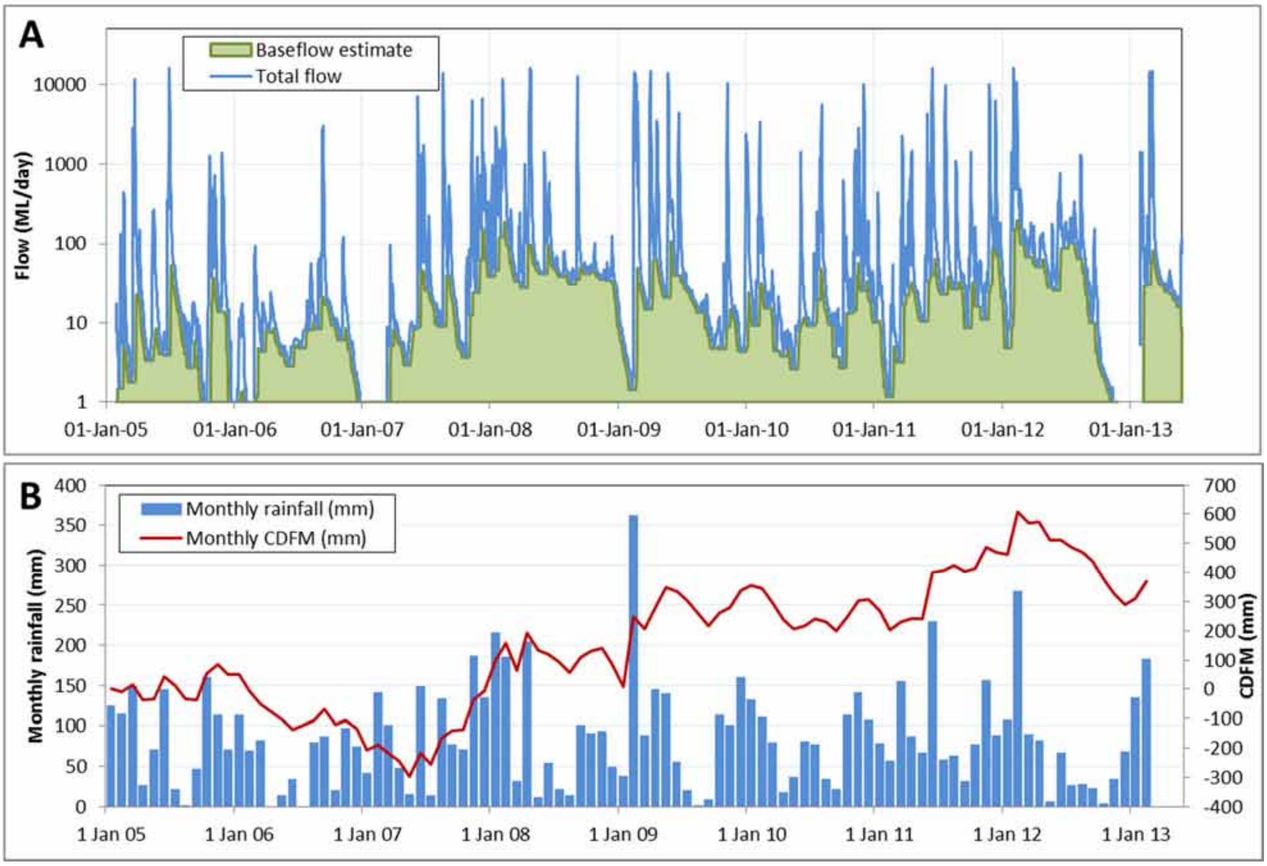


Figure 4.3 A) Avon River hydrograph at NOW station 208028; B) Monthly rainfall and cumulative departure from the mean monthly rainfall (CDFM) at Gloucester

The baseflow component was estimated at four gauging stations for streams with catchments that overlap with the Gloucester Basin (Table 4.4). The baseflow component was approximated by integrating flows below a line that links the hydrograph recession lows (approximated by a moving monthly minimum flow). This method is likely to underestimate the baseflow slightly but is considered adequate for this assessment.

Table 4.4 Estimates of stream baseflow at four gauging stations

Stream and Gauging station	Catchment Area (km^2)	Baseflow GL/year	Total flow GL/year	Baseflow Index	Baseflow as % of Rain
Avon River D/S Waukivory Creek	225	6.9	117.7	**6%**	**2.9%**
Mammy Johnsons River at Pikes Crossing	156	4.0	55.7	**7%**	**2.4%**
Karuah River at Booral	974	30.2	275.1	**11%**	**3.0%**
Karuah River at Dam Site	300	15.5	97.4	**16%**	**4.9%**

The *baseflow index* is the proportion of total flow that can be attributed to baseflow. For the catchments analysed, baseflow accounts for between 6% and 16% of total flow. The Avon River baseflow estimate is considered to be the most representative of the Gloucester Basin. Because the catchments (including the Avon catchment) extend outside of the Gloucester Basin, the baseflow component has been normalised to the catchment area and expressed as a percentage of the total rainfall that falls on the catchment or basin area (that is, ~2.9%).

If baseflow is considered to be entirely groundwater discharge and other components of groundwater discharge can be estimated, then this normalised index can be used to approximate total recharge to those catchments as a percentage of rainfall. Evapotranspiration of shallow groundwater is likely to be in the order of 1.5 GL/year (0.5% of rainfall; see below) and mining/groundwater use is relatively minor in comparison (~0.5 GL/year; 0.15% rainfall).

Therefore it can be concluded that recharge on a basin scale is likely to be in the range of 3% to 4% of rainfall based on this method:

4.2.3 Summary of recharge estimates

Three independent methods have been used to estimate recharge to the groundwater system within the Gloucester Basin. The results indicate that recharge is spatially variable, with recharge to the alluvium aquifers in the range of 4% to 13% of rainfall, and significantly less direct recharge to the shallow fractured rock, in the order of 0.5% to 1% of rainfall. Recharge to the alluvium may locally be higher than this rate where significant flooding occurs in response to high rainfall and runoff events.

On a catchment and basin scale, baseflow analysis suggests that groundwater recharge is in the range of approximately 3% to 4% of rainfall, which is consistent with the other estimation methods. It is assumed that most of this baseflow is derived via seepage from the alluvium and shallow rock units due to the elevated permeability of those two units compared with the deeper coal measures.

These results are consistent with isotopic evidence that suggests that alluvial aquifers contain 'modern' groundwater (<1000 years BP) and are relatively dynamic, rapidly recharging systems, whereas the shallow rock units and coal measures receive less recharge and have much longer groundwater residence times (typically >10,000 years BP).

4.3 Outflows

4.3.1 Stream baseflow

Stream baseflow (groundwater discharge) was calculated by stream hydrograph separation for four stream catchments that overlap with the Gloucester Basin (Table 4.4). Baseflow for the upstream catchments on the Avon and Mammy Johnson's Rivers (which together characterise the Gloucester Basin) equate to 2.9% and 2.4% of the total rainfall that falls on the catchments, respectively. Scaled up to the whole Gloucester Basin, this implies that the total groundwater discharge to streams over the area of the Basin is approximately 2.9% x 322 GL, or in the order of 9 GL/year.

4.3.2 Total stream flow

The average total stream flow at four gauging stations for streams with catchments that overlap with the Gloucester Basin are shown in Table 4.4. The average annual flow volumes for the Avon and Mammy Johnson's catchments are 117.7 GL and 55.7 GL, equating to 49.7% and 31.0% of the total rainfall on each catchment. Assuming that the Avon catchment is representative of the Gloucester Basin, the total surface water flow (and the overland flow component) that exits the Gloucester Basin is estimated as follows:

- Total flow (Gloucester Basin) = Total Rainfall (~322 GL) x ~50% = Approx. **150 – 160 GL/year**

Total overland flow is the total flow component, less baseflow. Baseflow for the Gloucester Basin is in the order to 8 to 9 GL/year; therefore overland flow will be in the range 140 – 150 GL/year.

4.3.3 Evapotranspiration (shallow groundwater)

Evapotranspiration (ET) can occur directly from groundwater where the water table is shallow and/or where vegetation accesses groundwater. This situation is common along major drainage lines and in alluvial aquifers.

Given the shallow depth to groundwater (<5 m bgl) in the lower reaches of the Avon and Mammy Johnson's Rivers and the gaining nature of those systems, it is likely groundwater discharge via direct evapotranspiration is a significant component of the water balance.

Evapotranspiration from the water table varies spatially and is dependent on multiple factors including the depth to groundwater, soil types, vegetation types and micro climatic conditions. As a first-order approximation however, it was assumed that shallow evapotranspiration is proportional to the depth to groundwater, decreasing linearly with depth from the maximum potential evaporation rate at the surface (~750 mm/year) to an extinction depth of approximately 3 m. These assumptions were built into a simple numerical model to provide an estimate of approximately 1.2 GL/year loss from groundwater via evapotranspiration.

