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Agronomic and on-farm infrastructure adaptations to manage economic risk in Australian irrigated broadacre systems: A case study

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ABSTRACT

Context: Irrigated agriculture is critical to feeding a growing global population. Irrigation contributes 30% of agricultural gross value in Australia, but water scarcity and the volatility of Australia's open water market are significant challenges.
Objective: In this paper we advance a context-specific, system-based approach that aims to identify financially feasible irrigation designs and decision making, with the goal to increase water productivity, whole-farm profitability, and risk management.
Methods: We use a new analytical framework that combines crop simulation, discounted cash flow, system profit gap, probability theory and risk aversion analysis to quantify economic risk and compare 16 adaptation scenarios in an irrigated broadacre farm of the Riverina region in Australia. The scenarios result from the factorial of four agronomic systems (*Baseline/Current, Diversified, Intensified, Simplified*) and four irrigation methods – including surface irrigation by gravity (*Flood*) and by pumps (*Pipe & Riser*), pressurised irrigation by overhead spray (*Pivot*) and micro-dosing (*Drip*).
Results and conclusions: A system profit gap of ~$10 M was quantified for the irrigated farm area over 30 years. Relative to the Baseline – flood-irrigated wheat-canola – significant long-term profit gains were identified for the *Intensified* (mean 273%) and *Diversified* (mean 80%) scenarios. *Current* and *Simplified* scenarios were less profitable than the *Baseline* (mean −16% and −37%, respectively). The benefits of intensification were accrued from large gains in crop gross margins – especially cotton yields – that consistently offset the set-up costs and additional water use. Diversification was superior in mitigating economic risk due to higher returns per ML of irrigated water and more diverse sources of income. Under the assumptions in our study, agronomic system had greater relative influence on financial performance than irrigation infrastructure.
Significance: We demonstrated the potential to inform investment decisions from improving our understanding of trade-offs between profits and risks in the face of high climate variability, market volatility and Australia's open water market.

1. Introduction

Irrigated agriculture is critical to feeding a growing global population (Pereira, 2017). In Australia, irrigation uses 40–60% of total fresh water consumption to produce 30% of agricultural gross value, while only using 2% of arable agricultural land (2.3 M ha) in 2018 (ABS, 2018). The combination of recurrent droughts, reductions in river flows (MDBA, 2019a), ongoing climate change (BOM, 2020; CSIRO-BOM, 2015) and the growing demand for environmental water flows (MDBA, 2019a) is limiting allocation of water for irrigation. The Murray–Darling Basin, which accounts for 45–60% of irrigation in Australia (ABS, 2018; Kirby et al., 2014), has been particularly affected (Adamson et al., 2009; Ejaz Qureshi et al., 2013; Reeson and Whitten, 2015). The limited availability of water coupled with an increased water demand has led to significant spikes in water price (Westwood et al., 2020).

Water scarcity challenges farmers together with the decline in terms

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of trade (i.e., lower prices received for outputs relative to the rising prices for irrigation water, fertilisers, agrochemicals, and energy). These are key drivers of recent declines in farm profitability (Hughes et al., 2019). However, to a point, productivity gains from farmer adaptations tend to offset the negative impacts in the long run (Hughes and Gooday, 2021). Interestingly, high water prices have also led to a highly speculative water trading market that is open to global investors (MDBA, 2019b; Reeson and Whitten, 2015).

