

# A detailed streamflow and groundwater salinity dataset for Muttama Creek Catchment, NSW, Australia

R. Willem Vervoort<sup>1</sup>, Floris van Ogtrop<sup>1</sup>, Mina Tambrchi<sup>1</sup>, Farzina Akter<sup>1</sup>, Alexander Buzacott<sup>1</sup>, Jason Lessels<sup>1</sup>, James Moloney<sup>1</sup>, Dipangkar Kundu<sup>1</sup>, Feike Dijkstra<sup>1</sup>, and Thomas Bishop<sup>1</sup>

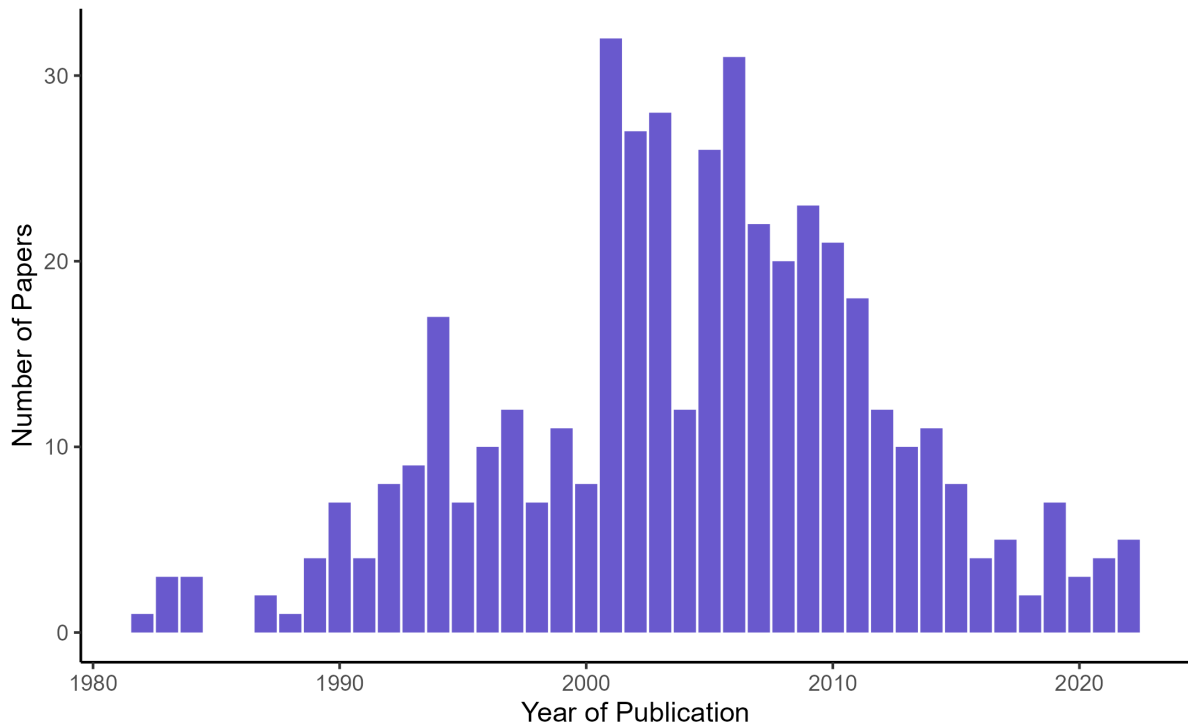
<sup>1</sup>Sydney Institute of Agriculture, The University of Sydney, NSW 2006

**Correspondence:** Floris van Ogtrop (floris.vanogtrop@sydney.edu.au)

**Abstract.** Dryland salinity remains a major global natural resource management concern, and specifically in Australia. However, limited detailed space-time data sets with observations of stream and groundwater salinity has constrained a deep understanding of the range of processes that can lead to dryland salinity problems in landscapes. The aim of this study is to report on the open data set resulting from a 12-year data collection effort in a subcatchment of the Murrumbidgee catchment in New South Wales, Australia. Over a 12 year period a series of different sampling campaigns has resulted in a large dataset with hydrogeochemical data which includes both in-situ (field) data and post laboratory analysis of major anions and cations. This augmented by observed groundwater levels and publicly available streamflow and climate data. The data set covers 23 groundwater sample sites and 39 surface water sites. Because the data was collected by four distinct groups and over many years we analyse if this has caused a bias in the dataset. In addition we show the major spatial and temporal trends to provide an overview of the dataset and highlight any possible biases. The dataset is made open access to encourage further research and the current paper shows the richness of the collected data and opportunities for further research.

## 1 Introduction

Dryland and irrigation salinity has long been a major natural resource management concern in Australia (Jolly et al., 2001; White et al., 2009; Scanlon et al., 2007; Walker et al., 2002; Finlayson et al., 2010). Globally, the success of management of salinity, while extensively documented, has remained patchy (Leblanc et al., 2012). As a result, the volume of research and number of publications in this area has decreased significantly in recent years (Figure 1). In Australia, this is partly due to the effect of the millenium drought on groundwater levels and the consequent reduction in the appearance of salinity effects in the landscape (McFarlane et al., 2016). However, the reduction in research is also because of the increased understanding that salinity processes are more complex than previously recognised. For example, salinity processes can vary substantially across the landscape (Conyers et al., 2008) and the processes of salt delivery to the stream also varies in the landscape (Summerell et al., 2006; Hughes et al., 2007) and is dependent on landscape characteristics (van Dijk et al., 2008; Dahlhaus et al., 2010). As a result, the investment required to improve the understanding and increase the effectiveness of management is considerable and this has limited the number of studies after the large investment in the late 1990s and 2000s.



**Figure 1.** Number of papers on the Web of Science related to the search terms (Dryland Salinity) AND Australia, 1980 - 2022

The poor spatial and timescale distribution of water quality datasets has long been an obstacle to measuring trends in salinity. Studies such as Jolly et. al. (2001) and White et. al (2009) used large historical datasets to detect broadscale trends over large periods throughout the Murray Darling Basin (MDB). This work identified that southern and eastern dryland regions in the Murray Darling Basin have rising salinity trends that were worse in areas of low rainfall (White et al., 2009; Jolly et al., 2001). However, the ion composition varied greatly throughout the MDB (White et al., 2009). More specifically, Conyers et al. (2008) tried to isolate which areas in the Murrumbidgee catchment acted as sources of salinity, as well as whether this was predominantly marine cyclic salts (NaCl) as previously assumed, or whether salts from mineral weathering were also involved (e.g. Ca, Mg,  $\text{HCO}_3$ ). While both can be measured using conventional methods such as EC, a rise in marine cyclic salts can be a major source of osmotic stress, whereas mineral weathering salts are far less harmful and more likely to precipitate at reasonably low concentrations (Conyers et al., 2008). The ratio of  $\text{Cl}:\text{HCO}_3$  ions was identified as the best indicator of the source of salinity, with  $\text{Cl}^-$  acting as a measure of marine cyclic salts and  $\text{HCO}_3^-$  acting as a measure of mineral weathering salts. The Muttama catchment was specifically identified as a candidate for future research as ion concentrations appeared to change from east to west, correlating with the underlying mineral types.

It is clear from these examples that detailed spatial and temporal datasets are key to understanding different hydrogeochemical processes in the landscape (e.g. Cartwright et al., 2010; Dahlhaus et al., 2010), but overall publicly available datasets on dryland

salinity in Australia remain limited to detailed data from small experimental catchments (< 100 ha) (Summerell et al., 2006; Hughes et al., 2007) or sparse government datasets from official monitoring (i.e. WaterNSW WaterInsights platform) which tend to be limited in hydrogeochemical data. Part of this is related to the sensitivity of the data given the relationship with possible land values. However, as the understanding of salinity occurrence grows, this argument is less valid. Making data more widely available would increase the opportunities for research and increase our understanding of dryland salinity processes.

Without regular and expensive automated sampling, field campaigns to collect water quality data tend to be “snapshot” activities (Grayson et al., 1997; Breuer et al., 2015; Lyon et al., 2008; Cartwright et al., 2010; Lintern et al., 2018) which can be biased due to the over representation of low flow conditions (Lessels and Bishop, 2020). Even the analyses of substantial government data bases (Lintern et al., 2018) are likely to be biased in this way. This means that overall there are limited streamflow and groundwater salinity data sets that combine multiple locations across a significant time period and that combine a range of flow characteristics.

