

Trends in water use efficiency of wheat in South Australia 1961–2024

Giles Forward¹ and Michael Wurst²

1: Department for Environment and Water

2: Department of Primary Industries and Regions
2026

DEW Technical report 2026/17



**Government
of South Australia**

Department for
Environment and Water

Department for Environment and Water
Government of South Australia
July 2026

81-95 Waymouth St, ADELAIDE SA 5000
Telephone +61 (8) 8463 6946
Facsimile +61 (8) 8463 6999
ABN 36702093234

www.environment.sa.gov.au

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Preferred way to cite this publication

Forward GR, Wurst M (2026). Trends in water use efficiency of wheat in South Australia 1961-2024, DEW Technical report 2026/17, Government of South Australia, Department for Environment and Water, Adelaide.

Foreword

The Department for Environment and Water (DEW) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEW's strong partnerships with educational and research institutions, industries, government agencies, Landscape Boards and the community ensures that there is continual capacity building across the sector, and that the best skills and expertise are used to inform decision making.

Ben Bruce
CHIEF EXECUTIVE
DEPARTMENT FOR ENVIRONMENT AND WATER

Acknowledgements

The water use efficiency (WUE) of wheat calculations for 1982–2020 and the draft report were compiled by Michael Wurst, formerly of PIRSA. Earlier WUE data was generated by Andy McCord and Jan Rowland, formerly of DEW predecessor agencies. Ongoing WUE data since 2021 was appended by Giles Forward, Biodiversity Science, Coasts and Information Branch.

The spatial calculations of monthly rainfall for the cropping districts for 1982–2020 were generated by Trevor Hobbs, Biodiversity Science, Coasts and Information Branch, and from 2021 onwards by Giles Forward, Biodiversity Science, Coasts and Information Branch.

Comments on the draft report were provided by Jeanette Chapman (formerly of DEW), Ruby Hume, Stuart Wright, Tim Herrmann and Andrea Stiglingh, Biodiversity Science, Coasts and Information Branch.

The external peer review was done by Mary-Anne Young, formerly of PIRSA.

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Summary

Crop water use efficiency (WUE) is a measure of the amount of crop yield produced per unit of water available to the plant during the growing season. It is an integrated indicator of soil health and agronomic performance. Examining trends in WUE can assist in the understanding of limiting factors to soil and crop productivity, opportunities for improvement, how these have changed over time, and the impacts on soil health.

This report outlines trends in WUE of wheat production in South Australia (SA) from 1961 to 2024. Two data sets are presented:

- WUE based on ABS wheat production data from the Australian Bureau of Statistics (ABS) 1961 to 2009 (state level), using the original *French-Schultz Model* (French and Schultz 1984a,b)
- WUE using Primary Industries and Regions (PIRSA) crop estimate data 1982 to 2024 (PIRSA crop districts and state level), using a modified water use efficiency model (Wurst unpubl. 2021) adapted from the *French-Schultz Model*.

Water use efficiency of wheat in the state increased overall over the data period from 1961 to 2024. WUE as a 10-year rolling mean (to smooth out year-to-year variations) increased by 115%, from 7.3 kg/ha/mm in 1970 to 15.7 kg/ha/mm in 2024. There was a slight decline in WUE through the 1970s, then a gradual increase through the 1980s and 1990s. A levelling off and slight decline occurred in the 2000s, followed by an increasing trend since around 2010. Much of this increase (84%) occurred since 1992 over the period of the PIRSA-based data.

In the crop districts, wheat WUE increased overall in all districts over the analysis period 1982 to 2024, although the WUE levels and rate of increase varied considerably across districts. WUE (10-year rolling mean) in 2024 was highest in the Yorke Peninsula (YP) district (23.9 kg/ha/mm) with the highest rate of increase since around 2010. The largest absolute increases since 1992 occurred in the YP district (11.7 kg/ha/mm; 95% increase), Lower North (LN) district (11.5 kg/ha/mm; 173%), and the Lower Eyre Peninsula (LEP) district (9.1 kg/ha/mm; 115%). In 2024, the WUE was lowest in the higher rainfall districts of Central Hills and Fleurieu Peninsula (CHFP) (7.5 kg/ha/mm), Kangaroo Island (KI) (8.8) and Lower South East (LSE) (10.7). The validity of WUE calculations for CHFP, KI and earlier years of the analysis period in the LSE is lower due to the relatively low wheat crop area compared to other districts.

The overall increases in WUE over time are due to a combination of improvements in agronomic practices, genetic improvement in wheat varieties, and improved soil management. The variations in WUE across the cropping districts and differing rates of increase can be related to a number of soil, agronomic, and climatic constraints that occur to varying degrees across the districts. For example, the relatively high WUE and high rate of increase in the YP district can be related to minimal soil constraints, relatively reliable rainfall and milder temperatures due to proximity to the coast. In the higher rainfall districts, crop yields and WUE tend to be limited by factors including waterlogging, higher incidence of foliar and root diseases, and higher weed competition. The general increasing trend in WUE probably indicate an overall improvement in soil health.

While these WUE models provide a valuable method to measure crop WUE, some limitations to the models are discussed.

There are opportunities for further improvement in wheat WUE, through better management of constraints where possible, and continued improvement in agronomic and soil management. Some soil constraints can be managed or treated, including liming of acidic soils, applying gypsum to poorly structured sodic soils, and incorporation of clay into water repellent or sandy surface soils. Other constraints such as unfavourable subsoil chemical properties (including high salt, boron, high pH) usually cannot be treated.

1 Introduction

Crop water use efficiency (WUE) is a measure of the amount of crop yield produced per unit of available growing season water. First proposed by French and Schultz in 1984¹ the model is expressed as:

$$\text{WUE (kg/ha/mm)} = \text{Crop yield (kg/ha)} / \text{Available water (mm)}$$

$$\text{Available water} = (\text{Stored soil water} + \text{Growing season rainfall} - \text{Evaporation})$$

Since 1984, modifications to improve estimates of available water have been introduced (refer to Methodology section), but the overall simplicity of the WUE model remains. Assumptions behind these models and supporting data are explained in the Methodology Section.

WUE can be used as an integrative indicator of:

- inherent yield or productive potential of different varieties
- soil constraints to plant water uptake or growth
- agronomic and soil management
- seasonal and climatic conditions
- general soil health.

Examining trends in WUE can assist in the understanding of limiting factors to soil and crop productivity, opportunities for improvement, and how these have changed over time.

According to Sadras and McDonald (2012), WUE relies on:

- the soil's ability to capture and store water
- the crop's ability to access water stored in the soil and rainfall during the season
- the crop's ability to convert water into biomass
- the crop's ability to convert biomass into grain (harvest index).

There are a range of inherent or induced soil constraints (pressures) to crop WUE, but also opportunities to increase WUE by modifying the soil profile or soil properties.

Soil constraints that occur on SA's agricultural soils include:

- soil acidity (inherent and induced)
- subsoil chemical toxicity (high pH, boron, salinity, sodicity)
- water repellence
- low inherent fertility (low cation exchange capacity and ability to store nutrients)
- high phosphorus fixing soils (ironstone soils, calcareous soils)
- soil structural constraints (such as compaction)

¹ French RJ and Schultz JE, (1984a,b)

- susceptibility to waterlogging
- induced soil degradation (e.g. topsoil removal by erosion).

Some of these constraints can be overcome or managed, for example by liming of acid soils, applying gypsum for some soil structural issues, and appropriate fertilizer application.

Soil modification methods (that have longer term effects) that have the potential to increase WUE include:

- clayey of sandy or water repellent sandy soils (by delving, spreading, spading)
- deep ripping (can include deep placement of organic or other amendments such as lime, gypsum).

The main agronomic factors that affect crop WUE include plant diseases, weeds and plant nutrition (fertilizer application).

Weather events can have a significant effect on crop WUE by reducing actual yield, including the timing and amount of rainfall, frost, heat stress on plants, and storm or wind damage to plants.

Wheat was chosen for this study as it is the most widespread crop grown in SA, particularly in low to medium rainfall zones, and therefore has the largest data set to provide best representation of crop WUE trends.

Two data sets of wheat WUE in SA are presented in this report:

1. WUE based on Australian Bureau of Statistics wheat production data 1961 to 2009 (state level)
2. WUE using Primary Industries and Regions SA crop estimate data 1982 to 2024 (PIRSA crop districts and state level).

1.1 Report purpose

This report documents:

- WUE trends for wheat production in SA, combining two data sets to assess long term trends
- soil, agronomic, weather, and related factors that have affected wheat WUE over time and across agricultural districts
- opportunities to address WUE constraints.

2 Methodology

2.1 State WUE 1961 to 2009 based on ABS production data

An initial analysis of wheat WUE was conducted by DEW predecessor agencies (McCord and Payne 2004) using wheat production data obtained from the Australian Bureau of Statistics (ABS) Agricultural Census and Agricultural Surveys for 1961 to 2009 [Agriculture | Australian Bureau of Statistics \(abs.gov.au\)](https://www.abs.gov.au). During this period, annual crop production estimates were reported for Statistical Divisions (and lower order Statistical Local Areas), which to some degree approximately align with agricultural region boundaries in SA.

In 2009, the ABS changed its geographic reporting framework hence collection of ABS wheat production data by DEW was discontinued.

Gridded monthly rainfall data was obtained from the Bureau of Meteorology (BoM). This was spatially processed for cleared agricultural land areas within the ABS geographical units.

WUE was calculated using the original *French-Schultz* model (French and Schultz 1984a,b). This estimated plant available water (PAW) using:

- growing season rainfall (GSR) = April to October rainfall inclusive
- available water (AW; stored out of season soil moisture)
 - add 25% January rainfall above 20 mm
 - add 33% February rainfall above 20 mm
 - add 50% March rainfall above 20 mm
- evaporation (E) = 110 mm.

$$\text{PAW} = \text{GSR} + \text{AW} - \text{E}$$

$$\text{WUE (kg/ha/mm)} = \text{Yield achieved per ha} / \text{PAW}$$

WUE for the state was calculated by area-weighting WUE data for the Statistical Divisions (SD), using the estimated area sown in the SD each year:

$$\text{State WUE} = \{ \text{WUE}(\text{SD}_1) * \text{ha}(\text{SD}_1) / \text{ha}(\text{SD}_{\text{total}}) + \text{WUE}(\text{SD}_2) * \text{ha}(\text{SD}_2) / \text{ha}(\text{SD}_{\text{total}}) + \dots + \text{WUE}(\text{SD}_n) * \text{ha}(\text{SD}_n) / \text{ha}(\text{SD}_{\text{total}}) \}$$

2.2 PIRSA crop district and state WUE 1982 to 2024 based on PIRSA production data

2.2.1. Production data

More recently, an analysis of wheat WUE has been conducted using PIRSA production data 1982 to 2024 obtained from the crop harvest estimates [PIRSA Crop and pasture reports](#) (Wurst 2021 unpubl.).

The crop harvest estimates provided an estimate of the area sown and the production of each crop in SA since the 1960s. These were based on knowledge of a network of regional agronomists, advisers and consultants, who provide estimates based on seasonal and economic conditions affecting production. From 1982, crop area and production estimates were reported on a district basis with districts based on collection of Local Government Areas. Some changes to crop district boundaries such as mergers have occurred over this period (Appendix D). Current PIRSA crop districts are shown in Figure 2.1.

State WUE was calculated by area weighting district WUE data according to the estimated area of wheat each year (as per the method described above for the ABS-based data). In seasons where low rainfall (failed crops), frost or storm damage reduce the area of sown crops that are harvested for grain, the crop area estimates are adjusted (reduced) accordingly (PIRSA pers. comm.).

There is a temporal overlap of these two data sets (Section 2.1 and 2.2) through 1983 to 2009, and a regression analysis was conducted to assess agreement of the two methods.

Both data sets were combined at the state level to reveal longer term trends in wheat WUE.

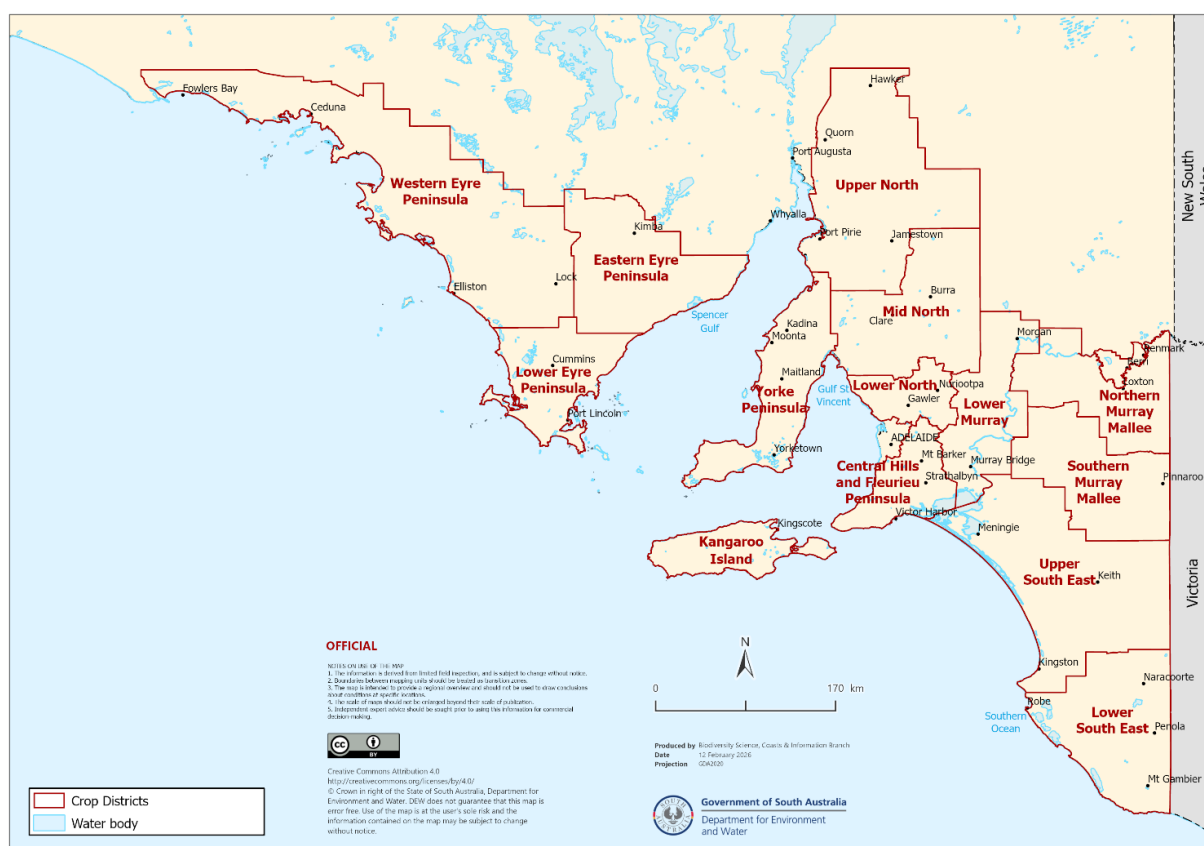


Figure 2.1. PIRSA crop districts

2.2.2. Rainfall data

BoM gridded monthly rainfall was spatially analysed to estimate average rainfall for dryland cropping land within each crop district (Wurst 2021 unpubl.).

