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## Analysis of water level and water quality trends within shallow groundwater systems of monitoring sites within the Southern Sydney Basin's Camden Gas Project.

Erik Bartrop

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# **Analysis of water level and water quality trends within shallow groundwater systems of monitoring sites within the Southern Sydney Basin's Camden Gas Project.**

## **Abstract**

AGL Energy Pty Ltd owns and operates the Camden Gas Project in the Southern Sydney Macarthur region and are currently extracting water and methane from the underlying Illawarra Coal Measures. Within the Macarthur region are two groundwater monitoring sites located at Menangle Park and Denham Court. At each site has four monitoring bores established to monitor the groundwater levels and allow water quality testing. These monitoring bores enable the characterisation of the local groundwater system and an assessment of impacts from coal seam gas extraction on the groundwater system. The Menangle Park monitoring bores are within 100 metres of active production bores whereas Denham Court is ~15km outside the current Camden Gas Project. Both Menangle Park and Denham Court monitoring bores record the groundwater levels of the geological units such as alluvium, the Wianamatta Group and the Hawkesbury Sandstone. Groundwater level hydrographs assess and compare the recharge/drawdown characteristics. In addition, water samples were taken from the Menangle Park monitoring bores (MPMB01, MPMB02, MPMB03 and MPMB04), the nearby production bore (MP17) and the Nepean River. The samples were measured for major ions, elements, radioisotopes and stable isotopes. The techniques involved AMS, CRDS, EA-IRMS, IC and ICPMS. The results characterised the Hawkesbury Sandstone at Menangle Park into an 'upper' and 'lower' level separated hydrogeologically by a 12 metre thick shale layer. The 'upper' level was dated at 600BP whereas the 'lower' level was dated between 14,500-16,000BP. The hydrogeochemistry of the coal seam water was significantly different to the Hawkesbury Sandstone however, the age calculations were unrepresentative and unreliable. The water quality was assessed in the Hawkesbury Sandstone and was found to be relatively fresh whereas the Bulli Coal Seam was saline. Interpretation of these results suggests no or negligible hydraulic connection between beneficial aquifers and the coal seam aquifer. Based on this the author concluded that there is negligible impact from coal seam gas extraction on the Hawkesbury Sandstone. However, the data available did not enable the author to make an assessment for the likelihood of long term impacts from coal seam gas extraction.

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Erik Bartrop

**Thesis submitted in part fulfilment of the requirements of the Honours degree of  
Bachelor of Science in the School of Earth and Environmental Sciences, University of  
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The information provided in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Erik Bartrop

A handwritten signature in black ink, appearing to read 'Erik Bartrop', with a long, sweeping underline.

Date: 14/10/2014

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## Abstract

AGL Energy Pty Ltd owns and operates the Camden Gas Project in the Southern Sydney Macarthur region and are currently extracting water and methane from the underlying Illawarra Coal Measures. Within the Macarthur region are two groundwater monitoring sites located at Menangle Park and Denham Court. At each site has four monitoring bores established to monitor the groundwater levels and allow water quality testing. These monitoring bores enable the characterisation of the local groundwater system and an assessment of impacts from coal seam gas extraction on the groundwater system. The Menangle Park monitoring bores are within 100 metres of active production bores whereas Denham Court is ~15km outside the current Camden Gas Project.

Both Menangle Park and Denham Court monitoring bores record the groundwater levels of the geological units such as alluvium, the Wianamatta Group and the Hawkesbury Sandstone. Groundwater level hydrographs assess and compare the recharge/drawdown characteristics. In addition, water samples were taken from the Menangle Park monitoring bores (MPMB01, MPMB02, MPMB03 and MPMB04), the nearby production bore (MP17) and the Nepean River. The samples were measured for major ions, elements, radioisotopes and stable isotopes. The techniques involved AMS, CRDS, EA-IRMS, IC and ICPMS.

The results characterised the Hawkesbury Sandstone at Menangle Park into an ‘upper’ and ‘lower’ level separated hydrogeologically by a 12 metre thick shale layer. The ‘upper’ level was dated at 600BP whereas the ‘lower’ level was dated between 14,500-16,000BP. The hydrogeochemistry of the coal seam water was significantly different to the Hawkesbury Sandstone however, the age calculations were unrepresentative and unreliable. The water quality was assessed in the Hawkesbury Sandstone and was found to be relatively fresh whereas the Bulli Coal Seam was saline. Interpretation of these results suggests no or negligible hydraulic connection between beneficial aquifers and the coal seam aquifer. Based on this the author concluded that there is negligible impact from coal seam gas extraction on the Hawkesbury Sandstone. However, the data available did not enable the author to make an assessment for the likelihood of long term impacts from coal seam gas extraction.

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## **Glossary**

AGL – Australian Gas and Lighting Pty Ltd.

ANSTO – Australian Nuclear Science and Technology Organisation.

Aquifer – Water bearing unit with permeable properties enabling water extraction.

Aquitard – Rock unit with very low hydraulic conductivity and permeability.

Aquiclude – Totally impermeable rock unit

BOM – The Bureau of Meteorology

CGP – Camden Gas Project

CSG – Coal Seam Gas

Drawdown – Downward vertical movement of the water table in a aquifer.

GWL – Groundwater level

m.bgl – metres below ground level

MPMB – Menangle Park Monitoring Bores

PB – Parsons and Brinkerhoff Pty Ltd

PEL – Petroleum Exploration Licence

PPL – Petroleum Production Lease

Produced water – Water extracted from the coal seam during dewatering process.

RMB – Denham Court Monitoring Bores

# 1. Chapter 1 - Introduction

## 1.1 Context

Coal seam gas (CSG) extraction is a contentious issue, debated within the public and scientific spheres of society with polarised views about its impact upon groundwater systems and the environment in general. It is evident that there is a myriad of misleading information in the public eye about CSG which has resulted in a generally confused and concerned view of the CSG industry.

Both environmentalist groups and universities are claiming that there is currently a lack of scientific research about potential impacts and risks involved with CSG extraction, and are requesting more independent scientific study into the impacts of CSG on groundwater systems. The current lack of independent scientific research into CSG extraction has led to political pressure on the NSW Government to commission a moratorium of CSG activities in NSW special drinking areas and extend the freeze on petroleum exploration application licences to September of 2015 (NSWDTI 2014). The central reason is the potential disturbance on beneficial groundwater aquifers and confining units from dewatering or depressurising extraction methods. CSG extraction involves the extraction of water from coal seams, and the volume of water produced differs with location. The overall water production of the Camden Gas Project is considered to be relatively small, with an average of < 4 ML per annum.

In order to confidently assess the potential risks of aquifer disturbances, it is crucial to understand the local hydrogeological system. The hydrogeological system relevant to this project is part of the Hawkesbury Nepean catchment and involves the geological units of the Southern Coalfields of the Sydney Basin. The major beneficial aquifer is the Hawkesbury Sandstone, overlying the Narrabeen Group which in turn overlies the targeted Illawarra Coal Measures.

This project offers a unique opportunity to provide independent scientific research into the characterisation of a hydrogeological system within an area of coal seam gas extraction. It should be noted here that results and conclusions from this project are relevant only to the study area and should not be regarded as universal.

## 1.2 Aims and Objectives.

The aims of this project are:

- a) To analyse the water level and water quality trends collected from the Menangle Park monitoring bores to assess hydrogeological attributes/relationships between the monitored groundwater zones and to interpret any recharge/drawdown trends.
- b) To provide an independent hydrogeological assessment of the likelihood for impact on the shallow groundwater resources as a result of the existing coal seam gas activities within the southern Sydney Basin.

The aims will be achieved by the following;

- a) Hydrograph analysis of the Menangle Park monitoring bores to assess the shallow groundwater levels including comparison with Denham Court monitoring bores.
- b) Hydrogeochemical analysis of the groundwater and surface waters at Menangle Park
- c) Isotopic analysis of the groundwater at the Menangle Park.

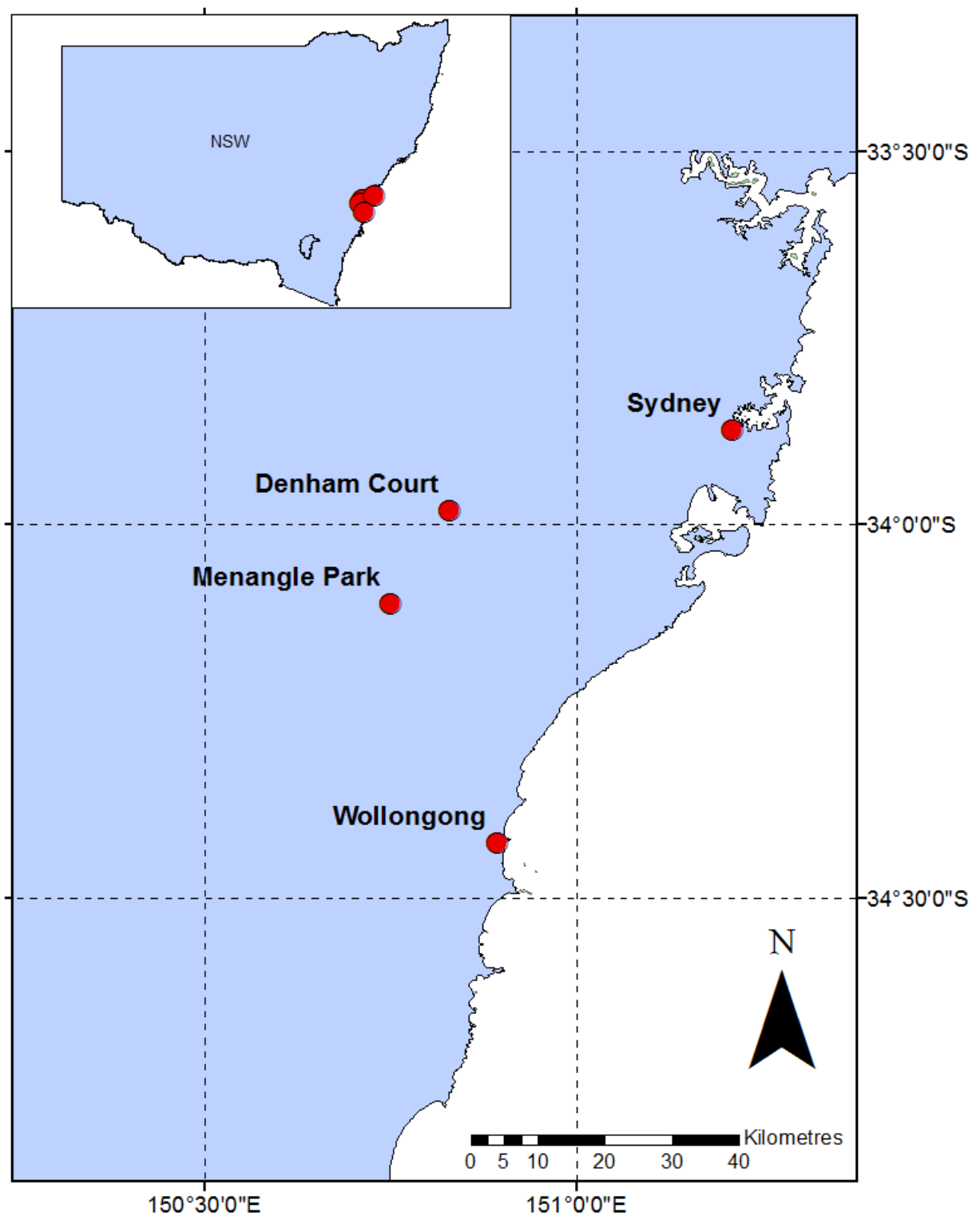
### 1.3 Location

The study site is located in Menangle Park in the Macarthur region, Wollondilly Shire Council of New South Wales, 56km south-west of Sydney's CBD (see Figure 1.1). The latest census population data finds that 241 people live within the village (ABS 2011). It has a predominantly rural and agricultural farming heritage (McGill 1995). The comparison site is Denham Court, sharing similar geological properties and is 15km away from the Menangle Park bore monitoring site.

### 1.4 Climate

The Menangle Park/Camden area experiences a moderately cool winter and warm summers with rainfall all year round (Bureau of Meteorology 2014). In late June of 2013, higher than average rainfall was recorded which produced a flood event at the site of the Menangle Park monitoring bores. The flood event presents a unique opportunity for hydrogeologists to assess the relationship of rainfall and infiltration into the groundwater systems. Significant rises in the groundwater levels were expected as a result of large volumes of infiltrating water moved into the groundwater system.





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Figure 1.1 - Study site location map - spatial reference of study site Menangle Park and comparison site Denham Court.

## 2. Chapter 2 – Background

### 2.1 The Camden Gas Project

The Camden Gas Project (CGP) is located within the Sydney Basin in the Southern Coalfields. Five petroleum production leases (PPL) and one petroleum exploration licence (PEL) have been granted to AGL Pty Ltd for the CGP (AGL Energy Pty Ltd 2013d). When considering the placements of well sites, AGL Pty Ltd was required to consider a set list of environmental, social and economic factors for each individual well. These factors, set out by the Petroleum Act 1991, included an assessment of the preservation of local Indigenous archaeology, land usage, noise pollution, flora and fauna, topography, architecture, historical features and the subsurface geology (NSWCA 1991; AGL Energy Pty Ltd 2013d). Since its opening AGL Pty Ltd have established a total of 144 production wells. However, not all wells are currently producing CSG (AGL Energy Pty Ltd 2013d). All wells have a finite amount of gas available for extraction; after their expiration the wells are cased in cement to ensure a closed system with no vertical flow (NSWDTI 2013b). 117 Of 144 (approximately 82%) of the production wells of the CGP have been hydraulically stimulated or ‘fracked’ (AGL Energy Pty Ltd 2013d). AGL Pty Ltd plans to increase the extent of the CGP in the near future with a ‘Northern Expansion’.

### 2.2 Coal Seam Gas

Coal Seam Gas (CSG) is predominantly methane ( $\text{CH}_4$ ). It is ‘trapped’ within coal seams, usually found at depths between 300-1000 metres below ground level (CSIRO 2012a). The gases are attached to the natural cleats and fractures of the coal (CSIRO 2012a; AGL Energy Pty Ltd 2013c). Australia’s largest reserves of CSG are found within New South Wales’ Sydney Basin and Queensland’s Bowen and Surat Basins (CSIRO 2012a). Compared with conventional coal combustion, CSG burns with half the amount of carbon dioxide per unit of primary energy which is why it is considered as a cleaner energy alternative (Rutovitz, Harris, Kuruppu & Dunstan 2011; Wigley 2011). Other gases such as carbon dioxide ( $\text{CO}_2$ ), ethane ( $\text{C}_2\text{H}_6$ ), propane ( $\text{C}_3\text{H}_8$ ) and other hydrocarbons are known to occur in CSG (SCA 2012).

Coal seam gas is naturally produced via two processes; thermogenic and biogenic production. A third method of methane production known as abiogenic or geogenic methanogenesis exists however it is not related to coal seam gas (Clark & Fritz 1997).

Biogenic production (methanogenesis) usually occurs in shallow groundwater systems as a result of two chemical reactions involving methanogens (simple methane producing bacteria) (SCA 2012). Table 2.1 displays the two methods of biogenic methane production where CO<sub>2</sub> represents the dissolved inorganic carbon (Clark & Fritz 1997).

Type	Equation	Description
Acetotrophic methanogens	$\text{CH}_3\text{COOH} \rightarrow \text{CH}_4 + \text{CO}_2$	Acetate fermentation
Hydrogenotrophic methanogens	$\text{CO}_2 + \text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$	CO <sub>2</sub> reduction

Table 2.1 – Biogenic methane production methods (Clark & Fritz 1997; SCA 2012)

Thermogenic production (also known as thermocatalytic) is related to the thermocatalytic conversion or break down of coal into smaller carbon chains such as methane, ethane, propane, carbon dioxide and other hydrocarbon gases and liquids (SCA 2012). This process requires temperatures >70°C and results in relatively higher amounts of hydrocarbons heavier than methane (Clark & Fritz 1997; SCA 2012).

### 2.2.1 Extraction and dewatering

In all CSG production bores water is removed from the coal seam via a sealed well (see Figure 2.1) in a process called ‘dewatering’ (Rutovitz et al. 2011). Dewatering processes transport the water and gas to the surface and subsequently decreases the pressure within the coal seam. The two main drilling methods used in NSW are vertical drilling and horizontal-directional drilling (NSWDTI 2013c; AGL Energy Pty Ltd 2013d).

Vertical drilling is an older style of drilling which is cheaper to construct (Rutovitz et al. 2011). Vertical drilling requires greater ground surface areas than horizontal-directional drilling because of the inability to ‘branch out’ with several drill holes from the one location on the surface. Vertical drilling is also more likely to require hydraulic stimulation (fracking). The fracking fluid mixtures are publically available in NSW and are usually water and sand; the sand acts as a proppant holding the fractures open to allow water and gas to the surface (CSIRO 2012b; AGL Energy Pty Ltd 2013b). At the Camden Gas Project 117 production bores are hydraulically stimulated wells, and 72 production bores used only sand and water as the frack fluid (AGL Energy Pty Ltd 2013a). Table 2.2 below shows the other ingredients that were potentially used in the frack fluids for the remaining 45 wells.

Frack fluid purposes	(Ave. %) v/v	Major compound
Main frack fluid	99.67%	Water
Clean perforations	0.05%	Hydrochloric acid
Iron sequesterant	<0.01%	Citric acid
Corrosion inhibitor	<0.01%	Ground coffee beans
pH adjusting Agent	0.03%	Acetic acid
Bactericide	<0.01%	THPS-tetrakis(hydroxymethyl)Phosphonium
Gelling agent	0.12%	Guar gum
Gel breaker	< 0.01%	Hemicellulase enzyme concentrate
Clay stabiliser	0.06%	Choline chloride
Cross linker	0.05%	Monoethanolamine borate
pH buffer	<0.01%	Sodium hydroxide

Table 2.2 – Hydraulic fracturing fluid ingredients. Adapted from AGL Energy Pty Ltd (2014d)

Horizontal-directional drilling is a more recent development and does not usually require the use of hydraulic stimulation (NSWDTI 2013c; AGL Energy Pty Ltd 2013d). Fracking is the act of pumping water or gases into coal seams in order to increase fracture size and extent to increase the hydraulic conductivity (Rutovitz et al. 2011; CSIRO 2012b; AGL Energy Pty Ltd 2013b). The horizontal drilling method begins by drilling a vertical hole from the ground surface which gradually ‘angles’ or ‘branches’ out horizontally until it intersects the coal seam. The major benefit of horizontal drilling is less surface disturbance because many holes can be drilled in any direction from the singular initial vertical hole at the surface (Rutovitz et al. 2011).

The major concern of hydrogeologists is the creation of a downward pressure gradient as a result of dewatering the coal seam (see Figure 2.2). If interconnectivity between the target coal seam and overlying aquifers were evident the water within beneficial aquifers would travel downwards into the depressurised coal seam and ultimately result in drawdown of the water table (Rutovitz et al. 2011). The common misconception is that this is likely to occur at every well site, however in the absence of any interconnectivity this cannot happen.

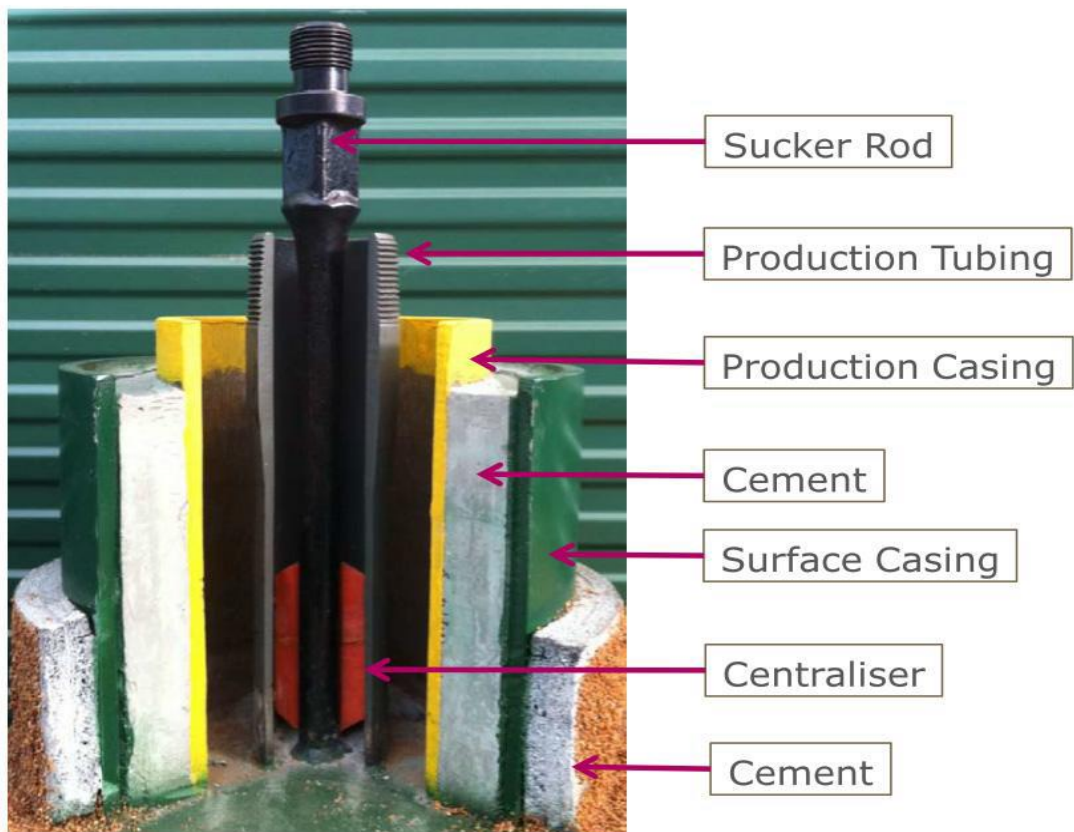


Figure 2.1 - The production well design, with inner and outer cement and metal casing to ensure a controlled extraction and minimalised chances of well failure (AGL2013b).

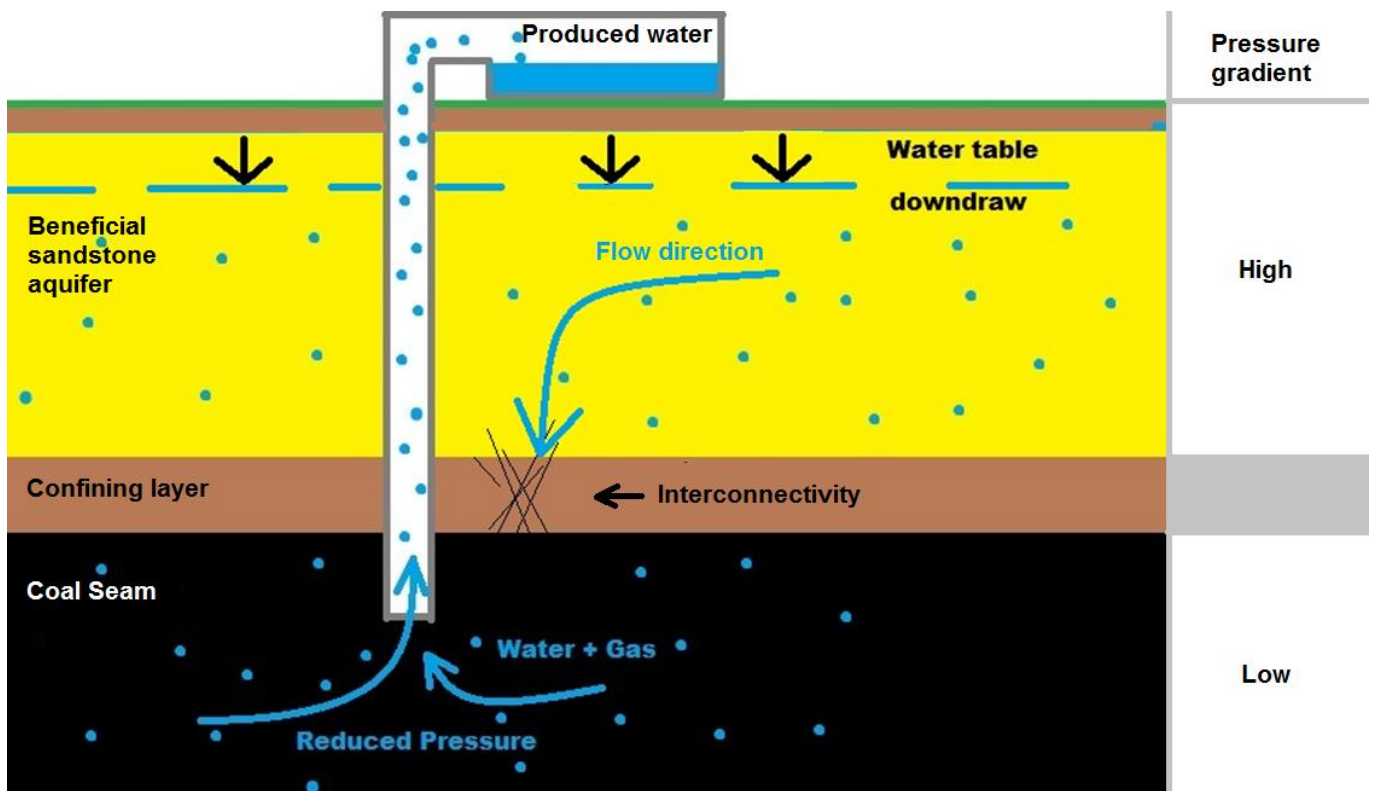


Figure 2.2 –Simplified conceptual model of coal seam gas extraction risk involved in groundwater drawdown.

### 2.3 The Menangle Park monitoring bores (MPMBs)

Menangle Park was chosen as the study site for this project because of the proximity to CSG production bores MP17, MP25 and MP16. Four monitoring bores (MPMB01, MPMB02, MPMB03 and MPMB04) are located at the study site; all located within 10m of each other at ground level. Only tens of metres away from the MPMBs are the CSG production wells MP16 and MP25 (see Figure 2.3). MP16 is no longer an active well however, MP25 is currently producing CSG. The Nepean River is also located within 100 metres of the MPMBs and the production bores.

Since their establishment in June 2013 the MPMBs have continuously recorded the groundwater levels in 6 hourly intervals resulting in a vast quantity of data. The MPMBs enable hydrogeologists to observe and assess the flow patterns, drawdown trends and recharge responses to rainfall events of the local groundwater system. The recorded heights of the water levels are representative of the groundwater pressure at that particular depth (commonly known as the pressure head). Figure 2.4 shows the averaged groundwater levels of the MPMBs in February of 2014. At that point in time it is clear that there was a uniform increase in pressure with depth that resulted in all bores rising to within ~1m of each other. Table 2.3 presents the physical and environmental properties of the each MPMB. The Hawkesbury Sandstone is the primary geological unit targeted by the MPMBs because it is considered to be a beneficial aquifer of the region, used by local farms for agricultural purposes.

Menangle Park Monitoring Bore	Depth of bore (metres below ground level)	GPS Coordinates		Geological unit
MPMB01	18	E N	291426.371 6223648.178	Quaternary Alluvium
MPMB02	42	E N	291426.853 6223656.095	Upper Hawkesbury Sandstone
MPMB03	108.5	E N	291425.335 6223662.800	Middle Hawkesbury Sandstone
MPMB04	192.6	E N	291418.472 6223664.149	Lower Hawkesbury Sandstone

Table 2.3 – Physical and environmental properties of the Menangle Park monitoring bores.



Figure 2.3 – The location of the monitoring bores, production bores (MP16 & MP25) and the Nepean River. (MPMBs), Map Data: Digital Globe 2014 ©



February 2014

Ground Elevation = 66.6m

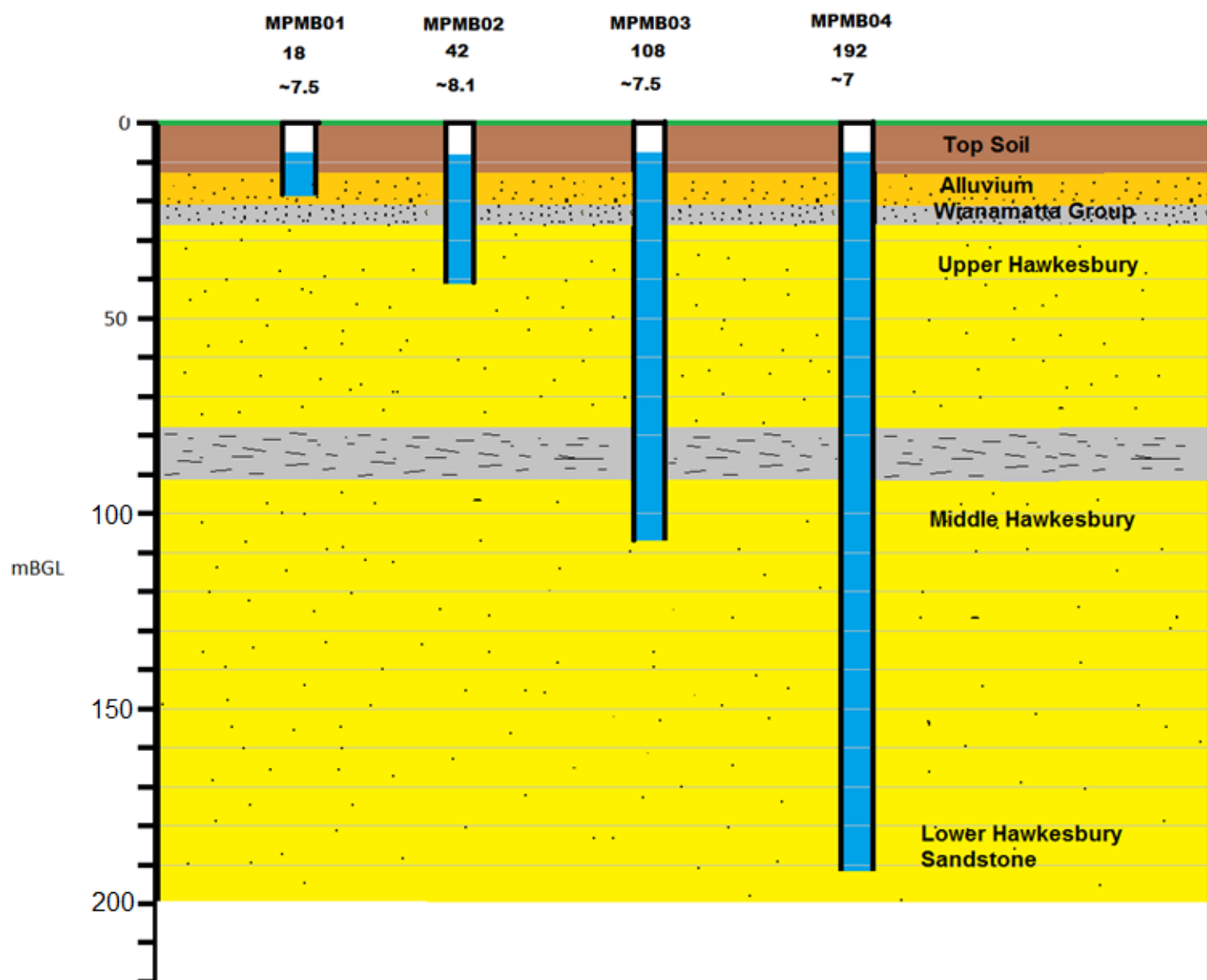


Figure 2.4 – Conceptual model of the MPMBs in February of 2014. Geological data adapted from Parsons and Brinkerhoff (2014)

## 2.4 Comparison site Denham Court (RMBs)

Denham Court is not a ‘control’ because it does not have identical hydrogeological, geological and environmental characteristics to the study site, however it is the best option available for the purpose of this study. Denham Court is considered as an appropriate area for comparison because the RMBs are located 15km away from any CSG production bores. Due to this distance between the RMBs and the closest production bores, it is statistically more unlikely that the groundwater system is affected by CSG production compared to the MPMBs.

At the Denham Court comparison site is a four groundwater level monitoring bores RMB01, RMB02, RMB03 and RMB04 (see Figure 2.5). The RMBs have continuously recorded groundwater levels in 6 hourly intervals since their establishment in November 2011. Two RMBs are situated within the Hawkesbury Sandstone aquifer and two are situated within the Wianamatta Shale (see Table 2.4). The most obvious hydrogeological difference between Menangle Park and Denham Court is the presence of a thicker aquitard unit (Wianamatta Group) overlying the Hawkesbury Sandstone at Denham Court. RMB04 and RMB01 are unlikely to be useful for the hydrograph comparison because they are not representative of the Hawkesbury Sandstone and have little or no measurable water to measure.

Denham Court Monitoring Bores	Total depth of bore (metres below ground level)	GPS Coordinates	Geological unit
RMB04	8.5	E 300412.627 N 6237189.692	Upper Wianamatta Group
RMB01	84	E 300465.860 N 6237305.080	Lower Wianamatta Group
RMB02	150	E 300474.930 N 6237308.700	Upper/middle Hawkesbury Sandstone
RMB03	300	E 300481.290 N 6237310.920	Lower Hawkesbury Sandstone

Table 2.4 – Physical and Environmental characteristics of the Denham Court monitoring bores.

February 2014

Groundsurface elevation = 73m.a.s.l

Groundsurface  
Elevation =  
62m.a.s.l

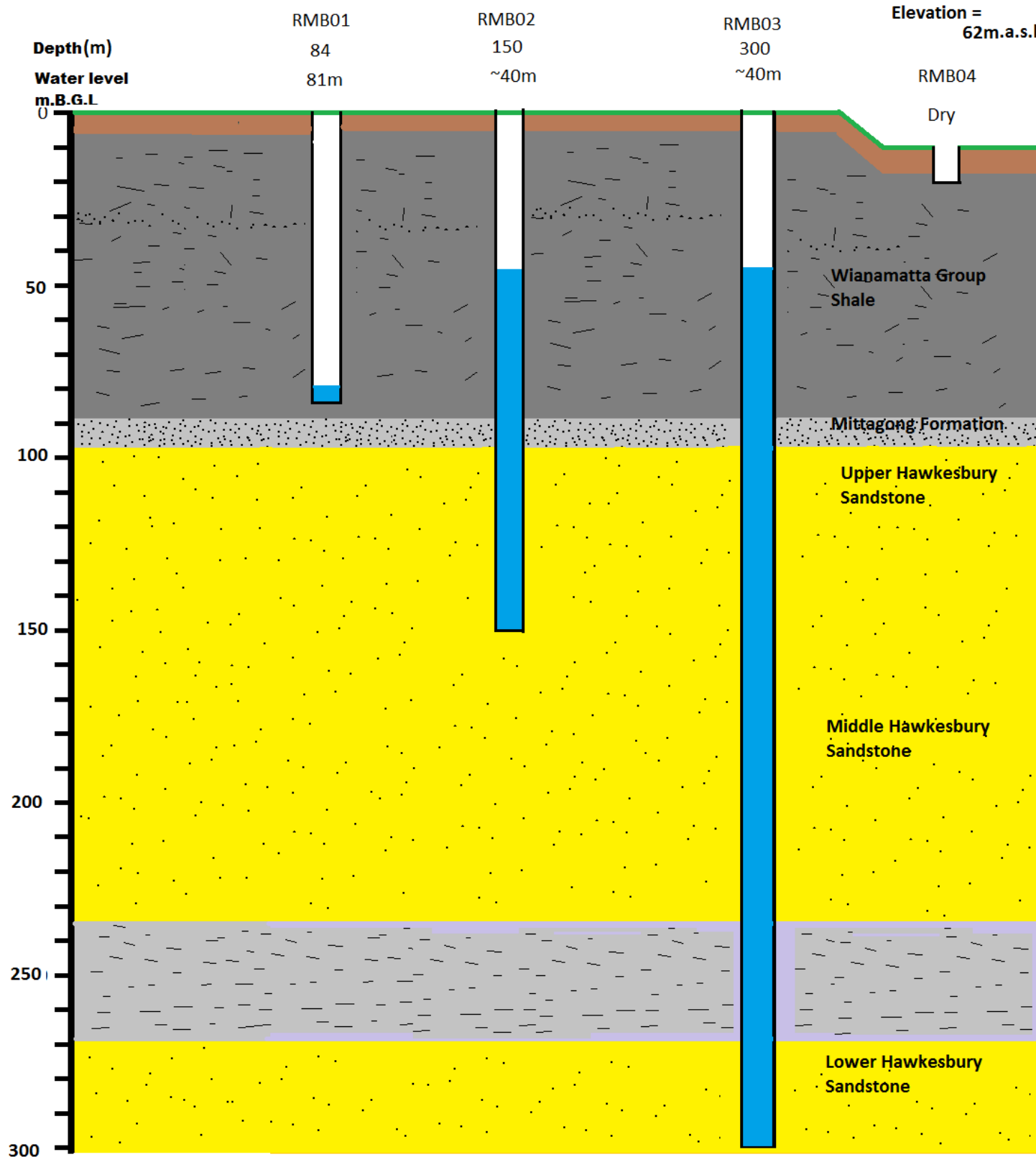


Figure 2.5 – Conceptual model of the RMBs in February of 2014.

## 2.5 Flood event of June 2013 at the MPMBs

A significant rainfall event at Menangle Park resulted in just over 100mm of rainfall during three days in June 2013 (Bureau of Meteorology 2014). As a result of this rain event the Nepean River flooded, submerging the nearby CSG production bore. Major public concern arose from this however; AGL and the EPA concluded that no gas leakages occurred due to the safety mechanisms installed on the production bores.

For the purposes of the hydrograph analysis (Chapter 4) the flood event in June 2013 is a significant point of interest. Large rainfall events are able to affect all monitoring bores in different ways through time, considering the large weight of water on the land surface and saturated zone. The information attained from the infiltrating flood waters gives insight into the discharge and recharge trends and flow regime of the groundwater system.

The unfortunate aspect of the flood event is that it occurred almost immediately after the establishment of the MPMBs. This means that any trend curves on the hydrographs are misleading because they project a negative downward trend indicating water table drawdown. As a result it is difficult to use statistical analysis to establish any long term groundwater level trends that represents a true long term trend. Continued monitoring of groundwater levels should help to negate the effects of the initial spike in hydrograph recordings.

## 2.6 RMB and MPMB sampling events

Each monitoring bore at Menangle Park and Denham Court was sampled periodically throughout 2013 and 2014, resulting in periods of drawdown in groundwater levels. This resulted in a problem for hydrograph analysis because it introduces unwanted and unnatural groundwater level disturbances. The ideal situation is to have only natural responses of groundwater levels/pressures to the rainfall with time, and periods of drawdown must be removed from the hydrographs to ensure that the natural responses are observed and tested. The interpolation method used to eliminate sampling events is described in Section 4.2. The limitations, considerations and ramifications of removing and interpolating periods of drawdown are explained in Section 6.3.1.

## 2.7 Regional Geology – Sydney Basin

The Sydney Basin is a Permian-Triassic depositional basin positioned between the Middle Palaeozoic Lachlan Fold Belt in the west and the New England Fold Belt to the east (Reynolds 1976; Branagan & Packham 2000). The Sydney Basin is part of a larger Sydney-Bowen Basin which reaches as far north as Central Queensland (Bembrick, Herbert, Scheiber & Stuntz 1973). The Mount Coricudgy Anticline marks the division between the Sydney Basin in south and Gunnedah Basin in the north (Bembrick et al. 1973). The Sydney Basin has a variety of topographies and stratigraphy as a result of isolated dykes, faults and variations in stress (Ward & Kelly 2013).

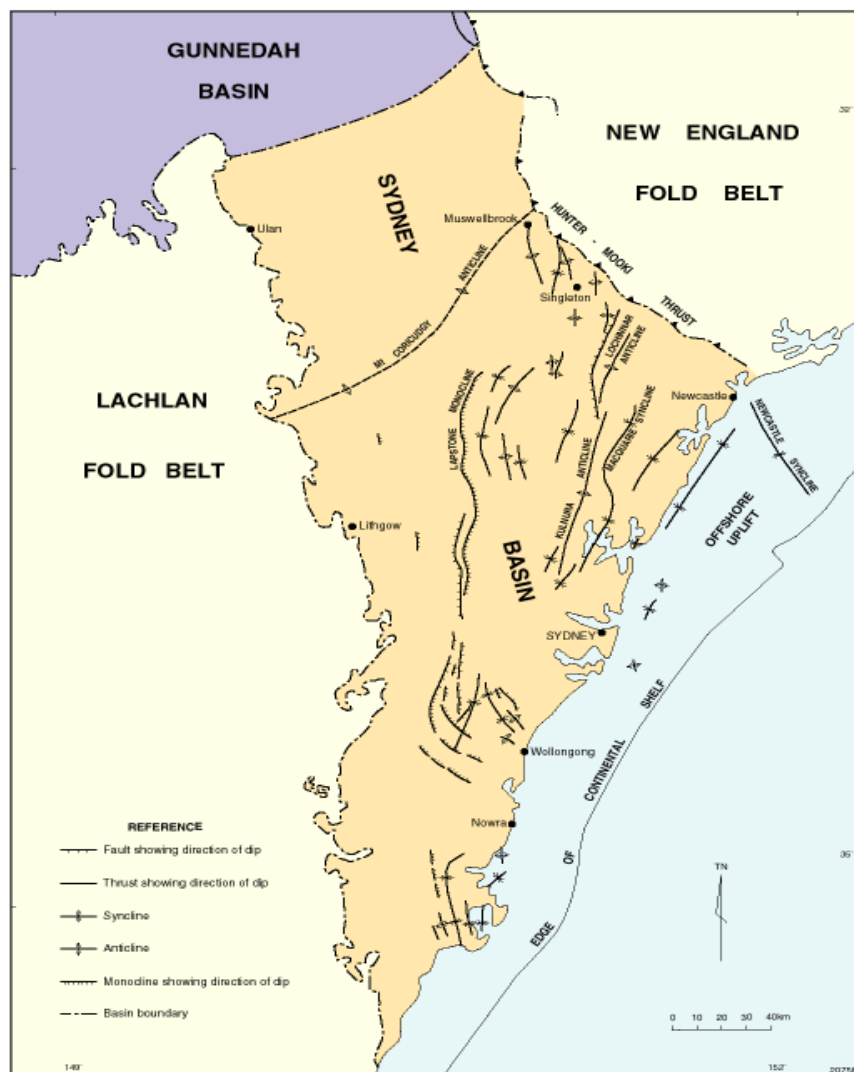


Figure 2.6 – Location of the Sydney Basin (Mullard 1995)

### 2.7.1 The Southern Coalfields – Southern Sydney Basin

The Sydney basin has five major and two minor coalfields in Figure 2.7 below. The Southern Coalfields is the southern section of the Sydney Basin and hosts the economically significant Illawarra Coal Measures, which are suitable for CSG production due to the high average methane concentrations between 90-95% and the < 1 km proximity to the surface (Thomson, Thomson & Flood 2014). The Camden Gas Project is situated within the Southern Coalfields near Wollongong. In addition to CSG extraction the Southern Coalfields are currently mined for coal via underground long wall mining.

