# Irrigation behaviours of wine grape growers in Australia

## Technical Report

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Australian Government
Department of Agriculture, Fisheries and Forestry

Future Drought Fund

TAS FARM INNOVATION HUB
Growing Climate Resilient Communities

UNIVERSITY of TASMANIA
TIA
Tasmanian Institute of Agriculture

This program received funding from the Australian Government's Future Drought Fund

**Acknowledgement of Country**

We acknowledge the palawa/pakana people, the Traditional Custodians of the land upon which we live and work. We honour their enduring culture and knowledges as vital to the self-determination, wellbeing and resilience of their communities. We acknowledge their continuing connection to land and sea, waters, environment and community. We pay our respects to their culture, and their Elders past and present.



**Cataloguing data**

This publication (and any material sourced from it) should be attributed as:

Song X and Evans KJ (2024) Irrigation behaviours of wine grape growers in Australia. University of Tasmania Technical Report for the TAS Farm Innovation Hub. 35 pages.

This publication is available at https://www.tasfarmhub.com.au/resources/

**Acknowledgements**

This study was funded by the Australian Government's Future Drought Fund. It was conducted for the TAS Farm Innovation Hub, as part of a collaborative project led by the SA Drought Hub, with the NSW and Vic Hubs.

We thank hub staff in Tasmania and Dr Harriet Walker from the Tasmanian Institute of Agriculture (TIA) for their support during this work. We also thank the cross-hub team led by the SA hub for their cooperation and collegiality. Dr Patrick Vaughan O'Brien and Dr Xiaoyi Wang from the SA hub contributed the interviews with the two growers in SA. We are most grateful to all the growers for sharing their knowledge and experiences.

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## Acronyms

| | |
|---|---|
| BOM | Bureau of Meteorology |
| ETc | Crop Evapotranspiration |
| ETo | Reference Evapotranspiration |
| GST | Growing Season Temperature |
| WUE | Water Use Efficiency |

## Key Findings

The following dot points highlight key insights from interviews for consideration by researchers, extension practitioners, and irrigation/AgTech service providers seeking to support on-farm practice change and/or to guide entrepreneurial experimentation during the process of commercialisation.

- Water use efficiency to grape growers generally means obtaining a financial return on irrigation.
- There is general recognition among growers interviewed of the need to use water wisely given limited water availability, high costs of irrigation and the need to protect the environment.
- Low water security, higher irrigation needs and higher costs for irrigation are growers' main concerns about the impact of a changing climate in which it is perceived that weather conditions will become more extreme and variable.
- Many growers are taking measures, or planning to take measures, to improve water security such as finding new water sources or methods to preserve soil moisture.
- All growers interviewed use drip irrigation, which reflects common practice across the sector. High maintenance needs and associated logistical challenges during operations were the main issues of drip irrigation experienced by interviewees.
- Many grape growers interviewed feel that they have sufficient experience to decide when, where and how much water to irrigate; decisions are influenced by market value of fruit and context-specific factors unique to the business or growing region.
- Objective environmental and soil data are valued to varying degrees; about 40% of growers view soil moisture sensors as having limited value in informing irrigation decisions.
- Solutions proposed by growers to optimise irrigation management include more accurate weather forecasts, irrigation technologies that support more informed decisions and drought-tolerant varieties or rootstocks.
- Growers need credible information and support to adopt irrigation technologies suited to their production context; the needs of small businesses are likely to differ from those of large businesses.
- Market-related issues of the Australian wine sector can limit growers' ability to invest in technology and infrastructure.
- Innovation must not focus solely on technology but consider change in many spheres and aspects of the farming system, including mechanisms to help growers transition to a state of greater economic and environmental resilience.

# Executive summary

**Background and aims.** Decreasing water availability and increasing needs for irrigation due to changing climate present a threat to the sustainability and profitability of growing wine grapes in Australia. Wise management of water across production regions will be needed to ensure a sufficient supply of fruit with desired qualities in the long term. Technologies or tools for scheduling irrigation can play a role in managing water wisely; however, adoption rates of technologies such as soil sensors have been found to be as low as 20% in some regions in Australia. An in-depth understanding of irrigation management from a farming system perspective is needed to understand factors promoting wise use of water and to guide development of new technologies and approaches.

The aim of this project was to obtain a nuanced understanding of irrigation behaviours of grape growers and their use of irrigation technology. Irrigation behaviours in this project include production goals achieved via irrigation, water sources, irrigation delivery and scheduling, and issues associated with these components of irrigation management. We also sought to explore growers' perceptions on future climate conditions and their plans to adapt to expected changes in climate. Semi-structured interviews were conducted with 32 growers from NSW, SA, Tas and Vic to explore these issues.

**Findings.** Growers mainly irrigate to achieve desired grape composition, ensure consistent yield and to establish and maintain vine health. Water use efficiency to growers generally means obtaining a financial return on irrigation and/or greater profitability. Growers also recognize water use efficiency in terms of the need to address limited water availability, high costs of irrigation and the need to protect the environment. Low water security is a major concern, along with the high maintenance needs of drip irrigation and associated logistical challenges during operations.

Key pieces of information that growers use to decide when and where to irrigate and how much water to apply include weather conditions, knowledge of water requirements of crops, soil moisture levels and experience. Other considerations are the growing stages of vines, soil types, varieties, production goals, topography, capabilities of irrigation systems and water availability. When access to water is restricted, then irrigation decisions for a given block of vines are also determined by the market value of the fruit.

When scheduling irrigation, most growers collect information on vine conditions through visual observations. Soil moisture levels are measured using soil sensors and/or by soil digging and visual assessment. One reason for non-adoption of soils sensors is that growers feel that they have sufficient experience to decide when, where and how much water to irrigate. About 40% of growers, including users and non-users of soil sensors, pointed to the limited value of this technology for informing irrigation decisions. The key issue is that information from one sensor is relevant to a small area of vines rather than the total area under management given spatial variability in land.

Growers generally believe that there will be more extreme weather conditions in future and that greater variability in the weather will present additional challenges for reliable weather forecasting. A few growers noted that rainfall patterns are being disrupted, leading to precipitation at times when vines may not need water. Water shortages, higher irrigation needs and higher costs for irrigation are growers' main concerns about the impact of a changing climate.

Many growers are taking measures, or planning to take measures, to improve water security such as finding new water sources or methods to preserve soil moisture. Actual or planned upgrades to irrigation systems and technology adoption are also part of growers' adaptation to climate change. Growers indicated that better irrigation technologies and associated

support for their adoption will be needed; however, market-related issues of the Australian wine industry can limit growers' ability to invest in technology and infrastructure. They also perceived that the technologies needed by small businesses might differ from those suited to large businesses.

**Conclusions.** Growers' irrigation management must be understood within the context of a system comprising production-related goals, water resources for irrigation, infrastructure delivering water to vines and scheduling of irrigation events informed by biophysical factors, farming experience, access to decision-support technologies and input costs.

While objective environmental and soil data are valued to varying degrees, decisions are also influenced by context-specific factors unique to the business or growing region. Solutions proposed by growers to optimise irrigation management include more accurate weather forecasts, irrigation technologies that support more informed decisions and drought-tolerant varieties or rootstocks. Growers seek credible information to evaluate alternative irrigation technologies or practices relevant to their production context.

Growers generally perceive that climate conditions will become more extreme and variable with disrupted rainfall patterns. Their perceptions contribute to concerns about water security when drought occurs, how best to adapt to changing circumstances, and what mechanisms and assistance will be available to help them to transition to a state of greater economic and environmental resilience. Innovation in this space must not focus solely on technology but must consider change in many spheres and aspects of the farming system.

# Background

The water resource for irrigated horticulture will likely become increasingly scarce due to rising temperatures, increasing frequency of extreme heat events and changing patterns of rainfall (Remenyi et al. 2019, CSIRO and the Bureau of Meteorology 2020). Crop evapotranspiration (ETc) for many production sites is expected to increase which entails higher demands for irrigation water. Decreasing water availability and increasing irrigation needs present a threat to the sustainability and profitability of irrigated agriculture in Australia, including grapevines (*Vitis vinifera*) for wine production.

Extreme water stress can restrict vine growth and berry development, thus lowering grape yield and/or quality (Ojeda et al. 2002, Romero et al. 2010, van Leeuwen et al. 2019). In Australia, for example, the dry conditions combined with water shortage in the 2019-20 growing season was associated with a 12% reduction in yield of wine grapes and 9% reduction in total value from the previous year (Wine Australia 2020, Bureau of Meteorology 2021). Given that droughts are likely to be more frequent and extreme in the future, growers need to manage irrigation wisely and prudently to ensure long-term vine health and sufficient yield of fruit with desired quality parameters.

