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THESIS

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STABLE ISOTOPIC SIGNATURES OF WATER RESOURCES OF METROPOLITAN ADELAIDE REGION

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ABSTRACT

The Adelaide metropolitan region has a semi-arid climate that has strong influences on water isotope variation. Isotopic signatures of waters are useful tracers to identify the source and evolution of water in the environment. Information from water isotopes may help to investigate problems and challenges in water resource management in urban areas. This thesis reports a preliminary characterization of stable water isotopes of water, including tap water and surface water resources in the Adelaide metropolitan area. Water samples were collected and analysed for δ^2H and $\delta^{18}O$ and deuterium excess ($d = \delta^2H - 8 \times \delta^{18}O$). Different types of water were characterised by referring to Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL). It is found that the $\delta^{18}O$ of surface water and tap water in the Adelaide metropolitan area are quite similar (-3.16‰ vs. -3.12‰ for $\delta^{18}O$, respectively) but they are different for δ^2H (-13.33‰ vs.-17.28‰) and d-excess (11.94‰ vs. 7.64‰). Stable isotopes of both tap water and surface water show evaporative influences; however, more depleted isotopes of tap water show stronger evaporative influences. The research found that mixing with desalinated water and longer residence time in the reservoirs, combining with evaporation play important roles in the enrichment of tap water isotopes. In term of spatial pattern, tap water isotope data do not follow hydrological, climatic or natural isotope gradients but shows clustering distribution for each water supply zones. The variation of tap water isotopes through various water supply zones reflects the environmental pressure on water resources and dynamics of water supply systems. Water from the River Murray as one of main water resources for the Adelaide metropolitan area has a meteoric signature; however, tap water supplied by it is more isotopically enriched in various water supply zones. The spatial distribution of surface water isotopes does not show a clear pattern across the Adelaide metropolitan area but water isotopes vary significantly across small areas of the catchment. The surface water from the Smith Catchment has more depleted isotopes, which are closer to meteoric water than surface water from the Onkaparinga catchment. This highlights the complex influences resulting from the combinations of evaporation, precipitation and landscape characteristics relating to residence time.

Keywords: Adelaide metropolitan, stable water isotopes, tap water, surface water, precipitation, evaporation, Picarro CSRD, spatial pattern.

DECLARATION OF ORIGINAL WORK

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Ngo Thi Le Trang

24 February 2017

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LIST OF ACRONYMS

Acronym	Definition
D or ^{2}H	Deuterium (^{2}H) / Stable isotope of hydrogen
^{18}O	Stable isotope of oxygen
ADP	Adelaide Desalination Plant
CRDS	Cavity Ring-Down Spectroscopy
d-excess	The deuterium excess
GIS	Geographic Information System
GMWL	Global Meteoric Water Line
GNIP	Global Network of Isotopes in Precipitation
IRMS	Isotopic Ratio Mass Spectrometry
LMWL	Local Meteoric Water Line
MAR	Managed Aquifer Recharge
NSIS	North South Interconnection System
RM	River Murray
V-SMOW	Vienne Standard Mean Ocean Water
WTP	Water Treatment Plant

CHAPTER 1. INTRODUCTION

1.1 Problems and challenges of water resources in urban area

Urban water management is important since many issues relating to water resources have increased significantly. Large population and increasing in the industrial and commercial activities have direct impacts on the water resources in both quantity, through increasing in water demand, and quality, through the release of contaminants, of the water (Howard, 2002). Surface water (including stormwater runoff) and tap water act as the major sources of groundwater recharge (Kim et al., 2001, Eiswirth and Hötzl, 1997). Leakage from tap and sewage pipelines as one of major sources of urban groundwater can contribute from 100-300 mm/year in average up to 3000 mm/year into the groundwater (Lerner, 1990). All of these water inputs cause water table rise and might pose potential dangers to urban infrastructure and foundation in urban areas (Al-Sefry and Şen, 2006). Thus, the study of disintegrating various sources is necessary for better identification of groundwater sources, and solutions to the issues can be suggested.

Stable isotopes of water have become a useful and an effective tool to research the hydrological system on both spatial and temporal scales (Yuan and Miyamoto, 2008). Due to the difference in the isotopic signatures for different types of water, it can be an efficient tracer to identify the sources of water, such as surface water, tap water, recycled water and rainfall which act as sources of groundwater (figure 1.1). A number of studies have shown how stable isotopes can help for various purposes, such as tracing the dynamics and origin of groundwater and surface water (Herczeg et al., 1992), tracing the origin and evolution of saline groundwater (Banner et al., 1989), estimating the groundwater exchange with lake by stable isotope mass balance method (Krabbenhoft et al., 1994, Bowser et al., 1990, Sacks et al., 1998, Dincer, 1968) or investigating the water balance of lakes (Dincer, 1968), and mostly providing valuable information of hydrological processes (Gat, 1996, Gat and Gonfiantini, 1981) and so on.

The stable isotopes of water can be useful to deal with many urban water management issues such as the leakage of main water pipes and identification of groundwater recharge source (Kumar, 2013, Darling et al., 2003). In case, tap water leakage occurs at a section of pipeline and infiltrates into shallow groundwater, isotopic ratios of the groundwater will change to the extent of leakage occurrence that the mixing of those waters is close to the signature of tap water. This principle for an identification of groundwater sources is similar for stormwater runoff and surface water. Since surface water (including stormwater runoff) and tap water act

as major sources of groundwater, the information of those water inputs can provide a foundation to assist the identification of groundwater recharge.

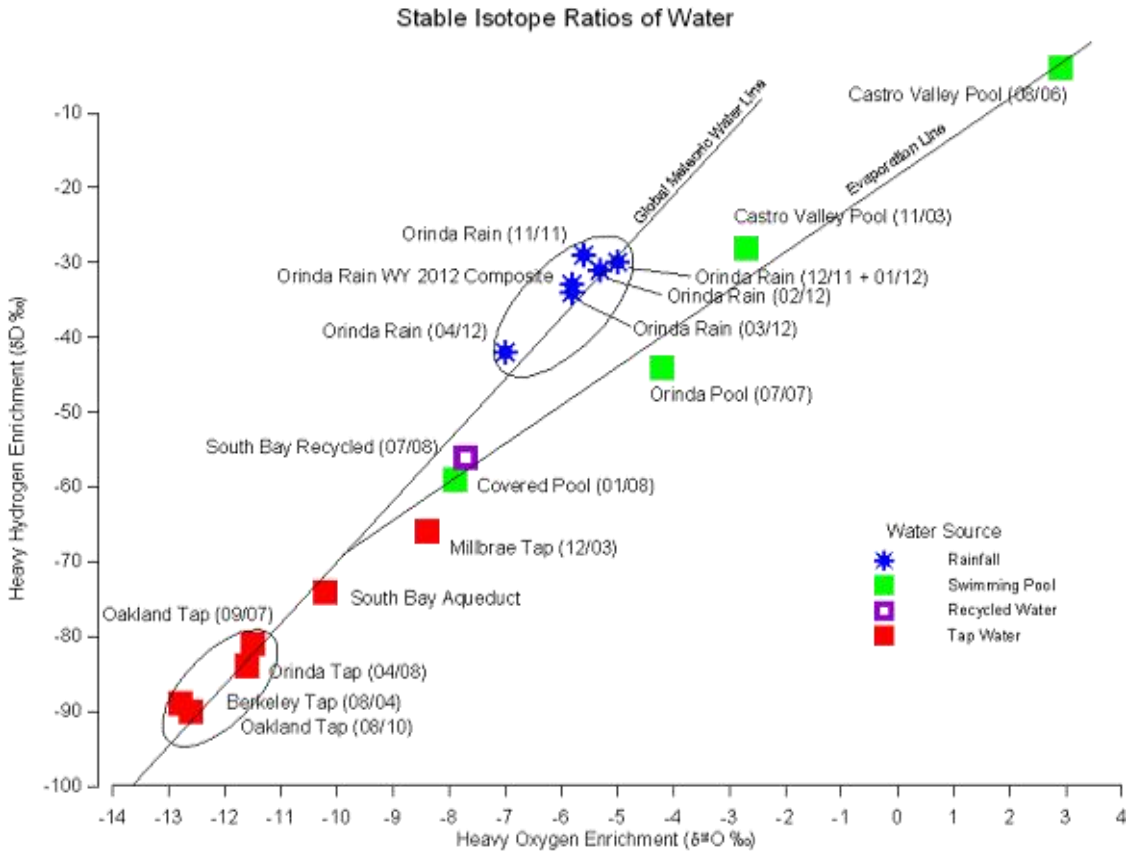

Figure 1.1 Different types of water have different isotopic signatures

Source: adapted from: Ulric & Associates (2014)

Precipitation and evaporation are two major factors that influence the variation of stable isotope ratios of surface and ground water (Darling et al., 2003, Bowen et al., 2007a). The meteoric water line and evaporation line indicated in figure 1.1 illustrate these influences. The evaporation can cause the isotopic fractionation that changes the water signatures leading to the isotopic enrichment of heavy water. The precipitation with different water isotopic signatures will also change the stormwater runoff into the basin, therefore it changes the signature of groundwater as it infiltrates into the shallow groundwater. To understand the variation of surface water and tap water isotopes, a preliminary investigation of the extent of impacts that precipitation and evaporation have on water are important.

1.2 Objectives

The thesis has three main objectives:

(1) Provide a preliminary characterization of stable water isotopes of waters in the Adelaide metropolitan area.

(2) Provide preliminary understanding of the patterns in stable water isotope distribution.

(3) Provide a clearer picture of main major factors driving the spatial variation of stable isotope ratios in tap water and surface water across the Adelaide metropolitan area.

1.3 Thesis outline

This thesis is organised into seven chapters as follow:

Chapter 1: Introduction outlines the challenges and problems of water resources, study objectives and research questions.

Chapter 2: Literature Reviews provide information on stable water isotopes ratio in nature, influences of evaporation and precipitation on stable isotope ratios, the interpretation of water isotopic data and stable water isotopes providing a useful tool to trace the sources of water.

Chapter 3: Study area describes location, climate and the tap water system and surface water system in the Adelaide metropolitan area.

Chapter 4: Methodology describes water sampling for both tap water and surface water, stable isotopic analysis experiment and mapping method.

Chapter 5: Results detail stable isotopes and d-excess of different types of water in the Adelaide metropolitan area.

Chapter 6: Discussion examines the characterization of the water isotopes and d-excess of water and major driving factors.

Chapter 7: Conclusion summarises the main findings, significance, implications and limitation of findings as well as suggestion in for future research.

Appendices: Appendices provide some pictures of wetlands and tap water sampling locations, the water isotopic data, Picarro Isotopic Water Cavity ring-down spectroscopy instrument.

CHAPTER TWO: LITERATURE REVIEW

2.1 Stable water isotope ratios in nature

Isotopes are atoms with the same number of protons, but different numbers of neutrons in the nucleus. Hydrogen and oxygen exist with a number of stable and radioactive isotopes.

All the data of stable isotope abundances are reported in delta (δ) notation in parts per thousands (‰) referring to Vienna Standard Mean Ocean Water (VSMOW):

$$\delta(‰) = \left(\frac{\mathrm{R} - sample}{\mathrm{R} - standard} - 1\right) \mathrm{X}\ 1000$$

Where R-sample represents the ratio of ^{2}H to ^{1}H or ratio of ^{18}O to ^{16}O of the sample and R-standard is the corresponding ratio in VSMOW.

For hydrogen, there are two stable isotopes, protium (^{1}H) which exists in the hydrosphere with a mass abundance of 99.985% and deuterium (^{2}H) at about 0.015%. The stable isotopes of oxygen include ^{16}O, ^{17}O and ^{18}O in which ^{17}O and ^{18}O have an average abundance of 00.0379% and 0.200% respectively (Gat, 2010). The variability of stable hydrogen and oxygen isotopes in the hydrological cycle and in other materials are the result of isotope fractionation process in the hydrological cycle ranging around ± 50‰ for $\delta^{18}O$ and around -500‰ to +300‰ for $\delta^{2}H$. On average, the hydrosphere has $\delta^{18}O$ of -64‰ (Gat, 2010) while in natural waters, the ranges of $\delta^{2}H$ and $\delta^{18}O$ are ±30‰ and ±5‰, respectively (Boato, 1961). As the largest water reservoir, the ocean was selected as the standard for both $\delta^{2}H$ and $\delta^{18}O$ compositions in the water cycle due to being relatively homogeneous (Craig, 1961). Snow and ice from the Arctic and Antarctic have $\delta^{2}H$ and $\delta^{18}O$ less than -160‰ and -22‰ yet small depletions relative to ocean water are shown from the tropical samples (Craig, 1961).

Table 2.1 shows the isotope ranges for different sources of water through a variety of researches on stable water isotopes. Both $\delta^{2}H$ and $\delta^{18}O$ show wide ranges in meteoric water compared to other water resources while ocean water has relatively low isotopic ratios.

Table 2.1 Isotope ranges for different sources of water from the literature

	Typical Range		References
Source	$\delta^{2}H$ (‰ - VSMOW)	$\delta^{18}O$ (‰ - VSMOW)	
General			
Rainfall			
Dalwhinnie, UK (Summer)		-16.04 to -2.47	(Soulsby et al., 2000)
Dalwhinnie, UK (Winter)		-20.93 to -4.55	(Soulsby et al., 2000)
Jakarta, Indonesia	-43.5 to -20.8	-6.76 to -3.46	(IAEA 1981)
Montana Pole Plant, Butte	-216 to -38	-28.5 to -3.2	(Gammons et al., 2006)
Costa Rica	-70 to -19	-10.1 to -3.5	(Lachniet and Patterson, 2002)
Perth, Canada	-132 to -30	-19.8 to -5.7	(Praamsma et al., 2009)
Groundwater			
Cambridgeshire, UK	-50 to -47	-7.3 to -7.1	(Darling and Bath, 1988)
Orange, USA	-93 to -43	-13 to -6	(Williams, 1997)
Orange, USA (Well)	-82 to -39	-10.5 to -5.7	(Williams, 1997)
Dalwhinnie, UK (Boreholes)		-9.74 to -8.45	(Soulsby et al., 2000)
Ikogosi, Nigeria (Spring)	-22.30 to -17.97	-4.16 to -3.66	(Talabi, 2013)
Surface Water			
USA (Lake)	-134 to 21.3	-17.6 to 4.2	(Brooks et al., 2014)
Dalwhinnie, UK (Stream)		-10.44 to -8.45	(Soulsby et al., 2000)

Orange, USA (runoff)	-93 to -35	-13 to -5	(Williams, 1997)
Perth, Canada (Surface)	-62 to -57	-8.0 to -7.2	(Praamsma et al., 2009)
New Hampshire, USA (Snow)		-20.6 to -4.7	(Gazis and Feng, 2004)
Arctic Ocean (Brine - ice melt)		4.06 to 4.40	(Rasmussen and Thomsen, 2009)
Ocean Water (Surface)		0.5	(Craig, 1965)
Tap water			
Utah, USA	-124.7 to -120.3	-16.9 to -15.8	(Jameel et al., 2016)
Africa	-54.5 to 17.5	-7.7 to 2.9	(West et al., 2014)
Desalinated water			
Korea (Bottle)	-4 to -1	-0.7 to -0.2	(Kim et al., 2012)

Australia

Rainfall			
Perth, Western Australia	-16.3 to -6.4	-4.18 to 1.45	(IAEA 1981)
Adelaide, Australia	-19.13	-4.1	(Crosbie et al., 2012)
Adelaide, Australia	-98.4 to 31.3	-12.41 to 2.55	(Guan et al., 2013)
Adelaide, Australia	-31.5 to -2.8	-5.56 to -1.11	(IAEA 1981)
Tasmania		-10.40 to -1.50	(Treble et al., 2005)
Groundwater			
South Mt. Lofty Ranges (SA)	-32.1 to 21.7	-5.98 to -4.00	(Guan et al., 2009)
Adelaide Metropolitan (SA) (November)	-24 to -17	-5.1 to -3.5	(Lamontagne et al., 2005)

Willunga Basin (SA) (November)	-25 to -19	-5.0 to -4.1	(Lamontagne et al., 2005)
Beachface Adelaide Metropolitan (SA) (November)	-35 to +16	-3.3 to +1.3	(Lamontagne et al., 2005)
Onkaparinga basin (SA)	-29 to -26.3	-5.74 to -5.52	(Green et al., 2007)
River Torrens catchment, (SA) (Fox creek)	-34.9 to -29.6	-6.11 to -5.86	(Green et al., 2007)
River Torrens catchment (SA) (Forreston Creek)	-26.2 to -21.9	-5.03 to -4.59	(Green et al., 2007)
Burra (SA)	-35.5 to -31.5	-5.69 to -5.53	(Banks et al., 2007a)
Bull Creek catchment (SA)	-5.27 to -5.11	-28.5 to -24.7	(Banks et al., 2007a)
Eden-Burnside Fault (SA)	-6.05 to -3.46	-28.2 to -16.3	(Green et al., 2010)
Victoria	-34 to -3	-4.8 to 1.5	(Herczeg et al., 1992)
Darwin	-46.1 to - 42.1		(Crosbie et al., 2012)
Northern Victoria (Upper aquifer)	-32.8 to -10.5	-4.8 to -0.4	(Chambers et al., 1996)
Surface Water			
Victoria (Lake)	-27 to -3	-3.8 to 0.9	(Herczeg et al., 1992)
River Murray	-51.5 to -1.2	-8.30 to -0.37	(Simpson and Herczeg, 1991a)
Desalinated water			
Adelaide Desalination Plant (Mineralised desalinated water)	0.95	7.73	(D Jardine 2017, personal communication, 20 February)

2.2 Influences of evaporation and precipitation on stable isotope ratios

Evaporation, condensation and diffusion processes during the transport of water between different reservoirs in the hydrological cycle can cause isotope fractionation, resulting in the variation of water isotopes (Gat, 1996, Gat et al., 2001, Tappa, 2013). During the condensation of water vapour, water molecules containing heavy isotopes move from water vapour to liquid, resulting in the isotope depletion in water vapour and the isotopic enrichment in the liquid. The fractionation during evaporation process results in the relative enrichment of light isotopes in water vapour, and heavy isotopes in the remaining water (Buttle, 2006)

This isotope fractionation results in an excess of heavier isotopes in seawater than evaporated water vapour and any subsequent rainfall. Dansgaard (1964) has found that the isotopic ratio values of precipitation decrease with latitude, altitude, distance of vapour transport, an amount of precipitation and increase with surface air temperature. The changes of the moisture's sources of meteoric water result in the variation of isotopic compositions of precipitation, and subsequently the variation of isotopic compositions of water input to the basin's surface water.