To balance the economic, social and environmental dimensions of sustainability (Cassman and Grassini, 2020) against a backdrop of climate change and declining terms of trade, farmers require information on profits, risks, and the opportunity costs of alternative irrigation systems and technologies (Culpitt, 2011; Khan et al., 2009; Mushtaq et al., 2013; Roth et al., 2013). So far, the economic benefits of irrigation in Australia have been assessed with a focus on crop and water management practices in multiple crops and irrigation systems (Brennan McKellar et al., 2013; Dalton et al., 2001; Gaydon et al., 2012; Harrison et al., 2017; Maraseni et al., 2012; Peake et al., 2016; Phelan et al., 2015; Power et al., 2011). Comparisons between full and deficit irrigated crops based on water saving vs. farm economic returns have been conducted for maize (Rodrigues et al., 2013) and wheat (Darouich et al., 2017) in Mediterranean conditions. The economics of water management has long been the focus in water-scarce irrigation contexts (Dinar and Zilberman, 1991; Hogan et al., 2006; Khan et al., 2020; Wild et al., 2021). It is notable that comparisons of irrigation infrastructure are rare in the scientific literature (Brennan McKellar et al., 2013; Maraseni et al., 2012; Mushtaq et al., 2013). This is despite their relevance, particularly in a global operational environment of high risks, significant trade-offs, increasing energy costs, labour shortages, and large capital costs (Ara et al., 2021).

For rainfed grain crops, nitrogen (N) deficiency often accounts for an important part of the gap between the exploitable water-limited yield and actual yield (Hochman et al., 2013, 2009; Monjardino et al., 2015, 2013; Sadras and Roget, 2004; Sadras et al., 2016). The yield gap attributable to insufficient applied N becomes negligible where irrigation eliminates the uncertainty in water supply (Christie et al., 2018; Grassini et al., 2011; Rawnsley et al., 2019). This effectively translates into lower yield risks associated with irrigated systems, assuming that sufficient water is available for timely irrigation. The average yield gap for irrigated wheat in sub-tropical Australia is 1.0–2.7 t/ha for non-lodged and lodged fields, respectively (Peake et al., 2014), and can be attributed to factors including crop and water management (Peake et al., 2016; Roth et al., 2013), the ratio commodity prices to input costs (Kirby et al., 2014), inadequate irrigation infrastructure (Khan et al., 2009; Maraseni et al., 2012), and environmental concerns and policy regulations that affect water availability (MDBA, 2019a; NWC, 2009).

Social factors also influence profitability. Farmer risk aversion affects farm productivity in rainfed systems (Monjardino et al., 2019, 2015) and is likely to influence irrigation decisions and water productivity (Fereres et al., 2014; Mallawaarachchi et al., 2020) because of significant price and financial risks incurred from high price volatility and costly irrigation infrastructure. Frameworks have been developed to expand the yield gap analysis from individual crops to the cropping system accounting for the spatial and temporal arrangement of crops (Guilpart et al., 2017). The concept of cropping system yield gap is particularly useful in irrigated systems because investments in infrastructure and water allocation affect multiple crops in space and time and affect whole-farm performance. Energy-based yield per unit of land and time has been used as a currency to aggregate contrasting crops (Guilpart et al., 2017). We use economic return for aggregation, thereby shifting the focus from yield gap to profit gap. Profit gap is defined here as the change in profitability associated with the irrigation system yield gap.

The aims of this article are to (i) develop a new analytical framework that combines crop simulation, discounted cash flow (DCF), system profit gap, probability theory and risk aversion analysis underpinned by realistic longitudinal trends in commodity and water price; and (ii) compare profit and risk trade-offs of 16 farmers' informed scenarios resulting from the factorial combination of four agronomic systems and four contrasting water delivery methods using a farm case study in the Riverina region of the Murray-Darling Basin.

2. Methods

2.1. Farm case study

The case study farm is located near the town of Finley in NSW (−35.6230°S, 145.5844°E) in the irrigation region of the Riverina, in the Murray-Darling Basin of eastern Australia. The region has an average annual rainfall of 380 mm (225 mm in winter and 155 mm in summer), making dryland cropping difficult. Soils are predominantly clay loam (topsoil) over clay and typically store less than 200 mm of water in a maximum depth of 1.5 m. The average farm area is 1000 ha, with 700 ha of irrigated winter crops (e.g., canola-wheat-wheat) in rotation with summer fallow. Typical of many in the region, the farm holds a permanent water licence with a median entitlement of 1400 ML/year taken from the Murray irrigation system. Water entitlements remain the same in wet and dry years (Goesch et al., 2020), whereas allocations against entitlements change according to rainfall, inflows into storages and how much water is already stored (MDBA, 2019b). Allocated water does not come at an extra cost to the licensed farmer because they are entitled to it. A temporary trading licence allows the farmer to buy and sell allocated water at market price. In addition, water carryover allows the farmer to hold up to 30% of water allocation in dam storage within and between years, which helps to limit the increase in allocation prices in dry years (Goesch et al., 2020). Average annual allocations (60–70% of the total water entitlement) are used to flood irrigate 70% of the farmland. Flood irrigation is presently the preferred choice of Riverina/Finley farmers.