Many technologies or tools have been developed to assist growers with irrigation scheduling decisions in terms of the timing and volume of water to be applied to vines. These tools can indicate water requirements of vines by generating plant-, soil- or weather-based information, such as sap flow of vines, soil moisture status and ETc. While a range of tools are commercially available, adoption rates of a given tool vary considerably among wine regions in Australia. For example, soil moisture sensors have been available for commercial use for over two decades; however, a survey of 180 growers in SA, NSW and Vic showed that, while more than 60% of the growers in the Murray-Darling Basin used soil sensors to inform irrigation scheduling, the rates were less than 50% and 20% for growers in the Riverland and Riverina regions (Dixon 2021). Variation is also evident in the adoption of different types of tools in the same region. Hornbuckle (2014) surveyed 72 grape growers in the Griffith region and found that 45 growers used moisture probes, six used evapotranspiration and one used a plant-based sensor. The reasons for the adoption or non-adoption of a given tool by grape growers operating in different production contexts in Australia are unclear.

Pannell et al. (2006) suggest that adoption of a technology can be influenced by its compatibility with existing technologies, practices and resources of the farm and its impacts on other components of the farming system in which all components are inter-dependent. As such, adoption of the technology can benefit from an in-depth understanding of the whole system in which it will be embedded. Enabling practice change towards more wise and prudent use of water for irrigation must therefore take a systems approach that treats irrigation scheduling as part of the irrigation management system comprising irrigation goals, water resources for irrigation, irrigation delivery, and irrigation scheduling.

The research presented here was conducted as part of a collaborative cross hub project “Modern Drought Management for the Health and Longevity of Perennial Horticulture Plants”(FDF Annual Report 2021-22). The aim of the project was to boost drought preparedness and resilience capabilities of horticultural farmers and rural communities engaged in wine grape, almond and citrus production across South Australia, Southern New South Wales, Victoria and Tasmania. Irrigation management plays a crucial role in resilience to drought. The project assumed that technologies that provide real-time information on canopy development and soil moisture can help growers optimise irrigation, thus enhancing drought resilience.

This report documents findings from a series of interviews that was designed to provide deeper insight into how growers in different regions currently manage irrigation, including use of

technology for irrigation management. It was intended to provide additional guidance on whether and how technology, like real-time canopy development information, could help improve irrigation or address problems growers have in managing irrigation. The findings are for use by researchers, extension practitioners, and irrigation/AgTech service providers seeking to support on-farm practice change and/or to guide entrepreneurial experimentation during the process of commercialisation.

## Project aims

Our objectives were to:

1. Obtain nuanced understanding of irrigation behaviours of grape growers, including production goals achieved via irrigation, water sources, irrigation delivery and scheduling, and issues associated with these components of irrigation management.
2. Investigate growers' use of technology in irrigation management and their perceptions of the technology.
3. Understand how growers perceive future climate and its potential impacts on irrigation and their plans to adapt to perceived climate change.
4. Identify opportunities and challenges associated with irrigation management and the role that technology can play in optimising irrigation.

The findings were expected to inform how farmers might be supported to address the challenges associated with managing irrigation and the role that technologies can play in supporting irrigation scheduling and other aspects of irrigation management to enhance growers' resilience to droughts.

## Materials and methods

This study used semi-structured interviews to collect information about irrigation management and related decisions of grape growers. This method enables data to be collected in a guided manner so that interviewees' answers to a given question can be compared and contrasted (O'Keeffe et al. 2016). Importantly, the method provides sufficient flexibility for the interviewer to explore a topic of interest while allowing the interviewee a degree of freedom to share their knowledge and experience and expand on issues that are important to them (O'Keeffe et al. 2016, Mason 2018). As such, semi-structured interviewing can contribute to in-depth understandings of not only how growers manage irrigation, but also underlying reasons for the management at a specific vineyard. The effectiveness of the method for collecting qualitative data, especially when they are scarce in literature, has been demonstrated by O'Keeffe et al. (2016) who applied it to explore irrigation practices of wheat farmers in India.

We used a purposive sampling strategy that considered demographic attributes including age, gender, education, experience in viticulture and employment type (Table 1), and business attributes including business type, vineyard size, wine region, viticulture type, business succession plan and grape price produced (Table 2). In doing so, we aimed to capture diversity in attributes of growers and the businesses where they work, given the evidence that these characteristics can influence growers' irrigation behaviours. Whittenbury and Davidson (2010) interviewed 36 winegrape growers in Griffith and showed that gender, farming experience, and business type (family or corporate) might influence irrigation scheduling. Seidl et al. (2021) surveyed 1,000 farmer irrigators in NSW, Vic and SA in terms of their adaptation plans for irrigation management in a changing climate. They found that education and gender of a farmer and farm succession plan can drive the farmer to increase or decrease irrigated area, to improve irrigation infrastructure and/or water sources. Based on 37 interviews with winegrape growers in SA, Wheeler and Marning (2019) reported that viticultural type, conventional, organic or biodynamic, can affect growers' perspectives on water security and adaptive management of water in response to climate change. We also assumed that age, vineyard size, grape price and regional climatic conditions could influence growers' irrigation behaviours.

Potential interviewees were identified from existing networks of the authors, referrals by peer researchers, and a public online database Wine Industry Directory (Winetitles 2022). Recruitment and interviews were carried out from November 2022 to February 2023. Interviewees included growers who owned and managed the business, and vineyard managers who worked as an employee of the business. For ease of discussion, all interviewees were referred to as 'grower'.

In total, we conducted 32 interviews with growers from NSW, SA, Tas, and Vic. Interviews and data collection ceased once information saturation was observed; that is, new interviews were not revealing new information. Each interview involved a face-to-face or telephone conversation that lasted between 13 minutes to 2 hours. Interviews covered goals of irrigation, water sources for irrigation and related issues, delivery of irrigation, irrigation scheduling, growers' perceptions on future climate and its likely impact on the business, challenges that growers face in irrigation management and support needed to optimise irrigation management and decision-making. The full interview guide is provided in Appendix A). Demographic and business attributes of each interviewee were also recorded. All interviews were audio-recorded and transcribed for analysis.

Thematic analysis of the qualitative data was a two-step process carried out using the software, NVivo (QSR International Pty Ltd. 2020): (1) interviews were coded to pre-developed themes such as 'irrigation blocks in vineyards' and 'goals of irrigation' to categorise responses to interview questions; and (2) data under each theme were coded inductively multiple times to identify emergent subthemes such as 'desired quality' and 'increased yield'. Frequencies of

interviewee references to subthemes under each theme were recorded. In the quotes of interviewees, 'G' refers to 'Grower'.

This study was approved by the Social Sciences Human Research Ethics Committee of the University of Tasmania (H0027749).

**Table 1. Demographic attributes of interviewees (n = 32).**

| Attributes | Category | Number |
|---|---|---|
| Employment type | Business owner | 13 |
| | Employee | 19 |
| Gender | Male | 27 |
| | Female | 5 |
| Age[1] | 25–34 | 1 |
| | 35–44 | 8 |
| | 45–54 | 10 |
| | 55–64 | 6 |
| | >65 | 6 |
| Education[1] | High school | 2 |
| | Diploma | 12 |
| | Bachelor's degree or higher education | 17 |
| Experience in viticulture (years) [1] | <5 | 1 |
| | 5–15 | 5 |
| | 16–25 | 6 |
| | 26–35 | 12 |
| | >36 | 7 |

[1]Data of one grower was incomplete

**Table 2. Attributes of the vineyards that growers managed, and the associated wine regions and growing season temperature (GST†) in each state of Australia**

| State of Australia | No. vineyards / Wine regions | Wine regions and GST (°C) | Wine business type‡ and vineyard size (ha)§ |
|---|---|---|---|
| South Australia | 15 vineyards<br>8 regions | Barossa Valley (19.0)<br>Clare Valley (19.1)<br>Coonawarra (17.3)<br>Eden Valley (18.4)<br>Langhorne Creek (19.2)<br>McLaren Vale (18.6)<br>Riverland (21.1)<br>Wrattonbully (17.5) | Thirteen family-owned, one Australian corporation and one research farm.<br>Vineyard size: < 20 to 500. |
| New South Wales | 7 vineyards<br>5 regions | Hunter Valley (20.2)<br>Mudgee (19.5)<br>Orange (18.1)<br>Riverina (21.8)<br>Tumbarumba (17.5) | Five family-owned, two Australian corporations.<br>Vineyard size: < 20 to > 500. |
| Victoria | 4 vineyards<br>4 regions | Grampians (17.1)<br>Beechworth (17.8)<br>Mornington Peninsula (17.4)<br>Yarra Valley (16.3). | All family-owned.<br>Vineyard size: < 20 to 100. |
| Tasmania (single region) | 6 vineyards<br>3 sub-regions | Central North (14.5)<br>East Coast (14.2)<br>Southeast (13.8). | Five family-owned, one Australian corporation.<br>Vineyard size: 20–500. |
| **Total** | **32 vineyards**<br>**20 regions** | | |

†Growing Season Temperature (Remenyi et al. 2019) is the mean temperature (Oct–Apr) across all growing seasons for 1997–2017. Tasmania is considered as a single wine region; however, GST is available on a sub-region basis only.

