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Summary of main alluvial aquifers and groundwater use potential in the Murray–Darling Basin

Project RQ8b: Groundwater as an adaptation option to current water resources management

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Executive summary

This report summarises progress in the first 5 months of the MD-WERP Project RQ8b investigating groundwater as an adaptation option to current water resources management.

Groundwater accounts for about 13% of total water use in the Murray–Darling Basin. Eight alluvial systems (equivalent to 19 sustainable diversion limit resource units) account for 75% of the total groundwater use in the Basin. Almost 75% of the groundwater use in these alluvial systems occurs in New South Wales.

The project is currently prioritising the alluvial aquifers in the Basin. The basis for this prioritisation exercise is identifying areas with intensive groundwater use where opportunities for enhanced groundwater use could be explored (e.g. Managed Aquifer Recharge, MAR) to reduce risks to both users and the environment. This prioritisation will be achieved by combining the aquifer importance index and aquifer sensitivity index proposed by Currie et al. (2010) and Barron et al. (2011). The aquifer importance index reflects current levels of groundwater extraction, the volume of the resource, and the occurrence of groundwater-dependent ecosystems (GDEs). The aquifer sensitivity index describes the resilience of the aquifer to potential changes in groundwater recharge particularly under climate change.

Early results indicate the importance of alluvial aquifers in terms of groundwater extraction at Basin scale, in particular, the large alluvial systems located in New South Wales. The aquifer prioritisation method is also being improved to better account for the presence of GDEs. An exploratory area-based method is presented and discussed. This method does not make any assumptions about the relative importance of different GDE types, their groundwater interaction potential, ecotype or any other attribute, and is based on the latest available national-scale GDE information (GDE Atlas, 2019). This GDE metric is simple, quantitative and conservative and will be tested in the aquifer prioritisation methodology in the coming months.

The project has also established methods to characterise groundwater level and trend through time in the key alluvial aquifers prioritised above. Methods implemented in the Australian Groundwater Insight are presented and possible avenues for improvement identified by utilising the Gwydir alluvial system as test case. Early results suggest that frugal methods for large-scale analysis might not capture specific declining trends in groundwater levels, so potentially missing the occurrence of localised hotspots in aquifers under heavy groundwater use.

1 Introduction

There are 3 one-year activities in Project RQ8b on groundwater as an adaptation option to current water resources management. In Year 1, Activity 8b.1 will improve the understanding of groundwater level trends, groundwater use patterns and priority aquifers to identify where and when groundwater plays a substantial role in the Murray–Darling Basin (MDB), and where groundwater use could be enhanced when used conjunctively with surface water. Building on this, Activity 8b.2 in Year 2 will identify and assess opportunities such as managed aquifer recharge, brackish groundwater desalinisation and deep groundwater bores, for enhancing water supply across priority aquifers. Based on the outcomes of Years 1 and 2, Activity 8b.3 in Year 3 will apply an innovative modelling framework termed Groundwater Commons Game (Castilla-Rho et al., 2019) to integrate and assess social, economic and environmental aspects of conjunctive SW-GW management in a case study considered within the priority alluvial systems identified for the MDB.

The first year of RQ8b aims to provide insights on where (and when) the opportunities for enhanced groundwater use are located to benefit economic, social and environmental outcomes in the MDB. The research assesses opportunities to augment water security in key alluvial aquifers where most of the groundwater use takes place. This research aligns directly with the Murray–Darling Basin Authority (MDBA) statement of expectations for managing groundwater (Murray–Darling Basin Authority, 2019), where the role of groundwater supporting rivers, river ecosystems and communities is regarded as critical.

1.1 Scope of RQ8b: Groundwater as an adaptation option to current water resources management

During the first year 2 main activities will be addressed in RQ8b: a) identify priority alluvial systems across the MDB, and b) characterise spatial and temporal groundwater levels/use in priority alluvial systems of the MDB. The project aims to:

- improve the understanding of historical and current trends in groundwater use in alluvial systems across the MDB
- analyse long-term records (20+ years, when available) of groundwater levels in key alluvial systems and perform factor attribution through trend analyses
- identify priority aquifers applying revised concepts of importance and sensitivity indices defined in Currie et al. (2010) and Barron et al. (2011).

Data on groundwater use will be employed to prioritise alluvial systems in the MDB through the prioritisation methodology described in Section 2. Having identified priority alluvial aquifers, we will deploy a statistical trend analysis on groundwater levels of selected aquifers to disentangle factors contributing to these trends, e.g. increases/decreases in groundwater use, increases/decreases in groundwater recharge, increases/decreases in hydroclimatic variables, and potential combinations of these attributions. With these results we will equip the MDBA and stakeholders with updated knowledge to better manage groundwater resources in the MDB.

1.2 Groundwater use across the Murray–Darling Basin

Groundwater systems across the MDB can be subdivided into 3 major provinces (Stewardson et al., 2021; Walker et al., 2020):

- *Fractured rock aquifers* contained in the Mt Lofty/Flinders Ranges in South Australia, and in the Great Dividing Range, which forms the eastern and south-eastern margins of the Basin
- *Alluvial aquifers* contained in major river valley deposits of sand and gravel, where river leakage and flood events are major sources of recharge and most of the irrigated agriculture in the MDB is located
- *Tertiary Limestone* of the western Murray Basin where groundwater is primarily saline with areas of good quality groundwater.

Stewardson et al. (2021) acknowledge a fourth province associated with the Great Artesian Basin (GAB) sediments, located in the northern MDB sub-basin. Most of this province consists of recharging/intake beds or confining sediments (at the surface) to the underlying main (deeper) GAB aquifers. Some degree of connectivity is acknowledged between MDB and GAB sediments with deeper groundwater systems, however, flow exchanges are estimated to be low (Stewardson et al., 2021). This province is not included in the MDBA administrative process and is managed through an interstate agreement.

Figure 1 shows the water use across the MDB for the period 2012-13/2018-19 as reported from the Transition Water Take Reports (2012-13/2018-19) (Murray–Darling Basin Authority, 2020). This data covers the entire Basin use and is considered of high reliability in terms of quality assurance compared to previous reporting (2001-02/2011-12), thus providing valuable insights on total groundwater use. Average groundwater use in the MDB is 1482 GL/y and represents about 13% of the total water use reported in the MDB, ranging between 8% and 18% for the period analysed. Proportional contributions from groundwater to the total available water resources are complementary to surface water resources, and therefore they increase when surface water availability decreases.

The Murray–Darling Basin Authority (2020) highlights that 92% of the total groundwater annual actual take (use) was metered for the year 2018-19, whereas 100% of the groundwater take under basic rights (domestic and stock) is unmetered. This would suggest that recent statistics on groundwater use are more reliable compared to earlier estimates, notwithstanding the lack of metering for groundwater take under basic rights. The latter has been estimated as about 233 GL/y for the period 2015-16/2018-19.

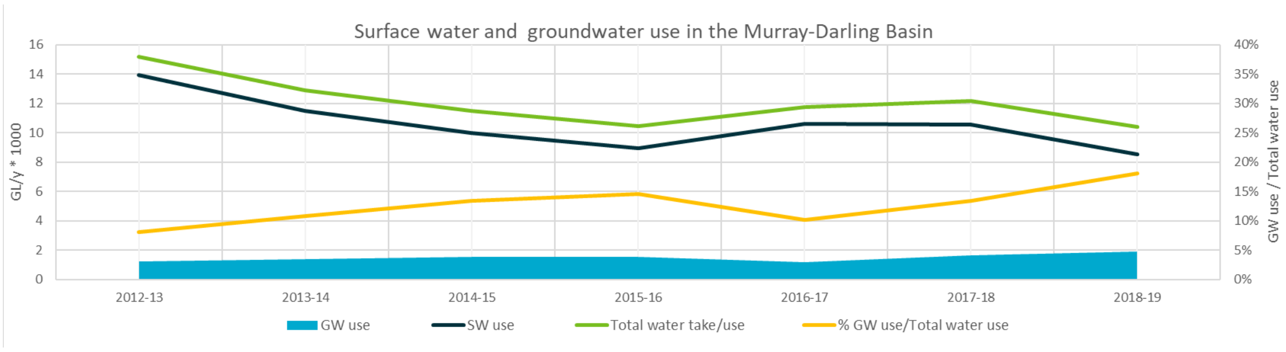


Figure 1 Water use in the Murray–Darling Basin for the period 2012-13/2018-19 as reported in the Transition Period Water Take Reports (2012-2019)

At Basin state level for the period 2012-13/2018-19, New South Wales (69%), Queensland (14%) and Victoria (13%) concentrate close to 96% of the total groundwater use reported in the Basin (Figure 2). As discussed in the next paragraphs, most of this groundwater use takes place in large alluvial systems in these States associated with 19 (out of 80) groundwater Sustainable Diversion Limit (SDL) resource units.

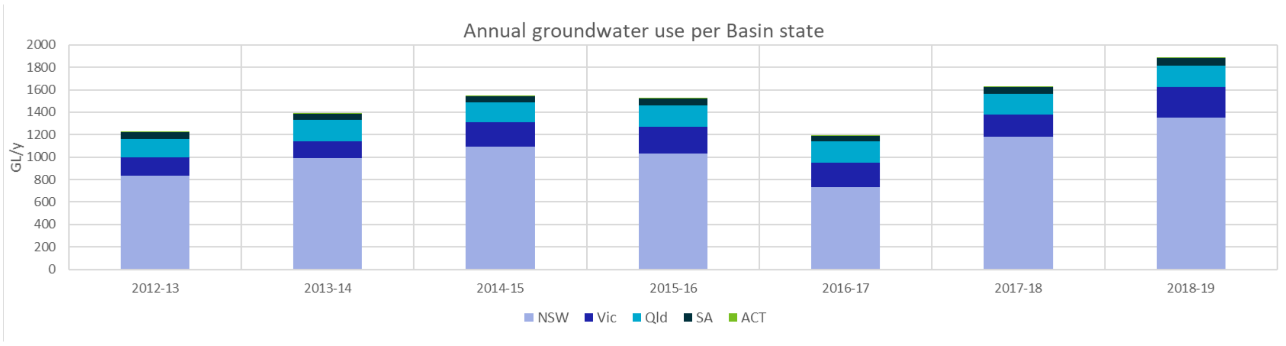


Figure 2 Total groundwater use per Basin State reported for the period 2012-13/2018-19

Preliminary data review and discussion with MDBA suggest most of the groundwater use is concentrated around 8 alluvial systems in the MDB as set out below. As such, it seems reasonable to concentrate the efforts of Project RQ8b in these systems. The main alluvial aquifers identified in the MDB are listed as follows (Figure 3):

- **Condamine** (Upper Condamine Alluvium – Central GS64a[1], – Tributaries GS64b). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 43% of the total groundwater use metered in SDL resource units of Queensland, with the most recent estimate bringing this value close to 50%. If groundwater use in the Upper Condamine Basalts (GS65) is also included, the average use amounts to 80% of groundwater use in Queensland.