In arid and semi-arid climates, evaporation has strong influences on surface water; therefore, the isotopes of surface water on semi-arid climate regions alter significantly due to evaporation fractionation (Cappa et al., 2003). By hydrogen and oxygen isotopes, Simpson and Herczeg (1991a) have calculated the water loss by evaporation from the River Murray and irrigated land which can be up to 40±15% of water released from reservoirs. Since isotopic fractionation does not occur during root water uptake, the loss of water causing isotopic changes should be attributed to only evaporation, not evapotranspiration in total (Gat, 1996). Research into the semi-arid climate area by Yuan and Miyamoto (2008) shows that evaporation occurring in stream channels and middle basin can cause water loss up to 33% of stream water. The enrichment of water isotopes might increase with the distance of transport from upstream to downstream of rivers due to the evaporation or the mixing with the isotopically heavier water from other sources (Yuan and Miyamoto, 2008). The standing water from reservoirs, lakes and ponds is prone to evaporative fractionation more than flowing water on streams and rivers because the residence time is normally longer which allow water to have more time for evaporation (Darling et al., 2003). The evaporation of water in the reservoirs and their tributaries can result in the depletion of tap water isotopes (Bowen et al., 2007b, West et al., 2014).

The variation of water isotopes in rivers might result from accumulating discharge from their tributaries, thus integrating various hydrological processes from their sub-catchments (Simpson and Herczeg, 1991a, Ferguson et al., 2007). The abrupt isotopic changes downstream might be a result of water releasing from reservoirs and storages causing the mixing of various sources (Rank et al., 1998, Wyhlidal et al., 2014).

The isotopic compositions of surface water and groundwater are derived primarily from the precipitation that supplies them (Gat and Gonfiantini, 1981, Smith et al., 2002, Kendall and Coplen, 2001). The natural mixing at the rivers, creeks or artificial mixing through the water supplied networks and reservoirs from different sources of water results in the propagation of isotopic signatures from different sources, and the preservation of integrated signals of precipitation isotopes, contributing to water supplies (Bowen et al., 2007b).

2.3 The interpretation of water isotopic data

The GMWL and LMWL as references for water isotopic interpretation

The worldwide isotopic compositions of meteoric water were integrated to form GMWL as a baseline for the reference and comparison of other types of water from various reservoirs in the hydrological cycle (Craig, 1961, Rozanski et al., 1993). To the extent that the measurement arrays from the GMWL, important insights of the hydrologic processes can be derived (Machavaram et al., 2006). The evaporative influence on water causes isotopic data to deviate from the GMWL in a correlated way, forming an evaporation line. The deviated values tend to define a lower slope comparing to the slope of GMWL, which has the δ^2H over $\delta^{18}O$ ratio slope of 8 (Gibson et al., 1993). The slope values are critically decided by the atmospheric humidity in a particular area, with the lowest slope correlated with the lowest humidity (Darling et al., 2003).

Together with the GMWL, precipitation samples of any region are collected monthly to form LMWL of that region, which is useful to explain the relationship between the water and respective hydrological processes (Buttle, 1994, Cartwright et al., 2004, Kennedy et al., 1986, Machavaram et al., 2006, Sklash and Farvolden, 1979, Turner et al., 1987). However, the isotopic composition of precipitation may vary due to the variation of local hydrological and climatological conditions resulting in the changes in the relationship between δ^2H and $\delta^{18}O$ of precipitation (Hoefs and Hoefs, 1997). Therefore, interpretation of local water isotope results will be more useful to refer to LMWL for understanding the local water movement, sources and processes to which the water has been subjected (Dansgaard, 1964).

The LMWL for Adelaide was determined as $\delta^2H=7.95\times\delta^{18}O+11.6$ by Poulsen et al. (2006) which is in good agreement with the LMWL ($\delta^2H=7.5\times\delta^{18}O+11.2$) calculated for Bedford Park at the western foothills of the MLR (Kayaalp, 2001).

Deuterium excess as a tool to study evaporation

The deuterium excess (d-excess), defined from the equation d-excess = $\delta^2H - 8 \times \delta^{18}O$, is the second-order isotope parameter, used as an index to research the effect of evaporation on water isotopes (Dansgaard, 1964, Clark and Fritz, 1997). Its value is close to 10‰ for meteoric water (Craig, 1961) at the sea surface temperature of 25^{o}C and a relative humidity of 80% (Merlivat and Jouzel, cited in Guan et al, 2013). However, this value might vary significantly at regional scale (Yuan and Miyamoto, 2008, Cappa et al., 2003). The d-excess value of water vapour is defined as a function of humidity, surface temperature, isotopic compositions of ambient vapour and evaporating water (Cappa et al., 2003). The low d-excess value of water vapour is likely associated with high humidity, high d-excess values of ambient air masses and low d-values of evaporating water (Cappa et al., 2003, Yuan and Miyamoto, 2008). Evaporative processes have significant impact on the d-excess value of precipitation. Rainwater has higher d-excess values when it evaporates as falling through relatively dry air, known as amount effect (Dansgaard, 1964, Clark and Fritz, 1997).

The d-excess value calculated for rainfall at the Adelaide station (Global Network of Isotopes in Precipitation (GNIP) stations by the International Atomic Energy Agency (IAEA) and the World Meteorological Organisation) is 13.68‰ which is higher than global average d-excess value of about 10‰ (Crosbie et al., 2012) which might be under influence of convective rainfall (Guan et al., 2013). The data from six GNIP stations shows that d-excess varies throughout year and the low d-excess during summer is likely to be a result of subcloud processes or from different moisture sources (Guan et al., 2013).

2.4 Stable water isotopes provide a useful tool to trace the sources of water

There has been a variety of studies on using the water isotopes as a method to investigate the groundwater recharge and/or residence time in South Australia in general and Adelaide in particular (Green et al., 2007, Banks et al., 2007b, Banks et al., 2007c, Banks et al., 2007a, Tweed et al., 2011, Lamontagne et al., 2005, Love et al., 1994, Poulsen et al., 2006). It is an efficient tool to research the hydrology of a catchment (Bestland et al., 2009, Bestland et al., 2017). However, researches on stable isotopes of tap water are still limited.

The study into the spatiotemporal pattern of tap water with the purpose to understand the dynamics of urban water system structure was given more attention in the USA (Bowen et al., 2007b, Jameel et al., 2016, Chesson et al., 2010b, Chesson et al., 2010a, Kennedy et al., 2011) or South Africa (Kennedy et al., 2011). The stable isotopes of tap water preserve the information of water sources provisioning the water demand and environmental pressure, and provide indicators to identify the impacts of human water usage on the ecological and hydrological system (Bowen et al., 2007a). If samples are well-preserved, information on isotopes of water samples can be kept for more than 15 years without being significantly affected, a limited set of tap water samples is adequate to present the variation of stable isotope across a large area (Förstel et al., 1997). The tap water database can provide geospatial pattern and local variability of isotope on which the archaeological data can be interpreted (Bowen et al., 2007a). The spatiotemporal variation of tap water isotopes was studied by identifying locations of human scalp hair in forensics science (Kennedy et al., 2011). Stable isotopes of tap water were applied to identify the sources of milk products (Chesson et al., 2010a) or drink products (Chesson et al., 2010b). The spatial pattern of tap water isotopes is an efficient mean to research the water stress and the changes in the environmental condition of water sources and complexity of urban supply systems (Bowen et al., 2007a, Jameel et al., 2016). When it is coupled with the other sources of water in the hydrological systems, it can be a good tool to identify the sources and quantify the mixing of various sources of water supply (Bowen et al., 2007a). Such studies about the isotopes of tap water coupling with surface water have not been conducted in Australia in general and the Adelaide metropolitan area in particular.

CHAPTER 3: STUDY AREA

3.1 Location

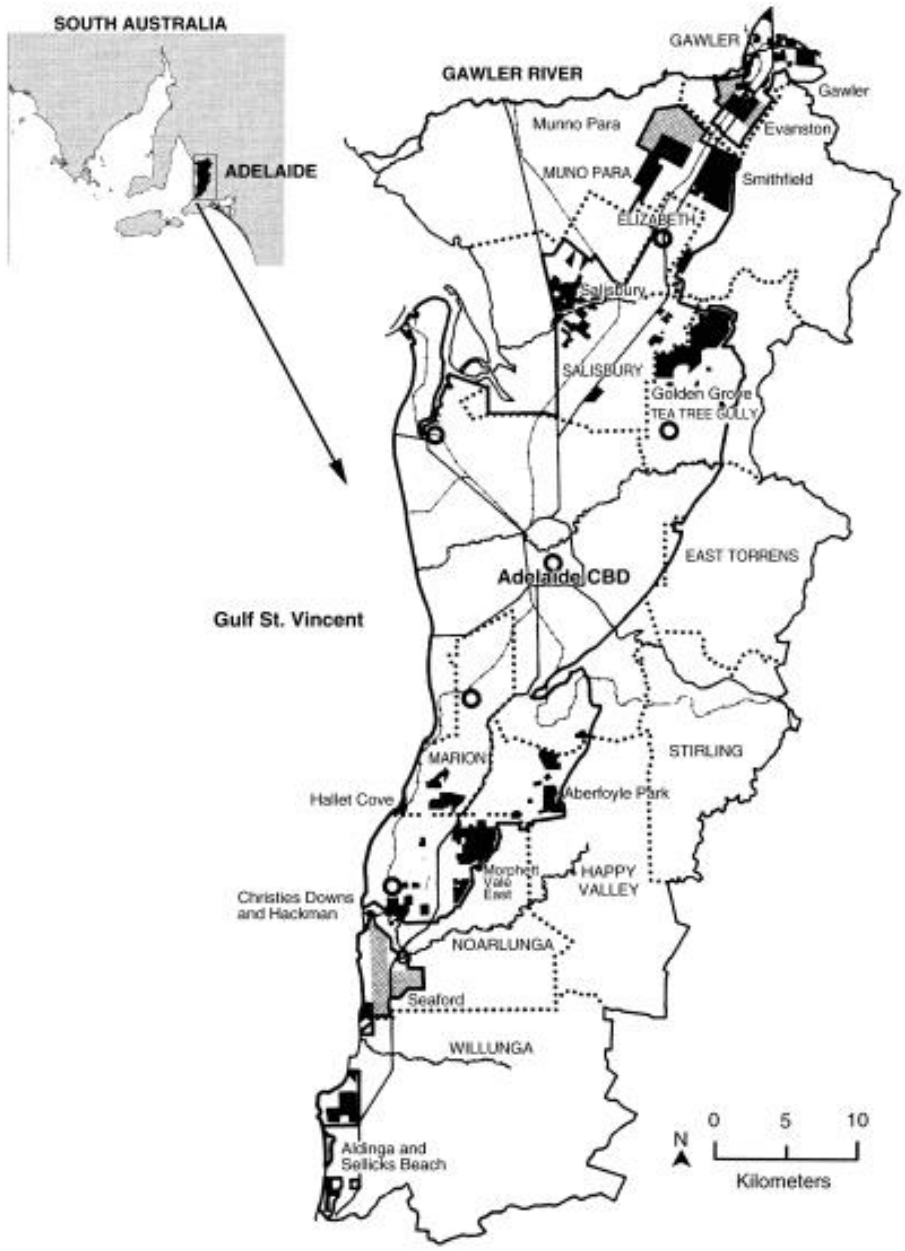

Figure 3.1 Maps of the Adelaide metropolitan area, Australia.

Source: reproduced from: Tait et al. (2005).

The Adelaide metropolitan region is located at the southern side of South Australia, Australia, between Gulf St. Vincent to the south-west side and low-lying Mount Lofty Ranges to the east side, (figure 3.1). The Adelaide metropolitan region is defined by the Australian Development

Act 1993 as the area spanning a length of 80 km from the north at Gawler River to south at Sellicks Beach, covering an area of larger than 1,850 km^2.

The Adelaide Metropolitan area is divided into 4 regions with 19 councils, namely: Eastern (Prospect, Walkerville, Norwood Payneham and St. Peter, Campbelltown, Burnside, Unley, Adelaide Hill and Adelaide), Northern (Playford, Salisbury, Tea Tree Gully and Gawler), Western (Charles Sturt, Adelaide Port Enfield and West Torrens) and Southern Adelaide (Holdfast Bay, Mitcham, Marion and Onkaparinga). This political boundary between these councils does not limit the utility service.

3.2 Climate

The Adelaide metropolitan area has a semi-arid Mediterranean climate with annual precipitation of 534.2 mm, hot summers with average maximum temperature of 23.6^oC and cold and wet winters with average minimum temperature of 12.5^oC (BOM 2016a). The mean daily maximum and minimum temperature and total rainfall recorded at Adelaide (Kent Town) station located 2.2 km away from Adelaide are presented in table 3.1. Average temperatures and annual precipitation in the last 4 years (2011-2014) were approximately 17.9^oC and 526.65 mm, respectively, which were considerably close to the long-term averages. 2016 had the abnormally highest annual precipitation in last 6 years with an increase of 214.1 mm compared to normal annual average temperature and total precipitation measured over 30 years from 1986 to 2015 (table 3.1). The monthly total precipitation in 2016 during the study period was 131.2 mm in September and 81.0 mm in October with September being the highest monthly precipitation occurring in 2016 (BOM 2016a). The adjoining Mount Lofty Ranges receives annual precipitation from 300 mm to above 1000 mm with an annual average of 600 mm, which is the main resource of surface water and groundwater for the Adelaide metropolitan area (Guan et al., 2009). The mean daily maximum and minimum temperature for the months August 2016 to October 2016, the period of the research, were 19.24^oC and 9.83^oC respectively (BOM 2016a).