‡A family-owned business is a business in which the majority of ownership lies within a family. An Australian corporation is a business owned by the shareholders and with operations in Australia only.

§Vineyard size is the total area (ha) managed by the interviewee.

# Findings

### Demographic and business attributes

The 32 interviewees include both business owners and employees. Most of them are male and aged above 35 years. Many have completed higher education and worked in viticulture for more than 16 years (Table 1).

Growers manage 32 vineyards with a total area ranging from < 20 ha to > 500 ha, linked to 30 businesses in 20 different wine regions with different climatic conditions across Australia (Table 2). Vineyards within the same business, but managed by different growers, are treated independently. Most of the vineyards are managed in a conventional way, with some of them being converted into organic or incorporating some organic or sustainable practices into management. A few vineyards are certified organic. The main income source of all the businesses was grape and/or wine production. The GST in wine regions ranged from 13.8°C for Southeast region in Tas to 21.8°C for Riverina in NSW.

### Irrigation blocks in vineyards

Among 31 growers who answered this question, 30 said that all blocks of their vineyards were irrigated. Some growers described factors necessitating their irrigation, including the volume of rainfall in the region, soil type, temperature, and humidity. Many of the businesses were located in wine regions that had limited annual rainfall and/or high temperatures that dictate the need for irrigating vines. Only one grower said that 2 ha of the vineyard was not under irrigation because they were on floodplain; however, they planned to install an irrigation system for the 2 ha given reduced grape yields associated with few or no flood events in recent years.

### Goals of irrigation

Most of the growers indicated that irrigation is one of the practices they use to achieve targeted berry composition of one or more varieties they grow as required by their own wine product or wine of external wineries (Figure 1).

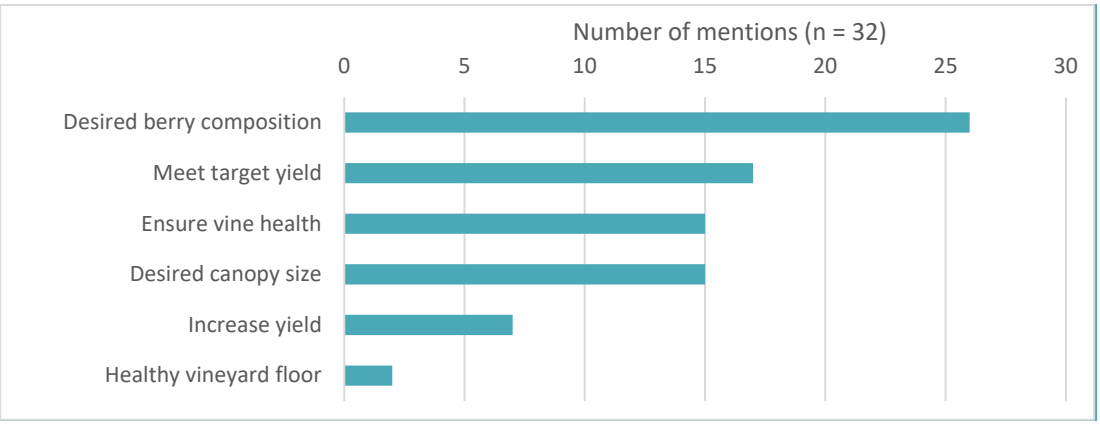


**Figure 1 Goals that growers aim to achieve through irrigation (n=32)**

Some growers pointed to the necessity of irrigating vines to produce consistent yields of required quality among seasons, especially for vineyards located in regions where annual rainfall is not reliable. Irrigation is also crucial for growers to establish and maintain healthy vines and canopies, which in return can produce desired fruits. One grower explained:

> "*So, if the vine is retaining its canopy and it's looking quite healthy and lush and dark green, then I feel as though there's the potential for the photosynthetic energy to transform and really work well and ripen the grapes to where I would like them to be... I was always told the old adage 'happy vine, happy fruit'*" (G13).

Another grower emphasised the importance of maintaining vine health which can affect yield and berry composition of the current and subsequent seasons.

> *"So, the aim we have is that the vines don't suffer at any stage… Because if they start to suffer, we lose quite a bit of time. They don't come to life as soon as we irrigate. It takes them a few days to continue to grow and develop… and the fruit will show stressed fruit flavours, so it won't make as good a wine. And then next season, when you ask the vine to wake up in spring and perform, it's not going to perform as well as it should because it's not been able to put away sufficient food reserves"* (G5).

Irrigating to increase yield was mentioned by some growers. Depending on the end use of a given variety, fruit composition may or may not be prioritised over yield. In addition to goals directly related to vines, two growers who managed organic vineyards used irrigation to maintain the health of cover crops under vines and inter-rows which is then expected to improve soil structure and organic carbon content.

**Water use efficiency**

Water use efficiency (WUE) to growers does not necessarily mean using less water, but often about achieving desired fruit production and obtaining financial return on irrigation. For example, a grower defined WUE as "*getting the maximum bang for your buck from your water*" (G12). As such, more water could be applied, when needed, available and affordable, to produce desired yield and/or quality and ultimately generate greater profits. Another grower described an instance where growers would increase irrigation to increase yield:

> *"When we've gone through periods of very, very low price* [of grapes]*, most growers are motivated to grow more. And the easiest way to do that is to apply more water. So, when you've got a low value product, we go on and waste precious resource to grow more of it, to get a greater return"* (G19).

Twenty-seven growers stated that WUE, as defined by them, is important to them. Eighteen growers provided reasons (Figure 2), with major factors including controlling costs of water and/or electricity for irrigation, serving goals around environmental sustainability, limited availability of affordable water, and obtaining greater return on irrigation inputs.

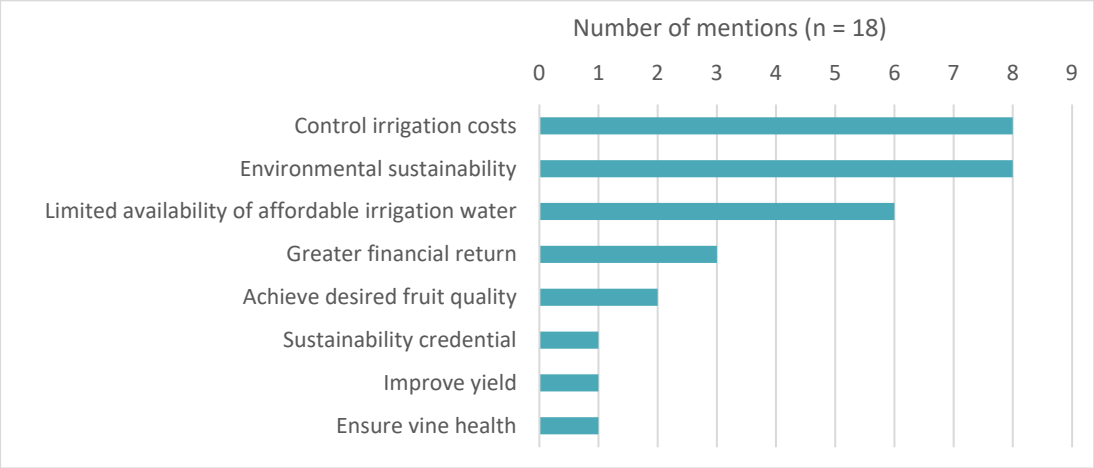


**Figure 2. Grower's reasons/motivations for using water efficiently (n = 18)**

Environmental objectives can compete with financial ones, with grower G14 describing the challenge of balancing competing priorities.

> *"We have competing priorities to use water efficiently as environmental managers, but we also have a lot of pressure to produce maximum yields… And so, the vines might only need two hours a day, 'Oh, we'll put three hours a day on, playing it safe'. So, you've got competing priorities there with, on the one hand, you're trying to save water because you have a responsibility to do that, and that's the right thing to do, environmentally, but also you have the business, profitability is really important"* (G14).

Using water efficiently was of little or limited relevance to a few growers. While irrigation is only supplementary for one grower, the major reasons are that these growers have sufficient water resources at affordable costs and/or there are few or no financial benefits of improving WUE.

> *"I know I use too much water but... And I would rather use too much than not enough. My efficiency is very, very poor. And I know it's very, very poor... I know I should be more diligent and use water more wisely than I do, but I've got no reason to have to do it… The access and the ability to use more water than required is actually cheaper than trying to be more water conscious"* (G9).

Interestingly, such behaviour was disapproved of by a grower who previously had high water security and applied irrigation generously.

> *"In the previous vineyard I worked at, we had more than enough water, from the license point of view.* [It] *made you turn the pumps on, turn it on when it suited, when it felt like it almost. Because it didn't matter if we wasted the water because we had plenty. And that's dumb"* (G8).