[1] This nomenclature corresponds to the 80 Groundwater Sustainable Diversion Limits (SDL) Resource Units reported by the Murray-Darling Basin Authority (https://data.gov.au/data/dataset/66e3efa7-fb5c-4bd7-9478-74adb6277955. Accessed on 15-November-2021).

- **Gwydir** (Upper Gwydir, GS43 – Lower Gwydir, GS24). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 4% of the total groundwater use metered in SDL resource units of New South Wales.
- **Namoi** (Upper Namoi, GS47, GS48 – Lower Namoi, GS29). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 18% of the total groundwater use metered in SDL resource units of New South Wales.
- **Macquarie** (Upper Macquarie, GS45 – Lower Macquarie, GS26). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 5% of the total groundwater use metered in SDL resource units of New South Wales.
- **Lachlan** (Upper Lachlan, GS44 – Lower Lachlan, GS25). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 16% of the total groundwater use metered in SDL resource units of New South Wales.
- **Murrumbidgee** (Lower Murrumbidgee Shallow, GS28a – Lower Murrumbidgee Deep, GS28b – Mid-Murrumbidgee, GS31). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 29% of the total groundwater use metered in SDL resource units of New South Wales.
- **Murray** (Lower Murray Shallow, GS27a – Lower Murray Deep, GS27b – Upper Murray, GS46). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 8% of the total groundwater use metered in SDL resource units of New South Wales.
- **Goulburn-Murray** (Shepparton Irrigation Region, GS8a – Sedimentary Plain, GS8c). For the period 2012-13 until 2018-19 this alluvial system concentrates on average 88% of the total groundwater use metered in SDL resource units of Victoria, with the most recent estimate bringing this value to 90%.

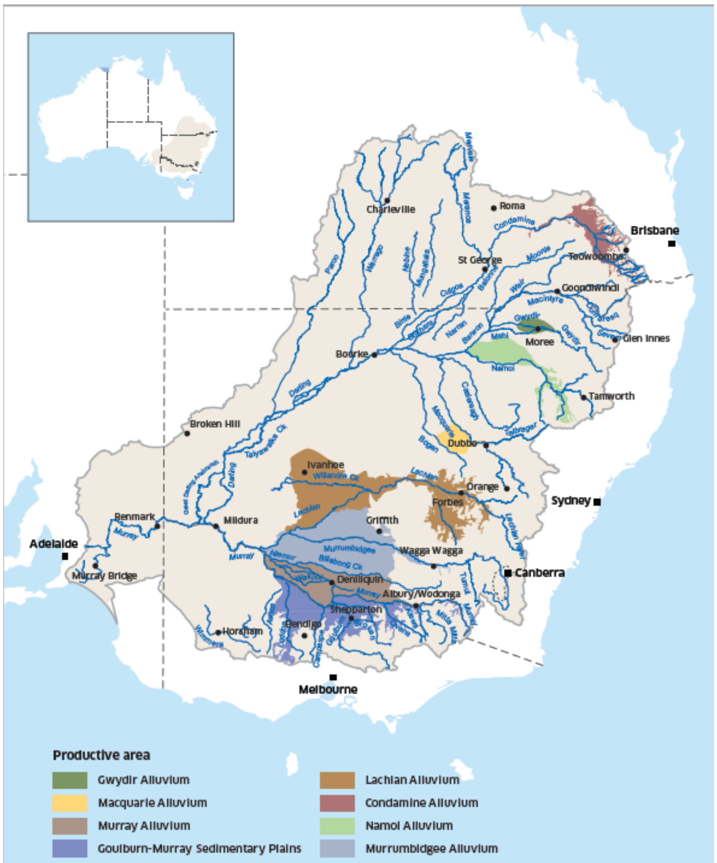


Figure 3 Main alluvial systems in the Murray–Darling Basin (from https://www.mdba.gov.au/publications/products/groundwater-alluvial-areas-map, accessed 12/11/2021)

These 8 alluvial systems concentrate on average 74% of the total groundwater use across the MDB for the period 2012-13/2018-19, with more recent estimates bringing this value closer to 80% (Figure 4).

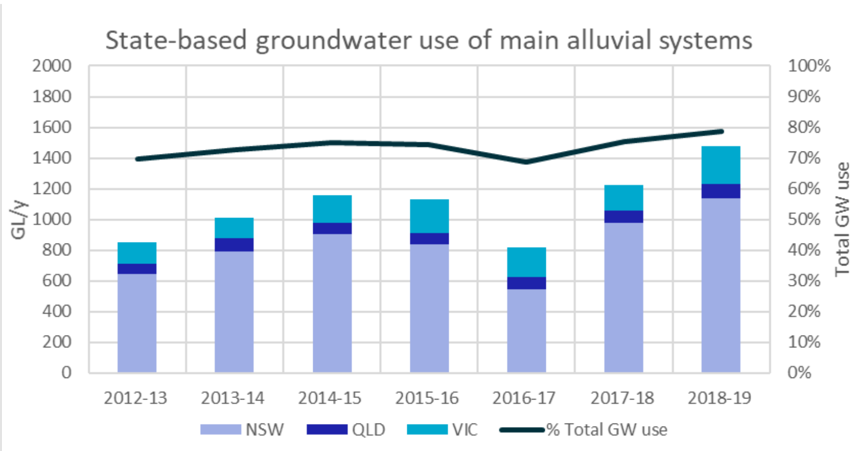


Figure 4 Groundwater use across states for the main alluvial aquifers listed and percentage of contribution to total groundwater use in the state

At Basin state level, in New South Wales **Gwydir**, **Namoi**, **Macquarie**, **Lachlan**, **Murrumbidgee**, and **Murray** alluvial systems represent on average 80% of the groundwater use, with more recent estimates bringing this value to 84%. Most of the remaining groundwater use is concentrated in 5 SDL resource units (Kanmantoo Fold Belt MDB – GS19, Gunnedah-Oxley Basin MDB – GS17, New England Fold Belt MDB – GS37, Western Porous Rock – GS50, and Lachlan Fold Belt MDB – GS20) ranging on average between 8.2 GL/y and 81 GL/y for the period 2012-13 to 2018-19. In Queensland, **Condamine** alluvial system accounts on average for 43% of the groundwater use, with other 3 SDL resources units accounting for a remaining 49% of the groundwater use (Upper Condamine Basalts – GS65, Queensland Border Rivers Alluvium – GS54, and St. George Alluvium: Condamine–Balonne (deep) – GS61b) ranging between 11.3 GL/y and 67.3 GL/y. In Victoria, the **Goulburn-Murray** alluvial system accounts on average for 88% of the total groundwater use, with the SDL GS8b (Goulburn-Murray: Highlands) bringing this figure to 95% by adding an average consumption of 14.2 GL/y for the period 2012-13 to 2018-19.

2 Prioritisation of alluvial aquifers of the Murray–Darling Basin

Alluvial aquifers can be prioritised according to different criteria, which ultimately should facilitate sustainable groundwater management. Criteria that can be used include the role of aquifers sustaining groundwater-dependent ecosystems (GDEs), vulnerability to changes in recharge patterns, and long-term sustainability of available groundwater resources. Currie et al. (2010) proposed a method to prioritise large-scale aquifers in terms of the relative impacts of climate change on recharge rates. This method is based on the concepts of “aquifer importance” and “aquifer sensitivity”, and is further explained in the following sections.

2.1 Aquifer prioritisation methodology

2.1.1 Aquifer importance index

Aquifer importance is defined as the *“significance of the groundwater resource for consumptive use and for the environment”* and is calculated following Currie et al. (2010) and Barron et al. (2011). It combines in a single index the current levels of groundwater extraction, the volume of the groundwater resource, and the occurrence of groundwater-dependent ecosystems (GDEs). Following Barron et al. (2011) the aquifer importance index is calculated as follows:

$$I = \frac{E}{E_{MAX}} * \frac{SY}{SY_{MAX}} * f(Baseflow\ GDEs) * f(other\ GDE\ types) \qquad [1]$$

where *I* is aquifer importance; *E* is current level of extraction (ML/y); E_{MAX} is the maximum level of extraction recorded for the aquifers being analysed in the dataset (ML/y); *SY* is sustainable yield (ML/y); SY_{MAX} is maximum sustainable yield for the aquifers being analysed in the dataset (ML/y). An equivalent metric for *E* corresponds to the *annual actual take* from the transition Period Water Take Reports (2012-2019), and for *SY* the long-term average sustainable diversion limit for SDL units. *f(baseflow GDEs)* represents a weighting factor accounting for presence of river baseflow GDEs; and *f(other GDEs)* represents a weighting factor representing other GDE types. Both GDE functions are numerically defined as:

$$f(GDEs) = \begin{cases} 0.85 & where\ GDEs\ are\ identified\ in\ the\ groundwater\ source \\ 0.15 & where\ no\ GDEs\ are\ identified\ in\ the\ groundwater\ source \end{cases} \qquad [2]$$

These weighting factors are arbitrarily defined by Barron et al. (2011) and their relative sensitivity is also analysed in the same study. The definition of these weighting factors can be done through spatial interception of alluvial aquifers and GDE data. The latest available GDE spatial data corresponds to the GDE Atlas published by the Bureau of Meteorology (BoM) (http://www.bom.gov.au/water/groundwater/gde/) and it is the main data source used for this analysis (see Section 2.2). From the GDE atlas it is possible to obtain spatial information on aquatic ecosystems relying on the surface expression of groundwater, which also includes surface water ecosystems which may have a groundwater component, such as rivers, wetlands and springs. Spatial features in this layer (GDE likelihood, GDE typology, etc.) can help further discriminate between river baseflow (RB) GDEs and other GDEs including wetlands, springs, swamps.

Improvements to the original methodology proposed by Currie et al. (2010) have been explored in order to improve the calculation of the importance index and are further explained in Section 2.2.