2.2. Scenarios

Our analysis focuses on 16 scenarios from the combination of four agronomic systems and four irrigation methods. These scenarios were selected from discussions with farmers and industry across the region to represent relevant and contrasting levels of system intensity as well as methods of water delivery. A key assumption in this analysis is that all adaptation scenarios – including the *Baseline* – are underpinned by a new upfront investment in irrigation infrastructure to allow for a simple and direct comparison between options. This is in contrast with: a) farms being already equipped with alternative infrastructure or only requiring partial adjustments and b) the *Baseline* flood infrastructure investment being considered a sunk cost – that is, a fixed cost that has already been incurred and cannot be recovered. In other words, the analysis assumes 16 possible scenarios in which a clean block of land is used for irrigation purpose, and where the *Baseline* scenario represents the current situation in terms of agronomy and irrigation for benchmarking.

2.2.1. Agronomic system

Four agronomic systems are defined in terms of crop choice, allocation of irrigation water, area of farm under irrigation, level of inputs, costs, and risk:

1. ***Baseline/Current***: current system as outlined in Section 2.1, further supported by farmer records and regional statistics (JLacy_Consulting, 2021). The *Current* system with flood irrigation is the *Baseline*. Note that variations of *Current* with different irrigation methods (see 2.2.2) are considered separately to the *Baseline*.
2. ***Diversified:*** seeking diversification of crop income, i.e., more income derived from a variety of sources in any given year. The *Diversified* system has similar average water usage and irrigated farm area as *Baseline/Current*, a greater variety of winter crops grown within the

year – i.e., wheat, canola and a grain legume – but similar inputs and costs.

3. ***Intensified***: in general, this is a high-input, high-output, high-risk system. Relative to the *Baseline/Current*, more water per unit area and year is used for irrigation, a larger portion of the farm area is irrigated (i.e., less unirrigated fallow), more crops are sown with greater water usage, higher inputs per unit area and year (e.g., N, herbicides), together resulting in higher cost and higher risk per unit area and year.
4. ***Simplified***: in general, this is a low-input, low-output, low-risk system. Relative to the *Baseline/Current*, this scenario uses less irrigation water per unit area and year, increases frequency of rainfed crops, and reduces inputs per unit area (e.g., N, herbicides), resulting in lower cost and lower risk per unit area and year.

2.2.2. On-farm irrigation infrastructure

Four irrigation methods are assessed and described in Table 1 (AgVIC, 2021; ThinkWater, 2021):

a. ***Flood***: surface irrigation in levelled bays, water applied by gravity.
b. ***Pipe & Riser***: surface irrigation in levelled bays, water applied by pumps.
c. ***Pivot***: pressurised spray irrigation applied by an overhead irrigator that rotates around a central pivot (fulcrum).
d. ***Drip***: pressurised micro irrigation, typically applied through small pipes laid on the ground surface. Irrigation is applied over a longer duration than the other irrigation types as the delivery pipe diameters are small.

2.3. Simulated crop yield and irrigation water use

The Agricultural Production Systems Simulator (APSIM v.7.10) (Holzworth et al., 2014) was used to simulate crop yield, irrigation water use, N fertiliser and fallow management practises for the 1989–2018 growing seasons (30 years). APSIM simulation of grain yield in response to weather, soil and management, including water application, has been widely tested in Australia across crops, soils and cropping systems (Brennan McKellar et al., 2013; de Voil et al., 2009; Gaydon et al., 2012; Ibrahim et al., 2019; Liu et al., 2020; Phelan et al., 2018; Power et al., 2011). Supplementary Table S1 highlights key features of these studies that support low uncertainty related to model structure.