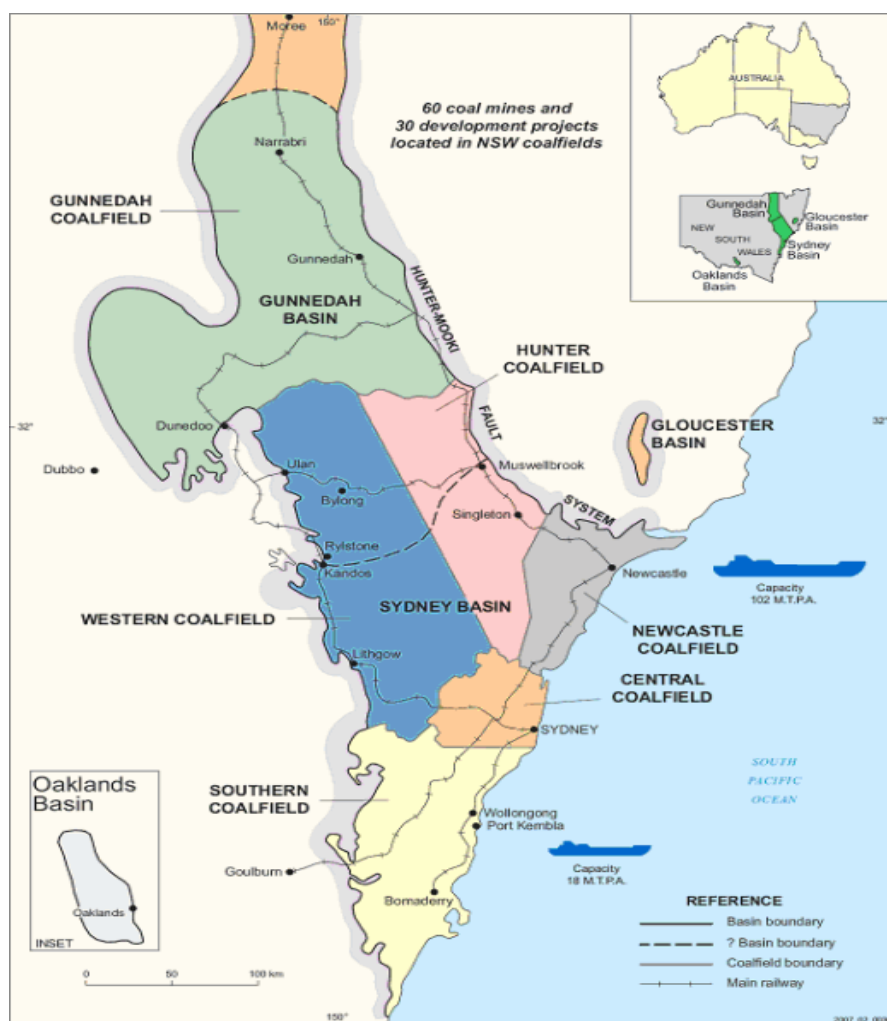


Figure - 2.7 The five major coalfields of Sydney Basin (New South Wales Department of Trade and Investment - Division of Resources and Energy 2012)

## 2.7.2 Regional Stratigraphy of the Camden Gas Project

The regional stratigraphy is illustrated in Figure 2.8, and is composed of alluvium, the Wianamatta Group, the Hawkesbury Sandstone, the Narrabeen Group and the Illawarra Coal Measures.

### *Alluvial sediments*

Quaternary and Paleogene-Neogene aged alluvial unconsolidated deposits that are <20m in thickness (AGL Energy Pty Ltd 2013d).

### *Wianamatta Group*

The Wianamatta Group is composed of middle Triassic aged interbedded quartz-lithic sandstones, siltstone and shale and was the last unit deposited during the Hawkesbury Tectonic Stage with a maximum thickness of 300m (Bembrick et al. 1973; Geoscience Australia 2012b). The deposition of the Wianamatta Group began in a shallow marine environment, grading to an estuarine environment and finally, an alluvial environment (Bembrick et al. 1973). Herbert (1976b) suggested that the marine to alluvial sedimentation is due to sea level regression during this time.

<b>Tectonic stage</b>	<b>AGE</b>	<b>Illawarra District</b>	
<b>Hawkesbury Tectonic Stage</b>	<b>Triassic</b>	<b>Wianamatta Group</b>	
		<b>Hawkesbury Sandstone</b>	
		<b>Narrabeen Group</b>	<b>Gosford Sub-group</b>
			<b>Clifton Sub-group</b>
<b>Bowen Tectonic Stage</b>	<b>Permian</b>	XXXXXXXXXXXXXXXXXXXX	
		<b>Illawarra Coal Measures</b>	

Figure 2.8 Stratigraphic nomenclature for the Camden Gas Project. Adapted from Herbert (1976a).

### *Hawkesbury Sandstone*

The Hawkesbury Sandstone is composed of non-marine medium to coarse-grained quartz rich sandstone with characteristic large-scale fluvial dominated depositional features such as tabular crossbeds, trough crossbeds and interbedded shales (Conaghan 1977; Russell, McKibbin, Williams & Gates 2009). It is a middle Triassic aged unit which has a maximum thickness of 290m and covers 20,000km<sup>2</sup> (Conaghan 1977; Geoscience Australia 2012a). Shale lenses are known to occur within the Hawkesbury Sandstone and can result in perched aquifers and a reduced vertical hydraulic conductivity. There are two major sandstone facies; the sheet facies and the massive facies. Also present is a less extensive mudstone facies (Conaghan 1977).

### *Narrabeen Group*

The Narrabeen Group is composed of marine and non-marine Triassic aged quartz-lithic to quartzose sandstone, conglomerate, mudstone and siltstone with a maximum thickness of 550m (Reynolds 1976; Russell et al. 2009; Geoscience Australia 2012c). The Narrabeen Group is composed of aquitards such as the Wombarra Claystone, the Stanwell Park Claystone and the Bald Hill Claystone and aquifers such as the Bulgo Sandstone, the Scarborough Sandstone and the Coalcliff Sandstone (see Table 2.5). The aquitard units are regarded as significant confining layers that restricts water flow between the Illawarra Coal Measures and above groundwater aquifers (Reynolds 1976; Bradd, Kiekebosch-Fitt, Cohen, Marx & Buckman 2012).

### *Illawarra Coal Measures*

The Illawarra Coal Measures are Permian aged coals, shales and lithic sandstones that overlie the marine sediments of the Shoalhaven Group (Bowman 1973). The Bulli Coal Seam marks the top of the Illawarra Coal Measures (Bowman 1973). The depositional environments in which the Coal Measures are deposited are point bars, floodplains and backswamps within a deltaic system (Bowman 1973). There are two subgroups within the Illawarra Coal Measures, the younger Sydney Subgroup and the older Cumberland Subgroup. The Bulli and Balgownie Coal Seams are the targeted seams in the upper Sydney Subgroup for the production of CSG (AGL Energy Pty Ltd 2013d). The Bulli Seam ranges from 2 – 5 m thick whereas the Balgownie Seam ranges from 5 – 30 m thick (Hutton 2009).



## 2.8 Regional Hydrogeology

Understanding the hydrogeology of Southern Coalfields is important for the protection of the drinking water catchments and beneficial aquifers. Table 2.5 is a summary of the hydrogeological properties of the units within the Southern Sydney Basin and Southern Coalfields. It has been suggested that the flow regime of the regional hydrogeological system is controlled by the claystone and shale aquitard units resulting in a predominantly horizontal (anisotropic) flow (Reynolds 1976; AGL Energy Pty Ltd 2013d). The varied depositional environments that make up the Hawkesbury Sandstone and Narrabeen Group has resulted in relatively heterogeneous units (Cendon, Hankin, Williams, Van der Ley, Peterson, Hughes, Meredith, Graham, Hollins, Levchenko & Chisari 2014), resulting in variations in hydrogeological parameters of confining layers and beneficial aquifers.

### *Confining layers*

The Narrabeen Group hosts three significant claystone aquitard units. The Bald Hill Claystone, Stanwell Park Claystone and Wombarra Claystone are on average > 30 m in thickness and have very low vertical and horizontal hydraulic conductivity (see Table 2.5). The claystone units are important aquitards that confine the sandstone aquifers and Illawarra Coal Measures (AGL Energy Pty Ltd 2013d). However, the presence of extensive permeable faulting that offsets the coal seam with the overlying sandstones is a potential risk, along with the chances of increased vertical conductivity from dykes (Ward & Kelly 2013). The Wianamatta Group consists of siltstones, sandstones and shales. In the Southern Coalfields region the shales can be extensive and have low hydraulic conductivity, forming an aquitard (see Figure 2.5).

### *Beneficial Aquifers*

The Hawkesbury Sandstone is regarded as the regional beneficial aquifer, although in many areas its ability to transmit water is low. The Hawkesbury Sandstone has a higher yield than the Narrabeen Group (Reynolds 1976). Both the Narrabeen Group and the Hawkesbury Sandstone are anisotropic groundwater systems, meaning they have preferential flow in a horizontal direction rather than vertical (Reynolds 1976; Bradd et al. 2012). This is due to several aquitard layers that are horizontally positioned and restrict the vertical flow (see Table 2.5).

Geological period	Unit		Average Thickness (m) at CGP	Hydrogeological Description	Horizontal Hydraulic conductivity $K_x$ (m/day)	Vertical Hydraulic conductivity $K_x$ (m/day)	TDS (mg/L)
Paleogene/ Neogene	Alluvium		<20	Alluvium surface level, unconfined aquifer.	1-10		-
Triassic	Wianamatta Group		80	Aquitard-Unconfined	1.00E-12 to 2.00E-5*		3000-5000*
	Hawkesbury Sandstone		217	Unconfined to semi-confined, some areas confined aquifer	0.1	0.05	<500
	Newport Formation		49	Unconfined and semi-confined porous rock	-	-	-
	Garie Formation		8	Unconfined and semi-confined porous rock	-	-	-
	Narrabeen Group	Bald Hill Claystone	34	Aquitard	1.00E-05	2.00E-06	-
		Bulgo Sandstone	251	Semi confined aquifer	5.50E-04	1.10E-04	1500-5000
		Stanwell Park Claystone	36	Aquitard	3.00E-05	6.00E-06	-
		Scarborough Sandstone	20	Semi confined aquifer	0.01	5.00E-03	-
		Wombarra Claystone	32	Aquitard	3.00E-05	6.00E-06	-
		Coal Cliff Sandstone	9.1	Confined porous Aquifer	5.00E-5	5.00E-4	-
Permian	Illawarra Coal Measures	Bulli Coal Seam	2-5	Water bearing zone, confined	5.00E-02	2.50E-02	>5000

Table 2.5 - Hydrogeological properties of the stratigraphy present at the study site. Adapted from (Reynolds 1976; Russell et al. 2009; Broadstock 2011; Ward & Kelly 2013; AGL Energy Pty Ltd 2013d)

### *Groundwater production*

The Sydney Basin generally produces low yields from the alluvium, Narrabeen Group and the Hawkesbury Sandstone aquifer (Mckibbin & Smith 2000; Ward & Kelly 2013), however parts of the Southern Highlands are known to produce high yields within the Hawkesbury Sandstone, with rates from 5 – 40 L/second (Ward & Kelly 2013). The unconfined alluvium and the upper portion of the Hawkesbury Sandstone are the most utilised for domestic and agricultural purposes in Sydney's south-western region (Ward & Kelly 2013; AGL Energy Pty Ltd 2013d). The Hawkesbury Sandstone produces the highest groundwater yields in the CGP, with average flow rate of 2 L/second (AGL Energy Pty Ltd 2013e).

### *Groundwater usage*

A Bureau of Meteorology defined subcatchment area was used as the study area for this groundwater usage assessment. The groundwater usage in the Menangle Park area is predominantly agriculturally related (see table 2.6). A total of 326 bores are related to domestic and agricultural usages however there is no information about their rate of extraction and their activity to the author at present. A water balance is presented in Chapter 3 to assess the abstraction rate versus CSG extraction rate.

Type of bore	Number of bores	Description
CSG Production	117	Dewatering production bores from the Bulli Coal Seam groundwater system. Average total of < 4 ML per annum.
Agricultural/ Domestic	254	Suspected to have low extraction rates, unfortunately no gauge flow data are available to assess the extent of extraction. Bores are used for stock and domestic uses. Irrigation is not prominent in the region. Other bores exist however, they are not known if they're used for agricultural purposes.
Monitoring test bores	42	Used for groundwater level monitoring. Most are owned by the NSW Office of Water.

Table 2.6 – Water usages of subcatchment HydroID -12107829 (NSW Government 2011; Australian Bureau of Meteorology 2012; NSW Government 2012)

## 2.9 Radioactive and stable isotopes in hydrogeology

Isotopic analysis of groundwater comprises a considerable portion of this study. Radioisotopes  $^{36}\text{Cl}$  and  $^{14}\text{C}$  and stable isotopes  $^{13}\text{C}$ ,  $^{18}\text{O}$  and  $^2\text{H}$  provide a vast quantity of data that can be used to characterise the local groundwater system and potentially be used to infer any impacts from CSG extraction. Table 2.7 below is a brief summary of isotopes that are used in hydrogeological assessments.

Isotope	Half life	Stability	Use	Decay formula
Chlorine-36	301,000 years	Unstable	Groundwater tracer, dating 60,000 – 1,000,000 years old	$^{36}\text{Cl} \rightarrow ^{36}\text{Ar} + \beta$ $^{36}\text{Cl} + \beta \rightarrow ^{36}\text{S}$
Carbon 14	5730 years	Unstable	Dating 0–40,000 years old	$^{14}\text{C} \rightarrow ^{14}\text{N} + \beta$
Tritium $^3\text{H}$ or TU	12.3 years	Unstable	Dating 0-55 years old	$^3\text{H} \rightarrow ^3\text{He} + \beta$
Carbon-13	-	Stable	Tracer, carbon-14 corrections	-
Deuterium	-	Stable	Groundwater Recharge tracer	-
Oxygen-18	-	Stable	Groundwater Recharge tracer	-

Table 2.7 – Isotope summary table for usages with groundwater studies. Adapted from Mazor (1997).

### 2.9.1 Radioisotope Chlorine-36 ( $^{36}\text{Cl}$ )

$^{36}\text{Cl}$  is isotopically unstable and has a long half-life of 301,000 years. It is created naturally from solar interactions with the atmosphere and via in-situ production (Mazor 1997; Prych 1998).  $^{36}\text{Cl}$  is calculated in number of atoms and is represented as a ratio against chloride (eg.  $^{36}\text{Cl}/\text{Cl}^-$ ) and is expressed in an  $\times 10^{-15}$  notation. The atmospheric or cosmic-ray production of chlorine-36 is related to the spallation reactions of  $^{40}\text{Ca}$  and  $^{39}\text{K}$  and neutron reactions with stable  $^{35}\text{Cl}$ , where it is absorbed in rainfall and deposited over the ground surface and infiltrated into groundwater (Bird, Davie, Chivas, Fifield & Ophel 1991). On average the global rate of atmospheric production is 20-30 atom/m<sup>2</sup>/second (Phillips 2000). The majority of cosmic-ray production reactions occur in the stratosphere (50-15kms above sea level) and the remainder are produced within the troposphere (> 15 kms above sea level) (Bird et al. 1991). The production rate of  $^{36}\text{Cl}$  in the atmosphere was thought to be dependent on the geomagnetic latitude, because of the magnetosphere which shields incoming cosmic radiation (Phillips 2000). However expected values and measured precipitation values of  $^{36}\text{Cl}/\text{Cl}$  have sometimes been significantly different and left hydrogeologists puzzled. Phillips (2000) suggested four possible reasons for the errors in estimations from the latitude-deposition relationship of  $^{36}\text{Cl}$ :

- 1) Errors in the model for latitudinal dependence of deposition
- 2) Contributions from 'eroded surface material'
- 3) Recycling of bomb and anthropogenic produced  $^{36}\text{Cl}$
- 4) Additional undetermined cosmogenic production

$^{36}\text{Cl}$  can also be naturally produced by cosmic interaction with the rock minerals and soil at ground surfaces (epigenic production), via spallation reactions with  $^{39}\text{K}$  and  $^{40}\text{Ca}$  and thermal neutron activation of  $^{35}\text{Cl}$  (Bird et al. 1991; Phillips 2000). At distances of a few metres below ground surfaces (especially in limestone rock) negative muon  $^{36}\text{Cl}$  is an important production mechanism of  $^{36}\text{Cl}$  (Bird et al. 1991; Stone, Evans, Fifield, Allan & Cresswell 1997). Figure 2.9 displays the generalised *in situ* production rates of  $^{36}\text{Cl}$  with depth of different lithologies. The deep subsurface (>100 m hypogene) production of  $^{36}\text{Cl}$  is attributed to thermal neutron absorption of  $^{35}\text{Cl}$  due to the decay of U and Th (Phillips 2000). Understanding deep subsurface  $^{36}\text{Cl}$  is important in hydrogeology because of the different background production of different lithologies. Sandstones are generally low in U and Th and

therefore when  $^{36}\text{Cl}$  in water is in contact with sandstone long enough for it to reach equilibrium the  $^{36}\text{Cl}$  will be equal to the low production rate value of the sandstone.

Anthropogenic production of  $^{36}\text{Cl}$  is another significant factor for hydrogeology. The 1950-60's atomic weapons testing resulted in a spike in atmospheric production rates globally which infiltrated into soils and groundwaters and can be compared to with other radioisotopes affected radioisotopes (Mazor 1997; Cook & Herczeg 1998; Phillips 2000). Other anthropogenic production of  $^{36}\text{Cl}$  that increase production rates include nuclear reactors, however the overall extent of these effects are assessed on a case by case basis (Phillips 2000). Anthropogenic production needs to be taken into consideration when investigation  $^{36}\text{Cl}$  concentrations in hydrogeology.

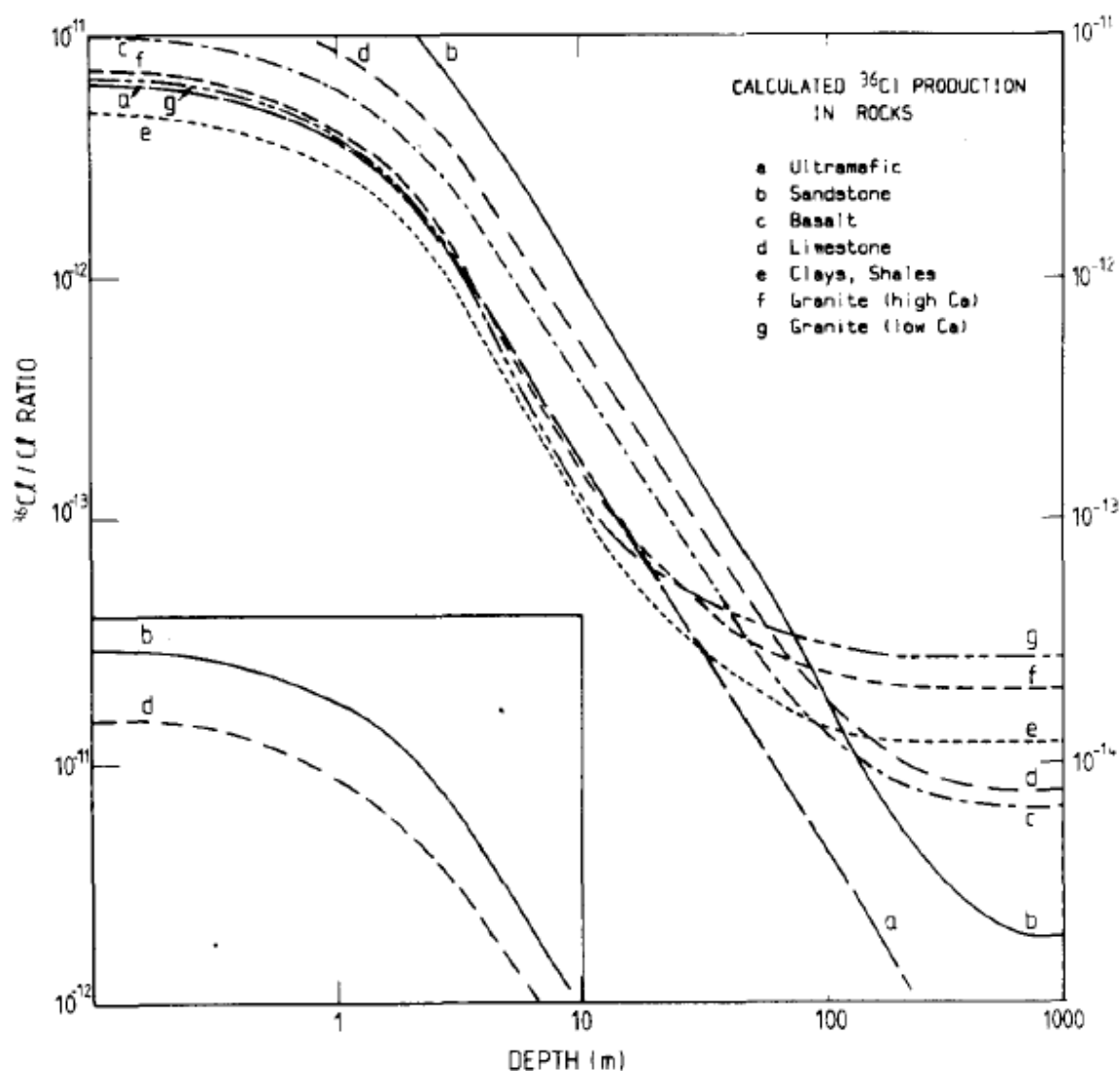


Figure 2.9 – Production rate of  $^{36}\text{Cl}$  versus depth in various lithologies. Taken from Fabryka-Martin (1988).

$^{36}\text{Cl}$  concentrations in groundwater are more often applied as a groundwater tracer, however in some cases it can also be applied as a dating method. There are several mechanisms that need consideration when interpreting the results of tracer and dating results. Andrews and Fontes (1993) suggests that  $^{36}\text{Cl}$  dating should only be applied to groundwater systems that neither gain or lose chloride through its migration. The  $^{36}\text{Cl}/\text{Cl}^-$  ratio is used in age calculation equations and changes with the addition or loss of chloride, even though the number of  $^{36}\text{Cl}$  atoms has not changed (Bird et al. 1991). This is the main reason why  $^{36}\text{Cl}$  is not a commonly used dating method, and why it is more suitable as a groundwater tracer. Once measured, the  $^{36}\text{Cl}$  ratio can be plotted on bivariate plots against various parameters and indicate different processes in the transportation of the water.

### 2.9.2 Carbon-14 ( $^{14}\text{C}$ ) Dating

#### *Carbon dating of groundwater*

Age determination from  $^{14}\text{C}$  dating does not necessarily represent the age of the water, but the age of the dissolved inorganic carbon (DIC) content within the water. This is determined by various physicochemical and biological processes (Clark & Fritz 1997). The calculated age represents the 'mean residence time,' because water of differing ages can potentially be within the sample area (Clark & Fritz 1997). Groundwater dating is used to verify estimated and modelled groundwater flow patterns and residence times (Appelo & Postma 2005). These must always be considered when assessing groundwater dating results to prevent the data being overstated. The  $^{14}\text{C}$  age measurements are presented in years before present (BP) where the 'present' is the year 1950 (Stuiver & Polach 1977). Because of this, negative ages (e.g. -20BP) are possible. The per cent of modern carbon (pMC) can be interchangeable with apparent ages; values greater than 100 pMC are likely to be ages post 1950 and are a result from nuclear testing whereas values equal to 0 are > 60,600 years BP, with some exceptions (see Figure 2.10) (Cook & Herczeg 1998). In hydrogeology dead carbon (no  $^{14}\text{C}$  = 0 pMC) is dealt with in a 'source and sink' (gain and loss) concept and is assessed and corrected from the stable isotope  $^{13}\text{C}/^{12}\text{C}$  ratio in programs like NETPATH (Plummer, Prestemon & Parkhurst 1994; Kalin 2000).

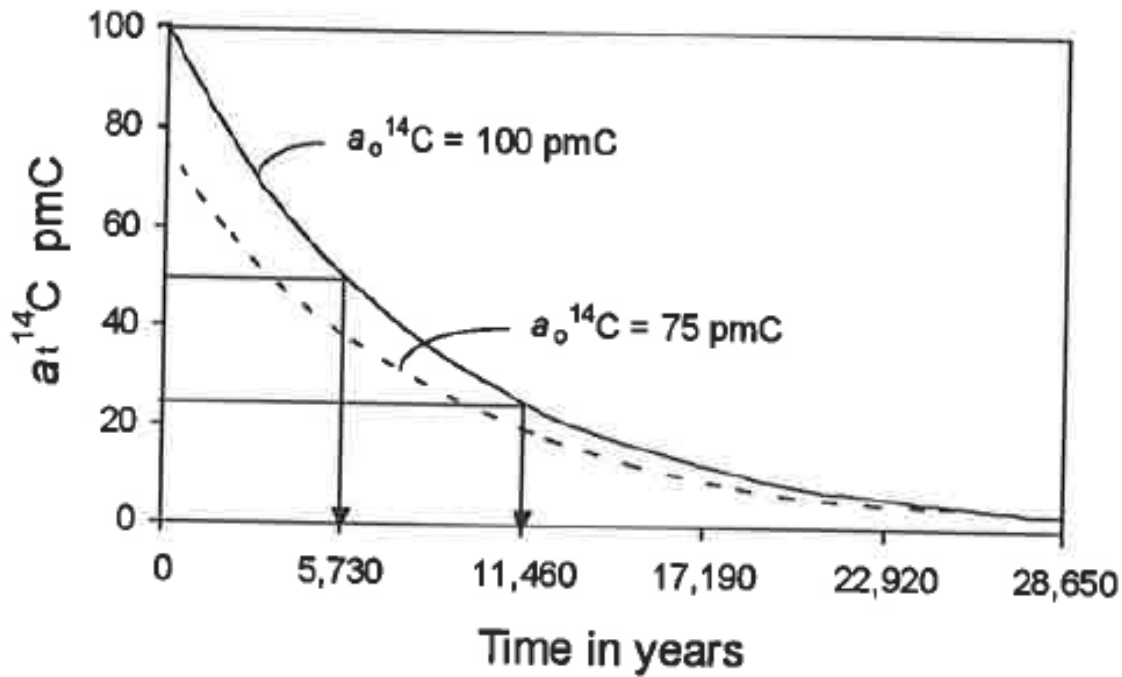


Figure 2.10 – generalised  $^{14}\text{C}$  decay age relationship with pMC, years are in BP. Taken from (Clark & Fritz 1997).

#### $^{14}\text{C}$ Production

$^{14}\text{C}$  makes up <0.1% of total carbon on Earth and has a half-life of 5730 years (Cook & Herczeg 1998). The half-life makes  $^{14}\text{C}$  a suitable groundwater dating method for most groundwaters, which is why it is the most widely used dating method.  $^{14}\text{C}$  is produced naturally from the cosmic interactions with  $^{14}\text{N}$  in the atmosphere (Cook & Herczeg 1998).  $^{14}\text{CO}_2$  (100pMC) is absorbed into plants through photosynthesis, and dissolved in rain, ocean and surface waters (Mazor 1997). Soils contain 100 times the amount of  $\text{CO}_2$  as the atmosphere and are a major source of  $^{14}\text{C}$  for water infiltrating into groundwater (Mazor 1997).

Similar to other radioisotopes ( $^3\text{H}$  and  $^{36}\text{Cl}$ ), the 1950-60's weapons testing programs increased the atmospheric natural production rates of  $^{14}\text{C}$  to levels up to 200 pMC in some cases (Mazor 1997). In addition, the massive increase of burning fossil fuels containing 'dead carbon' (0 pMC) since the industrial revolution has released  $^{12}\text{C}$  into the atmosphere and thus groundwater systems (Cook & Herczeg 1998).



### *Carbon-13*

Stable isotope (non-decaying)  $^{13}\text{C}$  is divided by  $^{12}\text{C}$  to form a ratio ( $^{13}\text{C}$  and  $^{12}\text{C}$  comprise ~1.1% and 98.9% respectively of the total carbon on earth) (Cook & Herczeg 1998). The ratio can be negative and small, measured in parts per thousand (per mil).  $^{13}\text{C}$  can be used to make corrections to the apparent age obtained from the  $^{14}\text{C}$  measurement (Cook & Herczeg 1998).  $^{13}\text{C}$  results can indicate various biochemical and physical processes that are occurring within the groundwater. Common complications with  $^{14}\text{C}$  dating of DIC in groundwater include the following processes: matrix diffusion of  $^{14}\text{C}$ , calcite dissolution, dolomite dissolution, sulphate reduction, incorporation of geogenic (abiogenic)  $\text{CO}_2$  and methanogenesis (Clark & Fritz 1997). The computer program NETPATH is able to correct the apparent ages in complicated groundwater systems using geochemical mass balance modelling which accounts for the various geochemical and biochemical processes (Plummer et al. 1994; Aravena, Wassenaar & Plummer 1995).

### 2.9.3 $\delta^{18}\text{O}$ and $\delta^2\text{H}$ – groundwater recharge origin tracer.

$\delta^{18}\text{O}$  and  $\delta^2\text{H}$  are considered rare heavy stable isotopes of oxygen and hydrogen (see Table 2.8). Their heavier properties have a useful application to hydrogeological and hydrological studies.  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  are represented as a ratio with light stable isotope equivalents,  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$ . These are expressed in per mil (‰) and are relative to the Vienna Standard Mean Ocean Water (VSMOW). When water samples are analysed for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  with an AMS it is easier to measure and compare the result using a ratio (Coplen, Herczeg & Barnes 2000). Ocean waters have a  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  ratio value close to 0‰, whereas inland rainfall is depleted ( $< 0‰$ ) (Cook & Herczeg 1998). The values of  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  ratios in rainfall are commonly  $< 0‰$  due to the processes involved in fractionation (Cook & Herczeg 1998).

Hydrogen			Oxygen		
Symbol	Abundance	Relative weight	Symbol	Abundance	Relative weight
$^1\text{H}$	99.958%	Light	$^{16}\text{O}$	99.758%	Light
$^2\text{H}$	0.015%	Heavy	$^{18}\text{O}$	0.204%	Heavy

Table 2.8 - Relative abundance of the stable hydrogen and oxygen isotopes adapted from Cook and Herczeg (1998).

#### VSMOW

The Vienna Mean Ocean Water (VSMOW) is used as the international representation for ocean water  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  ratios (Clark & Fritz 1997). It replaced the Standard Mean Ocean Water (SMOW) of Craig (1961) and with only minor changes to the original ratio. VSMOW is positioned at the origin of the plots generated from  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  analysis.

### *Global Meteoric Water Line (GMWL) and Local Mean Water Lines (LMWL)*

Equation 1 below is the straight line equation for the relationship of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in globally averaged rainfall values that represent precipitation without any evaporation or other physical or chemical process.

$$\text{Eqn 1: } \delta^2\text{H} = 8(\delta^{18}\text{O}) + 10 \quad - (\text{Craig 1961})$$

This straight line equation is used in hydrological studies to compare the measured results of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ . Plotted on a bivariate plot, the relative position of the measured  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values can indicate processes such as evaporation. However, there are several natural processes that can result in values not plotting on the meteoric water line (Coplen et al. 2000). An example of the meteoric water line and associated processes involved in relative positions is shown in Figure 2.11.

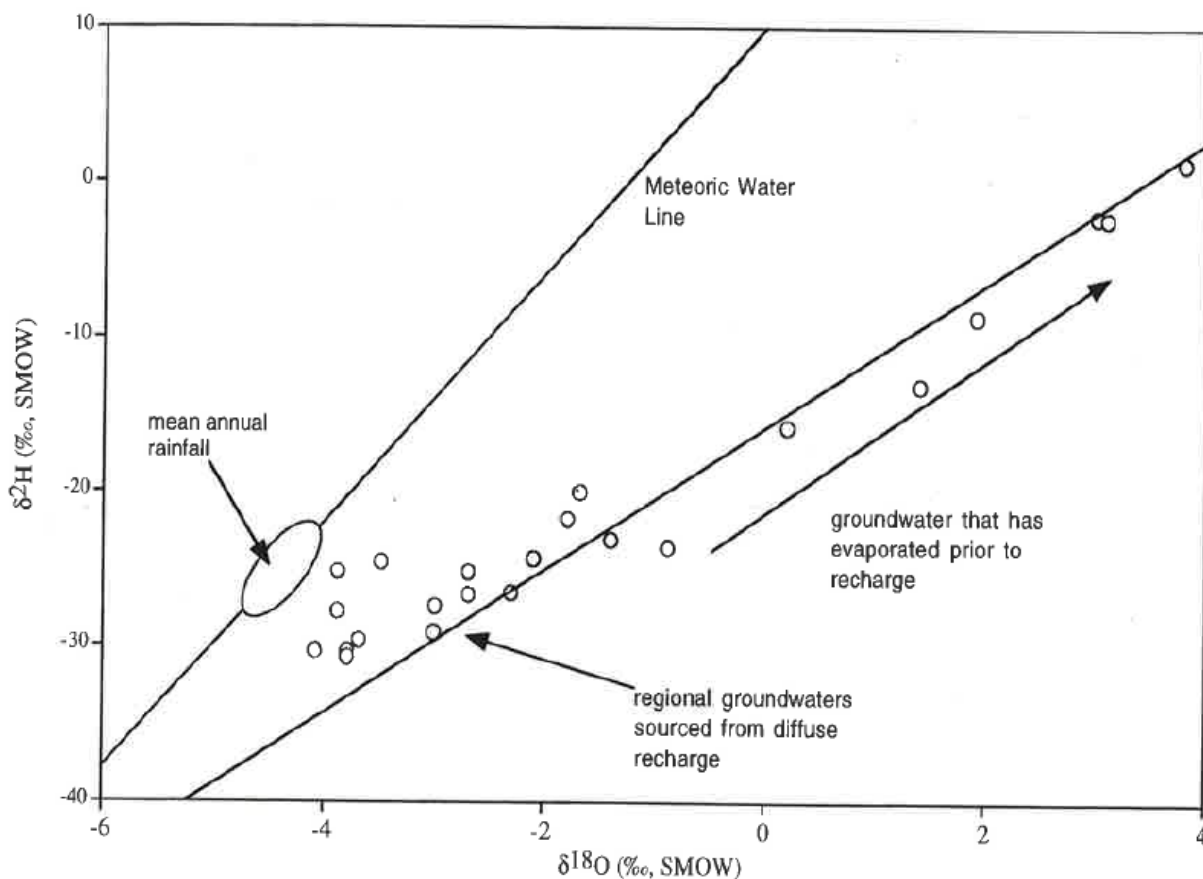


Figure 2.11 – example of groundwater  $^{18}\text{O}/^{16}\text{O}$  and  $^2\text{H}/^1\text{H}$  ratios plotted with meteoric line, indicating processes such as evaporation before recharge. Taken from (Cook & Herczeg 1998)

LMWLs are generated from a regional rainfall capture assessment, Hughes and Crawford (2013) generated equation 2 and 3:

Eqn 2:  $\delta^2\text{H} = 8.01 (\delta^{18}\text{O}) + 16.8$  (for the Sydney Basin)

Eqn 3:  $\delta^2\text{H} = 7.99 (\delta^{18}\text{O}) + 16.0$  (for Lucas Heights)

LMWLs can provide a different end result and interpretation compared to the GMWL, and should always be used if available (Clark & Fritz 1997; Hughes & Crawford 2013)

### *Isotopic Fractionation*

Isotopic fractionation is a process where stable isotopic abundances change (Gat 2010). There are two major types and these are dependent on the mass of the isotopes, different masses result in different concentrations or changes (Coplen et al. 2000);

1) Equilibrium fractionation (also known as thermodynamic fractionation) – small thermodynamic differences of two isotopes of in equilibrium (proportions are constant) at any temperature result in lighter molecules usually being marginally more reactive (Cook & Herczeg 1998; Coplen et al. 2000).

2) Kinetic isotope fractionation - unidirectional reactions with mass dependency, as lighter molecules of water have weaker bonds and are hence more reactive resulting in enrichment of heavier water molecules (Coplen et al. 2000).

### *Rayleigh fractionation and isotopic composition*

Rayleigh fractionation (or distillation) is the mathematical proof of isotopic changes in gas in distillation processes that can explain why enrichment and depletion of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in the hydrological cycle occurs (Coplen et al. 2000). Generally, all rainfall becomes more depleted in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  as clouds move further inland and further from the equator (Cook & Herczeg 1998). However, now several processes have been determined to explain why variations in fractionation occur over Earth, giving generally depleted values ( $< 0\%$ ) of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in all waters other than the ocean. An example of evaporation enrichment is illustrated in Figure 2.12-13. Table 2.9 describes the processes that are involved in the depletion of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$

in the hydrological cycle with a focus on rainfall.

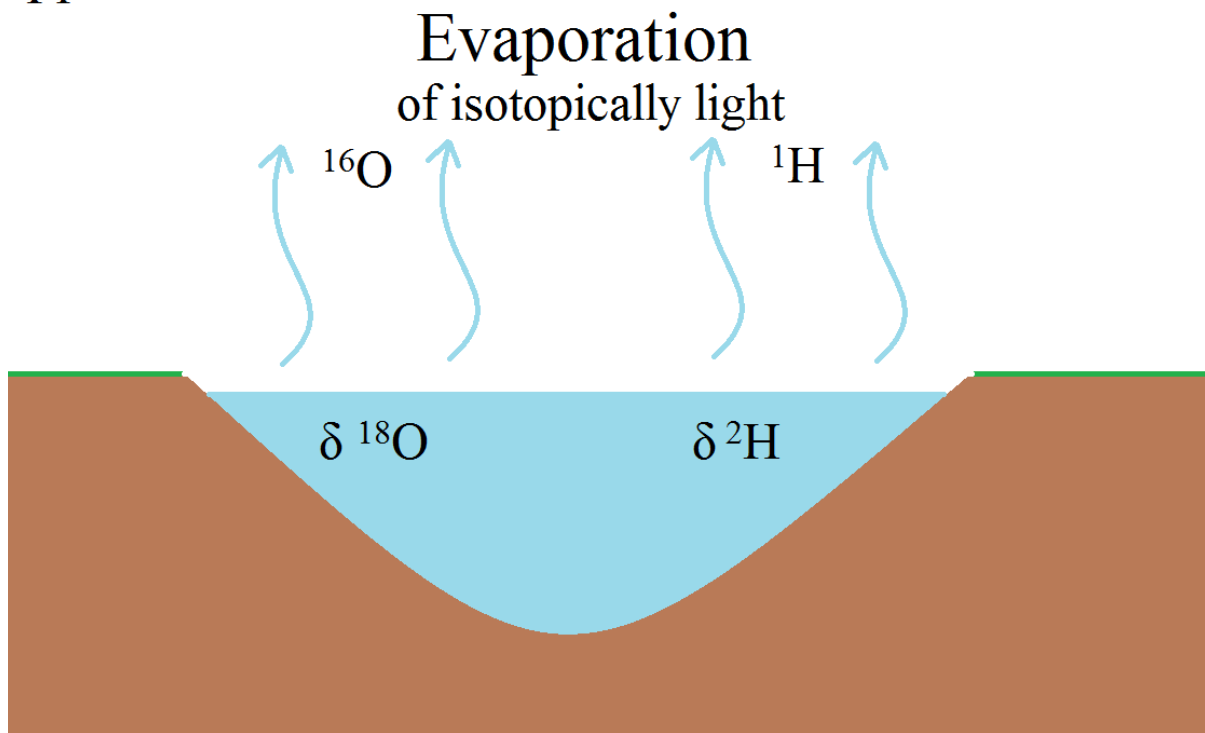
Effect	Description
Altitude effect	$\delta^{18}\text{O}$ and $\delta^2\text{H}$ depletes in rainfall with altitude (see Figure 2.13)
Latitude effect	$\delta^{18}\text{O}$ and $\delta^2\text{H}$ depletes with increasing latitude
Continental effect	$\delta^{18}\text{O}$ and $\delta^2\text{H}$ depletes in rainfall further inland it travels (see Figure 2.13)
Seasonal effect	Summer rainfall is enriched in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ relative to winter rainfall. Glacial periods need to be taken into consideration.
Amount effect	The larger the rainfall event the more depleted the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ .
Apparent temperature relationship	Rainfall travelling towards increased latitudes (or altitudes) with decreasing temperatures are hard to differentiate as to which effect is driving the depletion of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ .

Table 2.9 – Processes needing consideration for depletion-enrichment of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ . After Coplen et al. (2000).

### *Groundwater*

Groundwater with depletions in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  will plot differently to groundwater with little or no depletion. The relative position of groundwater to meteoric water lines on the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  plots can indicate the physical, environmental and chemical processes (eg. evaporation) rainfall undergoes before infiltrating.

T1



T2

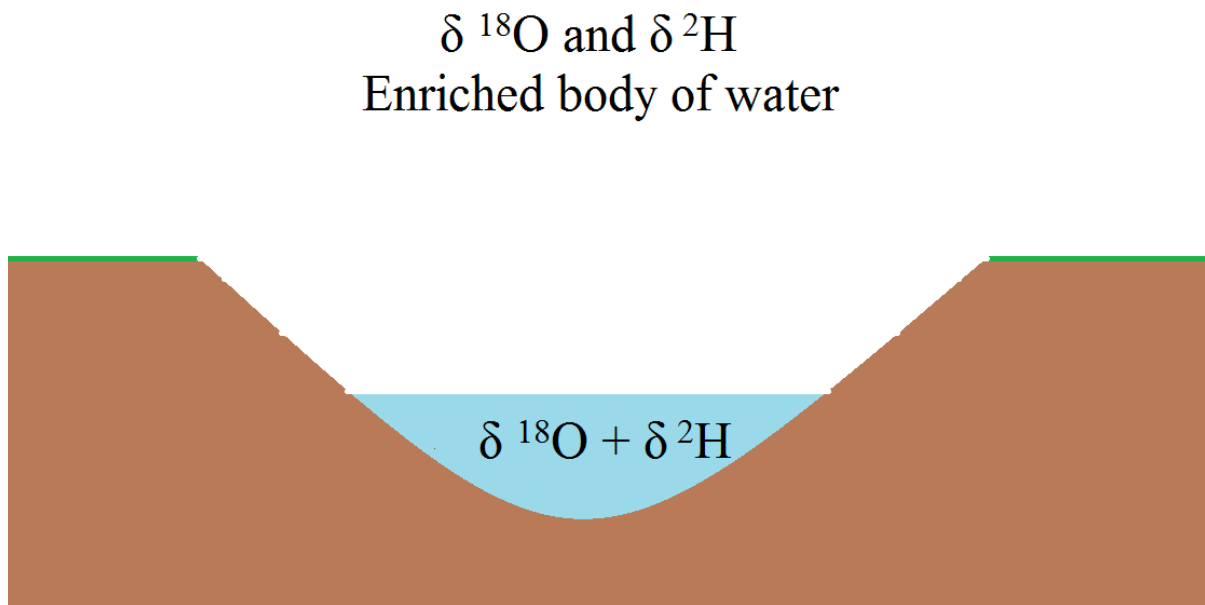


Figure 2.12 –Example of the behaviour of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  in relation to evaporation processes. Isotopically lighter  $^{16}\text{O}$  and  $^1\text{H}$  is preferentially evaporated to form clouds resulting in a  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  enriched body of water.