The aim of this paper is to present and describe the space time dimensions and basic relationships of a complex groundwater and surface water hydrogeochemistry dataset that was collected over a 10 year period in a 1000km<sup>2</sup> agricultural catchment in New South Wales, Australia. The Muttama catchment, which is the focus of this paper, provides a microcosm of groundwater and surface water salinity variability in Australia. Focusing on a medium size catchment in greater detail creates opportunities to test whether sources of salinity can be traced back to specific areas of land.

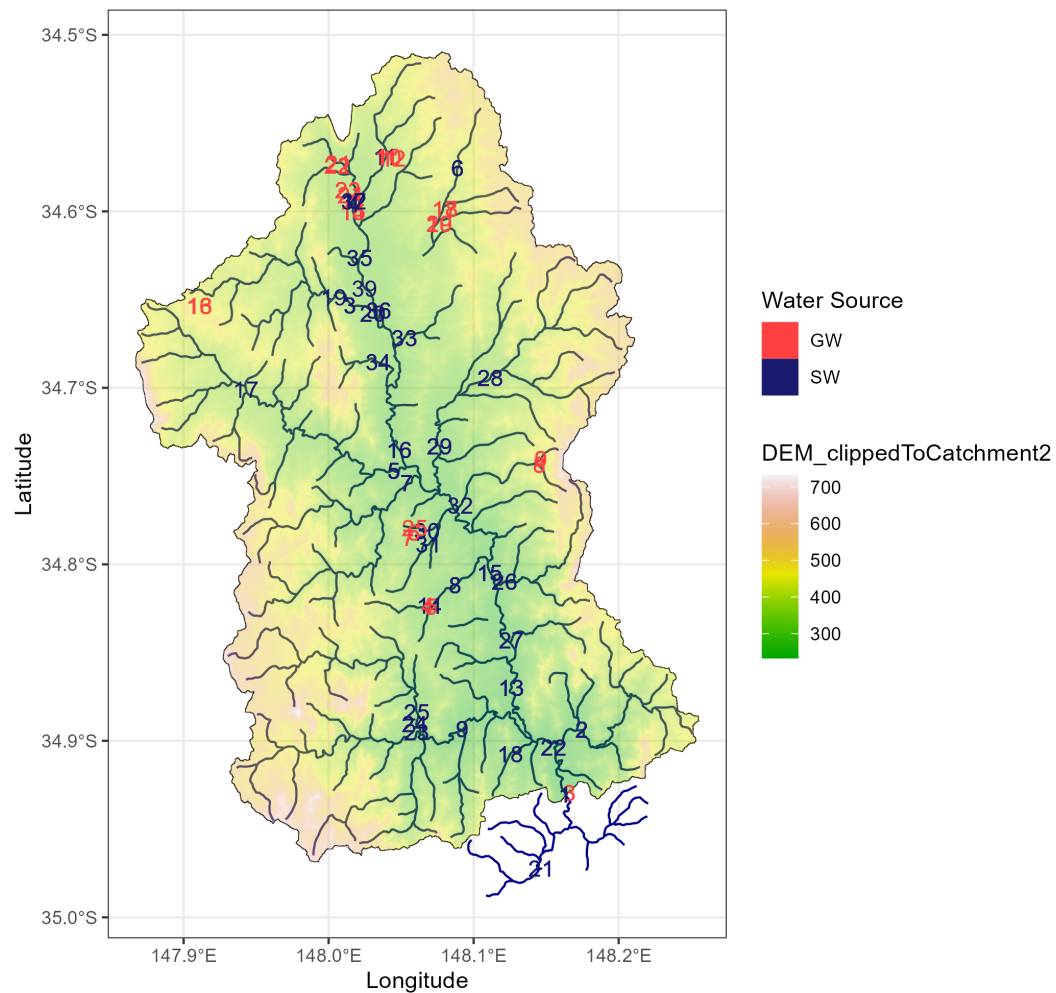
This paper gives a description of the dataset to facilitate open access of the dataset, but does not analyse the physiochemical relationships in the data in detail. This will be analysed in follow-up papers and was partly analysed in an earlier thesis (Akter, 2018). The main aim of this paper is to make the data set accessible to other researchers to encourage further research in this catchment and in salinity in general.

## **2 Methods**

### **2.1 Muttama catchment**

Muttama creek catchment (Figure 2) is located in the Mid-Murrumbidgee catchment area of NSW in south eastern Australia. The landscape is undulating with only limited elevation variations (227 - 719 m). Muttama creek flows north-south through the length of the catchment towards the Murrumbidgee River near Gundagai. The main township, Cootamundra is located in the upper half of the catchment. The dominant land use type of this catchment is about 93% agriculture, dominated by winter-spring cropping and pasture. Mean annual rainfall (1891-2024) in the catchment is 654 mm for the longest running Bureau of Meteorology Landgrove station (station 073022).

Streamflow is measured continuously by WaterNSW, the state agency responsible for water data collection, at three locations in the catchment: Coolac, station no. 410044, the main downstream point, and Berthong, station no. 41000207 and Jindalee, station no. 410112 on two branches above the Cootamundra township. This data is available as open access via the WaterNSW WaterInsights platform or through the Bureau of Meteorology. Here, we only use the data from the Coolac station as a comparison.



**Figure 2.** Muttama Catchment Sampling Locations with Elevation. Symbol colour indicates whether location was a groundwater or surface water source, with blue being surface water and brown/orange being groundwater. The numbers on the map represent the sample location number.

The depth to the nearest groundwater table varies across the Muttama catchment and it ranges from < 2m to 20m below ground level (Department of Environment and Climate Change NSW, 2009). Deep groundwater in the catchment occurs mostly in fractured rock aquifers common on the eastern, and western fringes of the catchment. In contrast, shallow groundwater is associated with unconfined alluvial, colluvial, and eluvial aquifers. Some aquifers in the northern part of this catchment show artesian behavior (Webb, 1999; Akter, 2018).

Saline areas of the catchment tend to be associated with geological heterogeneity, primarily the sedimentary materials in the west and rhyolite on the northwest side (Conyers et al., 2008). Overall, Muttama creek is a significant salt contributor to the downstream Murrumbidgee river with suggested contributions of around 58% from cyclic sources and 42% salts originating from mineral weathering (Conyers et al., 2008).

## **2.2 Data Collection**

### **2.2.1 Data Sources**

The water quality dataset contains data from 4 main sampling sources related to four distinct groups of “people” doing the sample collection. The term “people” is used loosely, as it mainly related to four different types of sampling campaigns, which potentially had differences in the rigour of the sampling campaign (Quality control, types of samples taken, training of the people taking the samples). These groups are designated as:

- Source 1: Data from the PhD study by Akter (2018).
- Source 2: Data from the sampling campaign of two former students, the PhD from Lessels (2014) and unpublished data from another student, E. Milne.
- Source 3: A dataset collected by undergraduate and postgraduate students as part of field trips in different units of study at the University of Sydney is identified as “Student data”. This data was sampled “ad-hoc” during the field trip period using standard sampling protocols as described for the data from Akter (2018).
- Source 4: Data from several autosamplers installed in the catchment during the PhD from Lessels (2014). Because these samples were not taken by a “person” and were taken on a flow weighted basis, we separated the data from the “grab” samples in the other methods. These samples are also missing field measurements, as these were only analysed in the laboratory.

Overall, 1160 water samples were collected from 62 sample locations over the 2010 - 2024 period. However, not all sites were sampled at all times and not all samples were fully analysed for all hydrogeochemical variables. Both surface water and groundwater samples were collected (23 groundwater sample sites and 39 surface water sites) distributed across the catchment, depending on standing water availability and access.

In addition to the water quality dataset, data from 23 groundwater data loggers is provided from the same groundwater sample sites as in the hydrogeochemical dataset.

**Table 1.** Variables measured in the field and laboratory

Field measurements	Lab repeat	Anions	Cations	Others
pH	pH	HCO <sub>3</sub>	Ca	Total Nitrogen
EC (Electrical conductivity)	EC	SO <sub>4</sub>	Mg	Total Phosphorus
SPC (temperature corrected EC)	SPC	Cl	Na	
Temperature			K	
Alkalinity (HCO <sub>3</sub> )				
Dissolved Oxygen (DO)				
Turbidity				

### 2.2.2 Hydrogeochemical Variables

The overall structure of the hydrogeochemical dataset consists of repeated measurements over time at multiple locations in Muttama catchment. For each location the name of the location and the spatial coordinates were recorded in decimal degrees (Longitude = x and Latitude = y) as well as whether the location was a groundwater or a surface water location. The names of the locations are fairly random and basic locality indicators, which cannot be interpreted exactly.