The model simulates a different crop rotation for each agronomic system, each with four levels of transfer efficiency broadly aligned with the four irrigation infrastructure options described in Table 1. All scenarios were parameterised with a combination of farm interview data, weather data from SILO (Jeffrey et al., 2001) and soil data from APSoil (Dalgliesh et al., 2012). Irrigated crops were sown on fixed dates (mid-April for winter crops, mid-November for summer crops), and dryland crops were sown when rainfall opportunities occur (i.e., 25 mm over four days).

Double cropping systems in the *Intensified* scenario were modelled as summer paddock and winter paddock where sowing and harvesting operations may overlap by a few weeks. N fertiliser was applied at sowing, and for the *Intensified* scenario 60 days after sowing. Each irrigation strategy depended on both crop and scenario. For the pressurised irrigation scenarios (*Pivot, Drip*), cotton was irrigated to 95% of drained upper limit, and rice was managed to maintain a surface pond of water between 50 – 150 mm deep. For the surface irrigation systems (*Flood, Pipe & Riser*) the soil was filled to drained upper limit when the fractional water content fell below 0.6; summer crops in the *Intensified* scenario were watered when the fractional content fell below 0.8. For all scenarios, watering of the crop finished at 75% of the grain-filling period. A simple hydrothermal-time model was used to estimate weed germination and consequent requirement for weed control during fallow periods. We deliberately did not model annual allocation limits, because

Table 1
Key characteristics and average costs of for irrigation methods and associated infrastructure: Flood, Pipe & Riser, Pivot, Drip. Transfer efficiency is the percentage of water supplied from the source that reaches the field. WHC = water holding capacity. R&M = repair and maintenance.

Characteristics and average cost of irrigation infrastructure	Irrigation infrastructure			
	Flood	Pipe & Riser	Pivot	Drip
Water delivery mechanism	Surface, gravity	Surface, pumped	Pressurised, spray	Pressurised, micro
Intensity of application	Low	Medium	Medium	High
Uniformity of application	Low uniformity on soils of variable properties; unsuitable for slopes, sandy soils	Low uniformity on soils of variable properties; unsuitable for slopes, sandy soils	High uniform distribution on different slopes and soils, e.g., with low WHC	High uniform distribution on different slopes and soils, e.g., with low WHC
Annual application frequency	Low	Low	High	High
Precision, crop water use efficiency	Low	Low	High	High
Annual water requirement	High	High	Low	Low
Irrigation water use index[a] for selected crops (t/ML for grain, bales/ML for cotton)	*Wheat*: Low *Canola*: Low *Maize*: High *Cotton*: High	Low Low High High	High Low High High	Low High High High
Average (range) transfer efficiency (%)	70 (60–80)	80 (70–90)	90 (75–95)	100 (95–100)
Fertiliser input	Low	Low	Low	High (+$100/ha/year N fertiliser)
Weed control requirement	Med-high	Med-high	Med-high	Low (less $20/ha/yr in herbicide costs)
Pump size (kW)	0	17	30	16
Water application rate (mm/hr)	0	25	0.5	3.2
Pumping time per season (h)	0	680	1273	1125
Seasonal power usage (kWh)	0	11,560	38,182	18,000
Pumping power (kWh/ha)	0	290	955	450
Power cost[2] ($/ha/year)	–	87	287	135
Labour – irrigation, R&M (hrs/ha)	8.0	5.5	2.0	2.0
Labour cost[2] ($/ha/year)	280	193	70	70
R&M cost[2] ($/ha/year)	20	20	70	60
Vehicle cost[2] ($/ha/year)	96	66	24	12
Total overhead cost ($/ha/year)	**396**	**366**	**451**	**277**
Productive life (years)	20	20	15	15
Capital cost of irrigation[3] ($/ha)	2500	3500	4500	5500
	500	500	500	500

(continued on next page)

Table 1 (*continued*)

