RIVER REGULATION IMPACTS ON WATER QUALITY IN THE LOWER MURRUMBIDGEE CATCHMENT

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Honours thesis project declaration page

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1. Abstract

Excess nutrients and contaminants in watercourses have detrimental consequences for human health and riverine ecosystems. During droughts, thousands of fish can die under poor water quality conditions, and these fish deaths often become the focus point for debates about how we should manage water allocations throughout the Murray-Darling Basin and wider Australia. Greater scientific data and knowledge of flow impacts are needed to guide water delivery decisions to minimise periods of poor water quality.

Using water quality (electrical conductivity and dissolved oxygen) and water stable isotope data (δ^2H and $\delta^{18}O$ signatures), we investigated the impact of dam water releases and other anthropogenic activities on water quality in the Lower Murrumbidgee Catchment (September 2018 - February 2020) during drought. Supporting precipitation and stream flow data were analysed to yield insights into the impact of dam water releases on water quality.

Dam water only took nine days to travel 560 km from its release at Blowering Reservoir, on the Tumut River, to Carrathool Bridge on the lower Murrumbidgee River. Along this reach of the river, both the electrical conductivity and water stable isotope data indicate that water quality was controlled by the dam water releases. Degraded water quality was restricted to water from irrigation channels and water management ponds.

During droughts, water quality in the Murrumbidgee is not impacted by surface water runoff from urban centre or irrigated agricultural districts. The primary influence on water quality was determined to be the regulated delivery of water from dams and weirs.
My research demonstrates that the conservative use of environmental water is required during normal and wet conditions to increase the availability of water during droughts.

2. Introduction

2.1. Aims and background

The human population relies heavily upon rivers for trade, transportation, industry, domestic water supplies and agriculture. Subsequently, rivers have become extremely regulated around the world, often resulting in the degradation of water supply and quality (Prosser et al. 2001; Gibson et al. 2002). Therefore, there is a basic need to improve the management of water supplies, which would in turn enhance human and riverine ecosystem health. To do this a greater scientific understanding of the hydrosphere and associated processes is needed on a catchment scale (Hughes & Crawford, 2013).

Water quality is defined by the physical, chemical, biological and aesthetic characteristics of water (DPIE, 2019). Water quality worsens as rivers flow through regions where land and water are intensely developed, impacted by pollution from increasing agricultural and urban activities (Prosser et al. 2001; Ren & Kingsford, 2014; Verstraeten et al. 2007; DPIE, 2020a). Excess nutrients and contaminants from these activities (such as nitrate from fertilisers) degrade downstream water quality and threaten local ecosystems, entering rivers through sediment delivery and surface water runoff (Prosser et al. 2001; Verstraeten et al. 2007). These excess nutrients can promote the growth of blue-green algae and lead to mass fish kills (Baldwin, 2019).

The sequence of water management decisions that result in poor water quality in some Australian rivers is not well understood (Harrison, 1994). There is an urgent need to improve water management decisions relating to the release of consumptive and environmental water from dams to mitigate detrimental environmental outcomes, especially in the context of drought (Page et al. 2005; Kingsford & Thomas, 2004).

My research aims to investigate the impacts of dam releases and off-farm movement of surface water on water quality in the Murrumbidgee Catchment of the Murray-Darling Basin. It also aims to provide industry, government and other stakeholders data and insights that will better guide water management decisions in future droughts. This is achieved through the utilization of water quality results and water stable isotope signatures collected as part of this study, supported with rainfall and streamflow data (BOM, 2020).

2.2. The study area

The Murrumbidgee river, part of the Murray Darling Basin in New South Wales (NSW), extents over an area of 84,000 km^2 from its source in the Snowy Mountains (Figure 1; Green et al. 2011; Wen, 2009). It is one of the most regulated river systems in Australia, with 26 dams and weirs and over 10,000 km of irrigation channels (Wen et al. 2011; Page et al. 2005). The major land use in this region is dryland pasture used for livestock grazing (Green, et al. 2011).

The Murrumbidgee Catchment is characterised by meandering channels and wide floodplains, which provides essential aquatic habitats for 23 recorded native fish species and over 400 recorded native invertebrate species (Green et al. 2011). The mid-Murrumbidgee Wetlands are nationally significant, supporting river red gum forest and blackbox woodlands. These wetlands include the Ramsar listed Fivebough and Tuckerbil Wetlands (Department of Agriculture, Water and the Environment, 2020a.; DPIE, 2020b.). The Fivebough wetlands receive approximately 2.5 million litres (ML) of water from the adjoining Sewage Treatment Plant under an environmental protection licence (DPIE, n.d.).

For the purpose of this study, we focus on the Murrumbidgee Catchment, from Tumut to Carrathool, which is separated by approximately 560 km of the Murrumbidgee River (Figure 1). This catchment was selected as its water resources are the most developed and regulated of the Murray-Darling Basin, with the Murrumbidgee River also typical of a semi-arid river system (Murrumbidgee Irrigation, 2019; Green et al. 2011). Irrigated commodities produced in the Murrumbidgee Catchment include annual crops including rice, pasture, cereals, vegetables and oil seeds and perennial crops such as wine grapes and citrus (Green et al. 2011). Most of these crops are grown in the Murrumbidgee Irrigation Area (MIA) and the Coleambally Irrigation Area (CIA). The two primary dams controlling water flow in the study area include Blowering Dam and Burrinjuck Dam that control water for the MIA and CIA (Figure 1) (Green et al. 2011; Wen et al. 2011).

Before river regulation, streamflow was seasonal, with peak flows occurring during winter and spring due to higher rainfall and snow melt. This has been altered by dams and weirs, with peak flows occurring in spring and summer to accommodate the needs of the irrigation industry (Kingsford & Thomas, 2004; Gell & Little, 2007).

Flood peaks and flows of the Murrumbidgee River have significantly decreased downstream of Wagga Wagga, due to factors including distributary diversions (Page et al. 2005; Chessman et al. 2010). These include the Main Canal and the Sturt Canal, which provide water for the MIA. The MIA covers an area of approximately 3,624 km^2 and is situated to the north of the Murrumbidgee River downstream of Narrandera. The CIA to the south of the Murrumbidgee River comprises of an area over 790 km^2. Water is diverted to the CIA from 41 km of the Main Canal and 477 km of supply channels (Figure 1) (Green et al. 2011).

In the Murrumbidgee Irrigation Areas, drainage water is recycled through the complex and interconnected irrigation supply, drainage and wetland systems. Excess water is discharged into lagoons and designated areas (Murrumbidgee Irrigation, 2019). For example, excess flows from the MIA channel system often escape to Mirool Creek, where it is abstraced by irrigators, diverted back into the channel system or released to Barren Box Swamp. Barren Box Swamp is used to store water from supply irrigators, stock and domestic users (Green et al. 2011).

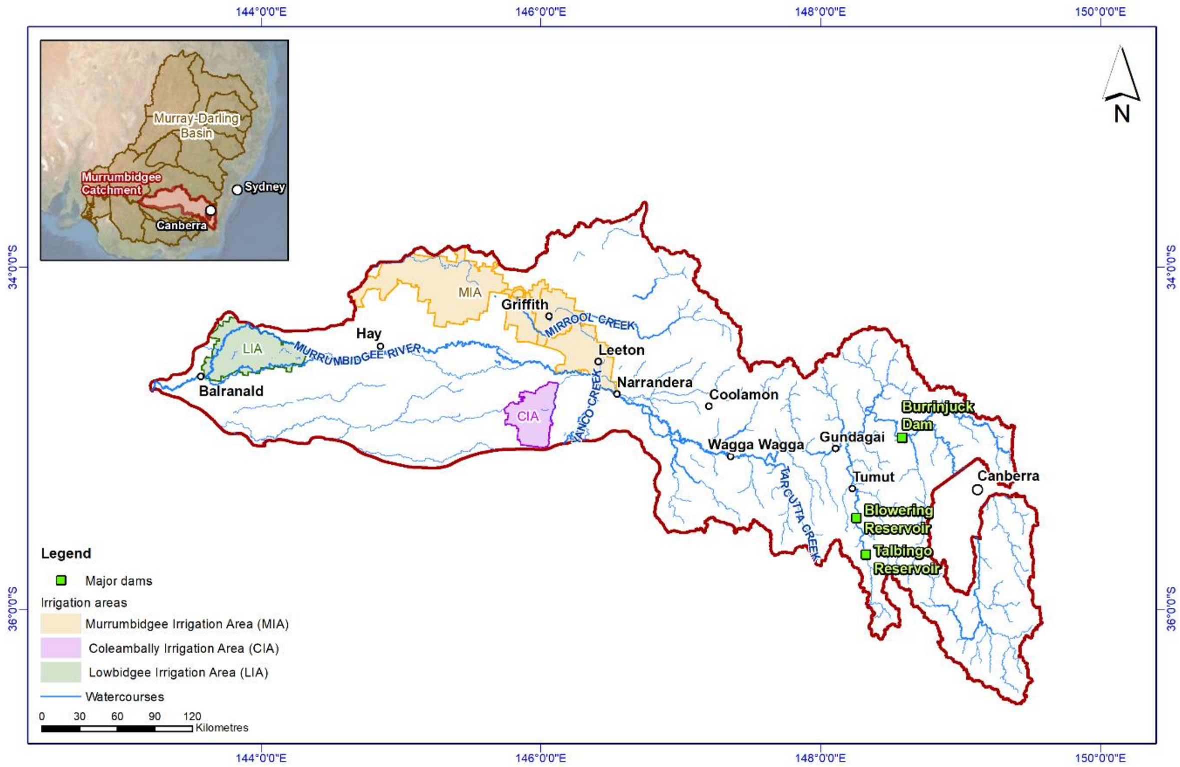

***Figure 1**: Site location – Murrumbidgee Catchment.*

Water quality degradation within the study area has been attributed to a combination of factors, including alteration to natural flow regimes, land use change and changes to catchment conditions by major dams (DPIE, 2020a).

Impacts of altered streamflow are seen downstream of the study area, to the west of Hay in the Lowbidgee Floodplain (Figure 1). This floodplain is nationally significant, providing an essential drought refuge and breeding habitat for waterbirds (Kingsford & Thomas, 2004; Rogers et al. 2013). Degradation of this floodplain has ocurred, with the development of 97,000 ha of the wetland into the Lowbidgee Irrigation Area (LIA, Figure 1), making the area even more sensitive to water resource regulation. Kingsford & Thomas (2004) reported the collapse of waterbird populations by 90% over 19 years (1983 to 2001), from approximately 140,000 between (1983 – 1986) to 14,200 (1998 – 2001) (Kingsford & Thomas, 2004).

The Lowbidgee Floodplain is still the largest wetland area remaining in the Murrumbidgee Valley, home to the largest contiguous river red gum forests in Australia, as well as significant black box, lignum and reed- bed communities (Rogers, et al. 2013; Figure 1).

These significant ecological communities must be protected and restored from impacts of water resource regulation under Commonwealth law (Commonwealth Environmental Water Office, 2019).

2.3. Management issues

Historically many of the largest ecological impacts of poor water quality have occurred during droughts (Mosley, 2015). The low stream flows, low oxygen levels and high temperatures associated with droughts cause blue-green algal blooms, triggering mass fish kills in the lower Murrumbidgee River (Baumgartner, 2004). The severity of impacts of drought conditions and subsequent low flow conditions is heightened by weirs and river diversions, reducing or eliminating flows and promoting the stratification of waterbodies. This is when cold, hypoxic deep water is separated from the warmer, oxygenated water at the surface (Kopf et al. 2019; Baldwin, 2019). Shallow waterbodies such as weirs are sensitive to changes in climate, with passing storms having the potential to cause destratification, whereby the mixing of stratified layers occurs that decreases overall oxygen concentrations (Baldwin, 2019).