**Water sources for irrigation and related issues**

Among the 32 wine businesses, 21 source their irrigation water from a major river (e.g. Murray River) or a lake under a water license, 12 from a catchment filled by rainwater, 11 from groundwater such as aquifers or bore water, and four from recycled water. A single vineyard can have more than one water source. Some growers have on-site dams to store water while others do not. One reason for the latter is that having a storage dam on the site is not cost-effective.

> *"If we also have a dam on the property, storage one, you have to then manage evaporation. So it's got massive infrastructure costs building a dam, and the evaporation of the* [region] *is too great. Some people have built them, but the numbers don't stack up. It's definitely not cost effective. We just don't have the rainfall to fill it, so we don't have run-off because it's sandy soils and we don't have enough rain to fill it"* (G12).

The growers discussed various issues associated with sourcing or using water (Figure 3). The most common was the potential for low water security when drought occurs because their water allocation can be reduced, and the water price can go up significantly. This situation not only makes it more difficult to obtain irrigation water, it also increases irrigation costs and decreases profitability. Accessing water in a drought is especially challenging for growers without on-site water. One grower explained:

> *"Once water becomes restricted under allocation, so say below 70%, prices sharply increase. So, water trading happens between people that are willing to irrigate for a season or not. And that market's out of whack with where we really can afford to stay in production. So, previously in years where the allocation has been low, price of irrigation water goes up to about a thousand or over $1000 a megalitre, which then makes the return on product virtually non-existent"* (G3).

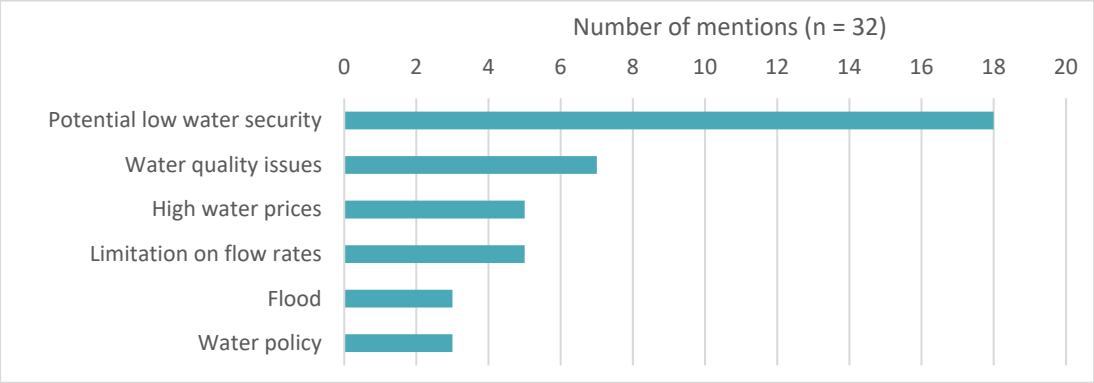


**Figure 3. Issues growers (n = 32) reported associated with irrigation water.**

Other issues raised included:

- Water quality such as salinity, which can contribute to blockages in drip systems described in the next section.
- High water prices at all times,
- Restricted flow rates when there is high irrigation demand during droughts. Low flow rates means that water may not be delivered when vines need it, resulting in negative impacts on vine health, yield and/or berry composition., and
- Flood events cutting off power supply to irrigation pumps.

Three growers criticised policies or rules associated with irrigation in their region as unfair or detrimental to the sustainability of the wine industry. Specifically, a grower sourcing recycled water is required to purchase two thirds of their entitlement every year regardless of actual water needs of the year; another grower is required to pay for storing water in their on-site dam which the government encouraged them to build. These policies increase their production costs.

Moreover, another grower expressed his concerns that the unrestrained development of irrigated agriculture, such as almond plantations, will likely exacerbate water shortage risk for all permanent irrigators in their region.

> *"In our region, we have a massive almond orchard being planted currently and in seven years' time in full production. That all will require 30 gigalitres of water. So the demand for irrigation water is gonna get higher and higher, and then in the meantime, there is less water becoming available. It is going to be a very, very serious risk indeed"* (G19).

This grower also felt that when drought occurs, it is inevitable that some businesses will not survive.

> *"That horse is already bolted. So, the lack of regulation with irrigation development means that that risk is getting worse every day. So we have irrigation water management through the Murray-Darling Basin Plan, but we've had state governments fully enthused to encourage economic development of irrigated agriculture. So, there will be blood in the streets when there's a dry year, because it's just like if you and me, and we all sit around the table and the food is delivered and there's not enough food for everybody at the table, it's gonna be a fight. And that's exactly what will happen, and there won't be a solution. There won't be a solution. So, whoever's got the food first will survive, those who don't have won't have it. I don't think we've had the start of it, let alone the end of it*" (G19).

**Delivery of irrigation**

All the growers use drip irrigation mainly because it is efficient in delivering irrigation. In addition to drip irrigation, four growers also use overhead sprinklers to control damage on vines caused by frost or extreme heat, and one grower uses micro irrigation that he inherited from his father.

While enabling efficient water use, a common problem associated with drip irrigation raised by growers is the high maintenance needs. Typical requirements of maintenance include monitoring of blockages, leakages and other damage, and regular cleaning of the system. These activities, which need to be undertaken constantly to ensure the system operates effectively and reliably, are often time- and labour-intensive. For example, one method used by a grower for monitoring the drip system during night-time irrigation is placing buckets under emitters in different blocks and checking the volume of water in them the next day. Another grower commented on the challenge of monitoring drip system without a comprehensive monitoring system:

> *"Unless you put in a really good system of reporting back what's going on at various stages through the system, unless you actually go down and watch it on a regular basis, you don't know if you've blown a pipe, you don't know if the pump suction is blocked up in dams... There's a lot that can go wrong that unless you've got a very, very sophisticated monitoring system, the easiest and best way is to actually go and look at it" (G18).*

A few growers reported other problems of using drip systems, including disposal of backwash water, high cost of installation, the lack of local drip tube recycling, and short lifespan of drip tubes.

The operation of valves of drip systems can be controlled manually or automatically via computer software or mobile phone applications. Most growers interviewed use automated control which allows them to flexibly manage irrigation off-site and saves time and labour from not having to travel to irrigation blocks. However, a control system can fail. For example, a solenoid valve can fail to operate due to damage on the wire connecting the valve and the controller, highlighting the importance of monitoring the system.

Nine growers manually turn on and off valves, but many of them pointed out the problems of this control method. In addition to being time- and labour-demanding, manual operation increases power costs and water loss from evapotranspiration given that irrigation is often applied during the day rather than at night.

While two growers interviewed had plans to change from manual to automated control, the other seven felt it was unaffordable. In addition, one grower expressed concerns about the reliability of remote control and that visually seeing the irrigation provided a sense of assurance. Another older grower preferred manual control systems due to their perceived lack of self-efficacy of using an automated irrigation system.

> *"Automation, yeah, it's great, but again automation takes knowledge or understanding of how it all works and if something goes wrong with it, I've gotta get somebody else in to fix it, so it's easier to stay away from it… If I use an example, I can fix the 50-year-old tractor, I can still do the job. But I can't fix the 1-year-old tractor that's got full of computers and things like that. Yeah. It might sound efficient, but that's how as an old farmer you operate"* (G29).

### Scheduling of irrigation

Growers were asked about how they decide when and where to irrigate and how much water to apply during a growing season. The key pieces of information that growers collect to schedule irrigation include weather conditions, water requirement of vines, and soil moisture level. They also draw on viticultural experience and take consideration of a range of factors related to the vineyard, crops, and business, such as growing stage, soil type, variety of vines, production goal, capacity of the irrigation system, and topography (Figure 4). This section discusses how various pieces of information are collected, used and/or perceived by growers in terms of irrigation decisions.