Table 3.1 Annual total precipitation, annual average temperature and their deviation from long-term average measured at the Adelaide metropolitan*

Year	Average Precipitation (mm)	Deviation (mm)	Average Temperature (°C)	Deviation (°C)
2011	537.8	1.5	17.5	0.1
2012	527.2	9.1	17.6	0.2
2013	507.4	-28.9	18.5	1.1
2014	534.2	-2.1	18.2	0.8
2015	395.2	-141.1	17.8	0.4
2016**	750.4	214.1	17.4	0.05

**The normal annual average temperature and total precipitation measured over 30 years (1986-2015) are 17.4°C and 536.3 mm, respectively. (Source: Bureau of Meteorology Climate data, http://www.bom.gov.au/climate/data/).*

********The annual values are calculated for the individual year from 1 January to 31 December. The precipitation and average temperature of 2016 are calculated until 24 December 2016.*

Source: reproduced from BOM (2016a)

The Adelaide metropolitan area has a total annual average pan evaporation varying from 1600-1800 mm where the north region experienced higher pan evaporation than the south region (BOM 2016b). During the study period, the total monthly average pan evaporation in September is from 60 mm to just under 80 mm while in October, the monthly average pan evaporation varies from 125 mm to 150 mm (BOM 2016b).

3.3 Surface water and drainage system in the Adelaide metropolitan area

The Adelaide metropolitan region can be divided into 5 major catchments with their area in this research as presented in table 3.2. The classification of those major catchments (major rivers) and major creeks (streams) is defined by Adelaide Coastal Waters Study Steering Committee that the major catchments have the total area which is larger than 200 km^2 in the study area (Wilkinson et al., 2005).

Table 3.2 Major catchment in the Adelaide metropolitan area

No.	Catchment	Area (km^2)	Major rivers and creeks	Main reservoirs
1	Gawler	883.3	North Para River South Para River	Warren South Para Barossa
2	Smith Creek	205.6	Smith Creek Little Para River Dry Creek Cobbler Creek	Little Para
3	Torrens	218.4	First to Fifth Creeks (Torrens River)	Millbrook Kangaroo Creek
4	Patawalonga	212.3	Sturt River Brownhill Creek Keswick Creek	
5	Onkaparinga	171.8 (lower part) 383.2 (upper part)	Onkaparinga River Field River Christie Creek Waterfall Creek Peddler Creek Maslin Creek Willunga Creek Sellicks Creek Silver Sands Creek	Happy Valley Mount Bold

Source: reproduced from: Wilkinson et al. (2005) and ECA (1991)

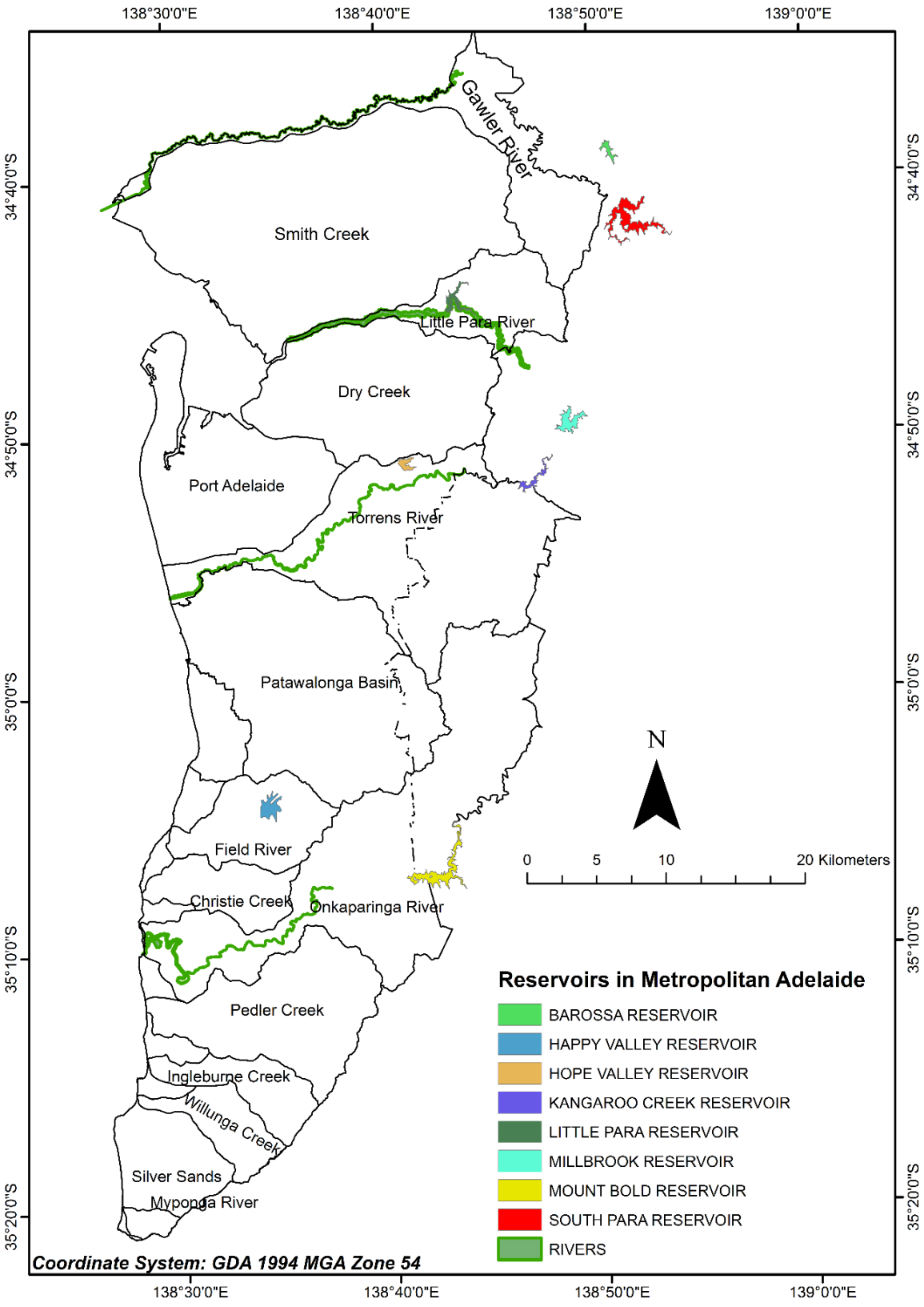

Figure 3.2 The major catchments and sub-catchments in the Adelaide metropolitan

Source: reproduced from: DEWRN (2014)

Figure 3.2 presents some major catchments with their rivers and creeks, including the Torrens, Gawler, Smith system, Patawalonga and Onkaparinga. These catchments except the Patawalonga constitute significant water resource infrastructure in the Adelaide metropolitan area (Wilkinson et al., 2005). Many natural and constructed wetlands in those catchments are connected to each other by natural temporary and permanent creeks or urban drainage (Walker and Hurl, 2002). These drainage and creeks are well-organised to drain water from surrounding industrial areas and urban areas to different ponds in wetlands, in which water is treated and returned to wetlands for different purposes, including watering parks and gardens or injected into aquifers.

The urbanised drainage of those catchments responds to rainfall all year round while the rural catchments where the soil moisture is extremely low only produce the significant runoff from July and October (Wilkinson et al., 2005).

3.4 Tap water supply system in the Adelaide metropolitan area

The Adelaide metropolitan water supply network that is operated by SA Water has major impacts on the natural flow of rivers and creeks over the catchments (Wilkinson et al., 2005). The natural catchments are split effectively by the water supply management operations and infrastructure between upstream and downstream where downstream of water supply systems serve the purpose of catchment area as stormwater contributing areas and stormwater drainage (Wilkinson et al., 2005). To collect the surface runoff from modified natural pathways and drainage networks, eight stormwater harvesting and reuse projects have been implemented in the Adelaide metropolitan area, along with the building of various wetlands to store stormwater for treatment (DEWNR 2014). The treated stormwater from these wetlands will be injected into aquifer(s) for future recovery (MAR) (Ringleb et al., 2016, Gale, 2005, Dillon et al., 2009b, Dillon et al., 2010, Dillon et al., 2009a).

In the Adelaide metropolitan area, tap water comes from three different raw sources for treatment including reservoirs, the River Murray and the Adelaide Desalination Plant (SA Water 2015a). There are 10 main reservoirs with different capacities to store water for various water treatment plants to supply the Adelaide metropolitan area as presented in table 3.3. These reservoirs receive water from different sources, including River Murray, major rivers and creeks and runoff in their own catchments. Most flows in the river and creeks across the metropolitan area are diverted by farm dams in the upstream catchments or by the reservoir and weir storage for water supply.

Table 3.2 The reservoirs providing water to the Adelaide metropolitan and sources of input

No.	Metro Reservoir	Capacity (GL)	Sources of input*
1	Barossa	4.4	RM, Warren Reservoir, South Para River
2	Happy Valley	12.7	RM, Mt Bold Reservoir, Onkaparinga River
3	Hope Valley	2.9	RM, Torrens River, Kangaroo Creek Reservoir, Millbrook Reservoir.
4	Kangaroo Creek	18.7	RM, Torrens River
5	Little Para	20.9	RM, Little Para River
6	Millbrook	15.7	RM, Torrens River
7	Mt Bold	46.5	RM, Onkaparinga River
8	Myponga	27.6	Myponga River
9	South Para	44.4	RM, South Para River
10	Warren	4.7	RM, South Para River
	Totals	198.5	

** RM: River Murray*

Source: reproduced from: SA Water (2015d) and Crawley and Dandy (1993)

The River Murray is one of the main raw water sources for the metropolitan reservoirs (excluding Myponga reservoir) pumped via two major pipelines, including Mannum-Adelaide and Murray Bridge-Onkaparinga (SA Water 2015b). In the North of the Metropolitan area, the Mannum-Adelaide pipeline is 60 km in length delivering water from Mannum to six reservoirs including Millbrook Reservoir, Kangaroo Creek Reservoir and Hope Valley Reservoir through the River Torrens and South Para Reservoirs, Warren Reservoirs and final destination to Barossa Reservoir. In the South of the Metropolitan, the second pipeline, Murray Bridge-Onkaparinga pipeline pumps river water from Murray Bridge through the Onkaparinga River to the Mount Bold Reservoir in Onkaparinga River, as well as the Summit Storage Water Treatment Plant before going to the Clarendon Weir where it is directed to the Happy Valley Reservoir (SA Water 2015b). The River Murray water varies from 42% of Adelaide water supply during moderate rainfall season up to 90% in dry seasons (Crawley and Dandy, 1993). The Myponga Reservoir located around 60 km south of Adelaide receives its water from the Myponga River and it supplies 5% of Adelaide city water supply (Thomas et al., 2000).

Desalinated water from the Adelaide Desalination Plant introduced in 2011 into the water tap supply is distributed to the Happy Valley Water treatment plant for the distribution (Water, 2008). Desalinated seawater is estimated to supply 28% of South Australia's total tap water in the 2013-2014 period (SA Water n.d.). At full capacity, it can provide 50% of Adelaide's annual water need; however, this varies over time (SA Water 2017). The Adelaide Desalination Plant operated at 10% of its capacity that supplied 5% of Adelaide's tap water currently in 2016 (SA Water 2017).

All these raw water sources are sent to the water treatment plants. Table 3.3 presents the water treatment plants with their designed capacity and raw water sources supplying the Metropolitan area. Capacities of the metropolitan water treatment plants range from 50 ML per day (Myponga) to 850 ML per day (Happy Valley) (SA Water 2012).

Table 3.3 Water treatment plants and their designed capacity and raw water supply sources in the Adelaide metropolitan area

No	Water Treatment Plant	Designed capacity (ML/day)	Supply Source
1	Anstey Hill	313	RM* / Millbrook Reservoir*
2	Barossa	160	RM / Barossa Reservoir* / South Para Reservoir / Warren Reservoir
3	Happy Valley	850	RM / Happy Valley Reservoir* / Mt Bold Reservoir
4	Hope Valley	273	RM / Hope Valley Reservoir* / Kangaroo Creek Res. / Millbrook Res.
5	Little Para	160	RM / Little Para Reservoir* / Millbrook Reservoir
6	Myponga	50	Myponga Reservoir*
7	Adelaide Desalination Plant	300	Seawater*
	Total	1,864	

** The main sources of Water Treatment Plant*

Source: reproduced from SA Water (n.d.)

The tap water in the Adelaide metropolitan area is mainly supplied by eight water supply systems and their sources of supply as presented in the table 3.4.

Table 3.4 Water supply systems and supply sources in the Adelaide metropolitan

No.	Water Supply System	Water Treatment Plant (WTP)	Supply Source
1	Barossa Metro	Barossa WTP	Res / RM
2	North Metro	Anstey Hill / Happy Valley / Barossa / Little Para WTPs / ADP	Res / RM / ADP
3	Anstey Hill Metro	Anstey Hill WTP	Res / RM
4	East Metro	Anstey Hill / Happy Valley WTPs / ADP	Res / RM / ADP
5	West Metro	Anstey Hill / Happy Valley / Hope Valley WTPs / ADP	Res / RM / ADP
6	Central Metro	Happy Valley WTP / ADP	Res / RM / ADP
7	South Metro	Happy Valley / Myponga WTPs/ ADP	Res / RM / ADP
8	Myponga Metro	Myponga WTP	Res

**Res: Reservoir*
**RM: River Murray*
**ADP: Adelaide Desalination Plant*

Source: reproduced from: SA water (n.d.).

When the North South Interconnection System (NSIS) project of SA water is completed to connect the Southern and Northern supply systems, water from Adelaide Desalination Plant will be delivered from the Central Metro to other supply systems on the North of Adelaide (SA Water 2015a). The water supply systems will be interconnected to provide enough reliable water with flexibility and functionality of the distribution system. This will add more complexity to the water supply systems.

CHAPTER 4. METHODOLOGY

4.1 Water sampling

4.1.1 Tap water sampling

To characterise the spatial pattern of tap water isotopes, the water samples were taken from between 10th September and 7th October, during early Spring. In all, 70 samples of tap water were collected across all 19 councils (figure 4.1). Most samples were collected from public water fountains and a small subset was collected from private houses from different councils across the Adelaide metropolitan regions. The water samples were collected in the different days and hours during the day. At each site, samples were collected by running the cold tap water for 20 seconds and after 3-fold cleaning of a 50-ml bottle. The bottle was subsequently capped and labelled, preserved at 4^{o}C in cold room before the isotope analysis. It is assumed that the fractionation of isotopes insignificantly occurs during water distribution within pipelines.

4.1.2 Surface water sampling

Sampling protocol follows IAEA guidelines to obtain samples for isotopes hydrology (IAEA n.d.) The samples are collected uniformly at the 10-cm depth to the water surface into polyethylene bottles, capped to avoid evaporation, then storage at the 4^{o}C before analysis. The water samples were filtered through 0.45-µm pore-size filter to remove suspended solids.

There were 64 surface water samples collected from five major catchments as presented in figure 4.1 between 17th September and 6th October 2016. The water samples were mainly collected from wetlands on the major catchments and major creeks, which drain water from their watersheds, presented in table 4.1. For each major catchment, water from creeks and rivers was drained between different ponds in a wetland for treatment and storage. Wetland water was sampled from the middle ponds to the storage pond (se appendix 1). The samples in the Gawler Catchment were collected at the Clonlea Reserve Wetland and the Gawler River in North Para sub-catchment. The water samples were also collected from different wetlands and creeks in Smith system drainage including Smithfield Wetland (Smith Creek), Waterside Wetland (urban drainage), Andrews Farm Wetland (Smith Creek), Curtis Wetland (Muno Para urban drainage), Kaurna Wetland (urban drainage), and Springbank Wetland (urban drainage). This catchment has a number of natural streams and rivers, and a network of stormwater drainages connected at some points to drain stormwater to Barker Inlet. The water samples

from Torrens system were collected at sections flowing through Adelaide CDB. In the Patawalonga Catchment, water samples were taken at the Sturt River (Warriparinga Wetland and Oaklands Wetland) and Brownhill Creek. Wetland samples were also taken from Christie Wetland (Christie Creek), Dalkeith rd. Wetland on Peddle Creek and Onkaparinga Wetland on the Onkaparinga River. For the major creeks in Onkaparinga Catchment, water samples were collected from Byards Wetland on Field Creek, Aldinga Wetland (urban drainage), Hard Road Wetland (urban drainage), Acacia Terrace Wetland from urban drainage.