Characteristics and average cost of irrigation infrastructure	Irrigation infrastructure			
	Flood	Pipe & Riser	Pivot	Drip
Additional capital cost[4] ($/ha)				
Total capital cost ($/ha)	**3000**	**4000**	**5000**	**6000**

[a] IWUI (t/ML) = total production (t or bale)/irrigation water applied (ML) [DPI (2017)]; [2]Calculations based on current rates: power charge incl. service fee (30c/kWh), labour wage ($35.00/hour), vehicle running costs ($12.00/hour including fuel); [3]Major capital cost items include the irrigation system, pump installation, motor, electrical works, earthworks (lasering, channel upgrade); [4]Additional capital cost of development may include new machinery for irrigated crops, motor vehicles and/or sheds for irrigation equipment.

the rotation specifies the water consumption (via frequency and sown area) and a combination of temporary water trading – where a fixed amount of water can be bought or sold at a point in time – and carryover transactions where unused allocation can be used in the subsequent year allowing the operator to buffer against both shortfalls and excesses of water consumption. However, the simulated water consumption fell within the allocated volumes broadly specified for each system (Section 2.4.2).

2.4. Assumptions

2.4.1. Irrigation infrastructure

Farmer choices of irrigation infrastructure are complex and often context-specific, involving trade-offs in terms of water management and efficiency, annual costs, capital investments, and farmers' preference.

Key characteristics and costs of different irrigation infrastructure are summarised in Table 1, based on a wide range of sources including farmer and consultant data and expertise, electronic databases, technical reports and scientific literature (Brennan McKellar et al., 2013; Culpitt, 2011; Dalton et al., 2001; DEEDI, 2011; Hogan et al., 2006; Khan et al., 2009; Maraseni et al., 2012; Moore et al., 2000; Petheram et al., 2016, 2013; RMCG, 2018; Roth et al., 2005; ThinkWater, 2021; Thompson, 2016a, 2016b).

2.4.2. Agronomy, prices and costs

Table 2 summarises parameters and model outputs for the 16 scenarios of agronomic system by irrigation infrastructure over 30 years. While water allocation limits were not imposed on the simulations (Section 2.3), they influenced system design and opportunities for trading water. The *Baseline/Current* scenarios are assumed to irrigate 700 ha of a canola–wheat–wheat rotation, with each winter crop followed by a summer fallow. The fallow generates no income but stores water and N and imposes a cost for weed control (0–4 herbicide spray events).[1] The *Diversified* scenarios include a canola–wheat–faba bean rotation, each winter crop similarly followed by a summer fallow (700 ha). In comparison to the *Baseline/Current*, the *Simplified* scenarios are assumed to have lower water supply which can only irrigate a reduced area of wheat (50% = 350 ha), while dryland canola grows on the original 700 ha area of the farm. The *Intensified* scenarios are assumed to have higher water supply, which is used to irrigate 700 ha of winter crops (canola, wheat) and a smaller area (25% = 175 ha) of summer crops (maize, cotton, rice), with the remaining 75% of the area in summer fallow.

Annual water allocations were drawn from a 20-year distribution, extrapolated from broader water allocations for the region (MDBA, 2019b; Westwood et al., 2020). Overall, in line with farmer experience, and depending on market forces, lower water allocations in dry seasons favour simplification, whereas high water allocations in wet seasons allow for greater intensification of the cropping program. Extra water may be carried over from the previous year and/or purchased at market price to top up annual allocation and meet higher crop demand. An initial drop to a low allocation (high price) year, due to drought for example, increases the likelihood of a lower-than-average allocation in the following year.

APSIM-simulated mean irrigation water applied varied from 1.0 ML/ha/year for canola (*Current_Drip*) to 19.4 ML/ha/year for rice (*Intensified_Flood*), broadly aligning with regional experience (Brennan McKellar et al., 2013; Dwyer et al., 2020; Gaydon et al., 2012; JLacy_Consulting, 2021). Finley farmers have reported annual irrigated yields of 3.0 – 9.5 t/ha from 1.5 – 4.0 ML/ha/year of water for wheat, 2.5 – 4.0 t/ha from 1.0 – 2.5 ML/ha for canola, 1.5 – 5.0 t/ha from 1.0 – 4.0 ML/ha for faba bean, 7.8 – 22.0 t/ha from 8.0 – 11.0 ML/ha for maize, 6.6 – 12.6 t/ha from 7.5 – 10.5 ML/ha for cotton, and 5.0 – 15.2 t/ha from 10.0 – 17.0 ML/ha for rice. Applications of N fertiliser varied between 100 and 500 kg N/ha/year (Table 2). The higher water and N rates simulated in *Intensified* fit a potential scenario with abundant water and unlimited N.