Growing season rainfall

The calculation of growing season rainfall (GSR) included an adjustment for the different crop districts according to the relative length of average growing season for wheat. This was based on expert opinion and local experience of PIRSA staff. The percentage of October and November rainfall included in the estimation of GSR is shown in Table 2.1.

Table 2.1. Percentage of monthly rainfall included in GSR calculation, and nominal soil texture class for evaporation estimates in the modified WUE model for crop districts

Region/district	Growing season rainfall calculation for modified WUE model			
	Percentage (%) of monthly rainfall included			Nominal soil texture class (evaporation estimate)
	April–September	October	November	
Eyre Peninsula				
Western EP	100%	30%	0%	Sandy loam
Eastern EP	100%	100%	0%	Sandy loam
Lower EP	100%	50%	0%	Light sandy clay loam
Northern and Yorke				
Upper North	100%	50%	0%	Light sandy clay loam
Mid North	100%	100%	0%	Loam
Lower North	100%	70%	0%	Light sandy clay loam
Yorke Peninsula	100%	60%	0%	Sandy loam
Central				
Central Hills & Fleurieu Peninsula	100%	100%	0%	Loam
Kangaroo Island	100%	100%	0%	Light sandy clay loam
Murraylands				
Northern Murray Mallee	100%	0%	0%	Sandy loam
Southern Murray Mallee	100%	30%	0%	Sandy loam
Lower Murray	100%	50%	0%	Light sandy clay loam
South East				
Upper South East	100%	100%	0%	Sandy loam
Lower South East	100%	100%	50%	Clay loam

Stored rainfall

The modified WUE model estimates the amount of summer-autumn rain that can potentially be stored in the soil profile as plant available water and be used by the subsequent crop as:

- add 25% November rainfall above 20 mm
- add 25% December rainfall above 20 mm
- add 25% January rainfall above 20 mm

- add 33% February rainfall above 20 mm
- add 50% March rainfall above 20 mm.

The remaining October rainfall not included as growing season rainfall for the various districts as above is not added to stored rainfall, as it is considered that it would almost always be lost via evaporation (PIRSA pers. comm.).

2.2.3. Evaporation data

The evaporation or water loss factor derived by Sadras et al. (2003) was used for these calculations. This was based on a method developed by Victor Sadras (PIRSA–SARDI), using the Agricultural Production Systems SIMulator (APSIM) model.

This method estimates evaporation using the nominal major topsoil texture in each PIRSA crop district (Table 2.1). The evaporation value is adjusted according to the total growing season + stored rainfall (such that the evaporation estimate increases with higher total rainfall) up to a recognised maximum evaporation value for the soil texture class.

This modification overcomes the limitations of using a standard 110 mm for evaporation as in the 1984 French-Schultz model (French & Schultz 1984 a,b), which is an overestimate for lower rainfall seasons in many cropping districts.

3 Results

3.1 State trends in wheat water use efficiency

An overlay of the 1982 to 2024 state WUE data (PIRSA-based data) with the earlier 1961 to 2009 WUE data (ABS-based data) as a 10-year rolling mean shows an overall increasing long-term trend in wheat WUE (Figure 3.1). From 1970 to 2024, wheat WUE increased in the state by 115% (8.4 kg/ha/mm), from 7.3 kg/ha/mm in 1970 to 15.7 kg/ha/mm in 2024. The PIRSA-based data shows an 84% (7.2 kg/ha/mm) increase in WUE since 1992.

The ABS-based data shows a slight decline in WUE through the 1970s, then a gradual increase through the 1980s. Both data sets indicate a continuing increasing trend in WUE through the 1990s until a levelling and slight decline in the 2000s. The PIRSA-based data then shows a strong increasing trend in WUE from around 2010 to 2024.

The WUE data in this Section is mostly presented as a 10-year rolling mean to effectively smooth out year-to-year variations in WUE, and reveal longer term trends.

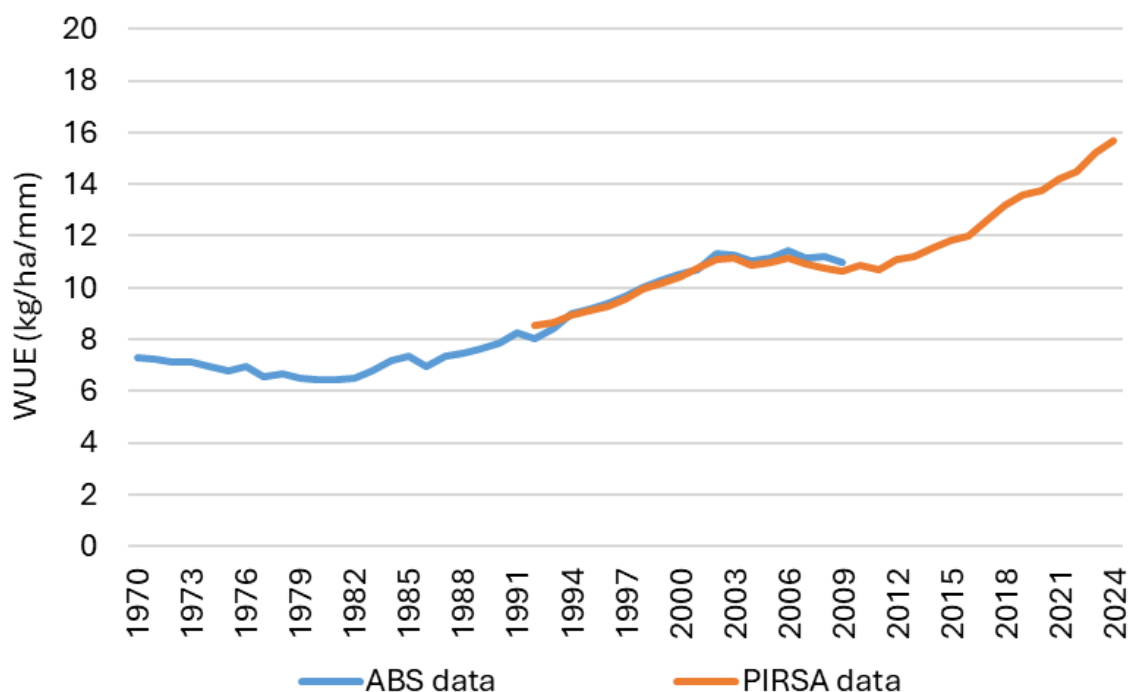


Figure 3.1. Water use efficiency of wheat in SA (10-year rolling mean), showing ABS-based data 1970–2009 (blue line) and PIRSA-based data 1992–2024 (orange line)

There is considerable fluctuation in the annual WUE (Figure 3.2). In medium to lower rainfall areas (i.e. less than 500 mm per annum), higher WUE (modified WUE model) usually tends to be achieved in below average rainfall years when soil moisture is the likely yield-limiting factor, and there is less evaporation from the soil surface. Conversely, there is usually lower WUE in above average rainfall years, where a proportion of the rain and soil moisture may not be utilised by plants (through waterlogging, surface runoff, drainage below the rootzone, and evaporation loss), and because other factors can become yield-limiting such as shortage of nitrogen (N) supply to plants, and inherent soil constraints.

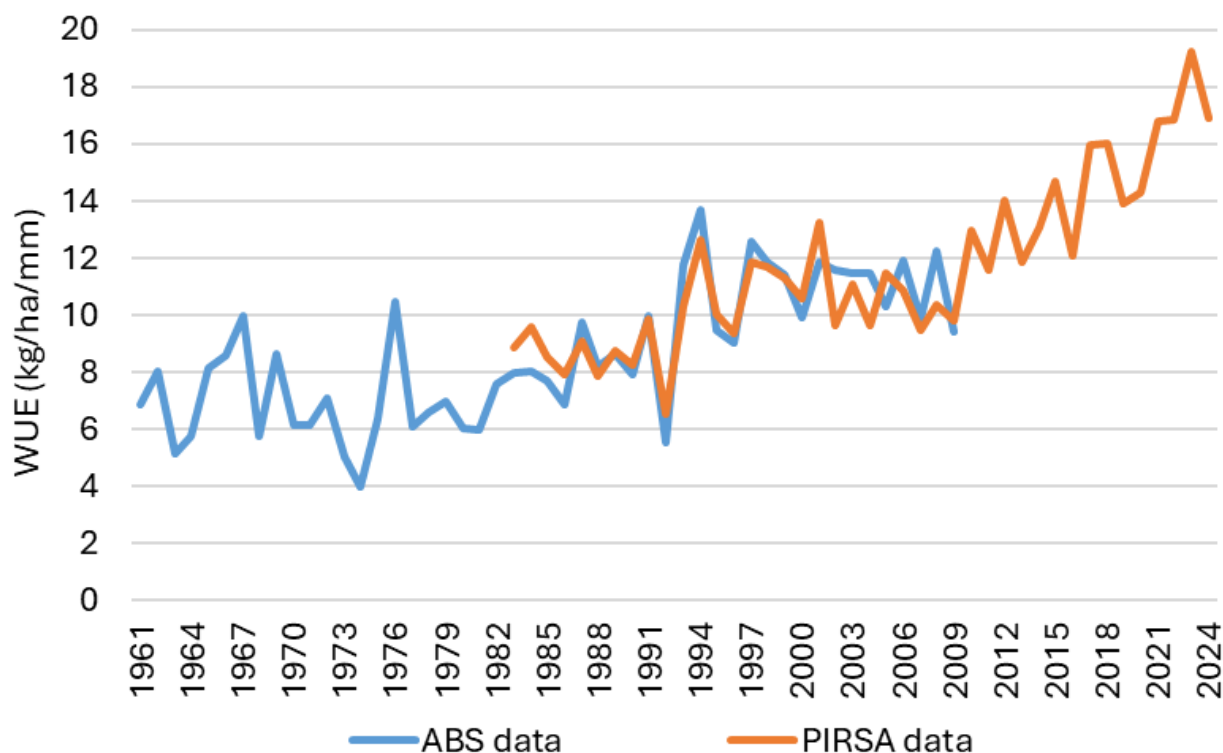


Figure 3.2. Water use efficiency of wheat in SA (annual), showing ABS-based data 1970–2009 (blue line) and PIRSA-based data 1992–2024 (orange line)

A linear regression analysis of the period of overlap in the two data sets (1983 to 2009, annual data) shows good agreement in WUE for the state (R^2 0.747) (Figures 3.3, 3.4). This indicates the ABS production data method is a satisfactory measure of historic WUE despite its relative limitations (Section 2.1).

The upward trend in wheat WUE for the state since the early 1980s has been achieved while there has been a slight declining trend in ‘growing season’ (April to October) rainfall within the analysis period (decreased by 26.5 mm in the past 50 years). There was an approximately corresponding increasing trend in ‘out of season’ (November to March) rainfall which increased by 25.1 mm in the past 50 years (Figure 3.4). The declining trend in ‘growing season’ rainfall is likely to continue in coming decades due to climate change (DEW 2022). In contemporary cropping systems, rain in the summer-autumn months prior to cropping is more commonly ‘conserved’ in the soil profile, mostly by chemical weed control, and has the potential to be used (at least partially) by the following crop.

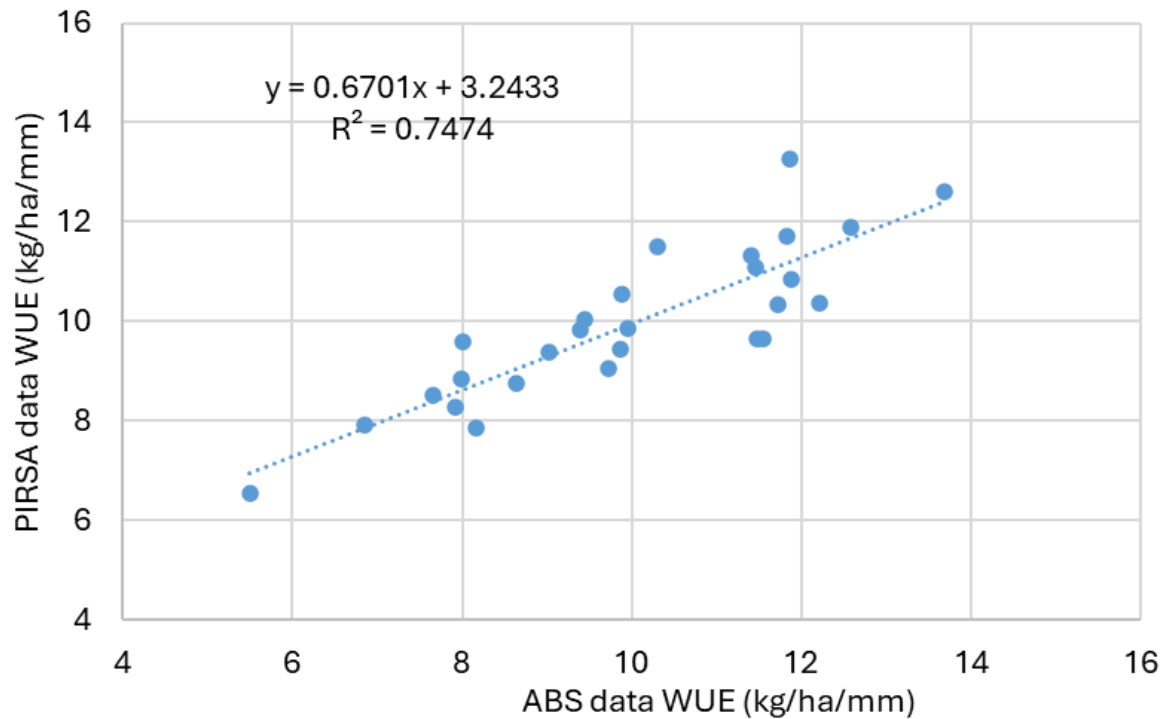


Figure 3.3. Linear regression of annual wheat water use efficiency in SA 1983–2009 comparing ABS-based data with PIRSA-based data