2.1.2 Aquifer sensitivity index

Aquifer sensitivity index combines the size of the resource, current level of groundwater use, and the aquifer's capacity to buffer potential changes in recharge rates. Following Barron et al. (2011) the aquifer sensitivity index is calculated as follows:

$$Se = \frac{E}{SY} * f(R:S) \quad [3]$$

where *E* is current level of groundwater use (ML/y); *SY* is sustainable yield (ML/y); and *f(R:S)* is a function describing the ratio between aquifer recharge (R) and aquifer storage (S), which is termed the 'responsiveness metric'. This responsiveness metric relates to the buffering capacity of individual aquifers to 'absorb' potential changes in recharge rates due to, for example, climate change. Given the uncertainties in recharge and storage estimations (Barron et al., 2011), *f(R:S)* is expressed similar to a membership function, which defines the following ranking for weighting the relevance of the responsiveness metric:

$$f(R:S) = \begin{cases} 0.9 & high\ R:S \\ 0.3 & moderate\ R:S \\ 0.01 & low\ R:S \end{cases} \quad [4]$$

In order to define the 3 categories defining the weighting factors for high, moderate and low R:S ratios the following approach can be implemented:

1. aquifer recharge rates for alluvial aquifers are obtained from historical simulations (see e.g. Crosbie et al. (2010) and Crosbie et al. (2011)). Zonal statistics are calculated for different aquifers
2. aquifer storage values can be obtained by using the depth of regolith as proxy or the sustainable yield values estimated for alluvial aquifers
3. R:S ratios can be estimated for alluvial aquifers preserving the relative classification system defined in Barron et al. (2011), i.e., middle-point of "high R:S" class being 3 times greater than middle-point of the "moderate R:S" class and nine times greater than the middle-point of the "low R:S" class.

2.1.3 Aquifer priority index

Importance and sensitivity indices can be combined following the standardisation process described in Barron et al. (2011). This process ensures that both indices are given equivalent numerical weighting before being combined. As both indices have a different number of individual metrics in their respective calculations, which span different orders of magnitude, this standardisation corrects for this inequality. The procedure considers the following calculations:

$$I_L = log_{10}\left(\frac{I}{I_{max}}\right) \quad [5]$$

$$Se_L = log_{10}\left(\frac{Se}{Se_{max}}\right) \quad [6]$$

$$Se_{alt} = \frac{Se_L[min(Se_L) - min(I_L)]}{min(Se_L)} \quad [7]$$

$$Se_{standardized} = 10^{Se_{alt}} \quad [8]$$

where I is the importance score, I_{max} is the maximum importance score in the dataset analysed, Se is the sensitivity score, Se_{max} is the maximum sensitivity score in the dataset analysed.

The final aquifer prioritisation is obtained by the multiplication of both metrics:

$$Final\ Prioritization = \frac{I}{I_{max}} * Se_{standardized} \quad [9]$$

A preliminary assessment of aquifer prioritisation is shown in Figure 5 using the standard definition of Currie et al. (2010) and Barron et al. (2011), and readily available information for New South Wales aquifer systems. This figure shows that the main alluvial systems within NSW are all high priority ranking in terms of importance and sensitivity.

The next step is to complete the information related to recharge rates, groundwater use at SDL resource unit scale, sustainable diversion limits (SDLs), R:S ratios to prioritise all alluvial systems identified in section 1.2.

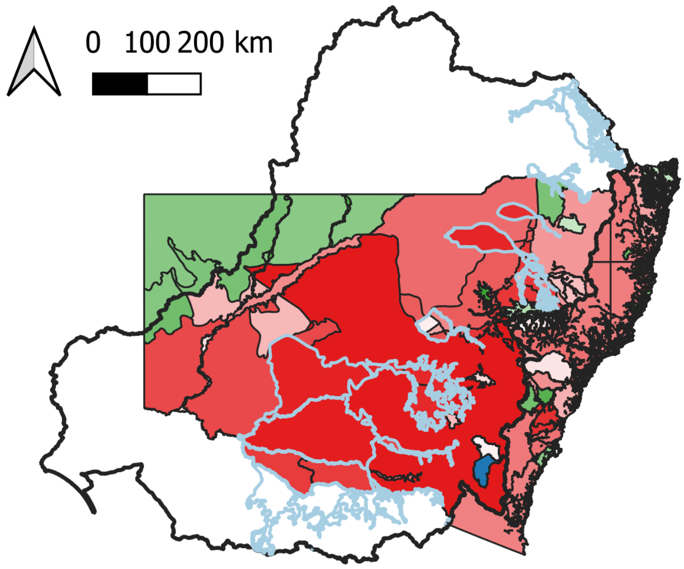


Figure 5 Preliminary aquifer prioritisation with readily available data from New South Wales and the main alluvial aquifers identified in the MDB. High priority aquifers in red colour, low priority aquifers in green colour

2.2 Methods for calculating GDE metrics for alluvial aquifers in the Murray–Darling Basin

To identify the degree to which the main MDB alluvial systems support GDEs, metrics based on proportional areas and counts were explored. This follows the methods of Currie et al. (2010) in developing the 'aquifer importance index' that for their purposes was defined as "the significance of the resource for consumptive use and for the environment". Their study represented this as a "function of the current level of extraction, the volume of the resource and the presence of groundwater dependent ecosystems".

This research aimed to refine the method for representation of GDEs beyond merely presence/absence of a GDE typology in the main alluvial aquifers of the MDB. A preliminary analysis is reported here that used the first version of the GDE Atlas (Doody et al., 2017) as it was readily available as a single dataset. Further analyses will use the latest version of the GDE Atlas (2019) that includes updated mapping of GDEs in NSW and Qld. Updates to other data sources and methods used to derive a prioritisation index is the subject of other activities in the current research project.

GDEs mapped in the Australian GDE Atlas (Doody et al., 2017) were spatially intersected with groundwater management areas (also referred to as SDL areas, CSIRO-SKM (2010)) corresponding to the main alluvial systems (Figure 3). There are 3 GDE types mapped in the Atlas; those relying on the surface expression of groundwater (e.g., rivers, wetlands, springs); those relying on the subsurface presence of groundwater (e.g., Acacia and Eucalypt woodlands and forests); and subterranean features (e.g., caves). It was noted that no subterranean GDEs are mapped in the alluvial areas. Springs in the upper parts of mainly the Condamine and Namoi alluvium areas are critical features that require explicit protection and are treated separately.

Two metrics were compared:

1. Weighted rank-sum proportional areas based on categories of groundwater dependence and ecotype.
2. Percent area of all GDE types.

In the first method the proportional areas of each GDE type were multiplied by a factor (ranging from 1-4) representing the relative importance of the different levels of groundwater interaction likelihood and ecotype classes. This method gave extra weight to features identified as being groundwater dependent in previous specific studies, or those with high potential for groundwater interaction predicted from remote sensing and spatial analysis, and weighted rivers and wetlands over terrestrial and floodplain vegetation. The index was calculated as:

$$GDE\_index = SUM(GDE\ percent\ area * GW\ interaction\ factor * ecotype\ factor) \quad [10]$$

This method was subjective and did not account for complexities of ecosystem roles and made assumptions about the relative importance of the nature or likelihood of groundwater dependence, e.g., those relying on episodic watering were less ‘important’ than those relying on the constant presence of water. The mapped weighted index shown in Figure 6a, resulted in the Gwydir and Mid-Murrumbidgee highlighted in the highest index score class. The weighting system results in lower index values for areas with extensive vegetation GDE types such as the woodland and forested areas common across large tracts of the Lower Lachlan (Figure 6a).

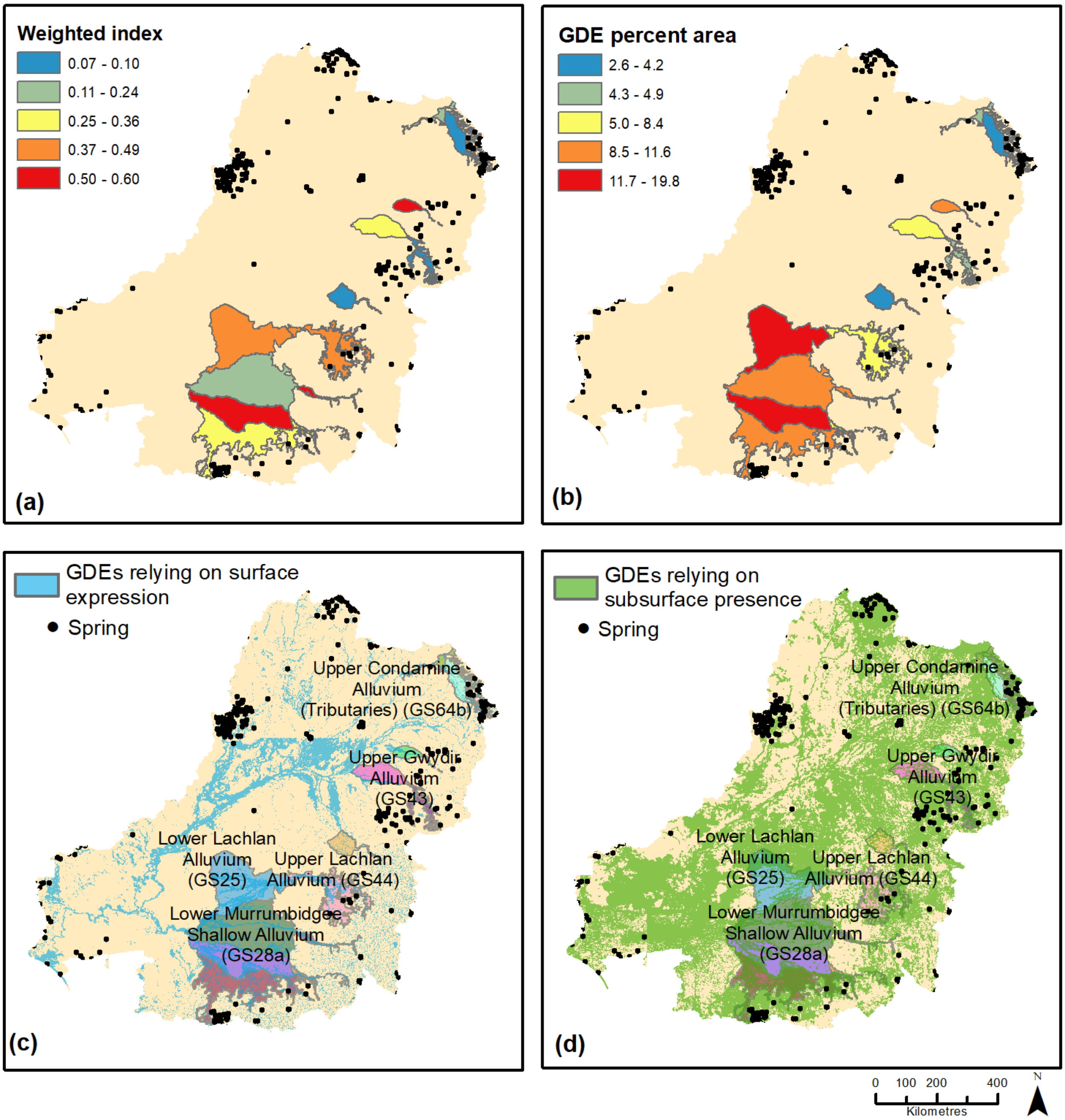


Figure 6 GDE weighted proportional area index (a); percent area of all GDE types (b) for management units corresponding to major alluvial groundwater systems in the MDB; GDEs relying on surface expression of groundwater (c); GDEs relying on subsurface presence of groundwater

The second method used the proportional area of all GDEs types. This did not make any assumptions about the relative importance of different GDE types, their groundwater interaction potential, ecotype or any other attribute in the dataset. This metric is simple, quantitative and conservative. Compared to the weighted index (method 1), the most notable differences are the higher relative values for the Lower Murrumbidgee Shallow Alluvium and Lower Lachlan Alluvium (Figure 6b). The percent area method captured the extent of GDEs relying on surface expression of groundwater (Figure 6c) and equally represented the extent of terrestrial and other vegetation GDE types that rely on the subsurface presence of groundwater (Figure 6d) all of which are attributed with different levels of groundwater interaction potential.