4.3.4 Evapotranspiration (Unsaturated zone)

The combined volume of water lost to the atmosphere by evaporation of intercepted rainfall, surface water and evapotranspiration from the unsaturated zone (before it reaches the water table) is one of the most significant components of the water balance, but one that is difficult to measure directly or estimate precisely. Given that most other components of the water balance can be estimated using various methods, the evapotranspiration component has been estimated by mass balance as follows:

- $ET_{(Unsaturated)}$ = Total Rainfall $_{(basin)}$ – Q_{out} – $ET_{shallow}$ – GW use – SW use – $G_{out.}$
- = 322 GL – ~160 GL – ~1.2 GL - ~0.5 GL – ~1.0 GL – ~0.1 GL.
- **$ET_{(Unsaturated)}$ = ~160 GL/year**.

Total losses to evapotranspiration represent approximately 51% of rainfall. This value is a high proportion of rainfall, and probably also includes other losses from the surface water system such as evaporation from surface water bodies (streams and dams) and any pumping from the streams that is not accounted for elsewhere.

4.3.5 Water use

Estimates of current groundwater and surface water use in the Gloucester basin are listed in Table 4.5 below.

Table 4.5 Estimate of groundwater and surface water use in the Gloucester Basin

Water source	Water use	Annual use (GL)	Source and reliability of data
Groundwater	Mining	0.5	Estimates based on modelled mine inflows and use by Merrick (2009); Approximate
Groundwater	Stock and domestic	0.02	NoW database shows 24 private bores for stock and domestic purposes; assume maximum of 1ML/year actual use per bore; Approximate
Surface water	Agriculture and stock	1.0	Scaled from the surface water allocations in the Water Sharing Plan; Approximate, low reliability

4.4 Aquifer storage

The storage potential for each of the main hydrogeological units was calculated using an estimate of geometry and storage parameters for each aquifer type. These are summarised in Table 4.6.

Table 4.6 Storage values for hydrogeological units

Unit	Volume (m^3)	Specific yield	Confined storage coefficient	Confined storage (GL)	Unconfined Storage (GL)
Alluvial unit (saturated)	2.6×10^8	0.2	N/A	N/A	53
Shallow rock unit (saturated)	2.9×10^{10}	0.01	10^{-5}	0.3	294
Coal measures (coal + interburden) (saturated)	1.1×10^{11}	0.01	10^{-5}	1.5	1505

Total groundwater storage is calculated by multiplying the total saturated aquifer volume by the storage coefficient, which in the case of an unconfined aquifer is the specific yield and in the case of a confined aquifer is the confined (or elastic) storage coefficient. A specific yield of 0.2 for the alluvial aquifer, and a specific yield of 0.01 for the shallow rock unit and the coal measures were used.

4.5 Inter-aquifer flows

Estimates of inter-aquifer flows are not readily obtained using mass balance approaches. Therefore a simple numerical model was constructed of the whole Permian basin using the finite difference code MODFLOW in order to simulate the main elements of the basin water balance and derive order of magnitude estimates of the groundwater flows between aquifer units.

According to the classification in the Australian Groundwater Modelling Guidelines (Barnett *et al* 2012), the model used equates to a *generic* model or class 1 model, in that it is a highly generalised model used to derive approximate fluxes, but not to predict absolute groundwater levels or groundwater level impacts. Nevertheless, the model was calibrated in order to achieve a plausible head distribution across the basin while honouring estimates of stream baseflow and recharge to within an acceptable margin (± 20%).

The model assumed a basin area of 306 km^2 and aquifer dimensions were based on the assumptions outlined in the preceding section. The basin shape was approximated by assuming canoe-shaped structure with a maximum depth of the Permian Coal measures along the axis of the basin of 1700 m. Aquifers were represented using five model layers with alluvium in layer 1, shallow fractured rock in layers 1 and 2, and deeper coal measures in layers 3 to 5. Hydraulic parameters were applied to the model aquifer units according to measured and reported values. A sixth layer was included to represent the Alum Mountain Volcanics but was assumed to be impermeable.

The basin was entirely enclosed by no-flow boundaries (impermeable units) apart from narrow northern and southern outflow zones (fixed head boundary). Stream flow was simulated using the MODFLOW drain package with invert elevations set at the ground surface (from a digital terrain model). Rainfall recharge was applied to the model at an average of 3.5% of rainfall with a larger proportion applied to the alluvium, consistent with calculations above. Evapotranspiration (ET) was simulated using the EVT package with an extinction depth of 3 m below the ground surface and a maximum ET rate of 750 mm per year. The model was calibrated by adjusting hydraulic conductivity, EVT and recharge within realistic bounds to achieve a plausible head distribution and a drain discharge similar to the observed baseflow. A close match was obtained between modelled and observed groundwater levels (the scaled root mean squared (SRMS) value was less than 5%) and all simulated water balance components were close (within 10%) to the estimated values.

Inter-aquifer flows derived from the numerical model are shown in Table 4.7 for the Gloucester Basin.

Table 4.7 Estimates of inter-aquifer flows

From unit	To unit	Description	Flux (GL/year) Gloucester Basin
Alluvium	Shallow rock	Downward leakage	0.02
Shallow rock	Alluvium	Upward leakage	1.7
Shallow rock	Deep Coal Measures	Downward leakage	0.02
Deep Coal Measures (coal + interburden)	Shallow rock	Upward leakage	0.02

The model results indicate that there is potentially a significant flux between the alluvial unit and the shallow fractured rock unit (in particular, upwards leakage in discharge areas), but groundwater leakage between the shallow rock unit and the deeper (low permeability) coal measures is lower by several orders of magnitude.

Groundwater outflow from the basin outlet is assumed to be minor; by applying a constant head boundary to the narrow basin outlet area, a groundwater outflow of 0.2 GL per year is estimated.

4.6 Water balance under average conditions

A summary of the water balance components for the whole Gloucester Basin under average seasonal conditions is shown in Table 4.8, and as a conceptual diagram in Figure 4.3. Because of the inherent uncertainties in estimating many of the water balance components, the values below should be considered initial approximations only.

Table 4.8 Gloucester basin water balance (assuming average seasonal conditions)

Flow	Gloucester Basin (GL/year)	Uncertainty in estimate
Inflows		
Total rainfall (including recharge)	322	Low (± 10%)
[Groundwater recharge]	11.4	Moderate (± 30%)
Groundwater inflow	N/A	N/A
Inter-aquifer flows		High (order of magnitude)
Alluvium – Shallow rock	0.02	
Shallow rock - Alluvium	1.7	
Shallow rock – Deep coal measures	0.02	
Deep coal measures – shallow rock	0.02	
Outflows		
Total surface water flow (incl. baseflow)	150	Low (± 10%)
[Stream base-flow]	9.5	Moderate (± 30%)
ET (Unsaturated and other losses)	159	High (order of magnitude)
ET (shallow groundwater)	1.7	High (order of magnitude)
Groundwater outflow	0.2	High (order of magnitude)
Mining - Groundwater use	0.5	Moderate (± 30%)
Surface water use	1.0	Moderate (± 30%)
Aquifer Storage (S)		
Alluvium	53*	Moderate (± 30%)
Shallow rock	294*	High (order of magnitude)
Coal measures	1505* (*1.5 confined*)	High (order of magnitude)
Balance (Inflows – Outflows)	-0.1% (balanced)	

* These values are GL (not GL per year)

The following conclusions are made with respect to the Gloucester Basin water balance:

