Department of Primary Industries
Department of Regional NSW

DPI Primefact

Benchmarking indicates that Australian irrigated cotton has increased long-term water productivity despite its vulnerability to climatic extremes

May 2024, Primefact PUB24/438
Malem McLeod, Peter Regan, Sarah Dadd, Jasim Uddin, and Steven Harden

Key messages

Improving water productivity is essential for Australian agriculture because of the increased pressure on available water supplies and market expectations for more sustainably produced food and fibre. Demonstrating that water is used sustainably will help the cotton industry to improve market access and social license.

The cotton benchmarking program shows that over the past 25 years, there has been a trend of improving cotton water productivity and sustainability. However, significant seasonal fluctuations are becoming more apparent.

Water productivity

- The average water productivity doubled from 0.62 bales/ML in 1997 to 1.22 bales/ML in 2021, and the top 20% of growers achieved 1.41 bales/ML or more in 2021.
- Climatic conditions had a significant impact on water productivity:
  - In 2022, excessive rain caused the average water productivity to drop to 0.98 bales/ML, with the top 20% of growers achieving 1.16 bales/ML or greater.
  - In 2019, the drought caused water productivity to drop to 0.94 bales/ML.
- The annual rate of water productivity improvement was 8—9% between 1997 to 2007, however it has now plateaued.
- Long-term benchmarking suggests yields over 9 bales/ha can be achieved with a lower total water input of around 6 ML/ha, resulting in water productivity over 1.41 bales/ML.

Water sustainability

- The amount of water used to produce one bale of cotton decreased by more than 50% from an average of 1.84 ML in 1997 to 0.84 ML in 2021.
- The average water usage increased to 1.05 ML/bale due to excessive rain in 2022 and 1.10 ML/bale during the drought in 2019.

Performance of Australian cotton from 1997 to 2022

- On average, Australian growers produce 1.06 bales of lint per ML of water, more than double the global average of 0.48 bales.
- In Australia, an average of 1.03 ML of water is required to produce one bale of cotton, less than half the global average of 2.07 ML.

Introduction

NSW Department of Primary Industries (DPI), in partnership with the Cotton Research & Development Corporation (CRDC) and growers, is benchmarking the water productivity of irrigated cotton. This includes updating the trends of water productivity obtained since the 1990s. The benchmarking is conducted by collecting farm records and comparing various water performance indicators at the whole farm level. These indicators include: the gross production water use index (GPWUI), which indicates whole farm water productivity; and the sustainable water use index (SWUI) which indicates how sustainably water is used. Both indicators are assessed at the farm scale and water input is expressed in megalitres (ML).

Benchmarking offers a variety of benefits to individual growers and the industry, including:

1. Evaluation of performance: Comparing GPWUI and SWUI across different cotton farms, years, and climatic conditions allows farmers to assess their performance compared to valley and industry benchmarks. This helps them understand how efficiently they use water, identify where water losses occur, and pinpoint ways to improve their farm water productivity.
2. Setting and monitoring targets: Benchmarking provides the average GPWUI and top 20% GPWUI values, which can be used to set and monitor targets for the industry and participating growers.
3. Identifying best practices: By highlighting strategies used by top-performing cotton growers, benchmarking can help identify best practices that other growers can adopt.
4. Optimising water use: Benchmarking can also help growers optimise their water use by achieving higher yields while minimising losses.

This Primefact updates the trends of water productivity and sustainability indicators for irrigated cotton from 1997 to 2022 seasons and discusses the impact of climatic extremes on these trends.

Establishing water productivity benchmarks

The Australian cotton industry has benchmarked its water productivity since the 1990s, albeit at irregular intervals of between 1 and 9 years until 2016. Since the 2018 season, DPI has conducted it annually. Samples are collected from all Australian cotton growing regions. Sample size has varied, with up to 57 farms accounting for approximately 8% of total industry output. The results from 2022 have been added to the long-term data in this Primefact. Additionally, the starting point of the trend is now 1997 when a complete dataset was available.

During the 2022 season, 62 growers were approached and 45 agreed to participate. However, due to heavy rainfall and subsequent flooding, only 16 growers could provide farm water records. They collectively grew 8,315 hectares of irrigated cotton and produced 95,573 bales. These bales account for 1.7% of the industry's total output. Despite the relatively small sample size, this study is still valuable in assessing the impact of a wet season on water productivity.

Growers who participate in the benchmarking provide farm records such as gin yield, farm water storage, soil water, rainfall (obtained from either the grower or from BOM/SILO database), farm layout and field information (crop management, irrigation system and soil type). These records are used to calculate several water performance indicators such as GPWUI, SWUI, crop water use, whole farm irrigation efficiency (WFIE), and water losses. The calculation methods for these indicators are described below.