The data for each location consist of up to six variables which were measured in the field (Table 1). These were complemented by laboratory analysis, which repeated some of the field measurements, and for additional major anion and cation variables (Ca, Mg, Na, K, Cl, SO<sub>4</sub>, HCO<sub>3</sub>), and total Nitrogen (N) and total Phosphorus (P) for part of the sample set. Some other variables were infrequently measured and are not included in the data set.

The variables pH, EC, SPC (specific conductance: field temperature corrected EC), Temperature, and in some cases DO and Turbidity were measured using a range of field probes. All field probes measured pH, EC, Temperature and calculated SPC. Early measurements (Samples up to November 2014) used a YSI probe that included a turbidity and DO probe (YSI 6600 and YSI 600 for surface and groundwater, respectively). Later groundwater samples (After November 2014) used a different YSI probe (YSI ProPlus multi-parameter) that only included a DO probe. Finally, (After mid 2019) surface water and groundwater sampling used a Xylem Exo probe with DO, pH, EC, Temperature and SPC. Some of the variability in the field measurements might be due to this variation in the field instrumentation, because the exact instrument information was not recorded with the data.

Anions in most of the samples were analysed using high-performance liquid chromatography method (Dionex P680 HPLC) and cations were measured on acidified samples using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES, Varian 720-ES) at the University of Sydney (Akter, 2018). Duplicate samples in the analysis had a reported relative percentage difference (RPD) lower than 5% in part of the sample dataset (Akter, 2018). Some of the later samples and the student sample set (Source 3) were analysed by a commercial laboratory (ALS Environmental, Smithfield, NSW). Alkalinity

concentrations were generally measured in the field within 24h of collection using a HACH digital titrator (model 16900) (Akter, 2018) up to 2017 and by the commercial laboratory after this.

The hydrogeochemical data is stored on the University of Sydney escholarship repository: [doi.org/10.25910/m0wp-8890](https://doi.org/10.25910/m0wp-8890)

## 2.3 Continuous variables

The logger data, which collected groundwater pressure levels at 15 min and later at 2 hour intervals, were adjusted for the length of the cable and the height of the standpipe above the ground level. They were subsequently summarised to raw daily values using an R script (`SummariseDailyData.R`), which is stored on the github repository.

The loggers in the field were uncalibrated. Due to logger failures, gaps occur in the daily data, followed by replacement of the faulty loggers. In some cases the cable length was adjusted and this was recorded in the field notes. Overall, this resulted in data with gaps and sometimes odd shifts in the recorded data.

Manual water level measurements were taken at each manual sampling date to allow calibration of the logger data.

To correct the groundwater logger data, the daily data was matched to the observed data using linear regression, if more than 3 manual observed data were available and slope and intercept of the regression had a p-value  $> 0.1$ . If there were less than 3 manual observed data point for the specific logger an adjustment to the data was based on the difference between the average observed data and the average recorded water levels. Otherwise no adjustment was made. This is slightly tricky: After the manual observations are made, the well is purged and the logger is temporarily removed from the well. This data (during the temporarily removal of the logger during the purging and subsequent recovery of the groundwater level) is removed from the logger data series. As a result, there is no direct time match between the logger data series and the manual observations. However, the data showed that, in most cases, the groundwater level recovered within 24 hrs.

To explain this more clearly the following pseudo code describes the process:

The code used to match the manually observed data with the logger data is in the script `Match_obs_logger_data.R`, which is stored with the raw data in the Open Science Foundation (OSF) repository associated with this paper <https://doi.org/10.17605/OSF.IO/BEUWK>.

After the automated process, two of the groundwater level data series still had substantial discrepancies in some sections of the data. This was most likely due to the a lack of observed data for the specific logger. A final manual correction was applied. As this process is based on judgement of the data by the authors of this paper, we documented this in detail in the supplementary material.

The final corrected data that is published with this paper includes a column which describes whether the data is based on the automatic correction or a further manual correction.

## 2.4 Boxplots and maps

Using the most complete data, boxplots and spatial maps were generated to highlight the spatial and temporal variation in the data set. We have chosen to use boxplots to visually highlight statistical differences between data variables rather than doing a full statistical analysis.

---

**Algorithm 1** Pseudo code cleaning groundwater level data

---

```
if sufficient points ≥ 3 then
  run a regression between interpolated depth and observed depth
  check the p-values of the slope and intercept
  if the slope is not significant (using p > 0.10) then
    use only the intercept to correct the logger data
  else
    if the intercept is not significant, but the slope is then
      use only the slope to correct the logger data
    else
      use both slope and intercept of the regression to correct the logger data
    end if
  end if
else
  There are not enough values for a regression, use mean difference between logged and observed value to correct the logger data
end if
```

---

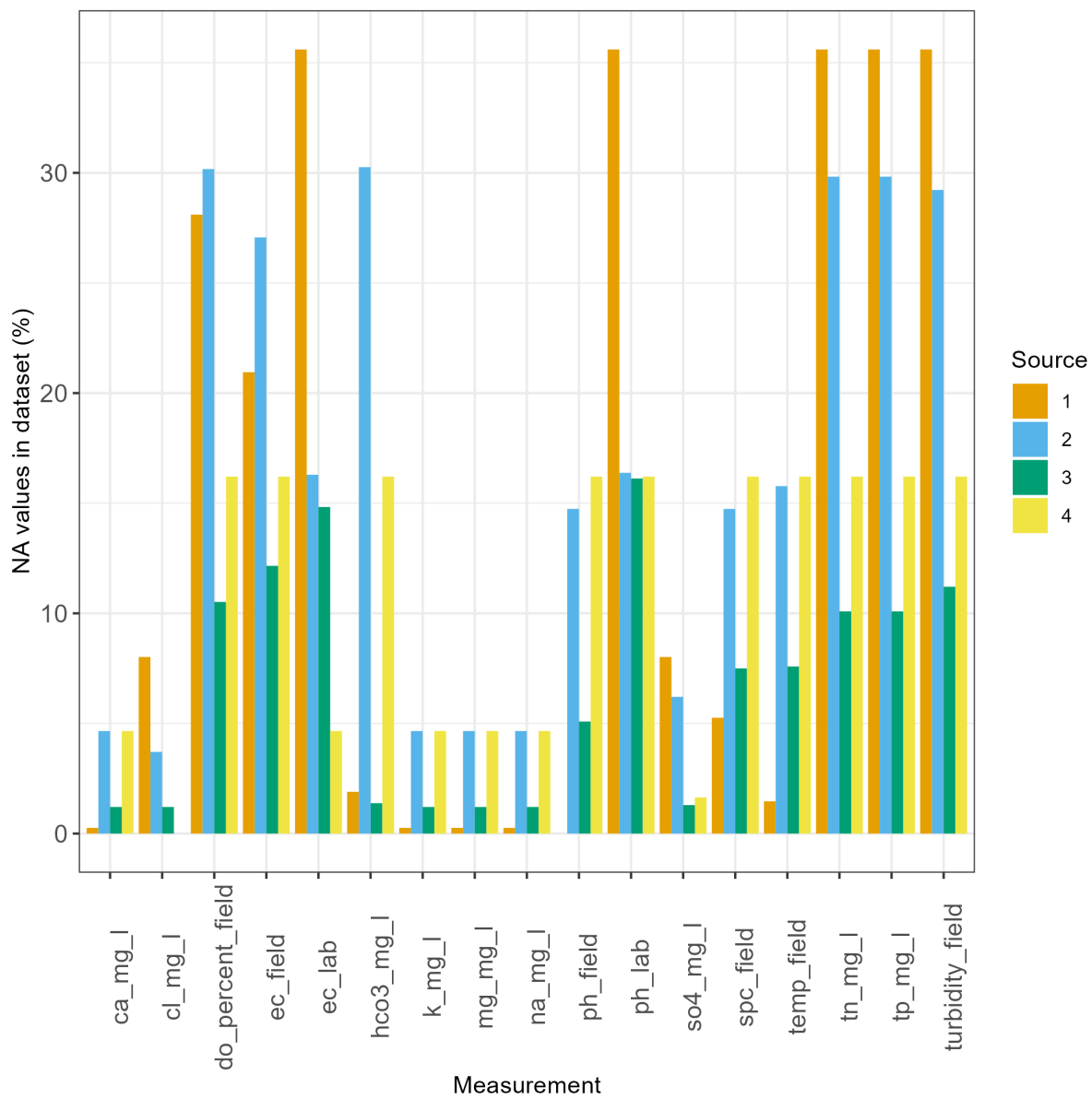
The mean concentration and interquartile range (25<sup>th</sup> - 75<sup>th</sup> percentile) of the concentration data distributions were calculated to give an indication of variance of the data in the spatial maps.