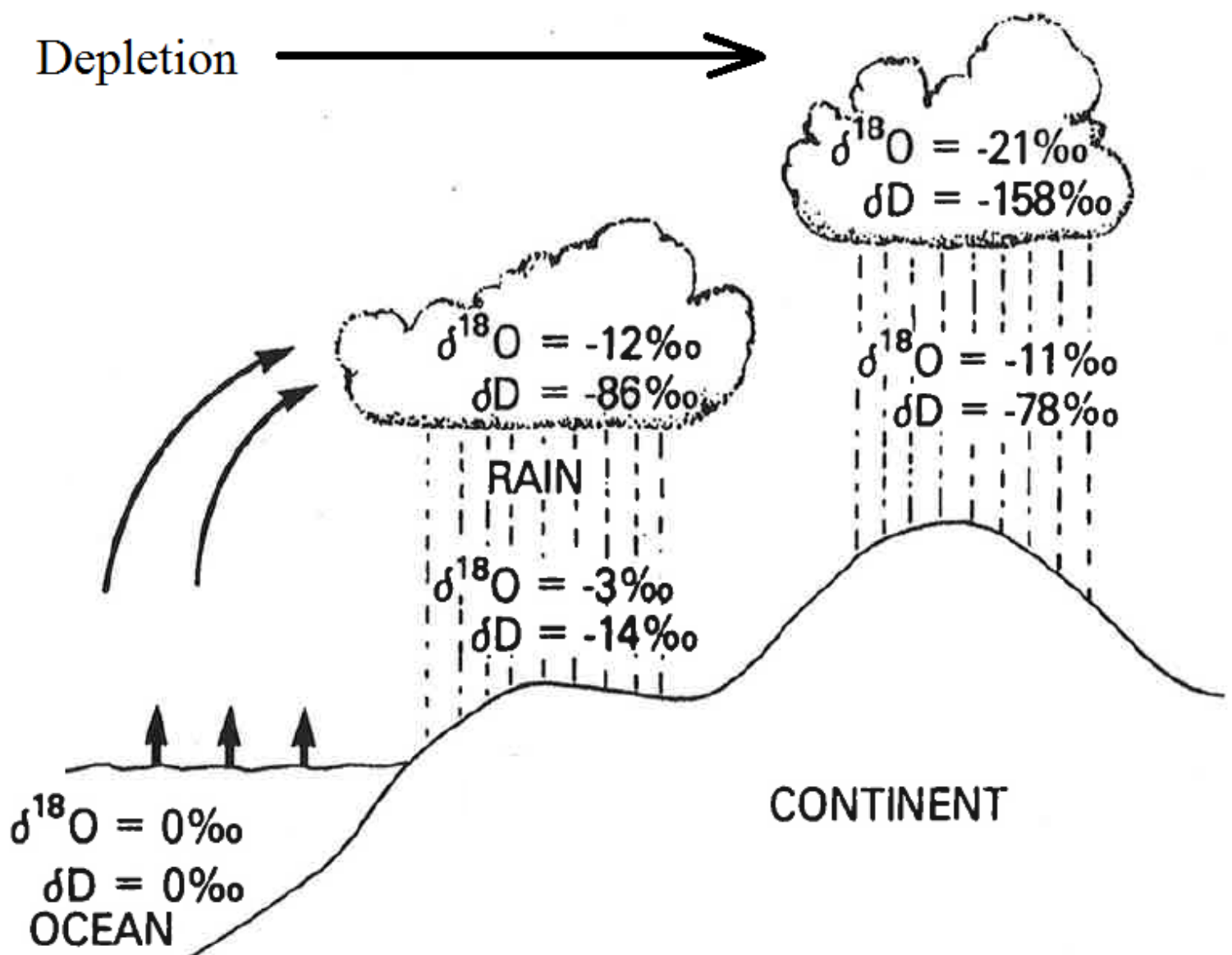


Figure 2.13 – Isotopic Fractionation.  $\delta^2\text{H}$  ( $\delta\text{D}$ ) and  $\delta^{18}\text{O}$  depletion as rainfall moves further inland. The heavier stable isotopes are more likely to precipitate, hence making it a useful indicator of water tracing. Adapted from Coplen (1993).

### 3. Chapter 3 Steady state lump-parameter water balance

#### 3.1 Water Balance equations

To understand the hydrology at MPMB a steady state lump-parameter model water balance was created. The equation involved in constructing the water balance is as follows;

P = Precipitation

Q = Runoff

$$P = Q + ET \pm \Delta S$$

ET = Evapotranspiration

$\Delta S$  = Change in storage

The changes in storage ( $\Delta S$ ) are attributed to the anthropogenic extraction of water from the surface and groundwater system. Since CSG activities and agricultural bores are known to extract water from aquifers and water bearing units it can be totalled and substituted into the equation as an outflow.

#### 3.2 Hawkesbury Nepean Subcatchment (HydroID 12107289)

A crucial factor in a water balance calculation is the spatial extent of the study area. As spatial extent increases the annual totals for estimated precipitation, evapotranspiration, runoff and changes in storage increase too. Therefore, the water balance calculation for the entire Hawkesbury Nepean catchment would be far larger than the CGP because of their obvious size difference. The subcatchment chosen for this project has a total of 520km<sup>2</sup> in area, more than double the size of the Camden Gas Project. Figure 3.1 contrasts the extent to the CGP.

The subcatchment is a Bureau of Meteorology defined area named HydroID 12107289 calculated from topographical calculations. In Figure 3.1 the extent of the domestic, agricultural and government owned bores located within the confines of this Subcatchment and the Camden Gas Project are shown. These bores are hydrogeologically significant outflows for the entire system and calculated as change in storage ( $\Delta S$ ).



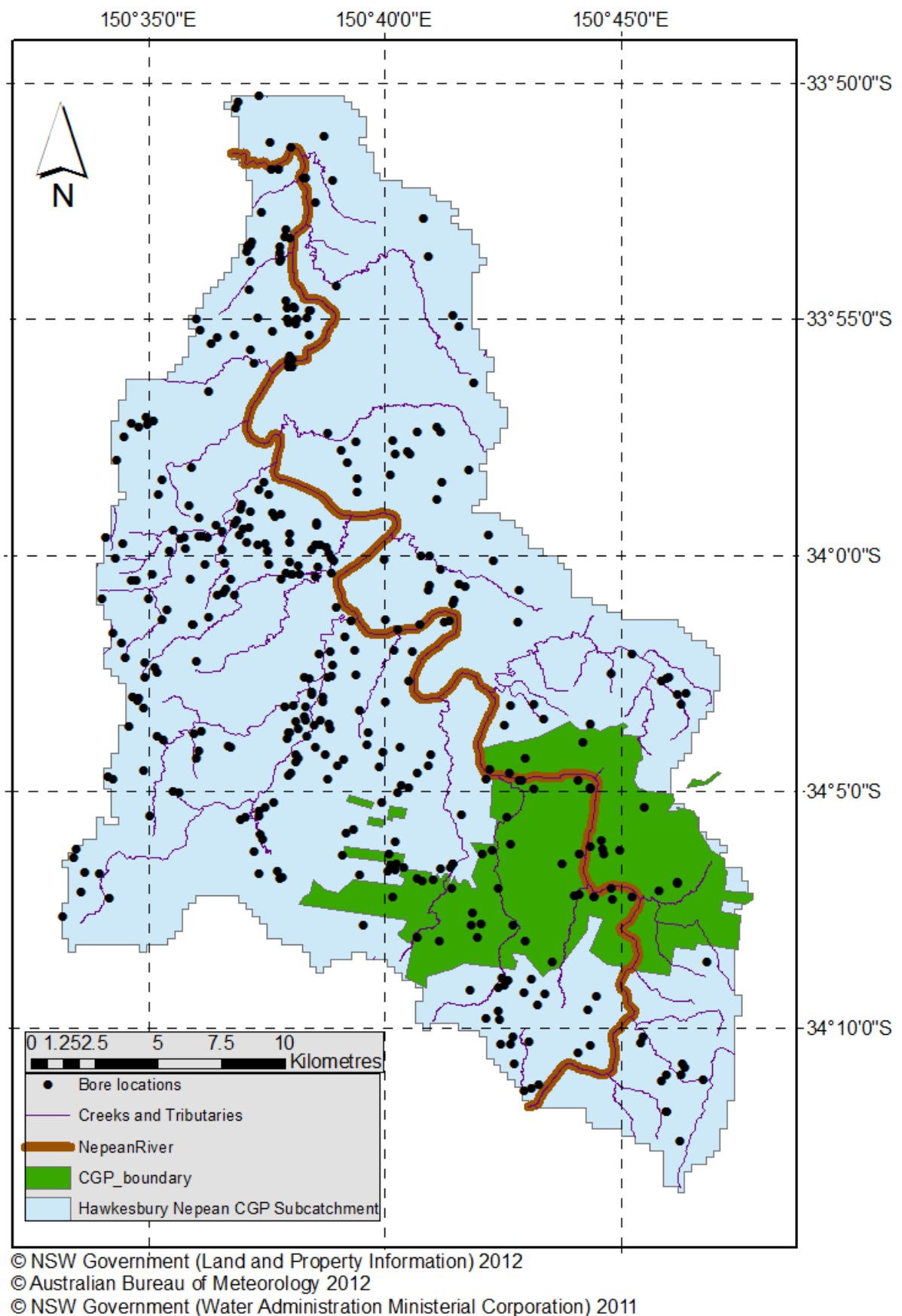


Figure 3.1 – The subcatchment (HydroID -12107829) and the CGP with all domestic-agricultural bores highlighted in black to show the extent of groundwater usage and activity within the region.

### 3.3 Inflows and Outflows

The inflows and outflows of the subcatchments hydrological system are summarised in Table 3.1 below.

Inflows	Description
Total Rainfall	Calculated as per annum averages from the Bureau of Meteorology's weather station recordings within 15km of the study site (Table 3. 2). Total area x average annual rainfall = Total rainfall volume
Recharge	Values are inferred from soil infiltration rates versus area and precipitation.
Outflows	Description
Evapotranspiration	Calculated from the Bureau of Meteorology's evapotranspiration map (Bureau of Meteorology 2012)(Figure 3.2). Between 600-700mm of evapotranspiration per annum.
Runoff	Based on Nepean River gauge data provided by AGL Pty Ltd on behalf of the Bureau of Meteorology
CSG dewatering process	AGL Pty Ltd provided data of the produced water volume for the entire CGP. It is most recently ~4ML per annum (AGL Energy Pty Ltd 2013a).
Agricultural/ Domestic water bores abstraction	Not all domestic and agricultural bores are active nor do they have extraction gauges to record the volumes removed. Therefore the uncertainty is increased. The bores were allocated low entitlement bore values <20ML/year (NSWOW 2010). However, the total number of bores 254 is and no supporting data suggest these are all active and currently extracting water.

Table 3.1 Inflows and outflows of the subcatchment

### 3.4 Precipitation

An average annual precipitation value was generated for the subcatchment from 8 weather stations surrounding the Menangle Park area. GPS coordinates, record lengths and mean annual rainfall values are summarised in Table 3.2 below. The average regional rainfall of 741mm was calculated for use in the water balance. This is calculated to be a total of 385GL of rain water per annum for the 520km<sup>2</sup> subcatchment.

Weather station site	GPS	Opened	Mean Annual Rainfall
Camden Airport AWS (Automatic weather station)	Lat: 34.04° S Lon: 150.69° E	1943	788 mm
Menangle Bridge	Lat: 34.12° S Lon: 150.74° E	1963	609.6 mm
Mount Annan Botanic Garden	Lat: 34.07° S Lon: 150.77° E	2002	660.4 mm
Ingleburn (Sackville Street)	Lat: 34.01° S Lon: 150.86° E	1992	716.5mm
Douglas Park ( St. Marys Towers)	Lat: 34.21° S Lon: 150.71° E	1974	757.6mm
Cawdor (Woodburn)	Lat: 34.10° S Lon: 150.64° E	1962	789.1 mm
Wedderburn (Booalbyn)	Lat: 34.17° S Lon: 150.81° E	1964	864.3 mm
Camden (Brownlow Hill)	Lat: 34.03° S Lon: 150.65° E	1882	743.0mm
Average regional rainfall per annum =			741.0 mm

Table 3.2 – Weather stations within and around the subcatchment area showing mean annual rainfall data. Sourced from Bureau of Meteorology (2013).

### 3.5 Evapotranspiration (ET)

Evapotranspiration is the process of water moving from vegetation, soil and water bodies into the atmosphere. This process does not extract water from the aquifers or water bearing units as such, but limits and reduces the water infiltration which would otherwise recharge aquifer units (Brassington 1988). Areal evapotranspiration values were utilised for the water balance calculations because they represent the actual ET that occurs with current existing water supplies on large scales (Bureau of Meteorology 2012). The Bureau of Meteorology's ET map (Figure 3.2) situates the area of the study site within the 600 - 700mm per annum contour.

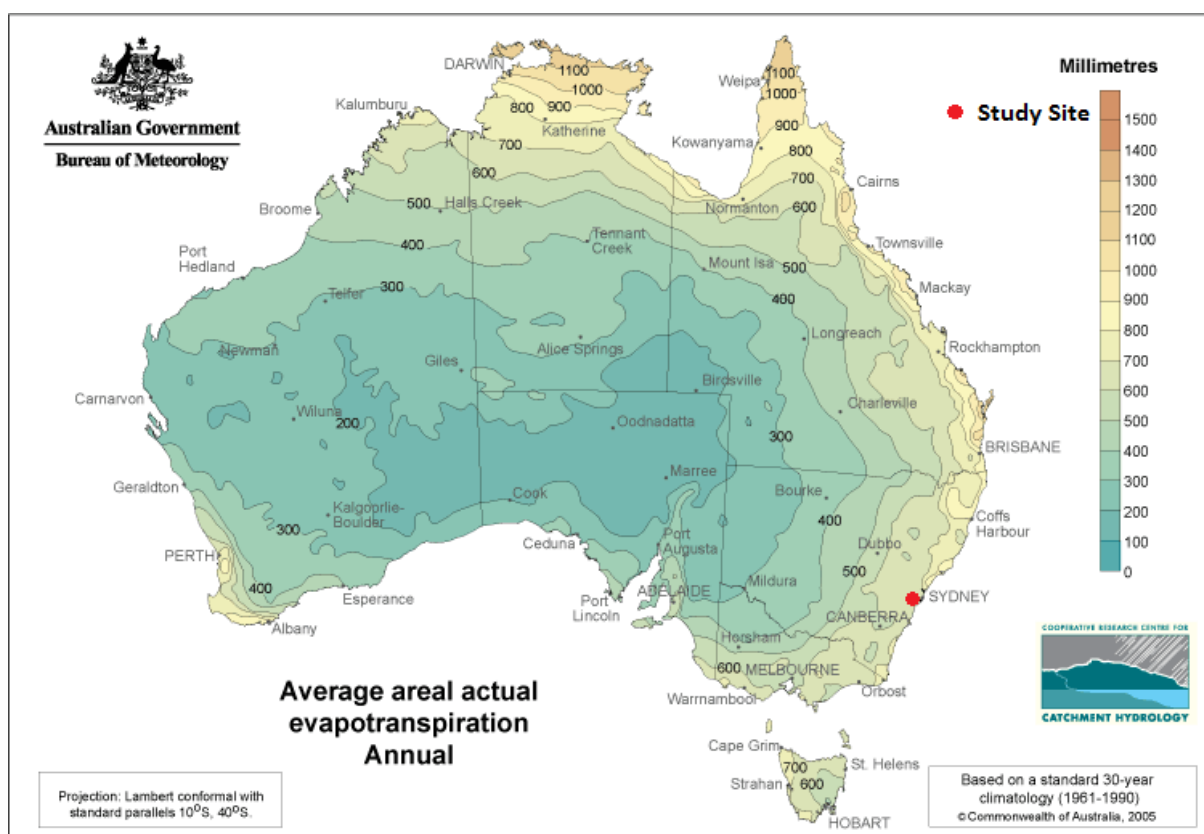
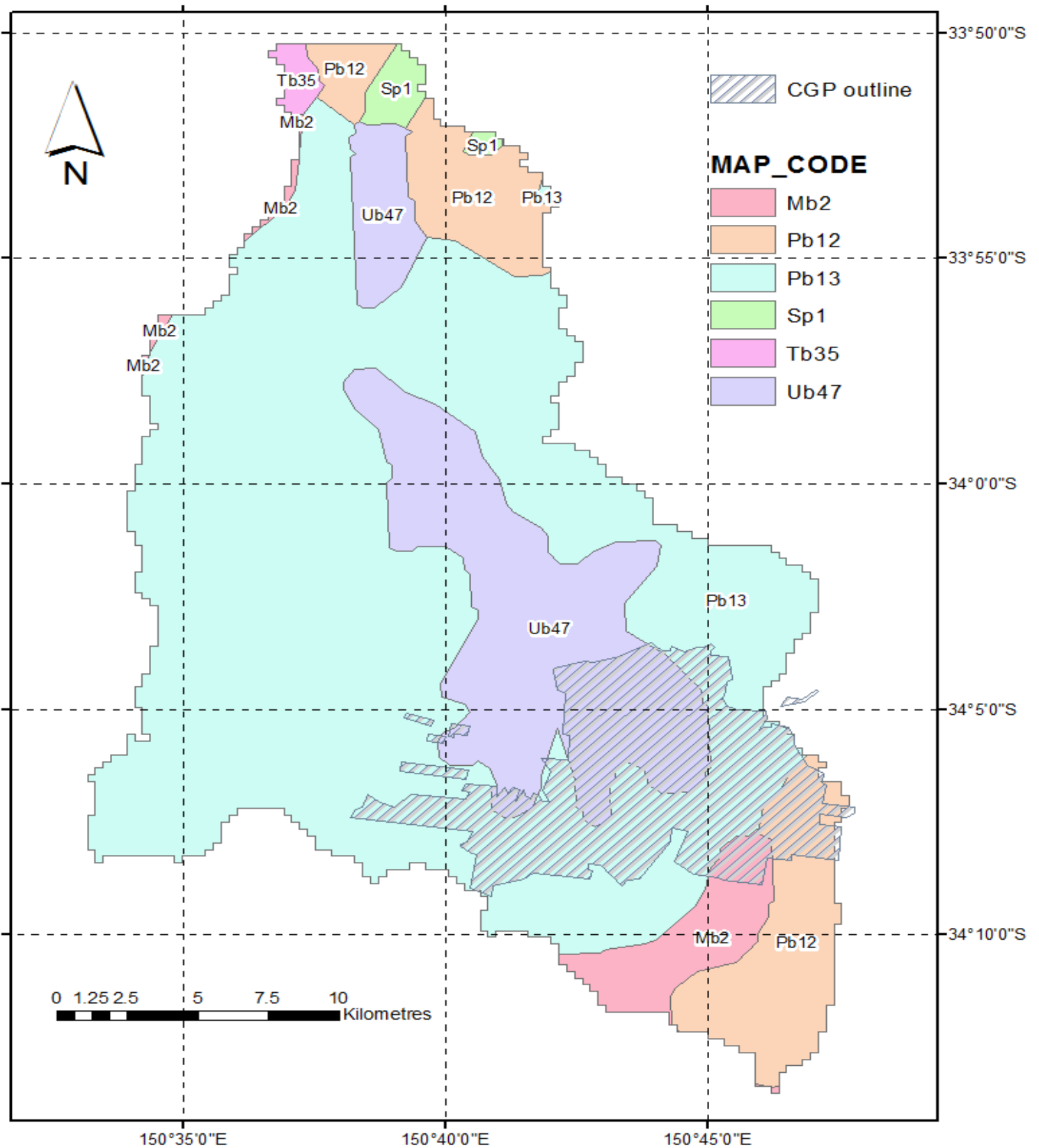


Figure 3.2 – Average annual evaporation of Australia, calculated by the Bureau of Meteorology (Bureau of Meteorology 2012)

### 3.6 Recharge

Recharge is difficult to accurately measure without access to monitoring bores throughout the entire subcatchment area. Therefore values must be inferred from other sources of information. A GIS layer was generated from Atlas of Australian Soils (© Bureau of Rural Sciences) and a study of water infiltration rates of Australian soils from McKenzie and Hook (1992) supply an approximate recharge rate over the study site (see Figure 3.3). The soil classification scheme used by the Atlas of Australian Soils was designed by Northcote (1971) which involved analysis of over 500 soil profiles. McKenzie and Hook (1992) added important environmental parameters of the soil types in the classification scheme created by Northcote (1971) including: permeability, water capacity, soil texture, soil reaction class, nutrient status and soil depth. Figure 3.3 is the soil map for the subcatchment. Each map code represents a geomorphological landscape with associated soil types.



Data: © Bureau of Rural Sciences, Atlas of Australian Soils

Figure 3.3 Soil map of HydroID – 12107829. For codes see Table 3.3.

Table 3.3 below combines the soil types in Figure 3.3 with their associated infiltration rate coefficients. The infiltration rates will be used to infer the range of likely recharge values for the groundwater system.

Map Unit	Area in Km <sup>2</sup>	Description*	Assigned Infiltration rate coefficient^
Mb2	20	Gently undulating or undulating lands with broad ridge crests and shallow drainage depressions: dominant soils are loamy or sandy bleached mottled yellow earths (Gn2.74), with similar (Gn2.64) and (Gn2.94) soils often closely associated.	3 (50-500mm/day)
Pb12	56	Gently rolling to rounded hilly country with some steep slopes and broad valleys: chief soils are hard acidic red soils (Dr2.21) with hard neutral and acidic yellow mottled soils (Dy3.42 and Dy3.41) on lower slopes and in valleys.	2 (5-50mm/day)
Tb35	3	Dissected plateau remnants--flat to undulating ridge tops with moderate to steep side slopes: chief soils are hard acidic yellow and yellow mottled soils (Dy3.41), (Dy2.21), and (Dy2.41) and hard acidic red soils (Dr2.21);	2 (5-50mm/day)
Sp1	5	Gently sloping bench or terrace--the Ridge Hill Shelf: chief soils are hard acidic yellow soils (Dy2.61) containing ironstone gravels.	2 (5-50mm/day)
Pb13	340	Ridge and valley country of gently undulating ridge tops and steep side slopes often with slumping, also rounded hilly to steep hilly areas and relatively narrow valleys: chief soils are hard acidic red soils (Dr2.21) with hard acidic yellow mottled soils (Dy3.41);	2 (5-50mm/day)
Ub47	96	River terraces and flood-plains: main high terrace of hard neutral and alkaline yellow mottled soil (Dy3.42 and Dy3.43) grading to (Gn3.9) soils, and possibly some (Uf6.4) soils in depressions.	1 (<5mm/day)

Table 3.3 – Soils of the subcatchment and their corresponding infiltration rates for groundwater recharge.

\*Description taken from Bureau of Rural Science (1991) .

^Infiltration rates are based on report by Mckenzie and Hook (1992).

### 3.7 Runoff

Two stream gauges on the Nepean River (the BOM station 68216 and Sydney Catchment Authorities (SCA) 568176) are located close to the MPMBs. Both stations have recorded river heights (stage) since January 2012. The river's stage responses to rainfall can be instrumental in determining runoff, however this requires field work to determine the river size and flow parameters. Furthermore, the discharge value is not entirely representative of runoff for the subcatchment because the Nepean River does not begin within the subcatchment. Water would be moving into the subcatchment, giving over estimations of runoff calculations. The Nepean River is also known to be an effluent 'gaining' river (groundwater flows into river) which needs to be considered when calculating the total recharge and runoff (Merrick 2009). This is a complex and dynamic problem that is outside of the timeframe for this project; however it has potential for a possible future research project.

Figure 3.4 shows the stage recordings of the Nepean River with time since 2012. It is clear that rainfall is related with river stage heights. The type of rainfall event that occurred in June 2013 also needs to be considered when examining the stage response, as large flash flood type rain events have a different recharge and runoff volume compared to a slow gradual rain event in terms of soil saturation.



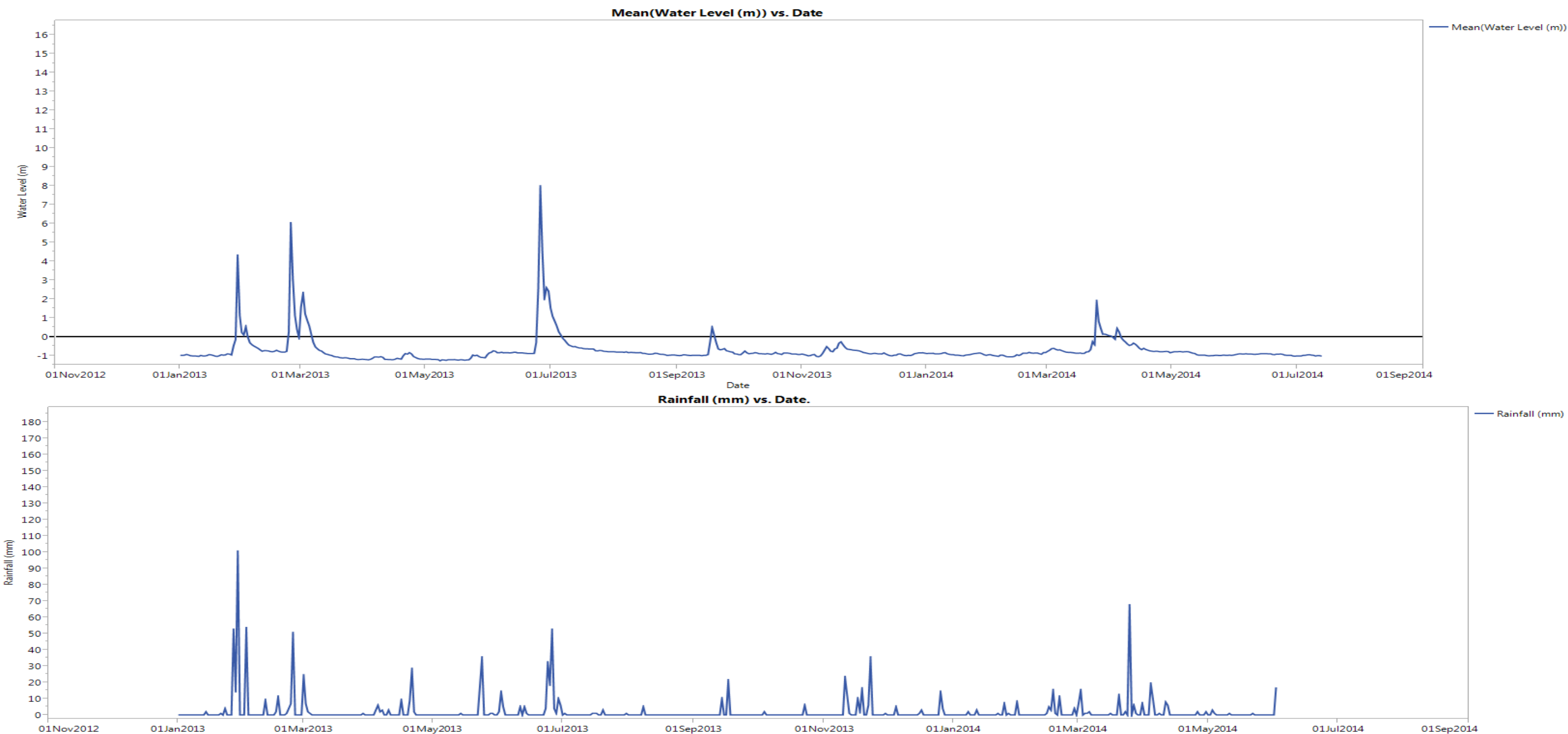


Figure 3.4 - Nepean River stage versus rainfall

### 3.8 Domestic, agricultural and industrial bore abstraction

A total of 411 agricultural, industrial, government and domestic bores are established over the entire subcatchment area. Figure 3.1 displays the location of the bores showing a well dispersed distribution over the entire subcatchment. Groundwater monitoring software 'Pineena' provided metadata of the various additional information about the nature of the bores including depth, date of instalment, salinity, GPS coordinates, ownership status and information about yields. Few of the bores have a complete set of data and some nearly no information.

The bores listed as private are legally allowed to extract water; these were the only bores used in the calculation however it is possible that the other bores contribute to the extraction output. Each bore has been assigned an appropriate value of annual groundwater extraction yields. All bores were assigned a low entitlement category, which includes an assessment of neighbour drawdown impacts and a 0-20ML/year yields (NSWOW 2010). For a background in domestic-agricultural extraction values the author directs the reader to the NSW Office Of Water document about coastal groundwater assessment guidelines (NSWOW 2010).

### 3.8 Calculations

Water balance calculations are dependent on the available information. Due to the restricted time involved in an Honours thesis, many of the possible improvements to the calculations could not be made. However, 3 scenarios were created with high, medium and low values of extraction, evapotranspiration and runoff to give a wider range to the overall water balance possibilities. All water balance calculations are calculated in a per annum time interval .

Scenario 1 –high extraction, high ET, low runoff, low recharge

Inflow

Precipitation

Study area of subcatchment =  $520 \text{ km}^2 = 520,000,000 \text{ m}^2$

Mean averaged annual regional rainfall = 741.0mm

Total rainfall = regional annual average x surface area

=  $520,000,000 \text{ m}^2 \times 741.0 \text{ mm}$

= 385,320,000,000L

= 385.32GL

Recharge

= 4.726GL

Outflow

CSG activities

Total dewatering from CSG in CGP = 4ML per annum=0.004GL

Evapotranspiration

Study area of subcatchment =  $520 \text{ km}^2 = 520,000,000 \text{ m}^2$

Mean evapotranspiration = 700mm

=  $520,000,000 \text{ m}^2 \times 700 \text{ mm}$

= 364GL or 94.5% of budget

Agricultural/domestic bore abstraction

254 known privately owned bores possibly extracting water for agricultural/domestic use

Total bore abstraction = 254 bores x 5ML max/year (Two Olympic swimming pools)

Total bore abstraction = 1.27GL/year

= 508 Olympic swimming pools

Runoff

= 15GL

A conceptual model of this scenario is shown in Figure 3.5.

Inflow

Precipitation

Study area of subcatchment =  $520 \text{ km}^2 = 520,000,000 \text{ m}^2$

Mean averaged annual regional rainfall = 741.0mm

Total rainfall = regional annual average x surface area

=  $520,000,000 \text{ m}^2 \times 741.0 \text{ mm}$

= 385,320,000,000L

= 385.32GL

Recharge

Soil Infiltration

= 10 GL

Outflow

CSG activities

Total dewatering from CSG in CGP = 4ML per annum = 0.004GL

Evapotranspiration

Study area of subcatchment =  $520 \text{ km}^2 = 520,000,000 \text{ m}^2$

Mean evapotranspiration = 650mm

=  $520,000,000 \text{ m}^2 \times 650 \text{ mm}$

= 338GL or 87.7% of budget

Agricultural/Domestic bore abstraction

254 known privately owned bores possibly extracting water for agricultural/domestic use

Total bore abstraction = 254 bores x 2.5ML/year (Olympic swimming pool per bore)

Total bore abstraction = 0.635GL/year

= 254 Olympic swimming pools

Runoff

= 36 GL

Scenario 3—low extraction, low ET, high runoff, high recharge

Inflow

Precipitation

$$\text{Study area of subcatchment} = 520 \text{ km}^2 = 520,000,000 \text{ m}^2$$

$$\text{Mean averaged annual regional rainfall} = 741.0\text{mm}$$

$$\text{Total rainfall} = \text{regional annual average} \times \text{surface area}$$

$$= 520,000,000\text{m}^2 \times 741.0\text{mm}$$

$$= 385,320,000,000\text{L}$$

$$= 385.32\text{GL}$$

Recharge

$$= 21.8 \text{ GL}$$

Outflow

CSG activities

$$\text{Total dewatering from CSG in CGP} = 4\text{ML per annum} = 0.004\text{GL}$$

Evapotranspiration

$$\text{Study area of subcatchment} = 520\text{km}^2 = 520,000,000\text{m}^2$$

$$\text{Mean evapotranspiration} = 600\text{mm}$$

$$= 520,000,000\text{m}^2 \times 600\text{mm}$$

$$= 312\text{GL or } 80.9\% \text{ of budget}$$

Agricultural/Domestic bore abstraction

254 known privately owned bores possibly extracting water for agricultural/domestic use

$$\text{Total bore abstraction} = 254 \text{ bores} \times 0.05\text{ML/year}$$

$$\text{Total bore abstraction} = 0.127\text{GL/year}$$

$$= 127\text{ML or } 50.8 \text{ Olympic swimming pools.}$$

Runoff

$$= 51.0 \text{ GL}$$

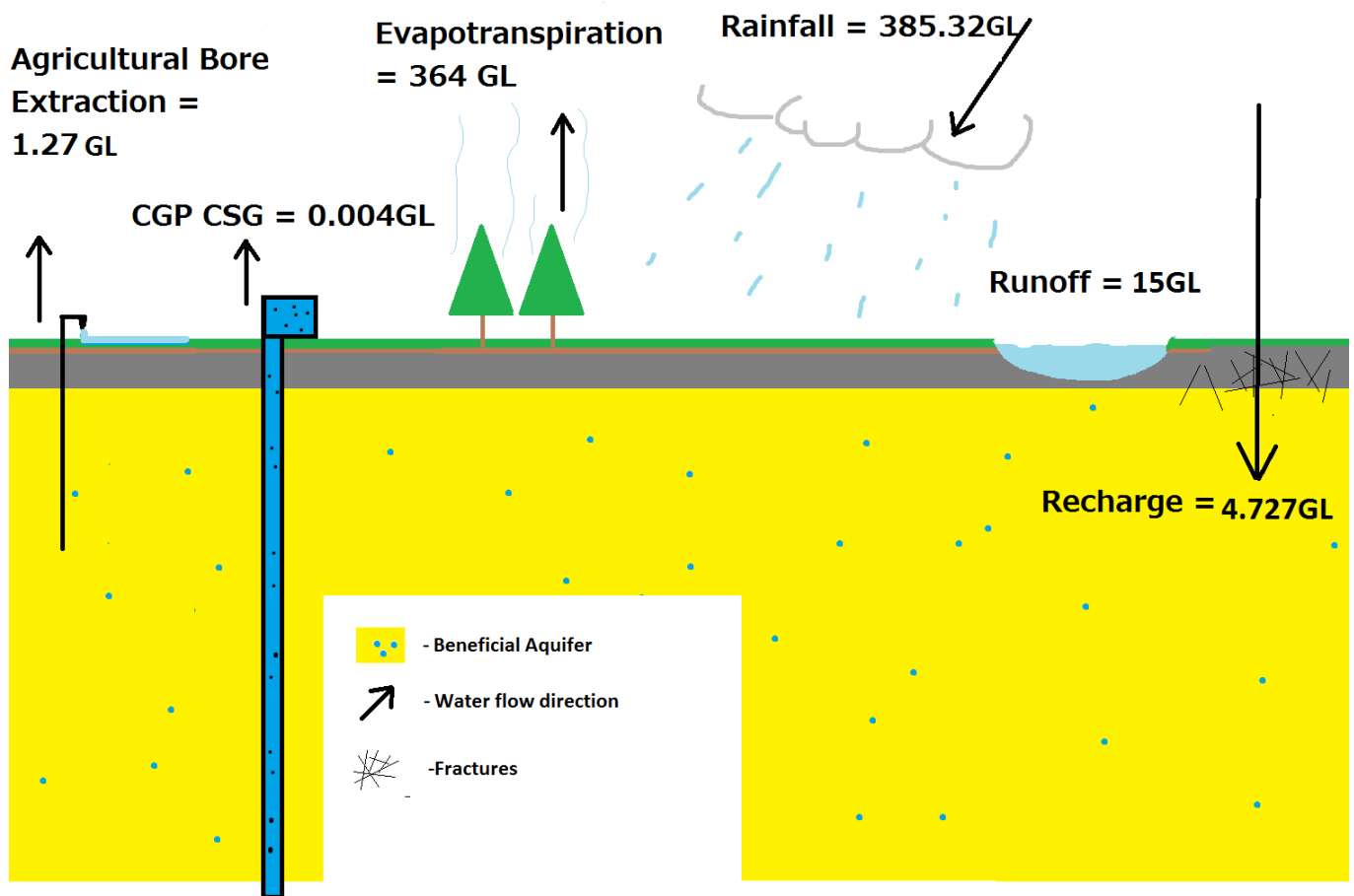


Figure 3.5 Conceptual model of scenario 1 water balance

## 4. Chapter 4 Hydrograph Analysis

### 4.1 Introduction

Bivariate plots of groundwater level versus rainfall and hydrographs of groundwater level against rainfall with time were created using MS Excel and JMP, respectively. The bivariate plot generates an  $R^2$  correlation coefficient the measure to strength of the relationship. The hydrographs display the relationships between rainfall against groundwater with time. The groundwater level data was obtained from AGL Energy Pty Ltd and the rainfall and river gauge data was sourced from the Bureau of Meteorology.

The aim of the groundwater hydrograph analysis was to assess the trends and relationships between rainfall and local groundwater systems at various depths with time. The study site and comparison site have been analysed and the results are compared for similarities and differences. The initial objective was to establish the dates and time of all the water sampling events at the MPMBs and RMBs. These events have resulted in periods of drawdown due to the pumping of water to the surface. These are problematic because they are not representative of the natural rainfall-groundwater level relationship. The sampling events were removed and a series of new points were interpolated from an estimation of the water table baseline.

The groundwater levels recorded at the MPMBs and RMBs are essentially the pressure head values (see Figures 4.2 to 4.3). The pressure head is mostly representative of the weight of the water on the surface and in the saturated zone of the ground. The more water on the surface and ground the more weight pushing down onto the underlying rock thus increasing the pressure, resulting in higher water levels in the monitoring bores. This is a similar concept to the barometric pressure effect or barometric efficiency, which can have an effect on confined aquifers or semi-confined aquifers. High atmospheric pressures push the water levels within monitoring bores downward whereas low atmospheric pressures enable water levels to rise (Brassington 1988). Barometric efficiency was taken into account and calculated by AGL Energy Pty Ltd before the data were given to this project.

For the MPMB study site river gauge and rainfall data was obtained from the Bureau of Meteorology's weather station 068216. This location is 1.29km upstream of the MPMB study site (see Figure 4.1). The river gauge data were used to establish the potential relationship between the river and the shallow MPMBs and to characterise the Nepean River as either influent or effluent. The same rainfall data are used in all hydrographs. Rainfall data for the comparison site was sourced from the Bureau of Meteorology's Ingleburn weather station 066190.



Figure 4.1 – BOM river gauge station 068216 location relative to the MPMB study site and the water sampling site. Spatial data obtained by © 2014 Digital Globe – Google Earth.



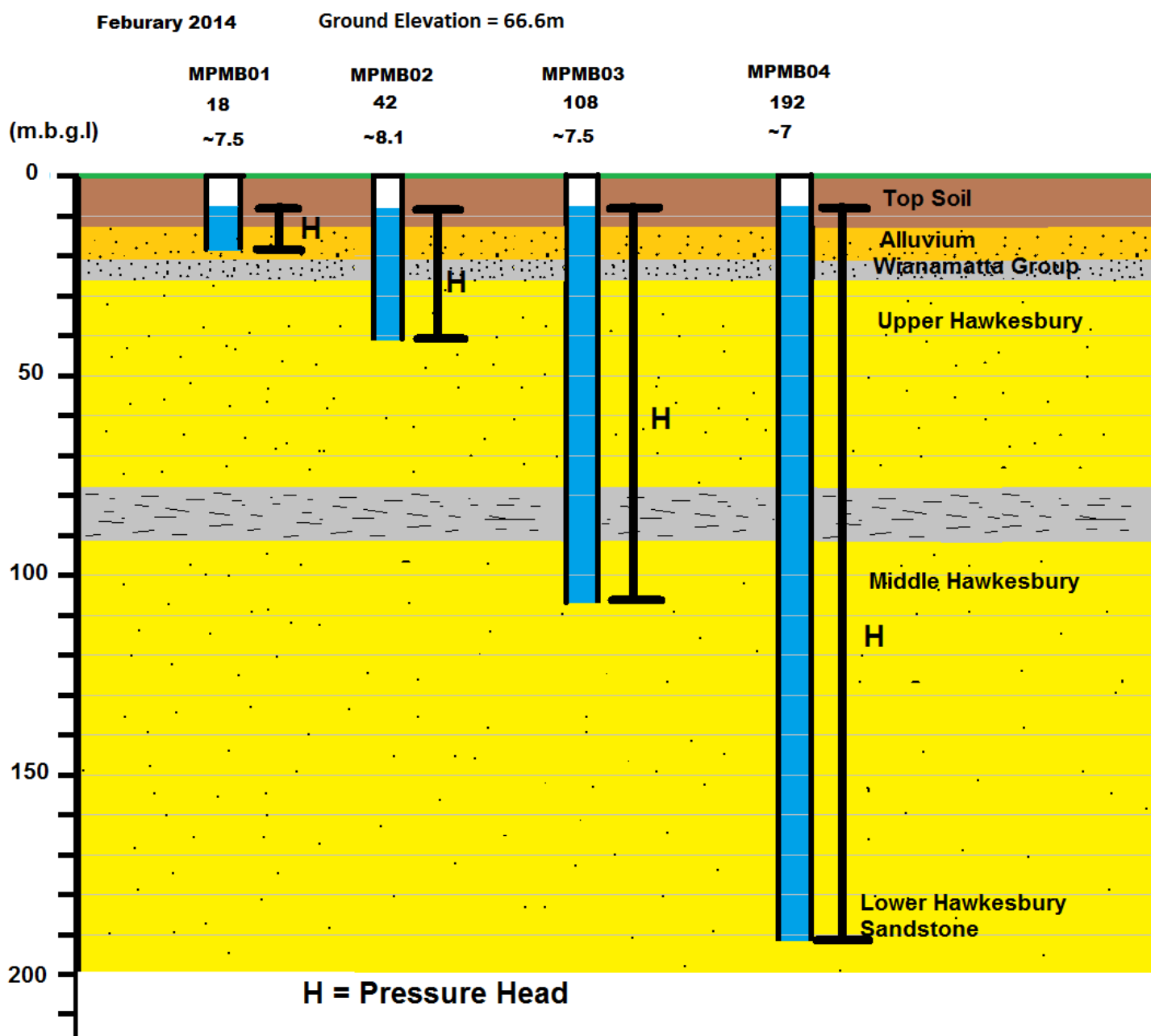


Figure 4.2 – Conceptual model of the average pressure head of MPMBs in February. Ground surface elevation is 66 metres above sea level. Geological data from Parsons and Brinckerhoff (2014).