Another visual comparison is given in Figure 7 showing the ranking of a subset of groundwater SDL resource units using the weighted (Figure 7a) and proportional area (Figure 7b) metrics and support the mapping shown in Figure 6a and Figure 6b. Figure 6b shows there are 10 springs; 6 in the Upper Condamine and 2 each in the Goulburn-Murray and Upper Lachlan. These are flagged in the analysis as critical features to protect for any proposal to change land use, extraction and water management planning.

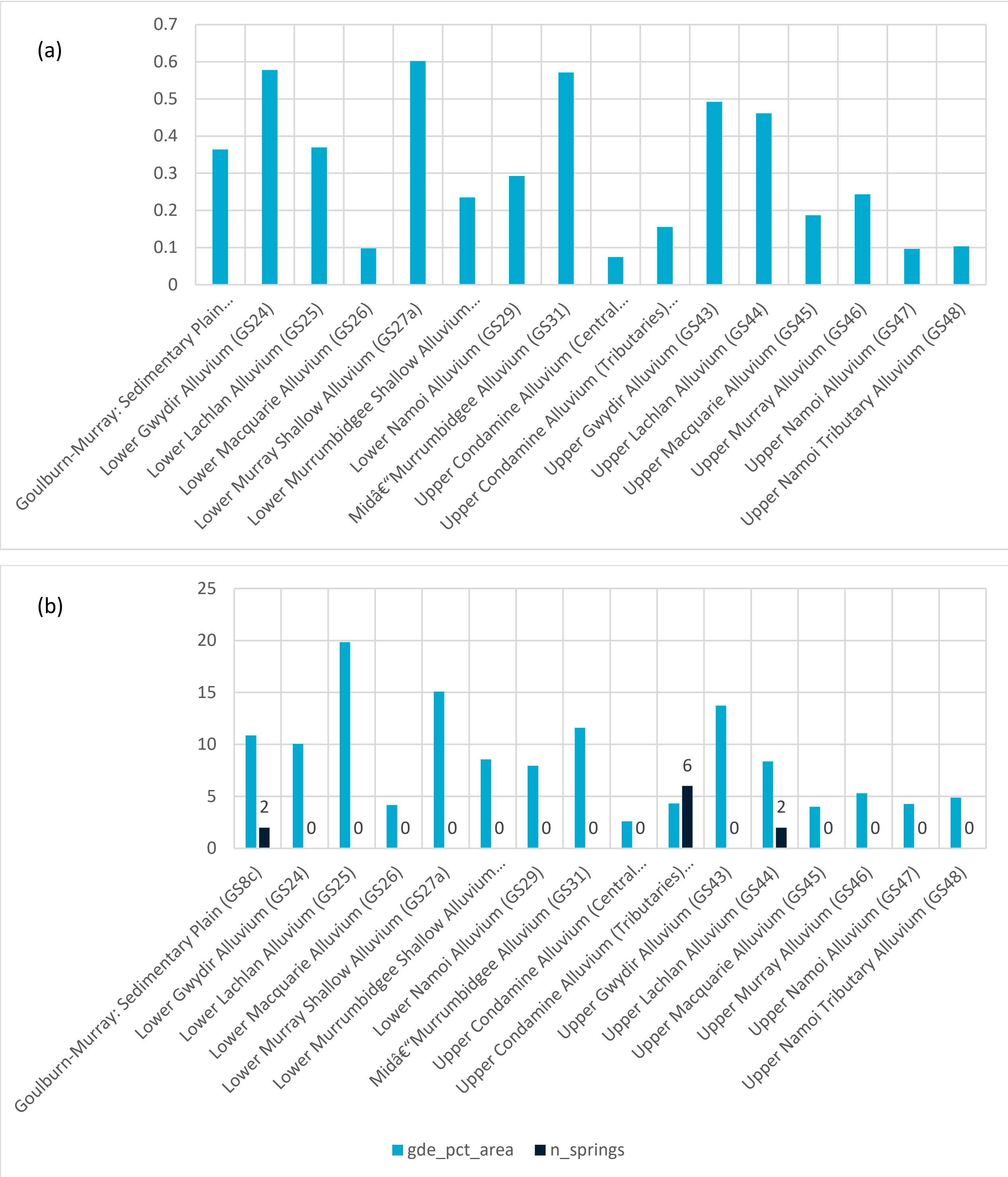


Figure 7 GDE weighted proportional area index (a); percent area of all GDE types and number of springs (b) within the SDLs corresponding to the major alluvial groundwater systems in the MDB

Based on recommendations by Currie et al. (2010) for improving the aquifer prioritisation work, the scope of this work includes to:

1. update GDE mapping with the latest available data (e.g., GDE Atlas which was first released in 2012 and subsequently updated in 2019, NSW high probability GDEs map (Kuginis et al., 2016)),
2. revision of metrics including weighting system in consultation with experts, and
3. inclusion of surface water vulnerability to climate change as an additional factor where aquifers rely on recharge through rainfall and runoff.

To this list, we have added updating of aquifer extraction and storage with the latest data and developing methods to account for climate change vulnerability for alluvial aquifers in different regions possibly in relation to the types of GDEs they support and the types of land use (e.g., seasonal or perennial cropping) that use groundwater for irrigation.

Progress has been made on updating GDE mapping used and on developing prioritisation metrics. The lead author of the GDE Atlas (T. Doody) was consulted in this preliminary study and recommended using percent area of all GDE types as this is simple, quantitative and conservative and does not make assumptions about the relative importance of different GDE types. The importance of prioritising springs as explicit features to protect was also stressed as well as the relevance of baseflow GDEs in unregulated parts of rivers.

3 Methodology for trend analysis of groundwater levels in alluvial aquifers of the Murray–Darling Basin

3.1 Methods for groundwater level trend analysis

Groundwater in the MDB is a valuable and limited resource. The most common method to assess the groundwater resource is to analyse groundwater levels, which are measured at specific (and limited) bore locations through time. Trends in groundwater levels are an integrative response to multiple forcing functions over different spatial and temporal scales (Tillman & Leake, 2010). Groundwater level trends can therefore be used to explain groundwater processes such as recharge and discharge/extraction cycles, as a direct reflection of rising or falling groundwater levels through time.

Literature about trend analysis in groundwater levels is abundant with methods such as Mann-Kendall/Sen's Slope estimator (Fang et al., 2019; Lasagna et al., 2020; Schmid, 2019), hydrograph analysis (Zeru et al., 2020), and regression analysis (Fu et al., 2019; Tillman & Leake, 2010; Zeru et al., 2020) dominating the literature. Alternative techniques such as innovative trend analysis (ITA) have been recently proposed (Dong et al., 2020).

The Bureau of Meteorology has recently deployed a valuable product termed "Australian Groundwater Insight", which presents groundwater levels trend analysis for 5-, 10- and 20-year periods across Australia. The methods report for the trend analysis describes 3 methodologies to detect trends in groundwater levels (Sharples et al., 2021): simple linear trend analysis, non-parametric Kendall test and Sen's slope tests, and mean change. The method used in the Australian Groundwater Insight corresponds to the simple linear trend analysis method.

3.1.1 Simple linear trend [Method 1]

This is a simple and commonly used statistical method to detect a linear trend of a time series of a variable of interest, such as rainfall, temperature, or groundwater level. The method basically builds a linear regression model between for the variable of interest vs time, which considers all data points equally and minimises the sum of the square of the distance of each point from the line (Figure 8). The trend magnitude is the slope of this line and its statistical significance can be tested by hypothesis testing of this slope being equal to zero.

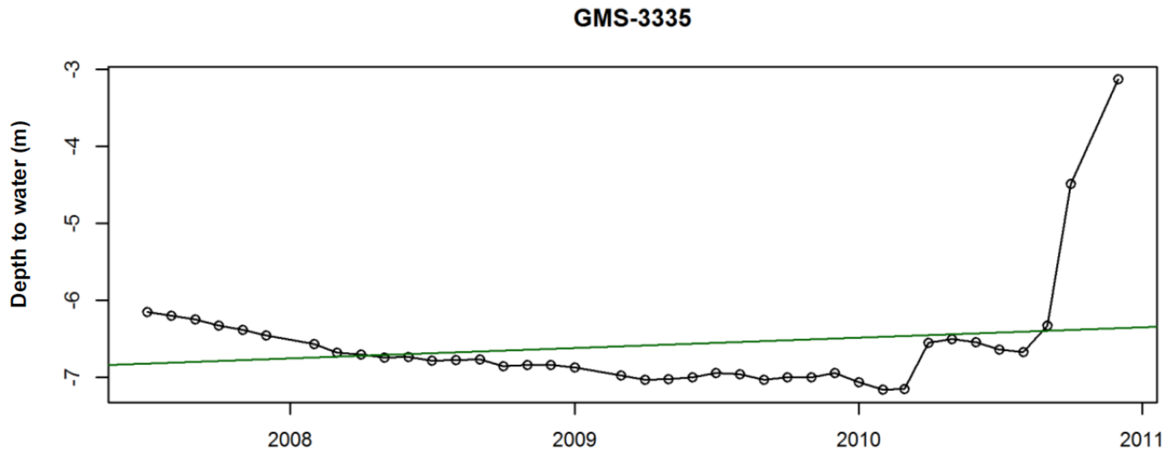


Figure 8 An example of linear trend (Figure A3 in Sharples et al. (2021))

3.1.2 Non-parametric Kendall test and Sen's slope [Method 2]

This method focuses on the majority of data points and ignores outliers (Figure 9). The trend magnitude β, an estimator developed by Hirsch et al. (1982) based on that proposed by Sen (1968), is defined as:

$$\beta = \text{median}\ \frac{X_j - X_i}{j - i} \qquad [11]$$

where 1 < i < j < n. The slope estimator is the median over all possible slope combinations of pairs for the whole data set. For a dataset of n years, the number of all possible combination will be n(n-1)/2.