Key indicators

The gross production water use index is the standard measure of farm water productivity used in the Australian cotton industry. To ensure a consistent representation of long-term trends, we have continued to use the average GPWUI value as the industry benchmark, as supported by numerous studies (Tennakoon and Milroy 2003, Williams and Montgomery 2008, Montgomery and Bray 2010, Roth et al. 2013, Montgomery et al. 2014, Perović et al. 2019, and McLeod et al. 2022). Since 2021 we also report the 80th percentile or the GPWUI from the top 20% of farms studied.

GPWUI is a measure of the number of bales produced from each megalitre (ML) of water used to grow cotton on a farm and is a useful indicator of the potential profitability of the farm's water resource. GPWUI is calculated by dividing the cotton yield (in bales/ha) by the total amount of water available for cotton crops (in ML/ha) and is expressed in bales/ML (Equation 1). One bale contains 227 kg of cotton lint. The total water used for a season includes irrigation water, effective in-crop rainfall, and soil water storage used to grow the cotton crop. Total water is calculated using Equation 2 (Tennakoon and Milroy 2003).

Equation 1. $$GPWUI = \frac{cotton\ yield}{total\ water}$$

Equation 2 $$\begin{aligned} Total\ water = {} & Change\ in\ storage\ volume\ + metered\ water\ (river\ and\ bore)\ + \\ & effective\ rain\ +\ water\ harvested\ (FPH, rainfall\ runoff) + \\ & change\ in\ stored\ soil\ water - water\ used\ on\ other\ crops \end{aligned}$$

Whole farm irrigation efficiency is an index of how efficiently irrigation water is being used at the farm scale. It indicates the proportion of irrigation water used by the crop in relation to the total irrigation water brought onto the farm during the growing season (Equation 3). It is an important parameter to evaluate the system efficiency in terms of irrigation losses during the growing season (Tennakoon and Milroy 2003).

Equation 3. $$WFIE = \frac{crop\ water\ use\ - effective\ incrop\ rain - change\ in\ stored\ soil\ water}{total\ irrigation\ water\ brought\ onto\ the\ farm} \times\ 100$$

A high WFIE value indicates low losses from storage, transmission and field, and the crop has used a higher proportion of the irrigation water brought onto the farm. Tennakoon and Milroy (2003) suggested 60% as a critical level for WFIE. When it falls below this level, the system needs to be examined for potential improvement.

The sustainable water use index indicates the amount of water required to produce a unit of cotton lint (Equation 4). It was previously known as the inverse of $GPWUI_{partial}$ which is calculated without the stored soil water component in the total water input, based on the assumption that most cotton-producing countries do not measure soil water storage (Perović D, pers.com. 2021). Later it was called the water sustainability index or WSI (McLeod et al. 2022). In some contexts, WSI is used as an abbreviation for the watershed sustainability index (Chaves and Alipaz 2007). To avoid confusion, the term sustainable water use index (SWUI) is now used as the water sustainability indicator for cotton. SWUI tells us how much water is needed to grow cotton, in either ML/bale or litres/kg. Essentially, a lower SWUI value indicates more sustainable water use. Buyers and consumers are increasingly interested in sustainable production (CRDC and CA 2020a,b) and SWUI is a suitable indicator for this. A low SWUI can potentially improve the cotton industry's market access and social license.

Equation 4. $$SWUI = \frac{total\ water}{cotton\ yield}$$

We have updated the method used to calculate SWUI from the previous Primefact (McLeod et al. 2022) where it was calculated using the inverse of $GPWUI_{partial.}$ We could not find sufficient justification for the assumption that most cotton-producing countries do not measure soil water storage. As a result, we have calculated SWUI using the total water input as in Equation 4. We also could not find a global standard method for calculating a sustainable water use indicator. SWUI (Equation 4) can potentially be used as a universal standard method.

The trend of water productivity and irrigation efficiency

Gross production water use index

Over the past 25 years, there has been a trend of increasing cotton water productivity, but it has plateaued after 2007 and significant seasonal fluctuations have become more apparent (Figure 1). The annual rate of improvement was 8 — 9% between 1997 to 2007.

The average GPWUI for Australian irrigated cotton has increased from 0.62±0.06 bales/ML in 1997 to 0.98±0.04 bales/ML in 2022, with the long-term average of 1.06±0.02 bales/ML.

During the 2022 season, the GPWUI values ranged from 0.72 to 1.25 bales/ML. The top 20% of participating growers achieved a GPWUI of 1.16 bales/ML or greater.

The highest average GPWUI achieved was 1.22±0.04 bales/ML in 2021. The top 20% of growers in that season achieved 1.41 bales/ML or more. During the drought of 2019 the average GPWUI decreased to 0.94 bales/ML and during the wet season of 2022, it decreased to 0.98 bales/ML (Figure 1). The reasons for this reduction are explained below.