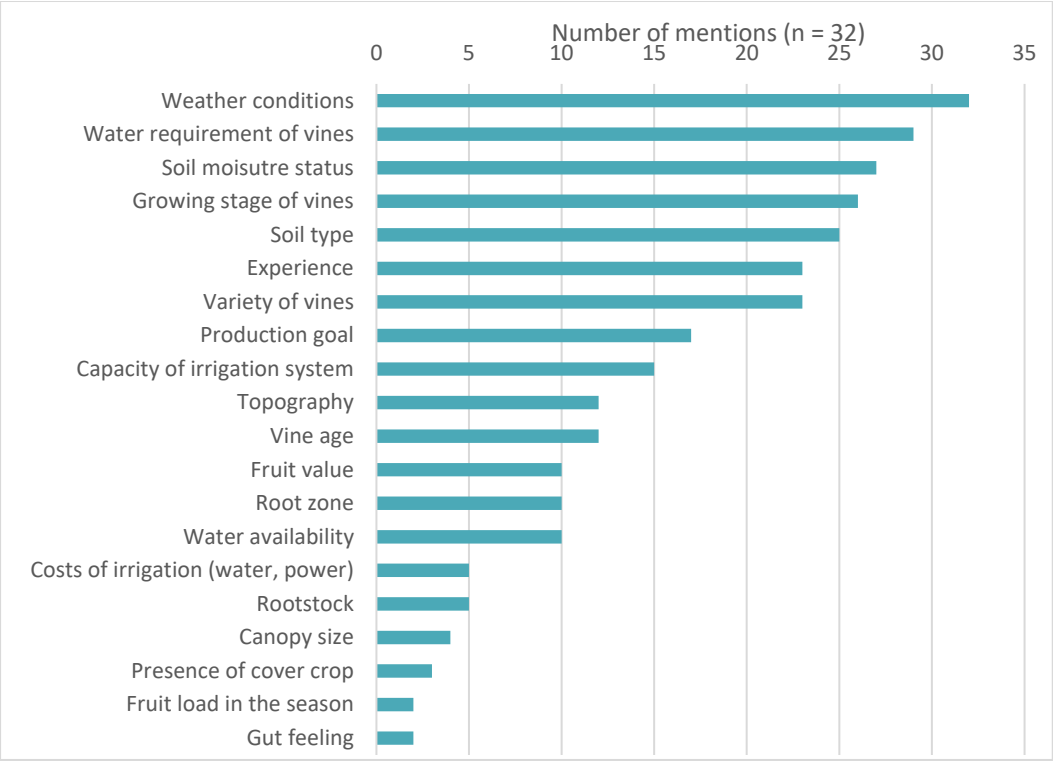


**Figure 4. Considerations growers reported that support irrigation scheduling decisions (n = 32).**

*Weather conditions*

Commonly collected weather data include evapotranspiration (ETo), previous and predicted rainfall, temperature and humidity sourced from Bureau of Meteorology (BOM), on-site weather stations and/or other smartphone applications. Accurate weather forecast is vital for growers to avoid over- or under-irrigating which can negatively impact yield or berry composition, especially when they occur at critical growing stages such as veraison. Several growers expressed frustrations over inaccurate forecasts from BOM, such as overestimation of rainfall volume, although some acknowledged the challenge of accurate forecasts due to changeable weather conditions in some regions.

*Water requirements of vines*

Water requirements of vines are predominantly assessed through regular visual observations of the vineyard. This activity also enables growers to monitor pests and diseases. While emphasising the importance of visual observations, "*you can't manage a vineyard effectively by just being in the office"* (G27), growers indicated that visual signs of vine stress may be too late to be useful for irrigation scheduling:

> *"More often than not, by the time you see the vines starting to struggle, lose their chlorophyll and start showing signs of stress, that soil moisture has already gone past the point of where it should have been"* (G13).

Physically inspecting vines is time demanding. Growers managing large areas of vines, such as a few hundred hectares or more, usually do not have sufficient time to visually inspect all blocks for informed irrigation decisions. To avoid risks of under-watering, growers may apply more water than needed.

> *"Because the vineyard is quite big here, I can't go out every day and walk through the blocks. So that's where it can be a challenge. And that's why I said sometimes, from risk management point of view, you defer to, 'Okay, we'll put a little* [more]*', perhaps play it safe in terms of applying water"* (G14).

In addition to in-vineyard observations, several growers use satellite imagery to obtain an overview of crop performance in different parts of the vineyard, which could then inform irrigation application. Satellite imagery is also used to detect issues associated with irrigation system, such as water leaks. Growers using satellite imagery mostly felt that its resolution and frequency of image captures are sufficient to guide their irrigation except one who said that the 8-meter resolution they receive is too low to be useful for them.

Some growers are trialling or have adopted crop sensors that indicate water status or stress of vines and they generally viewed the sensors positively. A grower commented that the sensors provide them with data to base decisions on, thus enabling them to be pre-emptive in irrigating.

> *"Now, all of our irrigation decisions are very, very easy because they're actually based on digital data coming out of the sensors in our vineyard. It is not guesswork. And as I said, we can now be pre-emptive in what we do, so we can actually control our vines rather than the other way around, rather than them controlling us"* (G19).

Differing from this grower, a grower who has trialled the same sensor and decided not to adopt it said that it is not suitable for wine grapes because it falsely suggests irrigation requirements which causes mental stress.

> *"They* [the sensors] *were telling us to irrigate, I assume this model is based on table grape industry and almond industry scenarios. It was stressful because I'd*

> *wake up in the morning, have a look at the* [sensors*] and it would indicate red, red, red, 'irrigate, irrigate, irrigate'. At this particular point of the growing season, we were trying to reduce or stop active growing tips. So yes, it was quite stressful actually, the computer program was telling me to irrigate when we would usually be drying down to stop shoot tip growing making the bunch the sink"* (G21).

This grower then suggested that the sensor needs to be adapted before it can be adopted by wine growers.

> *"I think the program just needed tweaking. Tweak the water requirements at different growth stages, specific for wine growing. It's probably different for every region as well. But yes, look at that growth cycle of the vine and relate that back to the parameters for growing premium fruit. Varietal requirements would possibly differ as well. So yes, it's difficult to have a one-product-fits-all, I guess"* (G21).

*Soil moisture status*

Soil moisture status is another key factor for growers' irrigation decisions. More than two thirds of the growers measure soil moisture using some types of soil sensors while many also dig into the soil and visually assess the moisture status.

Growers using soil sensors regard them as useful for informing irrigation decisions because the sensors enable them to conveniently view real-time moisture status of the soil at different depths and then gauge the amount and frequency of irrigation needed for a block of interest. Importantly, seeing the measurements gives growers confidence in irrigation decisions, especially for those who are inexperienced in viticulture and/or irrigation management. A grower explained that using soil sensors has enabled him to make confident decisions.

> *"I think earlier in my career trying to get my head around water, I found a lot of difficulties and a lot of frustration because no one could give me an answer of how much water I should be watering a vine. It was often talked about, you know, 'it's just a feeling'. So, I'd like to measure something and say… well, I can't measure feeling. If I feel like they've had enough, that's not suitable. And so I felt like I put enough water on, but with the measurements that we do and the work that I've done in the past, I've got a lot more confidence and I could justify my case if I was asked whether or not I put enough water on or not"* (G6).

Using soil sensors also helps growers learn about changes in soil moisture in response to irrigation and to water use by vines, thus allowing them to predict irrigation needs and schedule irrigation events proactively. As growers build up more knowledge about irrigation, they become more experienced and less reliant on using sensors that "*almost to the point now where we just use our soil moisture probes as an indicator of has it irrigated or has it not irrigated*" (G6).

While growers value soil sensors, some pointed out that they only inform soil moisture status of a restricted area. However, there are typically variations in soil types, topography, varieties, clones, vine ages and canopy sizes in a vineyard or even within an irrigation block; damage of the drip system, such as leakages or blocked emitters, can also occur near the sensor. These variables mean that soil sensors have limitations in informing irrigation beyond the area where they are installed. However, it is not economically or practically feasible to install multiple sensors to account for every variable across the vineyard. Another limitation of soil sensors is that the measurements do not inform water use by crops. A grower explained:

> *"A soil probe just tells you how much water is in the soil or how much suction is in the soil depending on what system you've got. It doesn't tell you how much water the vine is using or the vine water status. But for me, that would be the ideal scenario is actual measurement of vine water, use vine water status, not soil moisture, which is an indirect method, vine water status is direct"* (G14).

Additionally, several growers reported the complexity of interpreting soil moisture data to inform irrigation decisions, for example, "*it's a bit of a complex matrix to really be able to optimise the efficiencies that can come from that technology of understanding what's happening in our soils*" (G27).

That a soil sensor only measures a restricted area is a key reason for non-adoption by some growers who perceive it as not informative for irrigation decisions.

> *"My problem is with them they tell you exactly what's in the soil at that specific spot. And we've got a vineyard that's got quite a lot of different soil types within blocks. So yeah, what one moisture sensor might tell you might be perfect for that one-meter cube around that soil monitor sensor. But it doesn't necessarily tell you what the whole block needs" (G30).*

Given the limitation in measurements, a grower felt that using soil sensors is not cost-effective for time and effort inputs and can even lead to over-watering vines.

> *"I guess I find there's too many other variables in our farming practices and the monitors are only a guide and, basically that I got too frustrated with the time and effort putting into monitoring to the benefit I was getting out of it… From my experience, I found a lot of people use more water when they've got moisture probes because it tells you that it's too dry, and that's just my personal opinion. It is an accurate indication of what your soil moisture is, but when your moisture is supposedly low, I mean it's a number of factors, I mean, how deep are your roots? What's your soil profile?" (G29).*

Another key reason for not adopting soil sensors is that growers believed that they have sufficient experience to estimate water needs of vines and schedule irrigation accordingly. Soil sensors provide little value to them but are "*telling us stuff we already know*" (G17). These growers were more than 45 years old, have more than 16 years of experience in viticulture, and extensive knowledge of the vineyard they work in. A few of them acknowledged that using sensors would help them if they were inexperienced growers.