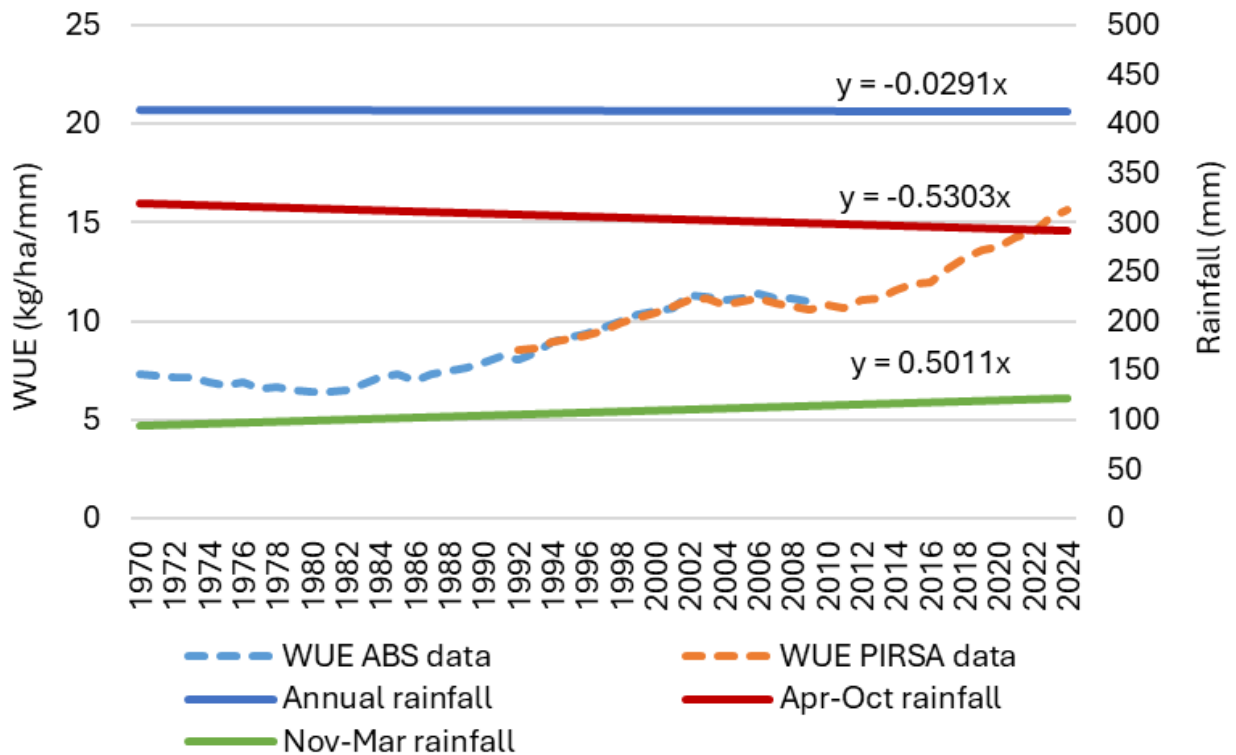


Figure 3.4. Trend in annual wheat water use efficiency in SA 1970–2024 (10-year rolling mean) with linear trends of total annual rainfall, 'growing season' (April–October) rainfall and 'out of season' (November–March) rainfall 1970–2024 for cropping land in the agricultural zone

3.2 District trends in water use efficiency

A summary of the values and trends in WUE for PIRSA crop districts and the state for the period 1991 to 2024 (10-year rolling mean) is shown in Table 3.1. This highlights that the highest WUE in 2024 was in the Yorke Peninsula (YP) district (23.9 kg/ha/mm). The largest absolute increase since 1991 occurred in the YP district (11.7 kg/ha/mm), followed by the Lower North (LN) (11.5), and Lower Eyre Peninsula (LEP) (9.1 kg/ha/mm). The largest percentage increase in WUE since 1991/92 was in the LN district (173%), followed by Kangaroo Island (KI) (158%), and increases of 100% or more in the LEP, Mid North (MN) and Lower Murray (LM) districts. The smallest increase occurred in the Northern Murray Mallee (NMM) district (43%).

The large variation in the WUE values and magnitude of WUE trends across the crop districts is highlighted in Figure 3.5. Details for each regional district are discussed within Sections 3.2.1–3.2.5.

Table 3.1. Summary of wheat WUE results (PIRSA-based data) for crop districts and the state, 1991 to 2024 (10-year rolling mean)

Region/District	WUE (10-year rolling mean; 1991/1992–2024)						
	WUE trend ^b	Year of lowest	Year of highest	1991 (1992) ^a (kg/ha/mm)	2024 (kg/ha/mm)	Change (kg/ha/mm)	Change (%)
Eyre Peninsula							
Western EP	↗↔↗	1996	2024	7.9	13.0	5.2	66
Eastern EP	↗↔↗	1991	2024	8.1	15.6	7.5	92
Lower EP	↗	1992	2024	7.9	17.0	9.1	115
Northern and Yorke							
Upper North ^a	↔↗	1993	2024	9.0	13.9	4.8	53
Mid North ^a	↗	1992	2024	8.2	16.6	8.4	103
Lower North ^a	↗	1992	2024	6.6	18.1	11.5	173
Yorke Peninsula ^a	↗↔↗	1992	2024	12.2	23.9	11.7	95
Central							
Central Hills & Fleurieu Peninsula	↔↗	1995	2024	3.8	7.5	3.6	94
Kangaroo Island	↗↔↗	1992	2024	3.4	8.8	5.4	158
Murraylands							
Northern Murray Mallee	↗↔↗	1993	2021	11.6	16.5	4.9	43
Southern Murray Mallee	↗↔↗	1995	2024	9.3	15.0	5.7	62
Lower Murray ^a	↔↗↔↗	1992	2024	7.9	15.7	7.9	100
South East							
Upper South East	↗↔	1991	2024	6.6	11.1	4.5	67
Lower South East	↗↔↗	1992	2024	5.5	10.7	5.2	95
State^a	↗↔↗	1992	2024	8.5	15.7	7.2	84

a. Data began in 1983 (10-year rolling mean data began in 1992); all other district data began in 1982 (10-year rolling mean data from 1991).

b. ↗ = increasing; ↔ = stable; ↘ = decreasing

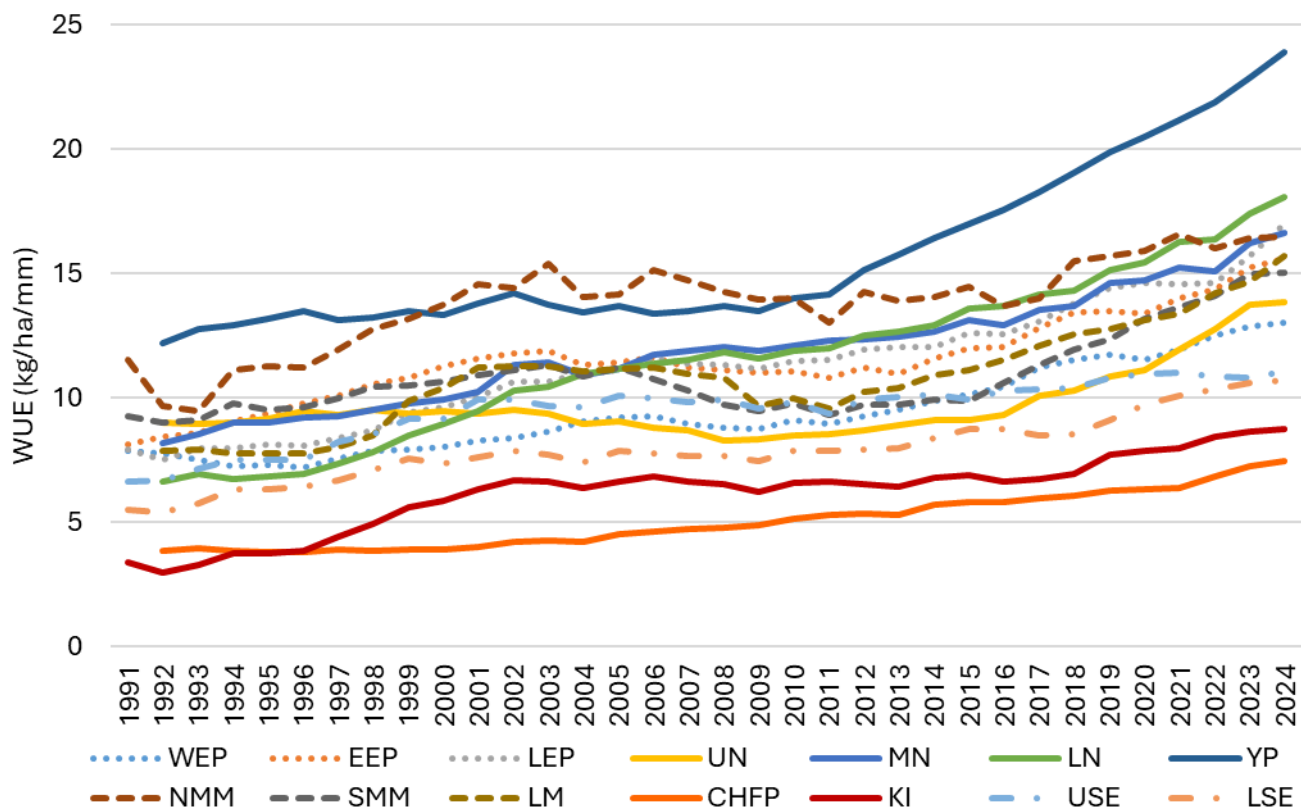


Figure 3.5. Water use efficiency of wheat as a 10-year rolling mean (1991–2024) for each of the SA crop districts: Western Eyre Peninsula (WEP), Eastern Eyre Peninsula (EEP), Lower Eyre Peninsula (LEP), Upper North (UN), Mid North (MN), Lower North (LN), Yorke Peninsula (YP), Northern Murray Mallee (NMM), Southern Murray Mallee (SMM), Lower Murray (LM), Central Hills and Fleurieu Peninsula (CHFP), Kangaroo Island (KI), Upper South East (USE), and Lower South East (LSE)

3.2.1. Eyre Peninsula

Water use efficiency has steadily increased in the Eyre Peninsula cropping districts since 1991, when it was around 7–8 kg/ha/mm (Figure 3.6). In all districts WUE increased up to the early 2000s then levelled out or declined slightly up to around 2010, then increased up to 2024.

The WUE on Western Eyre Peninsula (WEP) increased to 13.0 kg/ha/mm by 2024, while Eastern Eyre Peninsula (EEP) and LEP had reached 15.6 and 17.0 kg/ha/mm respectively. From 2018 to 2020, WUE in all three districts tended to level off or decline, but then increased after 2020.

The WUE in WEP increased by 66% (5.2 kg/ha/mm) from 1991 to 2024, compared to larger increases of 92% (7.5 kg/ha/mm) in EEP and 115% (9.1 kg/ha/mm) in LEP.

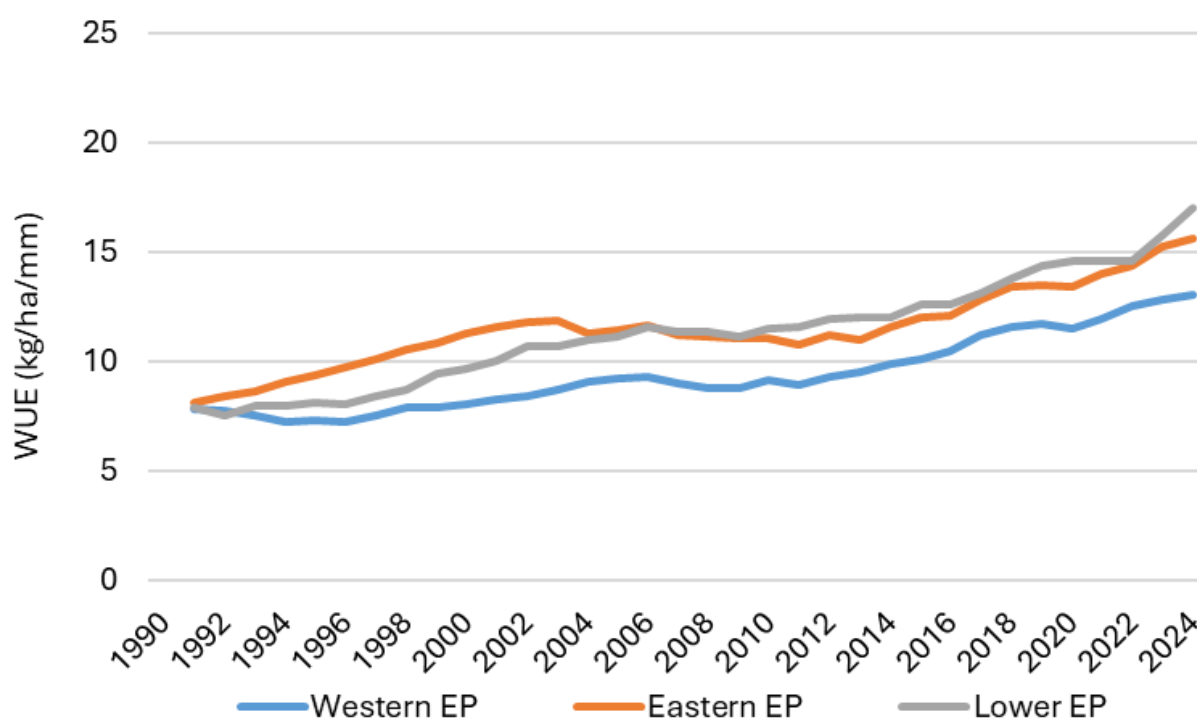


Figure 3.6. Wheat water use efficiency in Eyre Peninsula crop districts, 10-year rolling mean, 1991–2024

3.2.2. Northern and Yorke

There have been marked differences in WUE values and trends across the cropping districts in the Northern and Yorke region since 1992 (Figure 3.7).

The YP district had a relatively minimal increase in WUE from 12.2 kg/ha/mm in 1992 to 13.5 kg/ha/mm in 2009, but since then had a rapid increase to 23.9 kg/ha/mm in 2024. The annual WUE has remained above 20 kg/ha/mm since 2017, peaking at 30.7 in 2024.

The MN and LN had similar, steady increases in WUE. In the MN, WUE increased from 8.2 kg/ha/mm in 1992 to 16.6 kg/ha/mm in 2024. In the LN, WUE started at 6.6 kg/ha/mm in 1992, increasing to 18.1 kg/ha/mm in 2024.

In the Upper North (UN), WUE was 9.0 kg/ha/mm in 1992 and remained within the range 9.0–9.5 kg/ha/mm up to around 2003. It then declined to a low of 8.3 kg/ha/mm in 2008 before gradually increasing to 13.9 kg/ha/mm in 2024.

The UN district had a relatively small overall increase in WUE of 54% (4.8 kg/ha/mm) from 1991 to 2024, whereas WUE in the MN district increased by 103% (8.4 kg/ha/mm) and in the LN district by the highest percentage increase of 173% (11.5 kg/ha/mm) over the same period (Table 3.1). The YP district had the highest absolute increase in WUE of 11.7 kg/ha/mm (95%) from 1991 to 2024.