Other variable costs shown in Table 2 include the typical crop production costs (detailed in Section 2.5.1), along with the additional costs of shifting to cotton and rice cropping, through a $40/ha/year cost of hiring specific cotton harvest machinery (e.g., Cotton King, baler) and a $176/ha/year cost of preparing the ground for rice beds (e.g., laser levelling). Also included is an additional cost of $70/ha/year under *Drip* irrigation from changes in requirements in N fertilisers (+$100/ha/year) and herbicides (-$30/ha/year) (Table 1).

The relative annual economic performance of production – or benefit: cost ratio – was assessed with the Economic Water Productivity Ratio (*EWPR*) (Paredes et al., 2014), which encompasses the suite of annual irrigation costs (*C*) required to achieve the annual crop benefit (*B*) or revenue, based on simulated irrigated yields for each irrigation scenario *i*:

$$EWPR = \frac{Bi}{Ci} \quad (1)$$

Where higher *EWPR* indicates greater benefit per unit cost. Fig. 2 shows the disaggregated annual costs of irrigation and associated EWPR for all scenarios. As a rule, surface water delivery (*Flood, Pipe & Riser*) requires more water, labour and maintenance to run, whereas pressurised irrigation (*Pivot, Drip*) incurs the highest power and capital costs. In terms of benefit: cost impact, EWPR varied between 1.16 (*Simplified_Flood* and *Simplified_Pivot*) and 2.07 (*Intensified_Drip*). EWPR fluctuates with the terms of trade.

2.5. Discounted cash flow analysis

The financial performance of all adaptations was assessed using a Discounted Cash Flow (DCF) analysis across the crop rotation. DCF computes the present value of cash inflows and cash outflows, discounted over the time of the investment (Brennan McKellar et al., 2013; Petheram et al., 2016). The following measures were used in the analysis.

2.5.1. Net present value

The long-term profitability of each scenario is summarised as the Net

[1] A simple hydro-thermal time model of weed germination events was used in APSIM to calculate the frequency of spraying events – which have an economic, but no biophysical impact – during fallow periods. The model assumed that weeds emerged 250-degree days after a rainfall event (4 days total >25 mm) and adequate surface soil water content (>50%) triggered germination. If there was no follow up rain, germinated weed seeds stopped growing and died so no spray event was triggered. No seed bank was modelled, with seeds assumed to be ephemerally distributed.

Table 2
Mean agronomic and economic parameters and simulated outputs for 16 scenarios combining agronomic system and irrigation infrastructure for a Riverina farm, based on 30-year averages.