February 2014

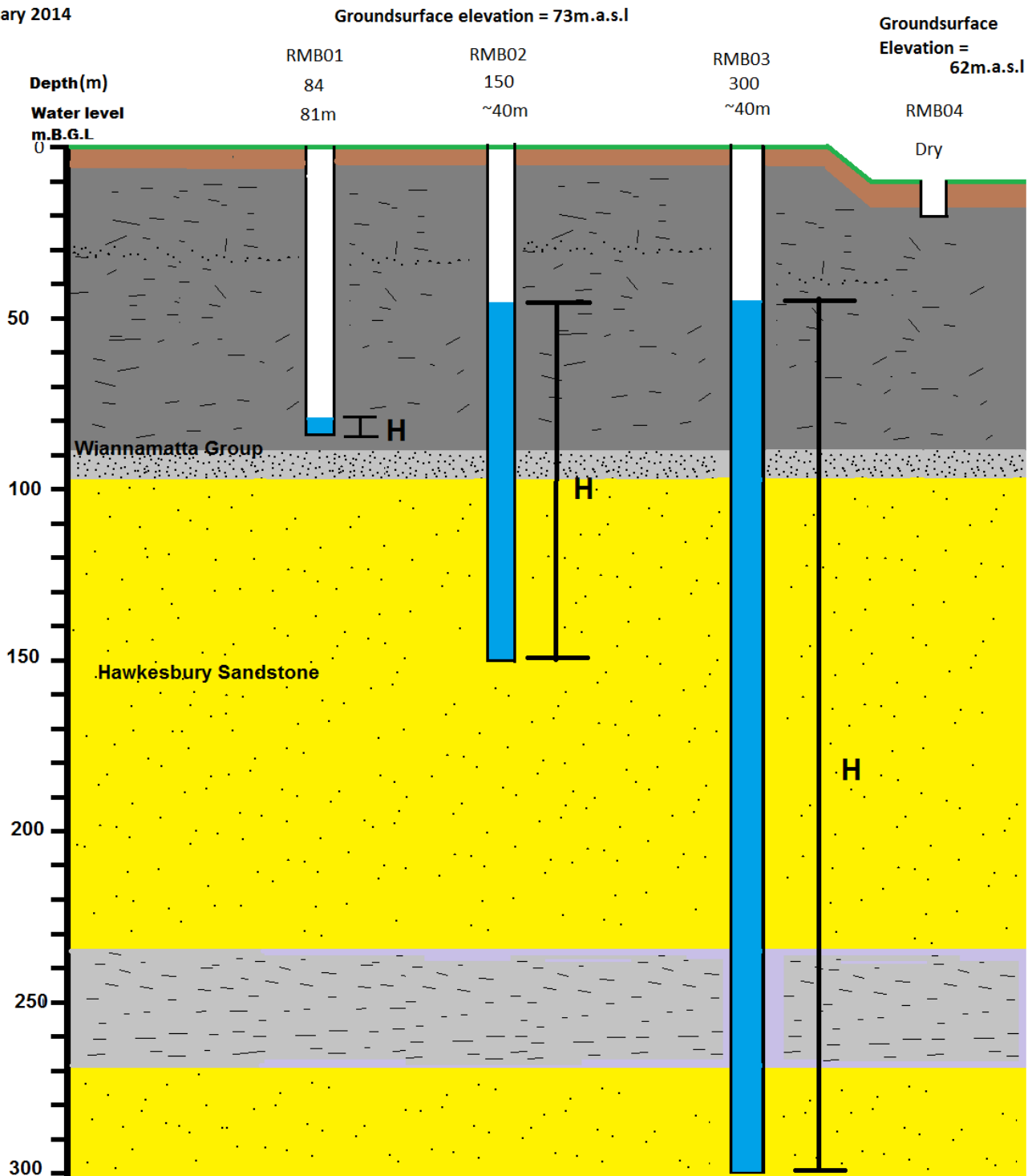


Figure 4.3 – Conceptual model of the average pressure head of RMBs in February. H= pressure head. Ground surface elevation is 73 metres above sea level. The Wianamatta Shale is an aquitard unit which restricts the vertical flow of water. RMB01 and RMB04 are bores within the Wianamatta Shale; their results are completely invalid for comparison with the MPMBs because they are a different geological unit and have little or no water within the bores to measure.

#### 4.2 Removal and interpolation of sampling events.

Since their establishment the groundwater in the MPMBs and RMBs has been periodically sampled. The dates of sampling are given below in Tables 4. 1 and 4.2

MPMB01	MPMB02	MPMB03	MPMB04
22/08/2013	22/08/2013	22/08/2013	22/08/2013
28/11/2013	28/11/2013	28/11/2013	28/11/2013
24/02/2014	24/02/2014	24/02/2014	5/12/2013
-	-	-	24/02/2014

Table 4.1 Menangle Park monitoring bore sampling dates

RMB01	RMB02	RMB03	RMB04
dry	3/11/2011	8/11/2011	dry
dry	21/05/2013	21/05/2013	dry (water level below screen)
dry	22/08/2013	22/08/2013	dry (water level below screen)
27/11/2013	27/11/2013	27/11/2013	-
dry	26/02/2014	26/02/2014	-

Table 4.2 Denham Court monitoring bore sampling dates

To improve the validity of results in the hydrograph analyses and bivariate plots the drawdown periods from sampling events were removed and new points were interpolated using Microsoft Excel (see Figure 4.4). The drawdown periods are unwanted disturbances in the bivariate plots because they are not representative of natural trends between groundwater levels and rainfall. The method used in Microsoft Excel is a simple straight line step interpolation formula described here;

$$= (\text{end-start}) / (\text{ROW}(\text{end}) - \text{ROW}(\text{start}))$$

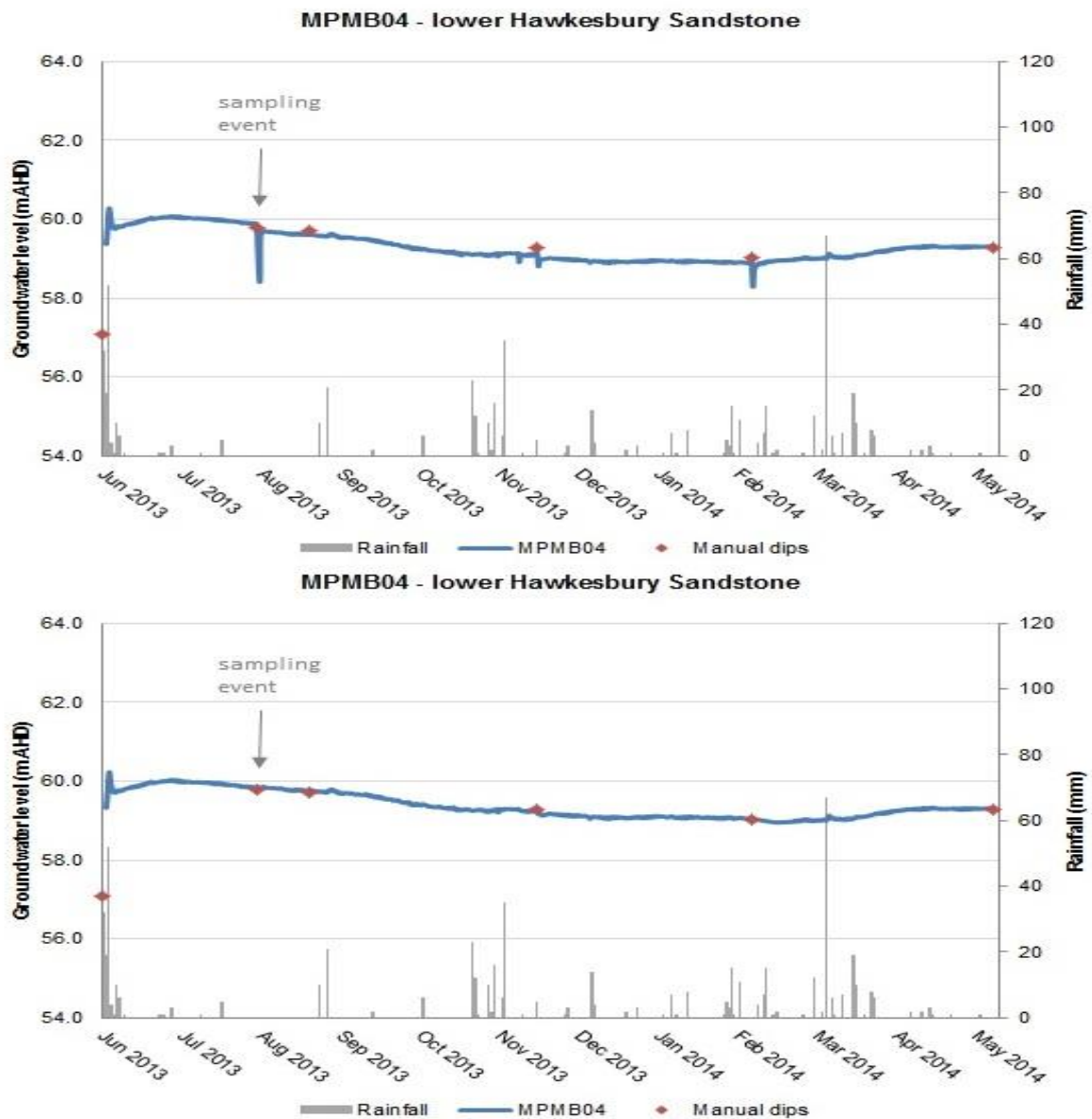


Figure 4.4 – MPMB04 example: the sampling events seen clearly in the top hydrograph are removed to reduce unwanted outliers in the correlation analysis. Graphs were taken and adapted from AGL Energy Pty Ltd (2014c).

Sampling event drawdown periods and give insight into the permeability and flow characteristics based on the response of the groundwater systems rebound. Table 4.3 below outlines the decisions made about removing sampling events and the possible implications about permeability.

Bore hole	Interpolation decisions
MPMB01	-No drawdown is visible on the hydrograph data from the sampling event and thus requires no editing/interpolation. This also indicates high permeability.
MPMB02	-Only one sampling event resulted in visible drawdown on the hydrographs. It was removed and interpolated.
MPMB03	-Very small amounts of drawdown is visible on the hydrograph data from the sampling event and thus requires no editing/interpolation.
MPMB04	-Several sampling events were removed and interpolated.
RMB01	- No sampling events were removed; this bore cannot be used for the purposes of the time series analysis because it cannot be compared to the Hawkesbury Sandstone MPMBs. It is an aquitard shale unit and has low permeability.
RMB02	-All sampling events were removed and interpolated. A logging failure caused major problems however interpolation was achieved through data collected from manual dips.
RMB03	-Sampling events were removed and interpolated. The stable level reached after periods of drawdown (32.76 mAHD – 32.73 mAHD) was chosen as the height to interpolate new data from.
RMB04	- No water table recorded at this location/depth. This bore is not able to be used for this study.

Table 4.3 –The decisions when interpolating new data for the hydrographs.

### 4.3 Bivariate plots

#### 4.3.1 Method

To assess the potential relationship between rainfall and groundwater at the MPMBs, bivariate plots were created using Microsoft Excel. This is the simplest form of analysis for identifying a correlation coefficient ( $R^2$ ). The analysis was conducted with daily, weekly and monthly time intervals to investigate the relationships more comprehensively.

### 4.3.2 Results

Daily, weekly and monthly interval bivariate plots can be found in Appendix B. Figure 4.5 shows the results of the bivariate plots of all MPMBs and their respective  $R^2$  values for a weekly time interval.

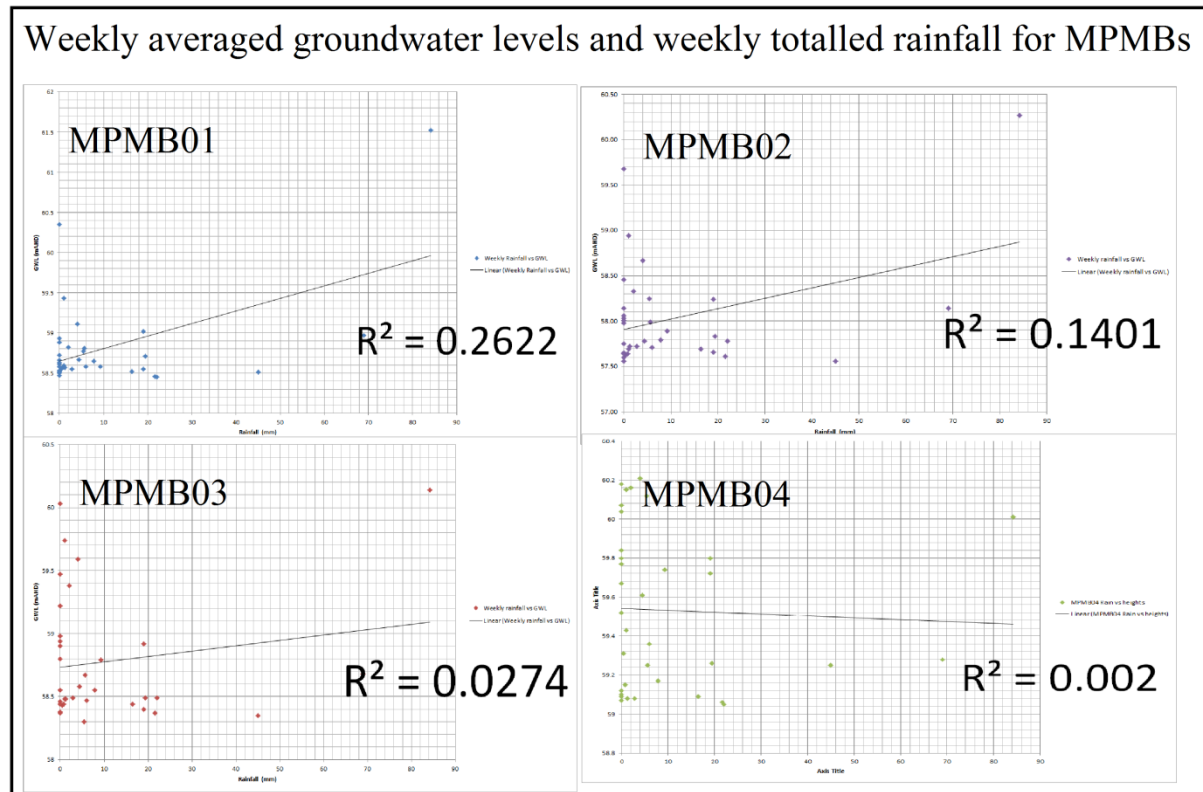


Figure 4.5 – The bivariate plots of weekly MPMB data generated using MS Excel.

Table 4.4 shows the  $R^2$  results from all MPMB bore bivariate plots based on different time intervals. The  $R^2$  values of daily, weekly and monthly time intervals failed to create high enough  $R^2$  values to indicate a strong correlation between the groundwater levels and the rainfall events.

Bore Number	$R^2$ daily averaged groundwater level daily totalled Rainfall	$R^2$ weekly averaged groundwater level weekly totalled rainfall	$R^2$ monthly averaged groundwater level monthly totalled rainfall
MPMB01	0.0381	0.2622	0.0546
MPMB02	0.024	0.1401	0.0354
MPMB03	0.0079	0.0274	0.00009
MPMB04	0.0004	0.002	0.0459

Table 4.4 – Bivariate plot correlation ( $R^2$ ) values

### 4.3.3 Interpretation

The correlation coefficient ( $R^2$ ) values generated were very low for daily, weekly and monthly time intervals. The results from this analysis indicate a weak relationship between groundwater levels and rainfall. A weekly time interval provided the best results, however the  $R^2$  values were still far too insignificant to represent a significant relationship between groundwater levels and rainfall. It is generally accepted that values below 0.70 or 70% are random or have no correlation. Because of this, the results could not be compared or used to characterise the relationship between rainfall and groundwater levels of the alluvium and Hawkesbury Sandstone.

The bivariate plots are considered to be a failure. An in-depth explanation of why the bivariate plots cannot be used to explore the relationships of groundwater levels and rainfall is given in Section 6.1.

## 4.4 Hydrographs

Time series analysis was attempted with JMP software however it ultimately failed to provide any useful results, due to the nature of the raw data; containing vast quantities of '0' for rainfall caused conflict for calculations with JMP software. Multivariate analysis and time series analysis are potentially useful techniques to quantify a correlation of the rainfall and groundwater levels however; it proved to be too laborious and complex for an honours thesis timeframe.

### 4.4.1 Method

Similar to the bivariate plots, the data was totalled and the 6 hourly groundwater data averaged into daily, weekly and monthly intervals to explore trends and relationships on different time scales. This analysis does not produce correlation coefficients; it simply projects the data for visual analysis. JMP statistical software was used to create the hydrographs however, Figure 4.13 was created using MS Excel. The y-axis represents the groundwater levels in the bores and rainfall whilst the x-axis represents time. The y-axis ranges have been adapted to exaggerate the rainfall and groundwater level trends to facilitate

analysis of the potential trends. The y-axis on Figure 4.6 has equal values for groundwater level for all bores, to see the true relationship of groundwater level with time and to prevent the reader from being misled by vertical exaggeration.

#### 4.4.2 Results

The extent of groundwater level responses is misleading due to vertical exaggeration on the y-axis. The range on the y-axis was manipulated in order to highlight the less obvious peaks and dips of the groundwater levels in the deeper zones of the Hawkesbury Sandstone, and careful consideration must be taken when making conclusions from the hydrographs with vertical exaggeration. Figure 4.6 should be used in reference to the hydrographs due to the lack of vertical exaggeration of the movement within all four MPMBs. The resolution is best in the daily time interval hydrographs (Figures 4.6 and 4.7).



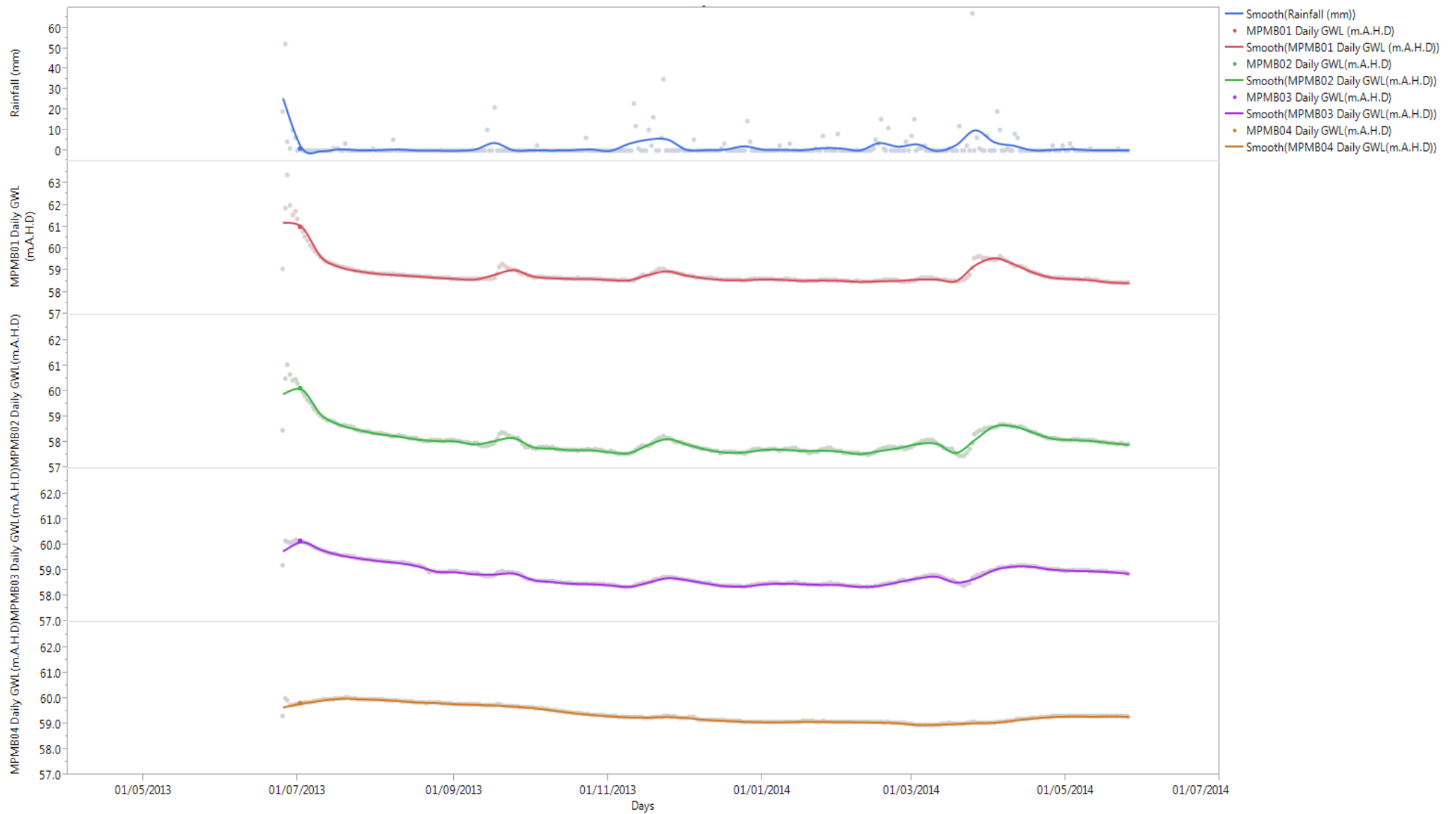


Figure 4.6 - Daily interval hydrographs for MPMBs. No vertical exaggeration.

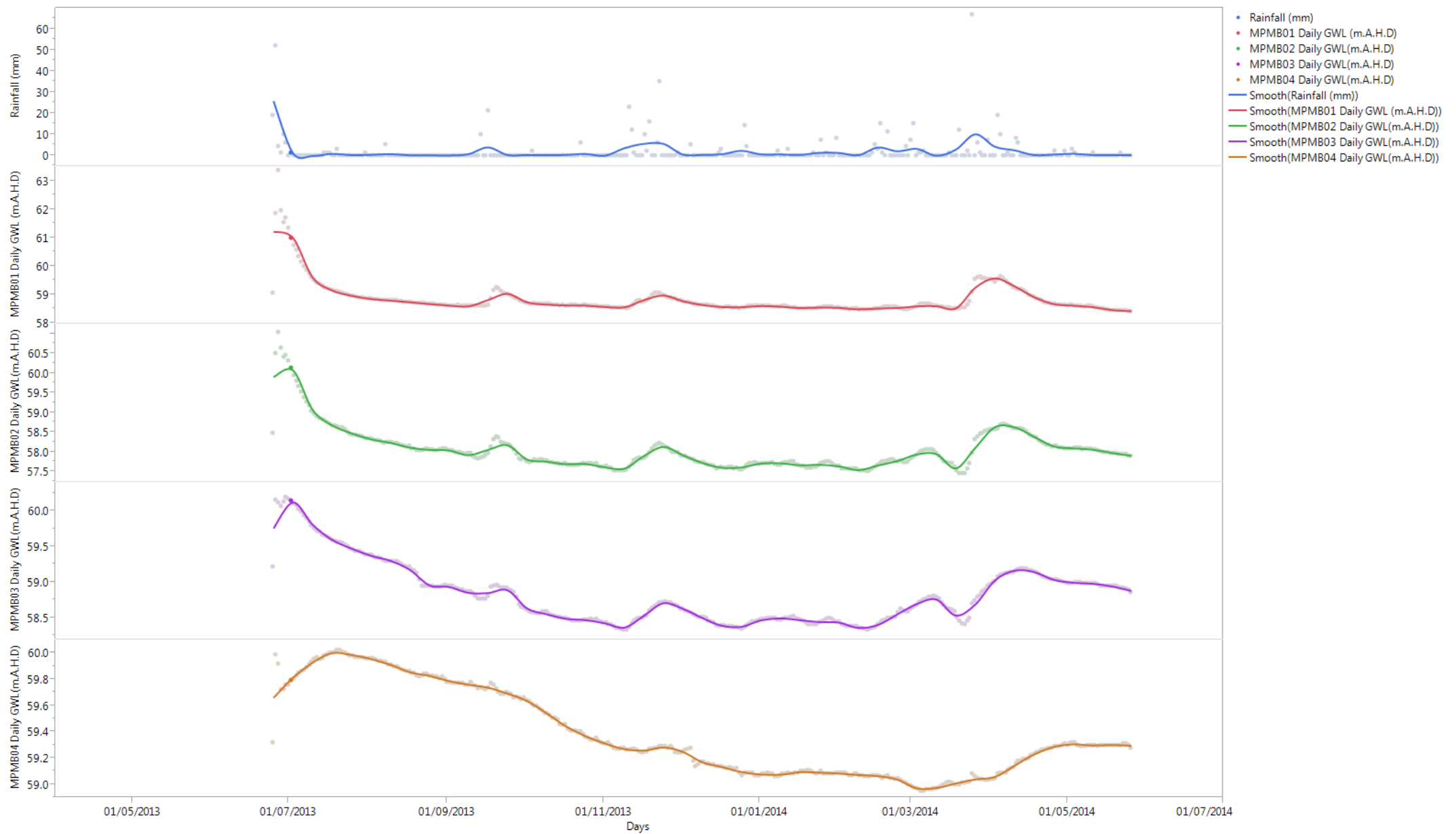


Figure 4.7 – Daily interval hydrographs for MPMBs. Note use of vertical exaggeration.

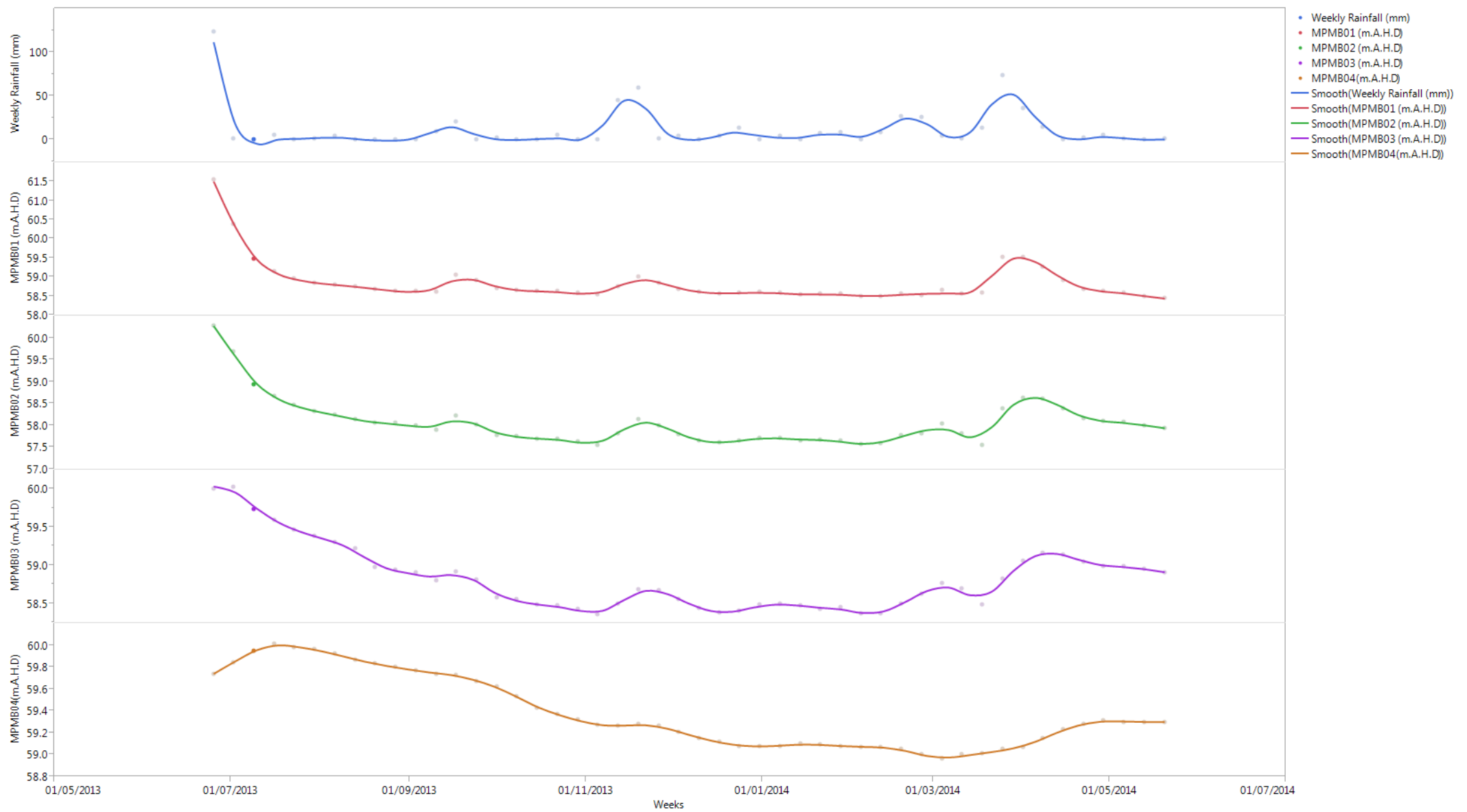


Figure 4.8 - Weekly interval hydrographs for MPMBs. Note use of vertical exaggeration.

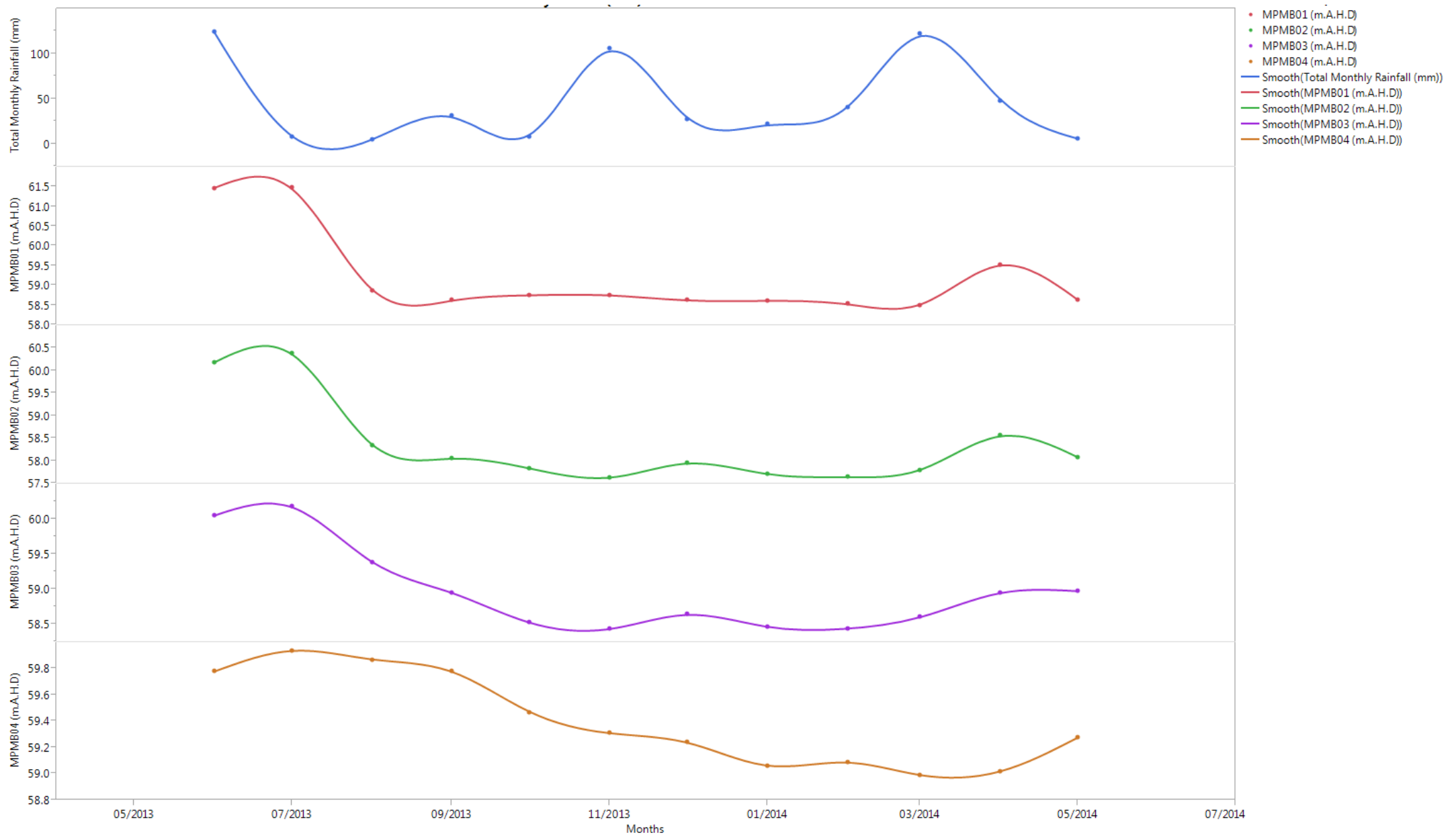


Figure 4.9 - Monthly interval hydrographs for MPMBs. Note use of vertical exaggeration.

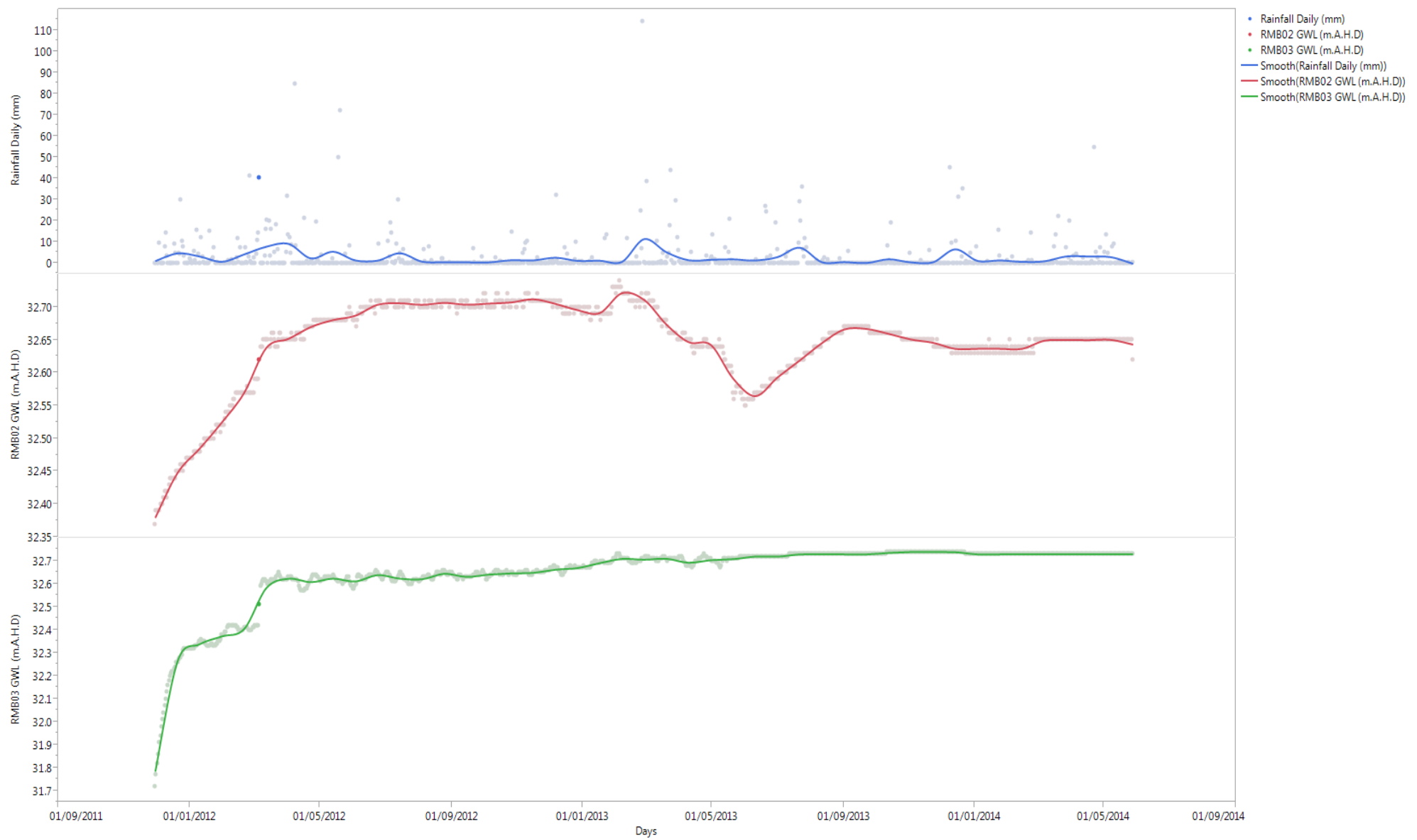


Figure 4.10 - Daily interval hydrographs for RMBs. Note use of vertical exaggeration.

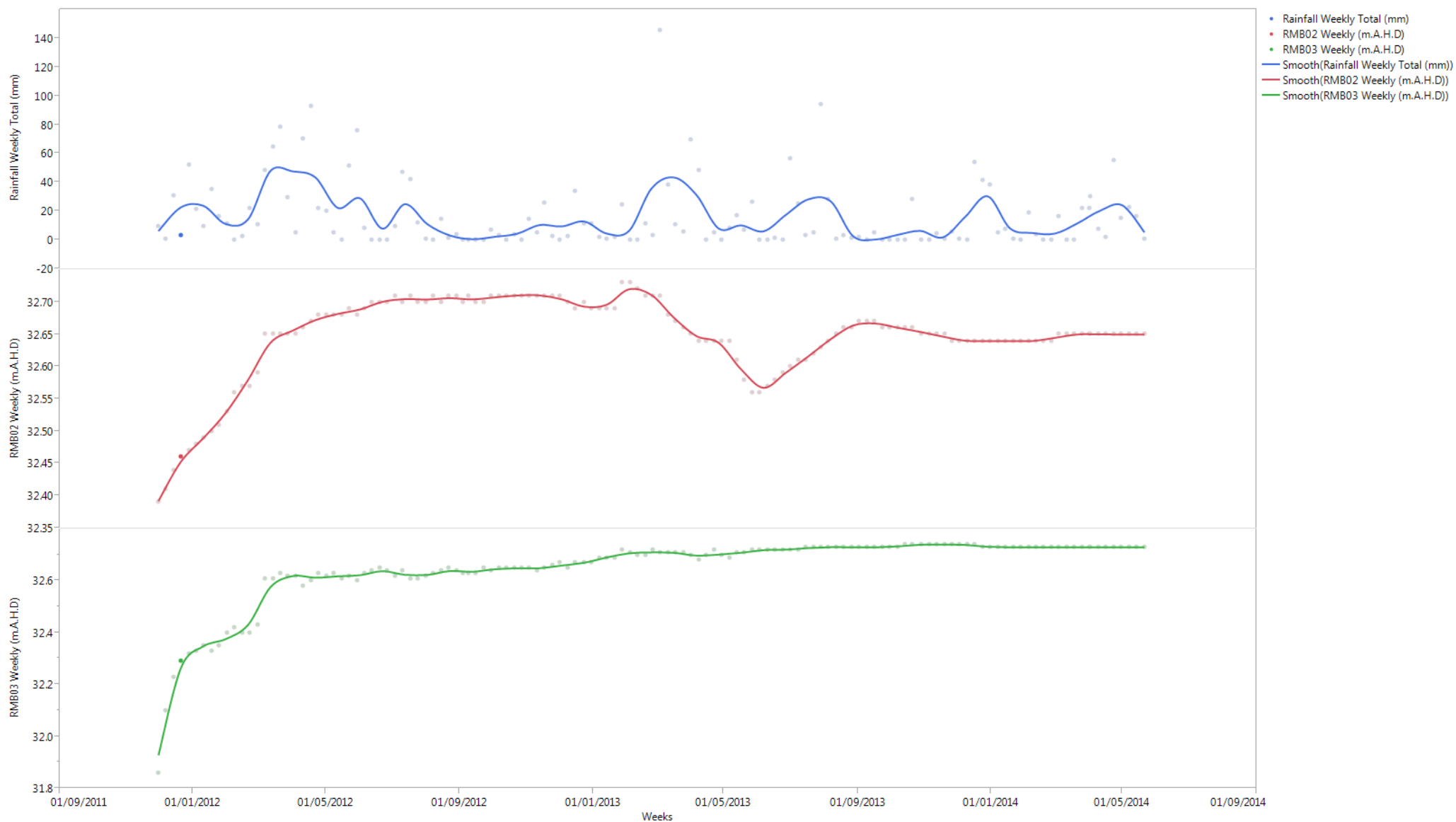


Figure 4.11- Weekly interval hydrographs for MPMBs. Note use of vertical exaggeration.