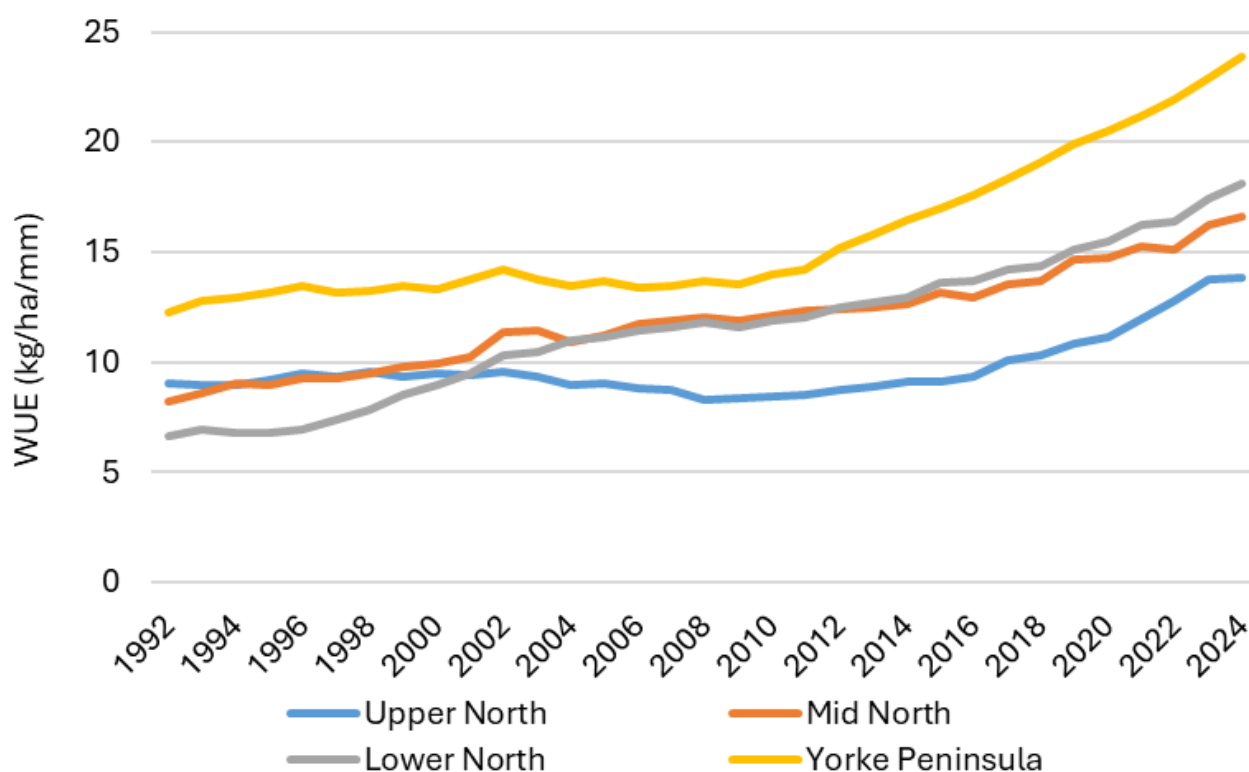


Figure 3.7. Wheat water use efficiency in Northern and Yorke crop districts, 10-year rolling mean, 1992–2024

3.2.3. Central

In the Central Hills and Fleurieu Peninsula (CHFP), and KI districts, WUE has been relatively low, although increasing overall since 1991 (Figure 3.8).

In the CHFP district, the area of land cropped to wheat has been relatively low throughout the analysis period. This ranged from about 3000 to 9000 ha (mean 6100 ha), and was only 2.5% (mean) of the area of cleared land, compared to a mean of 21% across all districts (Appendix E). Using this limited data size, the WUE was 3.8 kg/ha/mm in 1991, steadily increasing to 7.5 kg/ha/mm in 2024.

On KI, the area cropped with wheat was very low (<1000 ha) prior to 1996, and only increased to around 4000 to 6000 ha since then. The mean area of land cropped for wheat as a percentage of cleared land since 1982 was only 2.0% (Appendix E). This limited size WUE data showed an increase from 3.4 kg/ha/mm in 1992 to around 6.5–7.0 kg/ha/mm over the period from 2002 to 2018, increasing to 8.8 kg/ha/mm in 2024.

While WUE has increased by 94% (3.6 kg/ha/mm) in the CHFP district, and by 153% (5.4 kg/ha/mm) on KI from 1991 to 2024, the overall WUEs in these districts remain the lowest of all districts in SA.

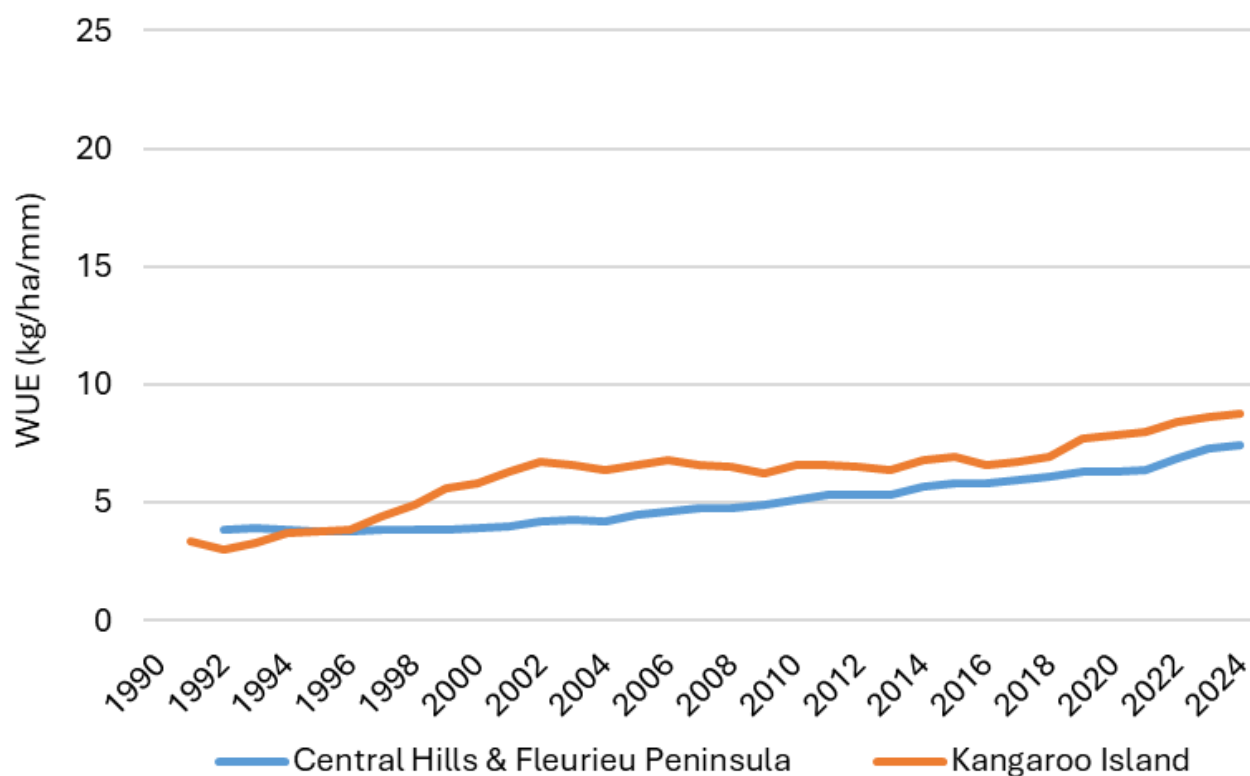


Figure 3.8. Wheat water use efficiency in Central Hills and Fleurieu Peninsula district and Kangaroo Island, 10-year rolling mean, 1991–2024

3.2.4. Murraylands/Mallee

In the Murraylands region, there have been moderate increases in WUE in all crop districts since 1991 (Figure 3.9).

The NMM district consistently had the highest WUE in this region. It increased from 11.5 kg/ha/mm in 1991 to 15.4 kg/ha/mm in 2003, levelling off to around 13–15 kg/ha/mm up to 2017, then increased slightly to 16.5 kg/ha/mm in 2024. The overall 10 year rolling mean WUE values were affected by a high calculated annual WUE of over 20 kg/ha/mm during most of the driest seasons, particularly 1982, 1994, 2006 and 2018.

The level and trends in WUE in the LM and Southern Murray Mallee (SMM) districts were relatively consistent over this period, particularly since 2000.

The WUE in the SMM was 9.3 kg/ha/mm in 1991, and this gradually increased to around 10–11 kg/ha/mm in the early 2000s before declining to 9.7 kg/ha/mm in 2011. Thereafter, the WUE has increased to 15.0 kg/ha/mm in 2024.

In the LM district, the WUE started slightly lower at 7.9 kg/ha/mm in 1992, increased to around 11 kg/ha/mm in the early 2000s, and then decreased to 9.6 kg/ha/mm in 2011. The WUE then increased to 15.7 kg/ha/mm in 2024.

The overall increase in WUE from 1992 to 2024 in the LM district was 100% (7.9 kg/ha/mm); 62% (5.7 kg/ha/mm) in the Southern Murray Mallee, and 43% (4.9 kg/ha/mm) in the NMM (both from 1991 to 2024).

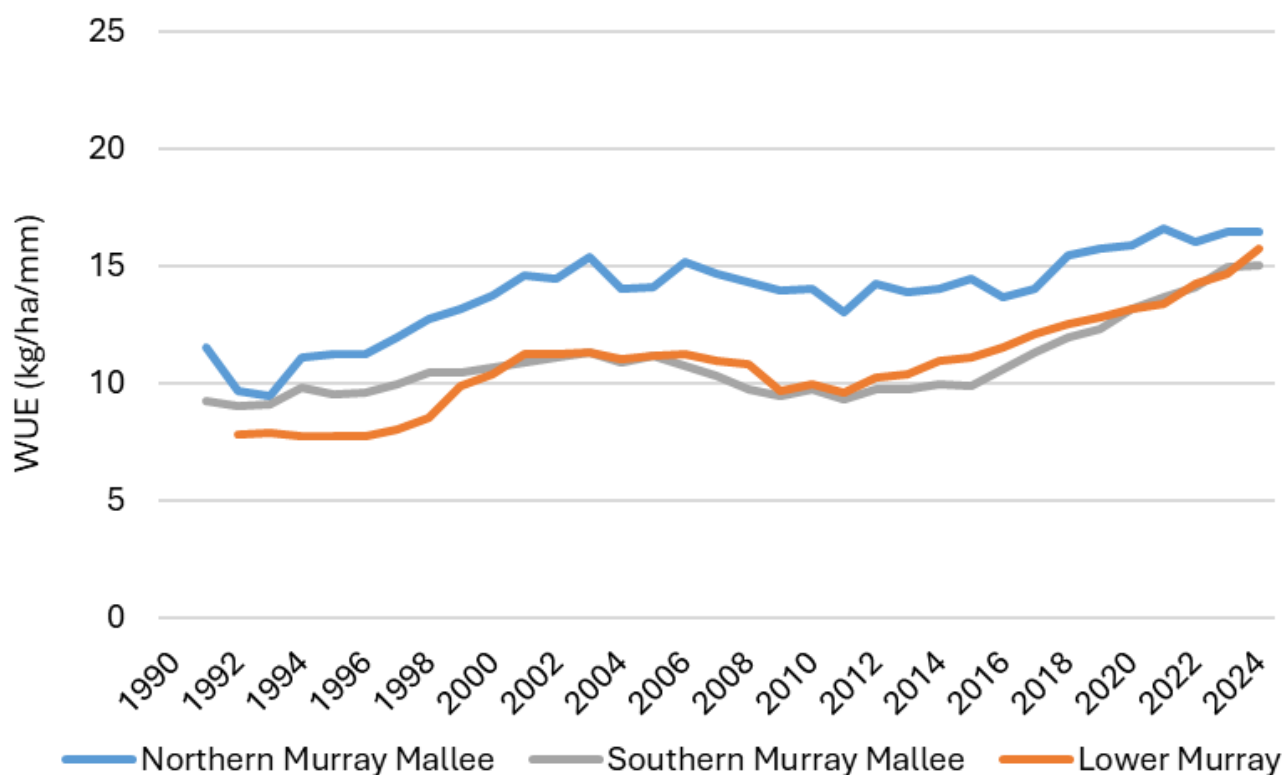


Figure 3.9. Wheat water use efficiency in Murraylands/Mallee crop districts, 10-year rolling mean, 1991–2024

3.2.5. South East

In the South East region, WUE in the Upper South East (USE) crop district was slightly higher than the Lower South East (LSE) district throughout the data period (Figure 3.10). The WUE has steadily, although slowly, increased in both districts over this period.

In the USE district, the WUE was 6.6 kg/ha/mm in 1991, increasing to 11.1 kg/ha/mm in 2024, with much of the increase occurring prior to 2001. The WUE was fairly steady around 10 kg/ha/mm from 2001 to 2015.

The WUE in the LSE district was 5.5 kg/ha/mm in 1991, and increased slightly through the 1990s before steadying at around 7.5 in the early 2000s. There was a further slight increase after 2009 to 10.7 kg/ha/mm in 2024. The area cropped with wheat in this district was comparatively low in the earlier years of this analysis, with a mean of approximately 6,000 ha from 1982 to 1998, then increased to around 15,000 to 25,000 ha since 1998. The mean area of land sown to wheat as a percentage of cleared land was only 1.7%, compared to 21% for the mean of all districts (Appendix E).

Both of these districts had similar increases in WUE from 1991 to 2024. In the USE, the increase was 67% (4.5 kg/ha/mm), and in the LSE was 95% (5.2 kg/ha/mm).

However, as with the higher rainfall Hills and Fleurieu Peninsula and KI districts, the WUE was relatively low in the South East districts, compared to remaining SA agricultural cropping districts.