Other reasons for not using a soil sensor include a lack of knowledge to confidently interpret sensor readings to guide irrigation decisions, not being aware of what sensors are available and suitable for their needs, high financial cost of adoption, and preference of personal observation: "*I really prefer to let the vines tell me rather than trying to measure it*" (G18).

Despite these issues, three growers expressed intentions to adopt soil sensors in order to: use water more effectively by avoiding over-watering; to obtain a better understanding of soil water status; to be pre-emptive in irrigating; and/or to save labour in visually observing vines. A grower who intends to adopt soil sensors described the challenge of irrigating proactively when relying on visual observations and how sensors could improve their irrigation scheduling.

> *"My old-fashioned system of feeling the leaves and looking at the vines is a slightly more reactive system in that, it's harder for me to forecast. They [soil sensors] know how much water is in the soil, and that is hard for me to tell, except by seeing when the vines are getting unhappy. I can tell a happy vine and I can tell an unhappy vine, but it's hard for me to tell how quickly they're gonna say 'I'm not happy'. After a while, if you have probes, you would then get*

> *to know that when the negative pressure is at a certain level at a certain depth. You would then learn that that's when you turn the irrigation on without even looking at the vines" (G5).*

*Experience*

Experience plays a critical role in irrigation management and is valued greatly by growers. As mentioned above, some growers do not use soil sensors because they are confident in relying on their experience. Indeed, a grower was told that *"a good viticulturist should not need any probes"* and believed *"if I'm a 60-year-old man that's been planting these vines and growing it, I probably don't need a probe"* (G20).

While being confident in using experience, a grower expressed mental stress of relying on it for decision-making without having objective data.

> *"I think the only difficulty is mental in the fact that you're relying on your own mental judgement to decide when to and how much to. And you can often look back after it's happened and think, 'oh, I made the wrong decision' or maybe if I had done this differently or maybe I could have done that differently. So, you are relying on your own mental ability to do something. If you are monitoring or were monitoring you've got something and you can sort of say, 'oh, well, the machine told me that I should have irrigated, so I did'. So, there is always that situation where you think, 'gee, maybe I should have put some more on or maybe I shouldn't. I don't. I do. I don't. I…' And the mental deliberation over 'do I' or 'don't I'"* (G9).

This stress was echoed by another grower who also pointed out potential negative impacts of a suboptimal irrigation decision on profitability.

> *"When you're confronted with a decision-making process based on no information, it's incredibly stressful because you don't know whether you have made the right decision or the wrong decision. When you're involved in trading water, you could go and spend $200,000 one day and then realise if you had done it two or three days later, you might have saved $50,000. There's no way of knowing or predicting what the outcome of your decision was going to be"* (G19).

Another weakness of purely using experience for decision-making is that irrigation management is not documented, contributing to a risk of losing corporate memory.

> *"Now, if I was to leave, I'm sure the next manager would have to put in a different system or he would have to be very, very, very vigilant on what we did to be able to do it. Because there is no graphs, nothing in historical, 'this is what it was, this is what we did'. Zero documentation"* (G9).

Experience, as stated by Grower 19, can be subjective and region-specific and therefore may not be applicable to a region of interest.

> *"Interestingly, growing grapes is like a lot of other commodities, myth becomes fact, right? So over time, what great grandpa did, and what grandpa did, and what dad did, and what the kid did in the end becomes fact. And in the end, it was a myth to start with. And we suffered that a lot in the wine industry here* [the region], *because so much of our historic viticultural advice has come from winemakers who only produce the best wine they believe, and out of the cool climate regions"* (G19).

*Other factors influencing irrigation scheduling*

In addition to collecting information about weather conditions, water requirements of vines and soil moisture levels, and using experience, growers also consider a large number of other factors (Figure 4). Growing stage of vine, soil type, variety, production goal, irrigation capacity, topography, vine age, fruit value and water availability were frequently mentioned as important factors influencing irrigation decisions (Figure 4).

These factors are considered together when designing irrigation programs rather than each one in isolation. For example, irrigation may be restricted to a certain degree after veraison for a block of a red variety that is targeted for premium fruit quality, which growers believe can result in "*a more complex with more distinct flavour fruit*" (G20). Compared to a red variety, a white variety will likely receive more irrigation to increase berry size and enlarge canopy size to protect berries from sunburn.

For a given variety in a block, topographic and soil characteristics of the block and vine age can affect the amount and/or frequency of irrigation and where in the block to irrigate. Specifically, younger vines tend to have shallower roots and be less resilient to dry conditions than older vines and therefore are likely irrigated more frequently. Vines planted on the top of the slope are often irrigated more frequently than those at the bottom on account of water runoff and/or lower water holding capacity of the soil at the top slope than the bottom. Growers said that soil type varies across their vineyard and even within an irrigation block, presenting challenges for estimating irrigation needs and/or applying the right amount of water when the irrigation system is not matched with soil variability.

If an irrigation is unlikely to downgrade the value of the fruit, growers may not be concerned about precise water requirements of vines. As such, vines could be under- or over-irrigated depending on irrigation capacity of the system and water availability.

> *"I know there is a variation in fruit quality from area to area because as I say, some vines are definitely getting overwatered compared with others that are possibly being underwatered. But over the entirety of the vineyards, the over watered vineyards and the under watered vineyards are still making premium grade fruit"* (G9).

> *"If you are just running a C or D grade and it was just juice going wherever, it's not such an issue because you just switch it on. If it gets overwatered a bit, it doesn't matter, it's just cheaper parcels of fruit. But when you're talking at the top end there, you have to be really precise with some of the gear"* (G26).

When there is limited water available for irrigation, the market value of a given block can influence the amount of water it receives.

> *"At the minute, red fruit's not worth anything. We are concentrating on our whites. Yeah. And the reds we can be quite mean to. Really. Because my Pinot Gris [a white variety], I've got a contract on that. Whereas right this minute, nobody is knocking at my door to buy Cabernet Sauvignon* [a red variety]. *That's the economic reality of what we have to do"* (G17).

Growers also need to consider whether an irrigation decision can be implemented easily and effectively by their irrigation system and the costs of power and water for implementing the decision. To lower irrigation costs, growers having solar powered irrigation usually irrigate during the day whereas those not having solar power irrigate during the night using off-peak electricity.

**Perceptions of future climate, potential impact and responses to the climate**

Two recurrent themes in the interviews about perceived future climate are more extreme weather events in both frequency and variation, and increasing variability which likely makes weather less predictable. A sign of increasingly variable climate, as suggested by several growers, is that rainfall patterns are being disrupted, resulting in rainfall at times when vines may not need water. Growers generally believed that the climate is not necessarily trending towards warmer and drier but that the opposite can also occur.

> *"Supposedly the planet is warming up, but we're* [a significant amount] *wetter this year than we've ever been. This is the wettest I've ever seen the vineyard. So, is that climate change, everything warming up or is it just climate change as in the climate's changing and we're experiencing more rain this year and next year we won't experience any rain at all? I agree that it's changing but I'm not prepared to say that it's going to get hotter and drier"* (G9).

Growers suggested that some of those changes in climate, such as extreme heat and extended dry periods, will likely lead to or aggravate water scarcity for irrigation and/or increase irrigation demand, thus leading to greater irrigation costs and/or negatively impacting grape yield or quality. When water is limited and/or return does not justify the costs, growers may choose to reduce or eliminate irrigation for some blocks of lower market value in order to preserve water for blocks of higher value.

> *"If we go into severe drought again, which will happen sooner or later, there's every chance that we will just not water some blocks at all. Because of the change in the dynamics of the market, like the marketplace generally, and the change in preference for some varieties" (G8).*

Extreme heat events can also challenge the capacity of the irrigation system. When the system is not capable of delivering water as required, growers may have to prioritise irrigation according to fruit value. A grower described the challenge of dealing with extreme heat events.

> *"I think when we get into the heat waves, when we really have a severe heat wave, the temperatures are pushing up like 45 degrees Celsius, and the pumping capabilities are really stretched, especially supplying that irrigation for the vineyard. So, I have to make decisions around what parts of the vineyard are worth the most money and what parts of the vineyard could probably handle a little bit of heat stress compared to other parts. Yeah, the most challenging is dealing with severe and extended heat waves"* (G15).

In addition to perceived drier and warmer conditions, some growers are concerned that wetter conditions can also impose challenges on growing grapes. For example, excessive rainfall around flowering and veraison can negatively impact fruit set and increase disease pressure, thus leading to yield and/or quality loss. Additionally, changing rainfall patterns means that growers might need to adapt irrigation programs accordingly.