- In 2019, due to drought conditions, growers had to increase the amount of irrigation water used to maintain crop growth. However, the additional water did not result in a higher yield due to the increased heat stress and atmospheric demand for water. As a result, the average cotton yield decreased from 12.23±0.31 bales/ha in 2018 to 11.39±0.56 bales/ha in 2019 (Figure 2a), despite the total water input increasing from 10.21±0.34 ML/ha in 2018 to

11.37±0.53 ML/ha in 2019 (Figure 2d). The lower yield and higher water input in 2019 resulted in the average GPWUI declining from 1.19±0.04 bales/ML in 2018 to 0.94±0.05 bales/ML in 2019.

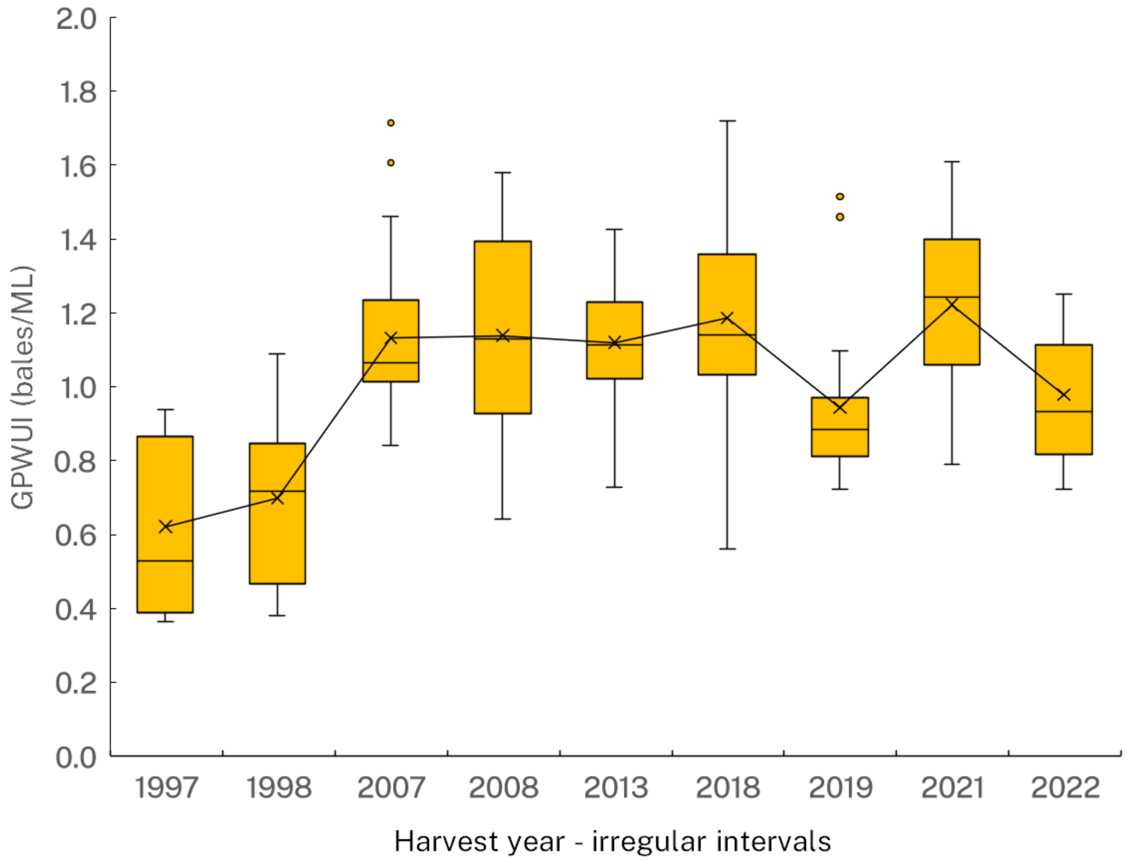

Figure 1. The variation in GPWUI[1] for cotton seasons from 1997 to 2022. The average value is presented as a solid line joining the average value (x) through each box. Data prior to 2022 was drawn using previous benchmarking results[2].

- In the wet season of 2022, there was a rise in the average total farm water input compared to 2021 (Figures 2d). The rainfall contribution to total water increased from an average of 2.84±0.12 in 2021 to 3.48±0.14 ML/ha in 2022, which was the highest recorded since 1997 (Figure 2c). However, the higher rainfall did not lead to less irrigation water being applied. Instead, the average irrigation water applied across participating farms increased by approximately one ML/ha compared to 2021, resulting in the total farm water input increasing by 31%, from 9.52±0.35 ML/ha in 2021 to 12.43±0.70 ML/ha in 2022 (Figure 2d). However, the average yield remained at the 2021 level (Figure 2a) and as a result, GPWUI declined from 1.22±0.04 bales/ML in 2021 to 0.98±0.04 bales/ML.

---

[1] The boxes represent the interquartile range where the middle 50% of the data lie. The x in the centre of each box is the average value, and the bottom and top whiskers represent the data range excluding outliers. The horizontal line inside the box represents the median value.