Since River Murray has provided a large part of tap water of the Adelaide metropolitan area, one sample of River Murray was collected at Murray Bridge where the river water was channelled to the reservoirs. Three samples were also collected from Lake Alexandrina (Milang) and Lake Albert (Meningie). Figure 4.1 presents the sampling location of both tap water and surface water. In the inset, the Adelaide metropolitan is shaded white over yellow background, and the extent of study area is indicated in white colour over grey background with 19 councils. The River Murray, Lake Alexandrina and Lake Albert are shaded green. The tap water sampling sites are denoted in red dots; the surface water sampling sites is marked in blue triangle dots.

All the water samples were collected and preserved in the cold room at 4^{o}C for isotope analysis. The isotope analysis of samples was conducted within one week of storage.

Table 4.1 The sampling locations in major catchments and major creeks and River Murray

Major catchment	Sampling location	Sample number
The Gawler	Clonlea Reserve Wetland Gawler River at North Para sub-catchment	3
Smith system	Wingfield Wetland (Dry Creek) Smithfield Wetland (Smith Creek) Waterside Wetland (Urban drainage) Andrews Farm Wetland (Smith Creek and Muno Para drainage) Curtis Wetland (Muno Para urban drainage) Kaurna Wetland (Urban drainage) Springbank Wetland (Urban drainage)	24
Torrens system	Torrens River	2
The Patawalonga system	Warriparinga wetland and creeks (Sturt River), Oaklands Wetland (Sturt River) Mitcham Reserve Stream (Brownhill Creek)	7
The Onkaparinga	Onkaparinga (Onkaparinga River) Dalkeith rd. Wetland (Peddle Creek) Christie Wetland (Christie Creek) Byards Wetland – (Glenloth Creek to Field Creek) Aldinga Drainage - Bayside Ave Aldinga Wetland – (Urban drainage) Hard Road Wetland – (Urban drainage) Acacia Terrace Wetland – (Urban drainage)	23
River Murray	River Murray – Murray Bridge Lake Alexandrina - Milang Lake Albert - Meningie	2 2 1
Total		**64**

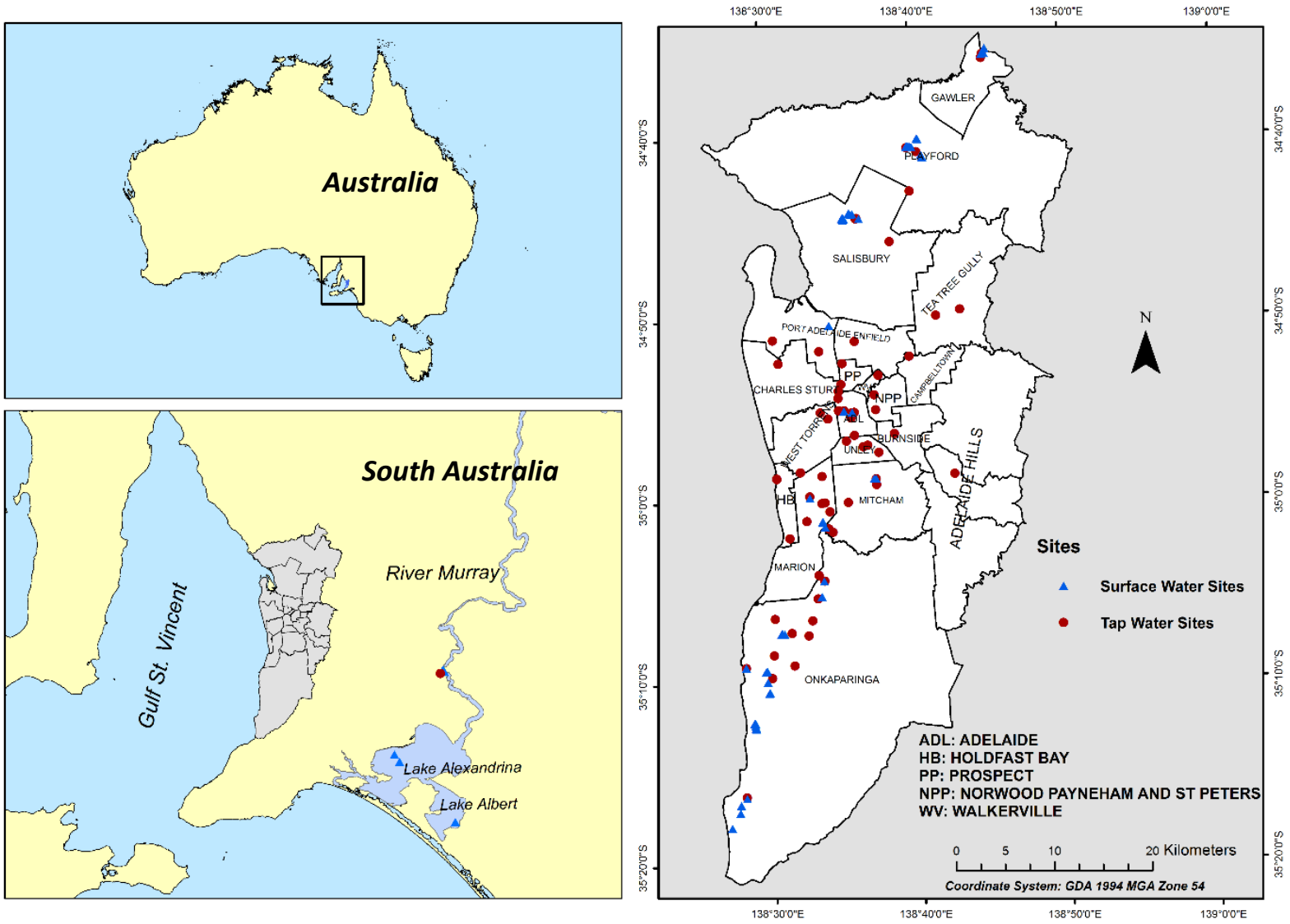

Figure 4.1 Location of the Adelaide metropolitan area showing sampling locations for this study

4.2 Stable water isotope analysis by laser-isotopic water cavity ring-down spectroscopy

Laser-Isotopic Water Cavity ring-down spectroscopy (CRDS) is a direct laser absorption technique to determine the δ^2H and $\delta^{18}O$ in water samples (Brand et al., 2009). CRDS has significantly higher sensitivity than conventional absorption spectroscopy such as Isotopic Ratio Mass Spectrometry (IRMS) (Godoy et al., 2012). It allows the direct detection of δ^2H and $\delta^{18}O$ without sample preparation (Godoy et al., 2012). The deuterium variability in natural samples is small which required an analytical precision of 0.15 ppm (1‰) (Brand et al., 2009). Isotopic fractionation of ^{18}O is even smaller and less abundant than ^2H which requires higher precision (<0.02 ppm or <0.1‰) (Brand et al., 2009). The Picarro CRDS L2130i experiments achieve a precision of 0.011‰ and 0.038‰ for δ^2H and $\delta^{18}O$ simultaneously for liquid samples, respectively (Picarro 2012). However, the Picarro CRDS measurements can be susceptible to organic contaminants (Brand et al., 2009, West et al., 2010).

The δ^2H and $\delta^{18}O$ of water samples were measured by Picarro Isotopic Water Cavity Ring Down Spectrometry (Picarro, P/N L2130-i) (Santa Clara, USA) for liquid water isotopic analysis. The CRDS analyser comprises a PAL auto sampler (Santa Clara, USA), vaporizer with injection port, a diode laser (1392 nm) and a 35-mL cavity ring-down cell to analyse water vapour (see appendix 2).

After the setup of the Picarro CRDS instrument is confirmed, the analysis is automatically proceeded as following sequential steps. The nitrogen as the carrier gas is pumped into the system. The microsyringe undergoes a three-fold cleaning step, and flushed with dry-air before 1.8 µL of liquid sample is injected into the vaporizer, which is kept at 110^{o}C. Water vapour from a sample is mixed with nitrogen to equilibrate in the vaporizer in 90 seconds and goes into the CRDS cell with a constant flow rate of 30 mL/min. The absorption peak areas are measured each 3 seconds in 3 minutes and the average values are computed. A complete cycle of a single injection lasts around 9 minutes. The number of injections needed per sample is one of the most important issues with respect to sample throughout and analytical costs (Geldern and Barth, 2012). Each sample was analysed eight times by eight consecutive injections, only the last three injections were considered into the average calculation of isotopic value. The first four injections were excluded from analysis to avoid memory effect.

The samples were analysed along with a set of three laboratory reference waters (DESAL0.95‰, 7.73‰; RAIN -8.62‰, -52.76‰; EVIAN -10.26‰, -73.28‰ for δ^2H and $\delta^{18}O$, respectively). The DESAL standard was re-mineralised from desalinated water from the

Adelaide Desalination Plant. These artificial standards were prepared by Flinders Analytical of the Faculty of Science and Engineering (Flinders University, Australia). They provide a wide range of $^{2}H/^{1}H$ ratio isotopic compositions of -73.28‰ to 7.73‰. This range is much smaller for oxygen isotopes with the value from -10.26‰ to 0.95‰. The measurement sequence observed as DESAL RAIN EVIAN – six samples - DESAL RAIN EVIAN.

The post-analysis was screened by Picarro Chemcorrect^{TM}. A total of 70 analysed results of tap water samples and 64 of surface water are for subsequent data analysis and interpretation (see appendix 3 and 4).

4.3 Spatial mapping of stable isotopes

All the spatial mappings were performed using ArcGIS geographic information system (GIS) software version 10.3.1 (Environmental Research Systems Institute). Coordinates of sampling sites were recorded in the field with Garmin handheld GPS unit. The maps of the catchment boundary were derived from South Australian Government Data Directory (https://data.sa.gov.au/). The background image of water supply zones was derived from SA Water (n.d.).

CHAPTER 5: RESULTS

5.1 Water isotopes of the Adelaide metropolitan area

Table 5.1 presents the descriptive statistics of stable isotopic compositions of different waters. Surface water isotopes ranged from -5.38‰ to 0.26‰ for $\delta^{18}O$ and -31.34‰ to 12.87‰ for $\delta^{2}H$, with the d-excess ranging from 0.28‰ to 17.25‰ (average $\delta^{18}O$: -3.16‰, $\delta^{2}H$: -13.33‰, d-excess 11.94‰; n = 59). The lowest value of $\delta^{18}O$ (-5.38‰) was at the second pond of the Smithfield Wetland (Smith system) and highest value of $\delta^{18}O$ (0.26‰) was at the mouth of the River Onkaparinga (Onkaparinga Catchment). Deuterium has the lowest value (-31.34‰) at the second pond of the Smithfield Wetlands (Smith system) and the highest value (12.87‰) at the first pond of the Smithfield Wetland (Smith system).

Table 5.1 The descriptive statistics of stable isotopic compositions of different waters*

Type of water		**n**	**$\delta^{18}O$ (‰)**	**$\delta^{2}H$ (‰)**	**d-excess (‰)**
Surface water	Average	59	-3.16	-13.33	11.94
	SD		1.17	7.88	3.12
	Minimum		-5.38	-31.34	0.28
	Maximum		0.26	12.87	17.25
	Range		5.64	44.22	16.98
Tap water	Average	69	-3.12	-17.28	7.64
	SD		0.91	4.73	2.75
	Minimum		-5.37	-26.27	-5.93
	Maximum		1.42	5.47	16.69
	Range		6.79	31.74	22.62
Murray Bridge Tap		1	-4.93	-29.07	10.36
River Murray **		2	-5.05	-29.21	11.21
Lake Alexandria **		2	-0.54	-4.13	0.20
Lake Albert		1	2.13	15.85	-1.22
De-mineralised desalinated water***		1	0.95	7.73	0.13

Statistics shown include average, standard deviation (SD), minimum, maximum, range, and a number of samples (n). The value of isotopes expressed in ‰ relative to Vienna Standard Mean Ocean Water (VSMOW). ** Isotope value is the average value of two samples * Desalinated water was re-mineralised from raw desalinated.*

Tap water isotopes ranged from -5.37‰ to 1.42‰ in $\delta^{18}O$ in -26.27‰ to 5.47‰ in $\delta^{2}H$ with d-excess ranging from -5.93‰ to 16.69‰ (average $\delta^{18}O$: -3.12 ‰, $\delta^{2}H$: -17.28‰, d-excess 7.64‰; n = 69). The lowest values of both $\delta^{18}O$ and $\delta^{2}H$ were recorded at Mount Lofty Summit (-5.37‰ and -26.27‰, respectively) while Gawler has the highest values of both $\delta^{18}O$ and $\delta^{2}H$ (1.42‰ and 5.74‰, respectively). Desalinated water from Adelaide Desalination Plant has substantial enrichment with heavy isotopes (0.95‰ for $\delta^{18}O$ and 7.73‰ for $\delta^{2}H$) and low d-excess at 0.13‰. River Murray and Murray Bridge tap water have a similar isotope distribution at around -5‰ for $\delta^{18}O$ and -29‰ for $\delta^{2}H$. Lake Alexandria and Lake Albert have high values of isotopes, even positive values for Lake Albert.

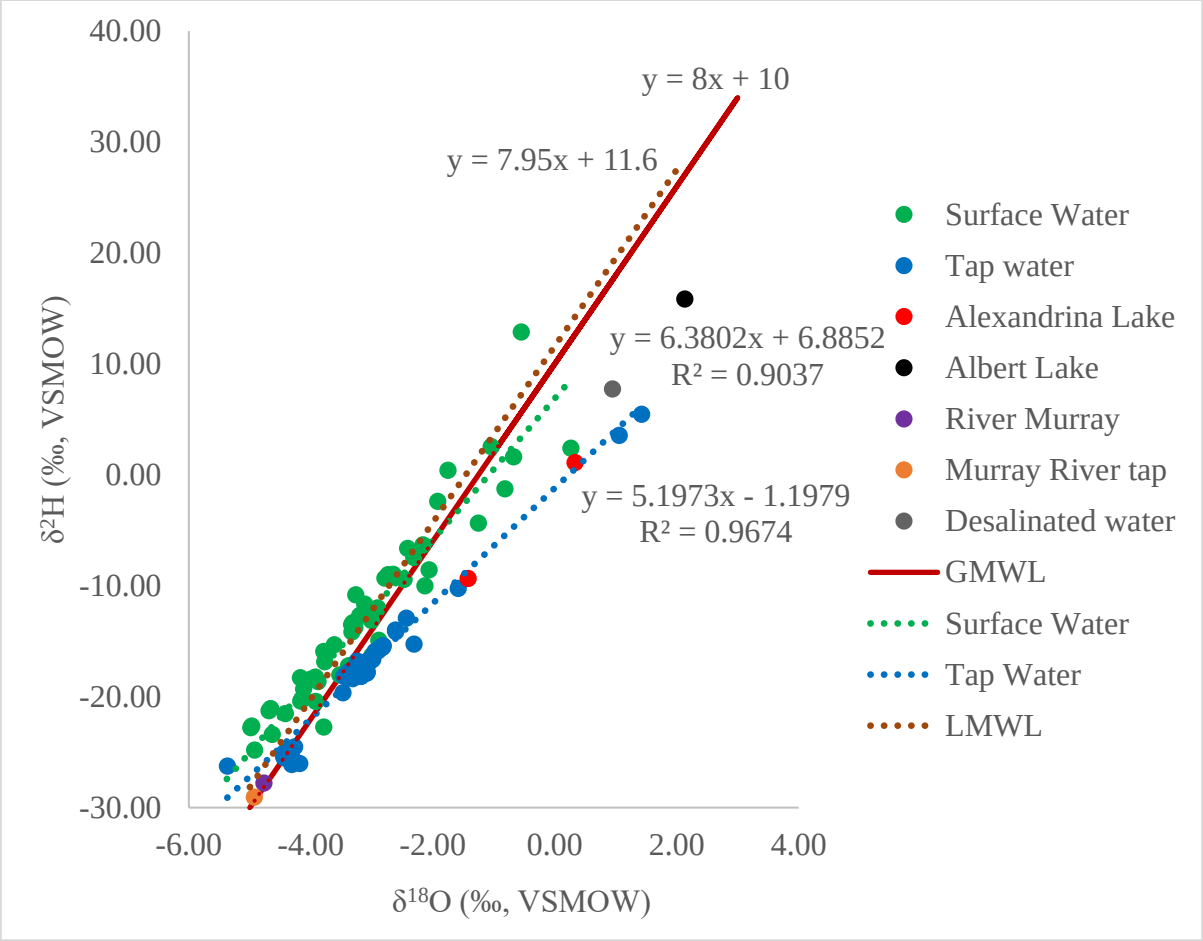

Figure 5.1 The $\delta^{2}H$ and $\delta 1^{8}O$ of tap water, surface water in the Adelaide metropolitan. GMWL, $\delta^{2}H = 8 \times \delta^{18}O + 10$ denoted in red line. LMWL, $\delta^{2}H = 7.95 \times \delta^{18}O + 11.60$ denoted in red dash

Figure 5.1 presents a dual isotope plot of $\delta^{18}O$ and $\delta^{2}H$ of different water in the Adelaide metropolitan area, along with two different lines GMWL reported by Craig (1961) and LMWL reported by Poulsen et al. (2006). Some of the tap water and surface water data points approach

the GMWL and LMWL of Adelaide at the lower ends, however, a majority of them array from the GMWL, particularly tap water points that fall far under GMWL and LMWL. Stable isotopic values of water from the River Murray and tap water from Murray Bridge region stay on or very close to the GMWL at the lower end. The water samples from Lake Alexandrina fell on the tap water line.