- Of the ~322 GL of rainfall that falls on the Gloucester Basin each year, approximately 150 GL (47 %) flows overland, bypassing the groundwater system, and is discharged via the Avon River and Wards River systems; a further 159 GL (49 %) is returned to the atmosphere via evapotranspiration or otherwise lost from the system. Surface water flows and ET losses therefore dominate the hydrological system, together accounting for 96% of rainfall (Figure 4.4).
- Based on the stream gauging records, the Avon and Karuah Rivers flow all year round except in very dry conditions (the rivers flow 96% and 98% of the time respectively). Of the total flow in these systems, approximately 6% (Avon River) and 11% (Karuah River) is baseflow derived from groundwater discharge. Most of this is derived from the alluvial deposits with a relatively minor discharge directly from the shallow rock. Groundwater discharge therefore represents a small component of the total surface water balance.
- On a basin scale, approximately 3.5% of rainfall (~11.4 GL per year) infiltrates the unsaturated zone to recharge the regional water table. Recharge rates are spatially variably however, being highest in the more permeable alluvial deposits (4% to 13% of rainfall) and significantly lower in areas where the less permeable shallow fractured rock unit outcrops (~0.5% to 1% of rainfall).
- There is substantial groundwater storage within the basin. The main unconfined aquifer unit (shallow fractured rock) has an unconfined storage of approximately 294 GL. By comparison, the alluvial aquifer has less storage (approximately 53 GL). The deeper coal measures unit (comprising coal seams and low-permeability interburden) is a large but tight groundwater reservoir, containing approximately 1505 GL of total groundwater storage, of which approximately 1.5 GL is held in elastic (confined) storage.
- It is evident from the water balance, that most groundwater flow in the basin occurs in the uppermost aquifer units; the alluvium and to a lesser extent, the shallow fractured rock where it is most permeable. The alluvial deposits have a throughflow of 8 to 9 GL per year, which, considering a total storage of ~53 GL, implies short groundwater residence times, consistent with the relatively young isotopic ages obtained from alluvial groundwater monitoring program and the relatively rapid stream baseflow recessions in low rainfall conditions. The shallow rock aquifer is of lower permeability and therefore transmits less groundwater (in the order of 2 to 3 GL per year). Much of the discharge from the shallow rock is via the alluvium adjacent to streams.
- Numerical modelling indicates that leakage between the shallow fractured rock unit and the deeper coal measures is very low and amounts to less than 0.02 GL per year. Leakage between shallow rock unit and the higher permeability alluvium is several orders of magnitude higher (up to 1.7 GL per year), driven mainly by the regional discharge to the rivers.

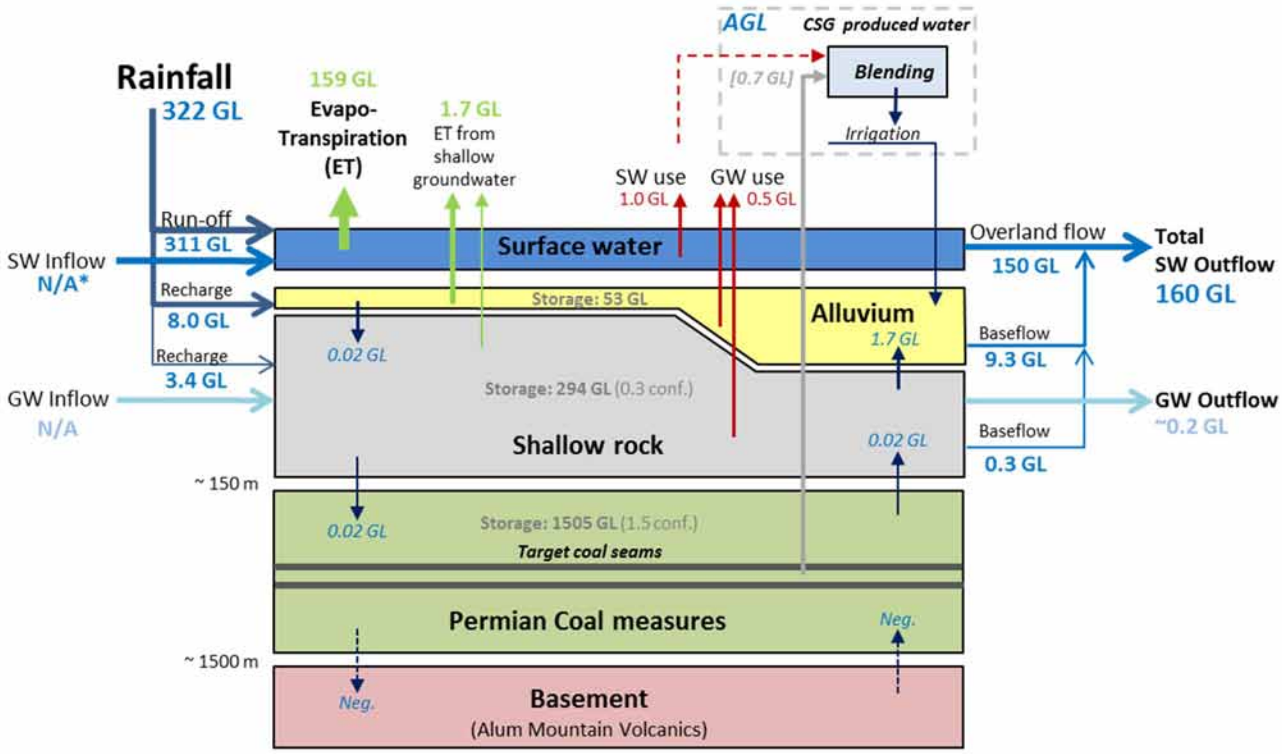


Figure 4.4 Conceptual groundwater balance for the north Gloucester Basin

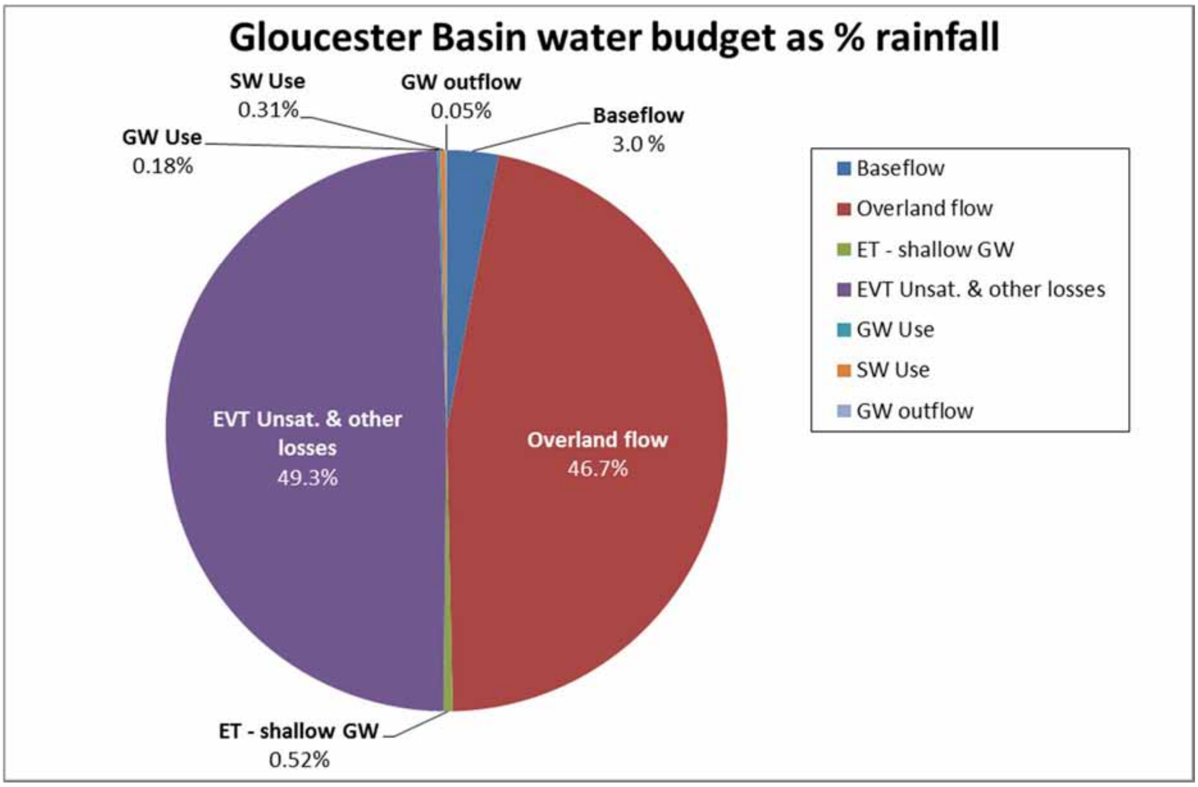


Figure 4.5 Estimate of total outflow as a proportion of total rainfall (322 GL)

4.7 Water balance under dry conditions

The water balance presented above is based on long term average conditions, using average values of monthly and annual rainfall, surface water flow and stream baseflow. This assumes a state of quasi-equilibrium over the long term. Over the timescale of months and years the basin water budget is constantly adjusting in response to variable climatic conditions. In assessing a regional water balance for the purpose of water management it is appropriate to consider the water balance under low rainfall conditions.

The response of the Gloucester Basin water balance during dry conditions was assessed in two ways:

1. Review of groundwater and surface water hydrographs during recent low rainfall conditions.
2. Running the water balance numerical model with reduced rainfall to assess changes to other water budget components. The model was re-run assuming rainfall at the 20th percentile (~750 mm) based on long term rainfall records.