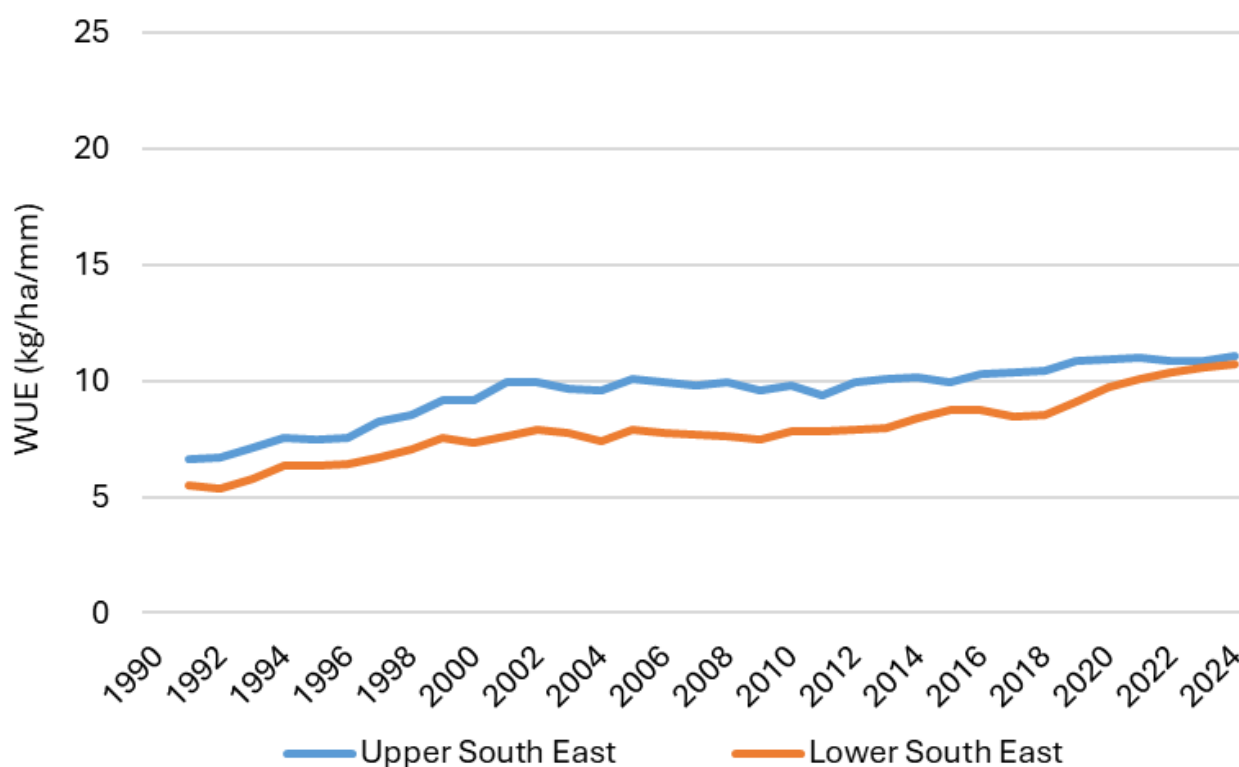


Figure 3.10. Wheat water use efficiency in South East crop districts, 10-year rolling mean, 1991–2024

4 Discussion

4.1 Water use efficiency results

4.1.1. Agreement between the two WUE data sets

The regression analysis of the overlap period for the two WUE data sets (1983–2009, annual data) for the state showed reasonably good agreement (R^2 0.747; Figure 3.3 and 3.4). This indicates the ABS-based WUE can be considered a comparable measure to the PIRSA-based WUE, and that these can be combined with reasonable confidence to show longer term trends.

Nonetheless, the modified water use efficiency model and method used for estimation of WUE with the PIRSA production data is more accurate than the standard French-Schultz Model used with the ABS production data due to:

- the time period that ‘growing season rainfall’ is calculated is adjusted for individual crop districts according to the average annual rainfall and typical length of time annual crops grow (germination to senescence), compared to just April–October rainfall with the standard French–Schultz model.
- ‘available soil water’ from rainfall in the November–March period preceding the crop season is more accurately estimated.
- evaporation for the growing season is estimated using the APSIM model and adjusted according to the dominant soil texture type in the crop district, and for the total available rainfall for the season by district (rather than the standard 110 mm with the standard French–Schultz model).

4.1.2. Trends in WUE

There was an overall increase in wheat WUE (10-year rolling mean) of 84% (7.2 kg/ha/mm) since 1991 for the state (agricultural zone), with all districts showing an upward trend of varying degrees. This is likely due to improvements in a range of factors that affect WUE including improved wheat variety genetics, improved weed, pest and disease control, improved nutrition, earlier sowing, improved soil management, and soil modification in some places.

While there was an overall increasing trend in WUE, there was a marked levelling off and slight decline in the early 2000s (10-year rolling mean period 2003–2011). This is likely due to several factors that have contributed to varying degrees. It has been suggested that during the millennium drought years (2006–2009) rainfall tended to be infrequent and poorly timed for critical plant growth stages, and that there appeared to be a higher incidence of frosts, which may have reduced yields (PIRSA pers. comm.). During this period, there was rapid adoption of no-till (Forward 2023), with farmers needing to adjust to different seeding equipment and implement changes to weed management, herbicides, nutrition, rotation, diseases, and stubble management. There may also have been a time-lag of a number of seasons while soil biota adjusted and responded to such changes in management.

Significant increases in annual WUE occurred in 2021 and 2023, over the state and in most crop districts. These increases occurred to a greater degree in the medium to lower rainfall districts (Appendix A). These could be related to significant rainfall events that resulted in substantial additions to stored soil moisture. A major rainfall event between 21–25 January 2022 produced the heaviest recorded rainfall totals in the

Kimba-Buckleboo area of EEP (up to 240 mm), with lesser but significant rainfall in other western and central agricultural areas (Figure 4.1) (Young and Masters 2022). The spring–summer of 2022–23 was very wet (decile 10 in many agricultural areas; Figure 4.1) and helped produce record high crop yields in 2022, in addition to increased stored soil moisture levels for the 2023 season. It is possible that the modified French-Schultz WUE model may have under-calculated the amount of stored soil moisture from these major rain events, or that the WUE results reflect contemporary crop management practices that conserve and use available soil moisture more efficiently.

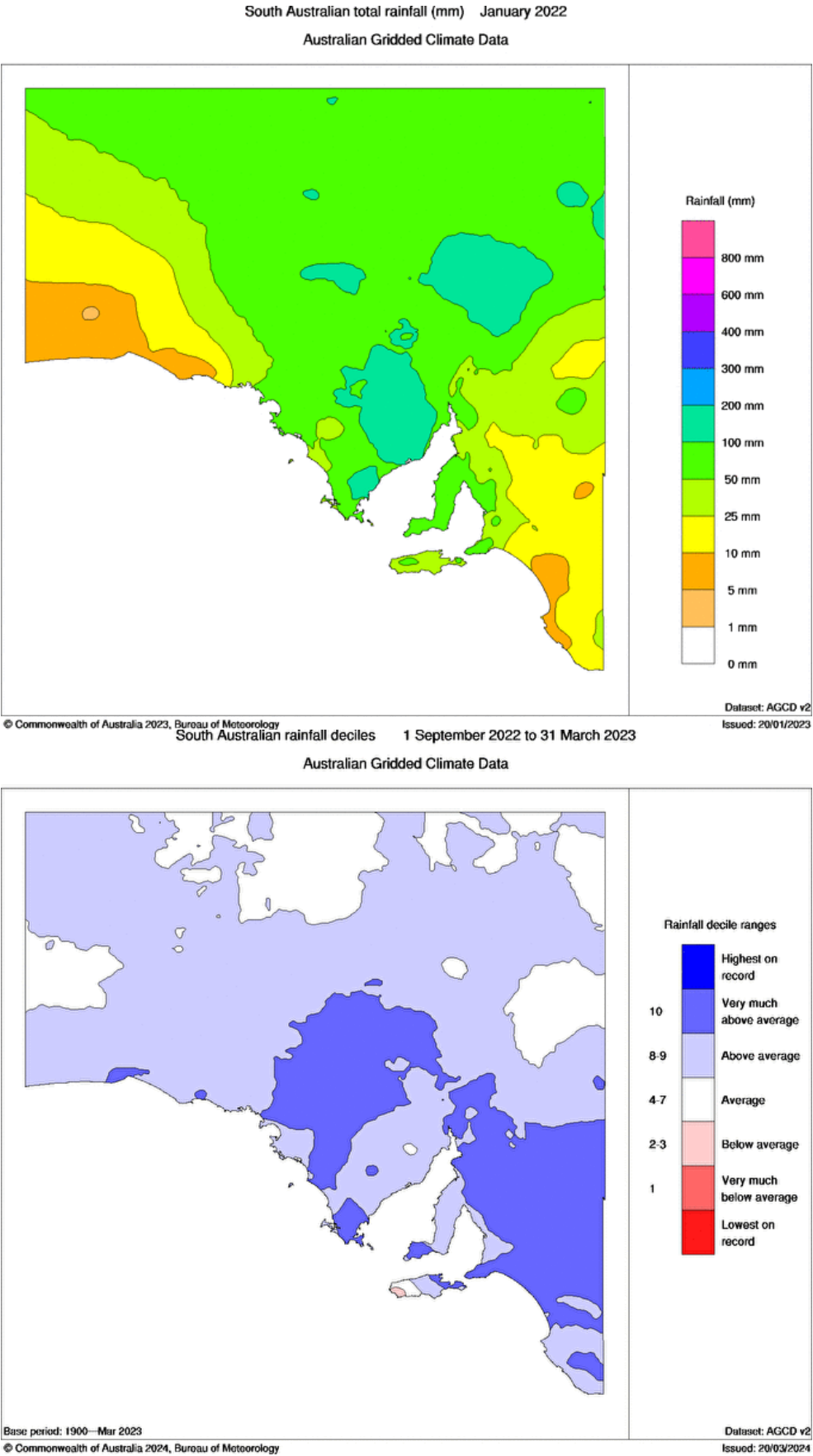


Figure 4.1. Rainfall totals in SA, January 2022 (above); SA rainfall deciles September 2022–March 2023 (below)

4.2 Factors affecting water use efficiency

A timeline of management practices and other events, which have affected wheat yields both positively and negatively in the different districts across SA since the mid-1960s, is presented in Appendix B.

4.2.1. Effect of management and environment on wheat yield

Historical progress in the yield of wheat in Australia has been well documented (e.g. [Kirkegaard and Hunt 2010](#)) together with attribution of various innovations in determining such progress. Aside from an initial phase of system rundown before 1900, yield progress was characterised by phases of gain interspersed with ‘plateau periods’ where progress slowed. The periods of rapid yield improvement occurred where packages of improved management combined to allow the underlying improvements in genetic yield potential to be realised. From 2000 to 2010 there was a noticeable flattening and even a decline of this upward progress in average yield and more year-to-year variation.

The CSIRO have developed an interactive map-based tool “[Yield Gap Australia](#)”, which shows the extent and geographic distribution of the yield gap between achieved yields and potential yield. This map indicates a yield gap of less than 1.5 t/ha in the Northern Mallee and West Coast (Eyre Peninsula), and more than 1.5 t/ha in the rest of the state. This equates to 50% or more of potential yield in many districts. In an effort to understand what was causing this yield gap, GRDC funded a National Paddock Survey (van Rees et al, 2019). Lawes et al (2018) analysed the data from 2015 and 2016 and found that the yield gap in the Southern region (southern NSW, Victoria and SA) varied from 0 to 3.7 t/ha with a mean of 1.3 t/ha, with only 38% of paddocks achieving 80% or more of the yield potential. The data includes 59 wheat paddocks surveyed across SA from 2015 to 2018. They did not find any significant relationship between yield gap and any single factor (in-crop rainfall, N fertiliser application, weeds, diseases, insects and previous crop) and suggested that the yield gap was caused by a combination of these effects. In the Southern region, the three most important variables were the amount of applied N, the previous crop grown, and root health. In contrast, weeds and growing season rainfall had relatively minor influence. These findings would apply to SA’s wheat growing areas.

Land manager surveys across SA’s agricultural regions conducted periodically from 2000 to 2017 highlighted substantial progressive uptake of soil and land management practices to improve soil health and reduce erosion risk (Forward, 2023). For example, the reported percentage of crop sown using no-till methods, which minimise the risk of soil erosion by minimising soil disturbance and retaining surface cover, increased from 16% in the 1999 season to 83% in 2016. No-till also enables the crop to be sown earlier or more promptly following rainfall compared to older multiple tillage crop sowing methods. This can increase crop utilisation of rainfall resulting in increased yield and WUE. The use of methods such as clayey to ameliorate water repellent soils, increased from 51% in the 2000 survey to 71% in 2017. Clay incorporation into water repellent or sandy topsoils improves plant water uptake, improves soil fertility and stability, and contributes to increased yields and WUE.

4.2.2. Yield limiting factors

Although agronomic practices and genetic improvement have been available to all regions across SA, their adoption by landholders has been highly variable. Even with adoption, their effect on yield improvement relative to the optimal yield based on available water is also affected by variation in soil constraints and climate. In addition to these factors, other agronomic pressures such as pests, diseases and weeds can also play a role.

Examples of significant inherent soil constraints on SA's agricultural land are 'available water holding capacity' (Figure 4.2), inherent soil fertility (Figure 4.3), and soil acidity (inherent and induced by agriculture) (Figure 4.4).