All graphs and maps were produced using R version 4.3.1 (R Core Team, 2023). All code can be found in the associated github repository, as part of the markdown document for this paper.

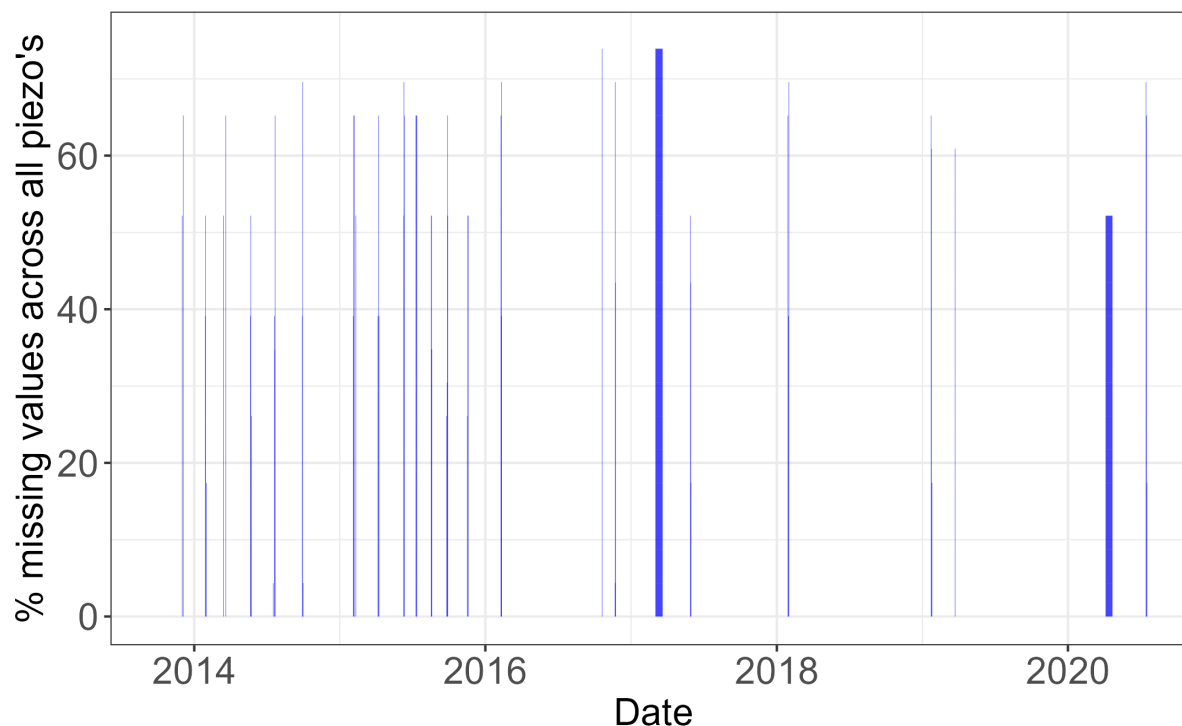
### 3 Results

#### 3.1 Distribution of missing Values





**Figure 3.** Distribution of missing values for the different data sources and measurement types.



**Figure 4.** Percent missing values for the groundwater data across all piezometers.

In the hydrogeochemistry data, data source 3 was the most complete in terms of variables analysed, because in this set more variables were analysed in the commercial lab (Fig 3). Some of the variables analysed in the commercial lab were not analysed with the equipment at the University of Sydney. However, source 3 had the smallest number of overall samples. Source 2 has the most incomplete data points. Source 4 has a very consistent number of missing values, possibly because not all samples were analysed in the set. For source 2, the missing data suggests that for many of the samples only a few of the variables were measured and analysed as highlighted above. In the data from source 2, almost 50% of samples are incomplete in terms of the measurement of all the variables in Table 2. Similarly, source 1 had more incomplete data, because some of the minor elements were not analysed. The field recorded variables pH, EC, SPC and Temperature were the most complete as they were generally measured directly in the field. Thus the distribution of the NA values in the overall data set is mostly a reflection of the time period of sampling and the change in methodology over the ten years of sampling.

In the groundwater level time series, the missing data relate mostly to logger failures and the different times that wells were instrumented. Rather than giving a full breakdown by well location, the overall level of completeness of the series is displayed (Fig 4).

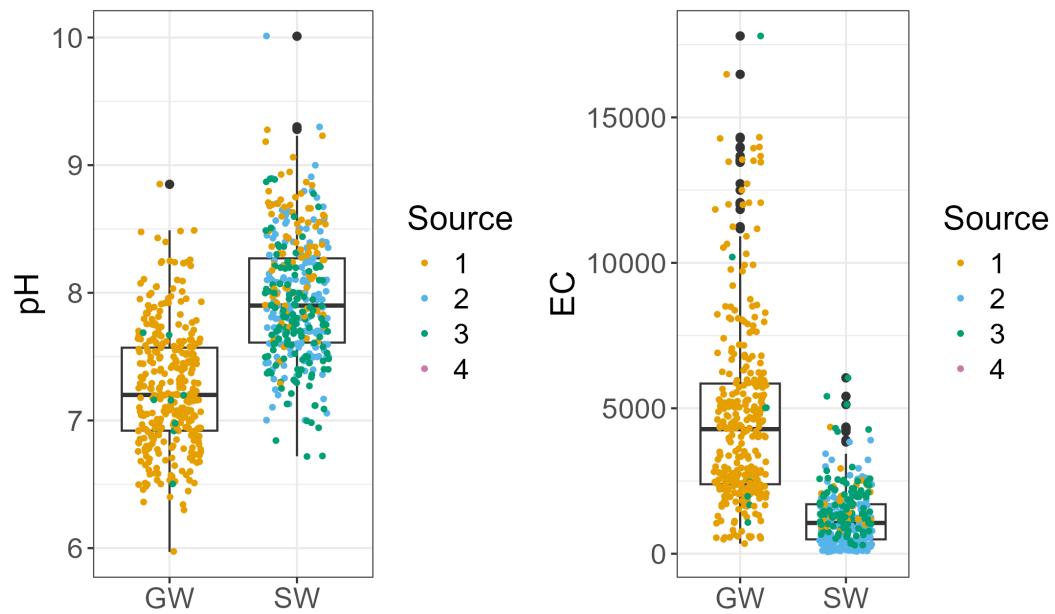
**Table 2.** Summary statistics for elements measured in the field

Element	GW			SW		
	Mean	Min	Max	Mean	Min	Max
temp_field	17.4	11.4	30.8	16	4	33
do_percent_field	20.1	-3.2	70.7	87	10	220
spc_field	4666.6	347.4	17799.0	1246	61	6046
ec_field	4006.5	457.0	14385.0	1411	117	4163
ph_field	7.3	6.0	8.8	8	7	10
turbidity_field	30.2	0.1	90.0	13	1	52
ec_lab	NaN	Inf	NA	1292	1	5230
ph_lab	NaN	Inf	NA	8	7	9
tn_mg_l	3.7	0.6	10.3	1	0	5
tp_mg_l	0.3	0.0	1.0	0	0	6
cl_mg_l	1218.3	73.0	4960.7	294	9	4577
hco3_mg_l	599.5	68.0	1115.0	334	26	782
so4_mg_l	261.1	0.0	1319.2	48	0	988
na_mg_l	492.1	17.8	2283.7	122	7	866
ca_mg_l	256.4	16.3	1354.2	62	2	682
mg_mg_l	167.6	6.4	654.6	67	1	277
k_mg_l	4.4	0.0	30.8	8	1	44