4.7.1 Observed responses to variable climatic conditions

The following conclusions regarding seasonal changes in the water budget are drawn from a review of groundwater and surface water hydrographs for the monitoring period:

- Rainfall was significantly below average in 2006 (671 mm) and 2012 (805 mm). Significantly above average rainfall occurred in the years 2009 (1234 mm) and 2011 (1149), as measured at Gloucester. These anomalous years are reflected in the cumulative departure from the mean rainfall graph shown in Figure 4.3.
- Higher than average rainfall in 2011 (and early 2012), resulted in an increase in groundwater storage as shown by gradually increasing groundwater levels in the shallow fractured rock aquifer (in the order of 0.5 m, or approximately 1 – 2 GL storage over the basin). Groundwater levels in the alluvial aquifer responded rapidly to large rainfall and runoff events whereas small rainfall events resulted in negligible recharge. Stream baseflow in the Avon River was higher than average in 2008, late 2009, 2011 and early 2012, corresponding with high rainfall in those years or the preceding months.
- Below average rainfall conditions (e.g. late 2012) resulted in gradual declines in groundwater levels in the shallow fractured rock aquifer (over ~6 – 12 months), whereas groundwater levels in the deeper coal measures showed no significant decline (and in some instances continued to rise). Groundwater levels in the alluvium receded rapidly after major rainfall, typically taking one to two months to return to pre-existing levels. Several monitoring bores in the alluvium show a more rapid decline in groundwater levels during the summer months suggesting that evapotranspiration has a strong seasonal influence.
- As noted earlier in this report, the Avon River at NOW gauge 208028 flows most of the time (96%) but periodically ceases to flow during dry conditions. The no-flow events corresponding with low rainfall, and specifically an absence of heavy rainfall events, in the months leading up to summer. Most of the baseflow to the Avon River is derived from recently recharged groundwater in the alluvial aquifer, the storage of which is depleted quite rapidly (months) during periods of low rainfall. During the summer months evapotranspiration becomes an important factor.

It is concluded from these observations that adjustments in the basin water balance in response to low (or high) rainfall conditions occur at different rates in different parts of the groundwater system. Low rainfall conditions lasting more and a month or two leads to rapid depletion of storage in the alluvium aquifer, and when evapotranspiration is high, a rapid decline in stream baseflow and ultimately to no-flow conditions.

During low rainfall conditions therefore, groundwater discharge to streams will decrease to the point where surface flow ceases and discharge is balanced by evaporation from the disconnected pools. Evapotranspiration from shallow groundwater will then be the main component of groundwater discharge across the basin. In prolonged dry periods it is expected that groundwater storage may continue to decline in areas where the groundwater is shallow (<3 m). Groundwater use is likely to increase under such conditions. It is evident from stream hydrographs that the alluvial aquifer replenishes after several months of high rainfall, restoring stream baseflow.

Groundwater levels in the shallow rock aquifer respond more slowly showing a gradual decline in storage as discharge continues to the alluvium and via evapotranspiration. Groundwater pressures within the deep coal measures respond over much longer time periods (years to decades), such that no changes in groundwater levels would be evident from the current baseline.

4.7.2 Simulated response to dry condition

The numerical model used to assess the average water balance components was run using a 20th percentile rainfall condition (750 mm which equates to 77% of the average annual rainfall). The results of the predictive run indicate the following:

- Groundwater discharge would decrease by a similar magnitude (~80% of previous discharge), comprising stream baseflow and evapotranspiration. After initial rapid depletion of the alluvial aquifer, the shallow rock aquifer would respond more slowly, taking more than 5 years to approach a new equilibrium level by discharging to the alluvium and by evapotranspiration.
- Rates of groundwater flow between aquifers would change very little (<4 %) for the most part. The very minor groundwater flux between the shallow rock and the deeper coal measures would be virtually unchanged (<1% change). The exception is groundwater flow from the shallow rock to the alluvium which would decline by ~12% over some 5 to 10 years.

4.8 CSG development

This water balance study is not intended to provide detailed or quantitative assessment of the impacts of dewatering associated with the proposed Stage 1 GFDA development. However, a comparison of the projected maximum groundwater extraction rates against key water balance parameters provides a useful perspective regarding the likely magnitude of impacts to the natural water balance.

It is understood that Stage 1 GFDA development may result in a net consumptive dewatering volume of approximately 730 ML/year in the initial years of the project. This consumptive use is expected to diminish substantially with time because of the low permeability strata overlying the targeted coal seams. Most groundwater abstraction will be from the coal measures and interburden at depths greater than 200 m.

It is noted that the maximum groundwater use of 730 ML (~0.7 GL) per year represents approximately 6% of the estimated 11.4 GL that is recharged annually to the groundwater system in the basin. It is also a very small proportion (~ 0.2 %) of the groundwater storage in the shallow fractured rock unit (~294 GL) and an even smaller percentage (0.05%) of the groundwater storage (~1505 GL) in the deeper coal measures. Based on (say) an operational life of 20 years for a CSG wellfield and these maximum extraction volumes, the produced water volumes are still very low in comparison with the shallow rock storage (5%) and the deeper coal measure rock storage (1%).

During operation, the produced water pumped from the deep confined coal measures will be initially derived from storage, and over the following years and decades will be derived from shallow rock leakage and recharge to and lateral flow through the sedimentary rocks. It is also expected that the inter-aquifer flows from the coal measures to the shallow rock and the shallow rock to the alluvium will diminish during development and recovery of the GGP. This CSG dewatering activity may cause a slight improvement in Avon River water quality due to slightly lesser discharge volumes of slightly saline water from deep groundwater.

Downward hydraulic gradients will develop due to depressurisation, and any subsequent downward leakage of groundwater will be limited by the very low permeability in the deeper coal measures. Those downward fluxes are likely to be minor compared with the recharge rates in the alluvium and shallow rock and the unconfined storage available in those shallow systems.

The water balance has shown that the Gloucester Basin is a dominantly surface water system such that only ~3 to 5% of stream flow is derived from natural groundwater discharge. Of this ~6 GL per year, more than 70% is likely to be derived from discharge from the alluvium which is rapidly recharged with only a very small percentage from the deep coal measures hydrogeological units.

5. Conclusions

This report presents an updated quantitative water balance for the Gloucester Basin within which the Stage 1 GFDA is located. The report provides additional technical information on the importance of the surface and groundwater components of the water cycle to further assess the proposed CSG development and impacts on water resources and aquatic ecosystems. It also provides a basis for developing numerical models to assess those potential impacts in more detail.

Gloucester Basin water balance

A water balance is an estimate of the storage and flow of water in a defined area, during a given timeframe. A mass balance equation is used in which the change of water stored within an open (natural) hydrological system, is equal to the inputs to the system minus the outputs from the system.

Under natural long term conditions (or steady state conditions), the Gloucester Basin water balance is assumed to be in equilibrium, where inflows equal outflows and the change in storage is (approximately) zero. This assumption and several other key assumptions underpinned the development of an initial water budget for the Gloucester Basin under the current climatic conditions.

Many components of a regional model cannot be measured or determined with precision. Some components such as inter-aquifer leakage may provide an order-of-magnitude estimate only, while other quantities (e.g. stream flow, rainfall) are accurately measured and known to reasonable precision (± 10%). Given these uncertainties, the water balance was developed by focussing on elements of the water balance that could be derived from data of high reliability such as rainfall and stream records. Other components were estimated using a simple numerical model of the basin, or through applying the water balance equations.

The main conclusions of the water balance study are as follows:

- Of the ~322 gigalitres (GL) of rainfall that falls on the Gloucester Basin each year, approximately 150 GL (47 %) flows overland, bypassing the groundwater system, and is discharged via the Avon River and Wards River systems; a further 159 GL (49 %) is returned to the atmosphere via evapotranspiration (ET) or otherwise lost from the system. Surface water flows and ET losses therefore dominate the hydrological system, together accounting for 96% of rainfall (Figure 4.4).
- Based on the stream gauging records, the Avon and Karuah Rivers flow all year round except in very dry conditions (the rivers flow 96% and 98% of the time respectively). Of the total flow in these systems, approximately 6% (Avon River) and 11% (Karuah River) is baseflow derived from groundwater discharge. Most of this is derived from the alluvial deposits with a relatively minor discharge directly from the shallow rock. Groundwater discharge therefore represents a small component of the total surface water balance.
- On a basin scale, approximately 3.5% of rainfall (~11 GL per year) infiltrates the unsaturated zone to recharge the water table. Recharge rates are spatially variably however, being highest in the more permeable alluvial deposits (4% to 13% of rainfall) and significantly lower in areas where the less permeable shallow fractured rock unit outcrops (~0.5% to 1% of rainfall).
- There is substantial groundwater storage within the basin. The main unconfined aquifer unit (shallow fractured rock) has an unconfined storage of approximately 294 GL. By comparison, the alluvial aquifer has less storage (approximately 53 GL). The deeper coal measures unit (comprising coal seams and low-permeability interburden) is a large but tight groundwater reservoir, containing approximately 1505 GL of total groundwater storage, of which approximately 1.5 GL is held in elastic (confined) storage.