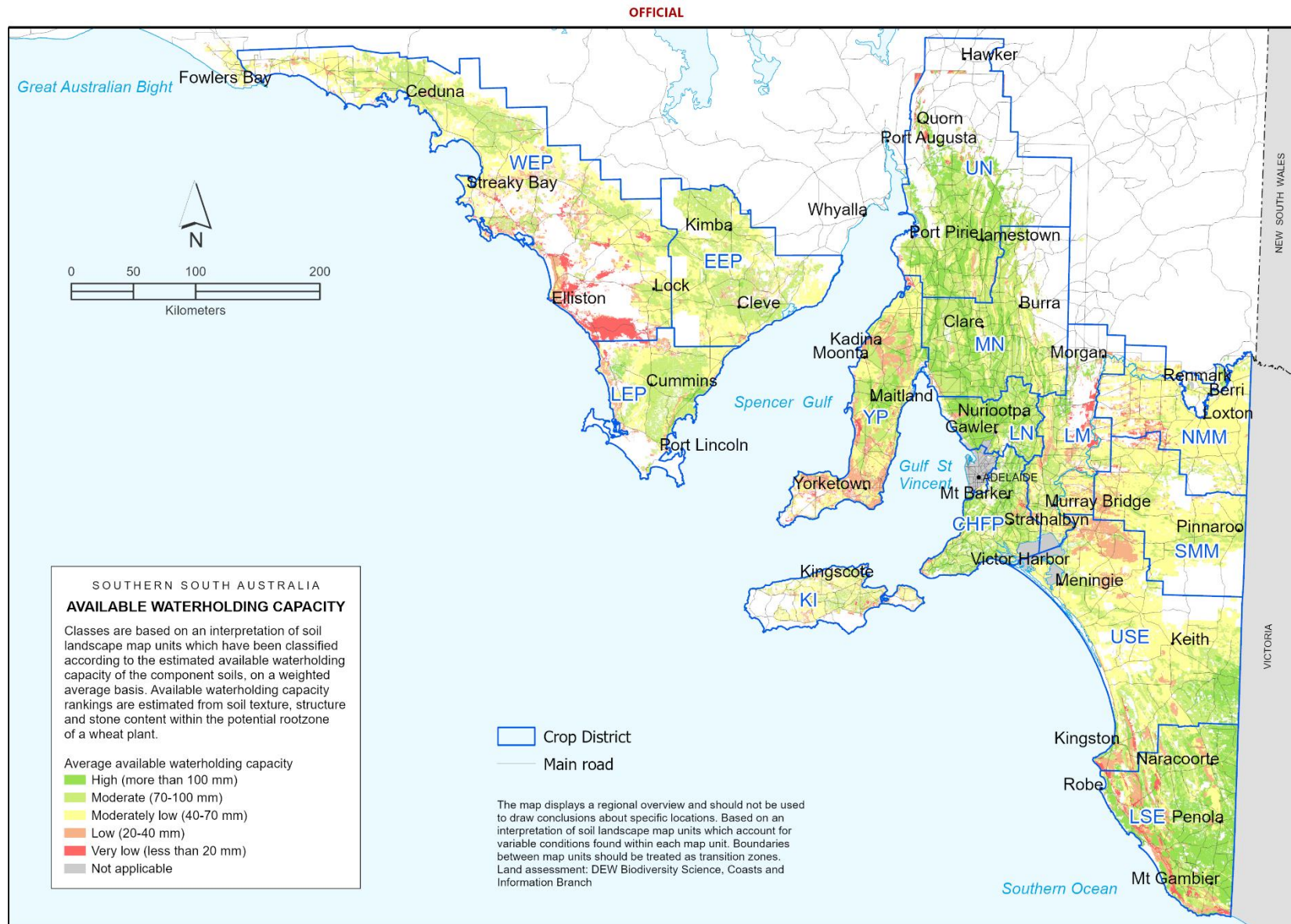


Figure 4.2. Available water holding capacity on agricultural land in SA

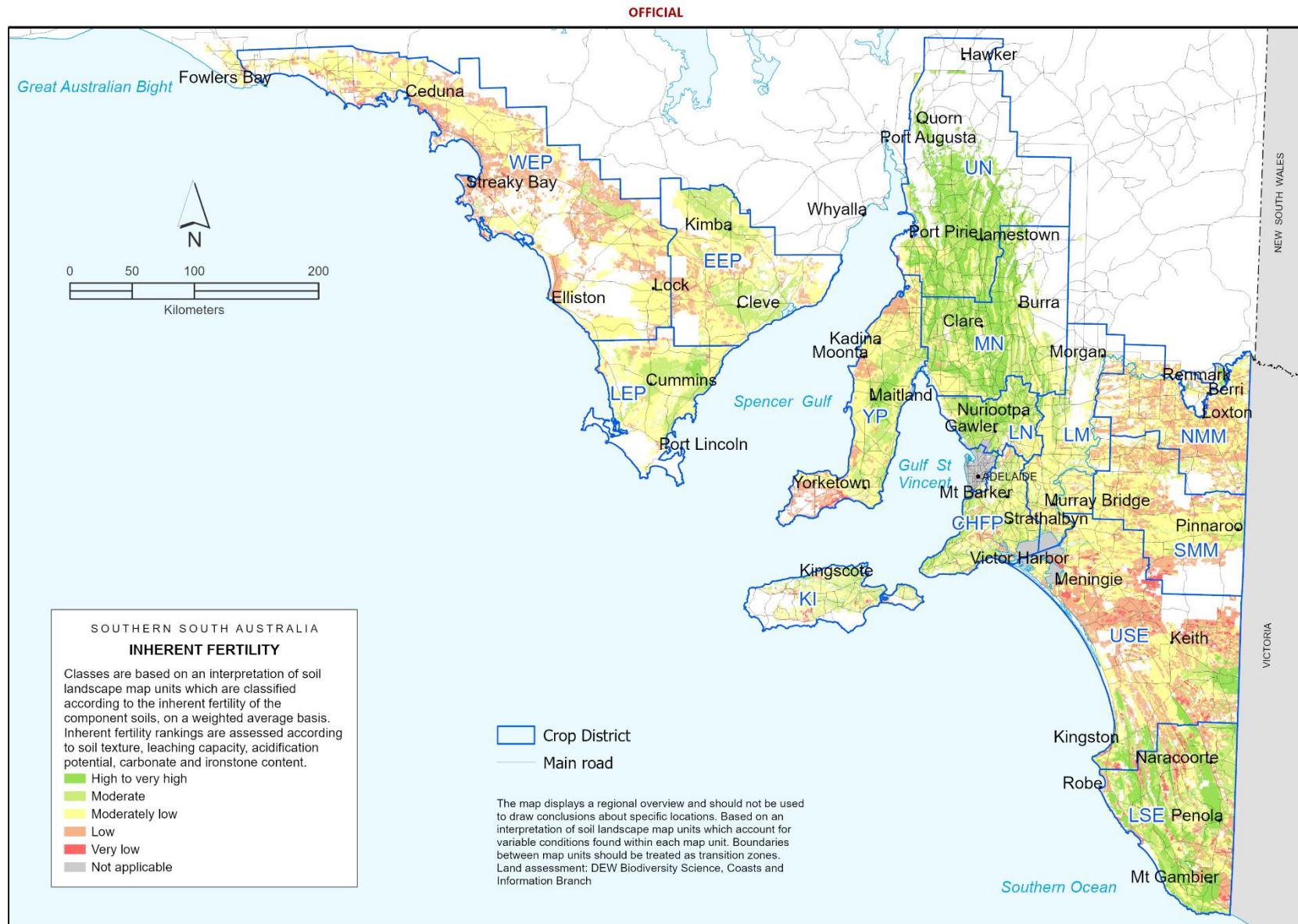


Figure 4.3. Inherent soil fertility on agricultural land in SA

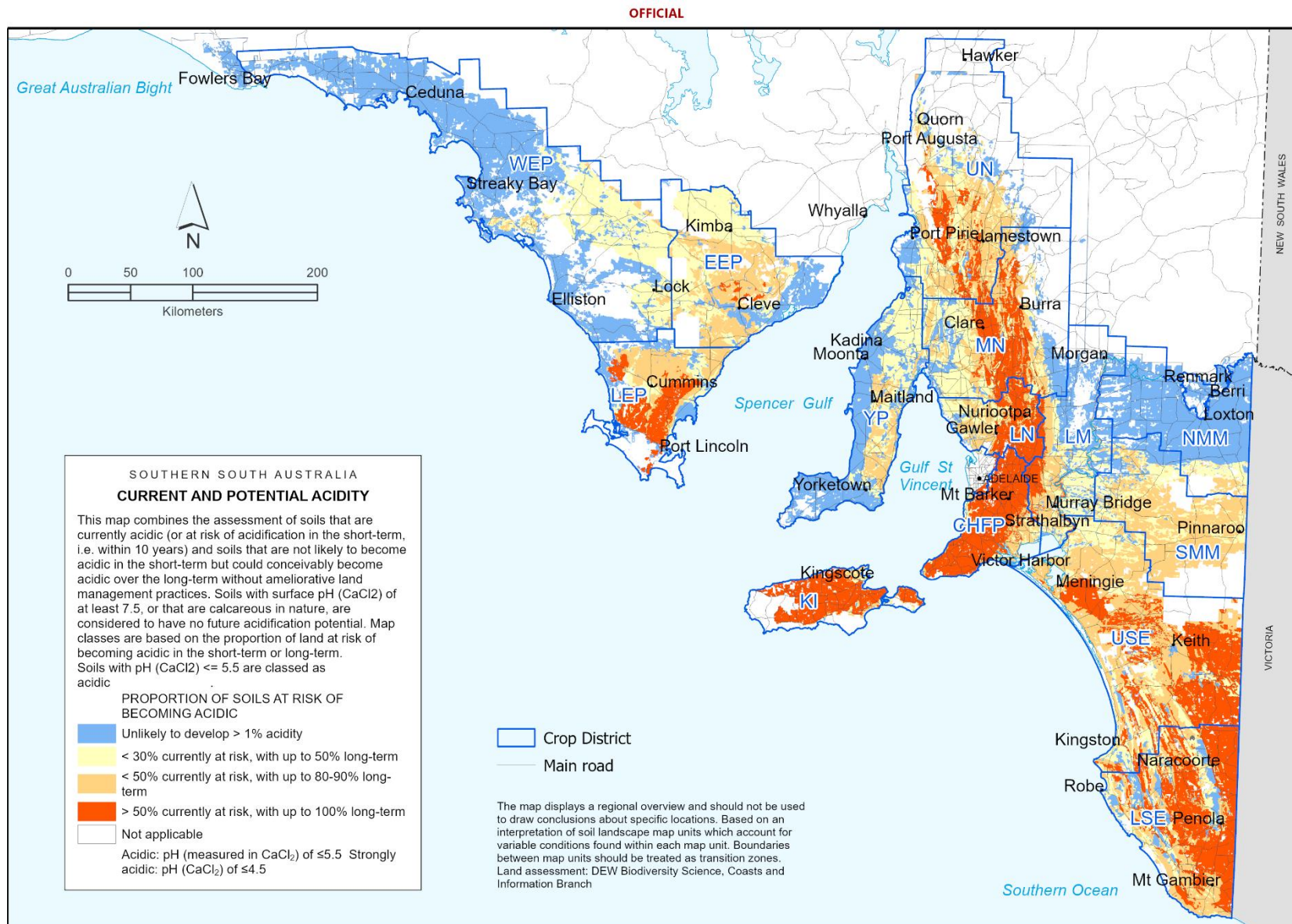


Figure 4.4. Current and potential soil acidity on agricultural land in SA

The relative level of impact of major soil, agronomic and climatic factors on wheat yields in crop districts across SA (on areas cropped) are summarised in Table 4.1. This highlights that in districts like YP, there are no high-level constraints to WUE, in contrast to districts such as WEP, NMM and the USE, which have multiple high-level constraints.

Dryland farmers do not necessarily aim to achieve maximum crop WUE due to:

- diminishing returns for increasing levels of inputs (e.g. fertiliser and soil amendments), such that farmers tend to choose input rates or treatments to achieve optimum net economic returns rather than maximum yields
- risk management, such as conservative N application rates, particularly in less reliable rainfall areas, to minimise economic losses if dry, warm spring finishes to the season occur
- Sowing after “break of season” rainfall rather than at optimum sowing times to reduce risk of crop failure in less reliable rainfall areas (to reduce risk of spring frost damage, and achieve better pre-sowing weed control)
- Significance of wheat cropping in the farm enterprise mix, such that minor enterprises do not necessarily attract significant investment in water use efficiency practices and technology (this tends to be more common in higher rainfall areas, and in some marginal low rainfall areas).

Table 4.1. Level of impact of major soil, agronomic and climatic factors on wheat yield in crop districts across SA

Issue	Impacts on wheat yields in crop districts													
	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Central Hills & Fleurieu Peninsula	Kangaroo Island	Northern Murray Mallee	Southern Murray Mallee	Lower Murray	Upper South East	Lower South East
Soil constraints														
Soil acidity		ML ^a	H	ML	H	H	ML	M	H		ML	L	H	MH
High subsoil pH, boron, salinity, sodicity	H	M	VL	M	ML		M			MH	M	MH		
Water repellence, low inherent fertility, compaction	M	M	L				ML		M	ML	M		MH	ML
P tie up – high surface pH	H	ML	VL	ML		M	M			L	VL			
P tie up – ironstone soils			M						M					VL
Waterlogging			M					ML	MH				ML	MH
Agronomy														
Disease			M			ML	M							M
N fertiliser inadequate			M	L			L		M	ML	L		M	L
Weeds	M		M	ML	M	M	M	ML		ML	ML		M	M
Climate														
Frost	L	ML	ML	ML	ML	L	L			ML	MH		MH	
Heat stress	H	H	M	H	M	M	ML		H		M	M	ML	

a. VL- very low; L- low; ML- moderate/low; M- moderate; MH- moderate/high; H- high

Source: Adapted from Wurst unpubl. 2021

4.2.3. Opportunities to improve WUE

There are opportunities to improve yields and, therefore, WUE via improvements in crop varieties, management, and treating some soil constraints where possible. Many soil constraints are inherent (for example, subsoil chemical toxicities), while some can be induced or worsened under agricultural systems (such as soil acidity, compaction). Practices to overcome or manage soil constraints include claying water repellent or sandy soils, liming acid soils, and applying gypsum to hard-setting or poorly structured sodic soils. Other inherent soil constraints to plant growth such as unfavourable subsoil chemical properties (high boron, salinity, high pH), and weather conditions or events such as frost, high spring temperatures or storms may be difficult or otherwise uneconomical to address.

Constraints to WUE and opportunities for improvement for the agricultural cropping districts are outlined in Appendix C.

4.3 Limitations of water use efficiency models

Despite the relatively high level of development of the modified water use efficiency model based on the *French-Schultz Model*, it is recognised there are some limitations to accurate estimation of WUE across the range of seasonal rainfall and soil conditions that can occur.

In the lowest rainfall seasons in lower rainfall districts, WUE calculations can produce high values, sometimes higher than that theoretically achievable. In the NMM district, in years with very low rainfall, the calculated WUE in most of the driest seasons (1982, 1994, 2018) was 25 kg/ha/mm or higher, which has not been achieved in most other districts (except YP) in this analysis (Appendix A). While the model was adjusted to try to account for lower evaporation in such very dry seasons, this may not have accurately estimated actual evaporation, therefore available water, possibly resulting in an overestimation of WUE. The estimated wheat tonnage and yields produced, for example, in 1982 were extremely low (6000 t or 0.1 t/ha). Therefore, such WUE calculations are likely to be inaccurate, and could be removed from the trend analysis.

In drier growing seasons, particularly in the low rainfall cropping areas, the incidence of rain events through the growing season can be spasmodic or irregular. This can result in prolonged plant moisture stress at critical growth stages which can significantly affect eventual yields.

In very dry seasons, some of the sown crop might not be harvested for grain due to crop failure (drought) or frost damage, and may be left for grazing or cut for hay. PIRSA adjusts its crop area estimates accordingly each season when this occurs. The model does not account for actual yield loss due to frost or other events such as storm damage.

In higher rainfall districts (particularly >600 mm p.a.), there are particular soil and agronomic factors that can limit achieved WUE, other than rainfall, which the model may not account for. These include waterlogging (leading to reduced plant growth), and reduced plant-available rainfall due to runoff and deep drainage below the root zone. The incidence of foliar and root disease and weed competition tends to be higher in high rainfall environments. The key constraints to WUE in the higher rainfall districts KI, CHF and LSE are listed in Appendix C.

The WUE calculations for CHFP, KI and LSE (earlier years of the analysis period) have lower confidence due to the relatively low area of wheat sown compared to other crop districts (Section 2.2). Confidence in the WUE has improved in recent years due to the higher area of wheat sown.

French and Schultz (1984) proposed a maximum achievable water-limited yield potential of 20 kg/ha/mm. More recent studies, including Harries et al. (2022), have reported values of up to 25 kg/ha/mm in Western Australia, reflecting improvements in farming practices, crop genetics and refinements to WUE estimation approaches. While, in this report, WUE values in some of the most recent years approach these higher levels, the model is primarily intended to support comparative assessments of crop performance relative to rainfall over time and between regions. As such, the observed trends and relative differences in WUE are generally more informative than the absolute values produced by the model.

5 Conclusions

Water use efficiency is a valuable indicator of long-term trends in soil health.

Wheat WUE has increased substantially (115%, 8.4 kg/ha/mm; 10-year rolling mean 1970–2024) in SA over recent decades, as a result of improved agronomy, plant breeding and soil management. There was considerable variation in absolute WUE and rate of increase across the crop districts. This can be due to a number of reasons including agronomy, soil constraints, weather and climate variation, and economic factors.

There are some limitations to these WUE models, such as reduced accuracy of estimation of evaporation in very dry seasons, inability to account for yield loss due to frost or waterlogging, and for loss of plant-available rainfall in wetter situations (runoff, deep drainage).

However, they still provide a valuable tool to assess agronomic and soil factors in relation to crop performance relative to rainfall.