The non-parametric Kendall's test (Kendall, 1975; Hirsch et al., 1982) can be used to detect the significance of the trends. A hypothesis test is based on the normalised Kendall's statistic Z:

$$Z = \begin{cases} \frac{S-1}{(\text{Var}(S))^{1/2}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{(\text{Var}(S))^{1/2}} & \text{if } S < 0 \end{cases} \qquad [12]$$

where,

$$Var(S) = \{\text{n}(\text{n}-1)(2\text{n}+5) - \textstyle\sum_t t(t-1)(2t+5)\}/18 \qquad [13]$$

$$S = \textstyle\sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \text{sgn}(x_j - x_k) \qquad [14]$$

$$\operatorname{sgn}(\theta) = \begin{cases} 1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases} \quad [15]$$

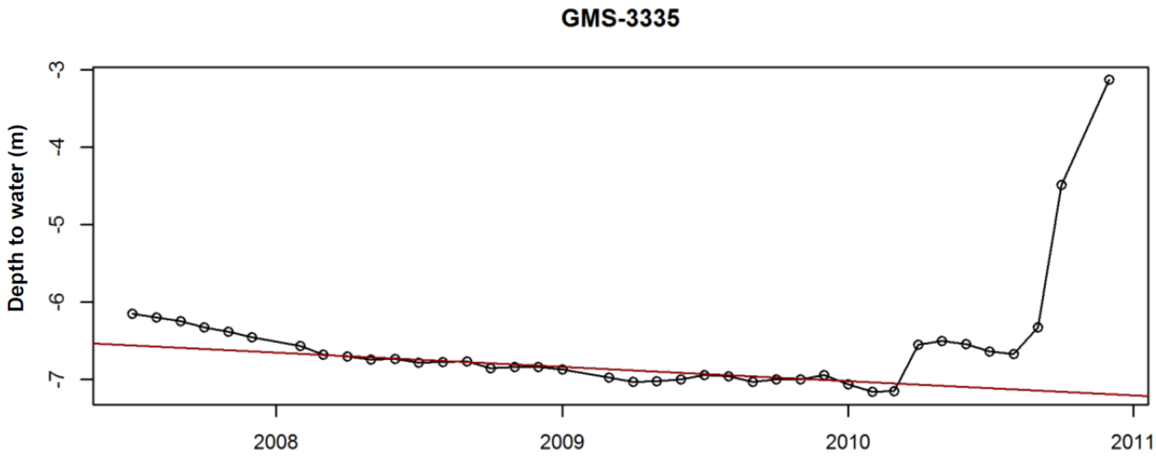


Figure 9 Trend magnitude based on Equation [11] for the same bore in Figure 8

3.1.3 Mean change [Method 3]

This method simply compares the mean groundwater levels between the first half and second half (or any period) of the data as shown in Figure 10.

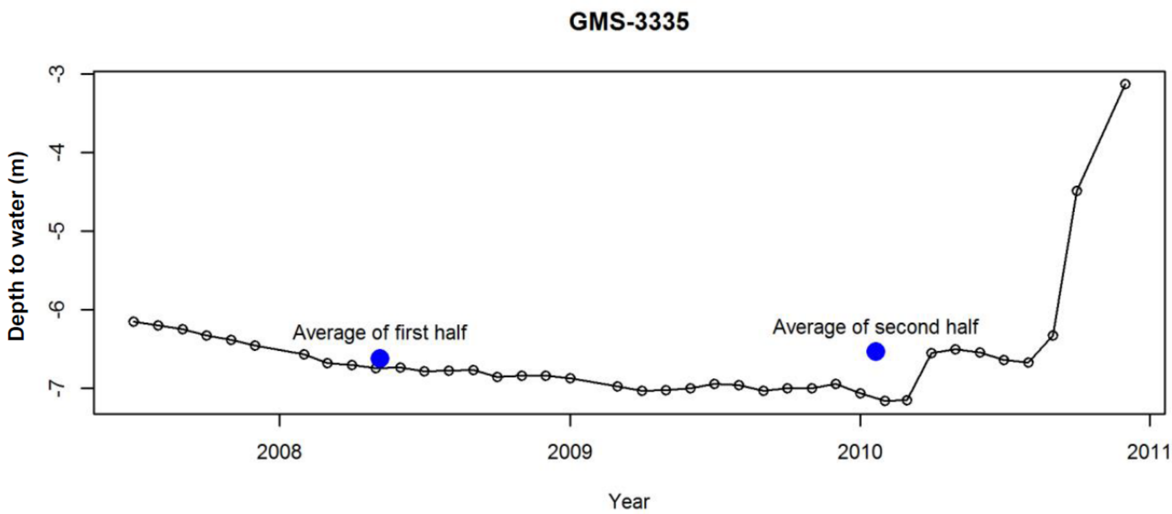


Figure 10 Comparison of groundwater level in two periods (Figure A5 in Sharples et al. (2021))

3.1.4 Methods for RQ8b

Each trend method has its own advantages and limitations, as well as assumptions. Sharples et al. (2021) reviewed these 3 methods, but only Method 1 is used in the Australian Groundwater Insight product (http://www.bom.gov.au/water/groundwater/insight/#/overview/introduction) "to minimise the amount of effort and interpretation required by a person and maximise the use of automatic rules".

In the context of RQ8b, we will explore all 3 methods for groundwater trend analysis in priority alluvial aquifers in the MDB, as this will provide more confidence in the trends detected if all explored methods show consistent results. We will modify Method 3 to explore the trends at different quantiles by using the innovative trend analysis (ITA) (Dong et al., 2020). For example, lower quantiles may show a decreasing trend whilst high quantiles may show an increasing trend.

A preliminary assessment of the groundwater level trends using readily available data from the Australian Groundwater Insight product is shown in Figure 11. Interestingly, all the main alluvial systems of the MDB show a mixture of declining, stable and increasing groundwater level trends over the 20-year period analysed (2000-2020). In addition, there seems to be a clear spatial pattern showing the occurrence of hot spots with persistent declining trends in groundwater levels, like in the upper and Lower Lachlan alluvial systems.

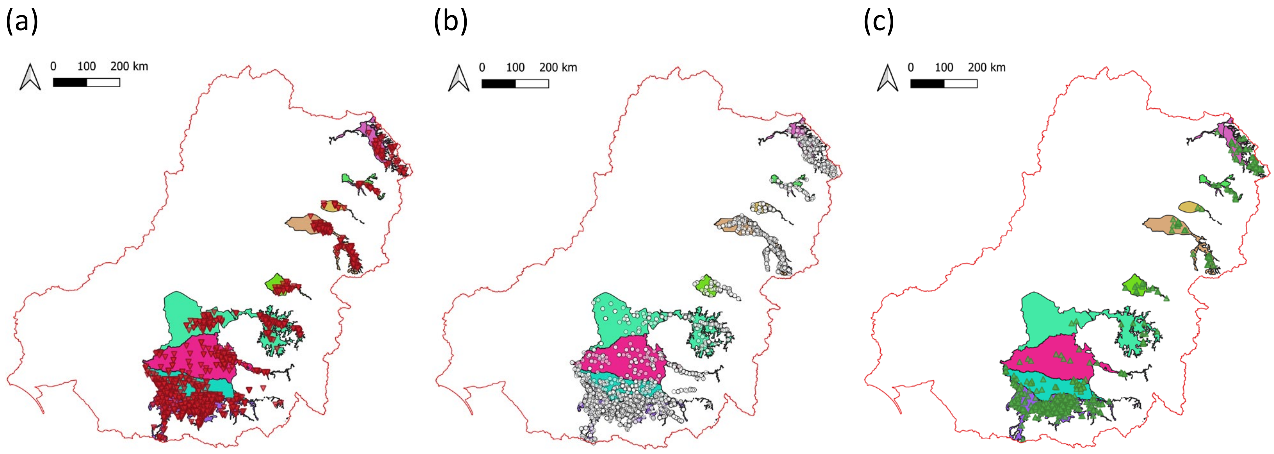


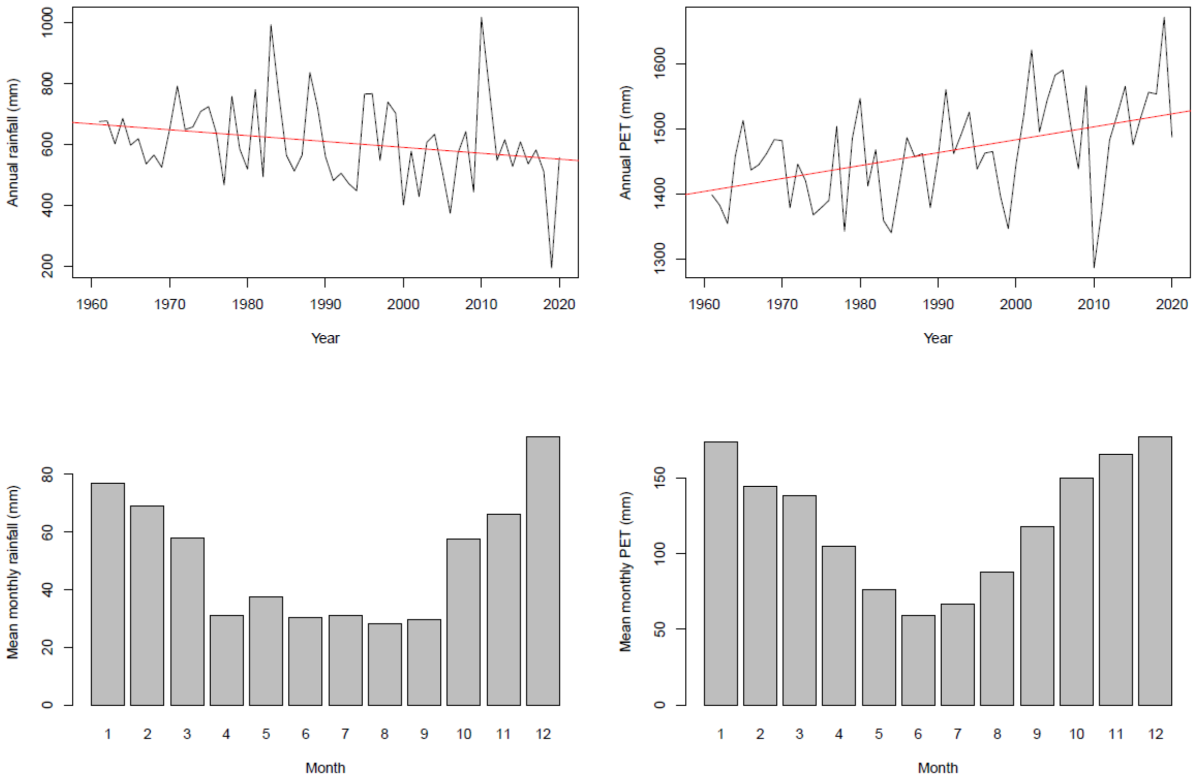
Figure 11 Preliminary assessment of groundwater level trends for the period 2000-2020 in alluvial aquifers of the MDB based on readily available data from Groundwater Insight product by BoM (Sharples et al., 2021). (a) declining trend, (b) stable trend, and (c) increasing trend