- It is evident from the water balance, that most groundwater flow in the basin occurs in the uppermost aquifer units; the alluvium and to a lesser extent, the shallow fractured rock where it is most permeable. The alluvial deposits have a through flow of 8 to 9 GL per year, which, considering a total storage of ~53 GL, implies short groundwater residence times, consistent with the relatively young isotopic ages obtained from alluvial groundwater monitoring program. The shallow rock aquifer is of lower permeability and therefore transmits less groundwater (in the order of 2 to 3 GL per year). Much of the discharge from the shallow rock is via the alluvium adjacent to streams.
- Numerical modelling indicates that leakage between the shallow fractured rock unit and the deeper coal measures is very low and amounts to less than 0.02 GL per year. Leakage between shallow rock unit and the higher permeability alluvium is several orders of magnitude higher (up to 1.7 GL per year), driven mainly by the regional discharge to the rivers.

This water balance study is not intended to provide detailed or quantitative assessment of the impacts of dewatering associated with the proposed Stage 1 GFDA development. However, a comparison of the projected maximum groundwater extraction rates against key water balance parameters provides a useful perspective regarding the likely magnitude of impacts to the natural water balance.

The Stage 1 GFDA development may result in a net consumptive dewatering volume of approximately 730 ML per year in the initial years of the project. This consumptive use is expected to diminish substantially with time because of the low permeability strata overlying the targeted coal seams. Most groundwater abstraction will be from the coal measures and interburden at depths greater than 200 m. The maximum groundwater use of 730 ML (0.7 GL) per year represents approximately 6% of the estimated 11.4 GL that is recharged annually to the groundwater system in the basin. It is also a very small proportion (~0.2 %) of the groundwater storage in the shallow fractured rock unit (~294 GL).

During operation, the produced water pumped from the deep confined coal measures will be initially derived from storage, and over the following years and decades will be derived from shallow rock leakage and recharge to and lateral flow through the sedimentary rocks. It is also expected that the inter-aquifer flows from the coal measures to the shallow rock and the shallow rock to the alluvium will diminish during development and recovery of the GGP.

Downward hydraulic gradients will develop due to depressurisation, and any subsequent downward leakage of groundwater will be limited by the very low permeability in the deeper coal measures. Those downward fluxes are likely to be minor compared with the recharge rates in the alluvium and shallow rock and the unconfined storage available in those shallow systems.

The water balance is dominated by surface water runoff and evapotranspiration, and most of the groundwater recharge and discharge is to the shallow alluvial and shallow rock aquifers. Therefore the initial water balance analysis implies that the proposed CSG dewatering from deep coal seams will have a minimal effect on shallow groundwater systems and surface water flows. This preliminary conclusion needs to be further evaluated using water level monitoring data and regional groundwater modelling tools.

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Appendix A

Groundwater and surface water hydrographs for the Stage 1 GFDA

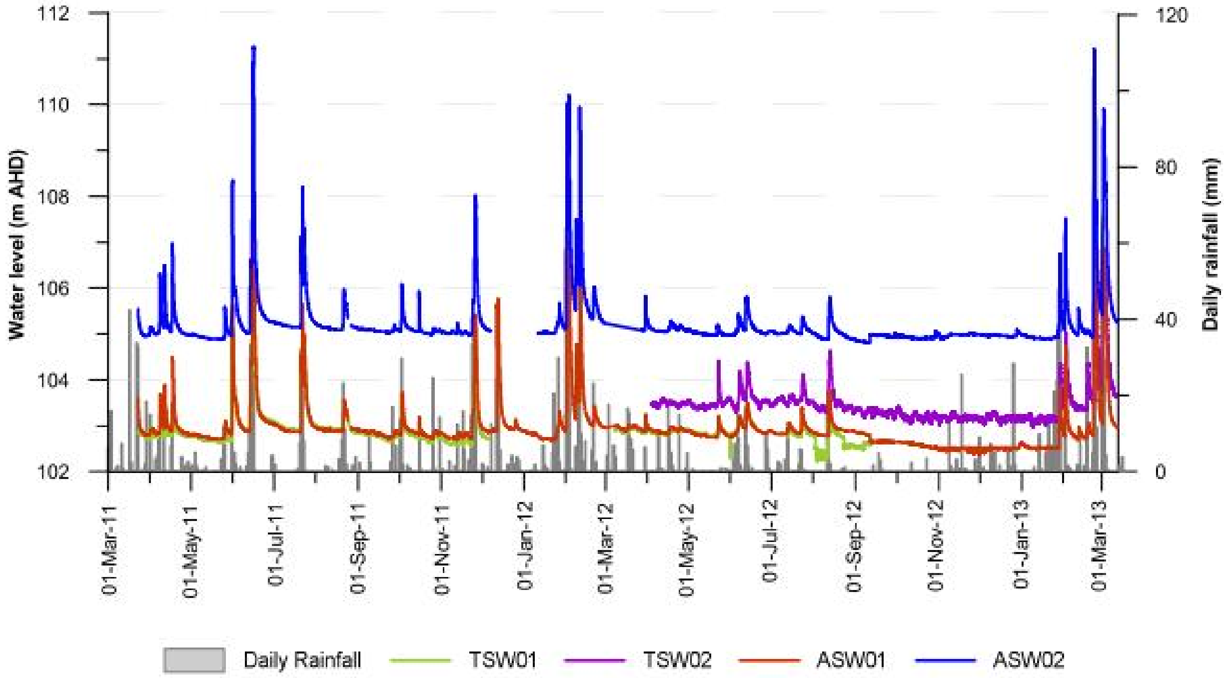

Figure A.1 Avon River and Dog Trap Creek stream level data and rainfall

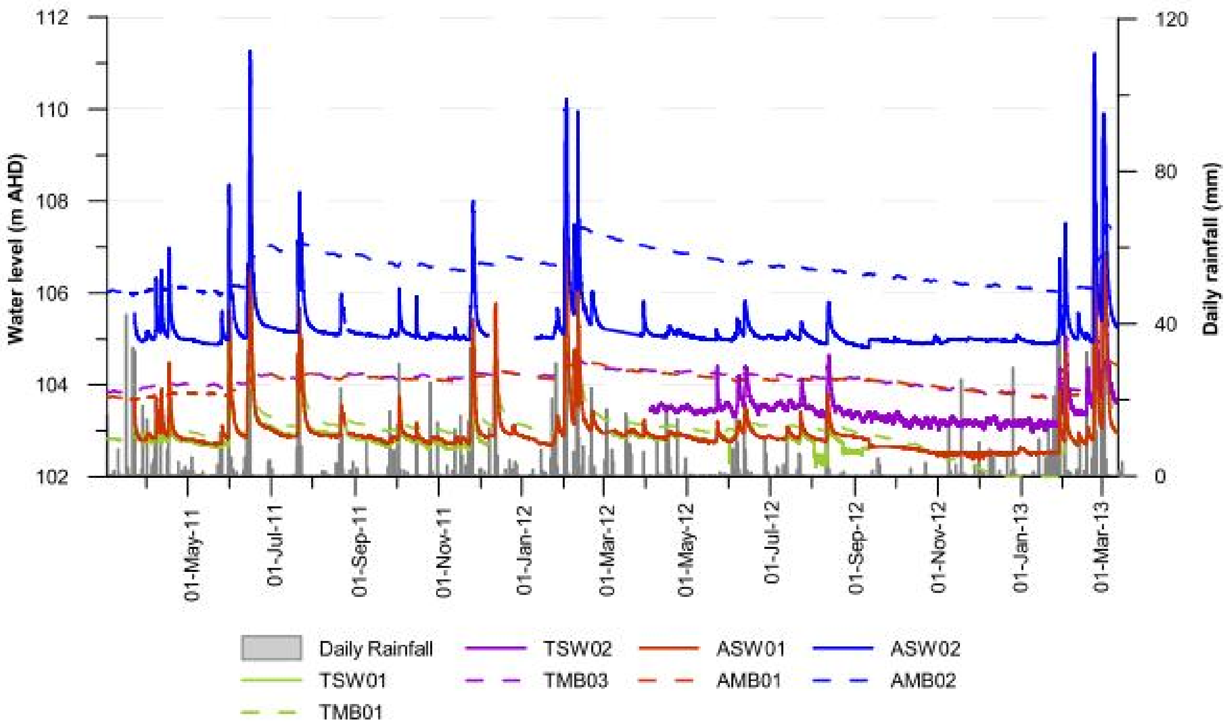

Figure A.2 River Avon and Dog Trap Creek water levels and adjacent alluvial groundwater levels