[2] Milroy 1996—1999 data (unpublished), Tennakoon and Milroy (2003), Williams and Montgomery (2008), Montgomery and Bray (2010), Roth et al. (2013), Montgomery et al. (2014), Perović et al. (2019), and McLeod et al. (2022).

- Some growers confirmed they continued irrigating the crop despite the high rainfall to ensure high yields were achieved.
- The likely reasons for increased total water input include: (1) a high proportion of the rain fell either early or late in the season when crop water demand was lower; and (2) the excessive rainfall early in the season caused waterlogging and the need to replant.

The seasonal fluctuation of the GPWUI has only been more visible after the yearly benchmarking commenced in 2018. However, no benchmarking was conducted in 2020 due to the continuation of the 2019 drought significantly reduced the cotton area.

The significant decline in the average GPWUI values in 2019 and 2022, compared to 2018 and 2021 values, highlighted the vulnerability of cotton water productivity to climatic extremes. After the drought (2019 — 2020), GPWUI increased from an average of 0.94±0.05 in 2019 to 1.22±0.04 bales/ML in 2021. This demonstrates cotton water productivity can bounce back from setbacks when favourable conditions return.

Despite yearly fluctuations, the Australian cotton industry is a leader in water productivity, with a 25-year average of 1.06±0.02 bales/ML. This is more than double the global average of 0.48 bale/ML, based on the latest available data published in 2011 (Mekonnen and Hoekstra 2011).

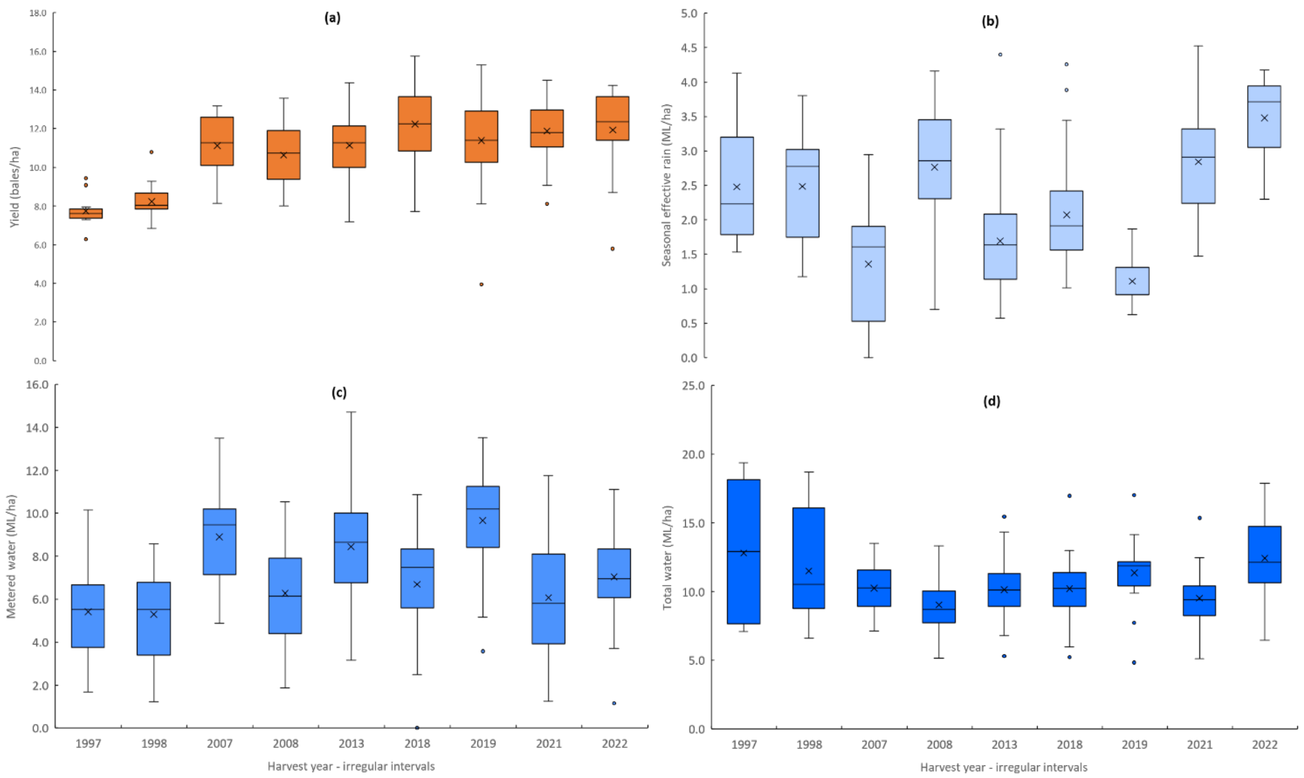

Figure 2. The trends of cotton yield (a), rainfall across farm sampled (b), metered water (c) and total water input (d) for cotton seasons from 1997 to 2022. Data prior to 2022 was drawn using previous benchmarking results[2].