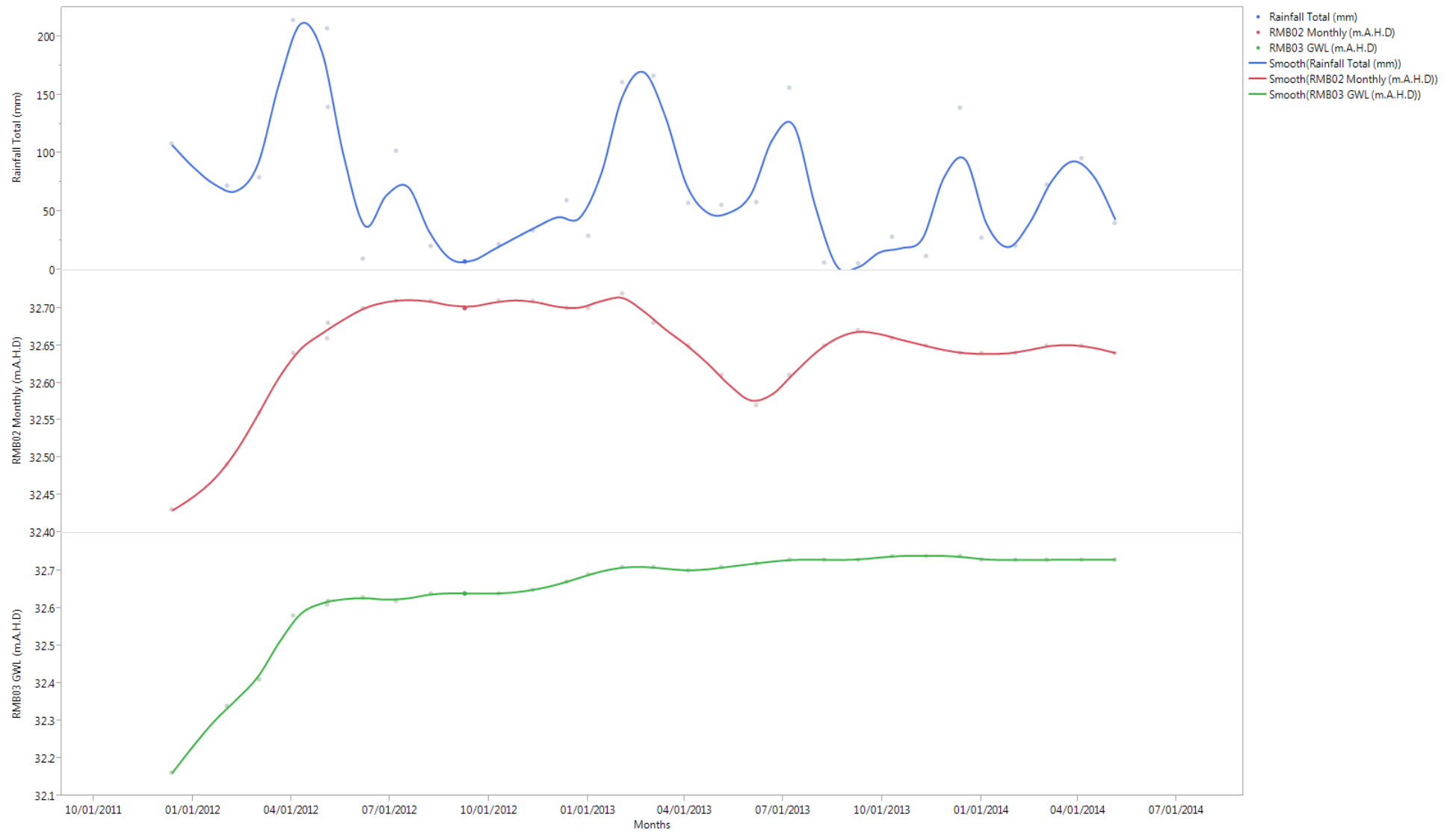


Figure 4.12 - Monthly interval hydrographs for MPMBs. Note use of vertical exaggeration.

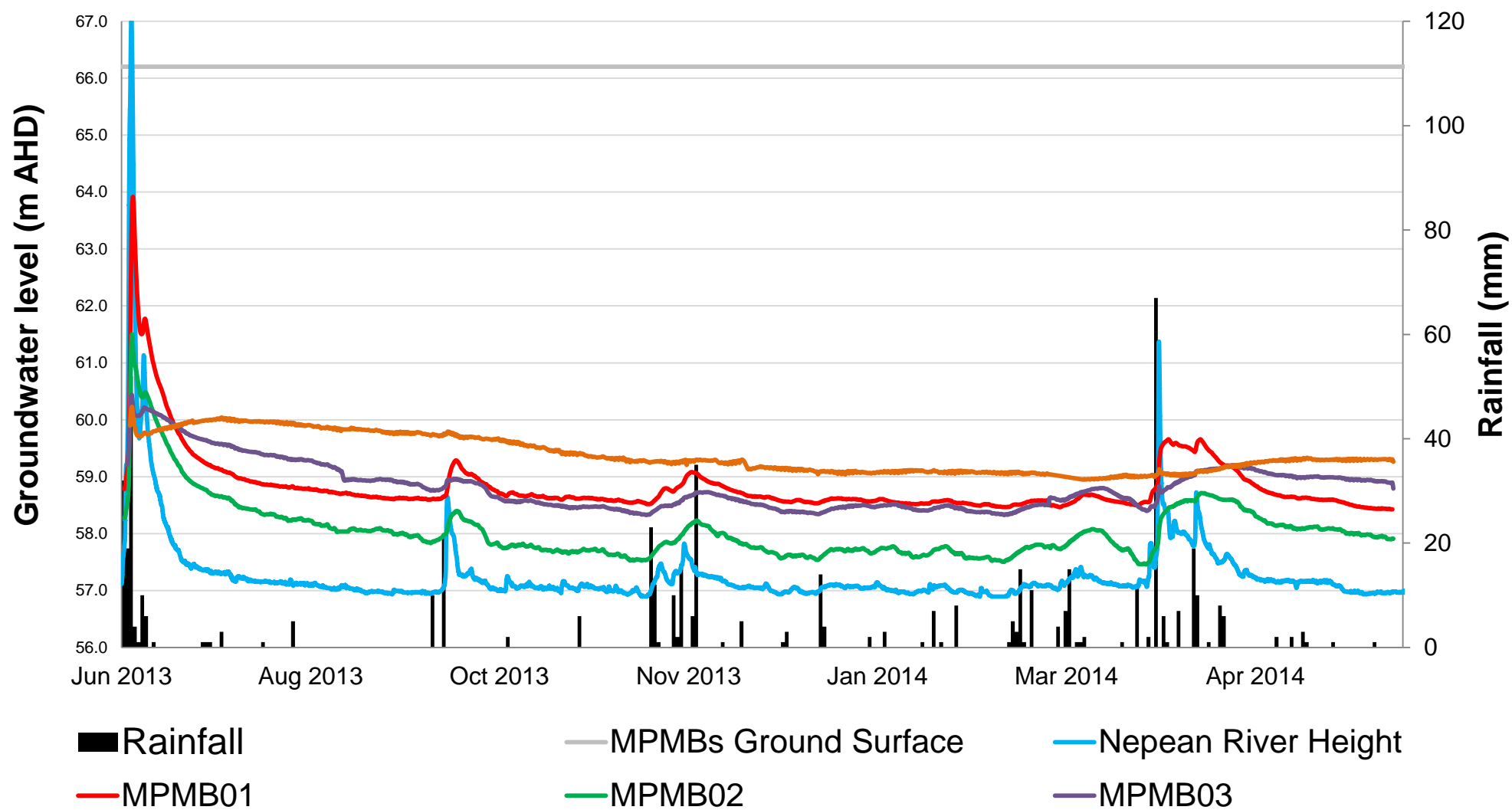


Figure 4.13 – Nepean River height gauge hydrograph with the MPMB groundwater levels.



#### 4.4.3 Hydrograph Interpretation

The hydrographs successfully compare the groundwater levels against the rainfall with time. The main objective of creating monthly and weekly interval hydrographs was to observe overall trends of the relationship between groundwater levels and rainfall with time. Totalling the rainfall into weekly and monthly time intervals has generated a problem for the analysis via the addition of several sporadic rainfall events into a single event. This gives the viewer the impression that there were large rainfall events and therefore should be a corresponding increase in groundwater levels. However, the groundwater level measurements are also averaged into a single value. This results in several infrequent small increases in groundwater levels being unaccounted for and therefore do not correspond with the rainfall trend. To avoid confusion the interpreter must always be aware of this fact before drawing conclusions from the monthly and weekly hydrographs.

Evapotranspiration was calculated in Chapter 3 as a significant factor of the water balance equation, at 312-364GL per annum. Overall only a small portion of the total annual rainfall is likely to move into the groundwater system because 80-95% of the total budget is potentially lost to evapotranspiration. The groundwater levels are not only indicative of infiltration into the groundwater system. It also represents a pressure increase from the increased weight of the ground surface. During the June 2013 and late March 2014 rainfall events the top soils and alluvium became saturated and increased in density. This would simultaneously increase the pressure on the underlying geology and push the groundwater level recordings of the MPMBs upwards. This is important when establishing infiltration trends because this process can be misinterpreted as strong evidence for infiltration into the Hawkesbury Sandstone. The downward trends may also be interpreted as drawdown from CSG extraction; however the upward and downward trends are relatively negligible (see Figure 4.6). Infiltration trends into the groundwater system can be further assessed by the results of the hydrogeochemical analysis which will provide insight into the residence times of the water within the Hawkesbury Sandstone. This will either support or contravene the conclusions made by this analysis.

#### 4.4.4 Groundwater/rainfall relationship

Unlike the bivariate plots in section 4.3 the MPMB hydrographs clearly show a strong correlation between rainfall and groundwater levels in the alluvium and Hawkesbury Sandstone. This cannot be said about the RMBs which do not have the same visual relationship. In all four MPMB hydrographs the groundwater level response mirrors the rainfall events, suggesting a strong relationship. A longer record is available for the RMBs, which should have resulted in reliable and more positive results. However, the effects of periodic sampling events has resulted in more numerous drawdown periods which needed to be interpolated, which reduced the overall validity of the hydrographs because of increased uncertainty.

#### 4.4.5 Local flow regime

The rapid and extensive changes seen in the shallow bores are thought to be associated with an effluent river and evapotranspiration. It has been suggested by Merrick (2009) that the upper Hawkesbury Sandstone flows to natural surface drainages, in this case the Nepean River. The Nepean River is known to be a gaining or 'effluent river', meaning it obtains water from the groundwater system (Merrick 2009; EcoEngineers Pty Ltd 2012). Comparing the groundwater levels of the shallow MPMBs and the Nepean River gauge data can support or contravene this claim.

Figure 4.13 is the rainfall, groundwater level and Nepean River gauge hydrograph of the MPMB study site. All groundwater levels are < 9m.b.g.l during the entire recording period from 2013 to 2014. The Nepean River is positioned below the MPMB groundwater levels at 57 m A.H.D. or 10m.b.g.l during periods of little or no rainfall events. During the June 2013 rainfall event 103 mm of rainfall was recorded at the Menangle Bridge weather station in three days. This event is represented as the initial spike in all values on Figure 4.13. The river height and shallow bores were significantly affected by this event with > 3m of vertical increases in river levels and pressure heads. MPMB03 and MPMB04 show insignificant rises relative to the shallow bores (Figure 4.7) however some effects are noticeable (Figure 4.9).

It is likely that the water at MPMB01 (alluvium and top soil) is a supplier of inflowing water to the Nepean River because it is permeable, responsive to rainfall and its groundwater levels are above the river water level (see Figure 4.13). The upper Hawkesbury Sandstone could also be a potential contributor to the Nepean River if the Nepean River has eroded through the Wianamatta Group unit. It is represented by MPMB02 and its recorded levels show similar trends to the Nepean River and MPMB01. Although the groundwater level in all MPMBs are above the level of the Nepean River the lower and middle Hawkesbury Sandstone zones are not involved in the movement of water into the river system because they are not adjacent to the river.

The groundwater levels in MPMB04 are the highest and suggest an upward hydraulic gradient flow from the lower to middle Hawkesbury Sandstone. The peak heights of MPMB04 are considerably lagged relative to the other MPMBs. If the shale lens within the Hawkesbury Sandstone is regionally or locally extensive (ie confining or semi-confining the lower Hawkesbury Sandstone, resulting in a pressured system) the infiltrating rainwater would not move from the lesser pressurised upper system into the lower pressurised zone, especially considering the low permeability of the shale. This negates the notion that water in the upper Hawkesbury Sandstone may be affected by the removal of water in the lower Hawkesbury Sandstone.

The peak values for MPMB03 occur at the same time interval as the shallower bores, unlike MPMB04 (Figure 4.9). MPMB03 shares a similar drawdown rate as MPMB04 however; the overall extent of change in groundwater level of MPMB03 and MPMB04 is insignificant as compared to the shallow groundwater system. Overall the deeper bores are not as greatly affected by rainfall events which can be seen in Figure 4.6. The higher pressures at MPMB03 and MPMB04 compared to the shallow bores are likely to be attributed to the ~13m thick confining shale lens at 70 to 90mbgl (see Figure 4.16) which confines the groundwaters within the lower Hawkesbury Sandstone.

Two conceptual models were generated to show the hypothesised groundwater flow regime in the top layer of the system. Figure 4.14 is the peak groundwater levels in the June 2013 flood, which are higher than the river at that time. Figure 4.15 shows the groundwater levels seven days after the rainfall event; notice the higher groundwater levels in MPMB01 again supporting the hypothesis of an effluent river system.

It is difficult to confirm if MPMB02 is actually contributing water to the Nepean River. The Wianamatta Shale is considered as a potential confining layer of vertical flow (Figure 4.16), which would restrict flow into the river. However, the shale unit could also have been eroded by the river allowing flow into the river however, this has not been confirmed.

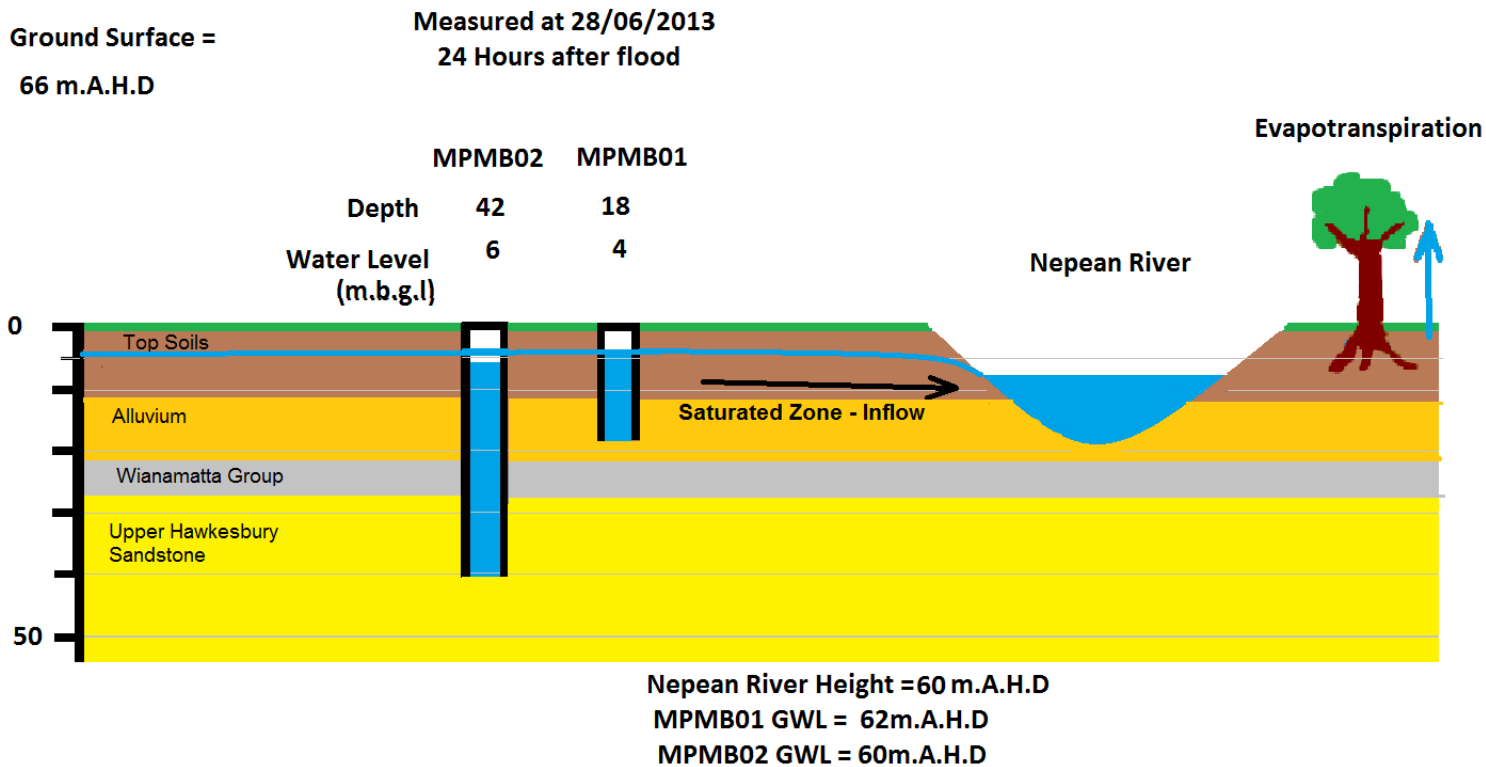


Figure 4.14 – Conceptual model of effluent water movement from alluvium into the Nepean River at the MPMBs. Water levels in the MPMBs projected their peak heights 24 hours after the June 2013 flood.

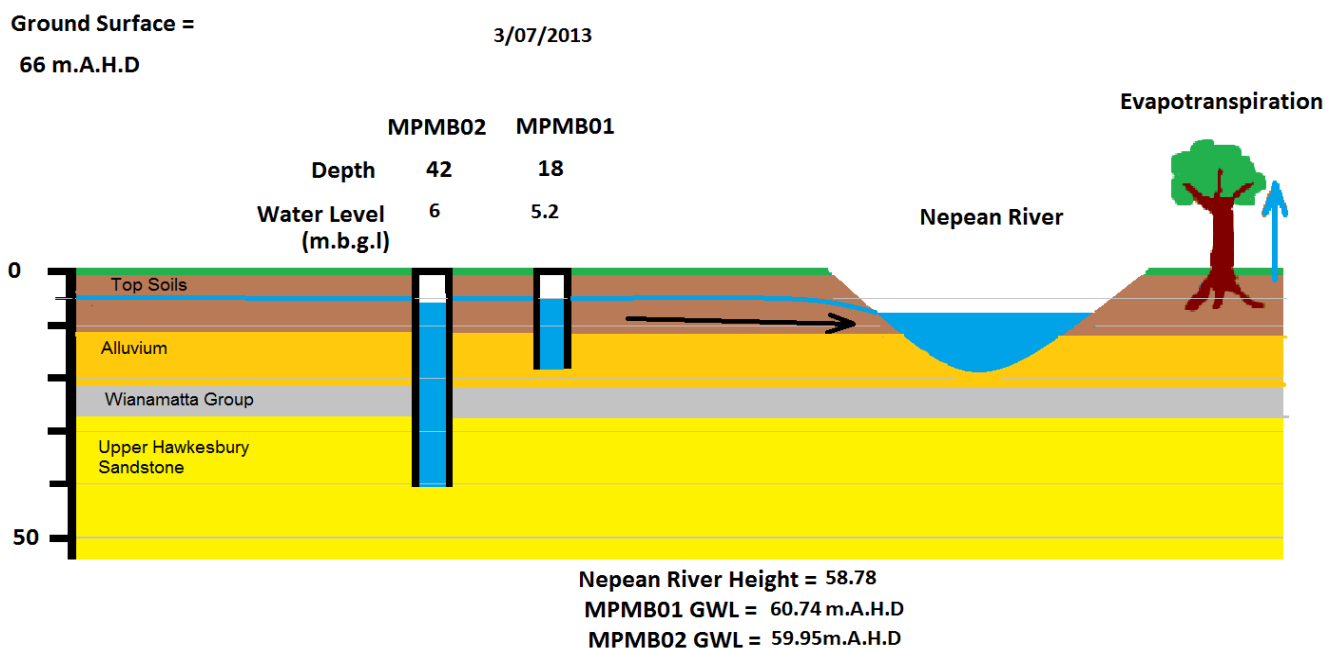


Figure 4.15 - Conceptual model of the groundwater flow regime into the Nepean River based on groundwater and river level data the week after the heavy rainfall event. High river heights are likely to be a result of groundwater inflow.

#### 4.4.6 RMBs and MPMBs

The Denham Court comparison site has a rain gauge and groundwater monitoring record starting in late 2011. With more than twice the length of data for the same regional groundwater system it should provide a useful comparison with the Menangle Park site. However, this is not the case. This is because of two reasons; geological-hydrogeological variance with space and sampling event drawdown

Denham Court may have the same regional geology as Menangle Park, but the specific hydrogeological and geological parameters are not the same at both sites. The most significant difference is the thickness of shale in the Wianamatta Group, which is considerably thinner at Menangle Park. Only ~10 m of shale occurs at the Menangle Park site compared with ~ 80 m at Denham Court (see Figure 4.16). Also, the upper Hawkesbury Sandstone is ~70 m closer to the surface at Menangle Park and has a stronger correlation to the rainfall events, whilst at Denham Court the Hawkesbury Sandstone is ~100m.b.g.l and has almost no visible trends with rainfall events in hydrographs. The Wianamatta Group effectively confines the Hawkesbury Sandstone at Denham Court whereas the upper Hawkesbury at Menangle Park is relatively unconfined with a uniform depth-pressure gradient, seen clearly in Figure 4.1 where all groundwater levels are within ~1m.

The RMBs have been significantly affected from the periodic sampling events. The ‘V’ shaped trend in June 2013 for RMB02 in Figures 4.10, 11 and 12 is the result of correcting the sampling event. Even after making the correction the hydrographs are significantly affected. Unfortunately this problem is unavoidable for the RMBs and is discussed further in Section 6.4.1. RMB03 suffers from the same problem and has had almost all data post-June 2013 affected by straight-line interpolation due to extensive drawdown periods (see Figure 4.10). This increases the uncertainty and error for the comparison. It is likely that the data for RMB03 after June 2013 is entirely invalid and unusable for any statistical analysis such as time series analysis or multivariate analysis. In summary, the RMBs lack validity and reliability to be compared with the MPMBs and suffer from problems that are fundamental and unavoidable.

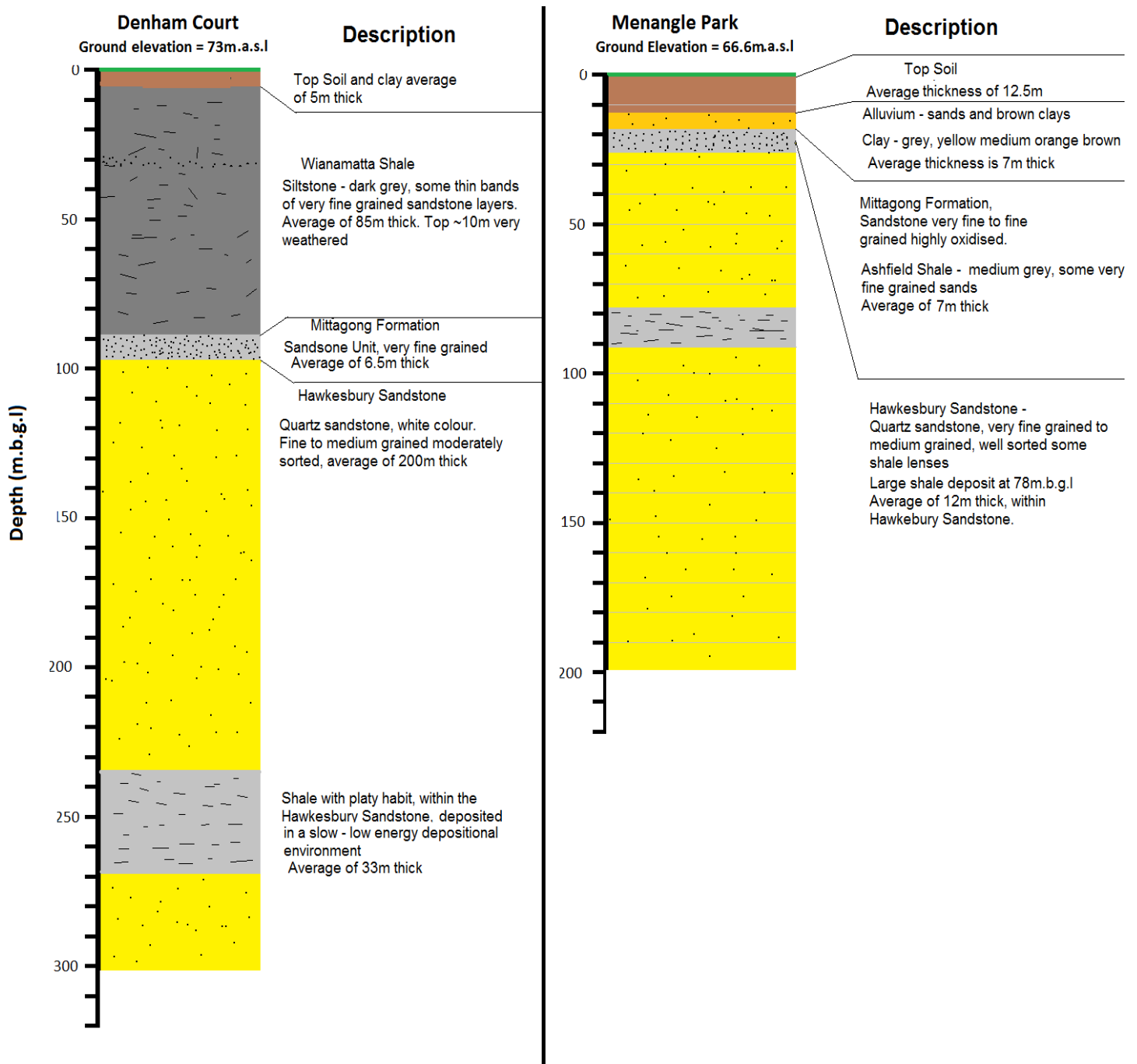


Figure 4.16 Geological logs of study site Menangle Park and comparison site Denham Court. Logs are adapted from (Parsons and Brinckerhoff 2014).

## Chapter 5 Isotopic and Hydrogeochemical Analysis

### 5.1 Introduction

The objective of the hydrogeochemical and isotopic analysis was to investigate the flow characteristics within the Menangle Park groundwater system and develop on the understanding of the groundwater quality and the hydrogeological relationships of rainfall and recharge. The results of the elemental and major ion analysis are primarily focussed towards further understanding of the chemical evolution of water with depth within the Menangle Park groundwater system. The results of the stable isotopes  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  are utilised to assess the recharge origins of groundwater. Radioactive isotope  $^{36}\text{Cl}$  results are predominantly used for subsurface groundwater tracer information, although it can also be used for construction of hydrochronology. Radioactive  $^{14}\text{C}$  is commonly used for groundwater dating and results will be compared against the  $^{36}\text{Cl}$  dates. Stable  $^{13}\text{C}/^{12}\text{C}$  ratios are used to make corrections on the  $^{14}\text{C}$  results with the use of the computer program NETPATH (Plummer et al. 1994) .

It is essential to take a conjunctive approach to analysing hydrogeological/geochemical data as the analysis of one isotope alone or major ion analysis, or hydrograph analysis does not provide sufficient reliability to confirm or otherwise an interpretation or conceptual hydrogeological model. Isotopic data should always be analysed in the light of hydrogeological and hydrochemistry data. The data is best interpreted when a conjunctive approach is applied (Bradd, Turner & Waite 1993).



### 5.1.1 Water sampling

AGL Pty Ltd contracted Parsons and Brinckerhoff Pty Ltd (PB) to take water samples from all four MPMBs and MP17. The quality control protocols followed are those standard for PB. These protocols are outlined in page 20 of (AGL Energy Pty Ltd 2013e). Water samples from the MPMBs and MP17 were collected on the 25<sup>th</sup> of February 2014.

Purpose	Description	Analysis
Radioactive Isotopes Cl <sup>36</sup> and C <sup>14</sup>	- 2 L Plastic bottle	AMS @ ANSTO and ANU
Stable Isotopes C <sup>13</sup> , δ <sup>2</sup> H and δ <sup>18/16</sup> O	-250ml Plastic bottle	AMS @ ANSTO
Anions	-125ml Plastic bottle	IC @ UOW
Elements and Cations	-125ml Plastic - Filtered 2 µm - Acidified in HNO <sub>3</sub>	ICPMS @ UOW

Table 5.1 – Bore water samples received from AGL Energy Pty Ltd

For ICPMS and IC analysis of the Nepean River at Menangle Park, water samples were collected and filtered on the 19<sup>th</sup> of May 2014 by the author. The samples were taken ~1.3km upstream from the MPMB site (see Figure 4.1). Two 1L sampling bottles were used for the fieldwork. The sampling bottles were acid washed with 10% HNO<sub>3</sub> (AR grade) for three days prior to the fieldwork and rinsed with MilliQ water ensure the least amount of contamination. In the field, both bottles were shake rinsed three times in the river water, with special care taken to avoid collecting suspended sediments or intake water that has contacted the outer side of the bottle. Both bottles were filled to the brim to avoid trapping oxygen in the bottle and immediately stored in an esky of ice to prevent algae growth. The samples were transported directly to the UOW's geochemistry laboratories and filtered through a 0.45µm filter. The samples for ICPMS were gravimetrically dissolved with 2% HNO<sub>3</sub> at a ratio 1 in 50 v/v (Suprapur 0.32M) totalling 50 cm<sup>3</sup>. Suprapur has a density of 1.39g/cm<sup>3</sup>, therefore the total sample weight measured > 50grams. Table 5.2 below shows the recorded weights of the acidification of the Nepean River water.

Sample	Sample weight	0.32M HNO <sub>3</sub> weight	Total weight
Nepean River	49.0320g	1.434g	50.422g

Table 5.2 – Nepean River water weight recordings for acidification, needed for ICPMS analysis. Both the river sample and the acid were slightly over the desired weights however, this resulted in negligible effects on the accuracy; it is within the parameters for consistent ionisation in the plasma.

## 5.2 Major Ion and elemental analysis

Major ion and elemental analysis consists of two separate analysis techniques, both conducted at UOW laboratories. Ion chromatography (IC) determined the concentration of the major anions in mg/L. Major cations and trace elements were determined with the inductively coupled plasma mass spectrometer (ICPMS) in mg/L. Carbonate and bicarbonate anions could not be measured at the UOW laboratories in time and therefore these results were obtained from the publicly available groundwater monitoring reports from AGL Pty Ltd (for references see Table 5.5). Piper diagrams were generated using the USGS computer program GW\_Chart (for reference see Figure 5.1), for a visual representation of the major ion chemistry of all water samples (Figure 5.1).

### 5.2.1 Major Cation and elemental analysis method

Samples for ICPMS were filtered through a 2µm filter and acidified in the field to 2% v/v or 1 in 50 with HNO<sub>3</sub>. Samples were quantified by Octopole Reaction Cell-Inductively Coupled Plasma-Mass Spectrometer (ORC-ICP-MS, Agilent 7500ce) utilising standard and collision/reaction gas modes where applicable (see Table 5.3). The analysis commenced on the 22<sup>nd</sup> of May 2014. Analytical standards for ICP-MS analysis were prepared in 0.32 M Suprapur HNO<sub>3</sub> using a multi-element standard (IV-ICPMS-71D, Inorganic Ventures, USA).

### 5.2.2 Major anion analysis method

IC analysis at UOW was utilised for all MPMB samples, MP17 and Nepean River. The specifications of the IC machine are tabulated below in Table 5.3. Water samples from MPMB01, MPMB02, MPMB04 and MP17 were diluted with MilliQ water to a 1 in 4 concentration, because results from the undiluted samples were outside the range of the

calibration curve. A gravitation method was used in order to accurately measure the weights/volume of the sample water and MilliQ water (see Table 5.4). MPMB03 and the Nepean River sample did not require diluting.

Date	30/4/2014
Instrument	Dionex ICS-1100
Eluent	3.5mM Na <sub>2</sub> CO <sub>3</sub> and 1.0mM HCO <sub>3</sub>
Column Temperature	35 <sup>o</sup> C
Detector Temperature	30 <sup>o</sup> C
Total Conductivity	16.2 - 16.5
Suppressor Type	ASRS 300 4mm
Pressure	2254psi
Column Type	Ion pak AS14
Loop Size	25µm
Flow Rate	120ml/min

Table 5.3 – IC specifications

Water sample weights	MilliQ water	Total weight
MPMB01 = 7.5063g	= 22.4966g	30.0029g
MPMB02 = 7.5185g	= 22.5290g	30.0475g
MPMB04 = 7.5532g	= 22.4495g	30.0027g
MP17 = 7.5163g	= 22.4844g	30.0007g

Table 5.4 – Recorded weight values from the dilution

### 5.2.3 Major ion results

Major ion results for all water samples are shown in Table 5.5.

Anions (mg/L)								
	F -	Br -	NO <sub>3</sub> -	PO <sub>4</sub> -	SO <sub>4</sub> -	Cl-	Carbonate as CaCO <sub>3</sub> -	Bicarbonate as CaCO <sub>3</sub> -
Nepean River	0.6	<0.1	0.9	<0.1	4	20	<1 <sup>1</sup>	56 <sup>1</sup>
MPMB01	<0.1	<0.1	<0.1	<0.1	5.827	276.477	<1*	14*
MPMB02	<0.1	<0.1	<0.1	<0.1	7.711	174.339	<1*	165*
MPMB03	<0.1	<0.1	<0.1	<0.1	1.1613	80.68	<1*	455*
MPMB04	<0.1	<0.1	<0.1	<0.1	3.3736	167.813	76*	206*
MP17	<0.1	<0.1	<0.1	<0.1	2.96	450.21	46^	5620^
Cations (mg/L)								
	Na	error	Mg	error	K	error	Ca	error
Nepean River	11	0	2.73	0.06	0.609	0.025	<5	-
MPMB01	111	1	22	0.1	<10	-	9.22	0.22
MPMB02	84	1	27	0.2	<10	-	24	0.9
MPMB03	98	3	20	0.6	16	1.1	63	0.3
MPMB04	181	6	10	0.4	19	1.1	11	0.6
MP17	5383	22	5.22	0.1	35	1.3	<5	-

Table 5.5 MPMB – major Anions analysis results

<sup>1</sup>Bicarbonate and carbonate sample values obtained from AGL Energy Pty Ltd (2013e).

\*Bicarbonate and carbonate sample values were obtained from AGL Energy Pty Ltd (2014a) for the same set of water samples provided for the study in February 2014.

^ MP17 bicarbonate and carbonate values were substituted from MP16 due to the proximity to MP17, and the unavailability of carbonate readings for MP17. The carbonate values are obtained from the report by AGL Energy Pty Ltd (2013e).

Ionic balances were calculated to test the accuracy of the major ion analysis. Results are shown in Table 5.6. Elemental analysis by ICPMS results are shown in Table 5.7.

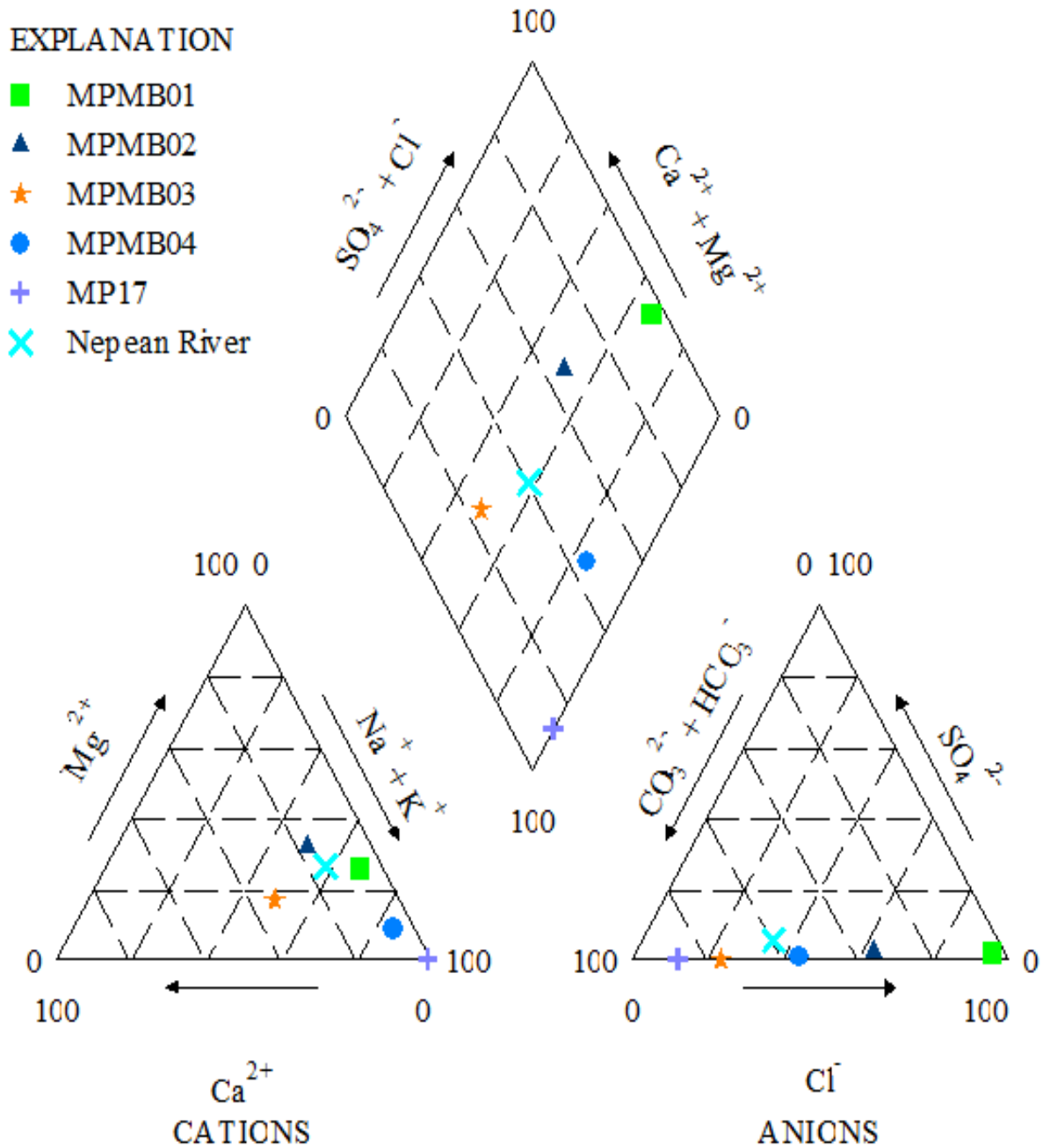
Sample Number	Ionic Balance – ratio of cations to anions
Nepean River	0.46 – very poor
MPMB01	0.93 – fair
MPMB02	0.86 – poor
MPMB03	0.83 - poor
MPMB04	0.93 - fair
MP17	1.87 – very poor

(Above) Table 5.6 – Ionic Balances of the samples

(Below) Table 5.7 Elements and trace elements of the ICPMS analysis.

	Sr (mg/L)		Ba (mg/L)		Mn (mg/L)		Fe (mg/L)	
	Con.	error	Con.	error	Con.	error	Con.	error
Nepean River	0.025	0.001	0.032	0.001	<0.05	-	<0.5	-
MPMB01	0.174	0.009	0.765	0.009	0.542	0.004	<0.5	-
MPMB02	0.369	0.004	0.534	0.011	0.185	0.001	3.948	0.027
MPMB03	0.934	0.018	3.311	0.143	0.067	0.001	0.933	0.018
MPMB04	0.323	0.006	0.979	0.035	0.066	0.001	1.056	0.015
MP17	1.467	0.041	8.710	0.088	<0.05	-	1.765	0.062
	Cr (mg/L)		Be (mg/L)		Al (mg/L)		V (mg/L)	
	Con.	error	Con.	error	Con.	error	Con.	error
NR	<0.005	-	<0.005	-	<0.5	-	<0.01	-
MPMB01	<0.005	-	<0.005	-	<0.5	-	<0.01	-
MPMB02	<0.005	-	<0.005	-	<0.5	-	<0.01	-
MPMB03	<0.005	-	<0.005	-	<0.5	-	<0.01	-
MPMB04	<0.005	-	<0.005	-	<0.5	-	<0.01	-
MP17	<0.005	-	<0.005	-	<0.5	-	<0.01	-
	Co (mg/L)		Cu (mg/L)		Zn (mg/L)		As (mg/L)	
	Con.	error	Con.	error	Con.	error	Con.	error
NR	<0.05	-	<1	-	<0.05	-	<0.1	-
MPMB01	<0.05	-	<1	-	<0.05	-	<0.1	-
MPMB02	<0.05	-	<1	-	<0.05	-	<0.1	-
MPMB03	<0.05	-	<1	-	<0.05	-	<0.1	-
MPMB04	<0.05	-	<1	-	<0.05	-	<0.1	-
MP17	<0.05	-	<1	-	<0.05	-	<0.1	-
	Cd (mg/L)		Pb (mg/L)		Th (mg/L)		U (mg/L)	
	Con.	error	Con.	error	Con.	error	Con.	error
NR	<0.05	-	<0.1	-	<0.001	-	<0.005	-
MPMB01	<0.05	-	<0.1	-	<0.001	-	<0.005	-
MPMB02	<0.05	-	<0.1	-	<0.001	-	<0.005	-
MPMB03	<0.05	-	<0.1	-	<0.001	-	<0.005	-
MPMB04	<0.05	-	<0.1	-	<0.001	-	<0.005	-
MP17	<0.05	-	<0.1	-	<0.001	-	<0.005	-

## MPMB Major Ions Piper Diagram



Graph/Chart created using GW\_Chart (V1.26.0.0) by U.S. Geological Survey  
[http://water.usgs.gov/nrp/gwsoftware/GW\\_Chart/GW\\_Chart.html](http://water.usgs.gov/nrp/gwsoftware/GW_Chart/GW_Chart.html)

Figure 5.1 Piper plots of MPMB water results from the analysis at UOW. \*Carbonate and Bicarbonate values obtained from ALS report in AGL Energy Pty Ltd (2014a) for MPMBs and AGL Energy Pty Ltd (2013e) for MP17 and Nepean River.