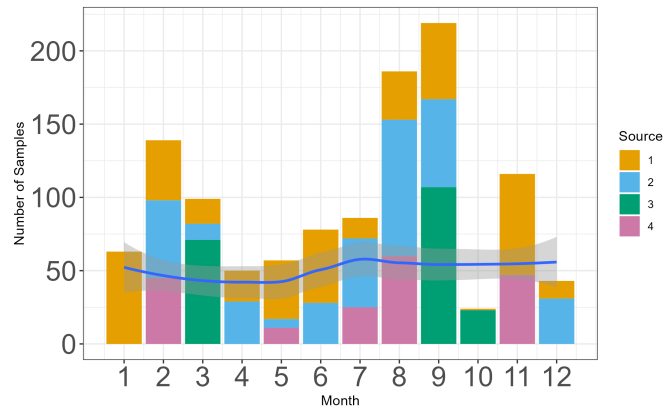
### 3.1.1 Comparisons of Groundwater samples with Surface water samples

Groundwater samples have quite a distinctive hydrogeochemical signature compared to the surface water samples (Fig 5). For example, groundwater samples tend to be higher in EC and lower in pH compared to surface water samples. Since ‘Source 1’ collected most of the groundwater samples, this results in differences between data collection sources. Field SPC measurements were used to represent EC since these samples had the best coverage.

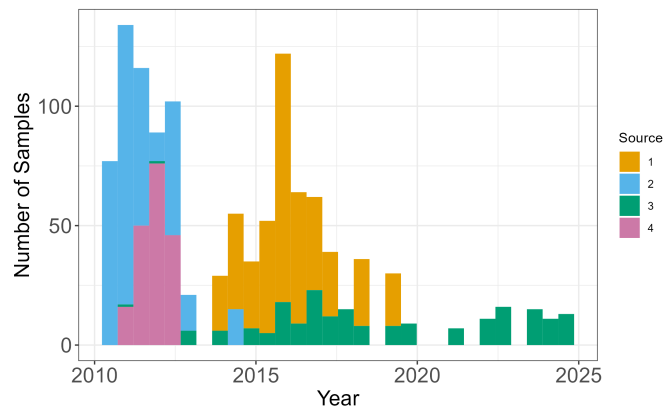
## 3.2 Temporal Distribution of Data



**Figure 5.** Difference in pH and EC for groundwater and surface water samples. The source of the data (the sampling group) is indicated with colour



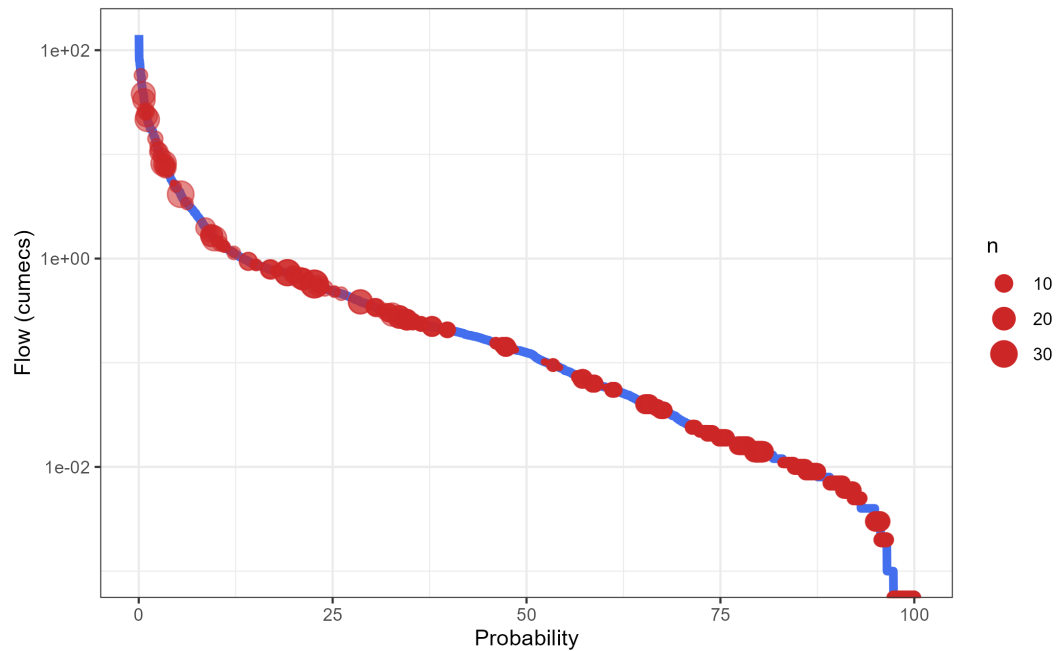
**Figure 6.** Distribution of samples throughout the year (total number of samples collected during each month) against average monthly rainfall during the study period.



**Figure 7.** Distribution of samples over the study period (total number of samples collected during each year) against average monthly rainfall during the study period.

Overall the water quality sampling appears to have a reasonable distribution across all months (Fig 6), so seasonal trends should be identifiable in the data. Average rainfall data (1995 - 2022) does not indicate any major seasonal trends, although there is a slight dominance of rainfall in the early Austral Spring (months 9 and 10, September and October). This also explains the higher number of samples because, more sampling trips were organised in this period, and spatially more channels could be sampled for surface water. The timing of Source 3, (the student data) is a clear effect of yearly field trips, which tended to occur at approximately the same time of the year in early March and late September/early October, coinciding with the University semesters.

The number of samples collected in each year relative to the different sources changes throughout the years reflecting the duration of the different studies and funding cycles (Fig 7); however the data is still well-distributed enough that overall trends



**Figure 8.** Sample distribution on flow duration curve derived from flow data from Coolac autosampler.

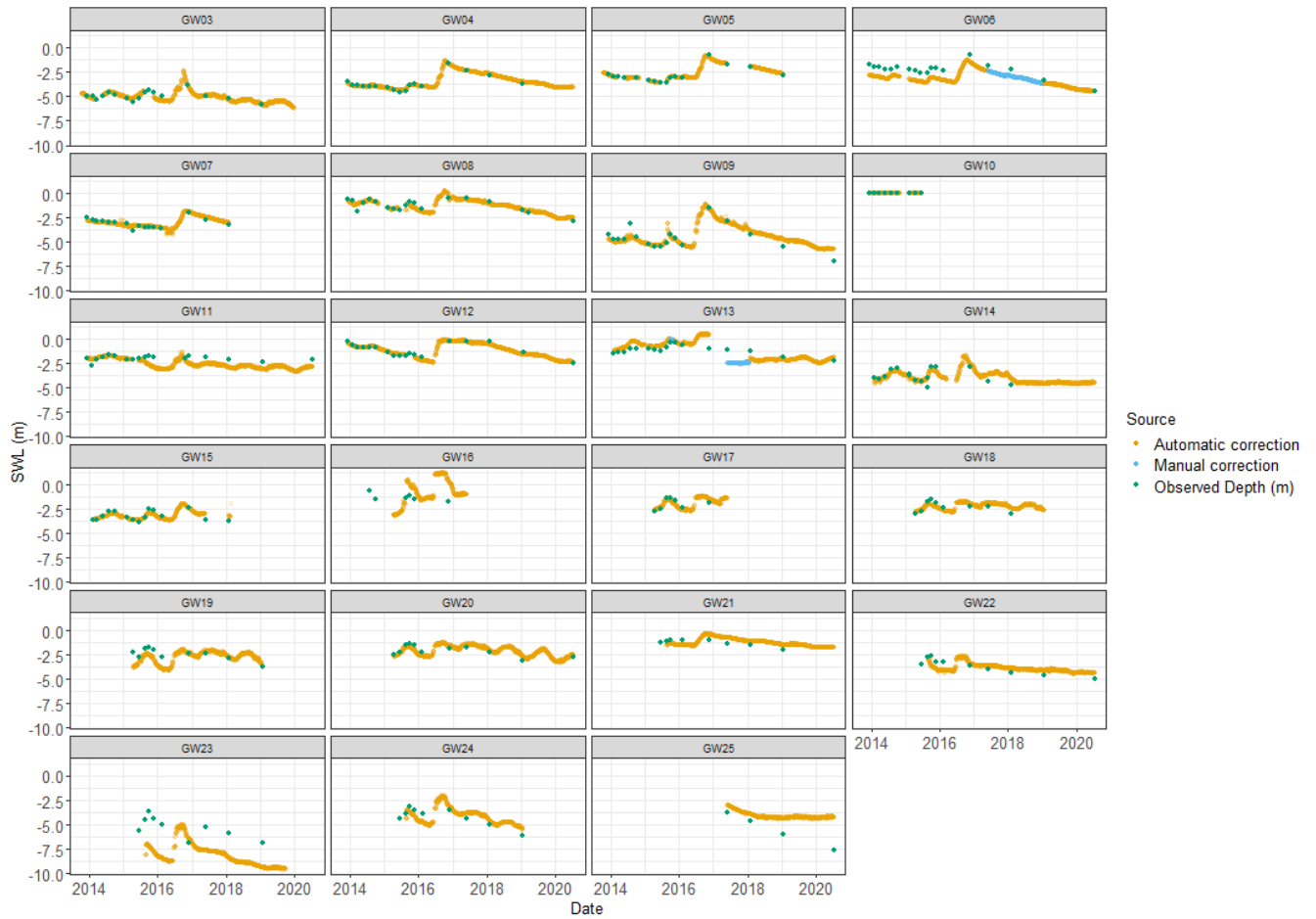
should be clear. In addition, some of the sample volumes can be related to the occurrence of rainfall, as in drier years several of the channels would be dry and no sampling of surface water could occur.