Several thousand fish are estimated to have died at Redbank Weir (100 km west of Hay) in late January 2020 due to destratification of water following a cold front (Balranald Shire Council, 2019). To maximise the survival of remaining native fish and improve dissolved oxygen concentrations and water quality at Redbank Weir, 27,600 ML of environmental water was released (Baldwin, 2019). The issue of mass fish kills extends beyond the Murrumbidgee Catchment, affecting other catchments within the Murray-Darling Basin. An estimated hundreds of thousands to millions of native fish also died in a series of fish kills in the lower Darling River in the summer of 2018 - 2019 (Jackson & Head, 2020).

The substantial degradation of ecosystems in basin wetlands due to river regulation led to the development of the NSW Water Management Act 2000, with the objective of the sustainable and integrated management of NSW's water (DPIE, 2019). This act governs water regulation and management in NSW and the Water Sharing Plan development framework, that outlines how consumptive and environmental water is delivered (Driver et al. 2013). Since 2009, Commonwealth environmental water has been delivered to sites across the Murrumbidgee Catchment to restore wetland habitats (Department of Agriculture, Water and the Environment, 2020a.). However, these environmental flows have been constrained by other demands within the catchment, comprising of smaller volumes of water than the natural flows they replace (Glenn et al. 2017).

Glenn et al. (2017) assessed the effectiveness of four environmental flow programs that aimed to restore riparian vegetation in four arid zone rivers in China, Arizona, Mexico and Australia. The Australian case study focused on environmental flows that were provided to small portions of the Yanga National Forest of the Lowbidgee Floodplains during the Millennial Drought (2000 - 2010). The effectiveness of this campaign was assessed through the analysis of satellite vegetation indices. This study found that larger volumes of total flows was needed over longer periods to achieve target restoration goals for the Murrumbidgee Catchment. A greater understanding of the hydrological cycle is needed to inform future watering actions and guide management decisions for Murrumbidgee Catchment.

2.4. Water quality indicators and streamflow

Water quality indicators, such as dissolved oxygen (DO), electrical conductivity (EC) and pH have been utilised extensively to assess the water quality of rivers and catchments within Australia. A study by Whitworth et al. (2012) delineated the causes of an extensive hypoxic blackwater event, characterised by high levels of dissolved organic carbon (DOC) and low DO concentrations of river water, that occurred in the southern Murray-Darling Basin from 2010 to 2011. Whitworth et al. (2012) utilised historical datasets of water quality and hydrology from 2010 - 2011 to find that the post-drought release of water from headwaters and the release of hypolimnetic (statified cold, deeper water) of weirs contributed to the observed hypoxia of localised waterways.

Studies such as Dyer et al. (2014) have successfully utilised publicly available historical data to assess the relationship between flow and water quality. Dyer et al. (2014) demonstrated the effectiveness of streamflow and water quality tracers to predict climatic influences within the Murrumbidgee Catchment. The relevance of this approach is recognised internationally, with findings from a study based in a river catchment in France, that found a strong correlation between climatic conditions, water quality (concentrations of nitrate, chloride, sulfate, and DO and inorganic carbon) and hydro-climatic variables (Aubert et al. 2013).

2.5. Water stable isotopes

Water stable isotopes offer a unique insight into the various processes that occur in the hydrosphere. Stable isotopes can be used as highly valuable tracers for processes relating to surface water, including precipitation, influx from groundwater and evaporation (Hughes et al. 2012). For this study, water stable isotopes have been utilised to provide insight into the potential mixing of sources of water and the extent of evaporation along the Murrumbidgee River and regions of distributed water.

The stable isotope signature of surface water largely represents the composition of rainfall, among other inputs such as groundwater inflows (Hughes et al. 2012; Hollins et al. 2018). Hydrogen has two stable isotopes (^{1}H and ^{2}H) and oxygen has three stable isotopes (^{16}O, ^{17}O, and ^{18}O). The cross analysis of the stable isotopic ratios of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$), reported in the relative delta scale as $\delta^{2}H$ and $\delta^{18}O$ respectively, can give insight into the processes of precipitation and evaporation in relation to surface water (Hughes et al. 2012). This isotopic signature is modified through kinetic isotopic fractionation, an irreversible reaction (Jasechko, 2019). Isotopic fractionation is defined by the partitioning of heavy and light isotopes in exchange reactions (Craig, 1961; Horita & Wesolowski, 1994).

The initial liquid phase of rain is enriched in ^{2}H and ^{18}O as compared to that of later precipitation. As rain falls, precipitation becomes isotopically depleted of ^{2}H and ^{18}O as it continues. Subsequently, precipitation becomes more depleted in ^{2}H and ^{18}O as it passes through the continental interior, a phenomenon known as the “continental effect” (Jasechko, 2019).

The relationship between $\delta^{2}H$ and $\delta^{18}O$ for isotopic compositions in precipitation at certain locations is characterised by a linear meteoric water line (MWL) (Figure 3). The global meteoric water line (GMWL) was first defined by Craig (1961) to be $\delta^{2}H = 8*\delta^{18}O + 10$, which provides a generic global representation of the isotopic composition of rainwater.

Local meteoric water lines (LMWL) are defined by a linear regression analysis of δ^2H and $\delta^{18}O$ at a restricted geographical region. LMWLs can give regression coefficients that differ from that of the GMWL, due to processes resulting in the kinetic isotopic fractionation of precipitation (Jasechko, 2019; Hughes et al. 2012). Hollins et al. (2018) defined the LMWL for Wagga Wagga to be $\delta^2H = 8.03 * \delta^{18}O + 14.38$, using monthly data recorded over eight to twelve years.

Through evaporation the proportion of heavy isotope species (^2H and ^{18}O) increases due to additional kinetic isotopic effects during diffusion (Figure 2). This means the lighter isotopes of ^{16}O and ^1H will preferentially enter the vapour phase first, with remaining surface water becoming enriched in heavier isotopes (^2H and ^{18}O) (Jasechko, 2019; Simpson et al. 1991). This isotopic enrichment of surface water can be seen along 'evaporation lines' defined as slopes less than the MWL (Hughes et al. 2012) (Figure 2).

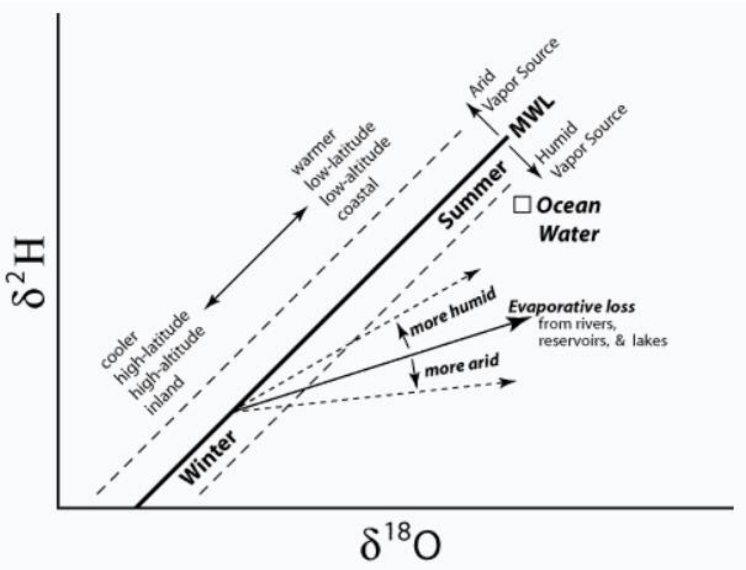

Figure 2: *Effects of various hydrologic processes on water stable isotope ratios (Arizona Board of Regents, 2005). Note: δ^2H = relative delta scale of hydrogen; $\delta^{18}O$ = relative delta scale of oxygen.*

Additionally, as rain falls its isotopic signature can be affected by moisture exchange with surrounding vapour and undergo sub-cloud evaporation, increasing ^{18}O and decreasing deuterium excess (*d*-excess) (Hollins et al. 2018). *D*-excess is related to the physical conditions (humidity, air temperature and sea surface temperature) of the original precipitation source, reflecting conditions during the evolution and mixing of air masses prior to precipitation. Internationally, *d*-excess has proved a useful tool to characterise circulation in polar regions and evaluate general circulation models (Froehlich et al. 2002).

Meredith et al. (2009) highlighted the need to use multiple tracers to understand hydrological complexities in dryland systems. This study compared streamflow with hydrochemical and stable isotope data from samples collected along the Darling River from 2002 to 2007. Meredith et al. (2009) found that temporal variation of isotopic and hydrochemical tracers was strongly related to changes in flow conditions. During periods of low flow, chloride (Cl^-), sodium (Na^+), magnesium (Mg^{2+}), suflate (SO_4^{2-}), δ^2H and $\delta^{18}O$ values increased, with d-excess values becoming more negative. After a storm and subsequent flow event, isotopically depleted waters were introduced to the system, returning *d*-excess to the local meteoric value.

On a continental scale, Hollins et al. (2018) interpreted δ^2H and $\delta^{18}O$ signatures, by incorporating historical Global Network of Isotopes in Precipitation (GNIP) data for seven Australian sites (1962 - 2002) with 8 to 12 years of monthly data from 15 sites from 2003 - 2014. This study developed annual isoscapes of δ^2H, $\delta^{18}O$ and *d*-excess for precipitation across Australia.

These local and continental studies have contributed significantly to international knowledge, by examining isotopic compositions to effectively trace complex processes within the hydrological cycle. The findings of Meredith et al. (2009) and Hollins et al. (2018) contributed to the Global Network for Isotopes in Rivers (GNIR) and GNIP programs. These shared platforms allow for a greater understanding of complex climatic processes on a continental and global scale. There is a need to further define regional and local isotope signatures to achieve a greater understanding of the hydrological system for dry-land rivers of semi-arid Australia (Hollins et al. 2018). My research will aid to address this knowledge gap, by examining water stable isotope ratios from the Lower Murrumbidgee Catchment of the Murray-Darling Basin.

3. Methods

The study consisted of six surface water monitoring and sampling rounds. These were conducted in September 2018, February 2019, June 2019, September 2019, November 2019 and February 2020 to capture seasonal influence on water quality in the Lower Murrumbidgee Catchment. A total of twenty-one surface water sampling locations were carefully selected based on their proximity to weirs and surface water diversions, irrigation areas and towns to assess the impacts of these various forms of land use. To support the analysis of the field data, publicly available rainfall and streamflow datasets were explored, placing the prevailing climatic conditions during the study into context.

3.1. Field measurements and sample collection

Water quality parameters of surface waters were recorded *in situ* at each location using a YSI-556 MPS multiprobe (YSI) water quality meter. This meter measures the temperature (°C), EC (µS/cm), total dissolved solids (TDS) (mg/L), pH, Dissolved Oxygen (DO) (%), and oxidation-reduction potential (± mV) (Table 1, Appendix A). The YSI meter was calibrated for all parameters before each sampling campaign and daily for DO and pH to avoid instrument drift between days. Calibration of the pH probe was acceptable with values within 0.01 +/- pH units of known values. The electrodes were placed deep enough into the surface water to establish electrical contact. The pH, temperature and EC of the sample were read immediately after 60 seconds and recorded to nearest 0.1 pH unit and 1.0 EC unit (µS/m). General notes were taken regarding the flow of the river with photographic evidence to record the condition of the embankment. River water stable isotope samples (δ^2H and $\delta^{18}O$) were collected using a peristaltic pump, purging the line for two minutes prior to sampling, with 30 ml bottles rinsed with sample water.

The primary sampling locations revisited throughout the study include sampling location 1, 12, 13, 4 and 5, from upstream to downstream along the Murrumbidgee River (Figure 3). Sampling location 2 and 3 were only visited in the initial monitoring round in spring 2018, to establish water quality conditions at headwaters (location 2) and other primary river channels (location 3). Revisited sampling locations from irrigation infrastructure include sampling location 13, an irrigation intake channel, and sampling location 14, an irrigation disposal site.

Additional sampling locations were also monitored that targeted irrigation infrastructure and wetlands to understand the effect of irrigation diversions on water quality (Figure 3).

The collection of water samples from such locations was often opportunistic. For example, after a period of heavy rainfall a water sample was collected at a pond adjacent to a large irrigated agricultural area (Location 18). A water sample was also collected at the irrigation wastewater and farm water runoff disposal site at Barren Box Wetlands (location 21, Figure 3) (Murrumbidgee Irrigation, 2019). This wetland is frequently dry, and water samples could only be collected at this site on one occasion.