5.2 Spatial pattern of tap water isotopes

Figure 5.2 presents the δ^2H and $\delta^{18}O$ of tap water from various water supply zones in the Adelaide metropolitan area over the LMWL.

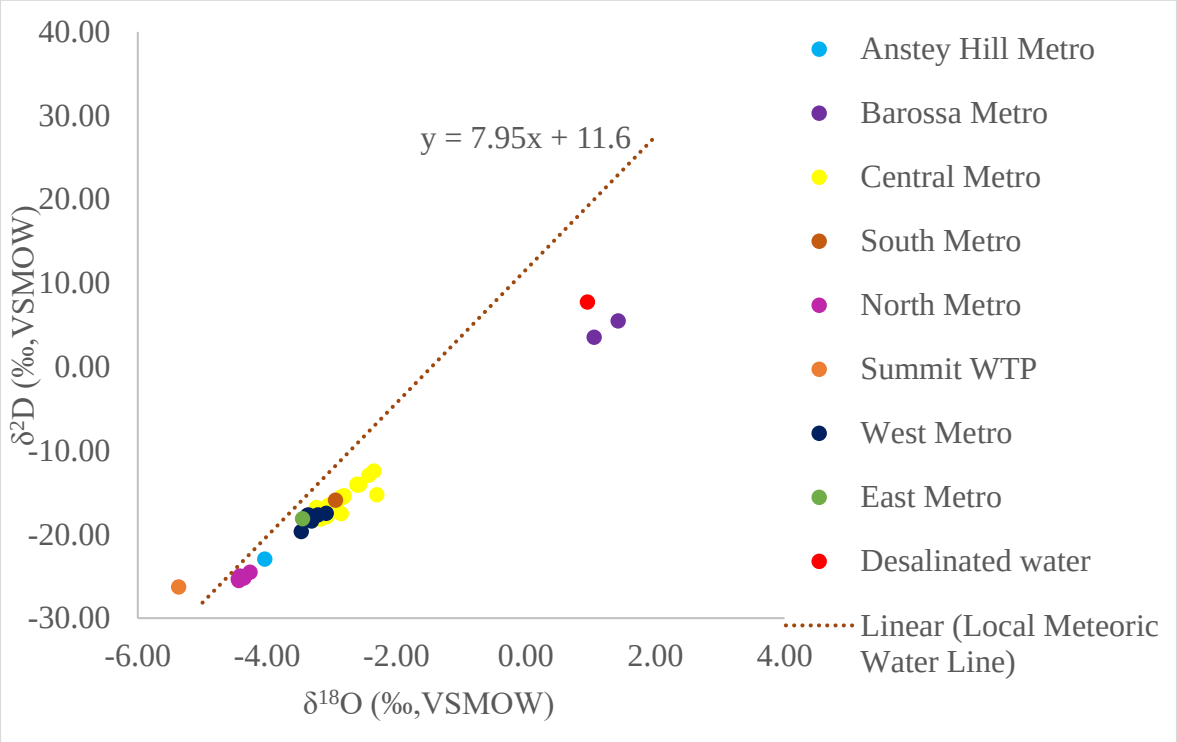

Figure 5.2 The δ^2H and $\delta^{18}O$ of tap water from various water supply zones in the Adelaide metropolitan over the LMWL

From the figure, stable isotopes of all the tap water samples fell under the LMWL, except the water from Summit Water Treatment Plant (WTP). The water isotopes from Central Metro, South Metro, West Metro and East metro tend to cluster in the middle with the δ^2H ranging from -20‰ to -10‰ and $\delta^{18}O$ ranging from -4‰ to -2‰. Water isotopes from the Barossa Metro with positive values fell down far from the LMWL while the North Metro has isotope water staying close to LMWL. The water sample collected from Summit WTP has stable isotopes falling over the LMWL. Desalinated water from Adelaide Desalination Plant has stable isotopes deviating from LMWL.

Since there were not enough samples taken in the Southeast of Metropolitan Adelaide, the spatial analysis focuses on the Northern and Eastern part of the Adelaide metropolitan. The figure 5.3 and 5.4 present the spatial distribution of stable isotope of tap water over the various water supply zones that are supplied by SA water. Visual inspection of tap water isotopes shows geographically clustered of both $\delta^{18}O$ and $\delta^{2}H$ according to each water supply area. There was a distinct area of more positive values of both $\delta^{18}O$ and $\delta^{2}H$ in Gawler at the Northern region where the tap water was supplied by the Barossa Metro system from Barossa Reservoir. The most negative values of $\delta^{18}O$ and $\delta^{2}H$ were measured in the Northern area where the tap water is supplied by the North Metro system and Anstey Hill Metro. The isotope values are stable across the areas supplied by the same systems. This observation also occurs in the Northwest area where tap water was supplied by West Metro system. Figure 5.5 presents the spatial distribution of d-excess of tap water over various water supply zones. The d-excess values of North Metro system, Anstey Hill Metro and West Metro were stable around 10‰ which is close to the observed global mean d-excess in precipitation (Pfahl and Sodemann, 2014). In the Southern part of the Adelaide metropolitan, where the tap water is mainly supplied by the Central Metro system, the isotopic values vary in a wider range from -3.35‰ to -2.30‰ for $\delta^{18}O$ and -22.9‰ to -12.42‰ for $\delta^{2}H$, leading to the fluctuation of d-excess values in a wide range. There is one sample from South Metro system which water isotopes range from -3.04‰ to -2.92‰ for $\delta^{18}O$ and -15.25‰ to -12.42‰ for $\delta^{2}H$. Its d-excess value is around 7.5‰.

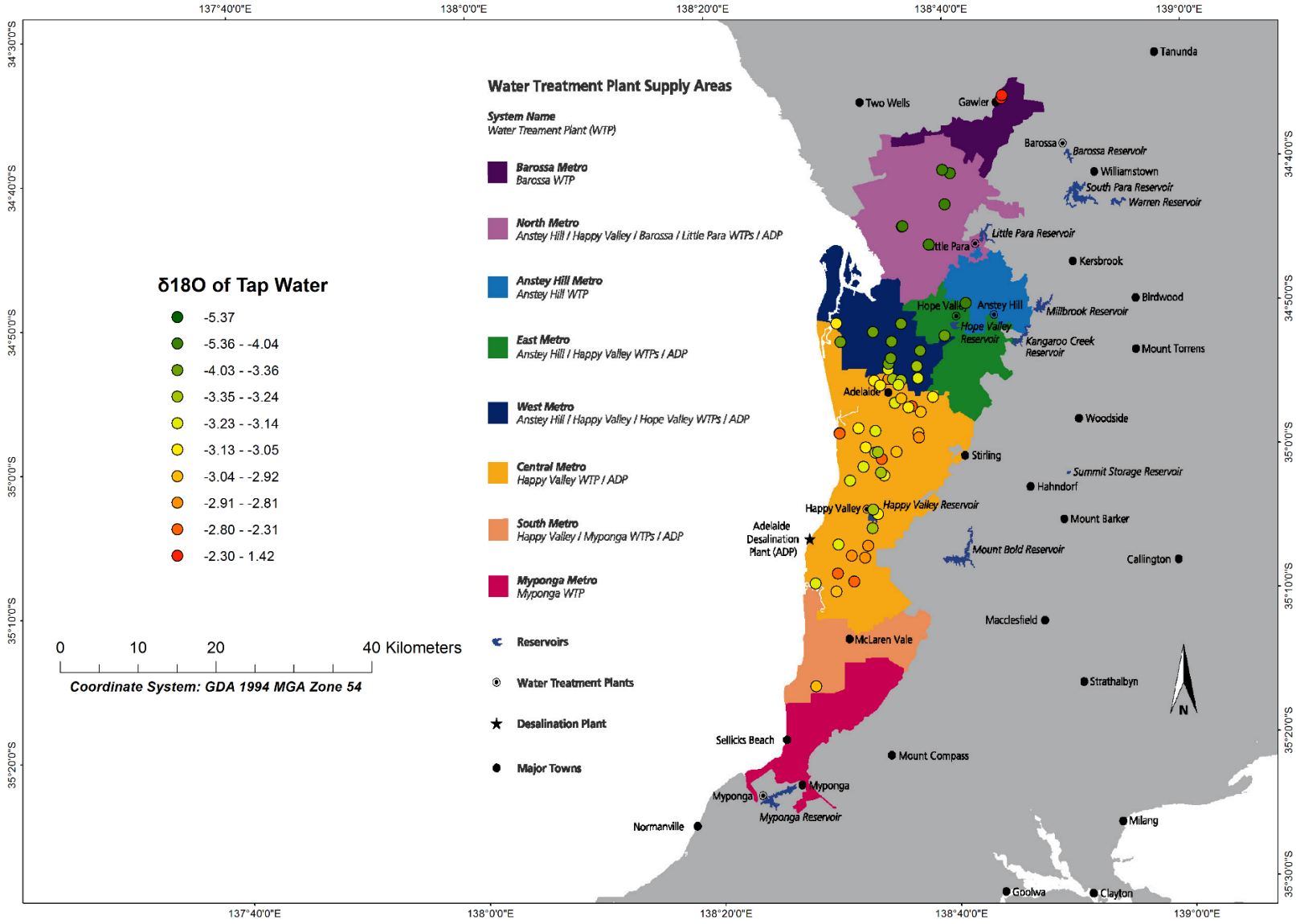

Figure 5.3 Observed $\delta^{18}O$ of tap water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

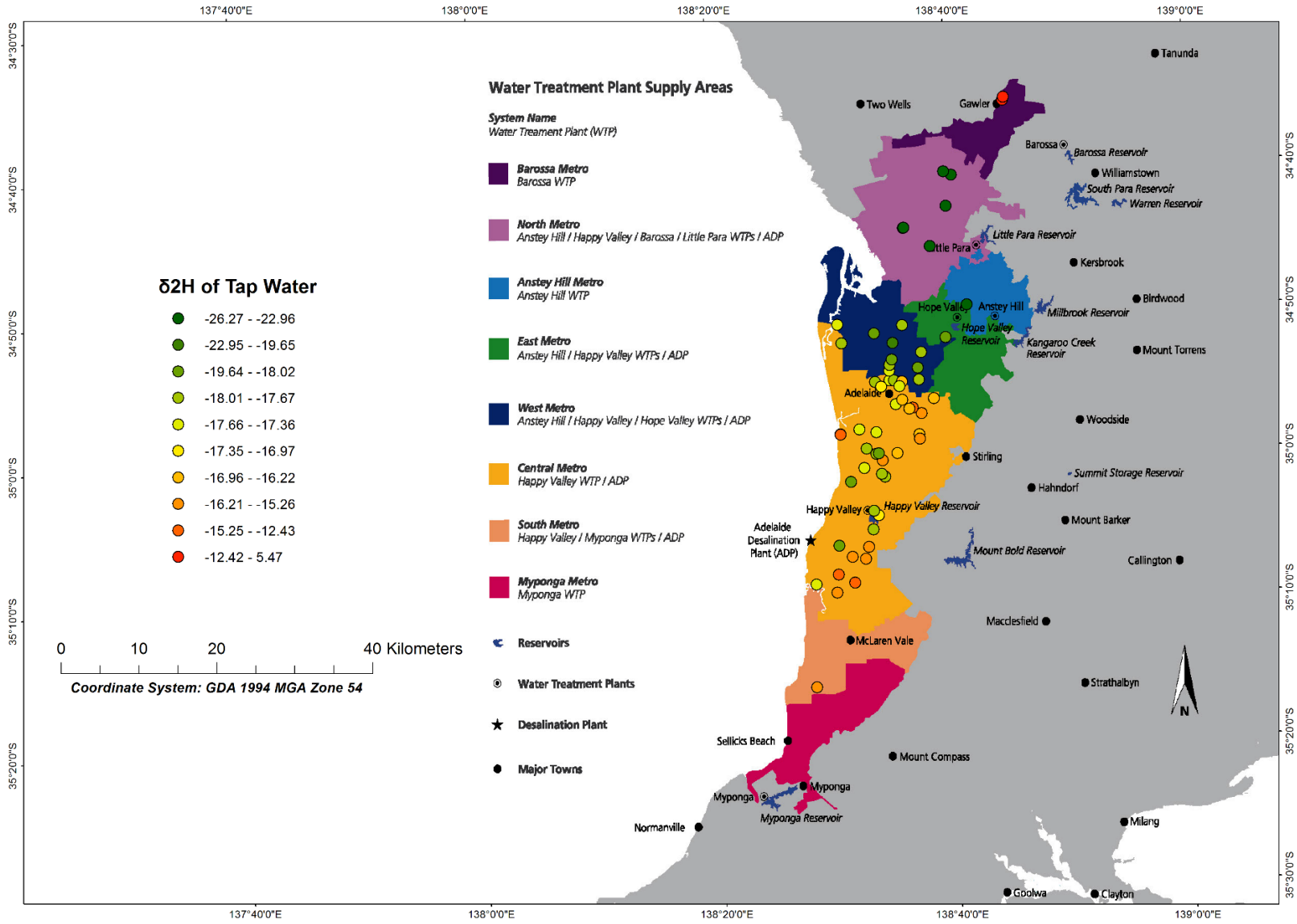

Figure 5.4 Observed δ^2H of tap water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

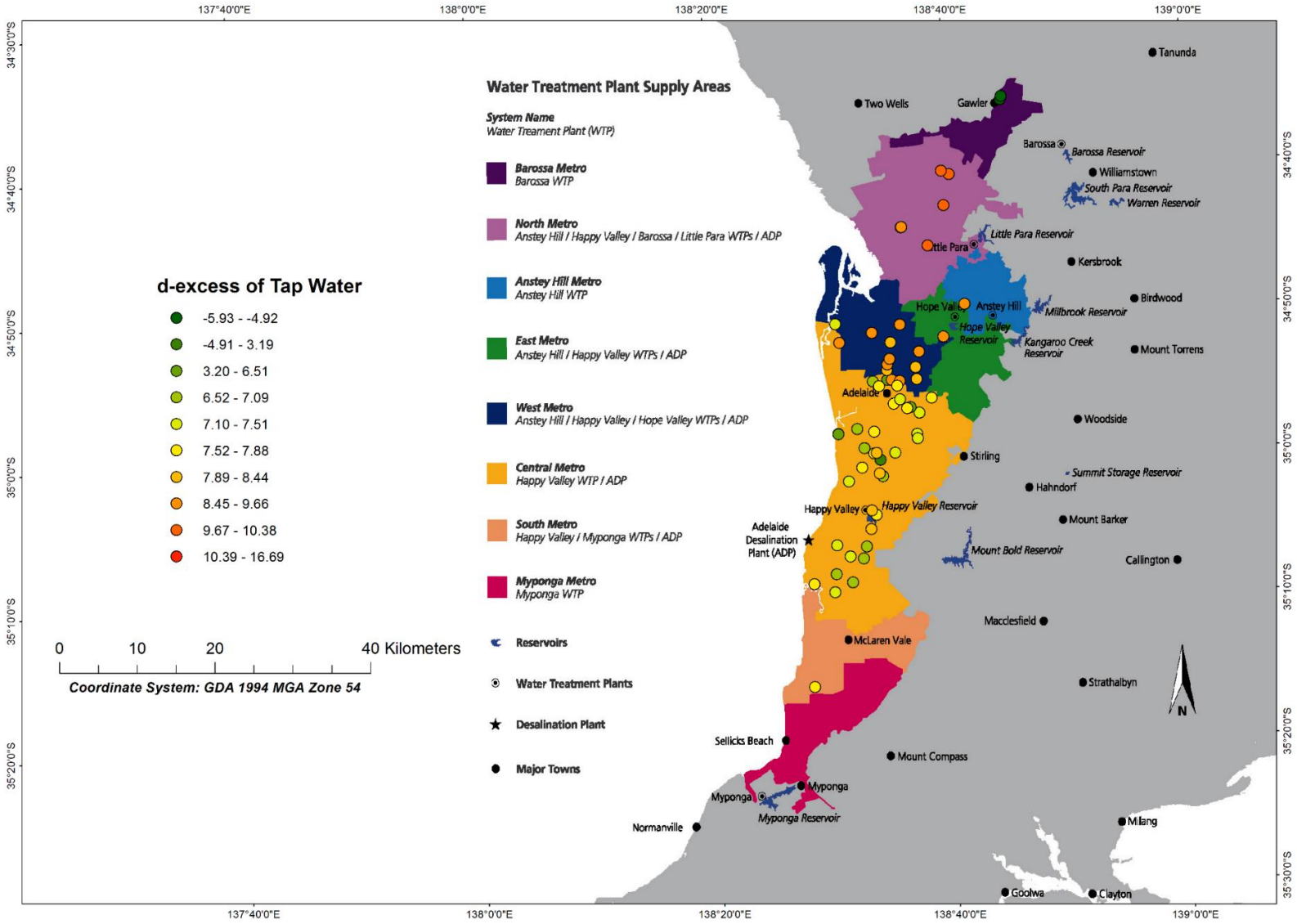

Figure 5.5 Observed d-excess of tap water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

5.3 Spatial pattern of surface water isotopes

Figure 5.6 presents δ^2H and $\delta^{18}O$ of surface water from various major catchments in the Adelaide metropolitan area over the LMWL. From the figure, the spatial mapping of surface water isotopes shows generally poorly clustered values. The isotopic data points of Onkaparinga and Smith catchments tend to spread along, fall on or under the LMWL meanwhile the data points from Patawalonga Catchment, Gawler Catchment and Torrens River system stay at the lower end.