Consistent groundwater sampling commenced later in the project, which means that there are very few groundwater samples before 2013. In contrast, the autosamplers were installed early in the project and there are no samples from this source after 2013.

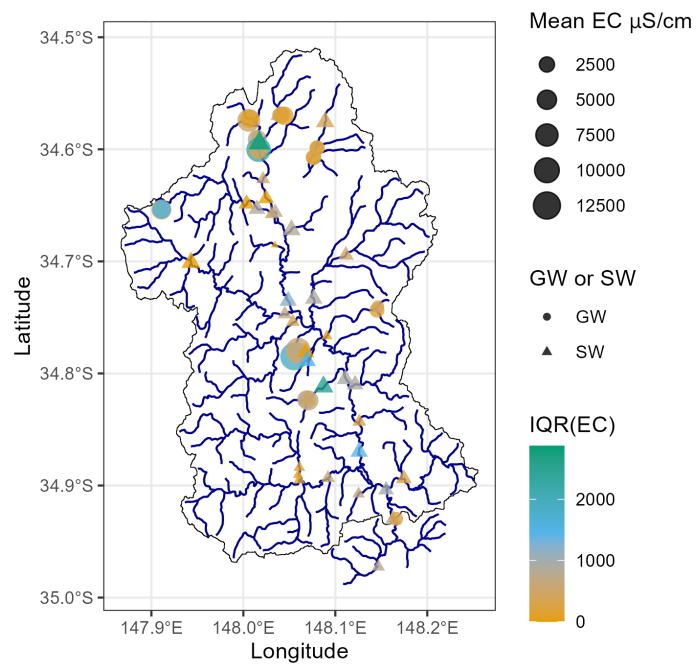
Surface water samples were reasonably well distributed across the flow distribution, measured at the Coolac station (410044), with only a possible bias towards periods of medium flow. This is most likely since many of the upstream surface water sampling points are often completely dry during periods of low flow at Coolac, and therefore cannot be sampled. Conversely, there are no manual samples during high or very high flow as during flood situations sampling was dangerous and restricted by work health and safety considerations. The samples at high flow are all from our automated sampling.

The overall corrected groundwater timeseries shows the shorter time that loggers were installed in the wells (9). It also indicates that the manual data is not always fully matched with the logger data, but further corrections are likely to be speculation.

### 3.3 Spatial variation

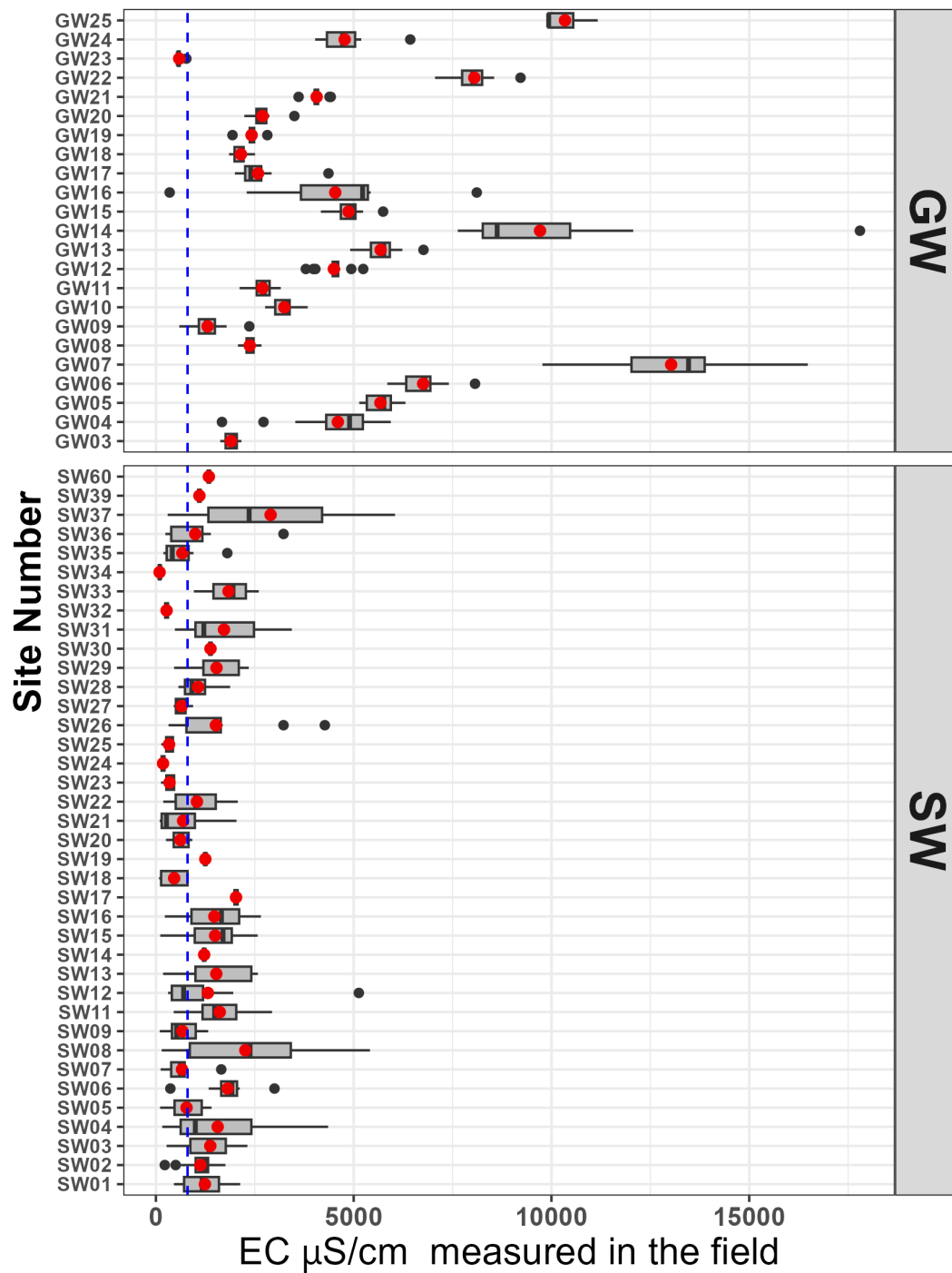


**Figure 9.** Overview of the corrected groundwater time series for all the wells

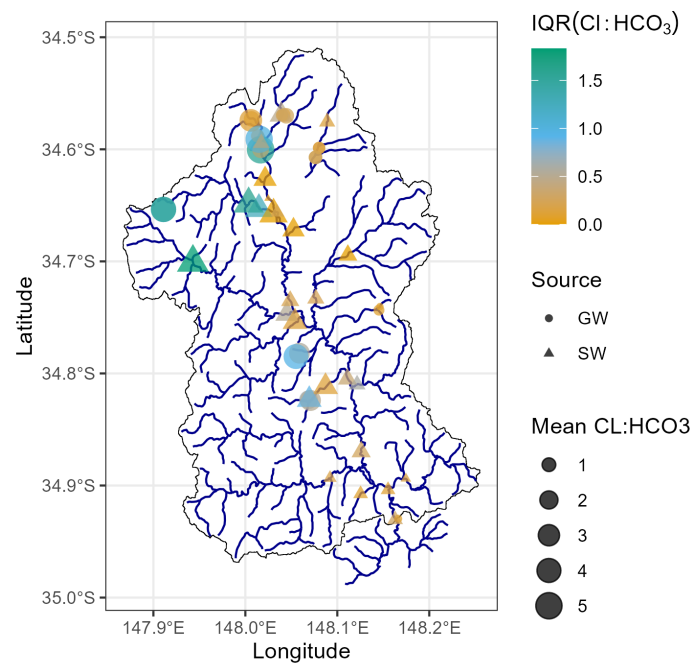


**Figure 10.** Spatial Variation of EC throughout the catchment, using Mean EC in  $\mu S/cm$  and interquartile range (IQR) for each sampling location.