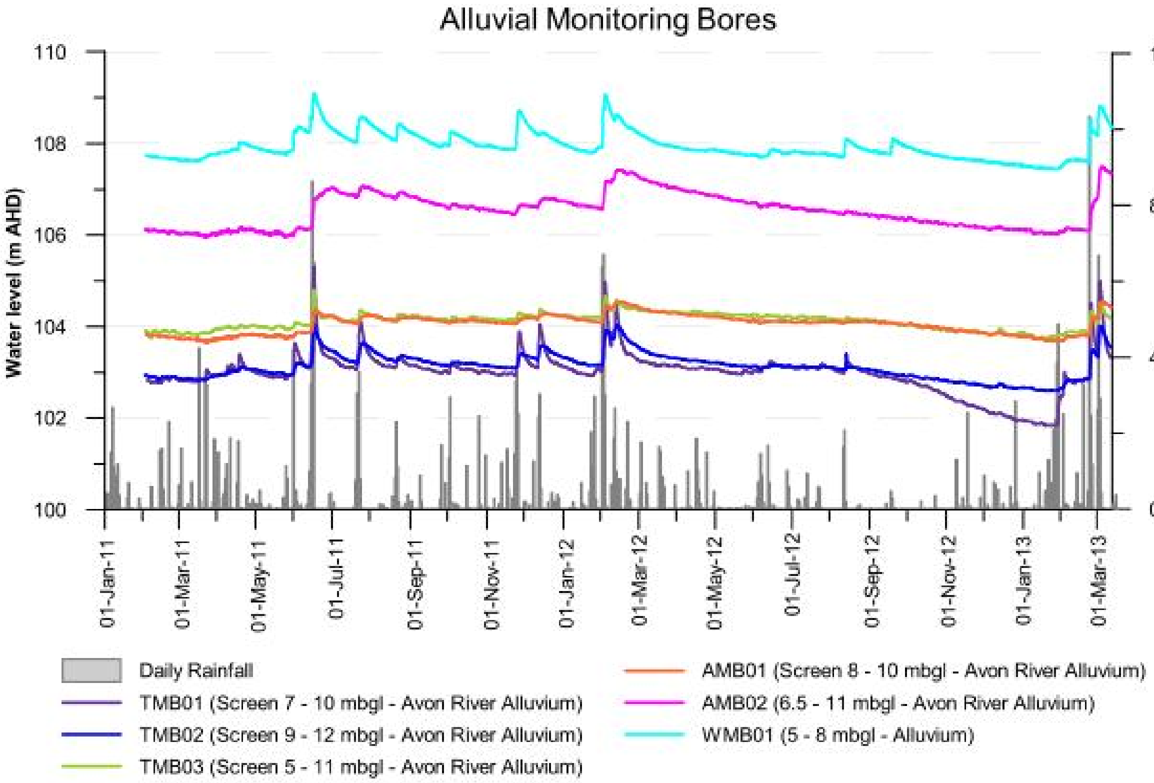

Figure A.3 Groundwater levels and rainfall in the alluvial monitoring bores

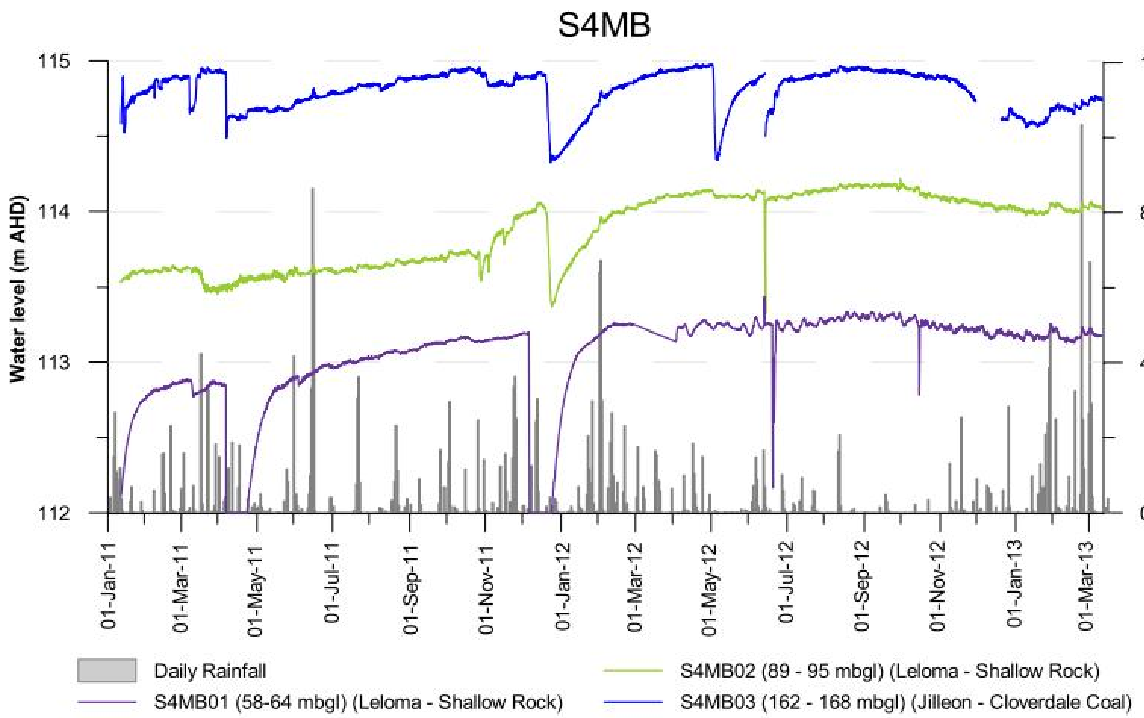

Figure A.4 Groundwater levels and rainfall at the S4MB site

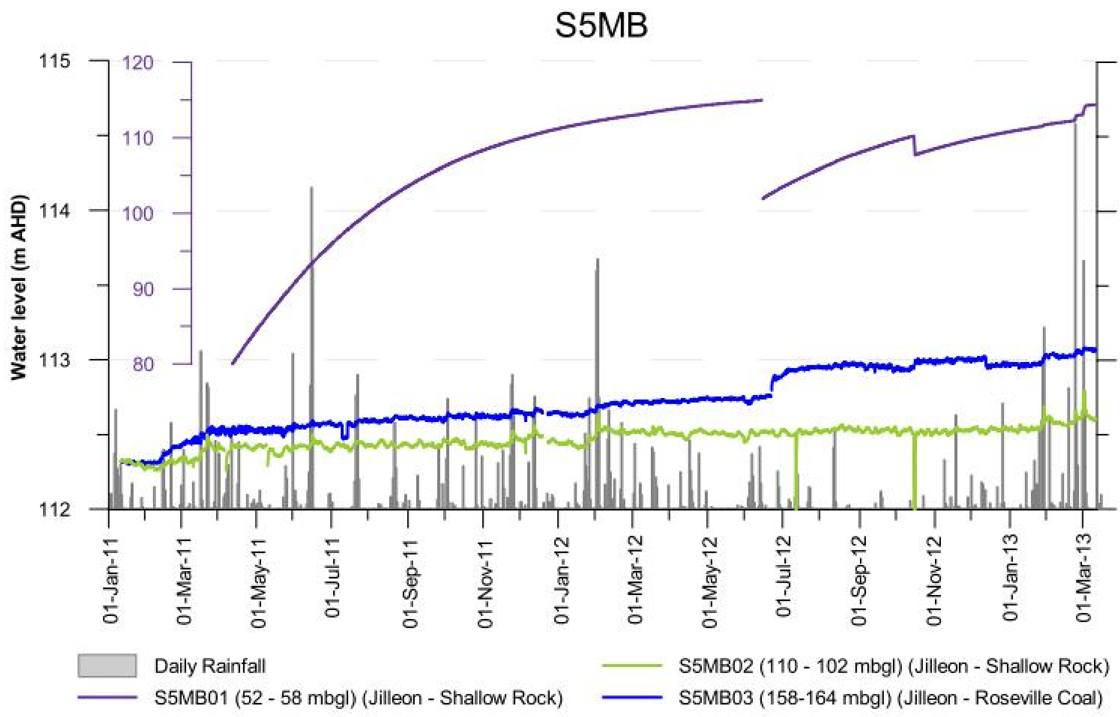

Figure A.5 Groundwater levels and rainfall at the S5MB site