Whole farm irrigation efficiency (WFIE)

The average WFIE values ranged from 45% to 83% during the benchmarking program and in 2022 it was 53% (Figure 3). In 2022 season, the WFIE values ranged from 30% to 83%.

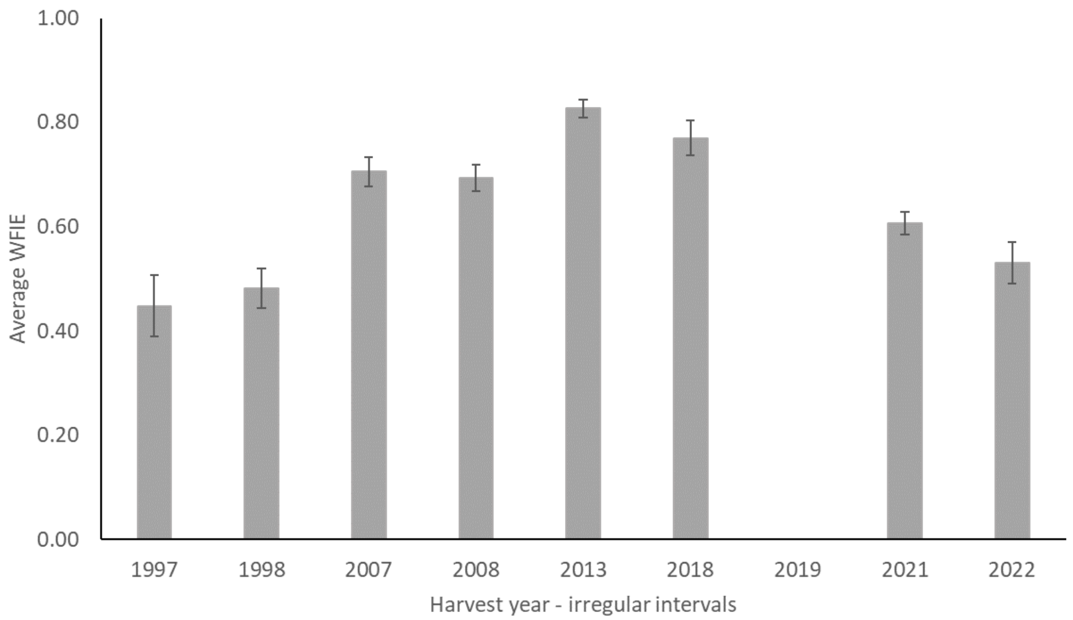

Figure 3. The average whole farm irrigation efficiency (WFIE) for cotton seasons from 1997 to 2022. There was no WFIE data for the 2019 season. Data prior to 2022 was drawn using previous benchmarking results[2].

The efficiency of a farm's irrigation system depends on how water is used or lost, as indicated by Equation 3. Cameron and Hearn (1997 *cited in* Tennakoon and Milroy 2003) proposed a target average WFIE of 75% for cotton. This target has been exceeded in 2013 and 2018 (Figure 3), which demonstrates the positive impact of strategies to improve water use efficiency implemented by cotton growers. However, flooding in 2022 caused the average WFIE to decline to below the critical level of 60%.

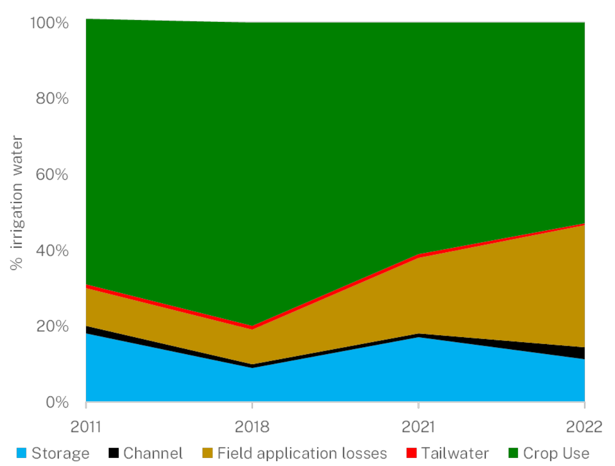

Figure 4. How irrigation water brought onto the farm is used or lost during the 2011, 2018, 2021 and 2022 cotton growing seasons. Data prior to 2022 was drawn using previous benchmarking results[2].

In 2022, the crop used only 53% of the irrigation water brought onto the farm, which is a significant drop from 61% in 2021 (Figures 3 and 4). The highest amount of water lost was through field application (32%), followed by storage loss (11%) and channel and tailwater losses (4%). The field application loss was estimated by solving the water balance equation on each farm. Any amount of water that is not accounted for is classified as field application loss. For instance, floods may damage the irrigation infrastructure, leading to undetected water loss. In some cases, the high proportion of field application loss may be due to the difficulty of measuring farm water in wet conditions, such as those experienced in 2022.