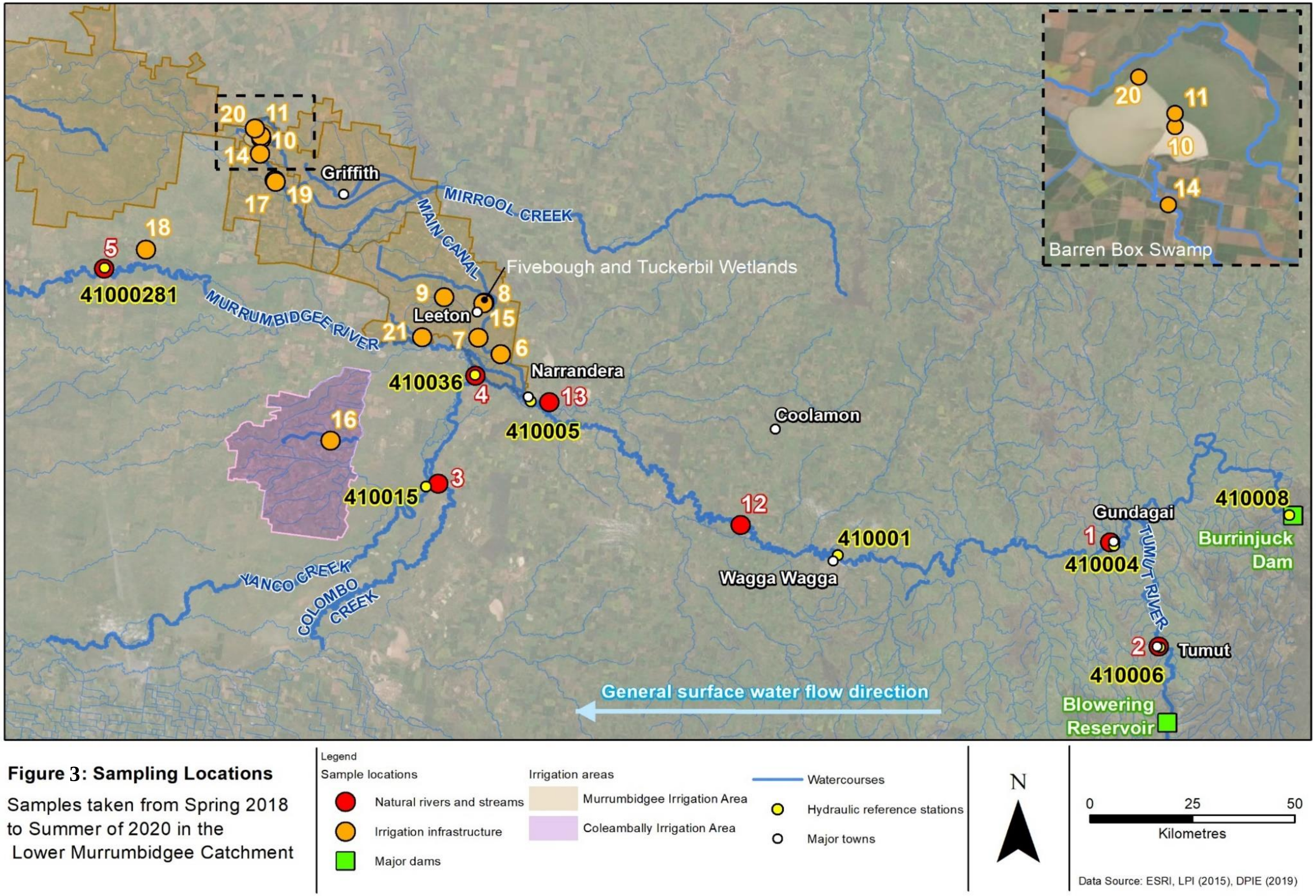

Figure 3: Sampling Locations

Samples taken from Spring 2018 to Summer of 2020 in the Lower Murrumbidgee Catchment

3.2. Water quality parameters

Water electrical conductivity (EC) is a measure of the concentrations of dissolved ions in water. These ions include Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^- , HCO_3^- and CO_3^-, which generally constitute the major ionic load in most freshwater (Zinabu et al. 2002). Raw EC measurements are corrected to a standard temperature of 25°C for direct comparison. The mean electrical conductivity (EC) (µS/cm) was mapped for all samples collected using ArcMap 10.8 software, using proportional symbols to show the variation of EC measured across the catchment. The distribution of EC has been visually represented by a box and whisker plot. This summarises the minimum, first quartile, median, third quartile and maximum EC reading for each location.

3.3. Water stable isotopes (δ^2H and $\delta^{18}O$)

The relative difference of stable isotope ratios (δ) was determined for deuterium/hydrogen ($^2H/^1H$) and oxygen ($^{18}O/^{16}O$) referred to as δ^2H and $\delta^{18}O$, respectively. Stable water isotope ratios for samples were analysed at ANSTO using cavity ring-down spectroscopy (CRDS) on a Picarro L2130-i analyser. The δ^2H and $\delta^{18}O$ precision values were reproducible to ±1 ‰ and ±0.15 ‰, respectively.

Water stable isotope values (δ^2H and $\delta^{18}O$) are reported as a per mil (‰) deviation from the Vienna Standard Mean Ocean Water (VSMOW) standard (Dansgaard, 1964; Wallace, 2010). This is expressed as:

$$\delta \text{ isotope (in ‰)} = ((R_{Sample}/R_{Standard})-1) * 1000.$$

Once generated, water isotope results and associated MWLs were plotted using Grapher Software. This allowed climatic conditions and evaporation trends to be assessed, complimented with *d*-excess values calculated by $d = \delta^2H - 8 \times \delta^{18}O$ (Hollins et al. 2018).

3.4. Rainfall and streamflow data

3.4.1. Rainfall Data

Historical rainfall data (1872-2019) at station 72042 was explored to establish long term climatic conditions (BOM, 2020). This station is located at the headwaters of the catchment and had the longest rainfall dataset in the study area.

A cumulative rainfall departure graph was produced, allowing the assessment of long-term rainfall trends (Weber & Stewart, 2004). The mean total annual rainfall (1872 - 2019) was calculated, which was was subtracted from the total rainfall of each year to give an annual residual rainfall value (positive residuals indicate above average rainfall, and negative are below average rainfall). The residual values were then accumulated and graphed.

3.4.2. Streamflow data

The assessment of streamflow allows for the nature and influence of dams and diversions to be evaluated. Streamflow data were retrieved from Water NSW Real Time Data (https://realtimedata.waternsw.com.au) for eight hydrologic stations. These stations were selected based on their proximity to the sampling locations, weirs, dams and towns. Details of these stations and associated sampling locations are provided in Table 2, Appendix B, with station locations also illustrated in Figure 3. Streamflow data is limited to primary river channels, as there is no available streamflow data from gauging stations north of Narrandera. Streamflow data at selected locations is still fit for purpose, as it effectively represents the rapid redistribution of water from headwater dams to the main river and irrigation districts.

4. Results

4.1. Rainfall data

The mean annual rainfall recorded at Tarcutta Post Office (Station 72042) for years 1872 to 2019 was 656 mm (Figure 4A). Mean annual rainfall over the study period was much lower than the long-term average, with 415 mm and 354 mm recorded in 2018 and 2019, respectively.

The cumulative rainfall departure graph visually represents the context of the sampling period relative to wet and dry runs. Where the slope of the curve is increasing, rainfall exceeds the long-term average, reflecting wetter conditions (1915 - 2000, Figures 4A and 4B). Conversely, where the slope of the curve is decreasing, rainfall for the period is less than the average, indicating arid conditions (2001 – 2009, Figures 4A and 4B) (Green et al. 2011). The calculation of cumulative rainfall departure has a negative slope for September 2018 to February 2020, indicating the study was conducted during an extremely dry period Figure 4A & B) (BOM, 2020).

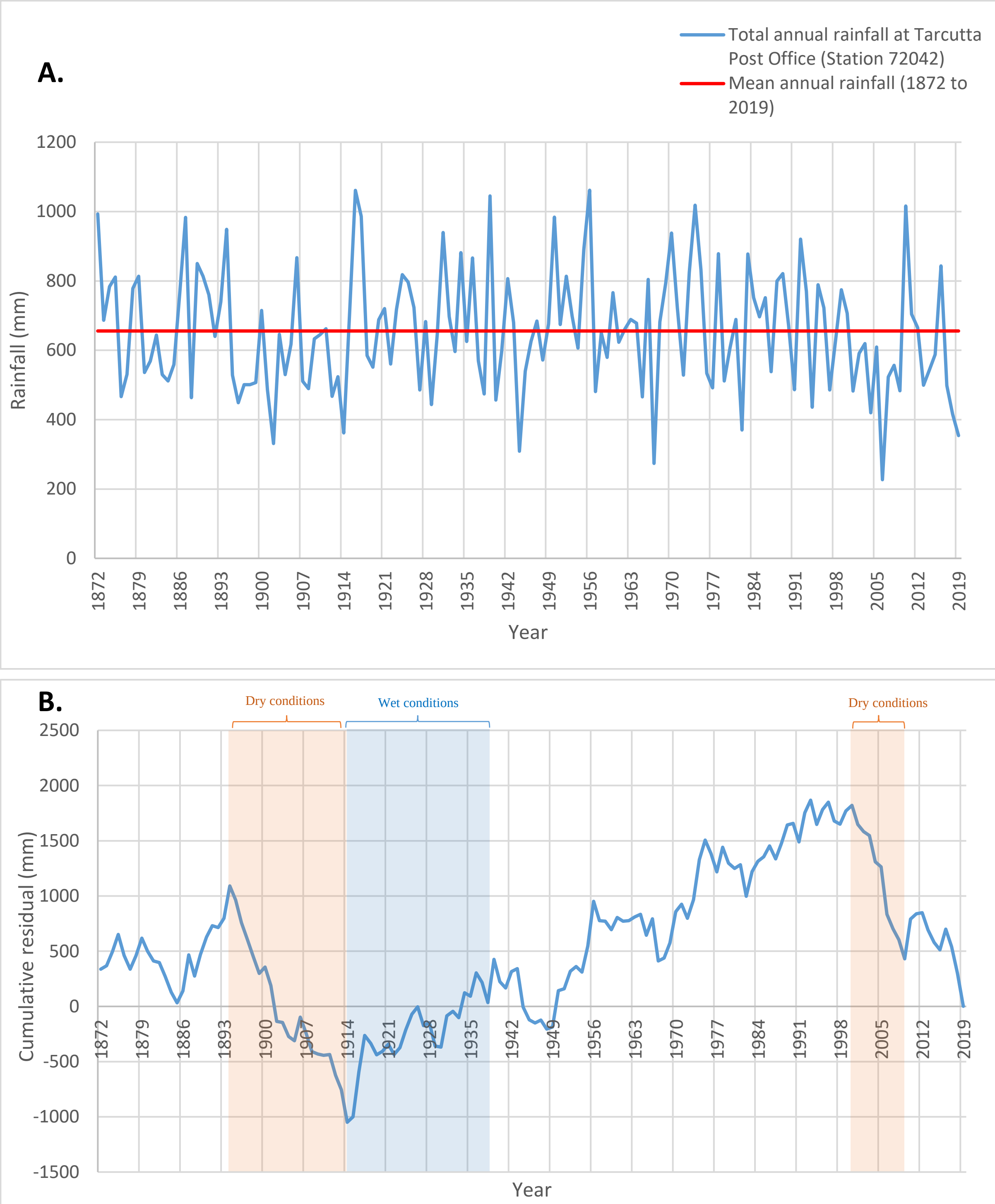

***Figure 4: A.** Total annual rainfall for Station 72042 (Tarcutta Post office), with mean total annual rainfall displaying drier than usual conditions during the period of sampling from September 2018 - February 2020. **B.** Calculated cumulative rainfall departure for Station 72042. The decreasing gradient of the line shows that the sampling period (September 2018 - February 2020) is part of an extend dry run that started in 2003 (with a small hiatus from 2008 - 2012)*

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4.2. Streamflow data

Streamflow, or discharge, is a measure of water flowing through the cross section of a stream (DPIE, 2019).