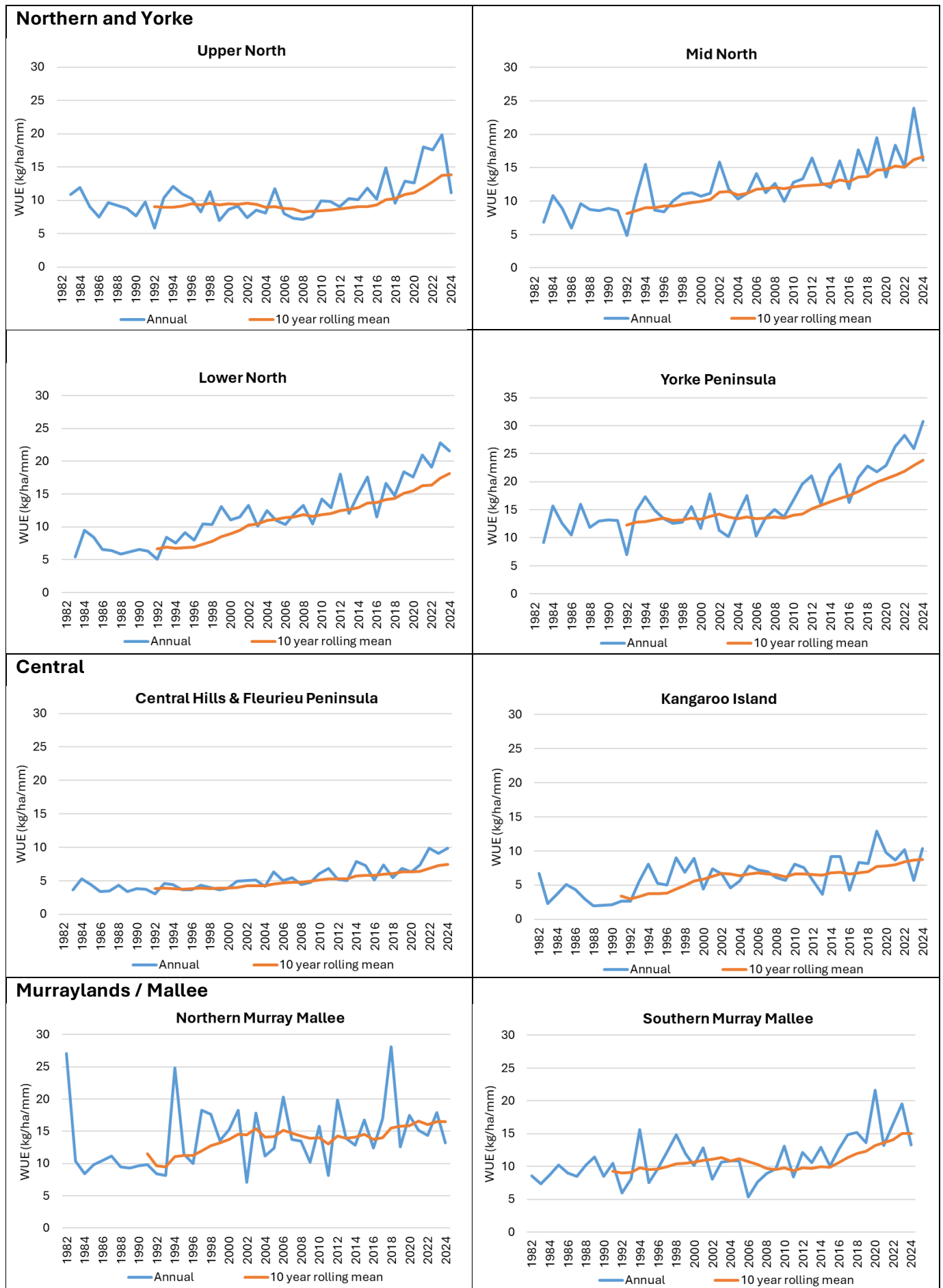
Managing and treating the soil constraints where possible, in addition to improved agronomy, crop breeding and improved technology, will be important to realising ongoing improvement in WUE in the future.

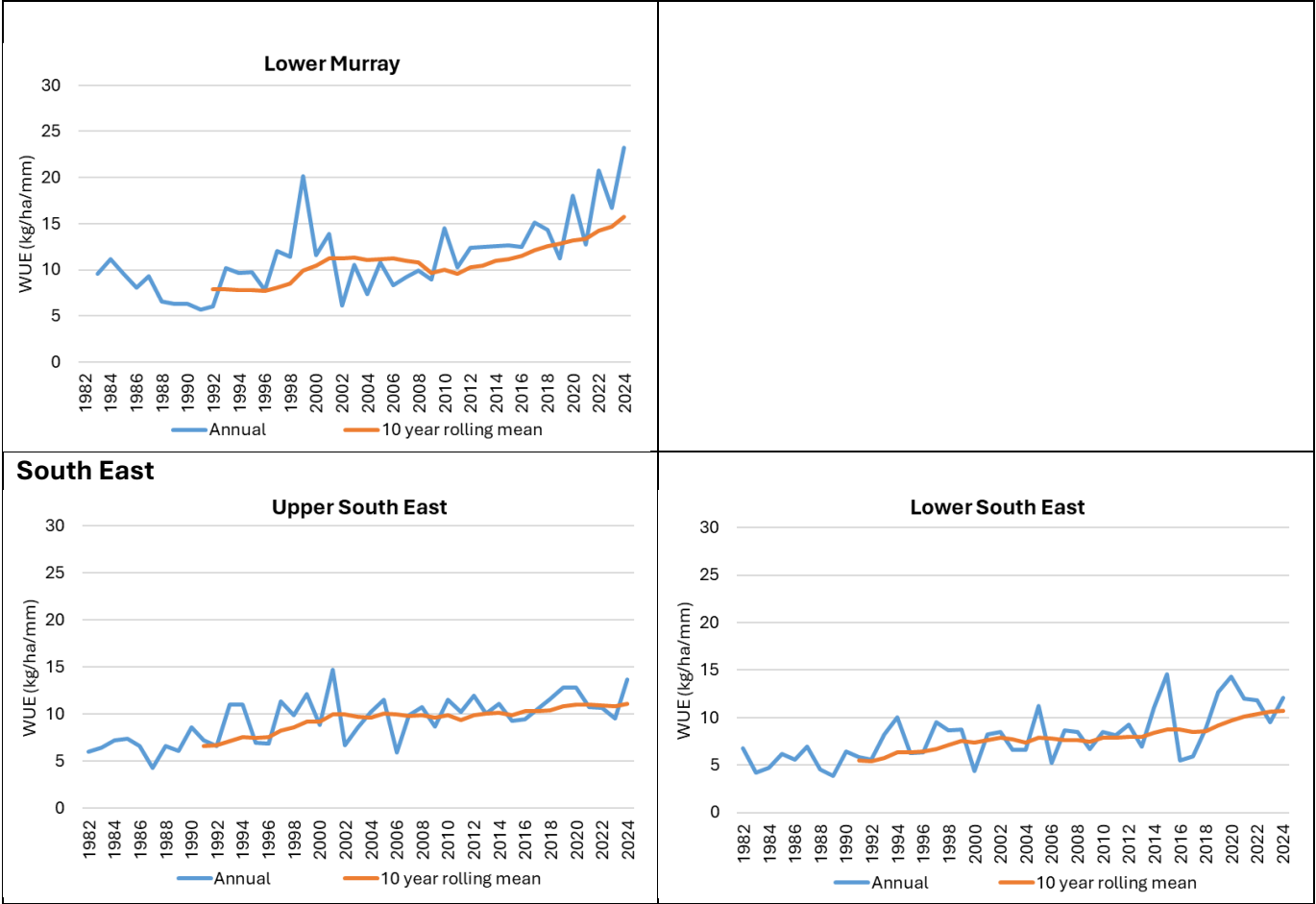
In the future, water use efficiency trends of other crops in SA could be studied, where there is adequate data.

6 Appendices

A. Annual and 10-year rolling mean wheat WUE, state and PIRSA crop districts, 1982–2024







B. Summary timeline of key management and environmental factors affecting wheat yield in PIRSA crop districts

The following table documents the emergence and availability of selected agricultural technologies, practices and innovations that were adopted over time, and does not imply immediate, widespread, or uniform adoption across cropping districts. A number of factors influence adaption or adoption of any newer technology; cost, perceived risks and benefits, compatibility with existing farming systems, and local conditions such as soil type and rainfall must all be considered. As such, this table serves as a broad guide only and should be interpreted with the additional context of local farming systems, environmental conditions and adoption pathways.

Time-line	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Kangaroo Island	Central Hills & Fleurieu Peninsula	Northern Murray Mallee ^a	Southern Murray Mallee	Upper SE	Lower SE
1965	Semi-dwarf cereal varieties												
	Improved legume pastures sown & P applied to pastures												
	Wheat quotas												
												Trace elements	
1970	Boron tolerant (BT) wheat			BT wheat						BT wheat			
	Trifluralin (pre-emergent herbicide) released												
	Above average rainfall												
	Alternative crops trialed												
	Stem rust			Stem rust									
	Cereal cyst nematode (CCN) and other cereal root diseases increase with more intensive cropping												
	Broadleaf herbicides & soursob suppression with Diuron/MCPA (IMI herbicides ^b)												
1975	Stem rust			Stem rust									
	Hot dry springs			Hot dry springs						Hot dry springs			
	Pasture aphids reduce production and seed set of medic pastures												

Time-line	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Kangaroo Island	Central Hills & Fleurieu Peninsula	Northern Murray Mallee ^a	Southern Murray Mallee	Upper SE	Lower SE
1980	Galleon release (CCN resistant barley)												
	Glyphosate (knockdown herbicide) begins to be adopted												
	Group A herbicides (selective grass weed herbicides) released												
	Spray topping to control grass seed set in pastures												
	Sulfonyl Urea herbicides to control soursobs and ryegrass												
	Severe Stripe rust infections												
			Lupins									Lupins	
1985	Manganese (Mn) fertiliser	Copper (Cu) & Mn fertilisers					Mn fert					Mn & Cu fertilisers	
	Minimum tillage with greater adoption of glyphosate and Sprayseed®(knockdown herbicides)												
	Stripe rust resistant wheats released												
1990	Right Rotations campaign (to improve yields and sustainability); increased cropping with low livestock returns – improved root disease & weed control; timely sowing & stubble retention												
	CCN tolerant and resistant wheats released												
	Minimum-till and Direct drill widely adopted												
	Stubble retention with improved stubble handling of seeding machinery												
	Grass free medic pastures			Vetch	Pulses & canola	Pulses & canola	Pulses & canola	Canola		Grass free medic pastures		Pulses & canola	
			Herbicide resistance									Herbicide resistance	

Time-line	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Kangaroo Island	Central Hills & Fleurieu Peninsula	Northern Murray Mallee ^a	Southern Murray Mallee	Upper SE	Lower SE
	Liquid P used on calcareous soils												
	Zinc and sulfur												
1995	N600 campaign (to increase N fertiliser rates); Increased N fertiliser use												
												Clay spreading and delving ^c	No-till ^d
			Canola 20% of wheat area		Lentils					Summer weed control			
1999	No-till crop area 9% ^e			No-till 27%				No-till 45%	No-till 25%	No-till 9%		No-till 14%	
2000			Triazine (herbicide) tolerant canola				Lentils					Summer weed control	
					Oaten hay for ryegrass management								
	Summer weed control												
	Herbicide resistance									Herbicide resistance			
2001	No-till 25%			No-till 20%				No-till 38%	No-till 23%	No-till 20%		No-till 23%	

Time- line	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Kangaroo Island	Central Hills & Fleurieu Peninsula	Northern Murray Mallee ^a	Southern Murray Mallee	Upper SE	Lower SE
2004	No-till 57%			No-till 42%				No-till 55%	No-till 41%	No-till 44%		No-till 37%	
2005			Clearfie ld (IMI tolerant) canola	No-till									
		Delving		Delving									
		Delving			Delving								
	Herbicide research and development to manage resistant and hard to kill weeds												
2007	No-till 63%			No-till 67%				No-till 58%	No-till 65%	No-till 46%		No-till 67%	
2010			Rapid adoption of summer weed control										
	Increase in dry & early sowing using pre-emergent herbicide packages												
	Cheaper fungicides allowing better leaf disease control												
							Lentils 80% of wheat area			Pulses & canola	Oaten hay		Long season wheats
		Spading ^e									Spading		
			Higher N rates post seeding								Higher N rates post seeding		
	No-till 67%			No-till 67%				No-till 62%	No-till 63%	No-till 60%		No-till 64%	
2013	No-till 67%			No-till 72%				No-till 90%	No-till 74%	No-till 57%		No-till 58%	
2015	New higher yielding wheat varieties (Mace, Scepter etc.)												

Time-line	Western EP	Eastern EP	Lower EP	Upper North	Mid North	Lower North	Yorke Peninsula	Kangaroo Island	Central Hills & Fleurieu Peninsula	Northern Murray Mallee ^a	Southern Murray Mallee	Upper SE	Lower SE
			Canola 50% wheat area		Liming	Liming		Beans	Canola		Frost		Higher inputs
	IMI herbicides tolerant cereals			IMI herbicides tolerant cereals						IMI herbicides tolerant cereals			
2016	No-till 75%			No-till 92%				No-till 88%	No-till 90%	No-till 77%		No-till 87%	
2020	Deep ripping with inclusion plates (creates slots behind rippers so topsoil can fall into furrows)												
			Liming for lentils				Liming for lentils						
	Adoption of genetically modified (GM) crops												
	Increased adoption of long season & winter wheats												

a. Information relevant to LM District apportioned to Northern Mallee or Southern Mallee

b. IMI: Imidazoline 'Group B' herbicides

c. Delving: ripping up subsoil clay and placing it in the topsoil layers

d. No-till: sowing in one pass with a narrow point or disc implement

e. No-till adoption data (% crop area) from Forward (2023)

f. Spading: mixing topsoil and subsurface soil with rotary hoe-type machine usually to incorporate clay

Source: Wurst 2021 (unpubl.)

C. Summary of key constraints and opportunities for improvement in WUE, for PIRSA crop districts (adapted from Wurst 2021 unpubl.)

This table highlights some of the key constraints and opportunities relating to crop WUE in each district. It provides a broad overview only and should not be interpreted as applying uniformly across entire districts. The relevance of individual constraints and opportunities will vary according to specific soil types, which can vary spatially within districts, as well as other factors such as local topography and distance to the coast. The distribution of soil types across SA's agricultural zone is shown on maps and spatial layers at [NatureMaps](#).