As presented in Figure 4, the partitioning of irrigation water could provide insights into the source of water loss and opportunities to reduce it. During wet seasons some growers may be able to capitalise on high rainfall and carry over irrigation water for the following season.

Opportunities for improving water productivity

The wide range of GPWUI values (Figure 1) and WFIE values in 2022 season suggest there is scope for most growers to increase their water productivity and irrigation efficiency. Growers who achieved the average GPWUI or less could aim for the GPWUI value achieved by the top 20% of growers when water productivity was highest in 2021. The technology and practices that can increase water productivity include increasing yield, reducing water loss and maximising effective use of rain (Mekonnen and Hoekstra 2014).

Cotton yield in Australia continues to increase but at a slower rate than between 1997 and 2007 (Figure 2a). Average WFIE has declined from its peak of 83% reached in 2013 to 53% in 2022 (Figure 3). This suggests the importance of increasing irrigation efficiency to greater than 60% by reducing total water input and preventing losses. This could be achieved by implementing partial or supplementary irrigation strategies and by using rainfall more effectively through water harvesting (Mekonnen and Hoekstra 2014).

Partial irrigation is a water management practice where crop water demand is not fully met with irrigation water (McLeod and Dadd 2023). The primary goal of partial irrigation is to use the available water strategically to maximise the yield per megalitre instead of yield per hectare.

Growers in Australia implement partial irrigation mostly in response to drought when water supply becomes limited. It can also be used by choice as a water management strategy. However, partial irrigation is not yet widely adopted in Australia. There is still a need to improve understanding of partial irrigation and its role in the cotton industry to increase adoption (McLeod and Dadd 2023). The Limited Water Decision Support research project co-funded by DPI and CRDC is addressing this issue.

Reducing water input addresses only one part of the requirement to increase water productivity. Improving yields through variety selection and agronomic management remains crucial to this effort.

The trend of the sustainable water use index

The sustainable water use index indicates the amount of water used to produce one bale or one kilogram of cotton. While GPWUI must be maximised, the SWUI should be minimised. A smaller SWUI value is preferred as it indicates that less water is required to grow a bale or kg of cotton.

In 2021, the average SWUI value was 0.84±0.03 ML/bale (3,716 litres/kg), the lowest compared with other years (Figure 5). At the same time, the GPWUI was the highest (Figure 1). In the wet season of 2022, the water required to grow cotton increased to 1.05±0.04 ML/bale (4,631 litres/kg). This is still a significant reduction from the 1.84±0.19 ML/bale (8,111 litres/kg) used in 1997.

The 25-year average of SWUI obtained from the benchmarking program in Australia is 1.03±0.02 ML/bale (4,531 litres/kg), which is significantly lower than the global average of 2.07 ML/bale equivalents (9,119 litres/kg) reported in 2011 (Mekonnen and Hoekstra 2011).

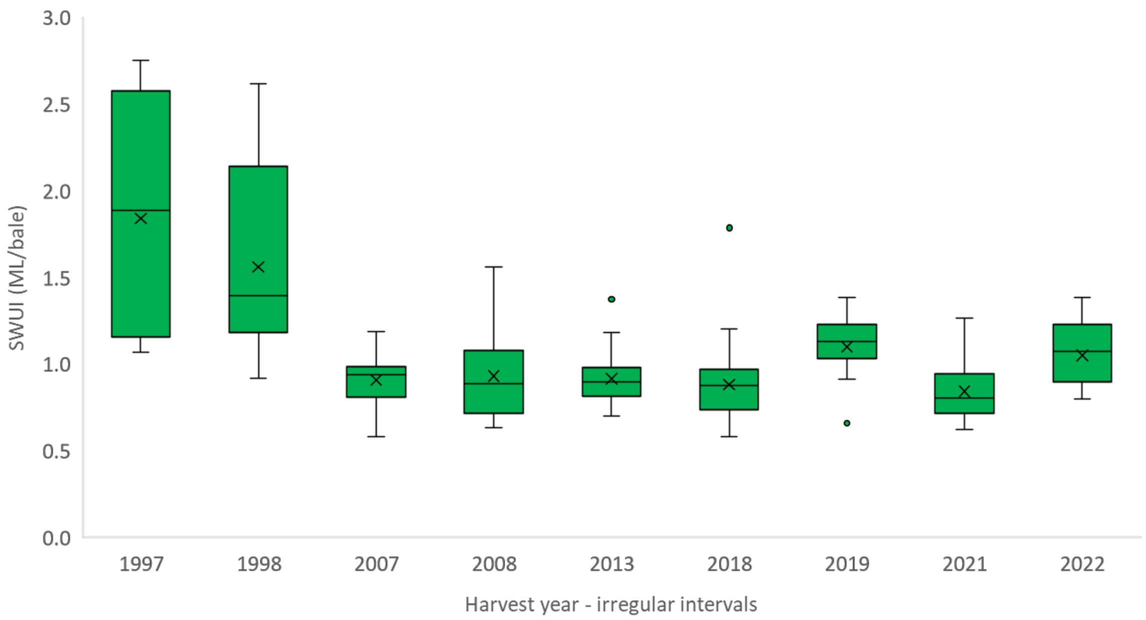

Figure 5. The variation of SWUI for cotton seasons from 1997 to 2022. Data prior to 2022 was drawn using previous benchmarking results[2].