Agronomic system	Irrigation infrastructure	Crop	Irrigated area (ha)	APSIM mean irrigation water applied* (ML/ha/yr)	Total mean irrigation water applied over irrigated area (ML/yr)	APSIM mean crop yield (t/ha or bale/ha)	Mean real grain price from historical distribution ($/t or $/bale)	N rate applied (kg N/ ha/yr)	Other crop costs (excl. N and water)** ($/ha/ yr)
Current	**Flood**	Canola	700	1.4	1007	2.6	521	100	439
	(BASELINE)	Wheat	700	2.8	2259	6.1	296	150	294
	Pipe & Riser	Canola	700	1.2	881	2.6	521	100	439
		Wheat	700	2.4	1977	6.1	296	150	294
	Pivot	Canola	700	1.1	783	2.6	521	100	439
		Wheat	700	2.1	1757	6.1	296	150	294
	Drip	Canola	700	1.0	705	2.6	521	100	509
		Wheat	700	1.9	1581	6.1	296	150	364
Diversified	Flood	Canola	700	2.6	1934	4.0	521	100	439
		Wheat	700	3.1	2163	6.1	296	150	294
		Faba bean	700	1.6	1284	4.0	484	50	473
	Pipe & Riser	Canola	700	2.3	1692	4.0	521	100	439
		Wheat	700	2.7	1892	6.1	296	150	294
		Faba bean	700	1.4	1123	4.0	484	50	473
	Pivot	Canola	700	2.0	1504	4.0	521	100	439
		Wheat	700	2.4	1682	6.1	296	150	294
		Faba bean	700	1.2	998	4.0	484	50	473
	Drip	Canola	700	1.8	1354	4.0	521	100	509
		Wheat	700	2.1	1514	6.1	296	150	364
		Faba bean	700	1.1	899	4.0	484	50	543
Intensified	Flood	Canola	700	2.7	2211	4.3	521	150	439
		Maize	175	15.0	2591	13.7	336	400	539
		Wheat	700	2.1	1545	4.7	296	250	294
		Cotton***	175	11.1	2150	11.3;	600; 329	300	761
		Rice	175	19.4	3472	5.0 14.9	368	500	1443
	Pipe & Riser	Canola	700	2.3	1976	4.4	521	150	439
		Maize	175	13.1	2261	13.8	336	400	539
		Wheat	700	2.2	1367	4.7	296	250	294
		Cotton***	175	9.6	1894	11.3;	600; 329	300	761
		Rice	175	17.2	3045	5.0 14.9	368	500	1443
	Pivot	Canola	700	2.1	1784	4.4	521	150	439
		Maize	175	11.6	2009	13.8	336	400	539
		Wheat	700	2.0	1244	4.7	296	250	294
		Cotton***	175	8.5	1678	11.4;	600; 329	300	761
		Rice	175	15.2	2710	5.0 14.9	368	500	1443
	Drip	Canola	700	1.8	1569	4.3	521	150	509
		Maize	175	10.4	1809	13.7	336	400	609
		Wheat	700	2.1	1107	4.7	296	250	364
		Cotton***	175	7.7	1491	11.2;	600; 329	300	831
		Rice	175	14.0	2496	4.9 14.8	368	500	1573
Simplified	Flood	Canola	700	2.3	940	1.8	521	100	375
		(Dry) Wheat	350			5.3	296	150	294
	Pipe & Riser	Canola	700	2.0	822	1.8	521	100	375
		(Dry) Wheat	350			5.3	296	150	294
	Pivot	Canola	700	1.8	731	1.8	521	100	375
		(Dry) Wheat	350			5.3	296	150	294
	Drip	Canola	700	1.6	658	1.8	521	100	445
		(Dry) Wheat	350			5.3	296	150	364

*Includes transfer efficiency losses; **Includes other annual crop input costs (seed, inoculants, soil amelioration, other fertilisers, herbicides, fuel, oil and hired labour for seeding, fertilising, spraying, harvesting, cartage, R&M of crop machinery, crop insurance and levies, etc.), but excludes N fertiliser and irrigation water, which are accounted for separately in the analysis; ***Cotton is split in cotton lint ($/bale) and cotton seed ($/t).

Present Value (NPV) of future cash flows, or the sum of future net cash flows discounted to their present value. NPV ($) is defined as:

$$NPV = \left(\sum_{t=0}^{t=30} \frac{(Y_t \times P) - V_t - W_t - N_t - O_t}{(1+r)^t} \right) - I \quad (2)$$

where the sum of annual cash inflows over a period of 30 years corresponding to half a typical Australian farmer's career, is calculated as the revenue from crop grain yield Y_t in year t by grain price P, and the sum of annual cash outflows includes – the bundled variable costs of crop production and fallow management (Vt), cost of irrigation water (W_t), cost of N fertiliser (N_t) and overhead costs of irrigation (O_t). A real discount rate (r) of 5.0% is used in the analysis to determine the present value of future cash flows, based on rates of return experienced for general investments in agriculture in recent years (Pannell and Schilizzi, 2008), and *I* is the initial investment made in year 0 (see Table 1 for capital costs of different infrastructure options).