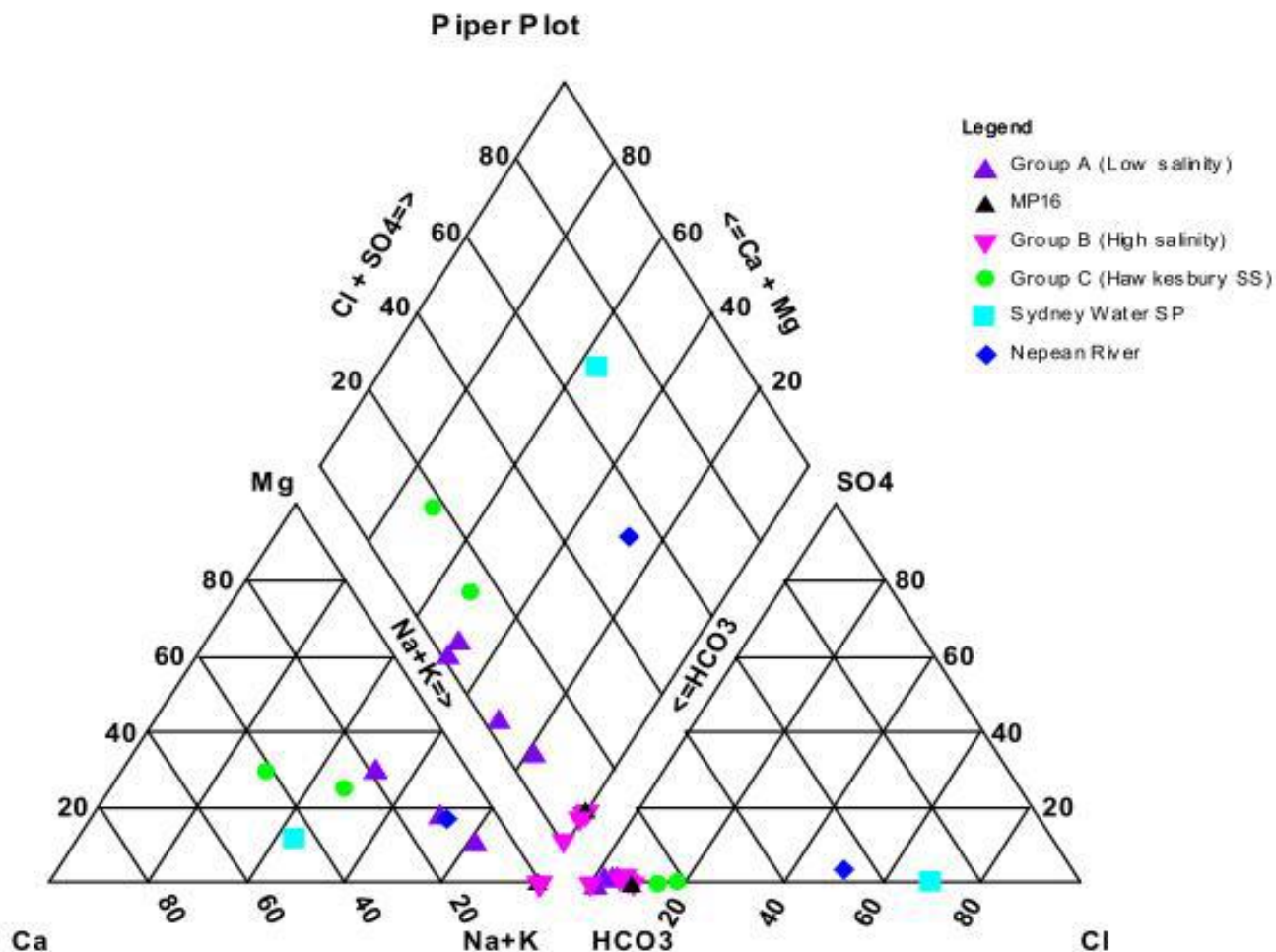


Figure 5.2- A comparative piper plot from taken AGL Energy Pty Ltd (2013e) which focusses towards characterising the produced water from the CSG wells and comparing it to the Nepean River, Hawkesbury Sandstone and Sydney Water (potable water).

Parameter	MPMB01	MPMB02	MPMB03	MPMB04
Field Temp (°C)	21.46	25.70	18.95	19.39
Field pH	5.09	6.37	7.09	9.80
Lab pH	5.86	7.00	7.71	9.18
Methane (µg/L)	<10	20	34,400	24,000
Ethene (µg/L)	<10	<10	<10	<10
Ethane (µg/L)	<10	<10	<10	<10
Propene (µg/L)	<10	<10	<10	<10
Propane (µg/L)	<10	<10	<10	<10
Butene (µg/L)	<10	<10	<10	<10
Butane (µg/L)	<10	<10	<10	<10

Table 5.8 –Results taken in the field and lab for the MPMBs, taken from AGL Energy Pty Ltd (2014a). Temperature results taken in the field, taken from AGL Energy Pty Ltd (2014c).

#### 5.2.4 Interpretation of Major ions and elements

##### *MP17*

It is clear that MP17 has significantly higher and different major ion concentrations compared to the MPMBs and Nepean River (Figure 5.1). The results for MP17 are nearly identical to the Group B high saline coal seam water classification in previous work by AGL Pty Ltd (Figure 5.2). MP17 has the worst ionic balance of 1.87 due to higher concentrations of anions however; this could be due to an inaccurate bicarbonate value. The elemental analysis results (Table 5.7) suggests slightly higher concentrations of Sr and Ba within the coal seam water due to environmental effects.

##### *MPMBs*

The ionic balances of the MPMBs range from 0.83 (poor) to 0.93 (fair) (Table 5.6). The MPMBs have the best ionic balances indicating the most reliable results from the analyses. The MPMB major ion results show a chloride dominated shallow groundwater system. MPMB01 is the shallowest and most chloride dominated. There is a general trend with depth as groundwater evolves from a chloride dominated system into a bicarbonate dominated system (Figure 5.1). However, MPMB03 has a higher bicarbonate value than MPMB04 (Table 5.5). It is hypothesised that irregular values for MPMB03 are due to the confining shale lens within the middle Hawkesbury Sandstone (Figure 4.6). The confining shale lens is suspected to restrict the vertical flow of water and inhibit intersystem mixing creating irregular and non-linear trends with depth.

Table 5.8 shows the field pH readings from previous research by AGL Pty Ltd (2014a). The pH of MPMB04 is unusually high for water within the lower Hawkesbury Sandstone. It is hypothesised that this is due to a gravel/cement groundwater reaction. These types of reactions can also potentially shift the results of  $\delta^2\text{H}$  and  $\delta^{18/16}\text{O}$  isotopes (Section 5.3) (Clark & Fritz 1997). There is also a potential groundwater interaction with carbonate filled fractures of the Hawkesbury Sandstone, which would have a similar effect however, bore logs from the MPMBs show no indication of carbonate vein structures within the lower Hawkesbury Sandstone (Parsons and Brinckerhoff 2014).

Barium concentrations at MPMB03 are measured at 3.3 mg/L. This is consistent with previous tests conducted by AGL Energy Pty Ltd (2014a), with a barium concentration of 3.03 mg/L. The measured concentrations are slightly above the Australian drinking water



standard of 2 mg/L. The daily recommended intake should not exceed 1 mg/L, and barium concentrations in Australian drinking waters are usually between 0.002 mg/L and 1.1 mg/L (NHMRC 2013). In light of this these results are not considered to be excessive, and not a cause for concern as up to 90% of barium can be removed by the process of lime softening (NHMRC 2013). However, the water of the lower Hawkesbury Sandstone (MPMP03 and MPMB04) is not utilised for human consumption.

Table 5.8 shows concentrations of methane and other hydrocarbons in the MPMBs, sourced from a previous groundwater monitoring report by AGL (AGL Energy Pty Ltd 2014c). Determining the origin of the methane as either thermogenic or biogenic is usually achieved from methane isotope discrimination analysis with  $\delta^{13}\text{C}$  and  $\delta^2\text{H}$  however; this analysis was not achieved due to lack of funding. A preliminary origin assessment can be achieved from the methane ( $\text{C}_1$ ) to ethane ( $\text{C}_2$ ) and propane ( $\text{C}_3$ ) ratio (see Table 5.9). Very low ratios ( $< 10$ ) are indicative of thermogenic production and large ratios ( $> 10$ ) are typical of biogenic production (Clark & Fritz 1997). Table 5.9 suggests biogenic methane production within the pores of the sandstone itself. The production of thermogenic methane requires temperatures between  $157^\circ\text{C} - 221^\circ\text{C}$  whereas biogenic methane production requires temperature conditions  $< 50^\circ\text{C}$  (Stolper, Lawson, Davis, Ferreira, Santos Neto, Ellis, Lewan, Martini, Tang, Schoell, Sessions & Eiler 2014). Field temperatures of all MPMBs are shown to be  $< 50^\circ\text{C}$ , supporting the biogenic methane hypothesis.

#### *Nepean River*

Nepean River major ion results are consistent with the results of previous work from AGL Pty Ltd (Figure 5.2) (AGL Energy Pty Ltd 2013e). The relative position of the Nepean River in Figure 5.1 and Figure 5.2 are very similar. However, chloride values were measured at 20mg/L, half the concentration found by AGL Pty Ltd. Water in the Nepean River is sourced from rainfall, runoff and inflow from the shallow aquifers. Lower chloride concentrations could potentially reflect the previous flood event in June 2013. Cation concentrations are relatively low whilst bicarbonate concentration is relatively high. As a result the ionic balance is poor (Table 5.6). Bicarbonate measurements were taken during 2013 from previous research by AGL Pty Ltd (AGL Energy Pty Ltd 2013e). Temporal changes in the Nepean River could be a potential source of error and be a reason why the ionic balance is considered poor.

Bore	Methane ratio = $(C_1) / ((C_2) + (C_3))$
MPMB03	$= 34,400 \mu\text{g/L} / ((<10 \mu\text{g/L}) + (<10 \mu\text{g/L}))$ = >10 Biogenic
MPMB04	$= 24,000 \mu\text{g/L} / ((<10 \mu\text{g/L}) + (<10 \mu\text{g/L}))$ = >10 Biogenic
Typical thermogenic production	$= (C_1) / ((C_2) + (C_3))$ = <10 Thermogenic

Table 5.9- Biogenic methane production is inferred from the methane to ethane and propane ratio (Clark & Fritz 1997; AGL Energy Pty Ltd 2014a).

### 5.3 $\delta^2\text{H}$ and $\delta^{18}\text{O}$ Isotopes

#### 5.3.1 Method

All water samples with the exception of Nepean River samples were analysed for stable isotope concentrations at ANSTO. The samples were analysed using the Picarro Cavity Ring-Down Spectroscopy (CRDS) method. The CRDS method involves measuring the time taken for light to decay or ‘ring –down’ within a closed system containing only the vapourised water sample. For more details the reader is referred to (Picarro 2014). Results of this analysis are plotted on a bivariate plot relative to the Vienna Standard Mean Ocean Water standard (Figure 5.3); this standard is representative of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values in ocean water for isotopes from around the world (Cook & Herczeg 1998). The linear equation of the meteoric water line was added to the plot (Craig 1961);

$$\delta^2\text{H} = 8(\delta^{18}\text{O}) + 10$$

Local Meteoric Water Lines (LMWL) are also added to the plot to add depth to the interpretation. The positions and trends of the results relative to the meteoric water line can indicate information about the source of recharge and whether evaporation has occurred prior to recharge (Craig 1961; Cook & Herczeg 1998).

### 5.3.2 $\delta^2\text{H}$ and $\delta^{18}\text{O}$ isotopic

Results of the  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  analysis are shown in Table 5.10.

		Hydrogen Data		Oxygen Data	
Sample No.	Name	Result $\delta^2\text{H}$ VSMOW (‰)	S.D $\delta^2\text{H}$ VSMOW (‰)	Result $\delta^{18/16}\text{O}$ VSMOW (‰)	S.D. $\delta^{18/16}\text{O}$ VSMOW (‰)
1	MPMB01	-33.2	0.2	-5.76	0.03
1	MPMB01	-33.2	0.1	-5.74	0.01
2	MPMB02	-34.4	0.0	-5.87	0.01
2	MPMB02	-33.7	0.1	-5.90	0.02
3	MPMB03	-34.4	0.1	-6.18	0.02
3	MPMB03	-34.5	0.1	-6.22	0.01
4	MPMB04	-34.2	0.2	-6.11	0.03
4	MPMB04	-34.3	0.2	-6.14	0.02
5	MP17	-54.2	0.2	-8.56	0.04
5	MP17	-54.2	0.1	-8.58	0.03

Table 5.10-  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopic results

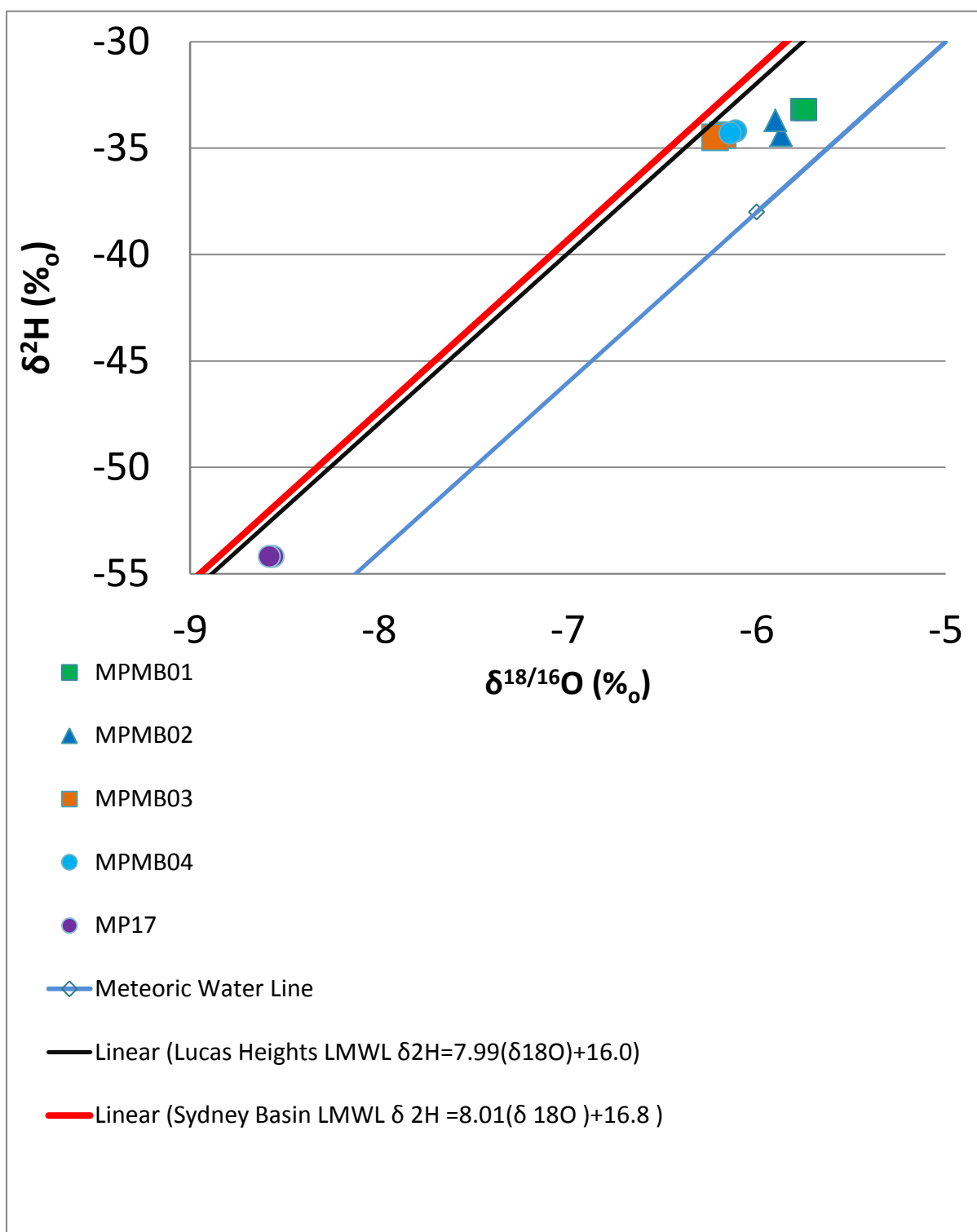


Figure 5.3 MPMB and MP17 isotopic results plotted alongside meteoric water lines. Lucas Heights LMWL and Sydney Basin LMWL are sourced from Hughes and Crawford (2013).

### 5.3.3 Interpretation

The  $\delta^{18}\text{O}$  results range from -5.67‰ to -6.22‰ in the MPMBs while MP17 is more depleted at -8.56‰ to -8.58‰. The  $\delta^2\text{H}$  ranges from -33.2‰ to -33.45‰ in the MPMBs and again MP17 is more depleted at -54.2‰ (see Table 5.10). All samples are positioned above and to the left of the meteoric water line (Figure 5.3) suggesting the absence of processes such as evaporation, mixing with sea water and high temperature rock-water interactions (Kinnon, Golding, Boreham, Baublys & Esterle 2010). A recent study by Hughes and Crawford (2013) established local meteoric water lines for the entire Sydney Basin and for the Lucas Heights, seen in Figure 5.3 as red and black lines respectively. The LMWLs provide a more reliable representation of the rainfall input for this analysis. All results for the MPMBs and MP17 are closely positioned to the right and below the LMWLs which indicates an origin from rainfall with only low amounts of evaporation before recharging into the system.

Results from the MPMBs are clustered and differences between them are negligible (see Figure 5.3). The clustering indicates that water recharged into the groundwater system at similar times for each bore and in the same geographic region. MPMB01 and MPMB02 are closely positioned to the right of the LMWLs indicating relatively small amounts of evaporation before recharging into the groundwater system. MPMB03 and MPMB04 have negligible differences in their  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  results, and their position on Figure 5.3 is indicative of groundwater undergoing slight evaporation before infiltration into the system.

It is clear that the  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  of MP17 is considerably more depleted than the MPMBs. This suggests that the water within the coal seam has a different origin to the water within the Hawkesbury Sandstone. This result was expected because of the vast differences in depth (MP17 is 580 m.B.G.L whereas the MPMBs are between 10-200 m.B.G.L). Between the Hawkesbury Sandstone and Illawarra Coal Measures is ~400 m of Narrabeen Group sandstones and claystone units. The aquitard units within the Narrabeen Group could potentially explain why the values of MP17 and the MPMBs are significantly different, as aquitard units can restrict vertical flow of water. Other hypotheses include that the recharge areas for the coal seam could potentially be further inland, and glacial maximum effects, as colder climates produce water more depleted in  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  (Cook & Herczeg 1998).

## 5.4 $^{14}\text{C}$ and $^{13}\text{C}$ isotopes

### 5.4.1 Method

The results from  $^{14}\text{C}$  analysis present an apparent age measured in years BP or radiocarbon years, which is number of years before the year of 1950 (Stuiver & Polach 1977). All MPMB bore samples were analysed for  $^{13}\text{C}$  and  $^{14}\text{C}$  using the Mass Spectrometry (MS) facilities at ANSTO. For stable isotope  $^{13}\text{C}$  the Elemental Analyser – Isotope Ratio Mass Spectrometer (EA-IRMS) was used.  $^{14}\text{C}$  values of dissolved inorganic carbon (DIC) such as carbon dioxide ( $\text{CO}_2$ ), carbonate ( $\text{CO}_3^{2-}$ ) and bicarbonate ( $\text{HCO}_3^-$ ) were measured using the Accelerator Mass Spectrometer (AMS). The USGS NETPATH software was used for correcting  $^{13}\text{C}$  values. The results are tabulated and graphed to illustrate a potential depth-age trend of the MPMBs (Table 5.11, Figure 5.4).

### 5.4.2 Results

Bore	$\Delta(^{13}\text{C})/(^{12}\text{C})$ ratio per mil(‰)	$^{14}\text{C}$ Per cent Modern Carbon (pMC)	$^{14}\text{C}$ Uncorrected Age years BP	$^{14}\text{C}$ Age Corrected years BP
MPMB01	-19 +/- 0.1	88.70 +/- 0.35	965 +/- 35	<100BP (Modern)
MPMB02	-15.1 +/-0.1	54.16 +/- 0.22	4,925 +/- 35	600BP
MPMB03	-0.8 +/- 0.1	0.40 +/- 0.02	44,250 +/- 490	14500BP
MPMB04	5.3 +/- 0.3	8.89 +/- 0.10	19,440 +/- 90	16000BP
MP17	19.2 +/- 0.3	0.00 +/- 0.1	NDFB*	NDFB*

Table 5.11 -  $^{14}\text{C}$  and  $^{13}\text{C}$  isotope results, \*NDFB = Not Distinguishable from Background.

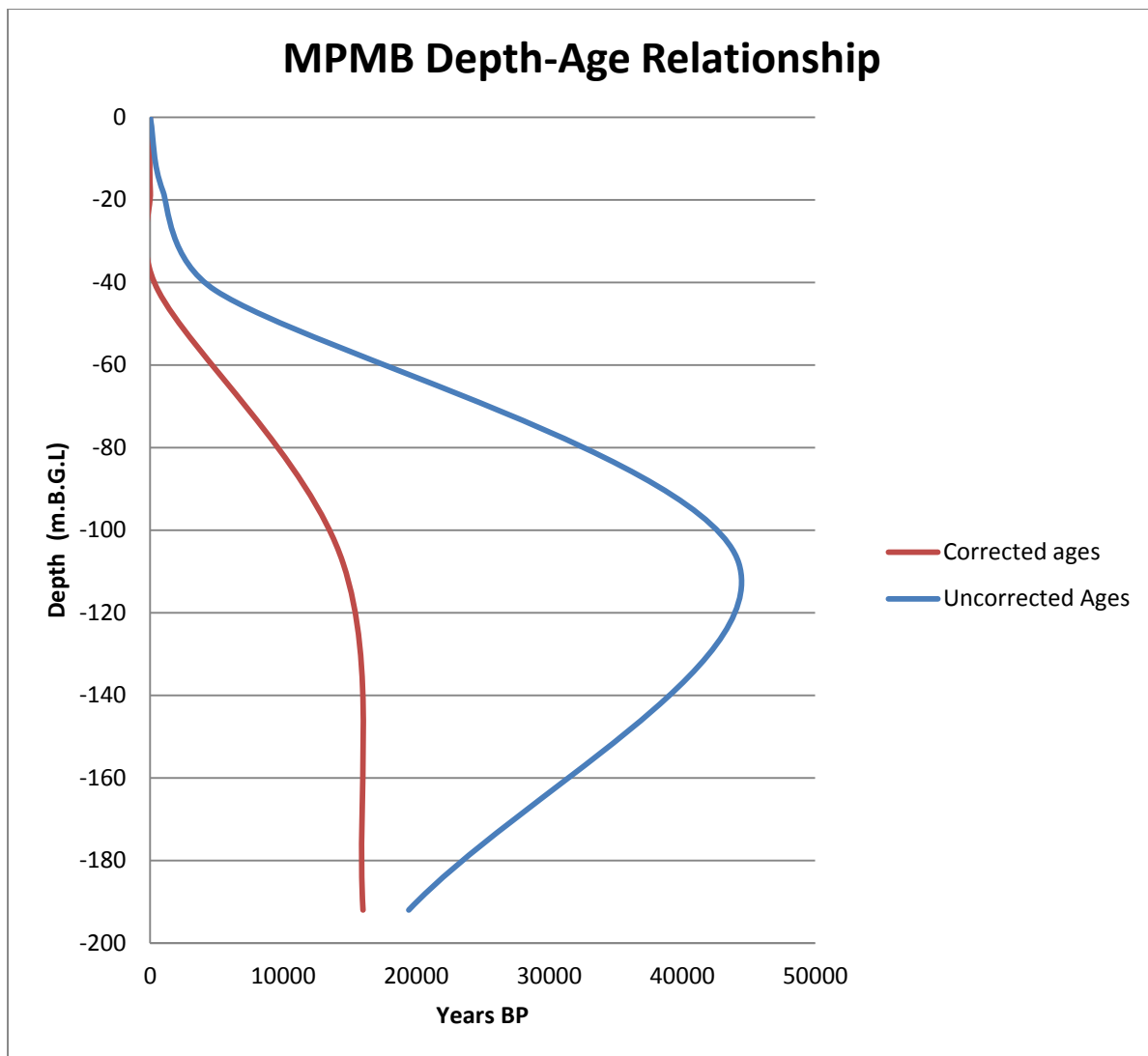


Figure 5.4 –Carbon-14 Depth-age trend of the MPMBs groundwater displaying uncorrected and corrected values (El-Kadi, Plummer & Aggarwal 2011; USGS 2013).

#### 5.4.3 Interpretation

The uncorrected depth-age relationship produced an irregular trend of age decrease with depths greater than 100m.b.g.l (see Table 5.11). However, the corrected ages produced a depth-age relationship that is more usual; with increasing depth is increasing age. The corrected results in Table 5.11 and Figure 5.4 suggest that the oldest mean residence times within the Hawkesbury Sandstone at the Menangle Park area are towards 16,000 years BP. Ages around 20,000 have been produced previously by the Sydney Catchment Authority (SCA) in parts of Western Sydney (Russell et al. 2009). This is consistent with the 16,000 year old result obtained by the author.

The uncorrected age of the water in the alluvium is ~1000BP and NETPATH software suggested a corrected age of <100 BP. Considering the proximity of the groundwater to the ground surface and the Nepean River, and considering the results of the hydrograph analysis, the results are interpreted to show modern water. The  $\delta(^{13}\text{C})/(^{12}\text{C})$  ratio is -19.0‰ which is possibly due to dissolved soil organic matter. Results from MPMB02 are as expected and are therefore not discussed.

Like the major ion analysis and  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopes, there is a reversed trend between MPMB03 and MPMB04. The uncorrected ages of MPMB03 are more than twice as old as the deeper Hawkesbury Sandstone (MPMB04). USGS NETPATH software corrected the results which show a more usual and expected increase in depth-age trend (Figure 5.4).

The water at MPMB03 and MPMB04 contain methane (Figure 4.6). Preliminary assessments with methane to ethane and propane ratios suggest a biogenic origin (see Table 5.9). Methanogenesis (biogenic methane production) results in additional ‘dead’ DIC being produced in groundwater and a characteristic enrichment of dissolved inorganic  $^{13}\text{C}$  (Clark & Fritz 1997). The positively enriched DIC  $\delta(^{13}\text{C}) / (^{12}\text{C})$  ratios and low pMC values in the middle-lower Hawkesbury Sandstone (MPMB03 and MPMB04) and the Bulli Coal Seam (MP17) (see Table 5.11) suggest methanogenesis interference affecting isotope analysis. Methane from this preliminary assessment is likely to be of biogenic origin naturally occurring within the pore spaces of the Hawkesbury Sandstone aquifer (see Table 5.8, 9). Aravena et al (1995) state that methanogenesis in groundwater enriches the DIC  $^{13}\text{C}/^{12}\text{C}$  ratio and lowers the  $^{14}\text{C}$  pMC, resulting in older than expected mean residence times. They then corrected the data with the NETPATH software which resulted in correction of up to -13,000 to -15,000BP. This is consistent with the results and interpretation of  $^{14}\text{C}$  and  $^{13}\text{C}$  isotopes in this study.

MPMB04 has an irregularly high pH which could be explained by the interaction of groundwater with grout/cement near or around the base of the bore or dissolution processes of localised carbonate-filled veins both of which dilute  $^{14}\text{C}$  with dead carbon and hence increase the measured ages. The  $^{13}\text{C}/^{12}\text{C}$  ratio also suggests possible interferences with dating processes by biogenic methane present in the water.

MP17 is a production coal seam bore that is proven to have dissolved methane in the water.



The  $\delta(^{13}\text{C})/(^{12}\text{C})$  ratio for MP17 is enriched to 19.2‰ and has a pMC of 0 due to the presence of methane. The produced water from MP17 is potentially older than 60,600BP, however the  $^{13}\text{C}/^{12}\text{C}$  ratio suggests significant methane interference with dating processes. Therefore,  $^{14}\text{C}$  age determinations for MP17 are inconclusive in terms of a radiometric age. Tritium ( $^3\text{H}$ ) has a relatively brief half-life (12.3 years) compared to  $^{14}\text{C}$  and thus could add confirmation of the age of water at this depth. If tritium was non-existent in the water at this depth it could then be said that the waters are >50 years old (Clark & Fritz 1997).

## 5.5 chlorine-36 ( $^{36}\text{Cl}$ ) isotopic analysis

### 5.5.1 Method

Five one litre water samples (one from all MPMBs and MP17) were taken to the Australian National University (ANU) and analysed for the radioactive isotope  $^{36}\text{Cl}$  by AMS. Preparation for analysis via AMS involves precipitating chloride out of the bore water samples as silver chloride ( $\text{AgCl}$ ) and purifying the sample before analysis (Prych 1998). The calculated number of  $^{36}\text{Cl}$  in atoms per litre is divided by the number of atoms per litre of stable chloride ( $^{35}\text{Cl}$  and  $^{37}\text{Cl}$ ) creating a  $^{36}\text{Cl}/\text{CL}$  ratio which can be used as an estimate of the residence time of the groundwater. Chloride values for water samples used in this calculation are obtained from IC results (Table 5.5).

The age calculation equation for  $^{36}\text{Cl}$  is written below (Torgersen, Habermehl, Phillips, Elmore, Kubik, Jones, Hemmick & Gove 1991);

T = Time

R = Measured  $^{36}\text{Cl}/\text{Cl}$  ratio

$R_0$  = Initial  $^{36}\text{Cl}/\text{Cl}$  ratio

$R_{se}$  = Secular equilibrium  $^{36}\text{Cl}/\text{Cl}$  ratio (hypogene production rate)

$\lambda_{36}$  = Decay constant of  $^{36}\text{Cl}$

$$t = -\frac{1}{\lambda_{36}} \ln \frac{R - R_{se}}{R_0 - R_{se}}$$

The following values were substituted for the age calculation equation:

1)  $R_0$  = Atmospheric production =  $80 \times 10^{-15}$  (Cendon, 2014 pers. comm.)

2)  $R_0$  = Atmospheric production =  $60 \times 10^{-15}$  (Cendon, 2014 pers. comm.)

$R_{se}$  = Deep *In situ* production (sandstone) =  $5.4 \times 10^{-15}$  (atoms/ $\text{m}^3/\text{s}$ ) (Bird et al. 1991)

$\lambda_{36}$  =  $^{36}\text{Cl}$  decay constant =  $2.303 \times 10^{-6}/\text{year}$  (Sturchio, Caffee, Beloso, Heraty, Bohlke, Hatzinger, Jackson, Gu, Heikoop & Dale 2009)

Currently there is an unknown atmospheric production rate of  $^{36}\text{Cl}$  over the Sydney area. It has been suggested that creating a range of production values will ensure a fairer attempt at generating the apparent ages and so two atmospheric production rates have been estimated (Cendon, 2014 pers. comm.).

### 5.5.2 Results

Results from  $^{36}\text{Cl}$  analysis by AMS are shown in Table 5.12.

Well number	$^{36}\text{Cl}/\text{Cl}$ ( $\times 10^{-15}$ )	No. Of $^{36}\text{Cl}$ atoms/L(in $\times 10^6$ )	Cl in mg/L	Error	Apparent $^{36}\text{Cl}$ age(years) Production rate $= 60 \times 10^{-15}$	Apparent $^{36}\text{Cl}$ age(years) Production rate $= 80 \times 10^{-15}$	Difference (years)
MPMB01	39.2	184.1	276.477	2.2	208,000	344,000	~136,000
MPMB02	28.0	82.75	174.339	1.9	383,000	520,000	~137,000
MPMB03	39.9	54.68	80.68	2.3	200,000	335,000	~135,000
MPMB04	31.4	89.5	167.813	1.8	322,000	458,000	~136,000
MP17	19.9	152.11	450.21	1.5	576,000	712,000	~136,000
Coefficient	R				T		

Table 5.12  $^{36}\text{Cl}$  Isotopes results

### 5.5.3 Interpretation

#### $^{36}\text{Cl}$ Ages

The  $^{36}\text{Cl}$  results are most commonly applied as a groundwater tracer. The relative positions of the measured samples on bivariate plots with various parameters can indicate different physical and chemical processes outlined from plots from Bird and Davie et al.(1991). The  $^{36}\text{Cl}$  apparent ages in Table 5.12 are overestimated and not representative of the true mean residence times. The age results range from 200,000 – 520,000 years old for the MPMBs and 570,000 – 712,000 years old for MP17. This result was an expected outcome of the  $^{36}\text{Cl}$  dating analysis. There was little chance of generating reliable  $^{36}\text{Cl}$  ages for the groundwater

within the MPMBs and especially for the coal seam water in MP17. There are several potential reasons why this dating technique has resulted in unreliable age determinations.

The first major issue is the lack of known  $^{36}\text{Cl}$  production rates for the Sydney Region in scientific literature. Generating the input ratios is considered complicated and often proves too difficult resulting in poor reliability of results for age determinations (Lenahan, Kirste et al. 2005). The measured  $^{36}\text{Cl}/\text{Cl}$  ratios indicate that the atmospheric deposition is  $> 40 \times 10^{-15}$ . This is because the atmospheric production could not be below the highest measured ratio, especially in this setting with subsurface sandstones producing low rates of hypogenic  $^{36}\text{Cl}$ . Atmospheric production rates are crucial values for the age calculation and have a significant effect on the result. Table 5.12 shows the effect of different atmospheric  $^{36}\text{Cl}$  production rates on calculated ages, with a higher production rate resulting in an average of ~136,000 years increase in age. The chosen production rates were  $60 \times 10^{-15}$  and  $80 \times 10^{-15}$  as these are regarded to be the best estimates representative of the Sydney Basin. Lenahan et al. (2005) suggests that using an input ratio equal to water from the top 2 m may be the most effective method of producing an age determination for systems where vertical infiltration is dominant. However the shallowest water collected was at a depth of 18m.bgl and is unrepresentative of the precipitation.

The addition of  $^{36}\text{Cl}$  through anthropogenic processes in the Sydney Area is also an issue. ANSTO's nuclear facility at Lucas Heights is a potential source of anthropogenic  $^{36}\text{Cl}$  production from the release of free neutrons in the Sydney Area (Bird, Davie et al. 1991, Phillips 2000). The study site is within 25km of Lucas Heights, and possible effects need to be taken into consideration in a regional production assessment. However, the effects from ANSTO would require centuries to be infiltrated to considerable depths and affect the natural  $^{36}\text{Cl}$  levels.

The in situ production of  $^{36}\text{Cl}$  depends on the length of time that water has been within the unit and the U, K and Th concentrations of that unit (Clark and Fritz 1997). The deep subsurface (hypogenic) and surface production (epigenic) of  $^{36}\text{Cl}$  for sandstones is understood well. However the deep subsurface production of  $^{36}\text{Cl}$  in the Illawarra Coal Measures is poorly understood and has no previous scientific research. The in situ production rate used for the MP17 calculation was the same value used for the deep subsurface sandstone;  $5.4 \times 10^{-15}$  (Bird, Davie et al. 1991). The substituted value is potentially

underestimated and should be considered as unrepresentative of the coal seam until further research concludes on its actual hypogenic production rate.

Another issue is mixing and the removal of water by evapotranspiration in the shallow groundwater system, which results in precipitation mixing with water of different  $^{36}\text{Cl}/\text{Cl}$  ratios (Bird et al. 1991). The age calculation model makes the assumption that the aquifer has not gained any chloride or  $^{36}\text{Cl}$  since its infiltration. A measured ratio of  $^{36}\text{Cl}/\text{Cl}$  is representative of water as  $^{36}\text{Cl}$  decays with time eventually meeting the in situ production rates in equilibrium or nucleogenic levels (Phillips 2000). However, groundwater often gains additional dead chloride and  $^{36}\text{Cl}$  through diffusion and mixing from adjacent aquitards and evapotranspiration (Clark & Fritz 1997). This is applicable to all MPMBs and MP17 because of the thick aquitard shale units present throughout the groundwater system creating segregation of  $^{36}\text{Cl}/\text{Cl}$  ratios and varied chloride intakes. Thus the dating of groundwater via  $^{36}\text{Cl}$  should be reserved for groundwater systems where there are no changes in the chloride or  $^{36}\text{Cl}$  concentrations (Andrews & Fontes 1993).

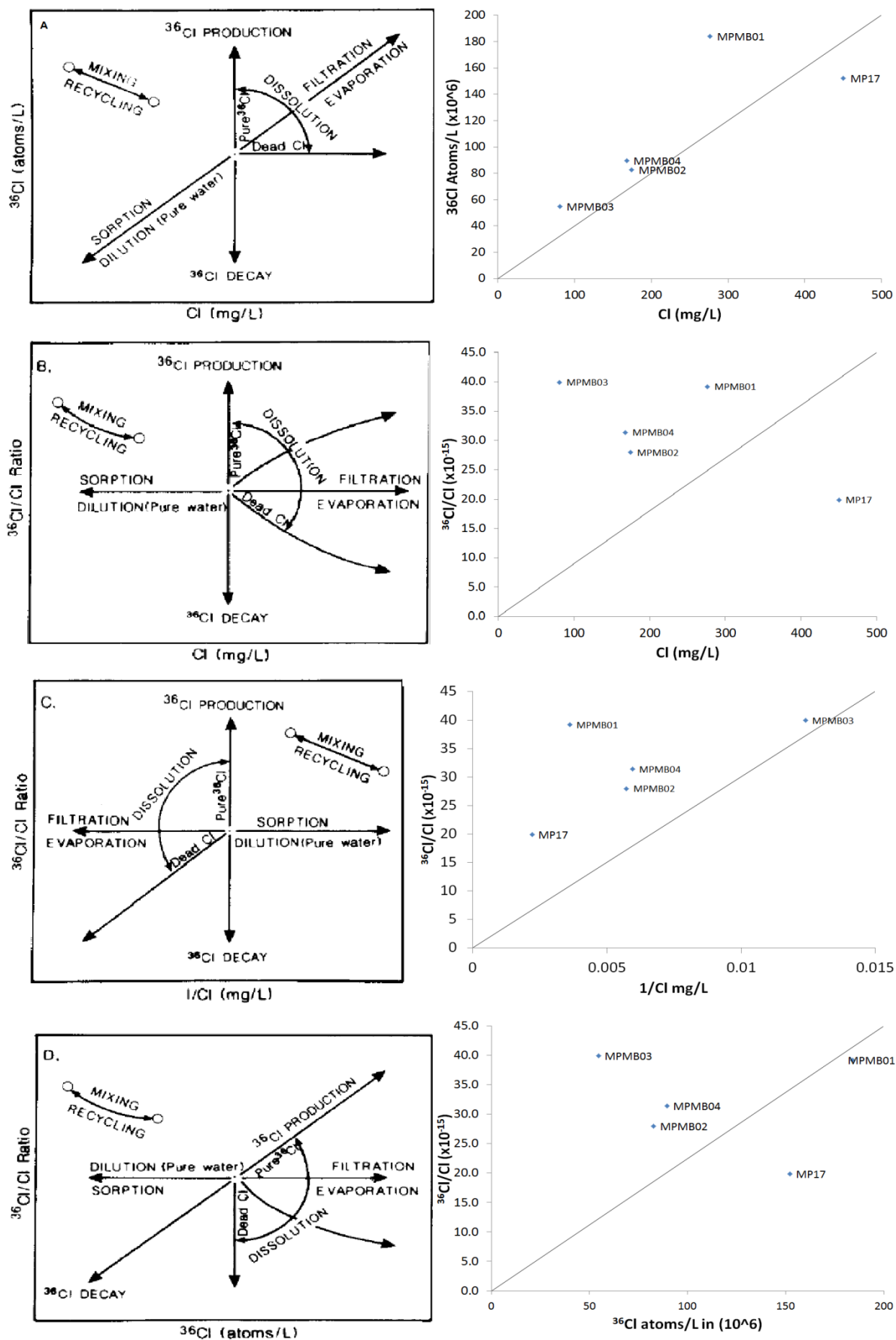


Figure 5.5 –  $^{36}\text{Cl}$  results plotted onto bivariate plots with varied parameters to assess the effect different processes have on concentration. All plots on the left hand side are from Bird and Davie et al. (1991).

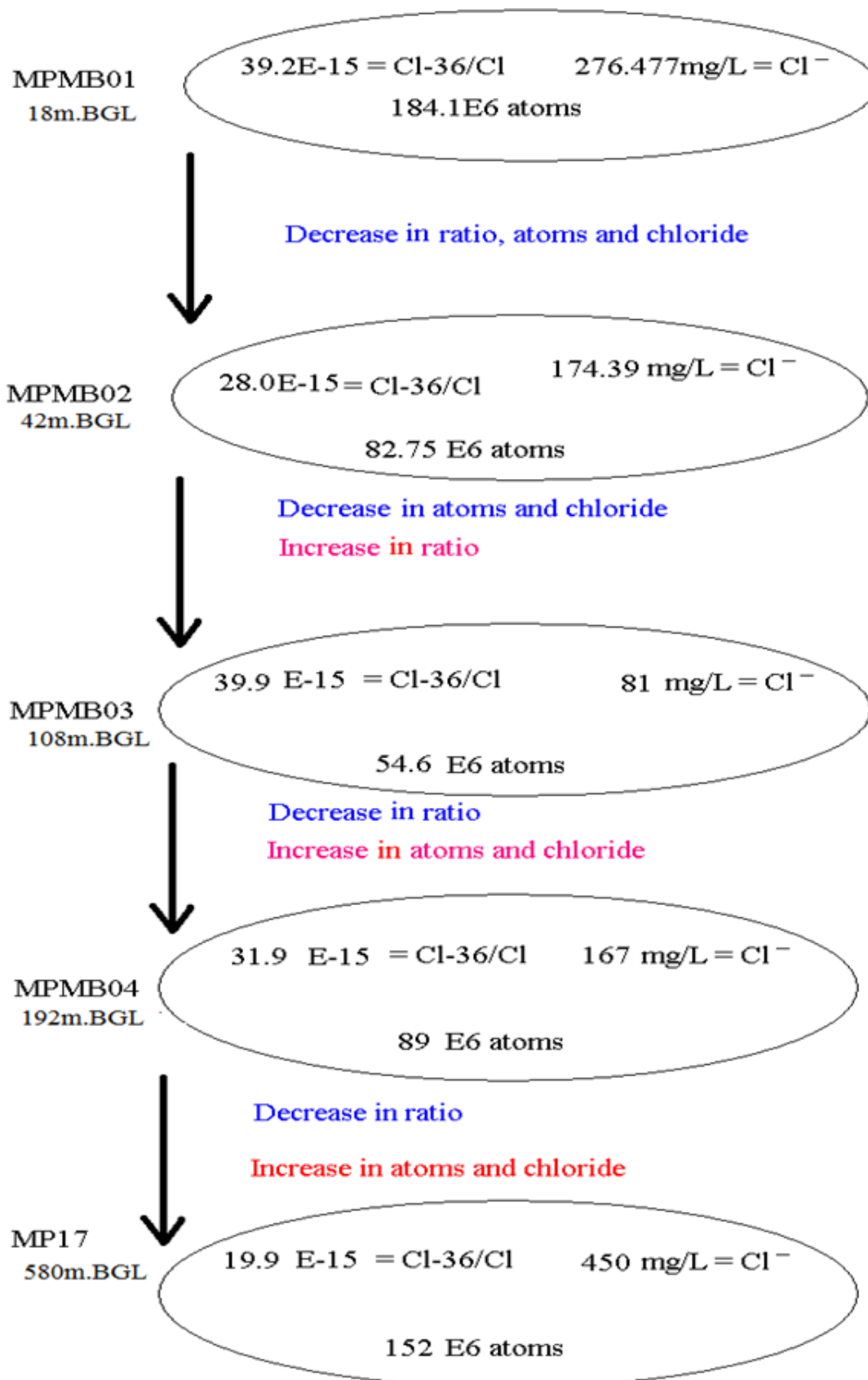


Figure 5.6 – conceptual model of the changes of the  $^{36}\text{Cl}/\text{Cl}$  ratio (in  $\times 10^{-15}$ ), chloride content and number of  $^{36}\text{Cl}$  atoms (in  $\times 10^6$ ) with depth.