In a natural river system, high rainfall would be predicted to increase expected river discharge. In the Murrumbidgee Catchment there is no significant correlation between rainfall and streamflow for stations located nearest to Blowering Reservoir (Figure 5).

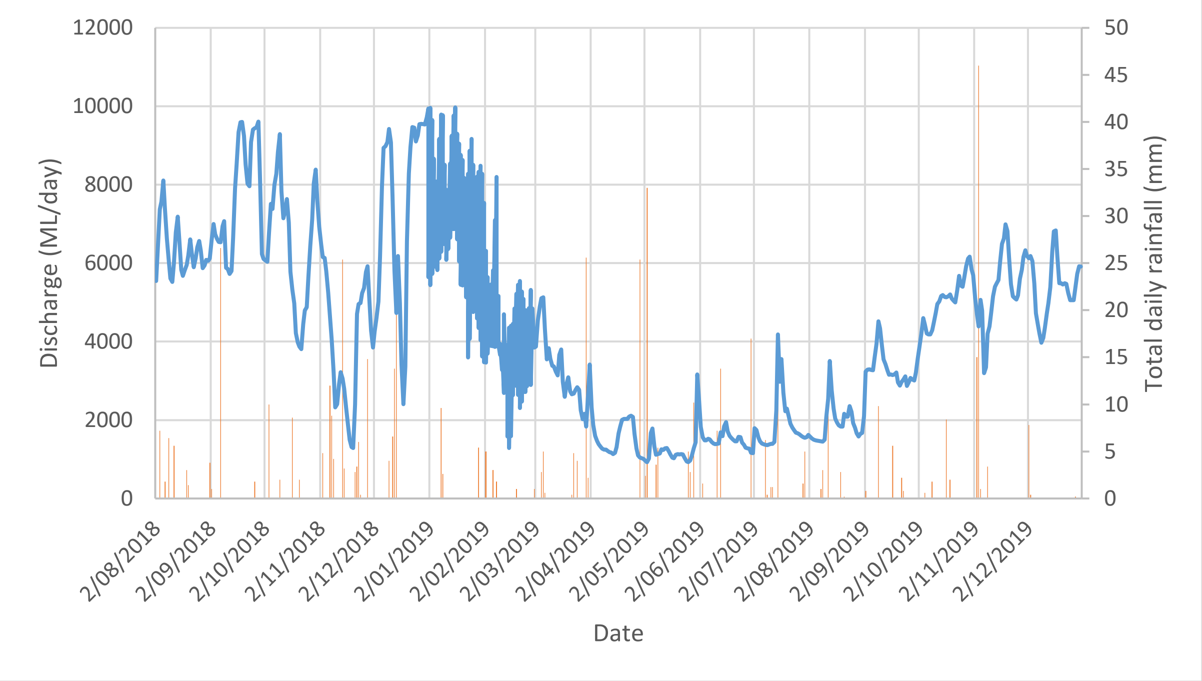
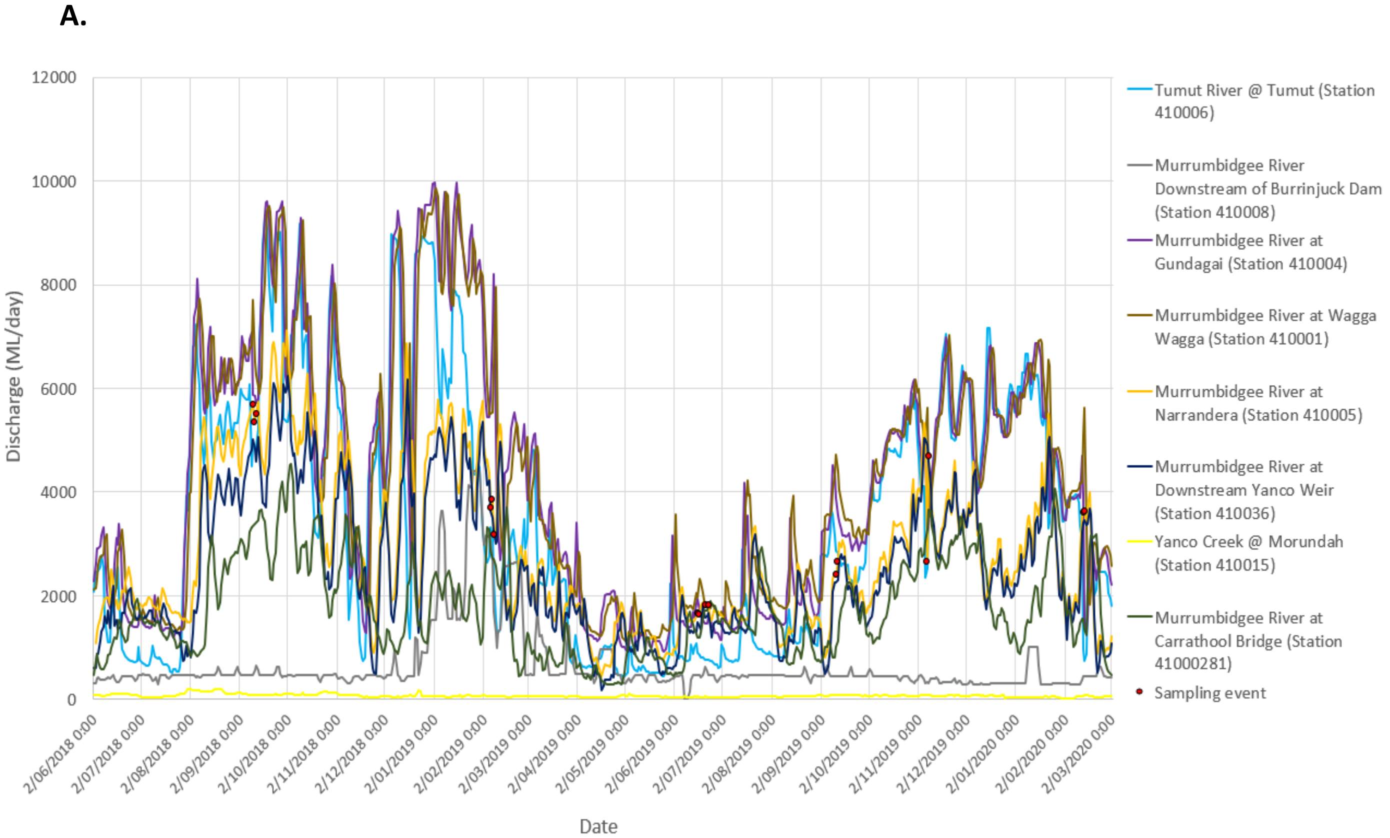


Figure 5: *Daily discharge (ML/day) recorded near headwaters at Gundagai (Station 410004) and daily rainfall recorded at the corresponding weather station at Tarcutta Post Office (Station 72042), showing no significant correlation between rainfall and discharge.*

Figure 6A shows the mean daily discharge recorded at eight stations during the study. Stations located closest to Burrinjuck Dam had the highest values for mean daily discharge, with discharge decreasing with increasing distance from the dam. Peak and trough values for discharge at Station 410004 was mirrored at all downstream station locations, demonstrating the rapid transfer of water from dam releases along the Murrumbidgee River. Figure 6A also shows that the timing of sampling events captured a range of flow conditions.

A dam water release on the 5th of August 2018 from Blowering Reservoir was tracked, arriving at downstream streamflow gauging stations (shaded blue in Figure 6B). The water was released into the Tumut River (where Station 410006 is located). The Tumut River joins the Murrumbidgee at Gundagai (Station 410004), before travelling west towards the Darling River. It took approximately 9 days for the dam water release to travel from the Tumut River gauging station (410006) to the Carrathool Bridge (Station 41000281) on the lower Murrumbidgee in the far west of the study area (Figure 6B, Figure 3). The streamflow rate decreases from east to west (moving downstream), due to various water losses attributed to back storage, urban and irrigation withdrawals and decreasing river gradient (Department of Agriculture, Water and the Environment, 2020b.). Discharge had decreased by 61% from 8109.7 ML/day at Gundagai (Station 410004) to 3160.9 ML/day at Carrathool Bridge (Station 41000281). Discharge in the study period is much lower in comparison to times of high rainfall. For example, the mean daily discharge recorded for Gundagai (Station 410004) decreased from 10,417 ML/day in 2010 to 3,675 ML/day in 2019, a decrease of 65%. Similarly, the mean daily discharge at Carrathool Bridge (Station 41000281) decreased 76% between 2010 and 2019, from 6,559 ML/day to 1,554 ML/day, respectively.



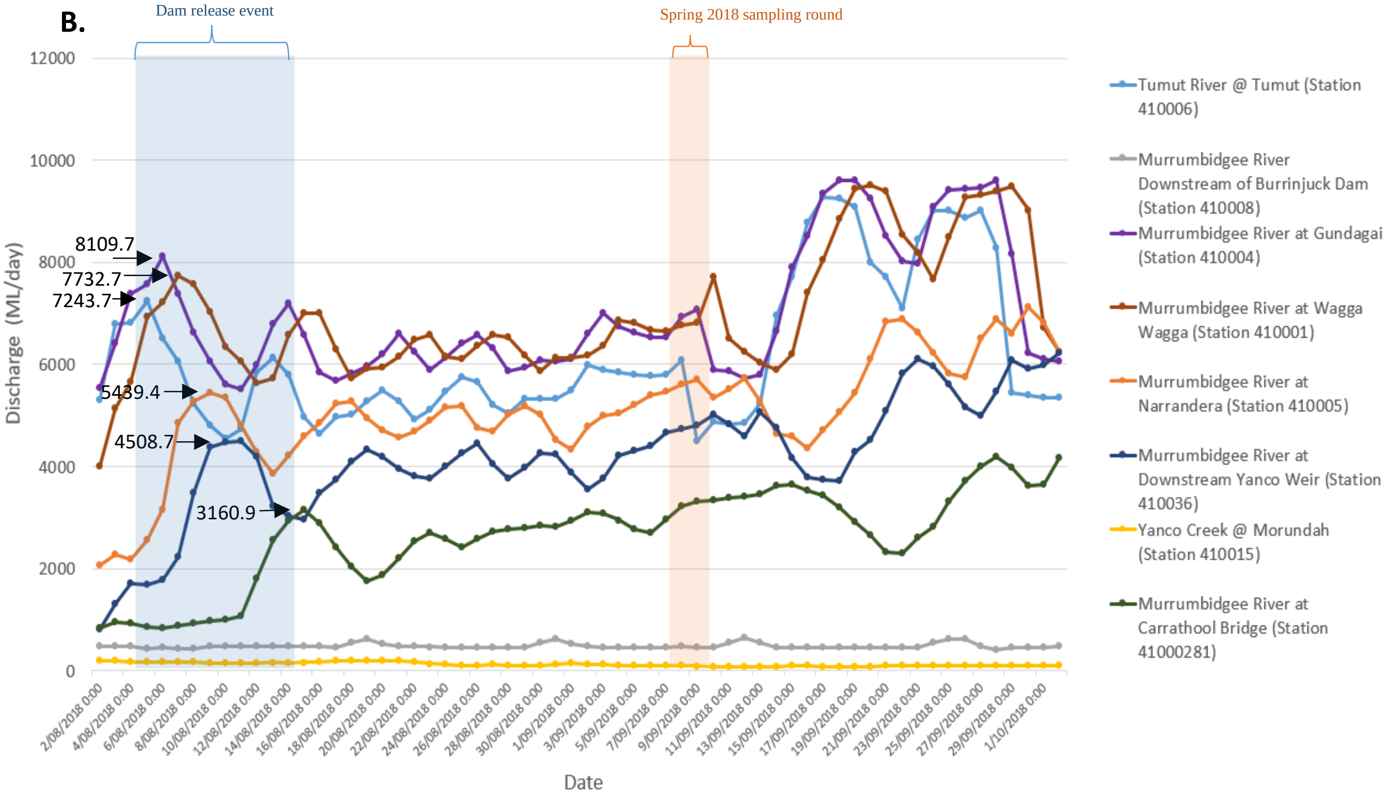


Figure 6: A. *Daily discharge recorded at station locations for the study period. Streamflow peaks and troughs are reflected at all stations located along the Murrumbidgee River, representing the rapid transfer of surface water from headwater dams downstream along the Murrumbidgee River.* ***B.*** *Discharge recorded at hydraulic stations during an artificial water release event at Blowering Reservoir in August 2018.*

4.3. Water quality results

EC ranged from 28 to 1880 µS/cm for all samples (n=49). EC was consistent across sampling rounds and from upstream to downstream locations along the Murrumbidgee River (sample locations east to west: 1, 12, 4 and 5) (Figure 7). Sample locations within the irrigation district had higher values for EC and high variability between sampling rounds (sample locations 13 and 14) (Figure 7).