**Figure 11.** Variation in EC throughout the catchment across time by sample location presented as boxplots. The blue dashed line is the drinking water limit of 800 EC or 800  $\mu S/cm$ .



**Figure 12.** Spatial Variation of  $Cl : HCO_3$  ratio throughout the catchment, using Mean and interquartile range (IQR) for each sampling location.

There is clear spatial variation in water parameters throughout the catchment, including between groundwater and surface water sampling sites (Figures 10 and 12). As examples, the spatial distributions for EC and Cl:HCO<sub>3</sub> are shown, as well as the space time boxplots for the variables. Similar maps can be easily generated for other parameters. In the map, the concentration is indicated by the size of the symbol, while the colour shading indicates the variability. This suggests surface water samples had lower variability and lower concentrations.

Below the maps, a boxplot (Figures 11 and 13) highlights the difference in the distributions from the surface water sample sites and the groundwater sample sites, and also indicates the difference between sample sites.

Previous studies have suggested there may be a difference in Cl:HCO<sub>3</sub> ratio in surface water between the eastern and western parts of the Muttama catchment (Conyers et al., 2008), and Figure 12 suggest a similar pattern. A clearer picture is limited by the spatial sampling, which relied on existing groundwater tube wells and accessible stream points.

### 3.4 Piper plot

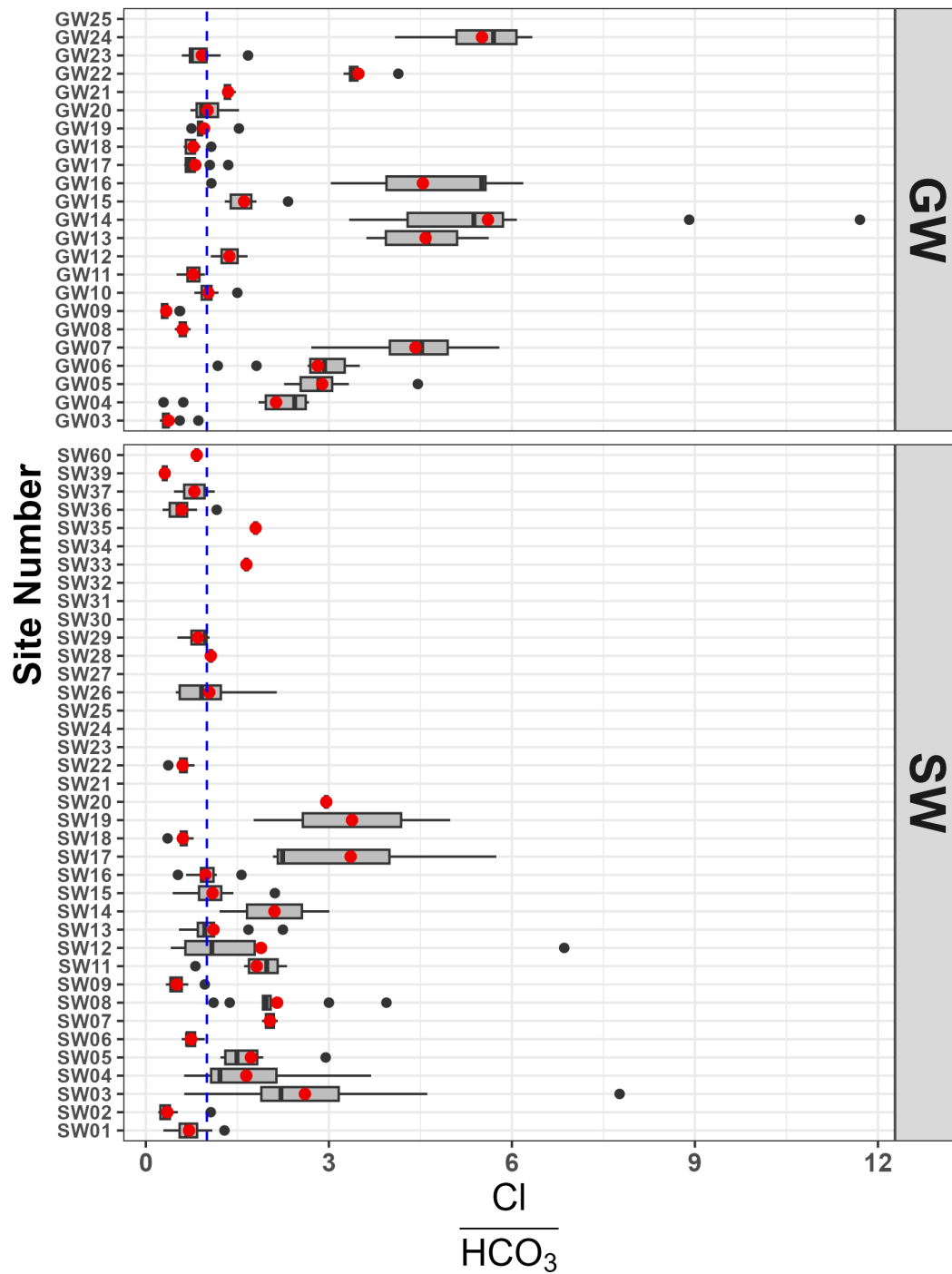
The piper plot of the data (14) does not provide much clarity as the samples cover a large area across the ternary space. There is a slight shift towards the HCO<sub>3</sub> and Ca/Mg type waters for the groundwater samples compared to the surface water samples, which are more Na dominated. There is also a small cluster of surface water samples that are more SO<sub>4</sub> dominated, potentially indicating different geological origins as mentioned earlier in the paper.

## 4 Conclusions

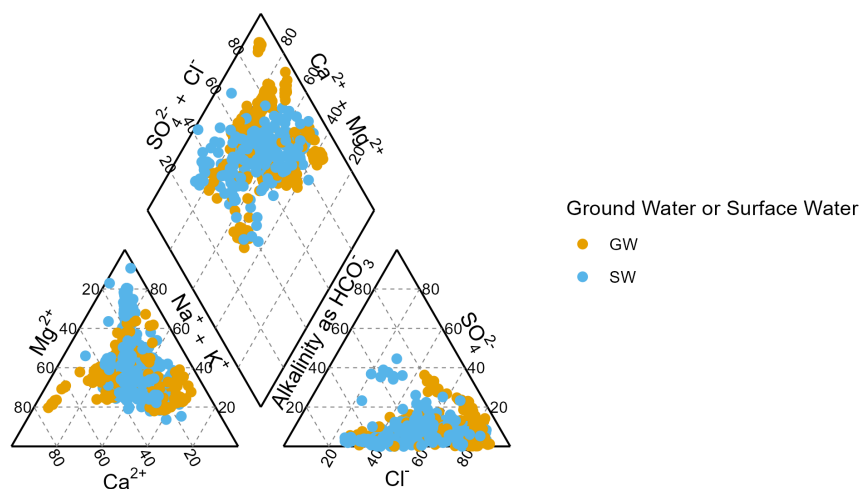
This paper reports on a long term (12 year) hydrogeochemistry dataset from a single catchment in NSW, Australia. This dataset includes both groundwater and surface water samples for 60 locations within the catchment. While the dataset was collected by different groups of people at different times and locations, it still provides a valuable long term and spatially diverse data set which can be used for research into the space and time variation of dryland and groundwater salinity.