Another likely impact of changing climate is that variable weather conditions, when not predicted accurately, can make it difficult for growers to estimate irrigation requirements of a given season and plan for irrigation programs.

> *"It's called climate change. Well, it makes managing the water very hard. You've gotta have, you know, how much water should I put on in that November, December period to optimise the yield? But at the same time, I've still got to have some water up my sleeve to get me through those hot summer months*

*and then small amounts of irrigation to keep the leaf area functioning during the lead up to harvest"* (G31).

To four growers, perceived changes in climate will bring little impact on their production or management. This is mainly because they have sufficient water resources and/or effective irrigation-related infrastructure, which give them confidence in being able to adapt to climate change.

The growers interviewed either have made, or plan to make various changes related to irrigation to better adapt to perceived changes in climate. Changes mentioned include improving water security by increasing water sources such as building new dams or exploring the use of recycled water, and improving soil moisture retention by planting cover crops or applying compost or mulch. Two growers who planted grass under vines noticed an increase in water use; however, it brings about other benefits to the vineyard, such as decreasing temperature and improving soil health.

Several growers mentioned changing to rootstocks or varieties that are drought- and heat-tolerant; however, there is then uncertainty in consumer acceptance of wines produced from new varieties. A few other changes that growers have made or plan to make are upgrading irrigation infrastructure to improve irrigation capacity, adopting technologies such as soil or crop sensors to better inform irrigation decisions, and learning to adapt irrigation to changing rainfall patterns. A grower who has taken on full responsibility of irrigation management for less than one season indicated a need for greater knowledge of the soil and water requirements of each block in order to deliver grapes to produce the desired wine.

**Market impacts on irrigation**

Seven growers reported market-based issues impacting irrigation management: oversupply of grapes, particularly red varieties; and low prices of grapes. The two issues, according to the growers, commonly exist in the Australian wine industry and financially restrict growers' ability to invest in irrigation systems and technologies. For example, maintaining the irrigation system can be a challenge because "*a lot of vineyards, small vineyard, like ours, there's a lot more* [cash] *going out than a lot more going in, sadly*" (G20).

Another grower criticised the 'low value, high volume' of wine grape in Australia:

> *"The Australian wine industry is only what, 4% or 5% of global wine exports. And we are still seen as being cheap and cheerful, and we still struggle in the global market. That is just inexcusable. There's no reason why all of the wine going out of Australia is not seen to be wine of a very high quality"* (G19).

This grower suggested that this commodity-based wine industry means that growers are not able to recoup the costs of production to invest in business improvement, "*so they use old technology because they can't afford new technology*". Moreover, this grower said this situation could harm the economic sustainability of commodity growers and the environment. He attributed this situation to some large wine businesses, explaining:

> *"The inland wine regions have been exploited by the very large wine companies to be the source of high volume, low value commodity product. What they didn't do is try to gain the greatest value out of the resource. So, the wine industry is an ugly business where we have very, very large companies in essence exploit not only our human resource, but our land resource as well. So there's no long-term sustainable motivation from any of the wine makers or the big wine companies, it's all about their balance sheet on June 30. So if they can buy the grapes for the least they can, they bear zero responsibility for the economic sustainability of commodity grape growers"* (G19).

**Support for improving irrigation management**

To better manage irrigation and/or adapt to a changing climate, growers reported various potential solutions, including varieties or rootstocks that can tolerate warmer and drier conditions, irrigation water that is accessible, affordable and of good quality, accurate weather forecasts, affordable tools or technologies supporting more informed irrigation decisions, and support for adopting the tools or technologies.

Water security, as aforementioned, is a common and major concern among growers and they felt that more efforts need to be made at the industry or national level to alleviate the risk and ensure the viability of wine businesses in the long term. A grower believed that it needs a change in mentality for people to use water consciously to achieve sustainable growth of farming businesses. Another grower suggested that the economic value of water should be recognised and be the dominant factor driving irrigation decisions. He explained:

> *"The most valuable resource in this country is water. Not oil, not coal, not gas, not gold, whatever. It's water. And we don't use it well enough, we don't store it well enough, we don't do lots of things that we should. And getting that message through to, particularly to the politicians and the funding people is critical. And it's not about the ducks and the frogs and the whatever. It's about life in general, including the ducks and the frogs, but also food, wine, in our case it's wine, but it's poorly used, poorly utilised. Yeah, the whole system sucks… Every time I turn on a pump, it should be purely an economic decision. Is it worth me spending $10 to make $50, or do I waste $50 to make $10?* [It is] *What it boils down to"* (G8).

About one third of the growers indicated the need for more accurate weather forecasts by BOM for their region and even for their vineyard where the managed area is of a few hundred ha or larger. The range of weather forecasts is also important. A grower said that accurate forecasts of three weeks would enable them to better plan irrigation events.

Tools or technologies related to irrigation, according to growers, need to be improved or developed to support more informed decision-making, thus contributing to production goals and/or improving water use efficiency. Growers desire technologies that can estimate water requirements of vines in a block at different growing stages and predict when and how much water to irrigate. One of the growers also wants to have objective and accurate information about the relationship between applied water and vine growth because it will enable him to better control the growth via irrigation. The tools or technologies need to be affordable and relevant to the needs of growers operating at both large and small scales while being simple and easy for users with various levels of digital knowledge; for example, '*a very simple dashboard which just basically tells you to water more or water less*" (G12). Moreover, a few growers emphasised the need for tools to visually monitor the irrigation system and vine performance which would save time and labour for field inspections.

Support for adoption of tools or technologies was reported. Two growers pointed out the 'missing step' from Research & Development to adoption that needs to be addressed to make an innovation available and usable to growers. A grower described the need:

> *"We get all this research done but the funding behind adoption is probably the crucial step I feel that is getting missed, because you are expecting people, businesses to pick up on this, and it is still trial and error, I guess. So, getting research to adoption, I think there's a missing step there with some funding to help businesses get products up, off the ground and improve them, I guess. Research is one thing, but you've then gotta make that product commercial and commercially viable"* (G21).

Information or independent consultancy to offer advice on technologies or tools that are available and suitable for growers was viewed important to support adoption. Such consultancy needs to take into account the needs of growers managing small businesses. A grower indicated that, while industry organisations provide information about innovations, they often neglect the needs of small growers. An interviewee commented on the challenge of acquiring reliable information about technologies as a small grower and need for support.

> *"I think a channel that isn't driven by commercial sensitivity, if I can put it that way, that will enable small operators such as ourselves, and we are very small, access to good quality information of what technology is available and the approximate costing. I think that's probably the one thing that I'd like to see change. Because at the moment, most of the information that we would get, unless I go to a consultant and most consultants I don't trust anyway. They've got commercial interests that they don't necessarily tell you about. A genuine approach to what technology is available or what technology is coming on stream on a fairly regular basis, or at least a website or a communication channel, that is updated and monitored as far as what.*
>
> *I know* [names of organisations redacted]*, they do a great job on that. But they are largely dictated to or largely concerned with big operators. They don't do a great deal for small operators like ourselves. And what would not be constrictive as far as costing is concerned to a big operator, makes it unobtainable for a small operator. So, yes, the ability to get the information without spending hours and hours trolling around the internet and working out what the costing of this technology is likely to be, I think that's probably a good thing, if we could get something like that"* (G18).

Support was also reported for trialling technologies before adoption and/or related training for using them, especially for growers in remote areas with limited access to technology suppliers. Additionally, some growers suggested knowledge needs about irrigation practices and their impact on quality parameters of berries and wine and irrigation requirements of different soil types; the latter was viewed as especially valuable for inexperienced growers, as a grower put it:

> "*Say in the* [region] *here, it's got several different types of basic soils here, and these are the irrigation requirements of them. Just like a bit of a beginner's guide to irrigate in a certain region for certain responses that you would like to create a certain quality of fruit or just typical soil types in a region, and vineyard regions all over Australia*" (G30).

A few growers also suggested facilitating learning and collaboration among wine regions and agricultural sectors. For example, growers in Tasmania could learn from those in the mainland how to cope with extreme heat events.

## Discussion and conclusions

The findings of this project suggest that growers' irrigation management can be seen as a system comprising production-related goals, water resources for irrigation, infrastructure delivering water to vines and scheduling of irrigation events. The scheduling is influenced by the other three components in the system, along with a range of biophysical variables in relation to weather, soil and vine, and irrigation costs. In circumstances where water is restricted, irrigation decisions for a given block of vines are also determined by its market value. Market-related issues of Australian wine industry impact irrigation management by limiting growers' ability to invest in technology and infrastructure. Moreover, climate change is likely to make irrigation decisions more challenging by reducing predictability of weather, intensifying water scarcity, and increasing irrigation demand. Therefore, optimising irrigation decisions as to where, when, and how much to irrigate requires understanding how the entire system works, issues associated with each component of the system, and factors influencing the system.