## $^{36}\text{Cl}$ as a Tracer

For a hydrological cycle containing ‘young’ waters with moderate salinity values like the Sydney Basin  $^{36}\text{Cl}$  analyses are likely to be utilised more effectively as a tracing technique due to the long half-life (301,000 years). Figure 5.6 are the bivariate plots of the various parameters and potential processes involved with  $^{36}\text{Cl}$  tracer analysis. These plots may have some contradictions and may be subjective to the viewer however there are some clear trends visible.

The MPMBs do not display an obvious depth trend with  $^{36}\text{Cl}$  concentrations, chloride concentrations or  $^{36}\text{Cl}$  ratios: in fact there are several changes with chloride, number of  $^{36}\text{Cl}$  atoms and  $^{36}\text{Cl}/\text{Cl}^-$  ratios with depth (see Figure 5.5). MPMB01 is a chloride dominate zone in the groundwater system and has a high  $^{36}\text{Cl}$  ratio and  $^{36}\text{Cl}$  concentration values. Plots A, B, C and D of Figure 5.5 position MPMB01 in a  $^{36}\text{Cl}$  production mechanism. The shallow zone is high in  $^{36}\text{Cl}$  as expected because of close proximity to surface production and infiltrating atmospheric deposition of  $^{36}\text{Cl}$

MPMB02, MPMB03 and MPMB04 are clustered in plots A, B and D in Figure 5.5. Their relative locations in plots B and D indicate mixing and recycling processes. MPMB03 shows a major decrease in the chloride and  $^{36}\text{Cl}$  atom concentrations, indicative of mixing and recycling processes according to Figure 5.5 B and D. The water at MPMB03 are naturally less concentrated in chloride resulting in an increase in the  $^{36}\text{Cl}/\text{Cl}^-$  ratio (see Figure 5.6). However, MPMB03 has the lowest concentration in  $^{36}\text{Cl}$  atoms. Without a conceptual model of a lateral flow mechanism is it difficult to explain these low chloride values. It is likely that the flow mechanism of the local groundwater system has a major impact on the dispersal of chloride. It is difficult to generate an understanding of the groundwater flow mechanism without extensive bores spread throughout the area, detailing the flow mechanism and providing evidence on chloride dispersal

MP17 is considered to be an outlier in all of the plots of Figure 5.6, and is placed within the evaporation process field. MP17 is ~580 m.bgl and is high in chloride but has a low  $^{36}\text{Cl}/\text{Cl}$  ratio. MP17 has the second highest concentration of  $^{36}\text{Cl}$  atoms but the lowest  $^{36}\text{Cl}/\text{Cl}$  ratio in the measured values (see Table 5.12). The hypogenic production of  $^{36}\text{Cl}$  in the coal seam could potentially increase the reason for the high number of  $^{36}\text{Cl}$  atoms. This would suggest that the water reaches equilibrium and therefore is slow moving and very old. However, as the deep subsurface production rates in the Illawarra Coal Measures is unknown at this stage. To establish this production rates the U, Th and K concentration of the coal would have to be measured and quantified. It is likely that the  $^{36}\text{Cl}/\text{Cl}$  ratio in the coal seam is representative of initial atmospheric production and journey through the overlying low in situ producing sandstone units of the Narrabeen Group and Hawkesbury Sandstone. However, interconnectivity is limited between the Bulli Coal Seam due to the several aquitard shale and claystone units. It is unclear from this  $^{36}\text{Cl}$  data as to where the water travelled from and how long it has been there. The scope for future research is to account for the  $^{36}\text{Cl}$  values throughout the entire Narrabeen Group to strengthen the data, and to investigate the coal seam in situ production rates.



## 1. Chapter 6 – Discussion and Conclusion

The goal of this project is to investigate two major aspects;

1) To analyse the water level and water quality trends collected from the Menangle Park monitoring bores to assess hydrogeological attributes/relationships between the monitored groundwater zones and to interpret any recharge/drawdown trends.

2) To provide a local hydrogeological assessment and an independent assessment of the likelihood for impact on the shallow groundwater resources as a result of the existing coal seam gas activities within the southern Sydney Basin.

### 6.1 Water level and water quality trends of the Menangle Park monitoring bores.

#### 6.1.1 MPMB and RMB comparison in recharge/drawdown trends

The pressure head measurements from the MPMBs and RMBs were compared and showed little or no similarity in groundwater trends within the Hawkesbury Sandstone. These dissimilar groundwater level trends are due to thicker confining units and increased drawdown impact from sampling events at Denham Court resulting in groundwater levels that are unrepresentative of natural trends. After the removal of sampling events and interpolation of new points the validity decreased and uncertainty increased. More research needs to be conducted into the interpolation of groundwater levels whilst giving consideration to lagged rainfall correlation concept. In summary, the variance in geological-hydrogeological properties with space is unavoidable and requires large estimations and generalisations in order to be used for a comparison.

### 6.1.2 Menangle Park groundwater levels

It is the opinion of the author that the upper Hawkesbury Sandstone bores (MPMB01 and MPMB02) should be considered as a separate ‘upper’ level to the ‘lower’ level Hawkesbury Sandstone (MPMB03 and MPMP04) due to a 12 m thick impermeable shale aquitard layer. The shale layer is potentially a regionally extensive continuous shale layer that reaches as far as Denham Court and confines the lower Hawkesbury Sandstone (see Figure 6.1). The hydrograph analysis provided the strongest supporting evidence for the two levels. MPMB04 water levels were consistently above the baseline levels for all other bores at Menangle Park. Furthermore the changes to pressure due to rainfall events in MPMB03 and MPMP04 were insignificant relative to the shallow groundwater, thus indicating hydrogeological separation from confining layers. However, the true extent of the shale layer is not fully understood.

Bore	Depth (m.BGL)	Infiltration/Recharge Type	Corrected Age (BP)	Infiltration rates (m/day)
MPMB01	18	Vertical	~31 days*	0.5625
MPMB02	42	Vertical	600BP	0.0001
MPMB03	108	Lateral	14500BP	-
MPMB04	192	Lateral	16000BP	-

Table 6.1 – Infiltration rates with depth inferred by the corrected  $^{14}\text{C}$  results.

\*estimated residence time taken from the interpretation of the hydrographs.

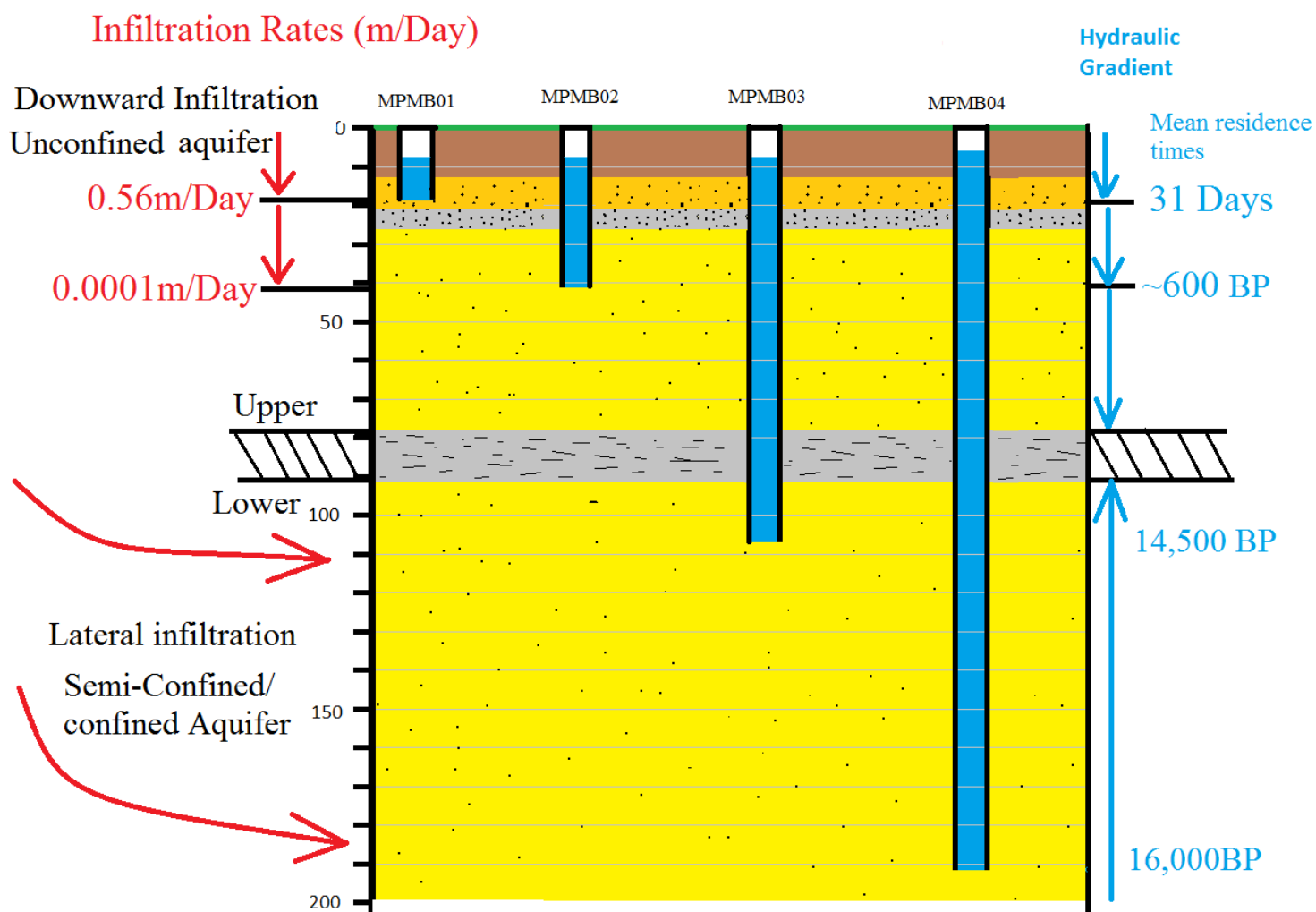


Figure 6.1 – Conceptual model of infiltration rates inferred from the  $^{14}\text{C}$  corrected. No vertical infiltration into the confined zone of the Hawkesbury Sandstone due to the Shale layer.

### *Upper level –MPMB01 and MPMB02*

The corrected  $^{14}\text{C}$  can be used to make a simplified infiltration model for the upper groundwater system because of a downward hydraulic gradient at that zone (i.e. infiltration). Figure 6.1 and Table 6.1 displays the changes in infiltration rates based on the distance (bore depth) over time using the corrected  $^{14}\text{C}$  values. A value of 31 days was chosen for the residence time of MPMB01 because within the alluvium water infiltrates relatively fast, indicated from the hydrographs analysis. The average vertical flow rate for the upper Hawkesbury Sandstone is calculated to be 0.05m/day (see Table 2.3 of). The infiltration rate at MPMB02 is significantly slower (0.0001m/day). The occurrence of the Wianamatta Group unit is inferred to be the reason for decreasing infiltration rates. The Hawkesbury Sandstone is anisotropic and this model does not take into consideration the lateral flow in the upper level flow downward infiltration is potentially a stronger contribution to recharge (Reynolds 1976).

The Nepean River is suggested to be an effluent river by Merrick (2009) and EcoEngineers (2012). The shallow groundwater bores, mainly the alluvium aquifer, at Menangle Park indicate an effluent relationship with the Nepean River. The groundwater levels were consistently above than the Nepean River after rainfall events. In addition, the Nepean River heights maintained a relatively high stage several days after a rain event. The contribution made by the upper Hawkesbury Sandstone (MPMB02) at Menangle Park is plausible, however the extent is unknown. The  $^{14}\text{C}$  NETPATH corrections produced reliable residence times and suggest that the carbon within the alluvium aquifer water was modern. This suggests that the water within the alluvium has a small residence time and further evidence in support of a fast flowing effluent river relationship. Tritium ( $^3\text{H}$ ) has a short half-life (12.3 years) and could test this hypothesis.

The  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  stable isotopes results indicate that the water in the alluvium (MPMB01) undergoes evaporation before infiltrating into the groundwater system. The results plotted on Figure 5.3 were also positioned in a small cluster with the other MPMBs indicating a similar process. All MPMB results were in a significantly different position to MP17, indicating dissimilar recharge origin.

### *Lower level – MPMB03 and MPMP04*

The lower level does display a relationship with rainfall especially with regards to the initial flood event on an exaggerated y-axis. However, the hydrograph levels are not indicative of infiltration. The hydrographs are representative of the saturation of the soils and ground surfaces and their corresponding weight onto the underlying geology, leading to an increase of the pressure heads. The pressure heads of MPM01 and MPM02 fluctuate more rapidly and extensively and are likely to be a mechanism of effluent river flow. However, the movement of the ‘lower level’ is relatively slow and has less extensive changes. This suggests a separate zone within the groundwater system due to the shale layer.

The  $^{14}\text{C}$  dating results show significant difference in residence time. The corrected  $^{14}\text{C}$  dating results suggest that the ‘lower’ level has a longer residence times. Under the shale lens is  $^{14}\text{C}$  ages of 14,500BP – 16,000BP whereas in the above ‘upper’ zone values are between modern – 600BP. The infiltration into the ‘lower’ level groundwater system is more likely to come from lateral flow of water rather than vertical. The groundwater pressure in the ‘lower’ zone is greater than the ‘upper’ so it is unlikely that if there was interconnectivity that the water would flow downwards. Also, the Hawkesbury Sandstone is known to be a anisotropic groundwater system (Reynolds 1976). Lateral hydraulic conductivity is considered a significant factor for groundwater flow in the ‘lower’ level and is thought to be the mechanism for recharge into this zone. It is impossible to generate an infiltration rate without knowing the lateral distance of the recharge path. The vertical distances are known; however any attempt at generating a recharge rate would only account for the vertical distance and not be representative of the true rate. The lateral extent of the shale lens is unknown however; the stratigraphy at Denham Court displays the same shale lens (33 m thick, see Figure 4.16) within the Hawkesbury Sandstone, indicating a potential sub-regional extent of the shale.

#### 6.1.3 Menangle park groundwater quality

The surface waters in the Nepean River have the lowest concentrations of major ions and elements of all samples measured. The results are consistent with previous measurements by AGL Energy Pty Ltd and are a water quality reflective of a freshwater inland river. The groundwater quality at Menangle Park varies with depth. Table 6.2 summarises the different groundwater quality trends and compares it to the coal seam water.

Groundwater quality trends summary		
Upper level water (above shale layer)	Lower level water (below shale layer)	Coal seam water
Chloride decreases with depth	Chloride increases with depth	Highest chloride concentration
Sodium decreases with depth	Sodium increases with depth	Extremely high in sodium
pH range = 5.09 – 7.00	pH range = 7.09 – 9.80	pH = 8.05
Bicarbonate increases with depth	Bicarbonate decreases with depth	Extremely high in bicarbonate
Relatively higher in chloride and Sodium than lower level	Relatively higher in bicarbonate than upper level	Relatively higher in all things than upper and lower level
Relatively young water	Relatively old water	Ages undetermined
iron concentration max ~4mg/L	Iron concentration >1.1 mg/L	Iron concentration >1.8 mg/L
Low barium and strontium concentrations (0.2- 0.7mg/L)	Barium levels 3 mg/L and strontium 0.9 mg/L at MPMPB03	Highest strontium and barium concentration (1.47 mg/L and 8.7 mg/L respectively)
No methane production	Suspected biogenic production of methane	Suspected thermogenic production
Evaporation occurring Positioned to the right of GMWL	Little or no evaporation -slightly to the right of GMWL	Significantly outlying stable isotope value on the GMWL and outlier radioisotopic <sup>36</sup> Cl value

Table 6.2 - Groundwater quality summary table, pH values from previous research. (AGL Energy Pty Ltd 2013e; AGL Energy Pty Ltd 2014a)

### *Upper Level*

The sodium and chloride concentration are relatively higher than the lower level and is possibly linked to evapotranspiration at the surface. Evaporation processes are suggested from the stable isotope meteoric water line plot ( $^2\text{H}$  and  $^{18}\text{O}$ ) plots (Figure 5.3), especially for the alluvium aquifer waters. The salinity is still relatively low when compared to the coal seam.

The hydrograph analysis shows that the interaction with the Nepean River is predominantly in the alluvium aquifer (MPMB01). The ages of the water suggest that the water within the upper Hawkesbury Sandstone is 600BP (MPMB02). If this is close to the actual ages of the water then the likelihood for the discharge from the sandstone into the Nepean River at this location is unlikely. The true extent of contribution made by the upper Hawkesbury Sandstone is unconfirmed; however a tritium tracer could provide more conclusive evidence.

### *Lower Level*

The salinity of the water within the lower levels was lower than the upper level and far lower than the coal seam. It is determined that the water is fresh, however the concentration of barium at MPMB03 is ~3 mg/L. This is consistent with the previous research by AGL Energy Pty Ltd (2014a). This is not considered to be an extremely dangerous level however the Australian drinking water standards suggest that a maximum of 2 mg/L in drinking water should occur (NHMRC 2013). According to the National Health and Medical Research Council (2013) <0.002 mg/L to 1.1 mg/L is known to occur within Australian drinking waters. The water from MPMB03 is separated from the overlying upper Hawkesbury Sandstone and alluvium aquifer due to the shale confining layer. The water is therefore not a threat to public wellbeing. At the present it is unclear why barium is occurring at this level and where it has come from. The occurrence of anomalous barium at MPMB03 suggests that it is separate from the 'upper' level. The chloride concentrations at MPMB03 are also considerably lower than all other bores. The outlier position of MPMB03 in the piper plots (Figure 5.1) generated in Chapter 5 suggests potentially slowed flow occurs.

## 6.2 Assessment of the likelihood for CSG impact on the shallow groundwater resources.

The three major aquitard units within the Narrabeen Group are the Bald Hill Claystone (15.24m thick), the Wombarra Shale (36.6m thick) and the Stanwell Park Claystone (36.6m thick). They exist between the Bulli Coal Seam and the Hawkesbury Sandstone (Reynolds 1976). Primary (through the pore spaces) and secondary (through fractures and faults) flow characteristics of the aquitards have not been assessed in this project. The interconnectivity between the Bulli Coal Seam and Hawkesbury Sandstone depends on the vertical conductivity of these aquitards. As this does not come under the scope of this project, the likelihood of long-term impacts of CSG extraction on the beneficial aquifers is unable to be assessed. However, from data analysed in this project, there are negligible impacts occurring at this stage due to dewatering from CSG extraction.

However, some inferences for the likelihood of impact from CSG extraction can be made from the results of this project:

$\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotopic results show that the Bulli Coal Seam is depleted in these isotopes relative to the shallow groundwater system. This indicates a different recharge point for the coal seam. The major ion results also suggest that the water from the coal seam is distinctly different to that of the shallow groundwater system. The actual age of water within the coal seam water is undeterminable at this stage, however revisiting the dating technique after appropriate background research into  $^{36}\text{Cl}$  could provide an accurate age for the water to compare against the Hawkesbury Sandstone.

The CGP has a relatively small abstraction rate compared to the potential groundwater extraction of domestic and agricultural bores (see Chapter 3). The threat of water table drawdown is a serious one, however long periods of drought are more likely to put stronger pressures and dependence onto the groundwater resources in the Hawkesbury Sandstone.



## 6.3 Limitations

### 6.3.1 Sampling event drawdown periods.

Drawdown is the downward movement of groundwater levels due to the extraction of water. Periodic sampling events for hydrogeochemical tests resulted in periods of sustained drawdown at the MPMBs and the RMBs. The major limitation associated with groundwater sampling events is the decrease in validity of the results; the data ceases to represent the natural groundwater levels/pressures of the groundwater zone. In order to make observations and decisions in regards to the flow mechanism and groundwater responses to recharge and discharge the periodic drawdown periods must be removed. In addition, the hydrographs at Menangle Park begin with the June 2013 flood event which has had a significant effect on the hydrographs, suggesting an overall downward trend in groundwater levels.

The central limitation is the method of removing and interpolating new groundwater level data. At the present no scientific literature has discussed methods of interpolating groundwater data with consideration to the rainfall. Groundwater levels can often reflect the rainfall, and sampling events make it difficult to interpolate new points whilst attempting to provide some correlation to the rainfall. The removal and interpolation of sampling events was attempted using straight line interpolation with consideration to the rainfall. However, it was a simplistic approach and a more sophisticated method could be designed. The straight line starting point and end point were subjectively chosen by the author. The straight line begins at a starting point located before the sampling event had occurred and an end point at a time of sufficient return to baseline. Longer drawdown periods require more interpolation resulting in increasing uncertainty.

The Denham Court bores were severely affected from sampling events. The drawdown periods made a significantly greater impact on the groundwater levels than at Menangle Park. This is a key issue as to why comparison of the Denham Court monitoring bores to the Menangle Park monitoring bores failed. Figure 6.2 is the raw data hydrograph of RMB03 between Nov-2011 to April-2014. Four consecutive sampling events resulted in drawdown of  $> 7$  m.AHD which took 85 days to recover back to baseline groundwater levels. Figure 6.2 is the same hydrograph as Figure 6.3 however, sampling events have been removed with a straight line interpolation. This method clearly fails to provide a consideration to rainfall events.

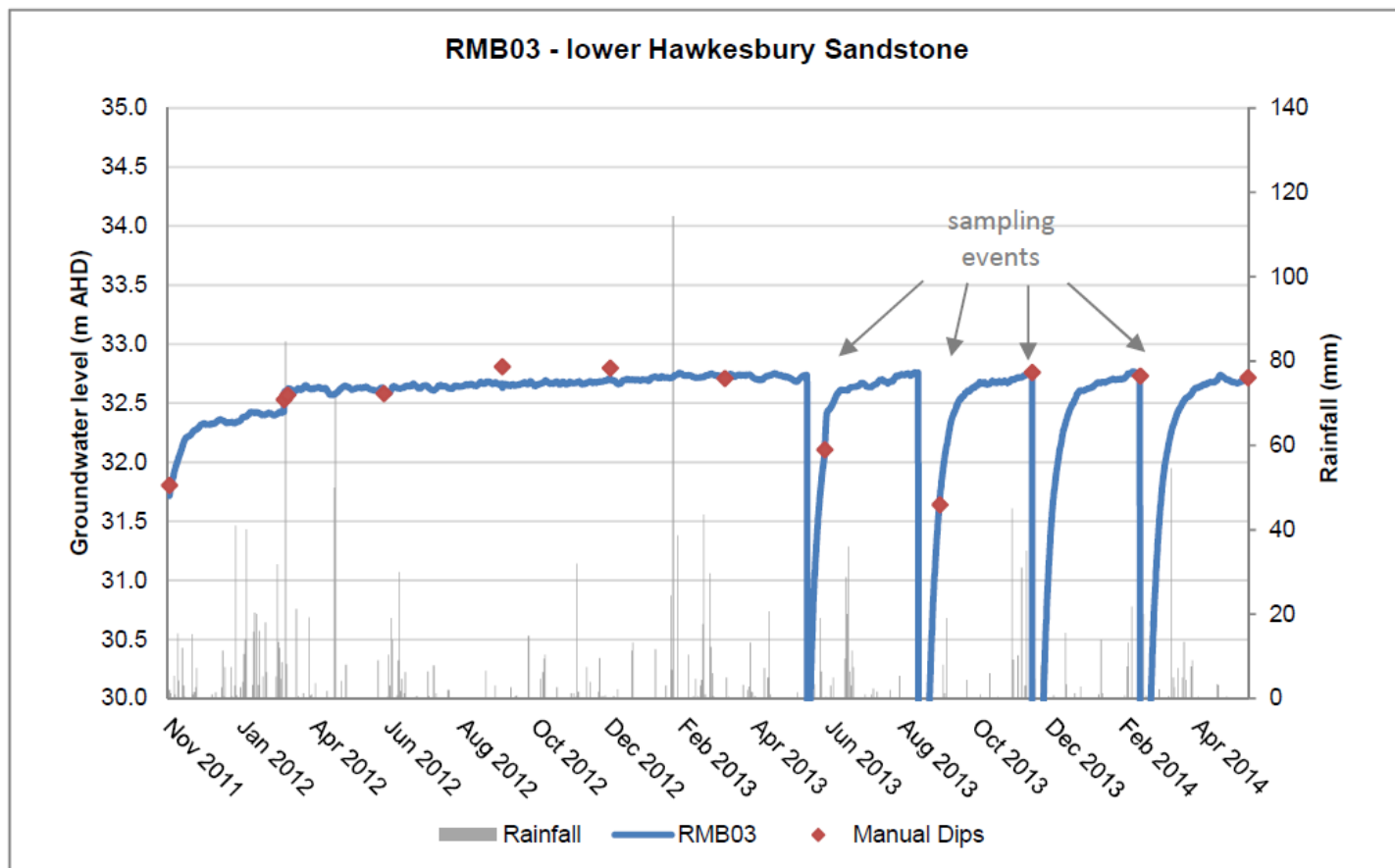


Figure 6.2 – Hydrograph showing the effects of sampling events on the groundwater levels at Denham Court within the lower Hawkesbury Sandstone unit. Adapted from AGL Energy Pty Ltd (2014c)

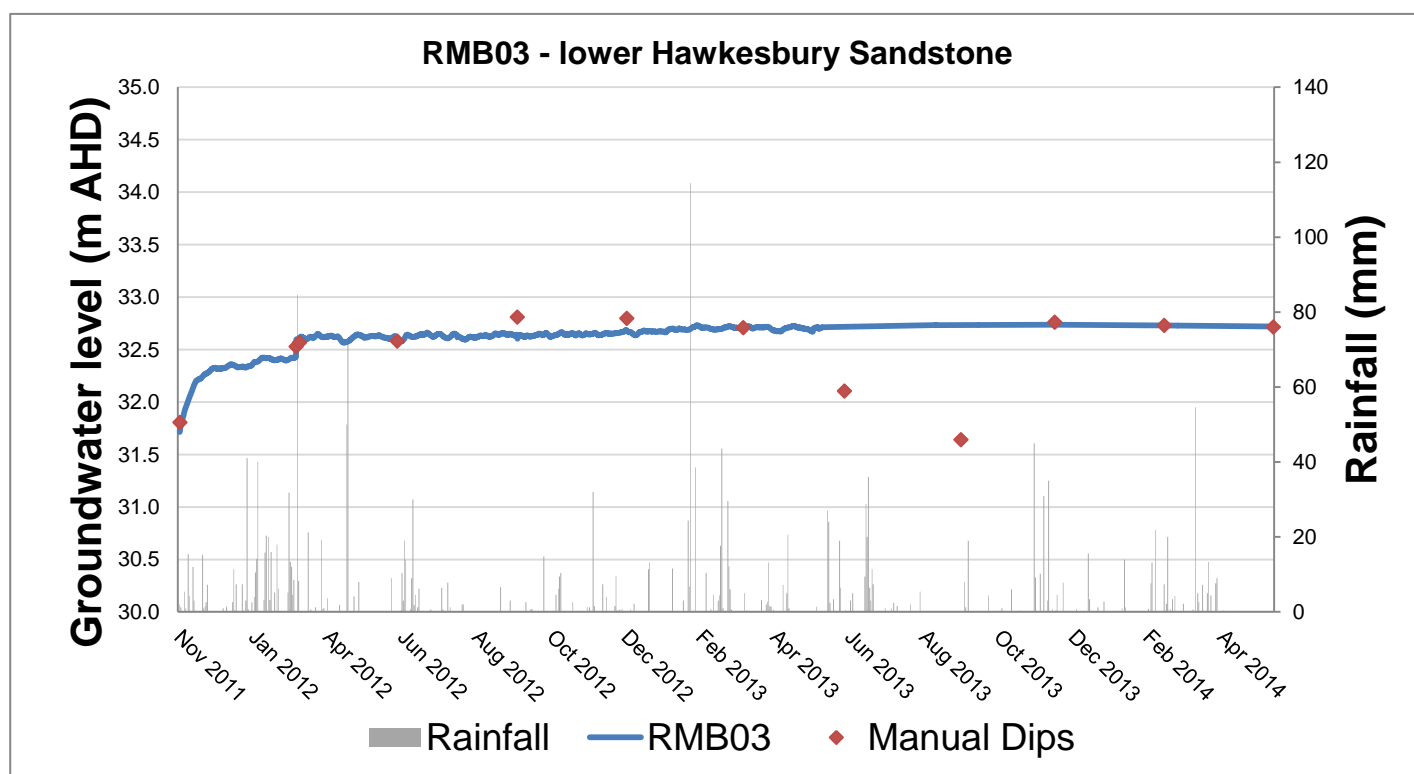


Figure 6.3 – Hydrograph of RMB03 after the removal and interpolation of new groundwater level data. Adapted from AGL Energy Pty Ltd (2014c).

### 6.3.2 Hydrograph data quantity

A central hydrogeological issue with regards to CSG extraction is the risks involved in depressurising interconnected groundwater systems and subsequent regional drawdown in beneficial aquifers. The monitoring bores are designed to measure the pressure heads of the groundwater system and establish the trends in recharge and discharge of rainfall.

The MPMBs have recorded the pressure head measurements in 6 hourly intervals since 6pm of 24/06/2013. In June of 2014 1358 measurements per bore had been generated. Due to the high frequency of measurements the resolution of the groundwater level is of a high quality. However, in order to make confident statistical conclusions about the groundwater recharge and drawdown trends the data quantity needs to increase substantially. The current dataset does not take into consideration the seasonal and yearly fluctuations in rainfall. Establishing reliable seasonal fluctuations in groundwater levels may take decades, especially when considering long term climatic changes. Climate mechanisms such as El Niño and La Niña affect seasonal rainfall and therefore groundwater levels. During drought periods abstraction rates increase and rainfall decreases. Long term climatic and environmental changes should be considered when establishing the long term characteristics of a groundwater system. Therefore we cannot rely on the current dataset to establish long term groundwater trends and to draw conclusions about an overall downward trend due to the impact of CSG extraction.

### 6.3.3 Flood event of June 2013

The flood event of June 2013 occurred immediately after the installation of MPMBs. This event caused a spike in the pressure head values predominantly in the shallow system hydrographs. If any form of statistical analysis were performed to establish long term drawdown trends (i.e. the impact from dewatering and interconnectivity of coal seams) the result would suggest a negative gradient line (i.e. drawdown). Therefore in order to assess long term drawdown trends the analysis must begin at time after the effects of the flood event had decreased in the hydrographs. A recommended solution is to continue to measure the groundwater levels, which should result in an increase of the reliability in observed long term trends.

#### 6.3.4 Limitations of hydrogeochemical and isotopic analyses

The  $^{14}\text{C}$  dating failed to produce reliable results for MP17.  $^{14}\text{C}$  dating was significantly affected and limited by the methane production and resulted in ages outside the range of  $^{14}\text{C}$  dating ability. The coal seam waters are potentially older than 60,600 BP however the analysis was unable to confirm this. Carbon dating does not date the water itself, it dates the dissolved inorganic carbon within the water (Clark & Fritz 1997). There are potentially several processes that have affected the  $^{14}\text{C}$  dating results of the MPMBs however it is thought that methanogenesis is the reason for the age anomalies at MPMB03 and MPMB04. Without stable isotopic discrimination analysis of the methane itself it is difficult to confirm the presence of biogenic methane production and difficult to investigate other potential processes affecting the  $^{14}\text{C}$  ages.

There are three central issues why the dating of the water at Menangle Park failed using  $^{36}\text{Cl}$ :

- 1)  $^{36}\text{Cl}$  atmospheric precipitation/production rates in the region are central to the age calculation equation. At this stage these rates are unknown. Therefore production rates were estimated, decreasing the accuracy of results.

- 2)  $^{36}\text{Cl}$  in situ production rates within the Bulli Coal Seam are not known. The number used was equal to the sandstone in situ production rate. However, the Bulli Coal Seam is not sandstone and the uranium and thorium content is unknown and could potentially be higher than the sandstone, thus resulting in a different age calculation result.

- 3) The addition and diffusion of chloride with depth, resulting in changes of the initial  $^{36}\text{Cl}/\text{Cl}$  concentration. An ideal situation to calculate ages using  $^{36}\text{Cl}$  is where no changes to the  $^{36}\text{Cl}$  ratio occur with depth, except of course natural radioactive decay. The groundwater system at Menangle Park shows irregular increases in the  $^{36}\text{Cl}$  ratio because of suspected diffusion/mixing processes. This is also the central problem involved in using  $^{36}\text{Cl}$  as a tracer. Without knowing the specific flow mechanism, it is difficult to account for the anomalous results from the  $^{36}\text{Cl}$  tracer analysis. The ionic balances suggest that major ion analysis for the Nepean River and MP17 could have been conducted poorly. However, the cause of the imbalance is most likely due to the reliance on outside data for carbonate values. The analysis relied on previous research conducted by AGL Energy Pty Ltd, especially for the Nepean River which relied on results obtained in 2013.

### 6.3.5 Bivariate plots

Bivariate plots created in section 4.3 are not able to be used to assess the groundwater recharge trends. This is because groundwater levels are a lagged in respect to rainfall events. The bivariate plots are unable to include time as a variable and therefore are unsuitable for analysing groundwater recharge/discharge trends. Table 6.3 and Figures 6.4-6.5 examine hypothetical data to illustrate this issue.

Day	Mon	Tues	Wed	Thurs	Fri	Sat	Sun	Mon	Tues
GWL (m AHD)	20	20	20	20	35	45	40	39	38
Rainfall (mm)	0	0	0	50	0	0	0	0	0

Table 6.3 – Hypothetical rainfall data, created in order to illustrate the real world problem involved in correlating rainfall data with groundwater levels. Simple bivariate plots cannot assess the relationship due to the time lag of rainfall infiltrating and saturating the ground surfaces.

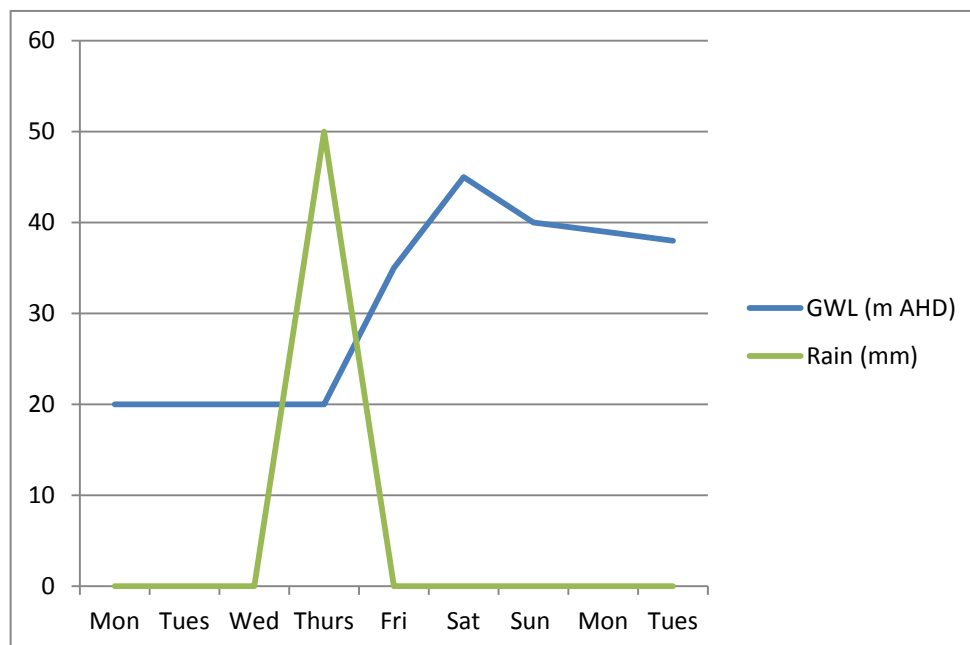


Figure 6.4 - Hypothetical hydrograph analysis – the effect on the groundwater levels is not immediate. The correlations would be very low because the cause is immediate whilst the effects are drawn out into a longer period.

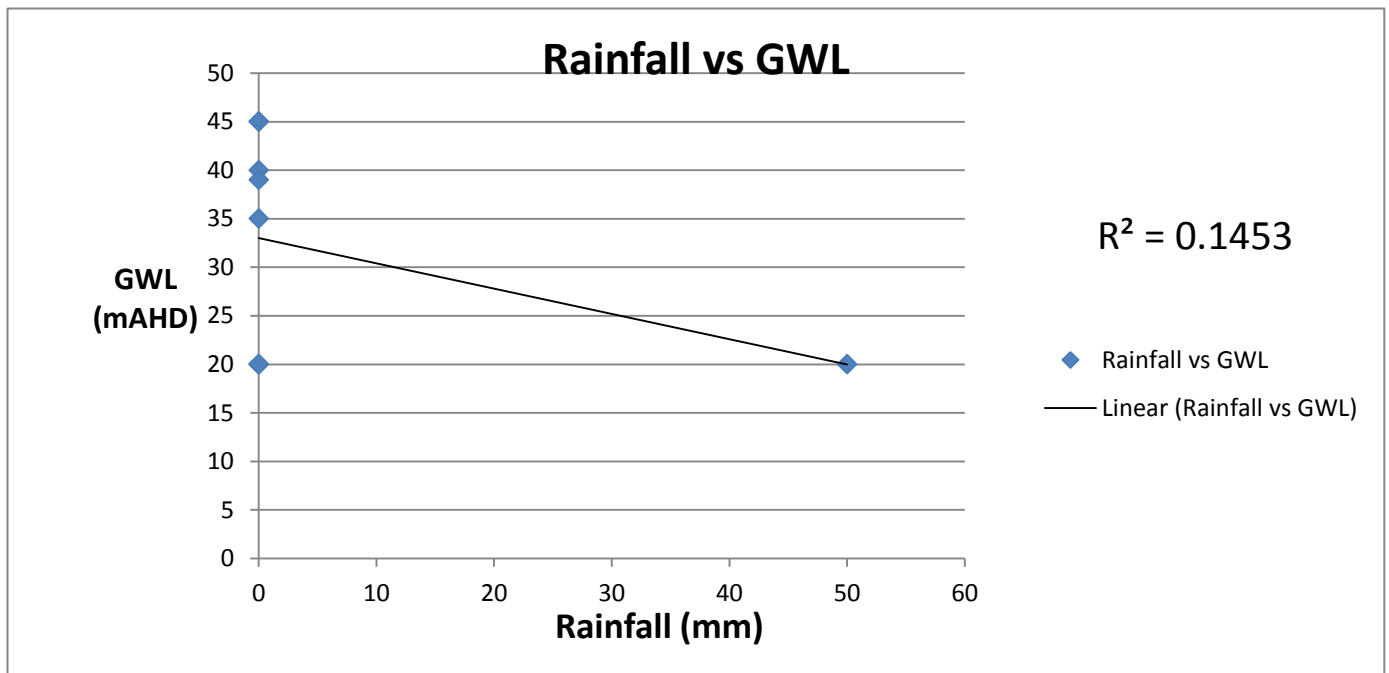


Figure 6.5 - Bivariate plot of the hypothetical groundwater response to rainfall. The bivariate plot has generated an expected low  $R^2$  coefficient of 0.1453.

Time series analysis was attempted with the computer software JMP however it was unsuccessful at generating an  $R^2$  value. The software's time series algorithms were unable to perform the analysis successfully because of the vast number of '0' values for rainfall. Due to the failure of the bivariate plots and time series analysis the recharge and drawdown trends must rely on the hydrograph analysis.

#### 6.3.6 Water balance

The water balance calculates the inflow and outflow of water within a hydrological cycle. Groundwater bores potentially used for agricultural and domestic purposes within the subcatchment area are numerous (> 300 bores) and have a potentially significant impact on the water balance calculation. However, there is little known about the rates of extraction, the target aquifer, groundwater quality and pressure head monitoring. This is important because the water balance for this project compares the rates of CSG dewatering against dewatering rates for other uses. Nepean River runoff calculations failed due to the unknown river flow

parameters. The runoff calculations would also have to address the runoff volumes from the ‘upstream’ catchment that adds to the total runoff gauge data at Menangle Park.

The soil infiltration rates were calculated from a generalised soils map of Australia. The intervals of rates of infiltration are large (eg. 5-50mm/day) and create a considerably large range of results. The rates do not consider the types of rainfall events and their corresponding effect on infiltration. The surface geology has not been taken into account for the infiltration calculations, although it could have a significant impact on the overall calculation. The geology underlying the soils should also be considered in the infiltration rates as porous sands are more likely to recharge an aquifer than a shale layer.

#### 6.4 Conclusions

The groundwater levels and quality of the Hawkesbury Sandstone is largely controlled by the impermeable shale layer within the unit. This layer separates the Hawkesbury Sandstone into two smaller systems characterised as the ‘upper’ and ‘lower’ levels. The recharge and discharge trends for these levels are complex. The ‘upper’ level recharges from rainfall and partially discharges into the Nepean River, whilst the ‘lower’ level moves into the local system horizontally. Flow mechanisms in the ‘lower’ level are undetermined at this stage. It could be determined with more laterally extensive monitoring bores. The mean residence times for the Hawkesbury Sandstone were obtained from corrected  $^{14}\text{C}$  results and have a trend that increases with depth. Dates for the Bulli Coal Seam were unable to be determined reliably, however  $^{36}\text{Cl}$  dating techniques could be utilised in the future if regional precipitation rates and *in situ* production rates are determined. Results show that there is a clear difference between the isotopic ratios and hydrogeochemistry of the shallow groundwater system and the coal seam aquifer. From these, the author concludes that there is no or negligible interconnectivity between the shallow groundwater system and the coal seam aquifer. It is therefore concluded that there are negligible immediate impacts on the shallow groundwater system from coal seam gas extraction. However, the likelihood of long-term impacts from CSG extraction on beneficial aquifers is unable to be assessed from the results of this project. With continued groundwater monitoring and hydrogeochemical testing the reliability of the data will improve and a more comprehensive assessment could be carried out.