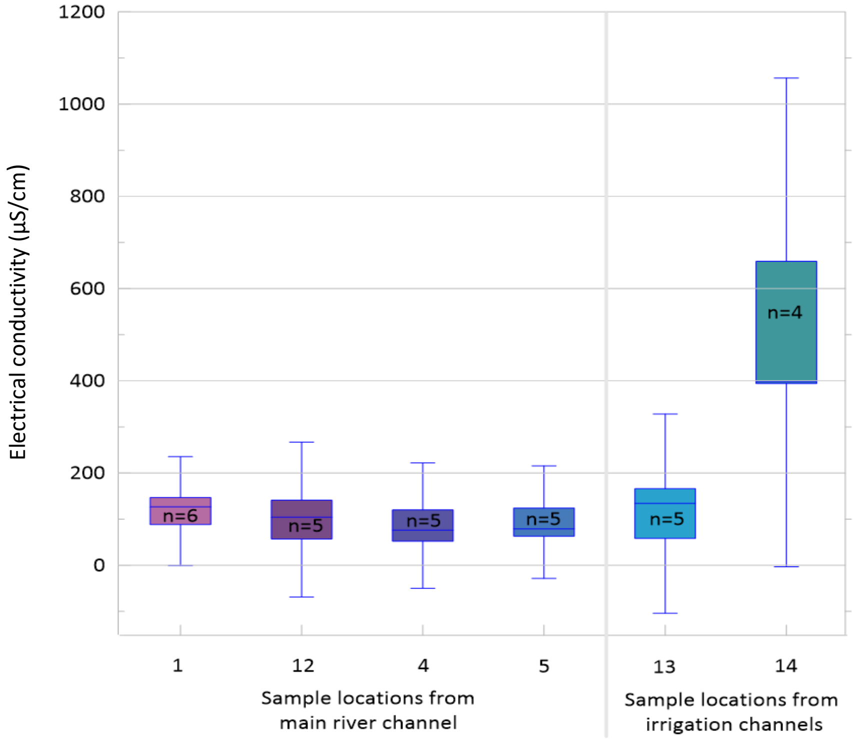


Figure 7: *Box plot of EC for sample locations revisited throughout study, showing very little variation between upstream and downstream sample locations along the Murrumbidgee River. In contrast, sample locations within irrigation infrastructure had a higher variation of conductivity values, with sampling location 13 representative of irrigation intake (at Talbot Lake) and sampling location 14 situated within an irrigation disposal site (terminal lake at Mirool Creek).*

The lowest EC result was 28 µS/cm, recorded at the first sampling location downstream of the Blowering Reservoir (sampling location 2), reflective of a freshwater source. This low value appears to coincide with a dam release on the 9th of September 2018, as depicted in Figure 6B. EC was only 79 µS/cm at Carrathool (sampling location 5), the furthest downstream location situated along the Murrumbidgee River. Mean EC values for locations along the Murrumbidgee River and other main river channels was below 200 µS/cm (Figure 8).

The highest EC values were recorded at locations disconnected from the primary rivers and channels (sites 13 and 14, Figure 7). The highest EC reading (of 1880 µS/cm), was recorded at Barren Box Swamp (Site 20, Figures 3 and 8), a natural wetland area that was partly redeveloped for the purpose of water storage and recycling (Murrumbidgee Irrigation, 2019).

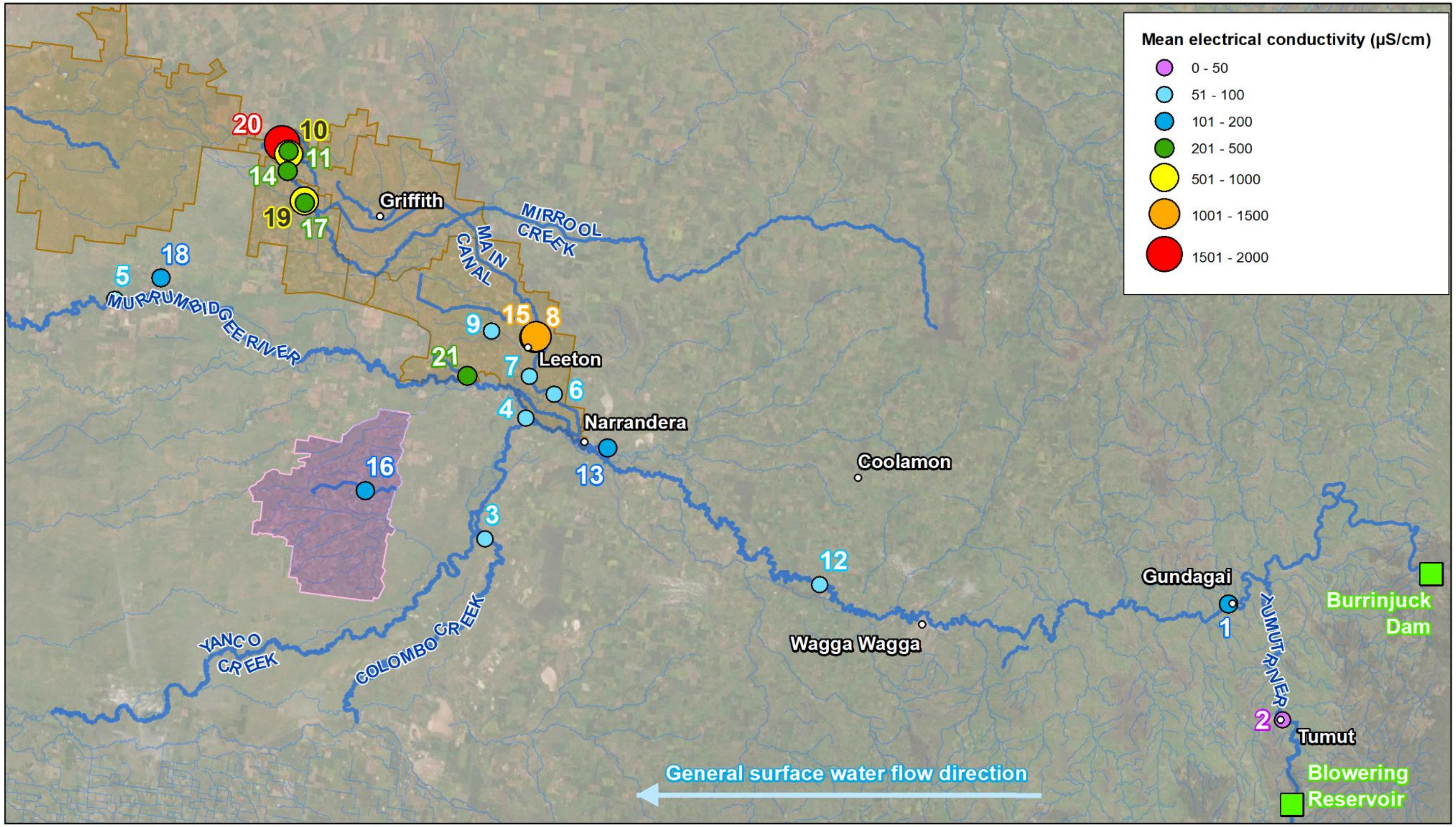


Figure 8: Electrical conductivity

Mean electrical conductivity (µS/cm)
for all samples
collected during study

Legend

Irrigation areas

- Murrumbidgee Irrigation Area
- Coleambally Irrigation Area
- Watercourses
- Major dams
- Major towns

N

0 25 50
Kilometres

Data Source: ESRI, LPI (2015), DPIE (2019)

There is an inverse relationship between EC and discharge at station locations situated along the Murrumbidgee River and Gundagai (Figure 9A) and Wagga Wagga (Figure 9B). This may be the result of headwater dams diluting solutes in surface water (DPIE, 2020a.).

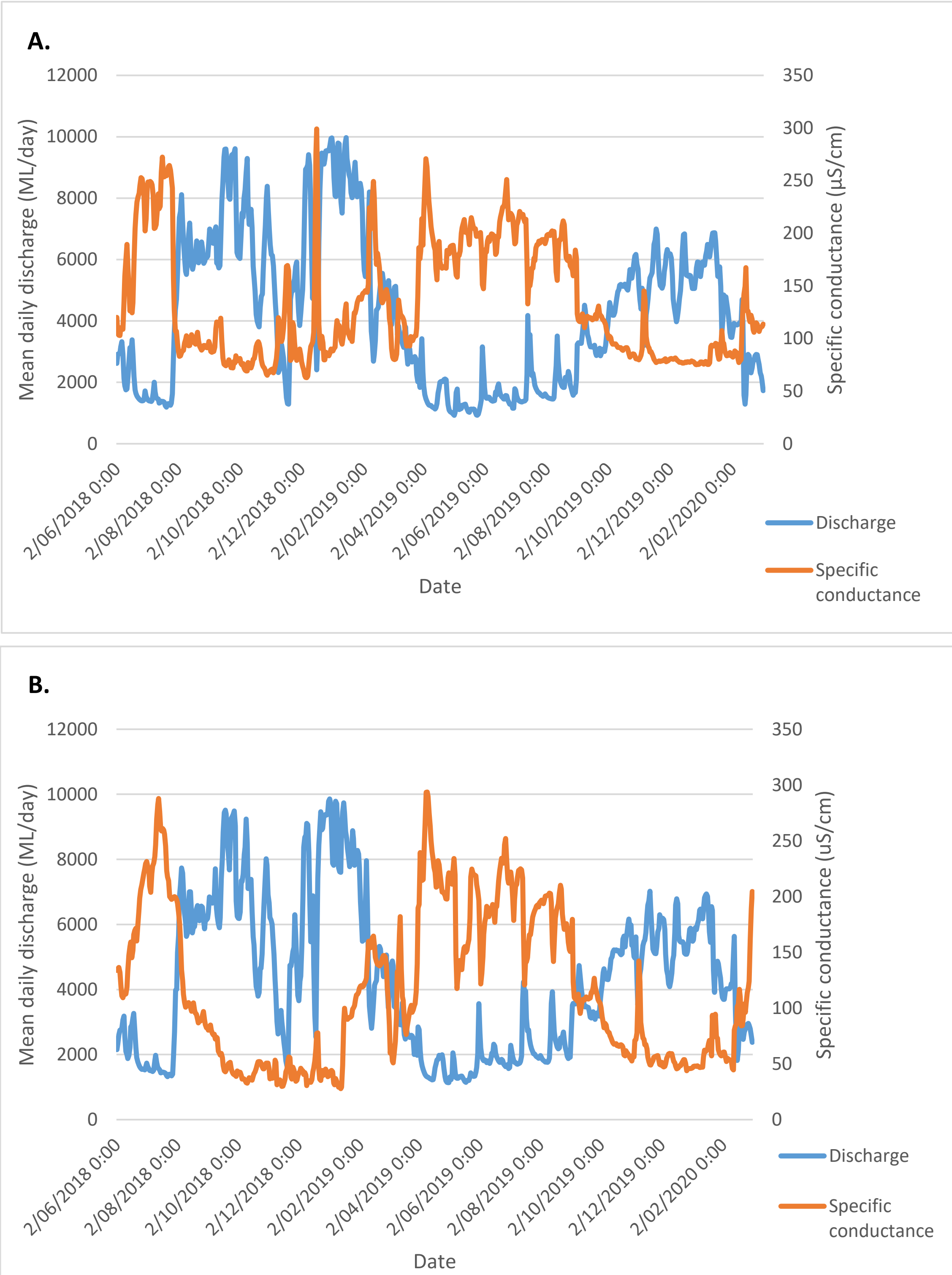


Figure 9: *Discharge vs EC along the Murrumbidgee River from June 2018 – February 2020 at* ***A****. Gundagai (Station 410004), and* ***B.*** *Wagga Wagga (Station 410001).*

There is a cluster pattern evident for relative values of surface water temperature and dissolved oxygen based on the season of sampling (Figure 10). Findings of this study support the seasonal influence on surface water temperatures, with recorded temperatures much higher in summer months (average temperatures of 25°C in summer, in comparison to 11°C in winter and 14°C in spring; Figure 10). In general, disconnected locations and irrigation channel water were characterised by higher temperatures (median of 22.1°C) and lower dissolved oxygen concentrations (median of 69%) than those locations along the main river channel, that have a median water temperature of 16.1°C and a median of 93% for DO concentrations (Figure 10). Notably, sample locations 18, 19 and 21 had high temperatures (greater than 25 °C) and low dissolved oxygen (below 11%; Figure 10). This trend could be the result of warmer temperatures and lower flows experienced in summer months (Murrumbidgee Irrigation, 2019).