3.2 Preliminary analysis of climate data for the main alluvial systems of the MDB

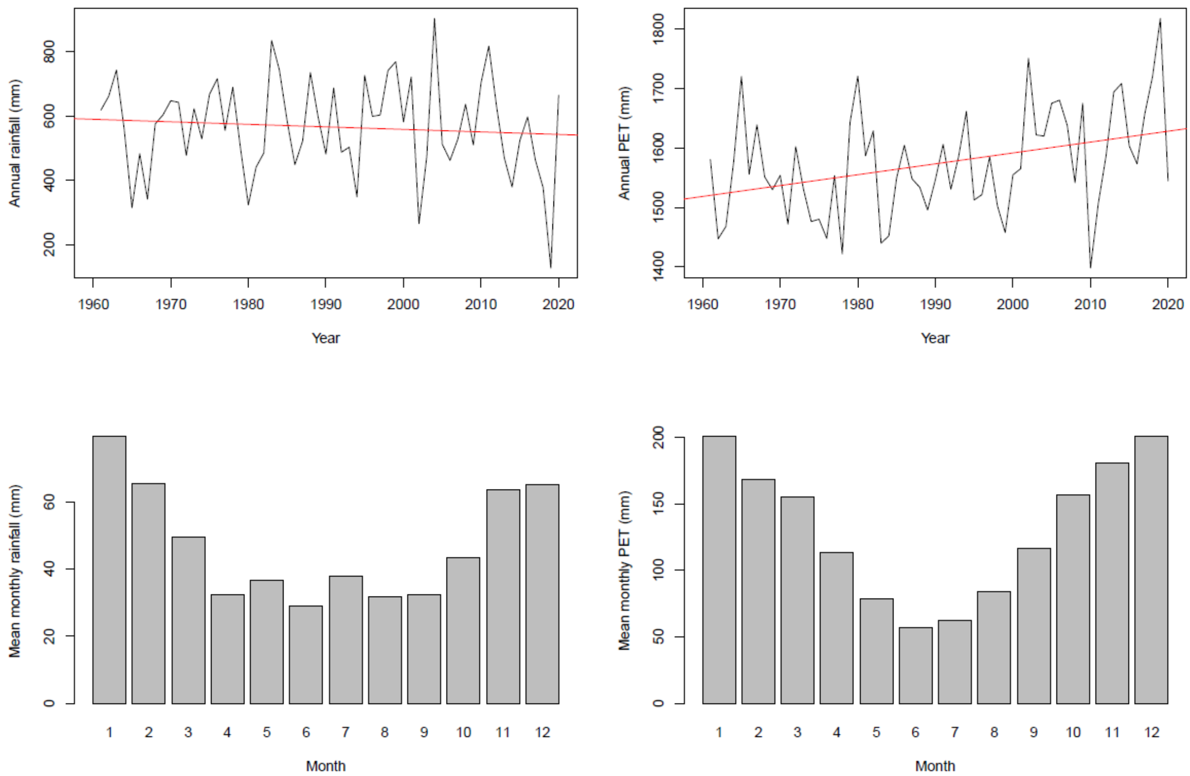
The SILO climate data at 0.05° grid cells for the 8 alluvial systems identified in Section 1.2 (Figure 3) have been downloaded. Preliminary exploratory data analysis (EDA) for the period 1960- 2020 for all the SILO grid cells contained in the alluvial aquifers identified in section 1.2 is shown in Figure 12. The preliminary analysis indicates that:

- annual rainfall shows a slightly decreasing trend and is dominated with year-to-year and decadal variability;
- potential evapotranspiration (PET), on the contrary, shows an increasing trend;
- rainfall annual cycles vary from summer-rainfall in the northern alluvial systems, to even-distribution in the middle, and then winter-rainfall in the southern alluvial systems.