. The majority of the code and associated data, including the Rmarkdown for this paper, is stored on Github <https://github.com/WillemVervoort/MuttamaDataPaper>. The hydrogeochemistry data is located on the University of Sydney escholarship repository. However, due to the volume of raw data, the groundwater logger data is stored in a separate Open Science Foundation project: <https://doi.org/10.17605/OSF.IO/BEUWK>

. T. Bishop initiated the sampling campaign. T. Bishop, F. van Ogtrop and R.W. Vervoort conceptualised the overall study, and managed the project. R.W. Vervoort and M. Tambrchi wrote the draft paper and analysed results. F. Akter and J. Lessels collected and analysed the majority of the samples. M. Tambrchi, A. Buzacott, J. Moloney, F. Akter analysed and managed the data. All authors participated in sampling, laboratory analysis and review of the paper.



**Figure 13.** Variation across time of the  $Cl : HCO_3$  ratio by sampling location represented as a boxplot. The blue dashed line indicate a  $Cl : HCO_3$  ratio of 1



**Figure 14.** Piper-plot of all groundwater and surface water data collected over the period

. The authors declare no competing interests.

. This dataset would not have been possible without the generous assistance and access to properties from the following land owners in the Muttama Creek area: R. Last, the Tozer family, M. Sullivan, P. McClintock, P. McGuire, S. Sharman, A. Hollihan, the managers at Brawlin Springs as part of the Romani Pastoral Company, and the managers and owners of Wavehill, in particular J. Litchfield. We would like to thank several generations of students in the units LWSC2002, ENVX3003 and ENSY5708, as well a multiple interns from French Institutions and University and Wageningen University for assisting with the sample collection.

## References

- Akter, F.: Groundwater salinity and interaction with surface water near Cootamundra, NSW, Australia, Thesis, 2018.
- Breuer, L., Hiery, N., Kraft, P., Bach, M., Aubert, A. H., and Frede, H.-G.: HydroCrowd: a citizen science snapshot to assess the spatial control of nitrogen solutes in surface waters, *Scientific Reports*, 5, 16 503, <https://doi.org/10.1038/srep16503>, 2015.
- Cartwright, I., Weaver, T. R., Simmons, C. T., Fifield, L. K., Lawrence, C. R., Chisari, R., and Varley, S.: Physical hydrogeology and environmental isotopes to constrain the age, origins, and stability of a low-salinity groundwater lens formed by periodic river recharge: Murray Basin, Australia, *Journal of Hydrology*, 380, 203–221, <https://doi.org/http://dx.doi.org/10.1016/j.jhydrol.2009.11.001>, 2010.
- Conyers, M. K., Hume, I., Summerell, G., Slinger, D., Mitchell, M., and Cawley, R.: The ionic composition of the streams of the mid-Murrumbidgee River: Implications for the management of downstream salinity, *Agricultural Water Management*, 95, 598–606, <https://doi.org/10.1016/j.agwat.2008.01.007>, 2008.
- Dahlhaus, P., Evans, T., Nathan, E., Cox, J., and Simmons, C.: Groundwater-level response to land-use change and the implications for salinity management in the West Moorabool River catchment, Victoria, Australia, *Hydrogeology Journal*, <http://dx.doi.org/10.1007/s10040-010-0616-y>, 2010.
- Department of Environment and Climate Change NSW: Salinity Audit Upland catchments of the New South Wales Murray–Darling Basin, Report, Department of Environment and Climate Change NSW, 2009.
- Finlayson, J., Bathgate, A., Nordblom, T., Theiveyanathan, T., Farquharson, B., Crosbie, R., Mitchell, D., and Hoque, Z.: Balancing land use to manage river volume and salinity: Economic and hydrological consequences for the Little River catchment in Central West, New South Wales, Australia, *Agricultural Systems*, 103, 161–170, <https://doi.org/http://dx.doi.org/10.1016/j.agsy.2009.12.003>, 2010.
- Grayson, R. B., Gippel, C. J., Finlayson, B. L., and Hart, B. T.: Catchment-wide impacts on water quality: the use of 'snapshot' sampling during stable flow, *Journal of Hydrology*, 199, 121–134, <http://www.sciencedirect.com/science/article/B6V6C-3SWM82P-P/2/c627f46d28b24f57cfb1095d36b7001d>, 1997.
- Hughes, J. D., Khan, S., Crosbie, R., Helliwell, S., and Michalk, D. L.: Runoff and solute mobilization processes in a semiarid headwater catchment, *Water Resources Research*, 43, W09 402, <https://doi.org/doi:10.1029/2006WR005465>, 2007.
- Jolly, I., Williamson, D. R., Gilfedder, M., Walker, G., Morton, R., Robinson, G. H., Jones, H., Zhang, L., Dowling, T., Dyce, P., Nathan, R., Nandakumar, N., Clarke, R., and McNeill, V.: Historical stream salinity trends and catchment salt balances in the Murray-Darling Basin, Australia, *Marine and Freshwater Research*, 52, 53–63, 2001.
- Leblanc, M., Tweed, S., Van Dijk, A., and Timbal, B.: A review of historic and future hydrological changes in the Murray-Darling Basin, *Global and Planetary Change*, 80–81, 226–246, <https://doi.org/http://dx.doi.org/10.1016/j.gloplacha.2011.10.012>, 2012.
- Lessels, J. S.: The optimisation of water quality monitoring schemes, Thesis, 2014.
- Lessels, J. S. and Bishop, T. F. A.: A post-event stratified random sampling scheme for monitoring event-based water quality using an automatic sampler, *Journal of Hydrology*, 580, 123 393, <https://doi.org/https://doi.org/10.1016/j.jhydrol.2018.12.063>, 2020.
- Lintern, A., Webb, J. A., Ryu, D., Liu, S., Waters, D., Leahy, P., Bende-Michl, U., and Western, A. W.: What Are the Key Catchment Characteristics Affecting Spatial Differences in Riverine Water Quality?, *Water Resources Research*, 54, 7252–7272, <https://doi.org/10.1029/2017wr022172>, 2018.
- Lyon, S. W., Seibert, J., Lembo, A. J., Steenhuis, T. S., and Walter, M. T.: Incorporating landscape characteristics in a distance metric for interpolating between observations of stream water chemistry, *Hydrol. Earth Syst. Sci.*, 12, 1229–1239, <https://doi.org/10.5194/hess-12-1229-2008>, 2008.

- McFarlane, D. J., George, R. J., Barrett-Lennard, E. G., and Gilfedder, M.: Salinity in Dryland Agricultural Systems: Challenges and Opportunities, pp. 521–547, Springer International Publishing, Cham, ISBN 978-3-319-47928-6, [https://doi.org/10.1007/978-3-319-47928-6\\_19](https://doi.org/10.1007/978-3-319-47928-6_19), 2016.
- R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, <https://www.R-project.org/>, 2023.
- Scanlon, B. R., Jolly, I., Sophocleous, M., and Zhang, L.: Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality, *Water Resources Research*, 43, W03 437, <https://doi.org/10.1029/2006wr005486>, 2007.
- Summerell, G. K., Tuteja, N. K., Grayson, R. B., Hairsine, P. B., and Leaney, F.: Contrasting mechanisms of salt delivery to the stream from three different landforms in South Eastern Australia, *Journal of Hydrology*, 330, 681–697, <http://www.sciencedirect.com/science/article/B6V6C-4KV2YJN-1/2/96f9cb43375a9d49e33b405593ee6c80>, 2006.
- van Dijk, A. I. J. M., Gilfedder, M., and Austin, J.: Influences of climate, terrain and land cover on stream salinity in southeastern Australia, and implications for management through reforestation, *Hydrological Processes*, 22, 3275–3284, <http://dx.doi.org/10.1002/hyp.6968>, 2008.
- Walker, G., Zhang, L., Ellis, T., Hatton, T., and Peterham, C.: Estimating impacts of changed landuse on recharge: review of modelling and other approaches appropriate for management of dryland salinity, *Hydrogeology Journal*, 10, 68–90, 2002.
- Webb, L.: Hydrogeology Report for the Muttama Catchment, Report, NSW Department of Land and Water Conservation, 1999.
- White, I., Macdonald, B. C. T., Somerville, P. D., and Wasson, R.: Evaluation of salt sources and loads in the upland areas of the Murray–Darling Basin, Australia, *Hydrological Processes*, 23, 2485–2495, <https://doi.org/10.1002/hyp.7355>, 2009.