Irrigation is an important tool that growers use to establish and maintain vine health and produce target yield of desired berry composition. All the growers in this study irrigated their vineyards, with the amount of irrigation during a particular season being influenced by rainfall received. For growers, water use efficiency (WUE) generally means tonnes of yield or gross margin per litre of water used. Growers' definitions of WUE may or may not be the same as those of researchers, policy makers and other industry stakeholders in Australia. While Dixon (2021) and Pagay (2022) define WUE as "the tonnes harvested per ML of water applied", Koech and Langat (2018) define it as "reducing the volume of water required to irrigate a crop and therefore improve field application efficiency", implying a water saving perspective. However, growers tend to prioritise greater profitability over using less water; that is, 'unnecessary' irrigation may be applied if it is believed to increase profits. Over-irrigation can also occur when there is no incentive for growers to save water, for example, when water is available and affordable, and excessive irrigation does not degrade fruit. Both scenarios lead to wasted water. Even though some growers are motivated to save water for environmental sustainability, financial goals of the business may not allow them to do so. Therefore, there is a need to balance financial goals of the business with environmental sustainability. Knox et al. (2012) suggested that farmers should focus on maximising the economic productivity of the water available to them and minimising waste or unreasonable use of water instead of saving water per se.

Water shortage during droughts has been a major challenge and remains a major concern for most growers. The issue will likely be exacerbated by climate change and competing demands from other industry sectors. Strong vulnerability to water shortage was also reported for grape growers in the Barossa Valley, McLaren Vale and Riverland in SA (Wheeler and Marning 2019). When limited water is available for irrigation, growers could face difficult decisions of prioritising some blocks over others or even 'mothballing' the whole vineyard to minimise irrigation costs while maintaining the vineyard for future production. However, mothballing may have risks of harming vine health and prolonging the recovery period (McGuire and Moulds 2009). Water shortages over the long term also threatens the viability of wine businesses.

Growers' irrigation decisions involve the use of experience and/or tools collecting data about weather conditions, soil moisture and crop water status. While experience is highly valued, it appears insufficient to support confident decisions given that it is subjective, limited to specific contexts and influenced by growers' own biases and beliefs (Mankad 2016). Relying on experience alone can lead to over or under-irrigating (Montagu et al. 2006). Tools such as soil sensors and crop sensors enable growers to objectively assess irrigation needs which gives them more confidence in decisions compared to using experience alone; however, the sensors also have limitations. For example, a soil or crop sensor does not inform soil moisture or crop status beyond where it is installed. It can be argued that identifying a so-called 'representative'

location in a block to install a sensor will allow growers to infer soil moisture status of the whole block. This method may suit vineyards where there is little variation in variables such as soil types, varieties and elevation. However, variability in land is common in vineyards in Australia (Bramley et al. 2011, Bramley 2022). Using data from a small number of soil or crop sensors to guide irrigation scheduling could lead to over- or under-irrigation in some parts of a vineyard and waste water if over-irrigation is practised to mitigate risks of crop stress due to concerns about underwatering.

The use of remote sensed imagery for estimating irrigation requirements of crops has been explored. For example, Pagay (2022) estimated water potential of leaves and stems at individual vine level for a Cabernet Sauvignon block in SA using high resolution imagery and machine learning. Concurrent cross-hub project work led by the University of Adelaide (unpublished) is tracking vine canopy growth to identify periods of rapid growth and potential stress indicators for integrating with other data streams to improve or develop models for informed irrigation decisions. Approaches like this, if commercialised, could aid growers to irrigate at desired scales according to crop needs and minimise unreasonable water use, provided that the irrigation system can implement the decisions. Remote sensing techniques could also act as a monitoring tool for growers to monitor the operation and performance of drip systems or other irrigation systems used.

Market-related issues of oversupply and low-prices have been reported to influence growers' ability to invest in irrigation management and their irrigation decisions. Over the past two decades, there has been global oversupply of commercial wines, particularly in red varieties such as Shiraz (Wine Australia 2023a). Over the past decade, red varieties, predominantly Shiraz and Cabernet Sauvignon, constitute the majority of crushed grapes in Australia (Wine Australia 2023b). Also, the average value of all crushed grapes was $642/tonne (Wine Australia 2023b), suggesting an overall low-price, high-volume strategy. As such, grape production is largely driven by maximising yield, which would aggravate oversupply while requiring a large amount of water for irrigation, thereby harming the profitability and sustainability of wine businesses. In more recent years, the global consumption of premium wine has been growing and is expected to continue to grow, offering a growth opportunity for Australian wine industry (Wine Australia 2019). Wine Australia's plan for the 'premiumisation' of wines, if successfully implemented, will likely reduce water use for irrigation while improving business profit margins.

Growers in this study were aware of potential impacts of climate change on irrigation management and have made various adaptations to perceived climatic conditions in future. These adaptations are mostly related to improving water security and irrigation decisions. In addition to their own endeavours, growers indicated the need for industry support to assist them with adapting to climate change. Potential actions could include appropriate water allocation policies and education to help growers make informed decisions about how to maximise production value per ML water, without undue environmental harm. Cost-effective use of recycled water for irrigation could be explored further.

To make more informed irrigation decisions, growers indicated the need for more reliable weather forecasts and information about water requirements of crops. Tools or technologies informing water status of soil, water or canopy growth of vines, or other variables assisting the scheduling irrigation events need to be simple to understand and operate because growers are often unwilling or unable to invest time and mental resources in learning to use complex technologies (Whittenbury and Davidson, 2010). Importantly, the development and application of tools should take into account different scales at which businesses operate so that they can be adapted to both large and small businesses. After development, the tools should be commercialised in an effective and timely manner to make them available to users, however growers also need reliable and objective information about the tools, and associated trialling, training and post-sale product support. Suitable communities of practice (Wenger 1998) might

provide an avenue for growers to trial and learn about tools for irrigation management with the assistance of experts while sharing of their experiences with other growers.

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# Appendix A: Interview guide

**Business structure and past drought events**

1. What are your responsibilities at this and/or other production sites in terms of irrigation management?
2. Who else in this business is involved in irrigation management?
    a. What are the responsibilities of each person?
3. What was the last drought event or prolonged dry conditions at this production site?
    a. What was the impact on the business?
    b. How was it addressed?
    c. What were the major issues or challenges when dealing with the drought? Do you still have the challenge/issue now?

**Current irrigation management**

4. Are there any areas of the production site that are non-irrigated? If so, why?
5. What are you trying to achieve through irrigation management?
    a. (Potential goals as examples: water use efficiency, crop health, yield, quality or?)
    b. How relevant is water use efficiency (WUE) to you? Why?
    c. What does WUE mean to you (definition)?
6. What is the irrigation water source?
    a. Are there any issues associated with accessing or using this resource?
    b. (Prompt: issues about water entitlement, viability, price, or **water security in a drought**?)
7. What irrigation system do you use (e.g. drip, sprinkler)?
    a. What are the issues or constraints associated with this system, if any?
8. Is the irrigation automatic or manually controlled?
    a. If it's manual, why?
9. During a growing season, how do you schedule irrigation (when, where and how much water to apply)
    a. (For the information used) How do you collect the information?
    - (Could include visual observations, sensors or other tools, technologies)
    b. (If not mentioned) what tools or technologies do you use to collect the info?
    c. What made you choose the tools/technologies?
    - (Or, what are your reasons for not using tools/technologies)
    d. (If not mentioned) How do you find these tech/tools for your irrigation decisions (strengths and weaknesses)?
10. How variable are the water requirements for crops **within** an irrigation block (an area covered by a single irrigation valve)?
    a. Are these variable needs an issue? If so, how did you address this issue?
11. What are the major difficulties you experienced in decision-making?
    a. Where do you think needs to be improved for better decisions?

**Climate, plans and support needed in future**

12. What changes you expect to see in climate conditions in the years ahead?
    a. How will the changes impact the production site?
13. What are the changes you plan to make in irrigation management in future, if any?
    a. What is driving the planned change?
14. (In addition to what has been mentioned) What are the challenges you have faced in terms of managing irrigation?

a. (For an employee of the business) What support do you think is needed within the business?
b. What support do you think is needed externally (e.g. research or industry bodies) to help you better manage irrigation and adapt to future droughts, if there any?

15. Is there anything else you would like to share on this topic (issues you think the industry should pay attention to or be aware of)?

TAS FARM INNOVATION HUB

Growing Climate Resilient Communities

*The TAS Farm Innovation Hub is one of eight hubs nationally, funded through the Australian Government's Future Drought Fund. The hub is based at the Tasmanian Institute of Agriculture (TIA) at the University of Tasmania and delivered through an extensive network of industry and community partners.*

*The hub helps Tasmanian farmers, and those who support them, build relationships, access essential information, and build critical skills and knowledge to prepare for drought and climate change.*

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Future Drought Fund

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This program received funding from the Australian Government's Future Drought Fund