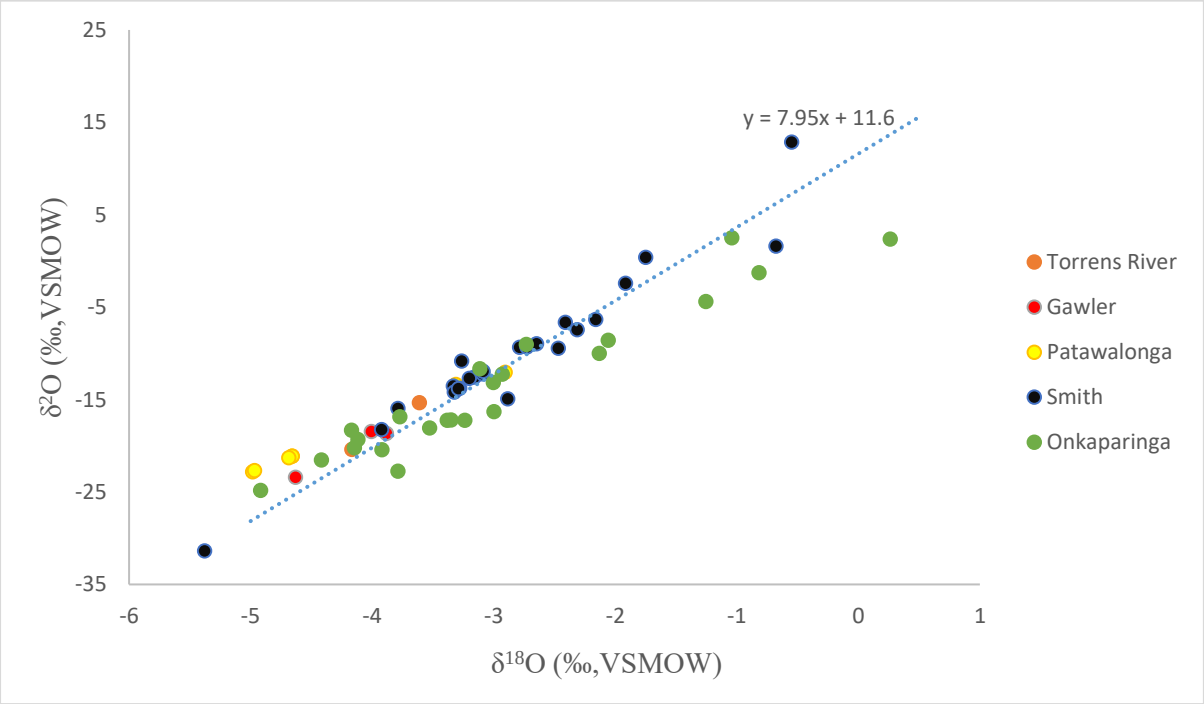

Figure 5.6 The δ^2H and $\delta^{18}O$ of surface water from various major catchments in the Adelaide metropolitan area over the LMWL

Figure 5.7, 5.8 and 5.9 present the $\delta^{18}O$, δ^2H and d-excess of surface water samples collected across the Adelaide metropolitan area respectively. Visual inspection does not suggest any spatially clustering of $\delta^{18}O$ and δ^2H. The d-excess of surface water in the Adelaide metropolitan area does not show a clear pattern in isotopic variation. The surface water sampling sites were close to each from the creeks and different ponds in the same catchments; however, they have very different values of stable isotopes and the d-excess. In general, the d-excess of surface water in the north and middle of the area is higher than d-excess of water from Onkaparinga Catchment.

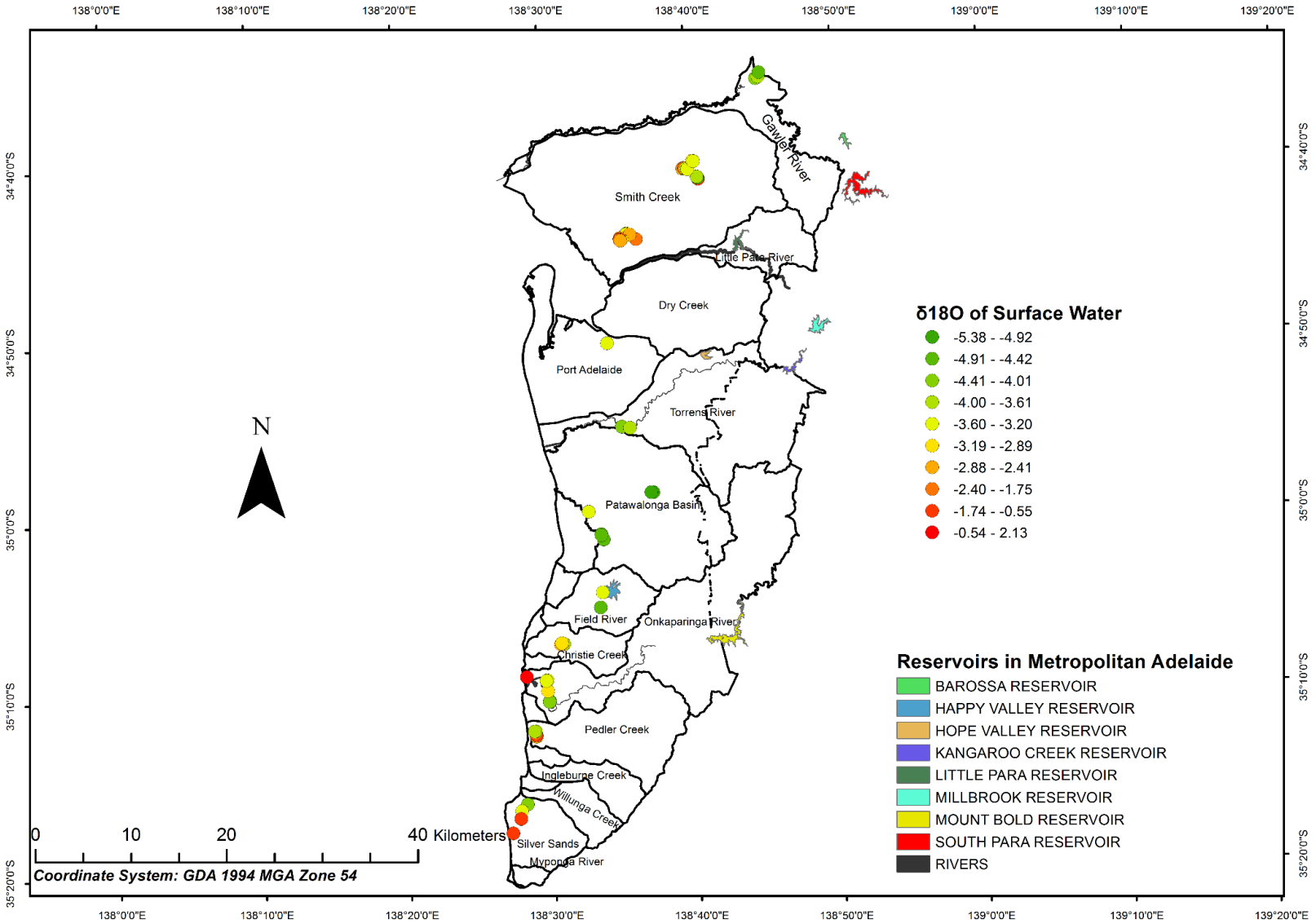

Figure 5.7 Observed $\delta^{18}O$ of surface water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

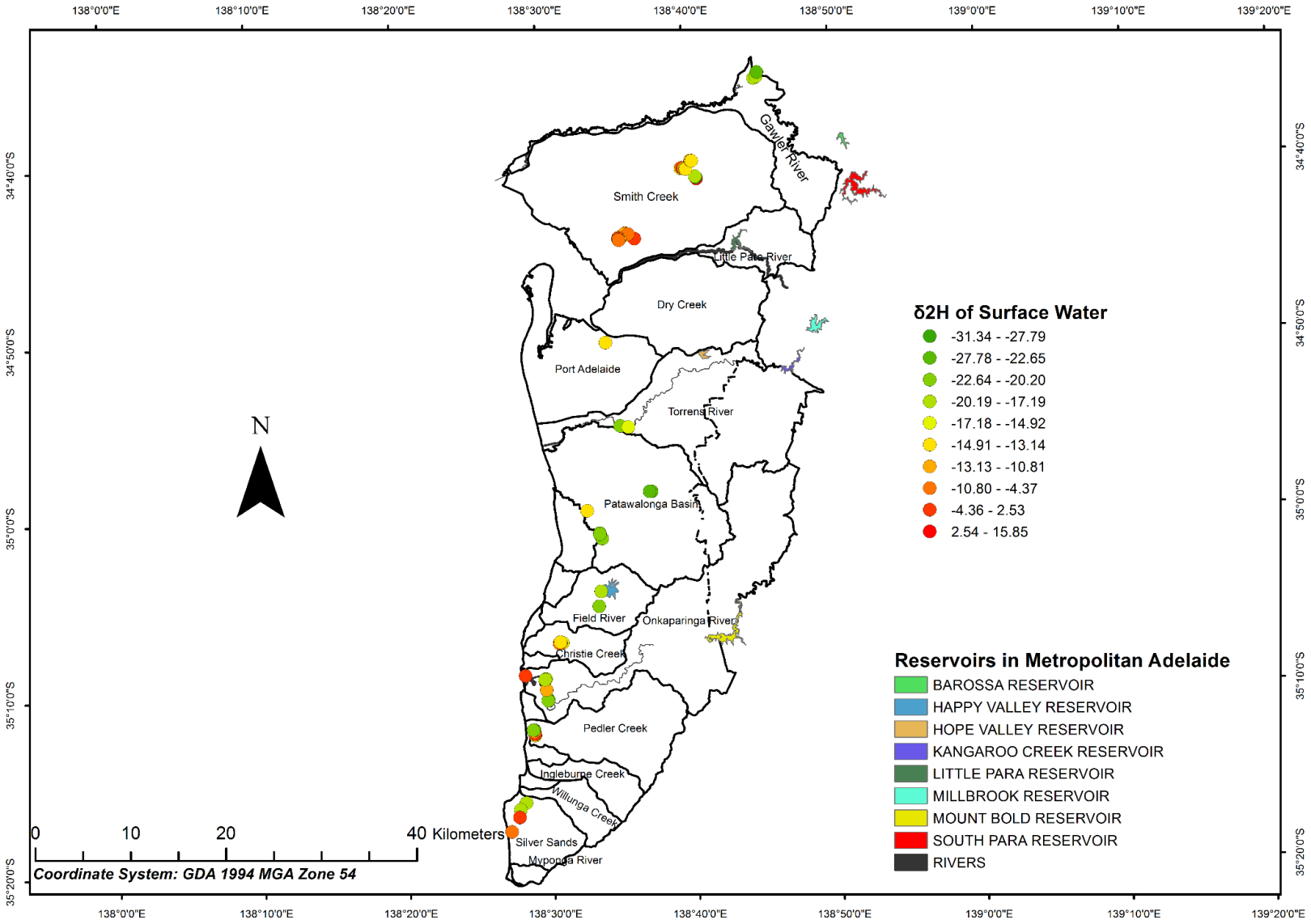

Figure 5.8 Observed δ^2H of surface water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

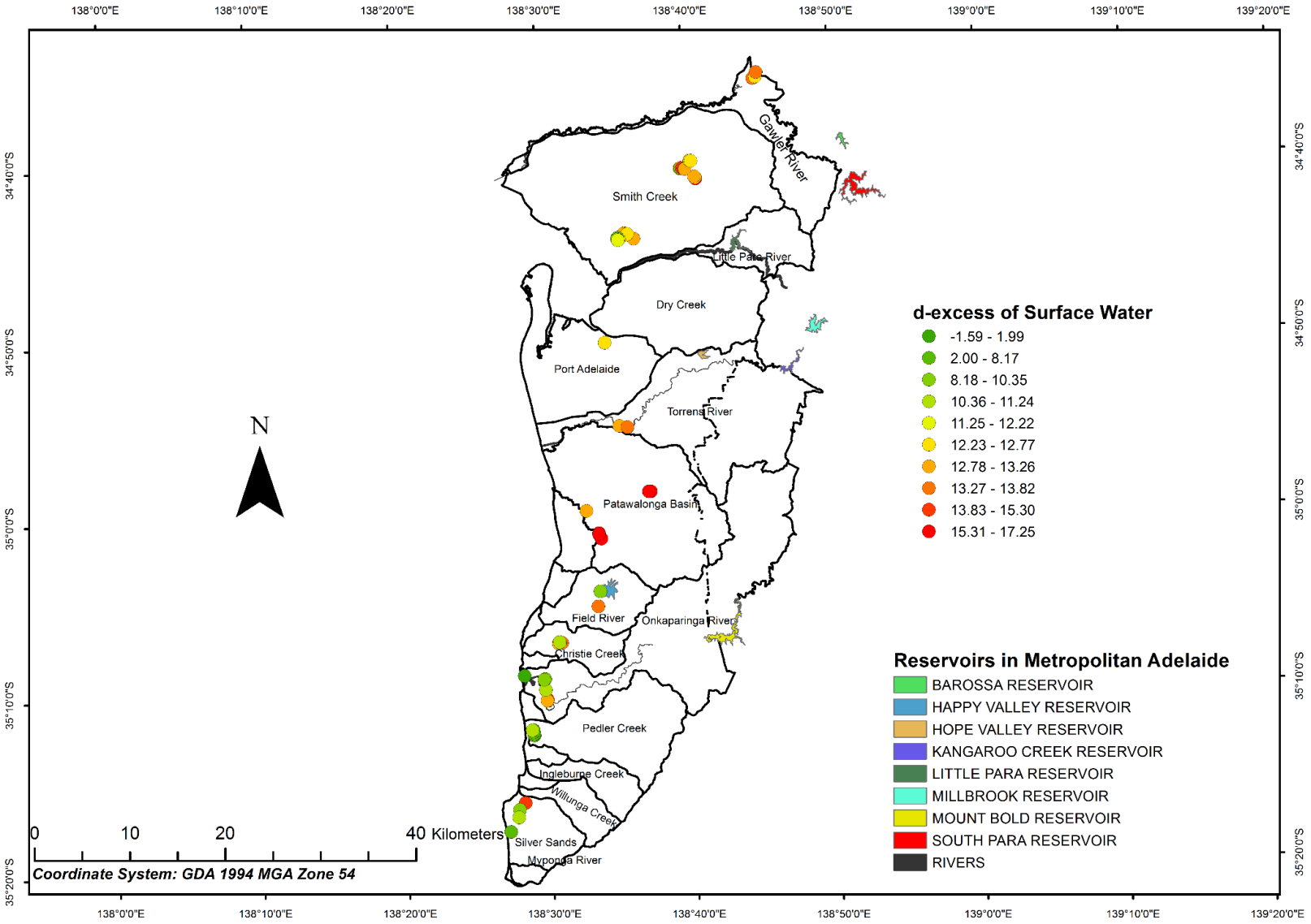

Figure 5.9 Observed d-excess of surface water samples collected across the Adelaide metropolitan area. All values are in ‰ relative to V-SMOW

CHAPTER 6: DISCUSSION

6.1 Characterization of stable water isotopes

Raw desalinated water originating from marine water underwent reverse osmosis for purification that is not likely to cause significant isotopic fractionation (Bowen et al., 2005, Kloppmann et al., 2008, Kloppmann et al., 2007). Thus, the desalinated water is isotopically heavy and stays under GMWL and LMWL.