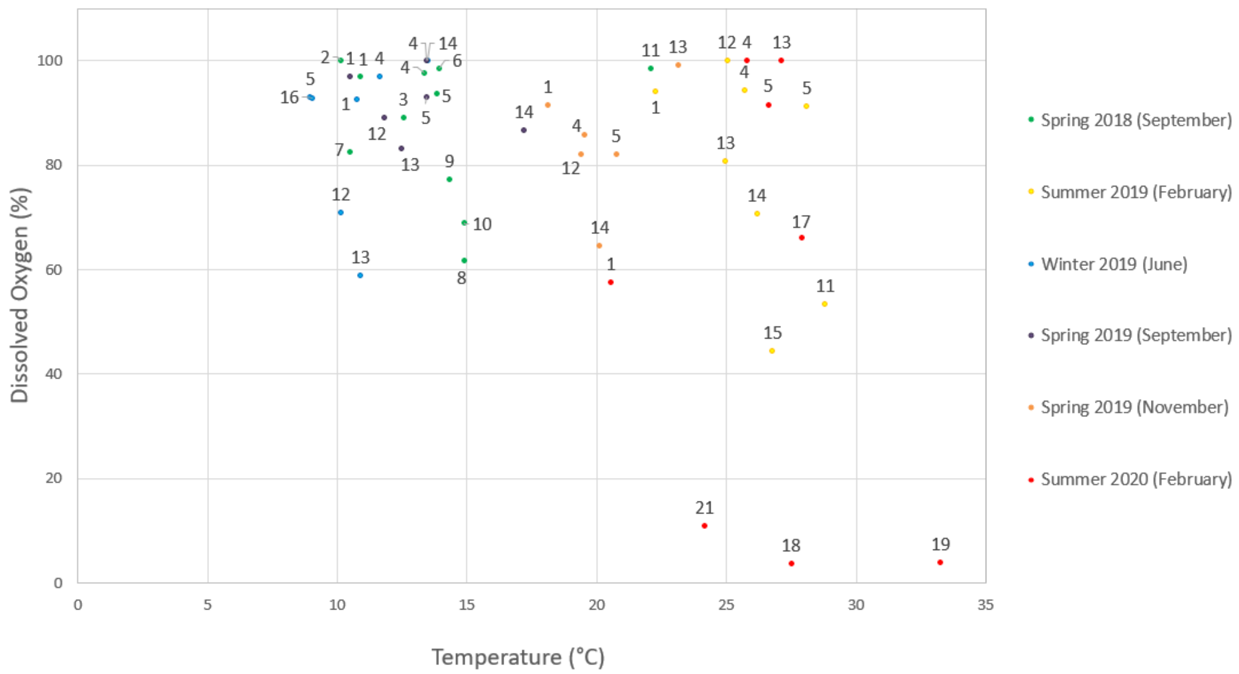


Figure 10: *The relationship between recorded surface water temperature (°C) and dissolved oxygen (%) for all samples (n=49).*

4.4. Water stable isotopes ratios

The δ^2H and $\delta^{18}O$ values ranged from their most enriched at +55.01‰ and +12.87 ‰ (sample location 20) to their most depleted at -89.19 ‰ and -11.53 ‰ (sample location 18) (Figure 11A). This is consistent with findings of Meredith et al. (2009) for samples collected at Cobar between September 2006 to January 2009. The δ^2H and δ^{18}O signatures reported by Meredith et al. (2009) ranged from their most enriched at +43.0‰ and +7.03‰ in October 2008 to their most depleted at -77.3‰ and -11.05‰ in September 2006. Unlike Meredith et al. (2009), the greatest differences between isotope signatures for samples collected in this study cannot be completely linked with the timing of sample collection, with differences instead attributed to location type (whether samples were collected from the main river or irrigation district channels) (Figure 11A and Figure 3).

The Murrumbidgee catchment water samples sit on a linear trend in the δ^2H vs δ^{18}O plot (Figure 11). The R^2 value of the fitted linear regression is 0.93, indicating a good fit. Compared to the GMWL and LMWL the local Murrumbidgee trend has a gentler gradient (5.46) and is downward offset to more negative δ^2H values for δ^{18}O >-4 ‰. This contrasts the findings of previous studies, with Gibson et al. (2008) reporting that ^{2}H and ^{18}O enrichment in dryland rivers typically follows evaporation lines with a gradient close to 4.

Weighted averages for *d*-excess values over this study were found to be 9.78 ‰ for samples collected along the main river channels (n=30). This is comparative to findings of Hollins et al. (2018), that reported average annual precipitation *d*-excess values of 14.18 ‰ for Wagga Wagga from 2003 to 2014. These *d*-excess values contrast those for samples collected along irrigation infrastructure (n=17), whereby average d-excess values of -1.39 ‰ were recorded.

Isotope values for samples collected from the Murrumbidgee River, Main Canal and Columbo Creek cluster together, with values from around -10.2 to -37.6 ‰ for δ^2H and -6.0 to -1.2 ‰ for δ^{18}O (Figure 11B). Within this cluster, the stable water isotope values for samples collected in spring of 2018 (September) and spring of 2019 (September and November) generally lie between the GMWL (Craig, 1961) and the Wagga Wagga LMWL (Hollins, 2018). However, values of δ^2H and δ^{18}O for samples collected in summer 2019 (February) and summer 2020 (February) lie below LMWL for Wagga Wagga, suggesting the influence of evaporation (Hollins et al. 2018).

In contrast, δ^2H and δ^{18}O ratios for samples collected in winter (2019) have a larger range, falling between the LMWL and GMWL for sample locations along the main river channel (1, 4, 5 and 12). δ^2H and δ^{18}O values follow a 'regional evaporation line' for disconnected sample locations (13, 14 and 16), indicating a greater influence of evaporation at these locations.

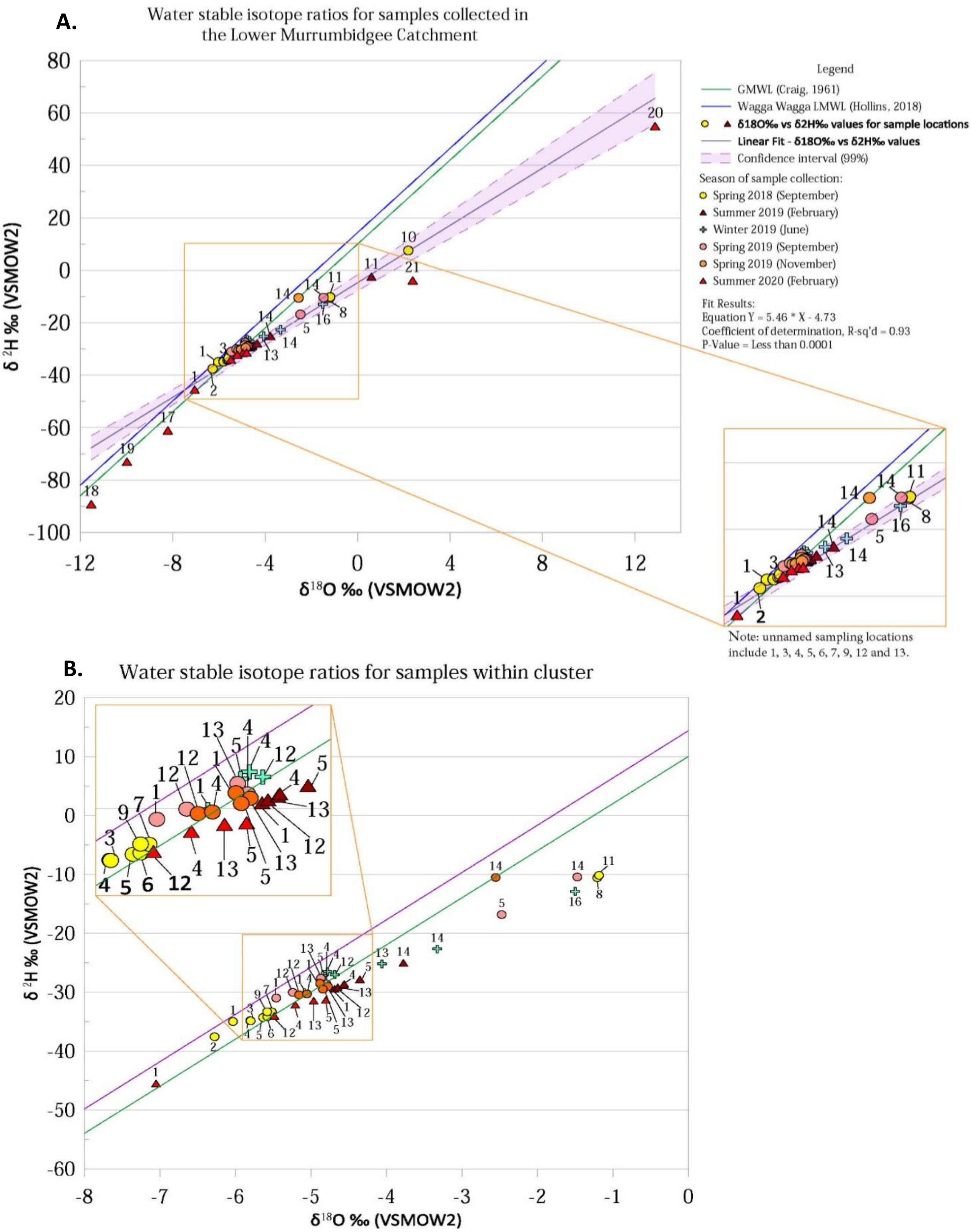


***Figure 11: A.** δ^2H and δ^{18}O ratios for all samples collected within the lower Murrumbidgee Catchment. **B.** Stable water isotope values for samples falling within primary cluster.*

Within the primary cluster, stable water isotope values for samples are closely grouped with others of the same sampling round, indicating minor seasonal influence. However, stable water isotope values for samples collected in June 2019 have a much greater range in comparison to those collected during other seasons within the primary cluster (Figures 11A and 11B).

There are multiple groups of samples outside of the primary cluster for sample locations 10, 11, 17, 18, 19, 20 and 21. Sample locations with stable water isotope values to the left of the primary cluster are associated with recent sources of precipitation from storm systems, with samples depleted in δ^2H and $\delta^{18}O$ values (Hughes & Crawford, 2013). Alternatively, samples to the right of the primary cluster correspond to locations that have been exposed to seasonal evaporation following local water storage, resulting in the enrichment of δ^2H and $\delta^{18}O$ values.

5. Discussion

My research provides insight into the drivers of water quality in the Lower Murrumbidgee Catchment from September 2018 to February 2020. Findings of my research may guide the development of improved water management strategies for the Murray-Darling Basin during future droughts.