## 6.5 Recommendations for future research

- 1) Continue monitoring the groundwater levels and groundwater quality and repeat this analysis in the future. The yearly and seasonal groundwater trends are not visible with a monitoring record that is less than 24 months long. The drawdown of aquifers is likely to be a long term process and may require several more years of monitoring. Longer groundwater records also increases the validity in conclusions made about the impact of CSG extraction in this area.
- 2) The construction of more monitoring bores in a lateral direction into the Hawkesbury Sandstone could enable hydrogeologists to determine the local groundwater flow mechanism. This type of information can help to understand the major ion and isotope trends with depth, especially  $^{36}\text{Cl}$ .
- 3) Use of multivariate or time series analysis to statistically assess the groundwater and rainfall relationship with depth. Although this was achieved with the hydrograph analysis in this project, it would be beneficial to provide numerical results to strengthen the arguments about correlation decreasing with depth.
- 4) Conduct stable isotopic discrimination analysis on the methane within the 'lower' zone to determine the origin. Although the hypothesis put forward in this project suggest that the methane is likely to have originated from a biogenic production, isotopic discrimination of stable isotopes  $^{13}\text{C}$  and  $^2\text{H}$  can provide more conclusive evidence.
- 5) Conduct stable isotopic discrimination analysis on the methane within the 'lower' zone to determine the origin. Although the evidence put forward in this project suggest that the methane is likely to have originated from a biogenic production, isotopic discrimination of stable isotopes  $^{13}\text{C}$  and  $^2\text{H}$  can provide more conclusive evidence.
- 6) The use of radioisotope tritium ( $^3\text{H}$ ) to assess the groundwater relationship with the Nepean River. An effluent mechanism is suggested to occur between the alluvium aquifer and the Nepean River. Tritium analysis could develop on the potential involvement of the upper Hawkesbury Sandstone.



7) A regional assessment of the  $^{36}\text{Cl}$  precipitation for south-west Sydney. If the precipitation rates are known then the  $^{36}\text{Cl}$  results in this project can potentially be used more successfully as a groundwater tracer and dating method.

8) Assess the in situ production rates of  $^{36}\text{Cl}$  in the Bulli Coal Seam. At the moment no scientific literature has assessed in situ production rates within coal or the Illawarra Coal Measures. In order to generate reliable groundwater dates within a geological unit, the in situ production rate must be known. The age results from this would be used to further distinguish the difference between the Hawkesbury Sandstone and Bulli Coal Seam waters.

9) The addition of at least two monitoring bores into the Narrabeen Group to further understand the impact of CSG extraction. Although this project aimed to understand the impact on the beneficial aquifers, the potential effect on the Narrabeen Group is ignored. The potential cost of installing more monitoring bores will undoubtedly be expensive. However, if the monitoring bores are installed and prove that pressures within the sandstone units are not depressurising over the long term it will strengthen the hypothesis of confining layers restricting vertical hydraulic conductivity between the coal seam and Narrabeen Group. The proposed Narrabeen Group monitoring bores are illustrated in the conceptual model Figure 6.6.

10) Runoff and infiltration were difficult to quantify in the water balance equation. The data from river gauges stations should provide an opportunity for research into the discharge (runoff) values for the subcatchment area. Quantifying infiltration rates could be attempted with the same data used in this project however, the incorporation of the surface geology should improve the end result.

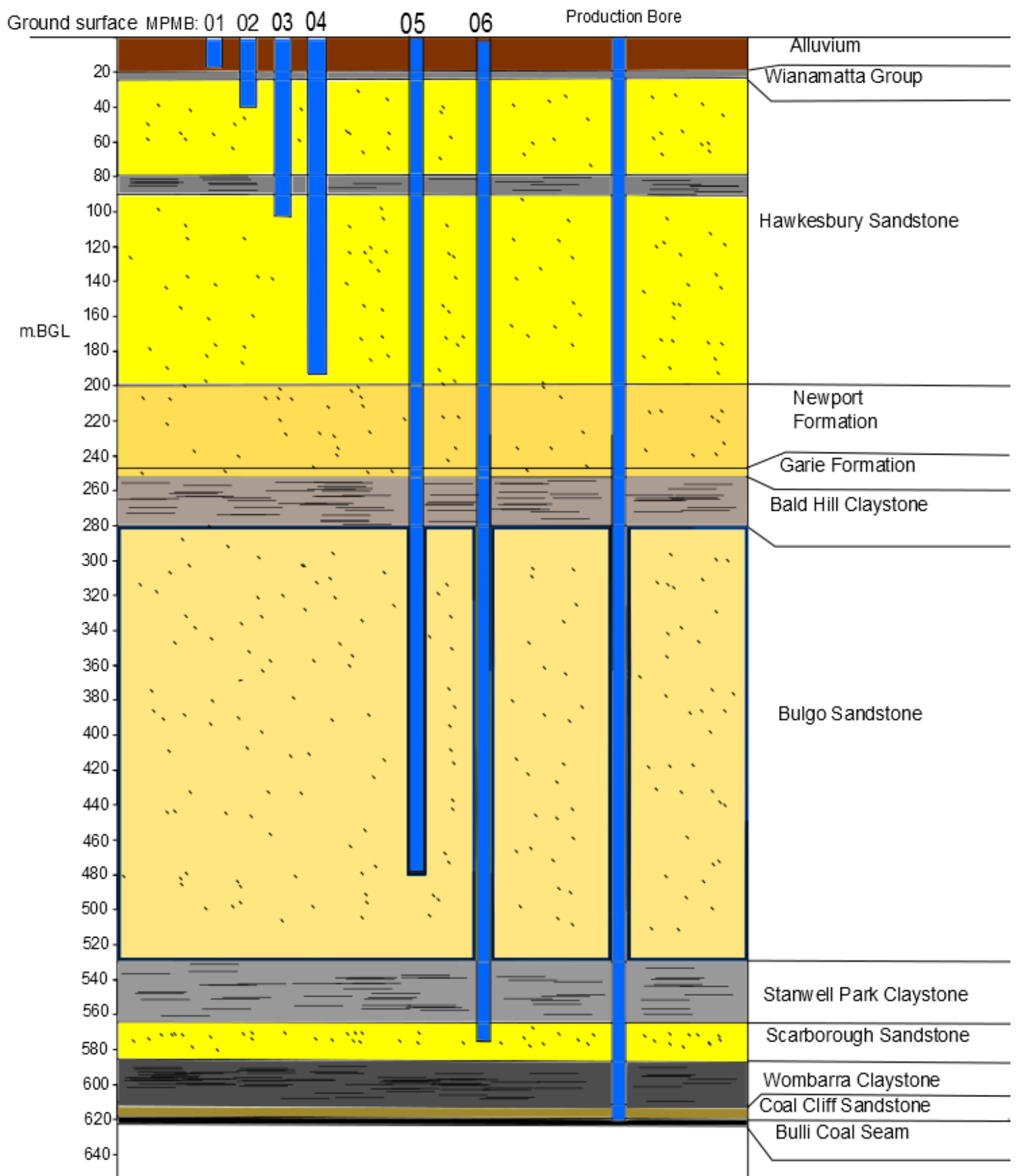


Figure 6.6 – Conceptual model of recommended future research

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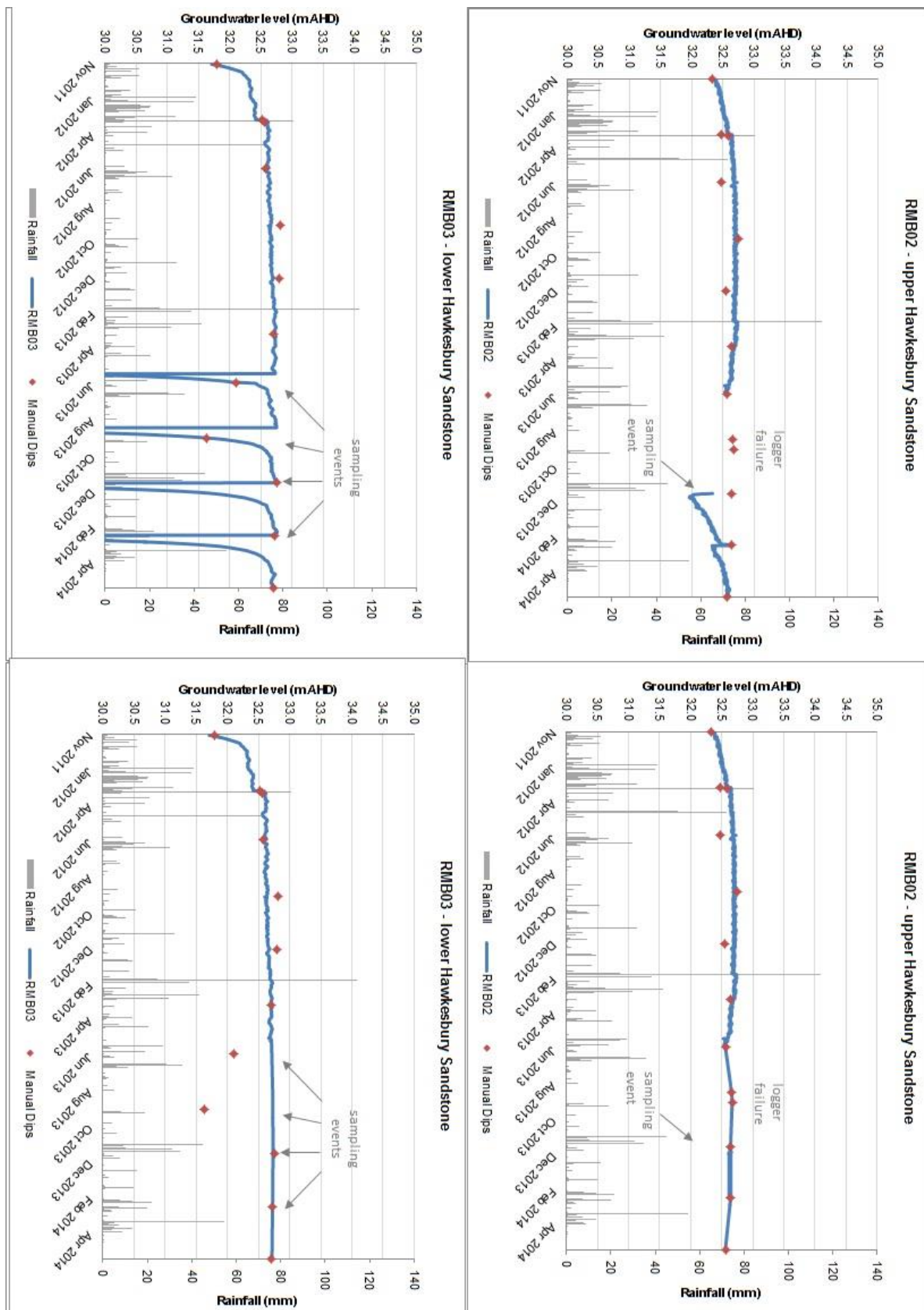
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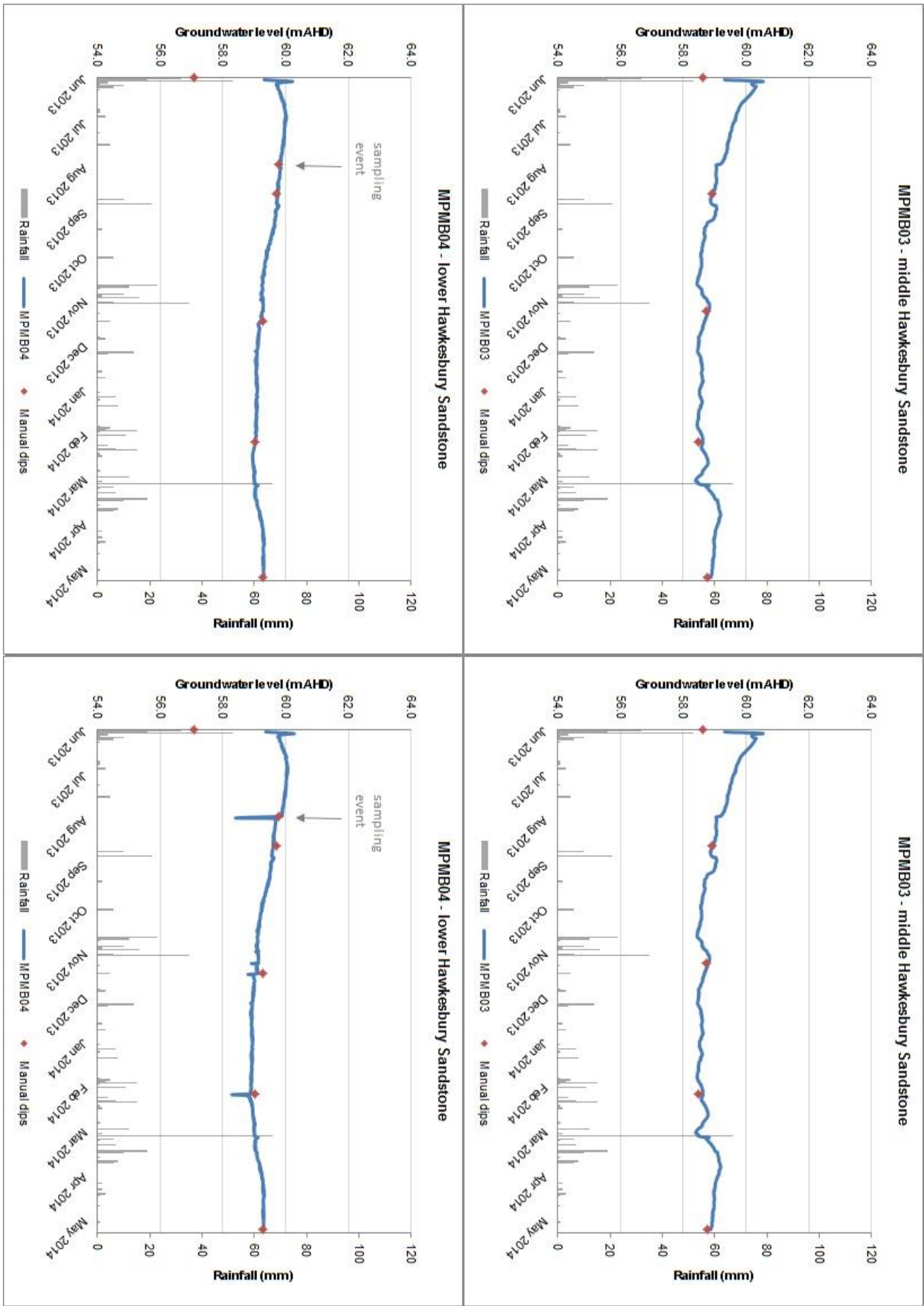
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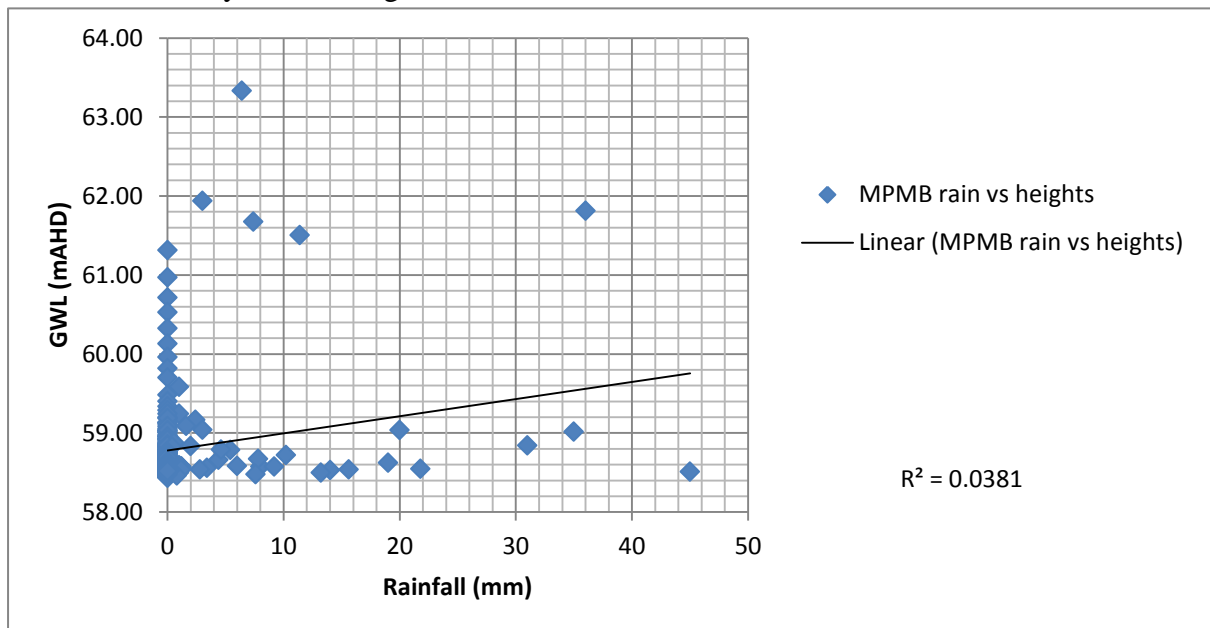
## Appendix A - Raw and interpolated hydrographs



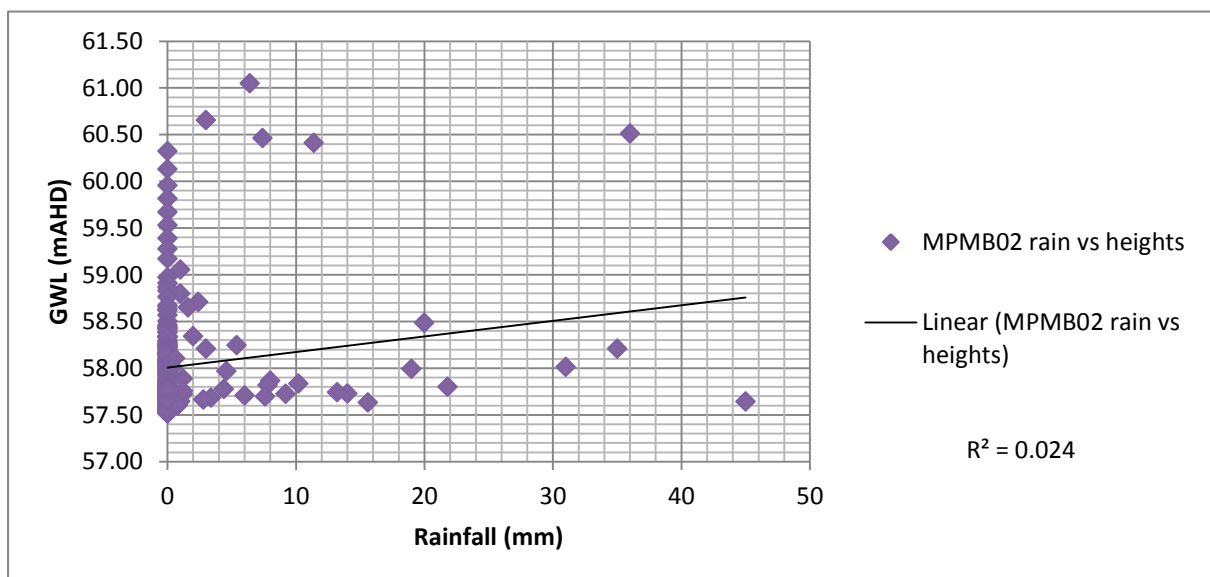


## Appendix B - Bivariate plots

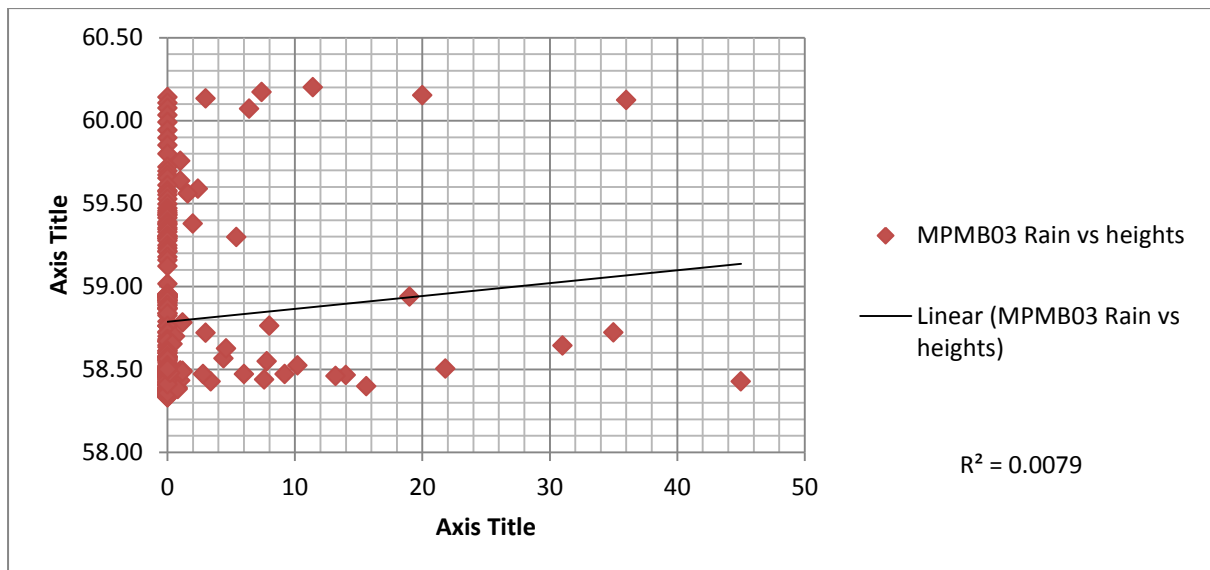
MPMB01 – Daily rainfall vs groundwater level



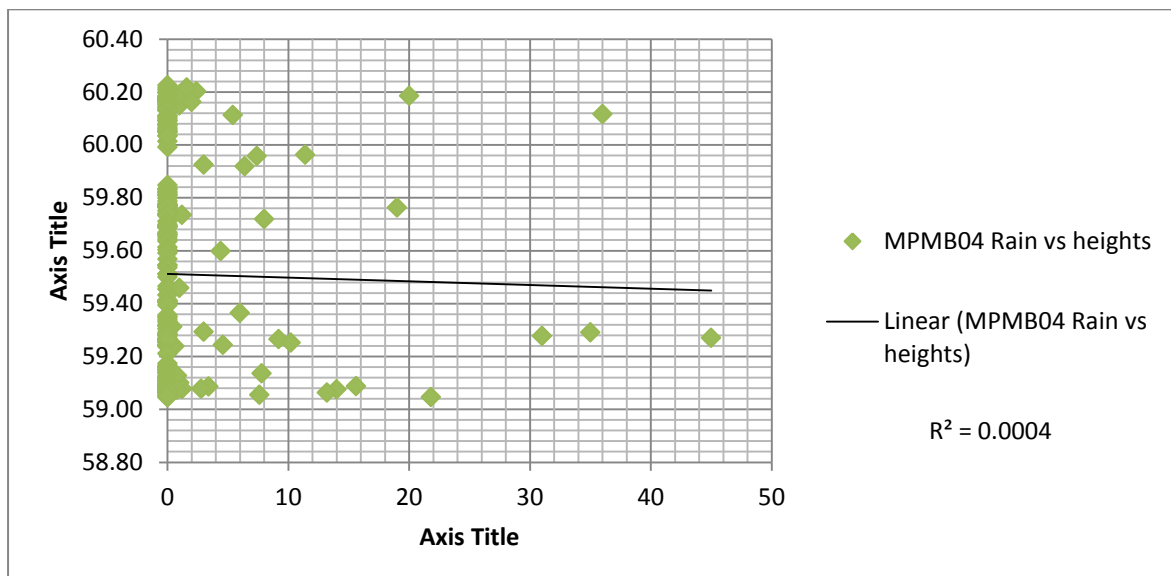
MPMB02 – Daily Rainfall vs groundwater level



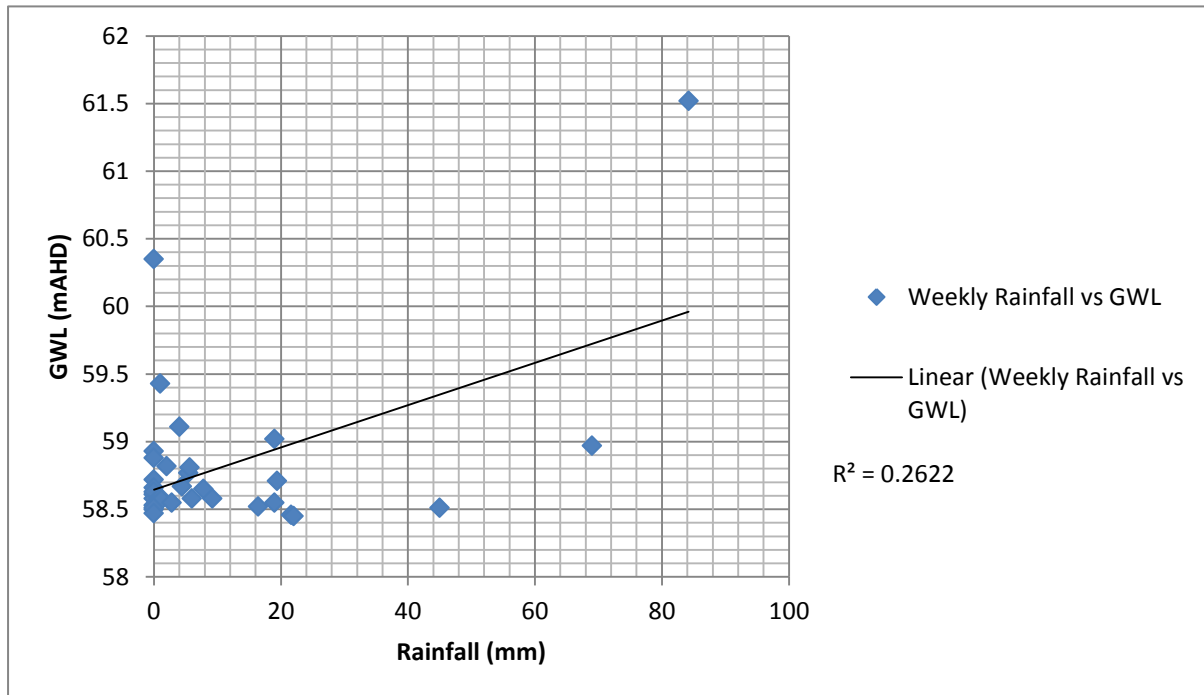
MPMB03 – Daily rainfall vs groundwater level



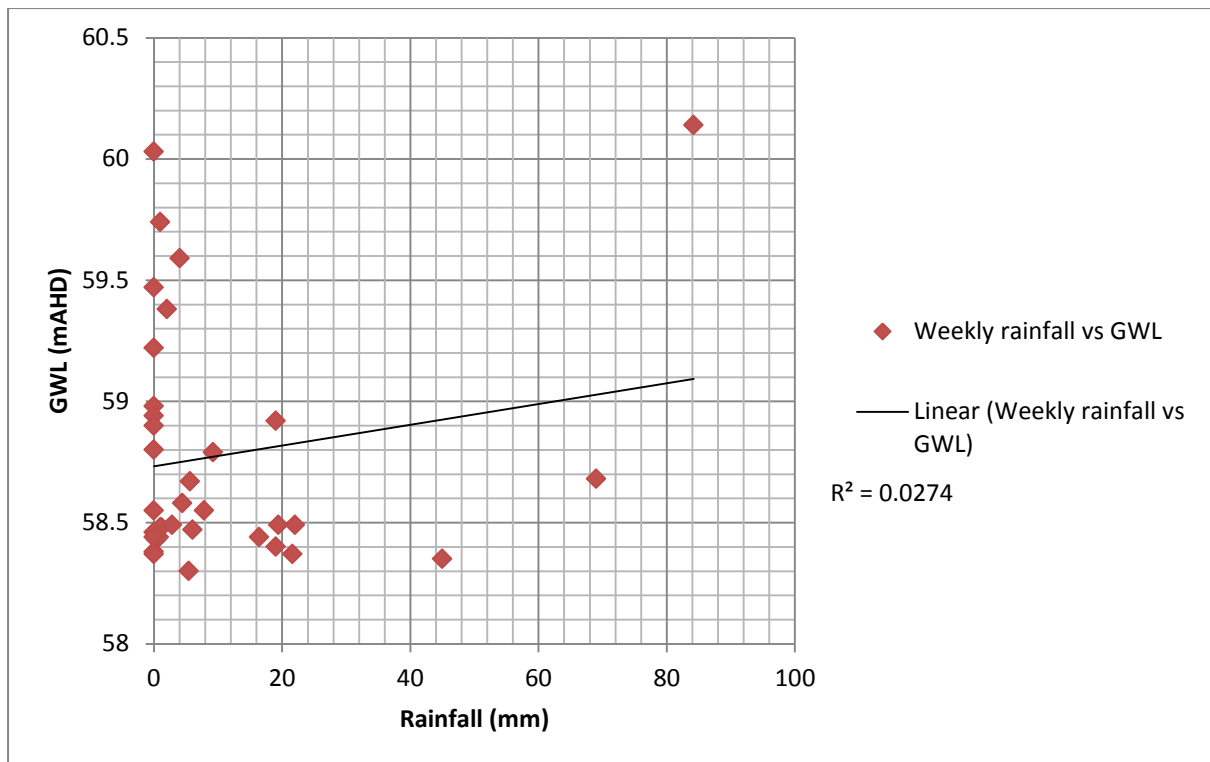
MPMB04 – Daily rainfall vs groundwater level



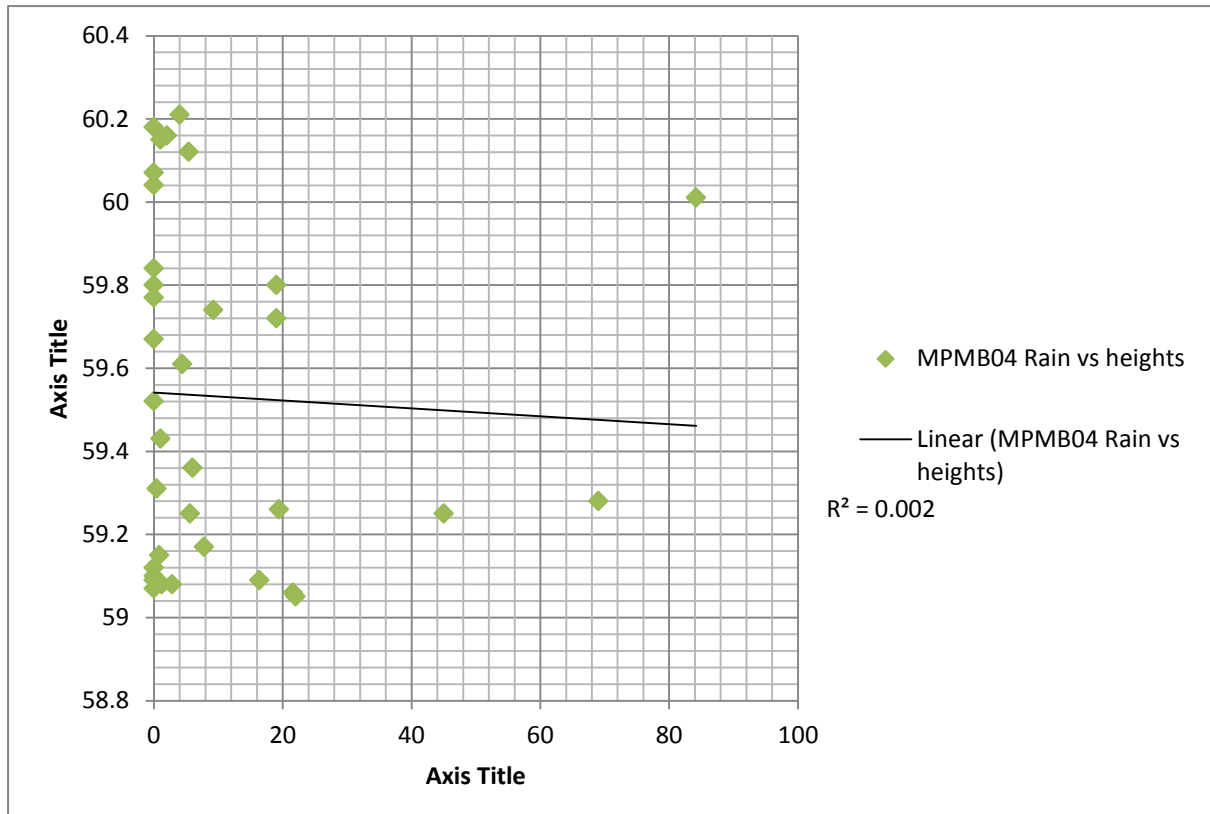
MPMB01 - Weekly rainfall vs groundwater level



MPMB03 – Weekly rainfall vs groundwater level

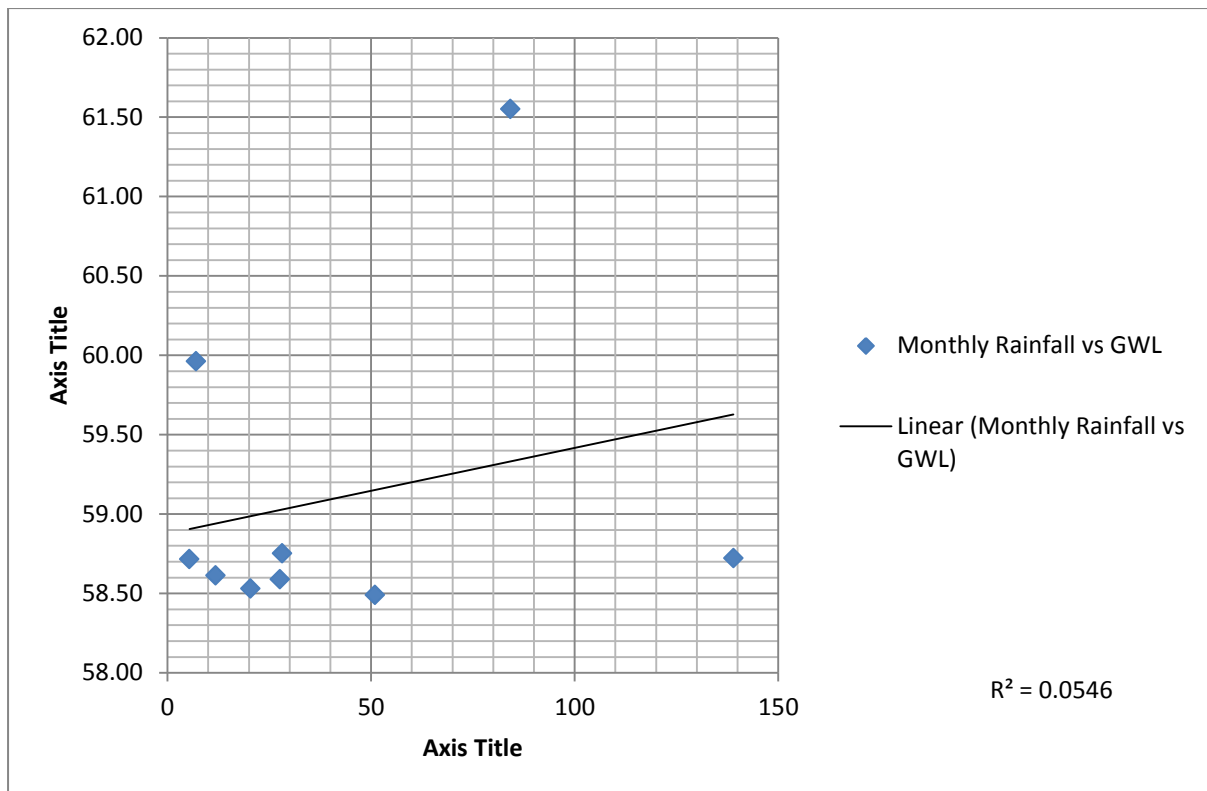


MPMB04 – Weekly rainfall vs groundwater level

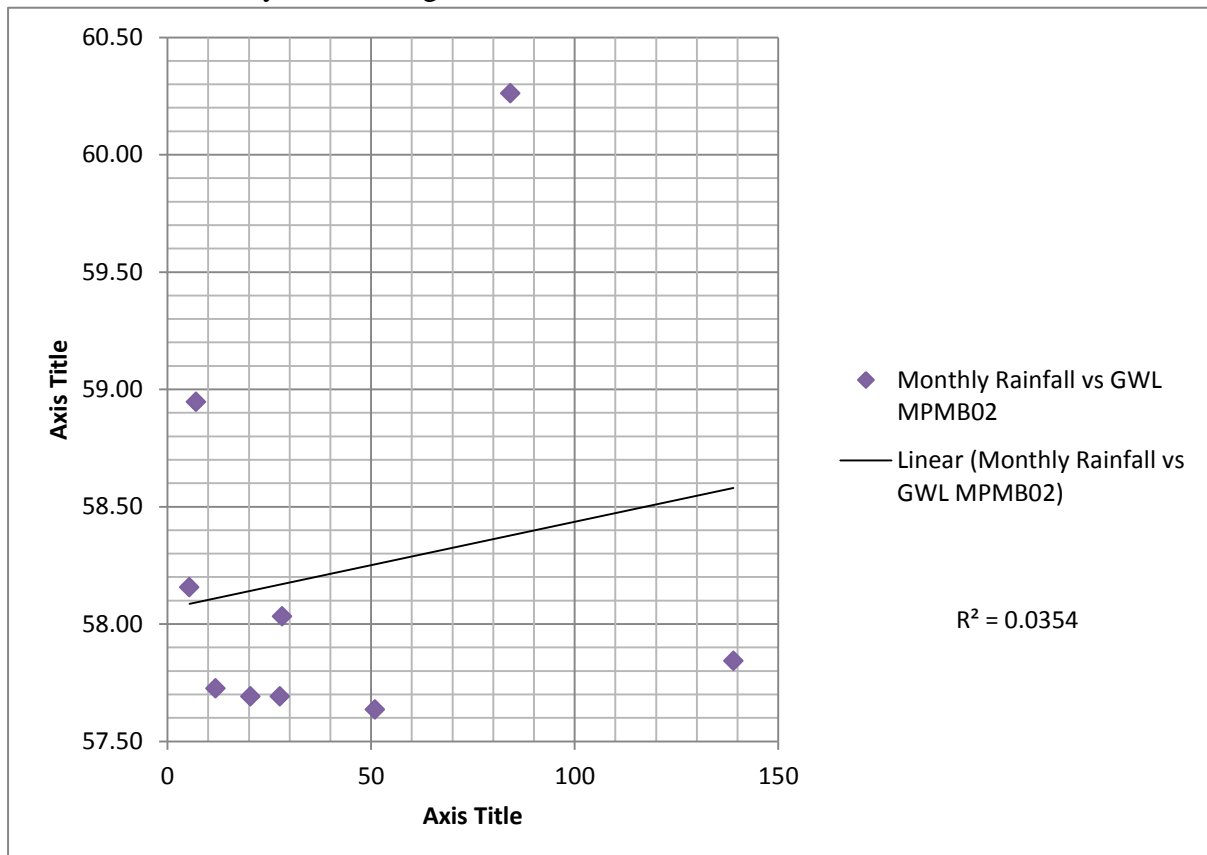




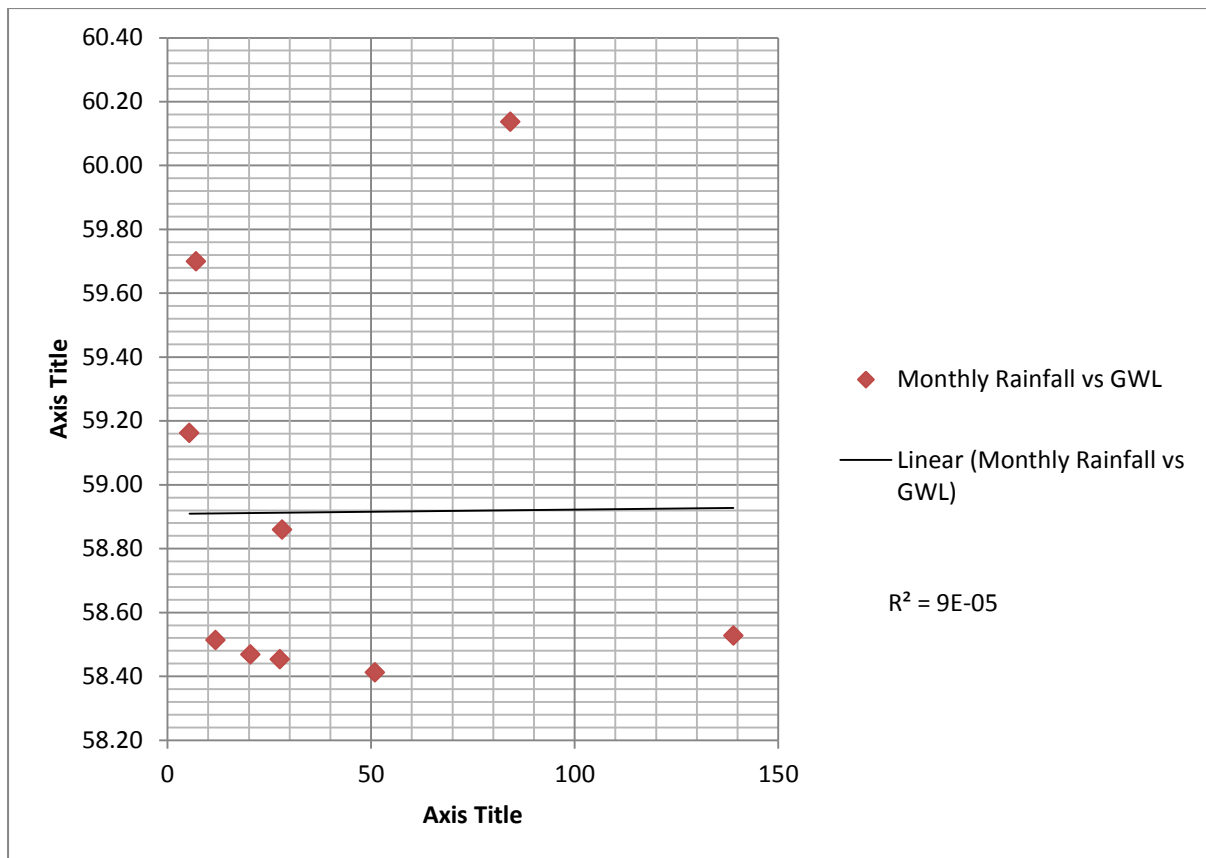
MPMB01 – Monthly rainfall vs groundwater level



MPMB02 – Monthly rainfall vs groundwater level



MPMB03 – Monthly rainfall vs groundwater level



MPMB04 - Monthly Rainfall vs groundwater level