The water isotopes of River Murray stay close to GMWL, reflecting the meteoric source. Its value in October 2016 was -5.05‰ for $\delta^{18}O$ that is similar to $\delta^{18}O$ value of -5.07‰ in June 1989 in the winter at Murray Bridge from previous study by Simpson and Herczeg (1991a). However, the $\delta^{2}H$ values are significantly different (19%) (-34.9‰ in June 1989 vs -29.2‰ in October 2016) (Simpson and Herczeg, 1991a). This difference might be a result of the temporal variation of River Murray water isotopes through the year. Due to the lack of isotope data of River Murray for comparison, this factor cannot be clearly identified.

The water samples from Lake Alexandrina (Milang) at the end of River Murray have high isotope values of around -0.54‰ for $\delta^{18}O$ and -4.13‰ for $\delta^{2}H$. These are similar to isotope values in June 1989 from the previous research from Simpson and Herczeg (1991a). Compared to the river water from Murray Bridge, the water from Lake Alexandria is more isotopically enriched. This is due to evaporation of river water during transport and evaporation on the lake itself (Simpson and Herczeg, 1991a, Simpson and Herczeg, 1991b, Mosley et al., 2012). The remaining water in the Lake Albert (Meningie) is expected to be more enriched in heavy isotopes due to the build-up of isotopically heavy isotopes during evaporation, resulting in the extremely negative d-excess value at -1.22‰.

The average isotopic values of $\delta^{18}O$ of surface water and tap water are similar (-3.16‰ vs. -3.12‰, respectively) but the $\delta^{2}H$ values are different (-13.33‰ vs. -17.28‰, respectively). This highlights the importance and necessity of inclusion of deuterium into distinguishing different water (Gibson et al., 2005). The slope of $\delta^{2}H$ versus $\delta^{18}O$ trend for all the surface water and tap water was 6.38 and 5.44, respectively (figure 5.1). This low slope of tap water can be interpreted by raw water in the reservoirs and rivers subjected to the evaporation from the transport and storage process (Gibson et al., 1993, Gibson and Edwards, 2002, Simpson and Herczeg, 1991a, Cartwright et al., 2004, Simpson and Herczeg, 1991b, West et al., 2014). The enrichment of water isotopes in tap water might be attributed to the mixing of desalinated

water into the water supply system. Since the operation of the Adelaide Desalination Plant, desalinated water was pumped to the Happy Valley Water Treatment Plant through the pump stations before being delivered to tap (Water, 2008). The desalinated water enriched with heavy isotopes (0.95‰ for δ^2H and 7.73‰ for $\delta^{18}O$) can be blended with the water from the Happy Valley WTP. In 2013 to 2014, desalinated seawater accounted for 28% of South Australia's total water supply (SA Water n.d.) and 5% of Adelaide's water. It means that a large amount desalinated water was drained to the Happy Valley WTP, which is likely to cause significant enrichment in both δ^2H and $\delta^{18}O$ of water delivered to tap.

The average d-excess value of surface water (11.94‰) is close to value at 11.35‰ for precipitation in Adelaide from Liu et al. (2010) and just over 10‰ in October (Guan et al. (2013) but it is significantly lower than the local average value of 13.68‰ by another research (Crosbie et al. (2012). The similar values between average d-excess of surface water and local meteoric water can be attributed to high rainfall in September and October 2016. The average d-excess value of tap water in the Adelaide metropolitan area in late September and early October is 7.64‰ that is significantly lower than d-excess of meteoric water, suggesting the evaporative influences on the water sources.

It appears that the isotopes of tap water and surface water in the sampling period are distinct from groundwater in the Adelaide metropolitan isotopes which are relatively depleted (-5.1‰ to -3.5‰ for $\delta^{18}O$ and -24‰ to -17‰ for δ^2H in November) (Lamontagne et al., 2005). Stable isotopes of water from River Murray are relatively similar to the groundwater isotopes. Water injected into groundwater from the 8 stormwater harvesting schemes or the leaked tap water is likely to change the isotopes of groundwater to more enriched isotopes. From the isotope information of various sources of groundwater water, the sources of groundwater can be identified.

6.2 Spatial pattern of surface water and driving factors

It is expected that the d-excess of surface water in the north Adelaide is lower than south area since the evaporation gradient is increasing to the north (BOM 2016b). However, the d-excess of the Northern part is generally higher than the Southern part (figure 5.9). Thus, evaporation is not only a major factor driving the spatial pattern of surface water isotopes.

In the Adelaide metropolitan area, the surface runoff originating from rainfall in the Mount Lofty Ranges drains through various creeks and rivers on the catchments, either to the various

reservoirs across the area or to Gulf St. Vincent. Due to the wide variation in the rainwater isotopic compositions in Mount Lofty Ranges and Adelaide (Guan et al., 2009, Guan et al., 2013, Liu et al., 2010), surface water isotopes are expected to be inherently variable in $\delta^{18}O$ and $\delta^{2}H$ since precipitation is primary water input to the basin.

The influence of rainwater compositions on the surface water isotopes of each major catchment is explored. Since a large number of samples was collected from Smith Catchment and Onkaparinga Catchment, the stable isotopes of the two catchments are separated from the figure 5.6 and plotted in figure 6.1 with LMWL for a better presentation.

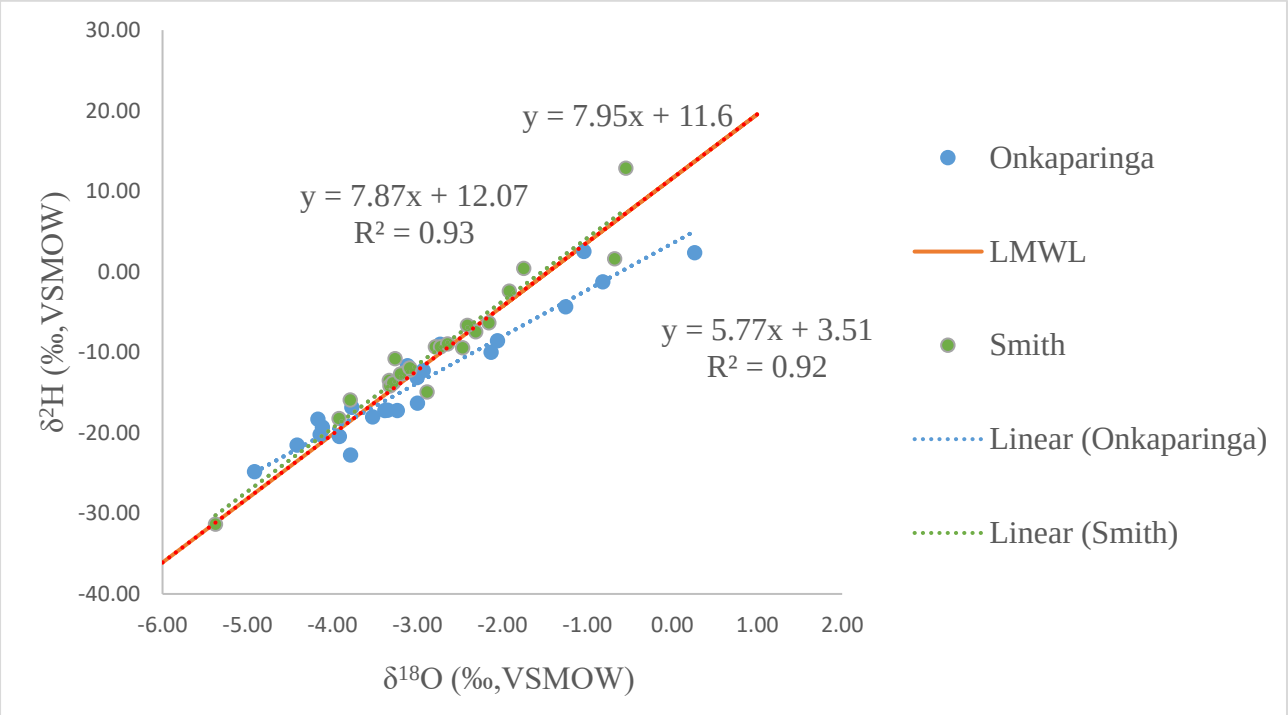

Figure 6.1 $\delta^{2}H$ and $\delta^{18}O$ of surface water from Onkaparinga and Smith catchment in the Adelaide metropolitan area. LMWL, $\delta^{2}H = 7.95 \times \delta^{18}O + 11.60$

The isotopes of surface water from Smith Catchment, which are composed of urban stormwater and runoff from the Mount Lofty Ranges fall along, even overlaps the LMWL. It forms a line with a slope of 7.87, indicating a short time integration of precipitation which has not undergone evaporation (Gibson et al., 1993). The Onkaparinga water falls under LMWL with slope of 5.77, indicating the evaporative impact. The difference in the impacts of evaporation on the surface water from two catchments reflect their residence time. The Smith system consists of both natural channels and stormwater drainage with the different wetlands connected to each other through this network into the Barker Inlet (Wilkinson et al., 2005). The

well-drained catchment has a rapid response to the rainfall (Wilkinson et al., 2005), leading to shorter residence time of run-off, and less influence of evaporation on the drainage system. The stormwater discharge of the Onkaparinga Catchment mainly depends on Field River, Christie Creek (Wilkinson et al., 2005). It is likely that water in the Christie Creek and Field River have longer residence time, leading to stronger evaporative influences. It is in accordance with the researches of residence time in relation with landscape characteristics, such as the topography (McGuire et al., 2005), accumulated areas (Stewart and McDonnell, 1991) or the nature of area accumulation within a catchment (McGlynn et al., 2002).

6.3 Spatial pattern of tap water and driving factors

The Adelaide metropolitan area was supplied by various sources of raw water, which adds more complexity to the already complex tap water supply system (SA Water, 2015a). The raw water provided for the water treatment plants in the Adelaide metropolitan area is subjective to evaporation occurring in creeks and rivers or open reservoirs. Raw water stored in the reservoirs is mixed with different sources of water from the River Murray, Adelaide Desalination Plant and runoff from creeks and rivers rising from the Mount Lofty Range. In the first case of mixing with desalinated water, the tap water would be more isotopically enriched. In the two latter cases, depending on the extent that evaporative influences have on the water in creeks and rivers, the water might have significantly or insignificantly enriched isotopes.

The pattern of tap water isotope ratios does not follow hydrological, climatic or natural isotope gradients within the Adelaide metropolitan area but it reflects the regional environmental influences on the isotopic compositions of the raw water supplied to water treatment plants and the dynamics of supply distribution systems. It shows clustering pattern the dual isotope plot of $\delta^{18}O$ and $\delta^{2}H$ reflecting the dynamics of tap water distribution system as well as the reservoirs in which the water from different sources is likely to be well mixed before being delivered to the final tap for each water supply zones.

In the Southern part of the Adelaide metropolitan area where the tap water is mainly supplied by the Central Metro system, the isotopic values vary in a wider range from -3.35‰ to -2.30‰ for $\delta^{18}O$ and -22.9‰ to -12.42‰ for $\delta^{2}H$, leading to the fluctuation of d-excess values in a wide range (figure 5.3, figure 5.4 and figure 5.5). This wide range of variation reflects multiple isotopically distinct of varying water sources from River Murray, to Onkaparinga River to

Happy Valley Reservoir and the Adelaide Desalination Plant, at the different time of water sampling. The Northern part of the Metropolitan area is supplied by five supply systems, including Barossa Metro, North Metro, Anstey Hill Metro, East Metro and West Metro. While the other four systems are supplied by different sources including Happy Valley WTP and ADP (figure 5.3 and table 4.5), the Barossa Metro derived water from only Barossa WTP (Barossa Reservoir). This can explain the distinctly high isotope ratios of Gawler tap water comparing to other regions in the Northern part. The water from the Barossa Reservoir is channelled from Warren Reservoir and South Para Reservoir that drain water from River Murray and South Para River (a tributary of Gawler River). Since the isotopes of surface water in the Gawler River and River Murray are moderately depleted (figure 5.6, 5.7, 5.8, 5.9), the input water from the tributaries is expected to undergo insignificant evaporative influences, however, experience significant evaporation inside the reservoirs. Thus, the strong enrichment of tap water in Gawler region can be attributed to evaporative influences occurring inside reservoirs as longer residence time in the reservoirs causes more significant evaporation (Darling et al., 2003). This result is in good agreement with several studies that evaporation in reservoirs, rivers and creeks are the main factors deciding the isotopes of tap water (West et al., 2014, Kennedy et al., 2011) and the longer residence time results in a stronger evaporative influence (Darling et al., 2003). Kennedy et al. (2011) stated that residence time is one of two factors along with the geographic pattern of precipitation driving the variation of $\delta^{18}O$ in tap water at least for non-managed water supplied.

Tap water in Murray Bridge is directly supplied by Murray Bridge Water Treatment Plant with one source from River Murray and its stable isotope compositions area similar to that of River Murray water (table 5.1). This indicates insignificant isotopic fractionation occurring in distributed pipelines since the water is unlikely to evaporate during transport and storages. In other case, tap water isotopes might not present the water from the single source since it has been mixed from different sources of raw water that has undergone different environmental conditions.

CHAPTER 7: CONCLUSION

7.1 The main findings

Stable water isotopic signature is an effective tool in urban water management to research the sources of groundwater recharge. The isotope information of water provides a foundation to identify different sources of water, then to be useful to deal with many urban water issues. The literature review has provided general approaches to interpret stable water isotope data of the water, and explore evaporation and precipitation as two major factors affecting the stable water isotopic ratio.

This study has characterised the stable water isotope ratios of the different water sources of tap water in the Adelaide metropolitan area and the major factors affecting their spatial variation. River Murray is one of the main sources of tap water in the Adelaide metropolitan area, thus, the signature of the River Murray that originates from meteoric water is important for the interpretation of water sources. Water from reservoirs and storages is isotopically enriched during evaporation and desalinated water, which causes the isotopic enrichment of tap water. The surface water and tap water in the area are both isotopically enriched and have distinct signatures from groundwater, which is more isotopically depleted.

The spatial pattern of tap water isotopes does not follow hydrological, climatic or natural isotope gradients but shows clustering distribution for each water supply zones. Its isotopic enrichment reflects a strong evaporative impacts on the sources of tap water and long residence time in the reservoirs. It might also be a result of the mixing with the isotopically enriched desalinated water, reflecting the dynamics of water supply system across the Adelaide metropolitan area.

The spatial isotopic pattern of surface water does not show a clear pattern across the Adelaide metropolitan area, but varies significantly in small areas in each catchment. It reflects the complex dependence of multiple factors. The spatial variation of surface water isotopes is a result of a complex combination of evaporation, precipitation and landscape characteristics relating to residence time. The surface water from the Smith system has more depleted water isotopes than surface water from Onkaparinga Catchment, reflecting those multiple influences.