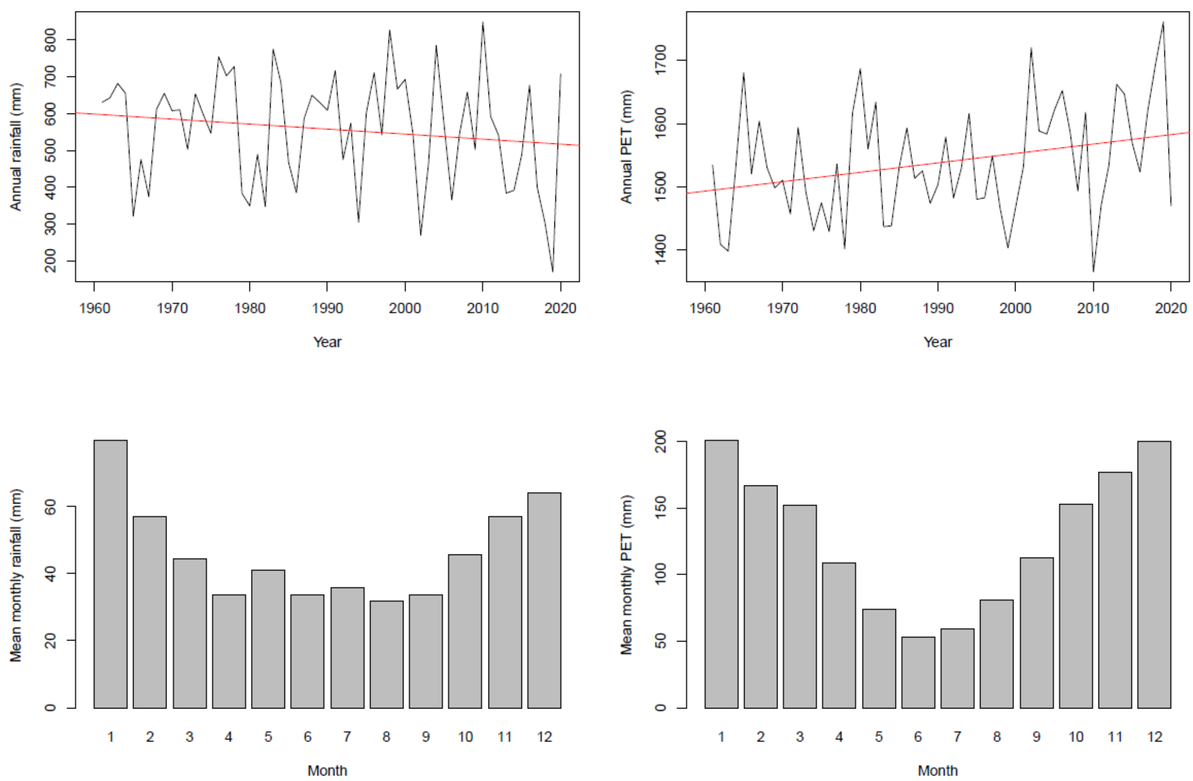
Condamine Alluvium



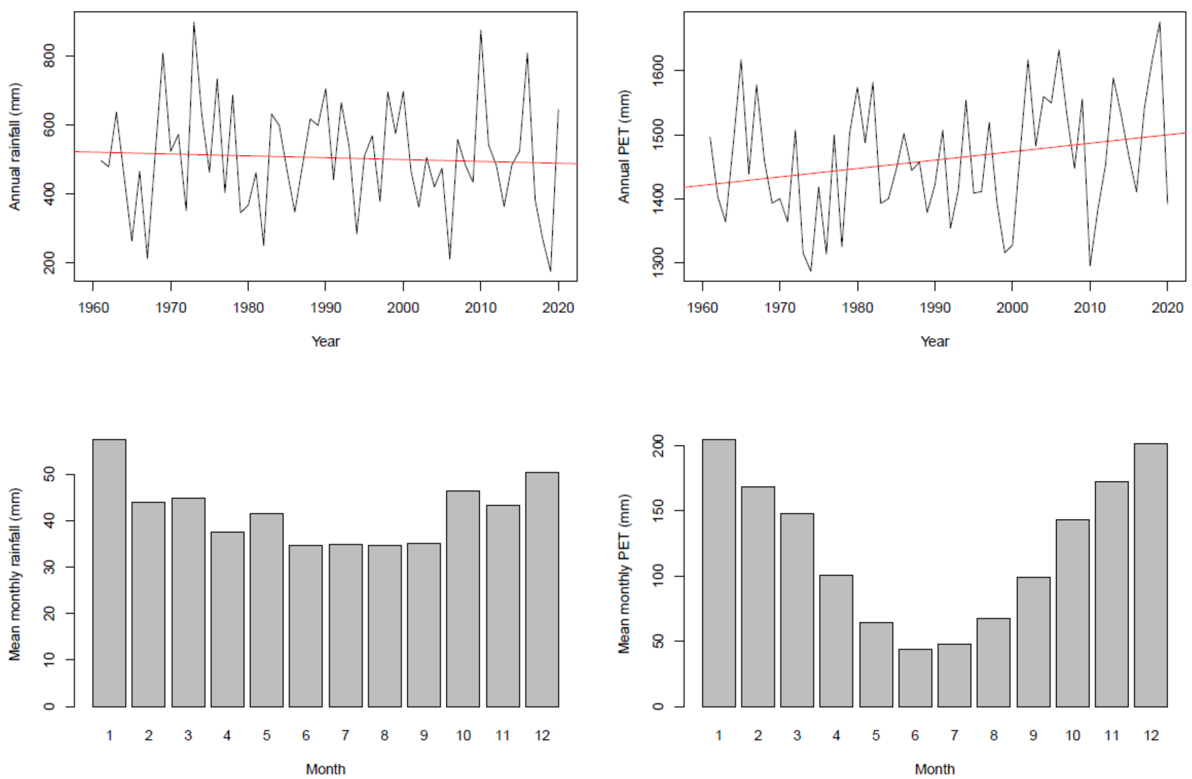
Gwydir Alluvium



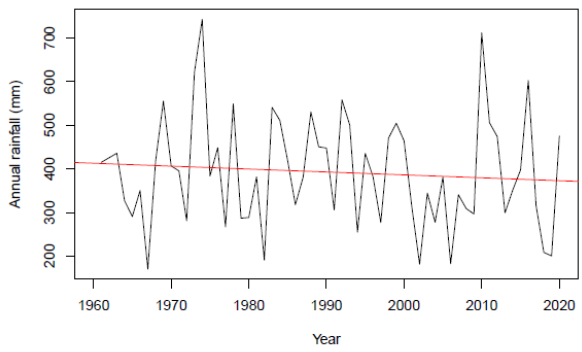
Namoi Alluvium

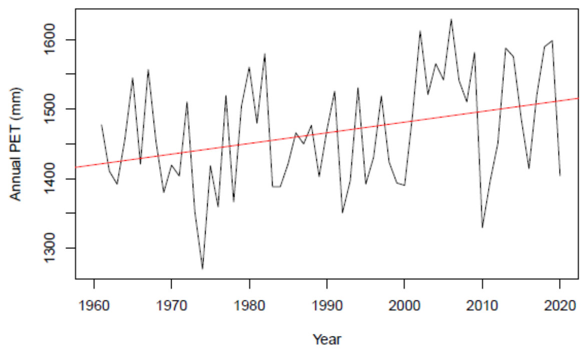


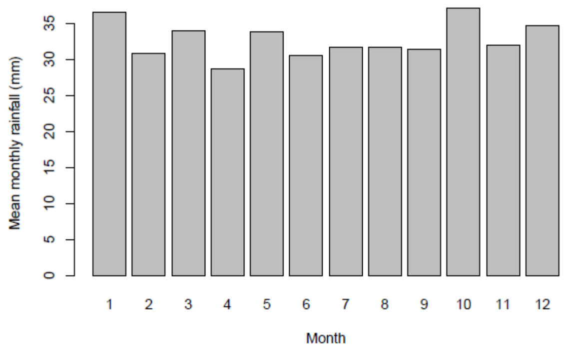
Macquarie Alluvium

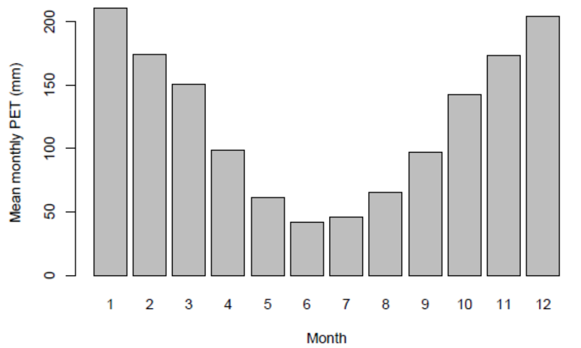


Lachlan Alluvium

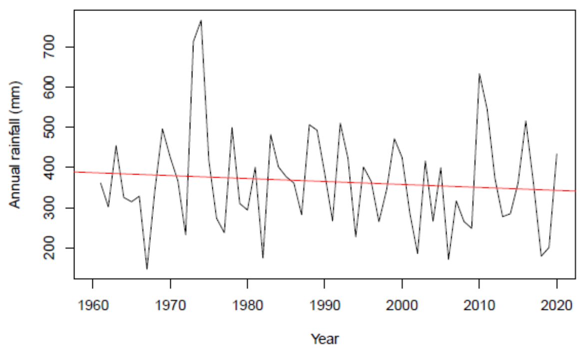


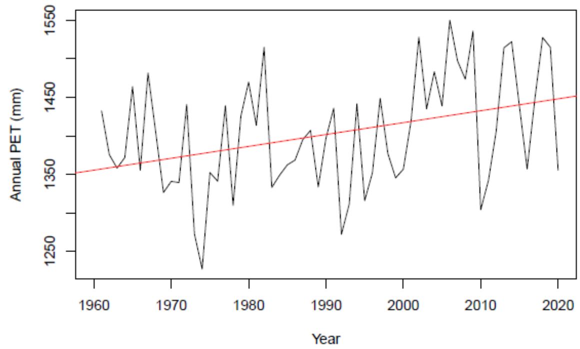


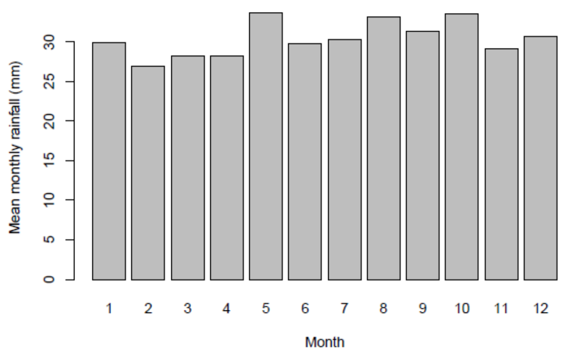


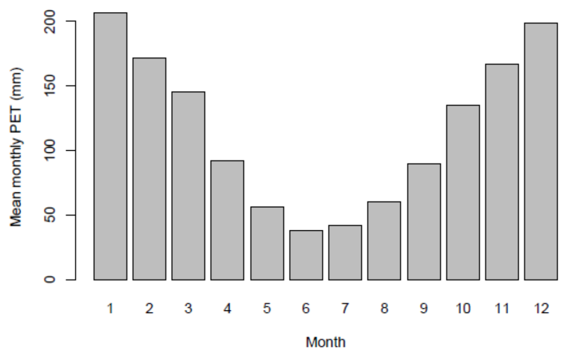


Murrumbidgee Alluvium









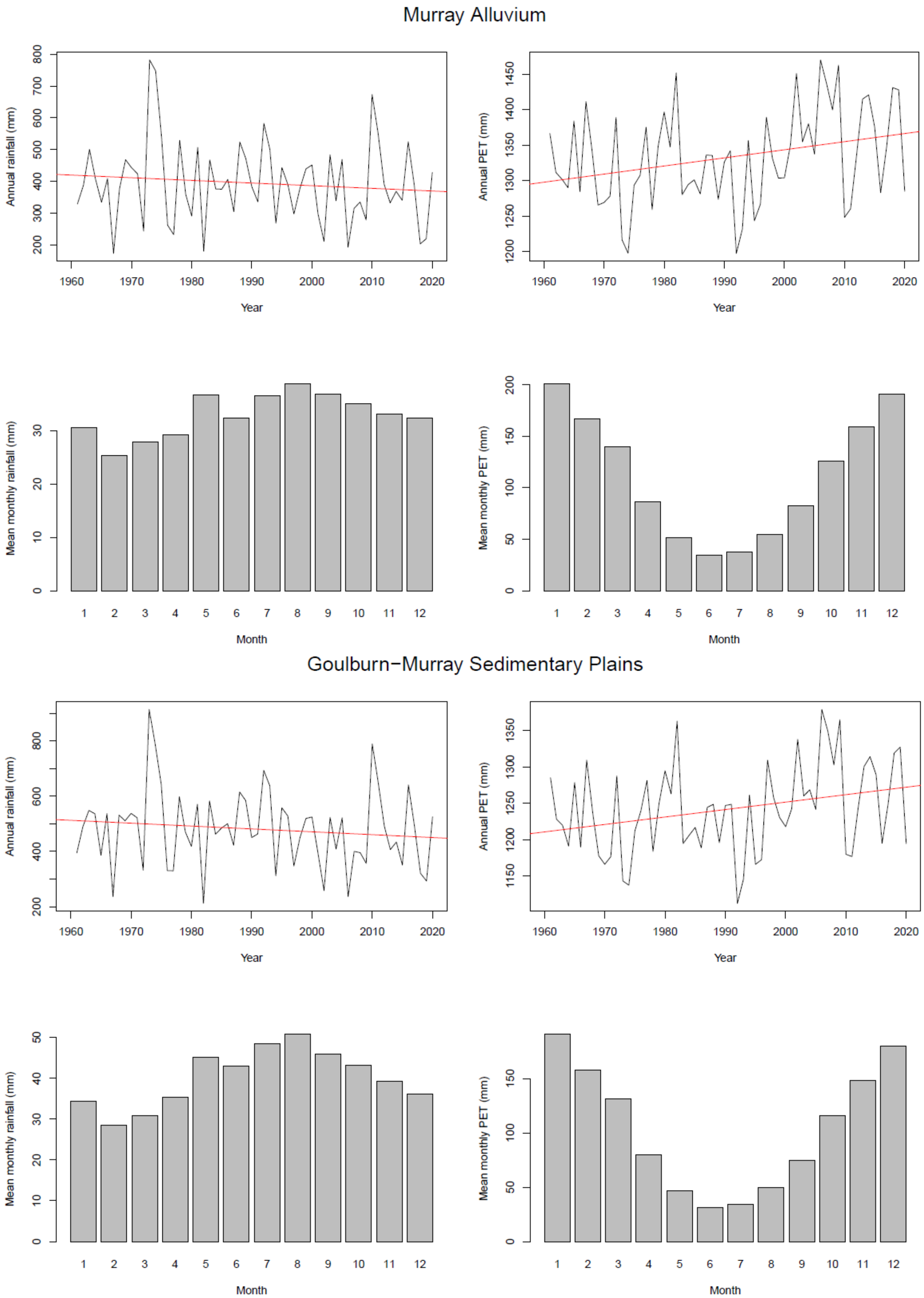


Figure 12 Annual and monthly rainfall and PET in 8 alluvial systems of the MDB (from north to south)

3.3 Groundwater level data preparation

Bore water level data were accessed from the National Groundwater Information System (NGIS) (BoM). The Lower Gwydir Alluvium was selected for testing time series analysis methods and deploying scripts for calculation. These results are preliminary as this is a work in progress.