Optimising cotton water productivity

Benchmarking data from 1997 to 2022 was used to investigate the relationship of GPWUI with total water input and yield (Figure 6). Figure 6a displays GPWUI as a smooth contour plot with total water input as x-axis and cotton yield as y-axis. Blue represents low, and red represents high GPWUI values. The black contour lines indicate the long-term average (1.06 bales/ML), 2021 average (1.22 bales/ML), and 80th percentile from 2021 results (1.41 bales/ML).

Figure 6b, shows the relationship of GPWUI (y-axis) with yield (x-axis) for selected values of total farm water input (6, 8, 10, 12, and 14 ML/ha). The horizontal dotted lines are the average GPWUI of 1.06, 1.22, and 1.41 bales/ML, as described above.

Figure 6 shows that high farm water input does not necessarily lead to a high GPWUI. This is because high water input does not always equate to high cotton yield, as other factors besides water affect the yield. Studies have found that crop yield increases with crop evapotranspiration up to around 700mm (7 ML/ha), and any additional crop water use does not result in an increase in yield (Tennakoon and Milroy 2003). In contrast, benchmarking data shows that lower farm water input (i.e. 6 — 10 ML/ha) could result GPWUI of greater than 1.41 bales/ML depending on yield.

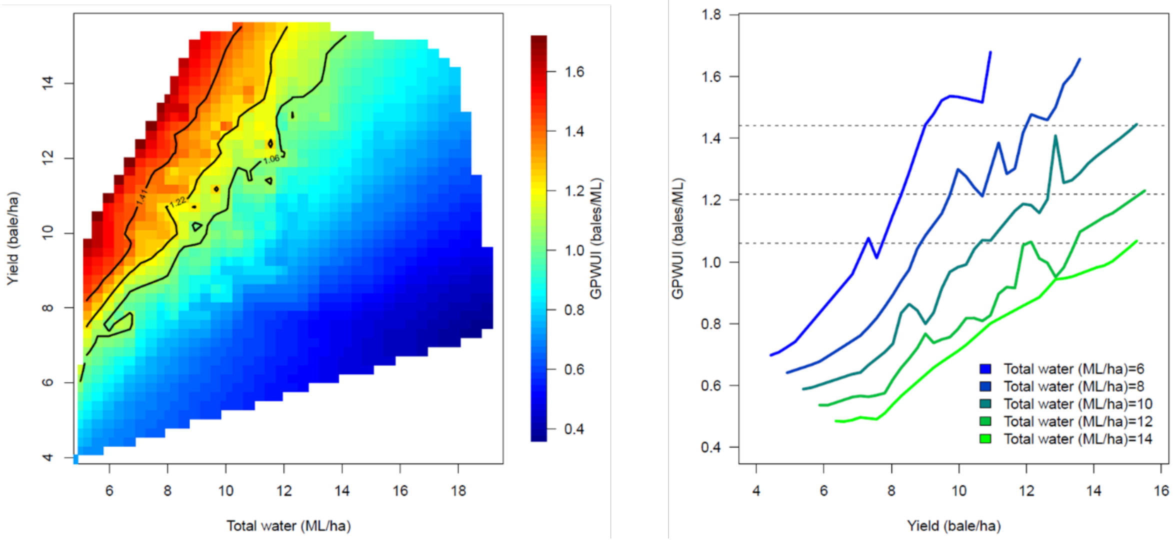

Figure 6. The relationship of GPWUI with yield and total farm water input: (a) contour plot of GPWUI where the blue colour represents low and the red represents high GPWUI, (b) the different coloured lines show the relationship of GPWUI with yield for selected values of total water. Data prior to 2022 was drawn using previous benchmarking results[2].

If the total water input on a farm exceeds 10 ML/ha, yield needs to be greater than 12.5 bales/ha to achieve GPWUI of 1.22 bales/ML which is the average from 2021. However, the benchmarking data has shown that yields over 9 bales/ha can be achieved with a lower total water input of around 6 ML/ha and resulted in a GPWUI greater than 1.41 bales/ML. Between 2008 and 2021, nine farms achieved a GPWUI of 1.42 to 1.72 with a total water input of 5.11 to 6.96 ML/ha, which supports the principle that partial irrigation can generate high GPWUI.