7.2 The significance and implications of the findings

These findings are useful in a variety of contexts such as identifying the sources of shallow groundwater recharge, providing a foundation for hydrological, ecological, archaeological and forensic studies or identifying the water supply leakage and sewage leakage. Since the tap water and surface water are distinct from groundwater, the source of reclaimed water injected into groundwater from stormwater can be identified. For SA Water to maintain and improve water supply systems, water isotopes might be helpful to identify where leakage is occurring. The isotope information contained in the tap water and their major influencing factors reflects the climatic conditions on the regional water sources which might be useful to research the sources of water and dynamics of water supply system from different sources through to different reservoirs to tap.

7.3 Limitation of the study

The water sampling was not conducted on the same day that makes the isotope values prone to errors due to the temporal variability. The tap water samples were taken between 10th September and 7th October on different hours. However, the stable isotopes of tap water from different zones are relatively stable which indicates that temporal variability of tap water is insignificant in sampling period and unlikely to have an impact on the stable isotopes of tap water. Surface water samples were taken between 17th September and 6th October 2016 on different hours with different climates. The temporal variability of precipitation on September and October 2016 is likely to induce the errors in the results since isotopes of surface water are directly affected by precipitation.

Water sampling was not conducted along the length of the rivers and creeks but at their different wetlands and ponds. Since the water in wetlands and ponds of river and creeks is more prone to evaporation, the surface water isotopes are more isotopically enriched. Thus, the data of surface water isotopes might not be representative for all study area.

Due to the access restriction to the reservoirs, water sampling at major reservoirs could not be conducted. Stable isotopes of different reservoirs can provide insights to understand the dynamics of water movement, from different sources through different reservoirs to water treatment plants and water supply zones. It might be useful for the interpretation of tap water isotope data, and the influences of long residence times and evaporation on the water in the reservoirs.

7.4 Suggestion in terms of future research

The precipitation sampling can be conducted to study the influences of precipitation compositions and amount on temporal variation of surface water isotopes. The seasonal variation of surface water and tap water isotopes can be a direction to study further to have a better picture of the temporal variation of water isotopes. The variation of tap water isotopes also depends on its water sources; therefore, it is important to study temporal variability of all source waters. The further work could aim to collect data from these sources over time to look at temporal variability of the different sources.

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APPENDICES

Appendix 1. Some pictures of sampling locations

Clonlea Reserve Wetland at Gawler

Curtis Rd Wetland

Mitcham Reserve Stream (Brownhill Creek)

Onkaparinga River

Warriparinga Input (Sturt River)

Warriparinga Wetland

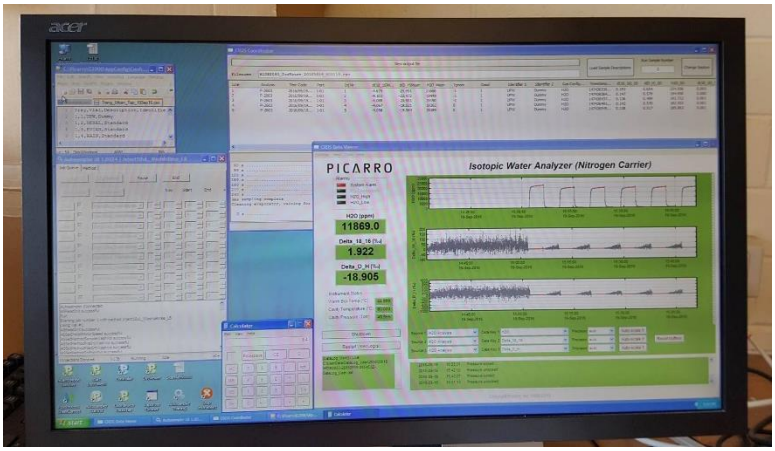
North Para River

Torrens River

Wingfield Wetland

Water over the pathway at Kaurna Wetland after a big storm

Appendix 2. Picarro CDRS instrument



Software to input sample information and operate Picarro instrument

Picarro analyser

Picarro vaporation module and sampler

Sample preparation and the filter

Appendix 3. Stable isotope data of surface water in the Adelaide metropolitan area

No.	Location	Easting	Northing	Sampling Date	$\delta^{18}O$	$\delta^{2}H$	d-excess
1	Torrens River	279619	6133395	18-Sep	-4.17	-20.39	12.94
2	Torrens River	280456	6133280	24-Sep	-3.61	-15.32	13.58
3	Gawler Catchment	293545	6169861	24-Sep	-4.01	-18.44	13.61
4	Gawler Catchment	293804	6170021	24-Sep	-3.88	-18.65	12.40
5	Gawler Catchment	293881	6170486	24-Sep	-4.63	-23.40	13.64
6	Patawalonga Catchment	276161	6124491	18-Sep	-2.91	-12.02	11.23
7	Patawalonga Catchment	276161	6124491	18-Sep	-3.31	-13.34	13.15
8	Patawalonga Catchment	282900	6126529	17-Sep	-4.98	-22.79	17.06
9	Patawalonga Catchment	277722	6121589	18-Sep	-4.66	-21.11	16.16
10	Patawalonga Catchment	277472	6122148	18-Sep	-4.66	-21.09	16.16
11	Patawalonga Catchment	277478	6122039	18-Sep	-4.68	-21.26	16.21
12	Patawalonga Catchment	282697	6126546	18-Sep	-4.97	-22.65	17.09
13	Onkaparinga Catchment	269679	6107173	17-Sep	0.26	2.39	0.27
14	Onkaparinga Catchment	277414	6114472	19-Sep	-4.12	-19.31	13.63
15	Onkaparinga Catchment	277414	6114472	19-Sep	-4.42	-21.52	13.81
16	Onkaparinga Catchment	270715	6100936	27-Sep	-3.00	-16.30	7.68
17	Onkaparinga Catchment	270701	6101023	27-Sep	-2.06	-8.57	7.89

18	Onkaparinga Catchment	270698	6101107	27-Sep	-0.82	-1.26	5.26
19	Onkaparinga Catchment	270637	6101290	27-Sep	-2.13	-10.00	7.04
20	Onkaparinga Catchment	270630	6101502	27-Sep	-3.79	-22.74	7.56
21	Onkaparinga Catchment	270514	6101484	27-Sep	-3.92	-20.43	10.92
22	Onkaparinga Catchment	269800	6093859	28-Sep	-4.17	-18.29	15.06
23	Onkaparinga Catchment	269192	6093148	28-Sep	-3.38	-17.22	9.84
24	Onkaparinga Catchment	269106	6092354	28-Sep	-1.04	2.53	10.85
25	Onkaparinga Catchment	268281	6090823	28-Sep	-1.25	-4.37	5.66
26	Onkaparinga Catchment	272114	6104683	6-Oct	-4.92	-24.82	14.53
27	Onkaparinga Catchment	272061	6104600	6-Oct	-4.15	-20.20	12.96
28	Onkaparinga Catchment	271899	6105719	6-Oct	-2.93	-12.24	11.20
29	Onkaparinga Catchment	271839	6106846	6-Oct	-3.35	-17.19	9.61
30	Onkaparinga Catchment	271730	6106792	6-Oct	-3.53	-18.04	10.16
31	Onkaparinga Catchment	273603	6110636	6-Oct	-3.77	-16.84	13.33
32	Onkaparinga Catchment	273423	6110608	6-Oct	-3.11	-11.65	13.26
33	Onkaparinga Catchment	273258	6110601	6-Oct	-2.73	-9.01	12.83
34	Onkaparinga Catchment	273345	6110723	6-Oct	-3.00	-13.14	10.88
35	Onkaparinga Catchment	277632	6116043	13-Oct	-3.24	-17.23	8.67
36	Smith system	287564	6159341	24-Sep	-0.55	12.87	17.25
37	Smith system	287503	6159465	24-Sep	-5.38	-31.34	11.67

38	Smith system	287426	6159567	24-Sep	-3.92	-18.23	13.15
39	Smith system	285903	6160385	24-Sep	-2.89	-14.92	8.16
40	Smith system	286025	6160453	24-Sep	-2.31	-7.44	11.07
41	Smith system	286130	6160443	24-Sep	-1.75	0.42	14.41
42	Smith system	286284	6160388	24-Sep	-3.26	-10.81	15.29
43	Smith system	286410	6160346	24-Sep	-3.79	-15.93	14.38
44	Smith system	286461	6160342	24-Sep	-3.33	-13.51	13.14
45	Smith system	286957	6161232	24-Sep	-3.16	-12.56	12.71
46	Smith system	287054	6161185	24-Sep	-3.28	-13.77	12.47
47	Smith system	278069	6142116	18-Sep	-2.79	-9.33	12.96
48	Smith system	278069	6142116	18-Sep	-2.73	-9.30	12.51
49	Smith system	278069	6142116	18-Sep	-3.32	-14.16	12.42
50	Smith system	280270	6153430	1-Oct	-3.29	-13.80	12.51
51	Smith system	280081	6153602	1-Oct	-3.09	-12.21	12.50
52	Smith system	280032	6153543	1-Oct	-3.20	-12.70	12.90
53	Smith system	281089	6153018	1-Oct	-1.92	-2.40	12.93
54	Smith system	280413	6153502	1-Oct	-2.41	-6.64	12.64
55	Smith system	279564	6153006	1-Oct	-3.09	-11.94	12.77
56	Smith system	279414	6153131	1-Oct	-2.47	-9.43	10.31
57	Smith system	279356	6153011	1-Oct	-0.68	1.61	7.01

58	Smith system	279393	6152927	1-Oct	-2.16	-6.33	10.94
59	Smith system	279454	6152843	1-Oct	-2.65	-8.96	12.21
60	River Murray (Murray Bridge)	343433	6112604	6-Oct	-5.34	-30.63	12.06
61	River Murray (Murray Bridge)	343433	6112604	6-Oct	-4.77	-27.79	10.35
62	Lake Alexandrina (Milang)	323856	6078831	6-Oct	-1.42	-9.35	1.99
63	Lake Alexandrina (Milang)	323856	6078831	20-Sep	0.33	1.08	-1.58
64	Lake Albert (Meningie)	348430	6051608	6-Oct	2.13	15.85	-1.22

Appendix 4. Stable isotope data of surface water in the Adelaide metropolitan

No.	Water Supply System	Council	Easting	Northing	$\delta^{18}O$	$\delta^{2}H$	d_excess
1	Anstey Hill Metro	Tea Tree Gully	291762	6144975	-3.17	-17.67	7.71
2	Anstey Hill Metro	Tea Tree Gully	288955	6143242	-4.04	-22.96	9.33
3	Barossa Metro	Gawler	293511	6169524	1.06	3.54	-4.92
4	Barossa Metro	Gawler	293611	6169920	1.42	5.47	-5.93
5	Central Metro	Port Adelaide Enfield	274116	6120401	-3.19	-18.08	7.46
6	Central Metro	West Torrens	275178	6127136	-3.05	-17.59	6.83
7	Central Metro	Unley	279870	6130379	-3.15	-17.43	7.74
8	Central Metro	Mitcham	278084	6121419	-2.97	-16.22	7.51

9	Central Metro	Onkaparinga	272633	6112189	-3.17	-18.19	7.21
10	Central Metro	West Torrens	272772	6126506	-3.18	-17.79	7.68
11	Central Metro	Marion	275836	6122176	-3.17	-17.58	7.81
12	Central Metro	Adelaide city	279061	6133468	-2.85	-17.51	5.31
13	Central Metro	Marion	277374	6126763	-3.16	-17.57	7.75
14	Central Metro	Adelaide city	280491	6133298	-3.16	-17.77	7.49
15	Central Metro	Marion	278204	6123163	-2.31	-15.26	3.19
16	Central Metro	Mitcham	278508	6121082	-3.07	-17.80	6.79
17	Central Metro	Marion	277096	6116664	-2.43	-12.94	6.51
18	Central Metro	Marion	277379	6124008	-3.18	-17.79	7.62
19	Central Metro	Mitcham	280068	6124115	-3.01	-16.77	7.35
20	Central Metro	Mitcham	282900	6126529	-2.98	-16.65	7.22
21	Central Metro	Unley	283191	6129244	-2.93	-16.07	7.34
22	Central Metro	Unley	282040	6129957	-2.35	-12.43	6.38
23	Central Metro	Mitcham	282960	6125950	-2.89	-15.83	7.28
24	Central Metro	Marion	277684	6116105	-3.11	-17.21	7.70
25	Central Metro	Onkaparinga	276445	6112048	-2.81	-15.40	7.09
26	Central Metro	Onkaparinga	276061	6110503	-2.82	-15.54	7.01
27	Central Metro	Onkaparinga	274349	6110752	-2.86	-15.55	7.31
28	Central Metro	Onkaparinga	274647	6107446	-2.61	-14.13	6.72
29	Central Metro	Onkaparinga	272363	6106162	-2.92	-15.95	7.42
30	Central Metro	Onkaparinga	269679	6107173	-3.15	-17.50	7.71
31	Central Metro	Onkaparinga	272540	6108465	-2.61	-14.01	6.89
32	Central Metro	West Torrens	272776	6126460	-2.57	-14.08	6.49
33	Central Metro	Adelaide city	280491	6133298	-3.05	-16.81	7.63
34	Central Metro	Adelaide city	280691	6130947	-2.99	-16.43	7.47
35	Central Metro	West Torrens	277206	6133248	-3.07	-17.68	6.87
36	Central Metro	Marion	276130	6124672	-3.08	-17.90	6.76
37	Central Metro	Marion	277703	6124081	-3.30	-18.27	8.14
38	Central Metro	Adelaide city	279619	6133464	-3.33	-17.76	8.91
39	Central Metro	Adelaide city	279009	6134713	-3.23	-17.36	8.44

40	Central Metro	Onkaparinga	277008	6114287	-3.25	-17.78	8.18
41	Central Metro	Marion	277096	6116664	-3.26	-17.77	8.30
42	Central Metro	Unley	281608	6129802	-3.05	-16.50	7.88
43	Central Metro	Marion	278084	6121419	-3.14	-16.97	8.17
44	Central Metro	Marion	278084	6121419	-3.16	-17.20	8.10
45	Central Metro	Marion	278084	6121419	-3.29	-18.03	8.26
46	Central Metro	Marion	278084	6121419	-3.27	-17.77	8.42
47	Central Metro	Adelaide city	280662	6133316	-3.24	-16.80	9.13
48	Central Metro	West Torrens	277976	6132639	-3.11	-17.19	7.71
49	Central Metro	Burnside	284759	6131172	-3.07	-16.76	7.76
50	Central Metro	Adelaide City	280344	6132719	-3.19	-17.62	7.87
51	South Metro	Onkaparinga	269768	6093979	-2.95	-15.93	7.63
52	East Metro	Campbelltown	286270	6139036	-3.45	-18.15	9.49
53	North Metro	Playford	286948	6159907	-4.42	-24.98	10.38
54	North Metro	Playford	285920	6160324	-4.39	-25.07	10.04
55	North Metro	Salisbury	284221	6150729	-4.44	-25.51	9.99
56	North Metro	Playford	286256	6155891	-4.45	-25.33	10.26
57	North Metro	Salisbury	280749	6153045	-4.27	-24.52	9.61
58	North Metro	Salisbury	280822	6153091	-4.36	-25.20	9.66
59	Summit WTP	Adelaide Hill	290924	6127104	-5.37	-26.27	16.69
60	West Metro	Port Adelaide Enfield	272328	6140595	-3.09	-17.49	7.20
61	West Metro	Norwood, Payneham and St Peters	282840	6133577	-3.21	-17.69	8.03
62	West Metro	Charles Sturt	272888	6138202	-3.37	-17.82	9.16
63	West Metro	Charles Sturt	279042	6135433	-3.36	-17.77	9.10
64	West Metro	Prospect	279318	6136142	-3.40	-18.02	9.20
65	West Metro	Prospect	279420	6138267	-3.47	-19.65	8.13
66	West Metro	Port Adelaide Enfield	277052	6139491	-3.41	-18.19	9.11

67	West Metro	Norwood, Payneham and St Peters	282694	6135094	-3.32	-18.39	8.14
68	West Metro	Port Adelaide Enfield	280660	6140547	-3.38	-17.74	9.30
69	West Metro	Walkerville	283099	6137105	-3.37	-17.69	9.24
70	Murray Bridge		342359	6111508	-4.93	-29.07	10.36