5.1. Sources and sinks of surface water

Streamflow in the study area (Figure 3) is heavily regulated by government water policies and does not mirror natural climatic conditions, shown by the cross-analysis of rainfall and discharge data (Figure 5). There was no relationship between daily rainfall recorded at Tarcutta Post Office and discharge recorded at Gundagai (Station 410004) over the study period. Discharge was lowest in winter months and highest in spring and summer months (Figure 6A). This reflects the demands of the irrigated agriculture sector, primarily for growing crops including rice, pasture, cereals, vegetables and oil seeds and perennial crops such as wine grapes and citrus (Kingsford & Thomas, 2004; O'Gorman, 2013; Green et al. 2011).

Water is very quickly transferred from headwater dams through the main river channels. Water released on the 5th of August 2018 took nine days to travel approximately 560 km from Tumut River to Carrathool Bridge along the Murrumbidgee River (Figure 6B). The high impact of streamflow diversions and subsequent rapid abstraction of water by irrigators is apparent in Figure 6B, with a 61% decrease in recorded discharge from Gundagai to Carrathool in August 2018, assuming no evaporation or transmission losses.

The homogeneity of water quality results and isotope signatures along the Murrumbidgee River is indicative of fast water transfer rates (Figures 7 and 8). Homogenous and depleted δ^2H and $\delta^{18}O$ values for water sampled in spring and summer along the main river channels suggests that in-channel evaporation is minimal (Figure 11B) (Simpson & Herczeg, 1991; Hughes et al. 2012). Under natural conditions, a large catchment such as the Murrumbidgee would be expected to show variability in water stable isotopes, due to forcing from seasonal climatic influences (Hollins et al. 2018). The cluster of stable water isotope signatures (10.2 to -37.6 ‰ for δ^2H and -6.0 to -1.2 ‰ for $\delta^{18}O$; Figure 11B) provides evidence of a single origin of surface water for each round monitored, with the mixing and subsequent homogenisation of water isotope signatures within the headwater dams prior to water release. The primary cluster of δ^2H and $\delta^{18}O$ for samples collected along the main river channels are consistent with findings of Hollins et al. (2018) for precipitation signatures, with values fitting closely to the LMWL for Wagga Wagga ($\delta^2H = 8.03 * \delta^{18}O + 14.38$). Hollins et al. (2018) reports annual weighted averages for precipitation of -28.7 ‰ for δ^2H and −5.36‰ for $\delta^{18}O$ for Wagga Wagga from 2003 to 2014, a period encompassing both the Millennial Drought (2001-2009) and major floods that occurred in 2010 (Glenn et al. 2017).

D-excess values of samples collected from the Murrumbidgee River are much higher (average of 9.78 ‰) than those from irrigation areas (average of -1.39 ‰). High *d*-excess values for river samples represents precipitation sources at the headwaters of the catchment (Hollins et al. 2018; Meredith et al. 2009).

Within the primary cluster (Figure 11B), there are smaller δ^2H and $\delta^{18}O$ clusters for samples within and between seasons, providing evidence for seasonal influence on water quality. This apparent seasonal influence may be confounded by river regulation, which is controlled by annual cropping cycles (O'Gorman, 2013; CSIRO, 2008). Conversely, there is some spread of isotope signatures for samples collected in winter 2019. It is unlikely that the greater variation of isotope values can be attributed to high rainfall and subsequent runoff degrading water quality, as average monthly rainfall for winter 2019 was 28.5 mm at Tarcutta Post Office (Station 72042). This is significantly less than the average monthly rainfall of 59.6 mm for winter across all years (1872 - 2019) and would not cause significant runoff. These findings contradict the CSIRO (2008) report, which conclude that runoff is highest in winter and spring. This may be true for periods of high rainfall, however these findings must be distinguished from drought periods in future water management reports.

The greater variation of δ^2H and $\delta^{18}O$ signatures for samples collected in winter 2019 indicates less altered streamflow conditions. Evidence for this is shown by the deviation of δ^2H and $\delta^{18}O$ to the right of the LMWL following a regional evaporation line (Figures 11A & 11B) (Hollins et al. 2018). The linear evaporation trend may be the result of greater residence times of water in river channels and water storages due to reduced irrigation and water abstraction occurring in winter months (Murrumbidgee Irrigation, 2019). This evaporation trend needs to be investigated by future studies that span across multiple winter seasons and quantify evaporation losses to accurately assess the impact of evaporation (Skrzypek et al. 2015).

A weak climatic influence is shown by the higher δ^2H and $\delta^{18}O$ signatures for samples collected in spring 2018 and 2019 (fitting to the left of the GMWL) relative to lower isotope values for samples collected in summer which fall below the GMWL to the right (Figure 11B). Hollins et al. (2018) supports this finding, reporting a weak seasonal variation in isotopic composition with maximum isotopic values recorded in spring and lower values in winter and summer. This variation associated with wet periods associated with tropical cyclones and the Intertropical Convergence Zone (ITCZ) (Hollins et al. 2018).

5.2. Potential changes of surface water quality along the flow path

EC was generally low (<200 µS/cm) for all sample locations along the Murrumbidgee River. This suggests that activities from adjacent land use, such as the MIA or towns such as Wagga Wagga, had little to no impact on water quality in the main river system. This is expected as the study was performed during an intense drought period, with low rainfall reducing the effect of surface water runoff (Meredith et al. 2009).

Homogenous EC, δ^2H and $\delta^{18}O$ values show little to no inputs from surface water runoff or groundwater infiltration for samples collected from the Murrumbidgee River (Figure 8 and 11B) (Meredith et al. 2009). Unlike the findings of my research, variable δ^2H and $\delta^{18}O$ signatures were reported by Meredith et al. (2009) for river water collected in the Barwon-Darling Catchment of the Murray-Darling Basin during the Millennial Drought (2002-2007). Meredith et al. (2009) utilised Cl^- concentrations, $\delta^{18}O$ and d-excess values of samples to calculate groundwater influx into the Darling River, finding that water comprised of approximately 60-99% of saline groundwater during periods of low flow. Meredith et al. (2009) concluded that the reduced water levels in the river during the drought conditions provided a pathway for saline groundwater to discharge into the river system.

There is notable degradation of water quality once it is diverted from the Murrumbidgee River into the MIA and CIA (Figure 8). The high EC values (average of 512.2 µS/cm), high temperatures (median of 22.1°C) and low DO concentrations (median of 69%) are consistent with NSW state reports on water quality (DPIE, 2019). These poor water quality conditions are likely the result of shallow, low-flow conditions from water regulation by dams, weirs and diversions (Kopf et al. 2019). Poor water quality can result in stratification and subsequent hypoxia of waterbodies, degrading important riverine habitats such as the Fivebough and Tuckerbil Wetlands (sample location 8 and 15; Figure 3) (Kopf et al. 2019; Baldwin, 2019; DPIE, 2020b). There is no risk of poor quality irrigation wastewater being discharged into the Murrumbidgee River, as water terminates at Barren Box Swamp (approximately 40 km away from the Murrumbidgee River, Figure 3) (Murrumbidgee Irrigation, 2019).

The Murrumbidgee River and the irrigation districts can be distinguished by the relative depletion and enrichment of their isotopic signatures, respectively (Figure 11A). The depleted δ^2H and $\delta^{18}O$ values for samples collected from the main river fit closely to the LMWL and are clustered together, reflecting sources of precipitation (Hollins et al. 2018). Conversely, enriched stable water isotope ratios indicate a strong effect of evaporation for sample locations of the MIA and CIA. This evaporation trend is shown by the linear deviation from the GMWL and LMWL (with a gradient of 5.46) (Figure 11A). There is some seasonal influence on evaporation trends, with δ^2H and δ^{18}O values of samples collected in summer following a linear deviation to the right of the LMWL. Conversely, the clustering of δ^2H and δ^{18}Ovalues for samples collected in winter and spring shows little to no influence of evaporation (Figure 11B).

Interestingly, the highest EC values recorded in the Murrumbidgee river and its tributaries were at the upstream location near Gundagai at Sample Location 1 (Figure 7). This may be the result of a combination of factors. There is a sewerage treatment plant at Gundagai, with effluent from the facility being recycled onto the Gundagai Golf Course and the neighbouring football oval (Cootamundra-Gundagai Regional Council, 2017). Higher EC may be the result of surface water runoff from these areas. Alternatively, relatively high EC values recorded at Gundagai (sample location 1) may be the result of salinity impacted areas transferring a higher solute load to the Yass River and subsequently increasing EC within Burrinjuck Dam (Jolly et al. 2001). Downstream dilution may then occur with freshwater inputs from the Snowy Mountains via Tumut River. Evidence for this is provided by relatively high EC values recorded at Burrinjuck Dam (Station 410008), with a mean daily EC value of 238.5 µS/cm recorded over the dates of sampling.

The sample size of this study was too small (n<6) to evaluate the relationship between water quality parameters (EC, temperature and DO) and discharge over the study period. However, EC results of my research provide evidence for the quality of long-term water quality datasets at select gauging stations (Table 2, Appendix B). The cross-analysis of publicly available EC and streamflow data (June 2018 – February 2020) suggests an inverse relationship between EC and streamflow at Gundagai and Wagga Wagga (Figures 9A & 9B). Thus, discharge events may decrease EC through dilution in the study area. However, there are many complex interactions between electrical conductivity and discharge (Aubert et al. 2013; Lloyd et al. 2016). This link needs to be further investigated using other tracers such as anions or cations, specifically during periods of drought when runoff is minimal. For example, Cartwright et al. (2019) investigated the relationship between streamflow and solutes (Ca, Na, K and Mg) in five headwater streams in the Yarra Catchment of Victoria from south-eastern Australia. Cartwright et al. (2019) found that some solutes (Ca, Na, K and Mg) do not change with streamflow, however others (NO_3 and SO_4) were higher in periods of high streamflow. Therefore, more detailed analytical techniques would be required to determine the relationship between streamflow and EC.

Samples taken in summer 2020 showed the greatest variation of stable water isotope ratios. This is because the number of sample locations increased to include locations within irrigation districts, to explore the impacts of agricultural activities on water quality in the catchment. The water stable isotope signature for sample location 20 (Barren black box-western pond) has the most enriched δ^2H and $\delta^{18}O$ value (55.01 ‰ for δ^2H and 12.87 ‰ for $\delta^{18}O$), suggesting that the sample has been heavily affected by evaporation (Meredith et al. 2012). Similarly, sample locations 21 (water disposal site) and sample location 10 (Barren Black Box, north-east pond) have been affected by high evaporation. These locations are greatly disconnected from high order Murrumbidgee River and Main Canal systems, only receiving intermittent flows (Murrumbidgee Irrigation, 2019).

5.3. Implications for river management

The sources and sinks of streamflow have substantial implications for the management of water. Discharge quantities were high in spring and summer months (Figure 6A), with averages of 5154.2 ML/day for spring and 6273.2 ML/day for summer from 2018 – 2020 (Station 410004 in Gundagai). Water losses were also high, with a 61% decrease in discharge recorded from Gundagai to Carrathool Bridge after a dam release event in August 2018 (Figure 6B). These substantial losses are attributed to water abstraction or diversion for irrigation (Murrumbidgee Irrigation, 2019). To mitigate associated environmental impacts, the release of environmental water should coincide with water orders placed for consumption by irrigators. This would reduce the proportion of water lost and maintain higher flows downstream (Commonwealth Environmental Water Office, 2019).

Changes in surface quality across the system from rivers to irrigation areas have important implications for future water management strategies. Water quality was high for samples collected from the Murrumbidgee River, from Gundagai to Hay (September 2018 to February 2020). However, high quantities of poor-quality wastewater were discharged to terminal lakes and lagoons (Barren Box Wetlands, Figure 3) (Murrumbidgee Irrigation, 2019). The potential for the reuse or treatment of this water should be investigated, particularly with projected climate change increasing the intensity and frequency of future droughts (OEH, 2018; Dryer et al. 2014; Grafton et al. 2014).