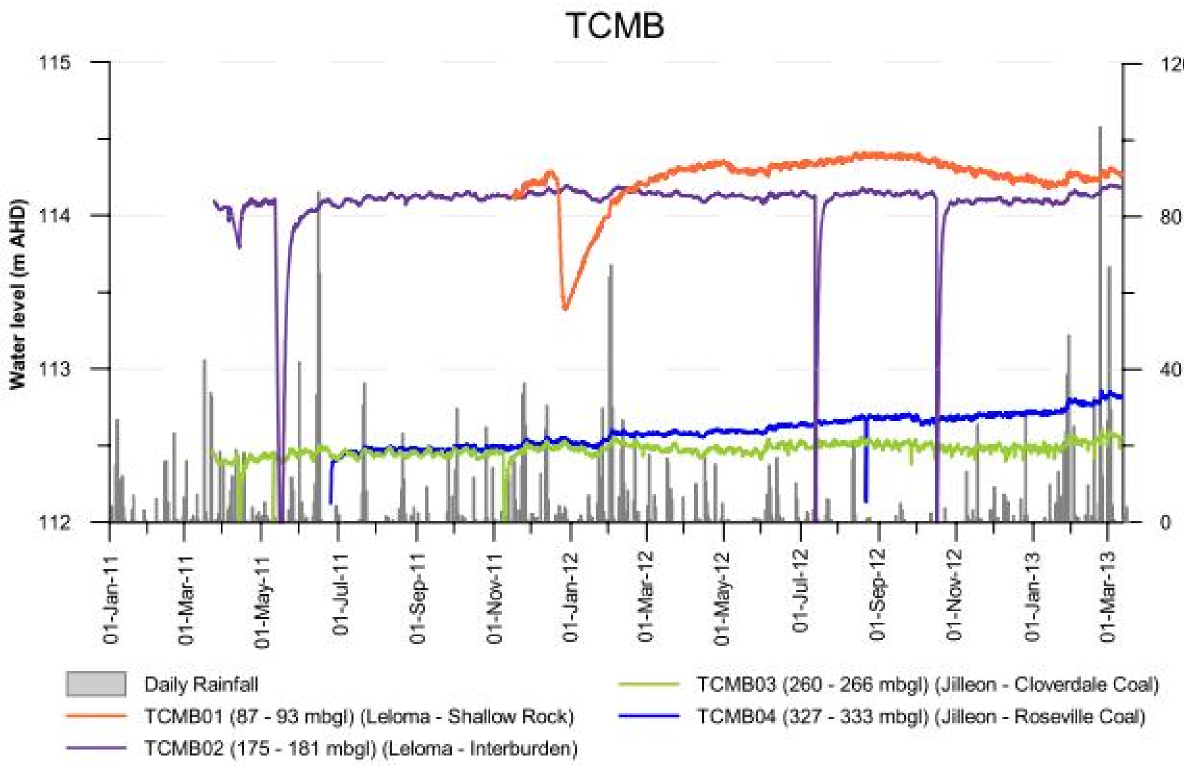

Figure A.6 Groundwater levels and rainfall at the TCMB site

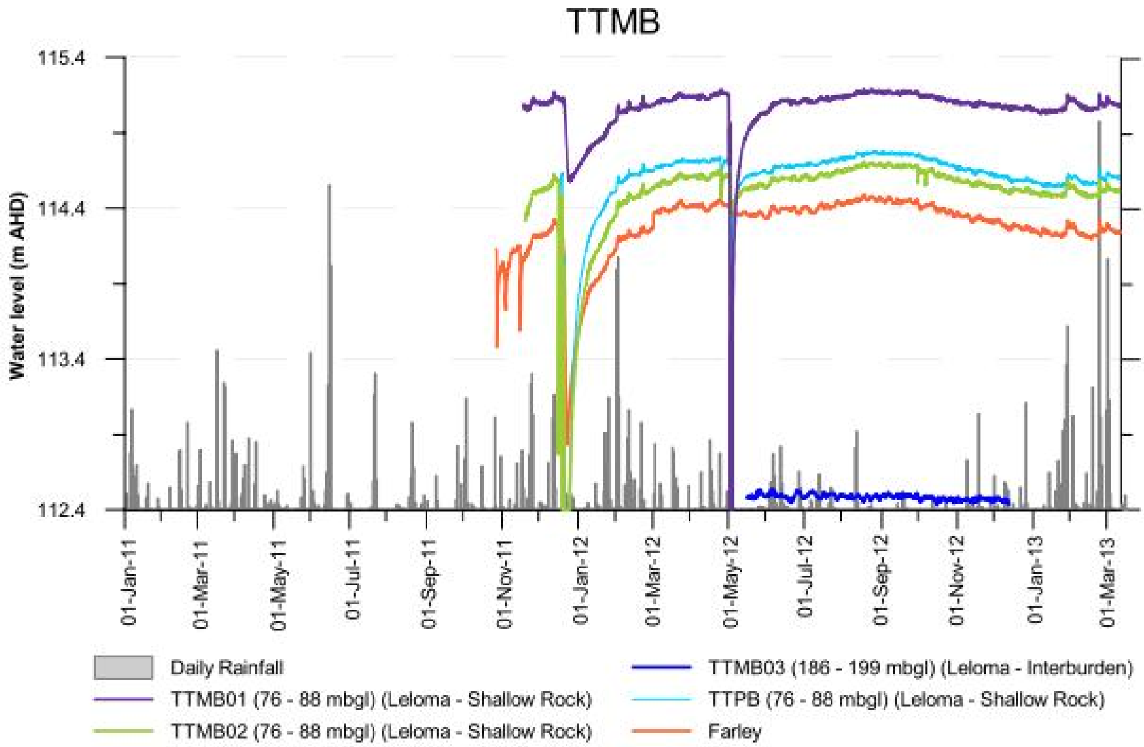

Figure A.7 Groundwater levels and rainfall at the TTMB site

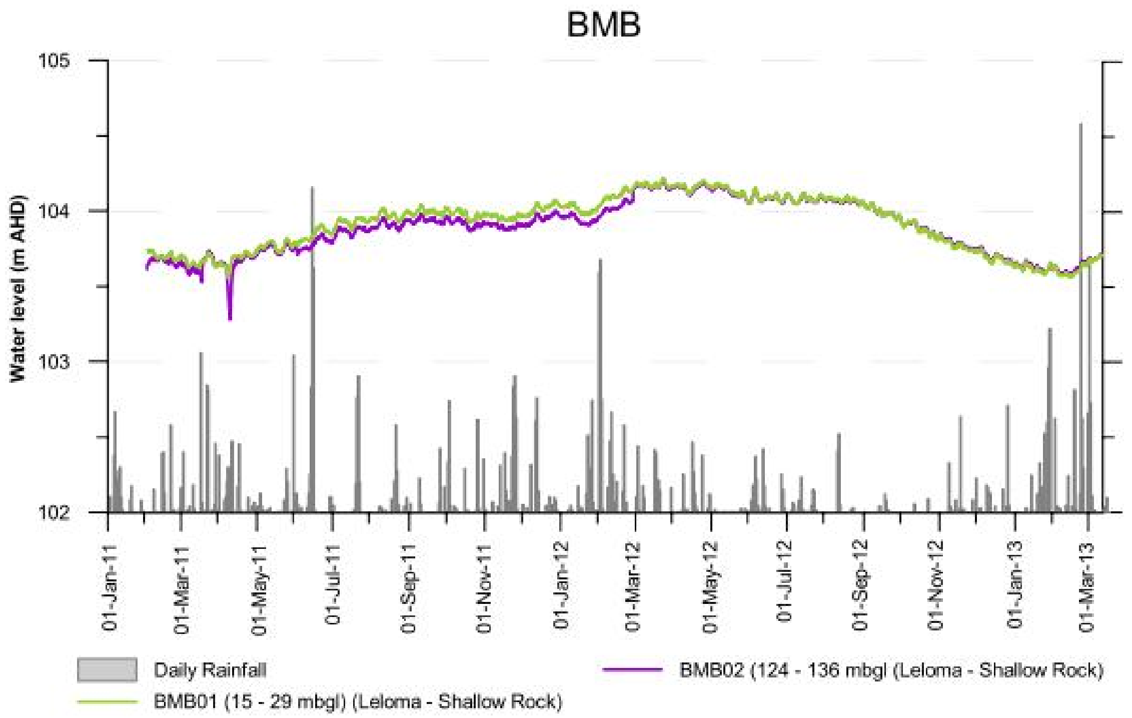

Figure A.8 Groundwater levels and rainfall at the BMB site