Constraints	Opportunities
Western Eyre Peninsula	
• Very alkaline subsoils limits root growth at depth • Very alkaline soil pH (commonly because of high calcium carbonate content) ties-up phosphorus • High spring temperatures reduce pollen fertility and grain number • Dry, warm conditions at crop ripening reduces grain number and size	• Sow other species break crops e.g. legumes to manage weeds and improve soil fertility • Sow varieties tolerant of very alkaline soils • Adjust rates, application methods and types of fertiliser to make nutrients more available to plants in highly calcareous soils
Eastern Eyre Peninsula	
• High spring temperatures reduce pollen fertility and grain number • Spring frosts can reduce yields • Water repellent soils impede early sowing and crop establishment	• Ameliorate non-wetting siliceous sands • Early sowing (mid-April) of slower developing winter cultivars • Adjust rates, application methods and types of fertiliser to make nutrients more available to plants in highly calcareous soils
Lower Eyre Peninsula	
• Soil acidity • Waterlogging on heavier soils and sand-over clay soils • Weed competition • Crop and root disease management	• Treat non-wetting siliceous sands by claying etc. • Reduce waterlogging by ameliorating sodic clays in sand over clay soils • Early sowing (mid-April) of slower developing winter cultivars • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots.

Constraints	Opportunities
	• Manage soil acidity by liming
Upper North	
• Subsoil salinity (dry saline land), particularly in lower rainfall areas • Boron toxicity, particularly in lower rainfall areas • Very alkaline subsoils limits root growth at depth • Soil acidity in more intensively cropped paddocks • Winter frost reduces early root and top growth of crops and pastures, limiting water uptake later in the season • Spring frost reduces grain yields • High spring temperatures reduce pollen fertility and grain number • Insufficient growing season rainfall, particularly on soils with higher clay contents, kills plant growth before maturation. • Elevated land (esp. >500m in altitude) experiences colder winter temperatures that slow plant growth and development, reducing yield if dry, warm springs occur	• Sow other species break crops e.g. legumes to manage weeds and improve soil fertility • Early sowing (mid-April) of slower developing winter cultivars • Treat soil acidity by liming
Mid North	
• Soil acidity • Spring frosts can reduce yields • Weed competition • Crop and root disease management	• Treat soil acidity by liming • Use a variety of weed management practices to avoid development of herbicide-resistant weeds. • Sow wheat varieties tolerant to high sub soil pH and salinity • Early sowing (mid-April) of slower developing winter cultivars • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots.
Lower North	
• Soil acidity • Weed competition • Crop and root disease management	• Early sowing (mid-April) of slower developing winter cultivars

Constraints	Opportunities
	• Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots. • Treat soil acidity by liming
Yorke Peninsula	
• Weed competition • Crop and root disease management • Soil acidity on intensively cropped soils	• Early sowing (mid-April) of slower developing winter cultivars • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots. • Treat soil acidity by liming
Central Hills and Fleurieu	
• Soil acidity • Waterlogging in lower lying areas • Weed competition • Crop and root disease management	• Improved agronomy and crop nutrition • Early sowing to reduce waterlogging damage • Sow long season high yielding varieties • Manage soil acidity by liming • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots.
Kangaroo Island	
• Soil acidity • Waterlogging in lower lying areas • Water repellent soils • Ironstone soils which tie up available phosphorus • Crop N deficiency in wetter seasons	• Improved agronomy and crop nutrition • Early sowing to reduce waterlogging damage • Sow long season high yielding varieties • Manage soil acidity by liming • Manage non-wetting siliceous sands by clay spreading and delving • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots.
Northern Mallee	

Constraints	Opportunities
• High spring temperatures which reduce pollen fertility and grain number • Subsoil constraints – high pH, salinity • Low soil carbon – reduced mineralisation (N deficiency)	• Early sowing (mid-April) of slower developing winter cultivars • Additional N fertiliser in average to above average rainfall seasons • Adjust rates, application methods and types of fertiliser to make nutrients more available to plants in highly calcareous soils
Southern Mallee	
• High spring temperatures which reduce pollen fertility and grain number • Water repellent soils which impede early sowing and crop establishment • Spring frosts which reduce grain yields, particularly in low lying areas	• Manage non-wetting siliceous sands by clay spreading and delving • Early sowing (mid-April) of slower developing winter cultivars • Additional N fertiliser in average to above average rainfall seasons
Lower Murray	
• High spring temperatures which reduce pollen fertility and grain number • Subsoil constraints – high pH, salinity	• Early sowing (mid-April) of slower developing winter cultivars • Additional N fertiliser in average to above average rainfall seasons
Upper South East	
• Soil acidity on many soils • Waterlogging in lower lying areas • Water repellent soils • Spring frosts which reduce grain yields, particularly in low lying areas • N and trace element deficiencies	• Managing non-wetting siliceous sands by clay spreading and delving • Manage soil acidity by liming • Early sowing (mid-April) of slower developing winter cultivars • Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots.
Lower South East	
• Soil acidity on most soils • Waterlogging in lower lying or poorly drained areas • Water repellent soils • Spring frosts which reduce grain yields, particularly in low lying areas	• Improved agronomy and crop nutrition. • Improve fertility of siliceous sands • Early sowing to reduce waterlogging damage • Early sowing (mid-April) of slower developing winter cultivars

Constraints	Opportunities
• N and trace element deficiencies • Crop foliar and root diseases • Weed competition	• Early sowing (mid-April) of quick to mid developing cultivars with ability to delay maturation by mid-season cutting / grazing of growing shoots. • Manage soil acidity by liming

D. Method used to manage changes in PIRSA crop districts

During the 1990s, several PIRSA crop districts were merged with surrounding districts, and production data was managed as follows (method used by Wurst unpubl. 2021):

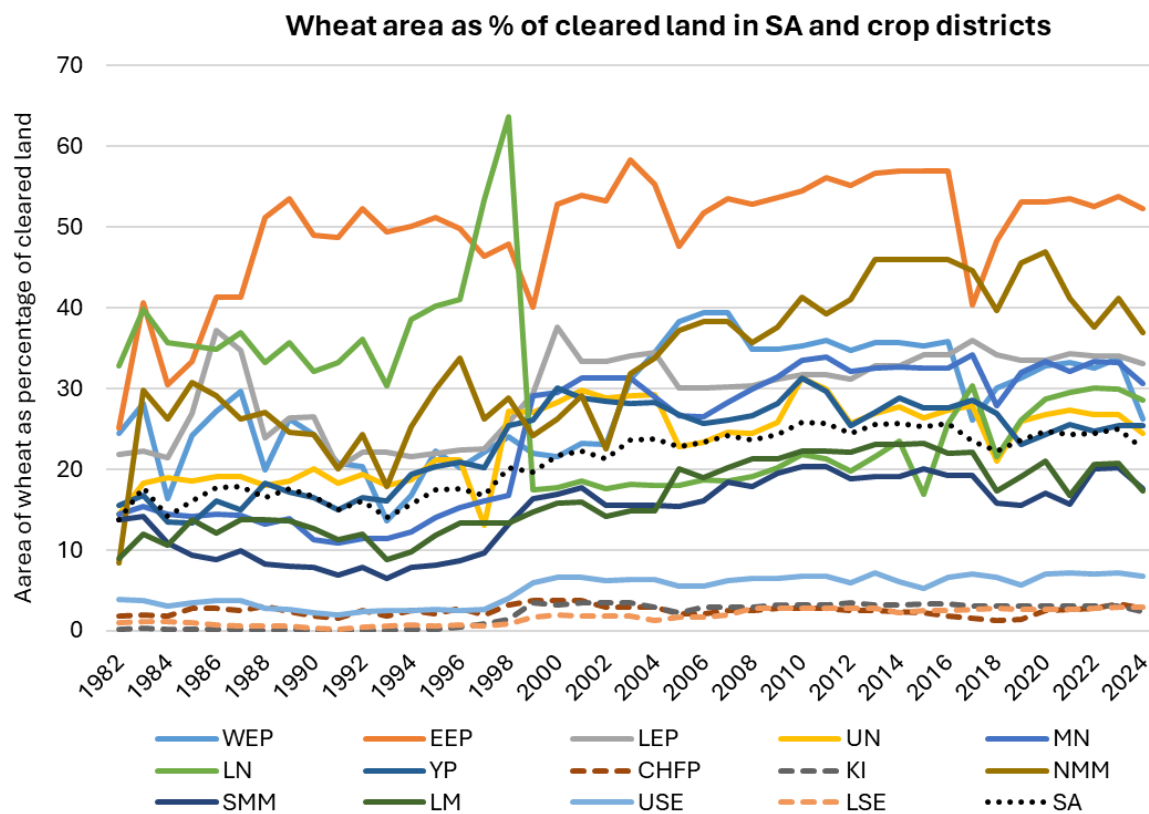
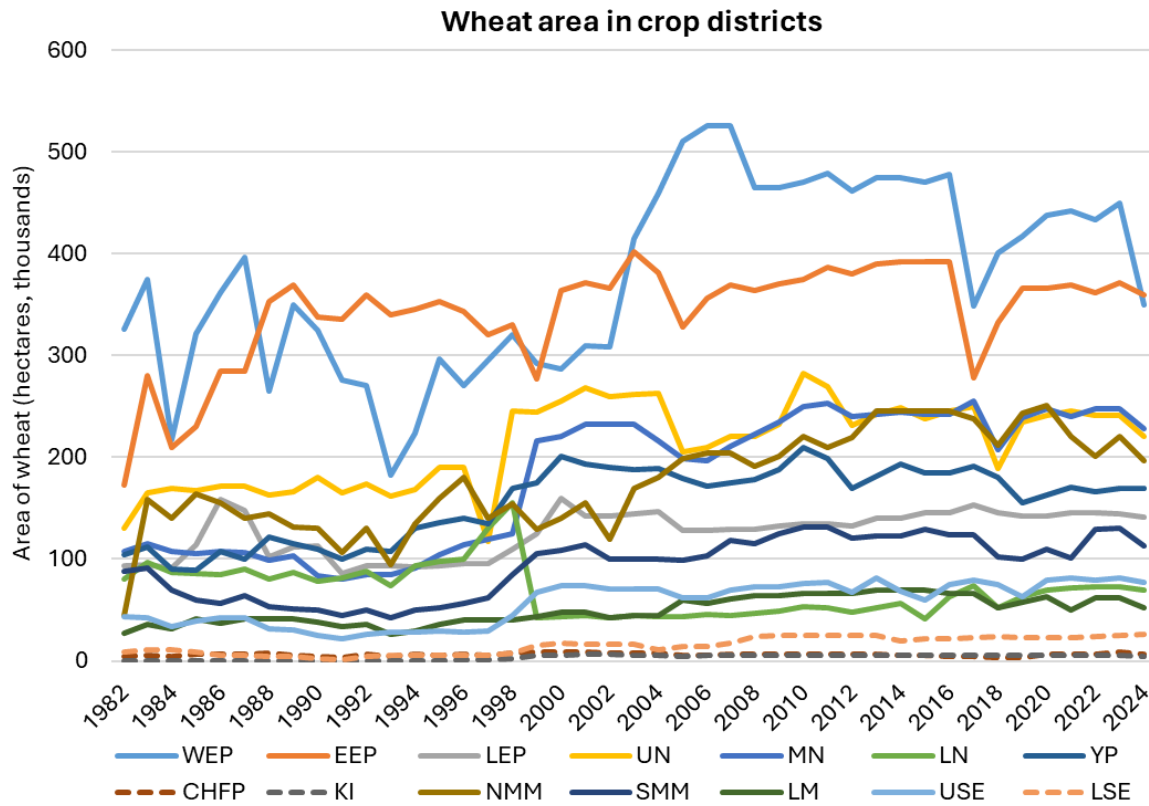
Upper Eyre Peninsula

- This part of the state was initially recorded as three districts: WEP, Central Eyre Peninsula (CEP) and EEP.
- In 1994, CEP was abolished, and the Wudinna and Elliston Councils become part of WEP; Cleve Council became part of EEP.
- The data from CEP prior to 1994 was split 50:50 between Western and EEP for both area and production.

South East

- This area of the state was initially recorded as three districts: USE, Mid South East and LSE.
- In 1993 it became two districts: USE, and LSE.
- The production data from the Mid South East prior to 1993 was split 55% to the LSE and 45% to the USE, and the crop area split 50:50.

E. Wheat for grain area estimates in crop districts (PIRSA crop harvest estimates), and as a percentage of cleared land area



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8 Glossary

ABS — Australian Bureau of Statistics

Acidic soil, acidity — soil with a pH less than 5.5 (measured in calcium chloride 1:5 solution)

APSIM — Agricultural Production Systems SIMulator

Biomass — quantity (mass) of plant material

BoM — Bureau of Meteorology, Australia

Cation exchange capacity — measure of a soil's ability to hold onto (and exchange with the soil solution) positively charged ions including essential plant nutrients such as calcium, potassium and magnesium

CEP — Central Eyre Peninsula

CHFP — Central Hills and Fleurieu Peninsula (District)

Clay spreading — method of ameliorating water repellent (or sandy) soil by spreading and incorporation of clay into the topsoil

CSIRO — Commonwealth Scientific and Industrial Research Organisation

Delving — mixing soil to a desired depth (e.g. 30 cm) using a rotary cultivator-type machine

DEW — Department for Environment and Water

EEP — Eastern Eyre Peninsula (District)

Growing Season — time span of plant growth, in this document referring to dryland crops in the southern South Australian environment, generally defined as from April to October

Harvest Index — crop yield relative to total above ground crop biomass

KI — Kangaroo Island (District/region)

LEP — Lower Eyre Peninsula (District)

LM — Lower Murray (District)

LN — Lower North (District)

LSE — Lower South East (District)

Mallee — Region of southern Australia where current landscape (or past landscape) is mallee woodland; often referred to as Mallee region or Mallee zone. Areas of the Mallee have been extensively cleared for agriculture.

MN — Mid North (District)

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change

NMM — Northern Murray Mallee (District)

No-till — method of sowing a crop with minimal physical disturbance of the soil, with no prior tillage

Pasture — Grasses, legumes and/or other herbage (i.e. vegetation, or land covered by) used or suitable for the grazing of animals (e.g. livestock).

Phosphorus fixation — chemical reaction (tie-up) that reduces the amount of soil phosphorus that plants can take up

PIRSA — Primary Industries and Regions South Australia (Government of South Australia)

Plant-available water holding capacity (PAWC) — the amount of water available to plants from when the soil stops draining (field capacity) to when the soil becomes too dry to prevent permanent wilting (wilting point).

Saline soil, salinity — soil with sufficiently high concentration of soluble salts (typically mainly sodium chloride) to reduce or prevent plant growth.

SARDI — South Australian Research and Development Institute, a division within PIRSA

SMM — Southern Murray Mallee (District)

Spading — deep ripping with an implement designed to lift sub-surface soil material into the topsoil

Sodic soil, sodicity — soil with a sufficiently high concentration of sodium ions (Exchangeable Sodium Percentage ESP >6%) that can result in surface crusting, hard setting, poor drainage and unstable soil structure, which can reduce plant growth.

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

UN — Upper North (District)

USE — Upper South East (District)

Water repellent soil, water repellence — soil with hydrophobic (non-wetting) properties, which results in reduced or uneven water infiltration, surface runoff, and reduced plant growth.

WEP — Western Eyre Peninsula (District)

WUE — Water use efficiency

YP — Yorke Peninsula (District)



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