Growers can use these analyses as a planning tool to determine their target yield for maximum water productivity (bales/ML).

Conclusion

The benchmarking results from 2022 confirm the long-term trend of improving water productivity and sustainability indicators for Australian irrigated cotton. However, the rate of improvement has plateaued since 2007.

Both the water productivity and water sustainability indicators also fluctuate significantly with seasonal climatic conditions. They decline under climatic extremes and improve under favourable conditions.

Despite the seasonal fluctuations, over the long-term Australia produces over twice the amount of cotton compared to the global average from the same amount of water. In other words, Australia uses half the amount of water compared to global averages to produce a bale or a kilogram of cotton lint.

There is scope for continuous improvement in water productivity by optimising yield and water input. Growers can use benchmarking results as a planning tool to maximise bales/ML as indicator of water productivity.

Authors:
Malem McLeod, Research Officer, Water R&D North, Tamworth
Peter Regan, Leader Water R&D North, Orange
Sarah Dadd, Research and Development Officer, Water R&D North, Tamworth
Jasim Uddin, Research Officer, Water R&D North, Trangie
Steven Harden, Biometrician, Plant Systems, Tamworth

References

Chaves H and Alipaz S (2007) An Integrated Indicator Based on Basin Hydrology, Environment, Life, and Policy: The Watershed Sustainability Index. Water Resources Management 21: 883—895.

CRDC and CA (2020a) Australian Cotton Sustainability Report 2019. Sustainable Australian Cotton Planet. People. Paddock. https://cottonaustralia.com.au/assets/general/Publications/Sustainability-Reports/2019-Australian-Cotton-Sustainability-Report-Full-Report-2.pdf

CRDC and CA (2020b) Australian cotton sustainability targets: Stakeholder consultation report executive summary -December 2020. Sustainable Australian Cotton Planet. People. Paddock. Sustainable Asia Limited. https://www.crdc.com.au/sites/default/files/Targets%20update_summary%20stakeholder%20feedback.pdf

McLeod M and Dadd S (2023) Key practices and research gaps of on-farm management practices that drive water productivity in partially irrigated cotton systems. Project DAN 2203 milestone report to the Australian Cotton Research and Development Corporation (CRDC). Submitted, 30 November 2023.

McLeod M and Regan P (2022) Benchmarking water productivity of Australian irrigated cotton – 2021 results. Primefact PUB22/702 https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0017/1441142/Primefact-Revised-19-Dec-2022-T-and-D-PUB22-702.pdf

Mekonnen MM and Hoekstra AY (2011). The green, blue and grey water footprint of crops and derived crop products. Hydrology and Earth System Sciences 15(5): 1577—1600.

Mekonnen MM and Hoekstra AY (2014). Water footprint benchmarks for crop production: A first global assessment. Ecological Indicators 46: 214-223.

Montgomery J, Bray S (2010) Benchmarking water use efficiency in the cotton and grain industries. In '15th Australian Cotton Conference', 2010, Gold Coast. (Sydney).

Montgomery J, Hoogers B, Shepherd K, Bray S (2014) Water-use efficiency in the Australian Cotton Industry. In '17th Australian Cotton Conference', 5-7 August 2014, Gold Coast, Qld.

Perović D, Crawley B, Hume I, Hoogers R, Sun D, Uddin J, and Regan P (2019) Benchmarking water productivity of Australian irrigated cotton. Primefact 1705. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0006/1185288/Benchmarking-Water-Productivity-of-Australian-Cotton.pdf

Roth G, Harris G, Gillies M, Montgomery J, Wigginton D (2013) Water-use efficiency and productivity trends in Australian irrigated cotton: a review. Crop and Pasture Science 64(12), 1033—1048.

Tennakoon SB, Milroy SP (2003) Crop water use and water use efficiency on irrigated cotton farms in Australia. Agricultural Water Management 61(3), 179 — 194.

Williams and Montgomery (2008) Bales per megalitre — an industry wide evaluation of the 2006/07 season. 14th Australian Cotton Conference. August 2008, Broadbeach, Queensland.

Acknowledgements

The benchmarking of cotton water productivity is a collaboration between the NSW Department of Primary Industries, Australian cotton growers and the Cotton Research and Development Corporation (Project DAN2002).

This benchmarking project is supported by Cotton Australia Sustainability Program (Chris Cosgrove), CottonInfo water TechLead (Lou Gall), CSD and CottonInfo regional extension officers, and the project's Steering Committee members.

We are grateful for the ongoing support from Dr Janelle Montgomery – CottonInfo Program Lead, and during her previous role as regional extension officer in the Gwydir Valley with CottonInfo.

David Cordina and Dr Sean Murphy internally reviewed the draft of this Primefact for NSW DPI and provided constructive comments.

CRDC
COTTON RESEARCH AND DEVELOPMENT CORPORATION

Copyright and disclaimer statement