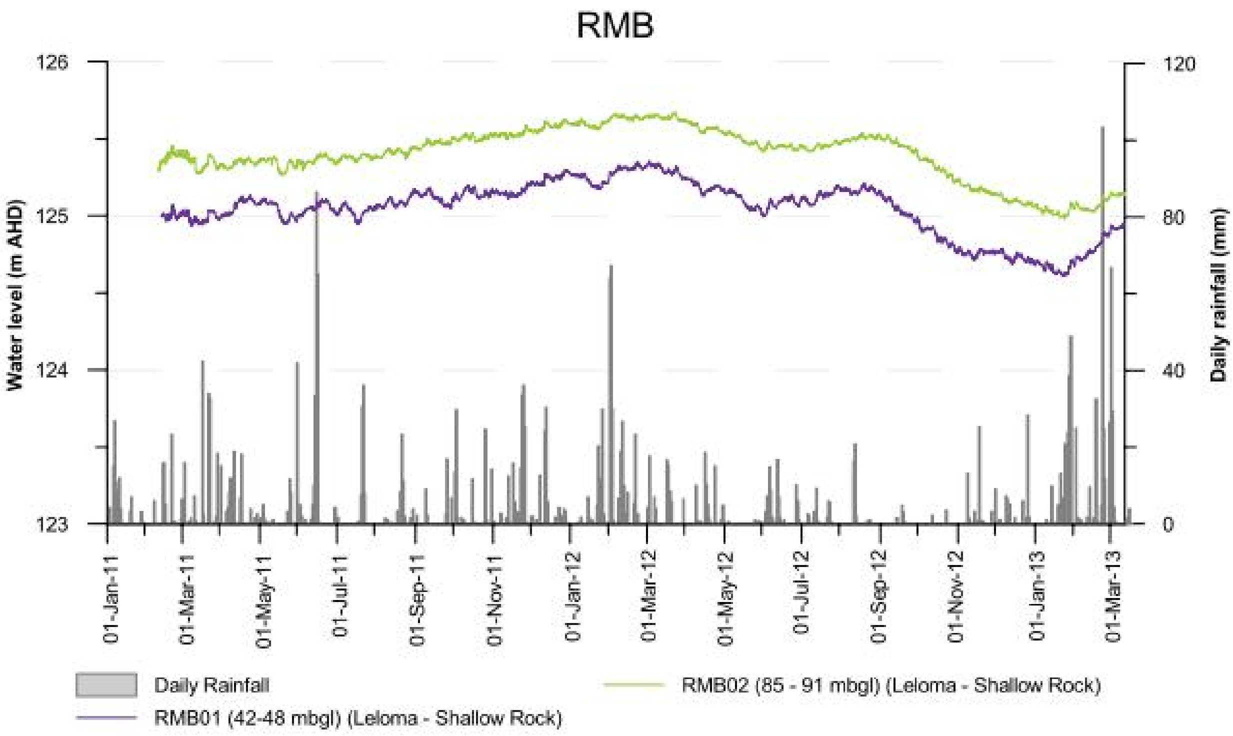

Figure A.9 Groundwater levels and rainfall at the RMB site

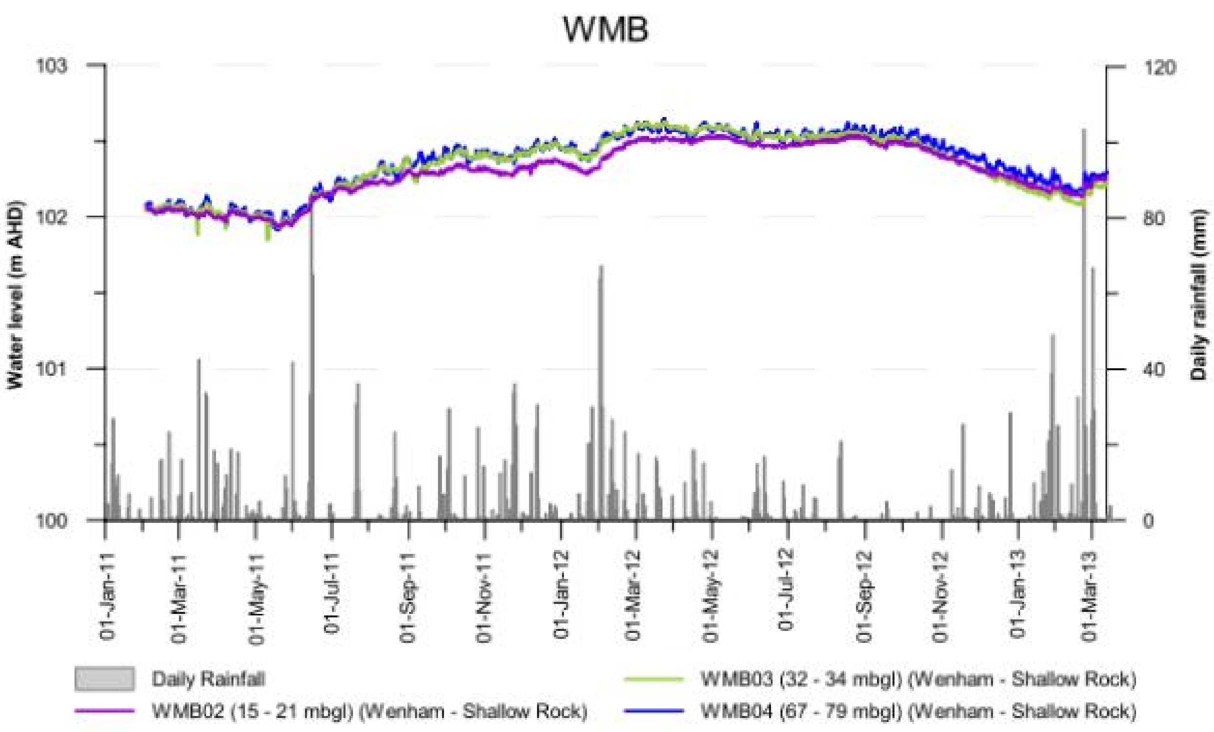

Figure A.10 Groundwater levels and rainfall at the WMB site

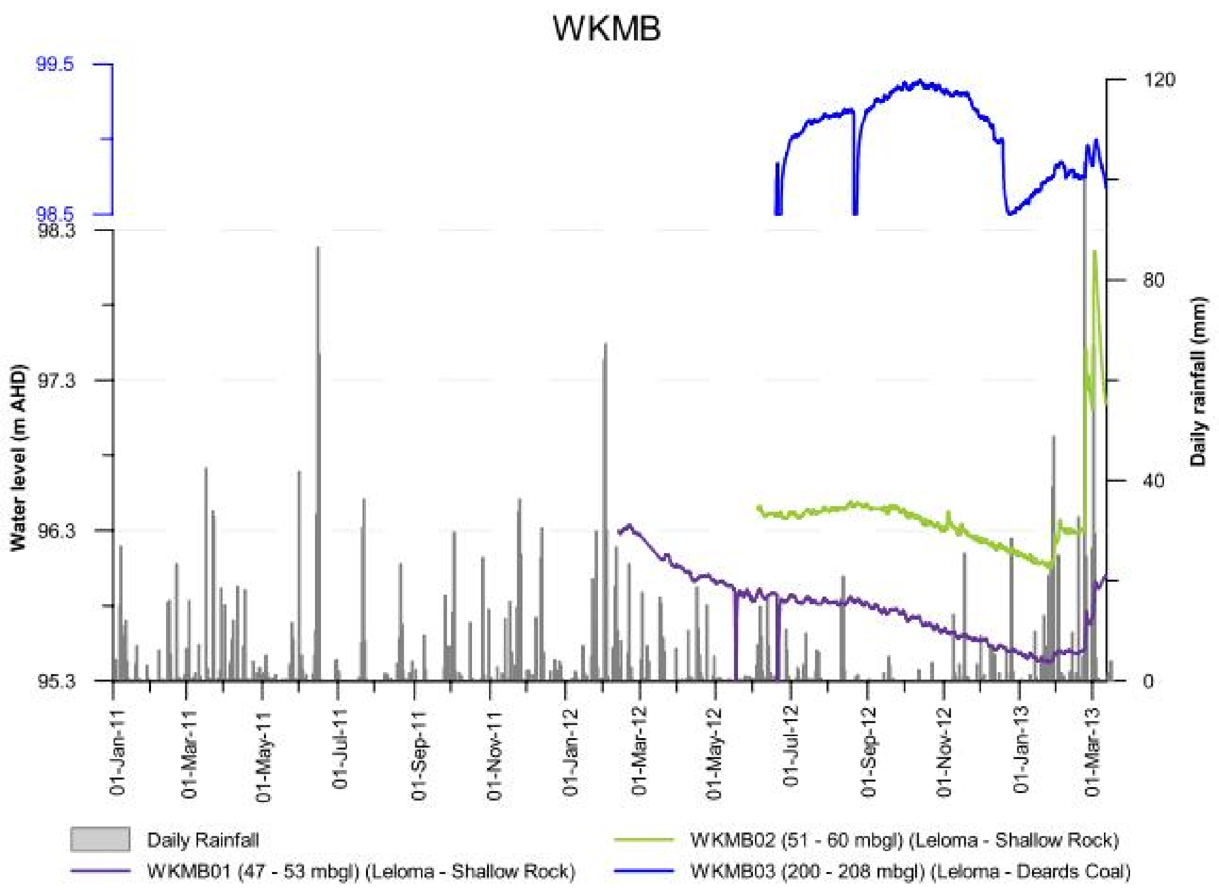

Figure A.11 Groundwater levels and rainfall at the WKMB site