The NSW Government has a responsibility to protect wetlands of the Murrumbidgee Catchment that support threatened species listed under the Commonwealth Environment Protection and Biodiversity Act 2016. This can only be achieved by the improvement of water management practices. The timing and quantity of current environmental water releases is insufficient to restore and maintain threatened fish, waterbird and vegetation populations of the Murrumbidgee Wetlands (Kingsford & Thomas, 2004). Commonwealth Environmental Water Holdings (i.e. the quantity of water allocated to environmental water releases) are greater during wet and normal conditions (average of 30,321 ML from 2010 – 2017; Figure 4B) in comparison to drought periods (average of 3,286 ML from 2017 – 2020, Figure 4B). However, the largest ecological impacts of poor water quality occur during droughts (Department of Agriculture, Water and the Environment, 2020b.; Mosley, 2015). For example, the environmental flows of 2018 to 2019 were unable to prevent the mass fish kill event at Redbank Weir in January 2019 (Balranald Shire Council, 2019).

The ineffective and variable annual delivery of environmental water is seen throughout rivers of the Murray-Darling Basin, including the Murray and Lachlan River systems (Department of Agriculture, Water and the Environment, 2020b.). For the improvement of water management practices, the climatic variability of dry-land river systems needs to be considered within Water Sharing Plans (Kingsford & Thomas, 2004). Effective water management can be achieved by the redistribution of environmental water allocations, with large quantities of water stored during normal and wet conditions ‘carried over’ to drought periods (Commonwealth Environmental Water Office, 2019). This may prevent future fish kills and the degradation of Murrumbidgee Wetlands by minimising periods of low streamflow (Balranald Shire Council, 2019).

To minimise periods of poor water quality in the Murrumbidgee Catchment and the wider Murray-Darling Basin during extended droughts, water allocations and delivery decisions made during non-drought years needs to be improved. This must be achieved with the objective to prolong the availability of consumptive water and environmental flows during droughts. Future water resource management strategies will need to balance the needs of all stakeholders, including those of farmers, irrigators, local communities and the environmental (wetland habitats and ecological communities). The improvement of water resource management is increasingly important in the context of projected future climate change and subsequent low streamflow conditions of Australian river systems (Adamson et al. 2009).

6. Conclusion

The examination of water quality results and water isotope signatures of this study, coupled with streamflow data analysis, has allowed for the influences on surface water quality in the Lower Murrumbidgee Catchment to be evaluated. The greatest observed impact to water quality along the Murrumbidgee River during the study period (September 2018 - February 2020), a period of drought, is attributed to river regulation and the timing of dam water releases.

Streamflow in the study area is heavily altered, with river regulation changing the natural winter and summer flow dynamics. Streamflow instead reflects the water demands of the irrigation industry, with a large proportion of flows diverted for irrigation of rice and perennial crops such as grapes, fruit and nut trees. Evidence for this is given by the homogenous values of water quality parameters and stable water isotopes for samples collected from the main river channel. Streamflow results demonstrate that water is rapidly transferred through the Murrumbidgee River channel, from its release at headwater dams to be taken up by irrigators in the MIA and CIA.

High quality water of the Murrumbidgee River was characterised by low EC, high DO concentrations and low temperatures, demonstrating that runoff from irrigation areas has no impact on river water quality during periods of drought. There is notable degradation in the quality of water once it is diverted from the Murrumbidgee River into the MIA and CIA, attributed to the disposal of wastewater from irrigation.

My research offers valuable insight into prevailing hydrological conditions during droughts in highly regulated river systems of the Murray-Darling Basin. Our findings provide guidance to government water resource strategies, that need to be updated to account for variable streamflow conditions of semi-arid Australian river systems. The reduction of environmental water allocations is required during wetter and normal periods to prolong water availability during droughts. This will increase water security for important community and ecological stakeholders. These findings are increasingly important in the context of projected climate change, which will increase the severity of droughts and prolong periods of low streamflow.

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9. Appendices

9.1. Appendix A

Table 1 – Water quality and stable water isotope results

Sampling location	Site ID	Sampling date	Temp (°C)	EC (µS/cm)	TDS (mg/L)	DO (%)	pH	δ^2H (‰)	$\delta^{18}O$ (‰)	d-Excess (‰)
MR @ Gundagai	1	9/09/2018	10.87	88	57	97	7.9	-35.01	-6.03	13.24
Tumut R.	2	9/09/2018	10.13	28	18	100	7.73	-37.58	-6.27	12.62
Yanko Ck @ Morundah	3	10/09/2018	12.54	76	50	89.1	7.62	-34.85	-5.80	11.58
MR @ Yanco Weir	4	10/09/2018	13.34	76	49	97.7	7.69	-34.88	-5.80	11.50
MR @ Carrathool	5	10/09/2018	13.83	79	51	93.8	7.95	-34.30	-5.63	10.76
Main Channel	6	11/09/2018	13.94	75	49	98.5	7.9	-34.16	-5.58	10.44
Secondary Channel	7	11/09/2018	10.47	98	64	82.6	7.34	-33.36	-5.52	10.76
Fivebough Wetlands@Brolga Shelter	8	11/09/2018	14.91	1025	666	61.8	7.75	-10.58	-1.21	-0.93
Main Channel 2	9	11/09/2018	14.32	79	52	77.2	8.05	-33.34	-5.58	11.29
Barren Black Box (small)	10	11/09/2018	14.89	746	485	69	7.96	7.55	2.20	-10.02
Barren Black Box (Large-NE)	11	11/09/2018	22.07	349	227	98.5	7.71	-10.18	-1.18	-0.71
MR@ Gundagai	1	5/02/2019	22.24	147	95	94.2	7.48	-29.46	-4.69	8.04
MR @ Mundowy Lane	12	5/02/2019	25.01	141	92	100	7.91	-29.18	-4.64	7.97
MR @ Talbot Lake	13	6/02/2019	24.96	134	87	80.7	7.74	-28.84	-4.57	7.74
MR @ Yanco Weir	4	6/02/2019	25.68	131	85	94.3	7.98	-28.62	-4.56	7.83
MR@ Carrathool	5	6/02/2019	28.09	116	75	91.3	7.46	-27.82	-4.35	6.98
Mirool Ck@near terminal Lake	14	7/02/2019	26.16	166	108	70.7	7.46	-25.03	-3.77	5.16
Barren Black Box (Large-NE)	11	7/02/2019	28.8	317	206	53.3	6.98	-2.49	0.60	-7.32
Fivebough Wetlands	8	7/02/2019	27.71	918	597		7.63			
Fivebough Wetlands (inflow SWTP)	15	7/02/2019	26.77	1305	848	44.5	6.67			
MR @ Gundagai	1	15/06/2019	10.76	162	105	92.6	7.46	-30.10	-5.09	10.59
MR @ Mundowy Lane	12	15/06/2019	10.13	148	96	70.9	7.06	-27.03	-4.68	10.42
MR @ Talbot Lake	13	16/06/2019	10.89	196	127	58.9	7.11	-25.22	-4.06	7.25
MR @ Yanco Weir	4	16/06/2019	11.62	154	100	96.9	7.59	-26.55	-4.78	11.69
MR @ Carrathool	5	22/06/2019	8.96	139	91	93	7.13	-27.19	-4.84	11.56
Mirool Ck@near terminal Lake	14	16/06/2019	13.49	659	429	100	8.52	-22.68	-3.33	3.94
Channel near multilevel piezo	16	20/06/2019	9.03	118	77	92.8	8.55	-12.93	-1.50	-0.94
MR @ Gundagai	1	10/09/2019	10.49	87	57	96.9	6.39	-31.01	-5.46	12.66
MR @ Mundowy Lane	12	10/09/2019	11.79	104	68	89.2	6.42	-30.05	-5.24	11.87
MR @ Talbot Lake	13	11/09/2019	12.47	166	108	83.1	7.44	-27.65	-4.87	11.28
MR @ Yanco Weir	4	11/09/2019	13.42	120	78	100	6.9	-28.62	-4.79	9.72
MR @ Carrathool	5	11/09/2019	13.44	124	81	93	6.63	-16.84	-2.47	2.94
Mirool Ck@near terminal Lake	14	11/09/2019	17.19	402	261	86.6	6.8	-10.46	-1.47	1.31
MR @ Gundagai	1	6/11/2019	18.11	121	79	91.5	7.21	-28.51	-4.88	10.52
MR @ Mundowy Lane	12	6/11/2019	19.4	57	37	82	6.84	-30.48	-5.16	10.77
MR @ Talbot Lake	13	6/11/2019	23.12	52	34	99.2	6.97	-29.03	-4.77	9.15

MR @ Yanco Weir	4	7/11/2019	19.53	48	31	85.8	6.98	-30.32	-5.05	10.09
MR @ Carrathool	5	7/11/2019	20.74	55	36	82.1	7.19	-29.52	-4.84	9.20
Mirool Ck@near terminal Lake	14	7/11/2019	20.11	394	256	64.5	7.2	-10.53	-2.55	9.88
Sampling location	**Site ID**	**Sampling date**	**Temp (°C)**	**EC (µS/cm)**	**TDS (mg/L)**	**DO (%)**	**pH**	**δ^2H (‰)**	**$\delta^{18}O$ (‰)**	**d-Excess (‰)**
MR @ Gundagai	1	12/02/2020	20.54	132	86	57.5	6.89	-45.53	-7.05	10.87
MR @ Mundowy Lane	12	12/02/2020	24.46	51	33		7.01	-34.03	-5.48	9.84
MR @ Talbot Lake	13	12/02/2020	27.12	58	37	100	7.12	-31.47	-4.96	8.22
MR @ Yanco Weir	4	13/02/2020	25.78	52	34	100	6.89	-32.15	-5.21	9.50
MR @ Carrathool	5	13/02/2020	26.6	63	41	91.6	6.98	-31.34	-4.80	7.07
Mirool Ck@alternative site	17	13/02/2020	27.89	351	228	66	7	-61.10	-8.21	4.58
Big Pond after rains	18	13/02/2020	27.48	115	75	3.8	6.39	-89.19	-11.53	3.01
Mirrol Ck tributary	19	13/02/2020	33.25	508	330	3.9	6.47	-73.00	-9.98	6.84
Barren Black Box (western pond)	20	13/02/2020	29.94	1880	1222		9.46	55.01	12.87	-47.99
LAG Disposal site	21	14/02/2020	24.15	226	147	10.9	6.99	-3.86	2.39	-22.96

9.2. Appendix B

***Table 2**: Details of hydraulic stations and locations selected for streamflow analysis (from upstream to downstream)*

Station number and reference	Corresponding surface water location	Details
410008: Murrumbidgee River Downstream of Burrinjuck Dam	*	Data collected includes level (m) (1961 to present), discharge (ML/day) (1961 to present), EC (µS/cm) (2001 to present), turbidity (NTU) (2001 to present) and water temperature (°C) (2001 to present)
410006: Tumut River at Tumut	2	Level (m) and discharge (ML/day) from 1970 to present
410004: Murrumbidgee River at Gundagai	1	Data collected includes level (m) (1886 to present), discharge (ML/day) (1886 to present), EC ((2010 to present), turbidity (NTU) (1993 to present) and water temperature (°C) (1993 to present)
410001: Murrumbidgee River at Wagga Wagga	12	Data collected includes level (m) (1868 to present), discharge (ML/day) (1868 to present), EC (µS/cm) (2010 to present), turbidity (NTU) (1993 to present) and water temperature (°C) (1993 to present)
410005: Murrumbidgee River at Narrandera	13	Data collected includes level (m) (1891 to present), discharge (ML/day) (1891 to present) and water temperature (°C) (2002 to present)
410036: Murrumbidgee River at Downstream Yanco Weir	4	Data collected includes level (m) (1972 to present) and discharge (ML/day) (1972 to present)
410015: Yanco Creek at Morundah	3	Data collected includes level (m) (1977 to present) and discharge (ML/day) (1977 to present)
41000281: Murrumbidgee River at Carrathool Bridge	5	Data collected includes level (m) (1995 to present) and discharge (ML/day) (1995 to present)

*Site selected based on its position at the headwaters of the catchment