This alluvial system is conceptualised in 3 layers; the Cubbaroo Formation, overlain by the Gunnedah Formation and then the Narrabri Formation. The Cubbaroo Formation consists of deep, coarse-grained palaeochannels. The Gunnedah Formation extends across the region, is finer grained than the Cubbaroo Formation and is the main extraction target within the Lower Gwydir Alluvium. The Narrabri Formation is a shallow alluvial fan with small, discontinuous sand lenses and varies in quality and yield. Recharge to the alluvial aquifers is rainfall driven, from stream and floodplain recharge, and from irrigation (CSIRO-SKM, 2010).

The following pre-processing steps were applied to the data:

- Filtering to include only bores attributed to the Narrabri formation (HGU 104006) and Gunnedah formation (HGU 109011); these are the main aquifers within the Gwydir Alluvium aquifer group and are reported to be hydraulically connected (CSIRO-SKM, 2010). There were 38 bores in the Narrabri formation and 15 bores in the Gunnedah formation and no record of the Cubbaroo Formation in the NGIS database.
- Standing water level (SWL) records for the Narrabri and Gunnedah formations were extracted resulting in 15027 and 9106 observations over the period of record (20 years) respectively. Filters to exclude relative standing water level (RSWL) measurements and zeros did not remove any records in this region.
- New columns were added to record the year, month and year-month to the dataset.

3.4 Groundwater levels at Gwydir alluvial aquifer

3.4.1 Bore depths

Figure 13 shows the bore depths in the 2 formations of the Gwydir alluvial aquifer, where a clear difference in the distribution of the drilled depths is observed for both formations.

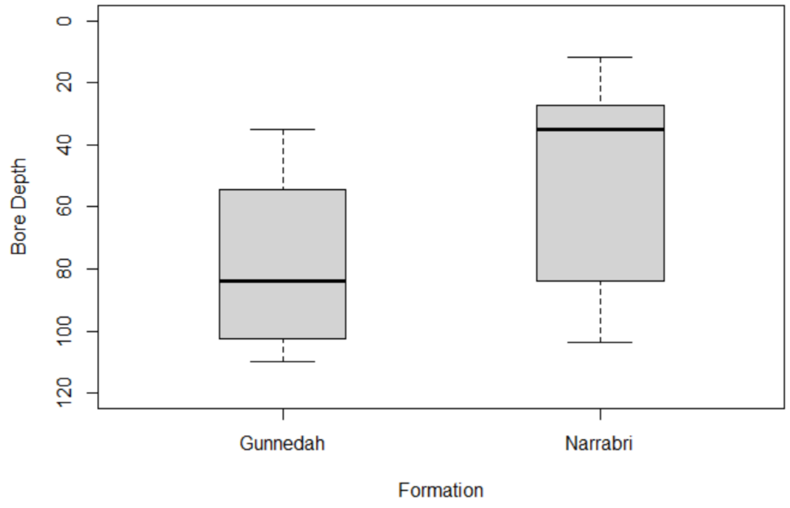


Figure 13 Bore depth from Gunnedah and Narrabri formation at Gwydir alluvial aquifer

3.4.2 Mean standing water level (SWL)

Figure 14 shows the mean standing water level (SWL) in the Gunnedah and Narrabri formations from 15 and 38 bores, respectively. Although the targeted depths are significantly different (Figure 13) for both formations, SWL measurements show Gunnedah and Narrabri formations are hydraulically connected as suggested by CSIRO-SKM (2010).

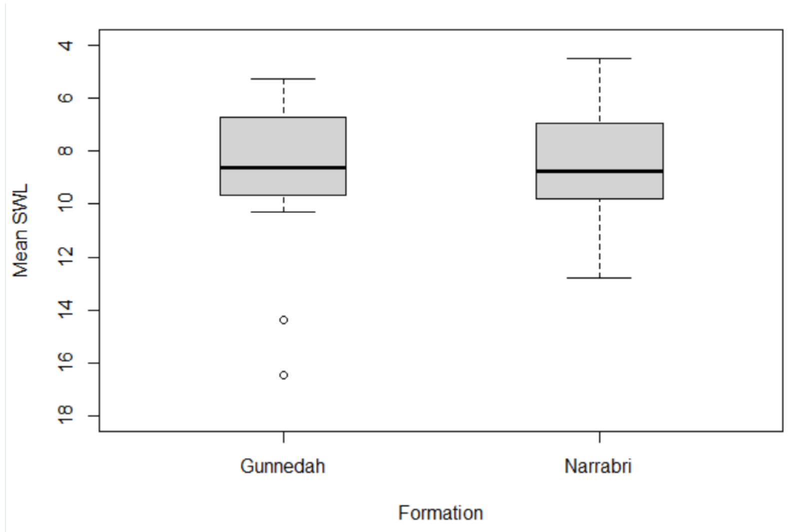
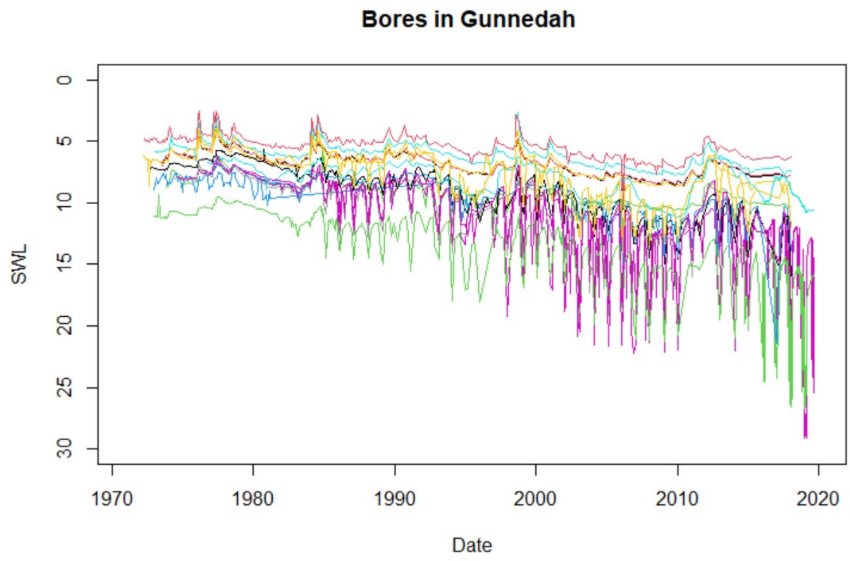


Figure 14 Mean values of standing water level (SWL) for the Gunnedah and Narrabri formations of the Gwydir alluvial aquifer

3.4.3 Preliminary analysis of groundwater level time series

A preliminary examination of groundwater levels provides few insights on the potential challenges we might expect when expanding the analysis to alluvial aquifers of interest in the MDB. This is not exhaustive and represents only a first pass to help refine the proposed methodology. Figure 15 shows the time series of groundwater levels for the selected bores in the Gwydir alluvial aquifer for the period 1973-2020. In general, persistent declining groundwater levels are observed, showing in some cases large fluctuations in groundwater levels between maximum and minimum SWLs, possibly attributable to recharge and discharge peak values. From a preliminary examination, few issues require further analysis:

(a)



(b)

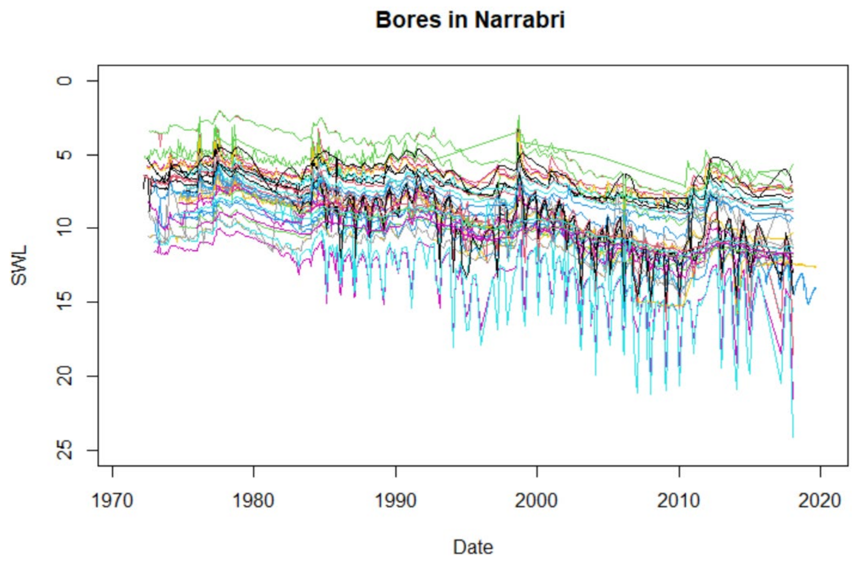


Figure 15 Time series of groundwater levels for bores in the Gunnedah and Narrabri formations of the Gwydir alluvial system

- Figure 11 indicates that nearly 75% of the bores analysed for the Gwydir alluvial system by the Australian Groundwater Insight (20-year period 2000-2020 using method 1, see section 3.1.1), show a stable trend, and only 21% of the bores show a declining trend. Figure 15 seems to contradict this as long-term declining groundwater levels are observed across both formations (Gunnedah and Narrabri) for a large proportion of bores. The causes of this discrepancy are not fully clear and require further analysis;

- groundwater levels are notoriously variable, have sporadic temporal frequency, highly variable lengths of record, and probably limited quality control of the observations. This will require a thorough quality control of bore data and the definition of a specific protocol for selecting bores for the trend analysis;
- groundwater levels are typically influenced by several factors that vary over time, such as rainfall amount and intensity, groundwater abstraction, land use and land cover changes, etc. To address this problem, the BoM developed a method which assesses the trends and status of groundwater levels based on annual recovery peaks, i.e., the maximum level observed in the bore each year due to recharge and/or water level recovery in the non-pumping season. This is useful but cannot reflect the full picture of groundwater level dynamics. Therefore, other metrics such as mean annual groundwater level or minimum groundwater levels are required to improve our understanding of long-term trends in groundwater levels;
- methods 1 and 2 used by the Australian Groundwater Insight report a trend magnitude only. It seems valid to include a statistical test to verify whether the slope is statistically equal to zero for a given confidence level;
- there is potential to expand method 3 to explore the trends at different quantiles by using the innovative trend analysis (ITA) (Dong et al., 2020). At the moment, method 3 simply compares the mean groundwater levels at 2 periods as shown in Figure 10;
- a closer look at groundwater levels might indicate that different formations (or bore depths) might show different trends. This might result in contradicting results of method 1 and 2. This will require a careful automation of the script for deployment at larger scale alluvial aquifers;
- the statistical methods of Fu et al. (2019) will also be potentially applied for attribution analysis, i.e., to explain the main reasons behind groundwater level trends and their respective contributions, thus providing insights on potential processes explaining those trends.

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