Yields for crop revenue were simulated in APSIM, as described in Section 2.3. The farm-gate price for grains (Table 2), temporary water (mean $138/ML) (Fig. 1) and fertiliser N (mean $806 per tonne of N, based on urea at 46% N) were drawn from frequency distributions of historical real prices (20–30 years) (ABARES, 2020; Indexmundi, 2021; Westwood et al., 2020), after adjusting for inflation using the consumer price index. Cotton, a summer crop grown for *Intensified* scenarios, generates two income streams, with the seed sold for stockfeed ($/t of fresh weight) and the lint sold to the cotton gin on a $/bale basis. Using the @RISK™ software (Palisade_Corporation, 2012), the price frequency distributions were fitted using probability density functions (PDF) of various forms, and the Anderson-Darling (AD) statistics test was used to measure the goodness of fit of each distribution (Supplementary Fig. S1). No significant correlation was found between grain, water and N prices, so the PDF with the best fit was selected for use in Monte Carlo simulation of annual cash inflows and selected outflows (water cost and N cost) for use in the NPV analysis through the process of generating 1000 random iterations to sample from the probability distribution.

Costs are an important component of irrigation investment and were drawn from a range of sources, including technical literature, ABARES (www.agriculture.gov.au/abares), gross margin budgets and expert opinion. We assumed that all infrastructure adaptations were new investments – rather than partially or completely existing – and that all capital costs were incurred in the first year (i.e., the development was not staged). Likewise, we assumed that land was not a constraint and that differences between farm system applied instantaneously (as modelled in APSIM) – as opposed to farm system transition taking place over time. The costs included in the analysis are:

- Capital costs (initial investment, $/ha) related to the irrigation infrastructure, including system purchase and installation, earthworks, pump installation, electrical works, storage if applicable, as well as other upfront costs such as machinery for new irrigated crops, motor vehicles/workshops/sheds attributable to irrigation. Interest and depreciation costs of capital are excluded from the NPV analysis to avoid double counting (Pannell and Schilizzi, 2008).
- Overhead or fixed annual costs associated with irrigation operation and maintenance ($/ha/year), and include power required for pumping, extra labour, R&M of irrigation system and vehicle running costs. These costs vary between irrigation methods and are assumed constant throughout the analysis period within each scenario. Another fixed cost related to irrigation is the purchase or lease of water entitlements – the product of water entitlement (median 1400 ML/year) and permanent water price (long-term average $1292/ML) – which has been excluded from this analysis because: a) it is accounted as a farm finance cost (along with lease on land, other farm capital assets, etc.), and b) it is the same for all scenarios.
- Water cost of irrigation ($/ML), calculated as the product of the temporary water price (mean drawn from a 20-year distribution) and the volume of water purchased for irrigation annually.
- Nitrogen fertiliser cost ($/ha/year), calculated as the N rate (per crop) by N price (drawn from a 30-year distribution).
- Variable costs of production ($/ha/year) are specific to each crop and include inputs other than irrigation water and N fertiliser (accounted for separately), such as seed, inoculants, soil amelioration, other fertilisers, herbicides, fuel, oil and hired labour for seeding, fertilising, spraying, harvesting, cartage, R&M of crop machinery, crop insurance and levies. The annual costs of shifting production into cotton and rice crops are included here as well. Variable costs are assumed unchanged throughout the analysis period within each scenario.
- Cost of fallow management ($/ha/year) includes the number of herbicide applications per fallow at an assumed cost of $15/ha/year per application.

2.5.2. *Internal rate of return and payback period*

Internal Rate of Return (IRR) is the discount rate that makes the NPV of all cash flows equal to zero. IRR (%) is the return received by investing capital in this enterprise. An enterprise is considered a good investment when the IRR exceeds the discount rate. Payback period is the number of years required to recoup the investment funds, i.e., to reach break-even point. Lower payback periods are preferred.

2.5.3. *Opportunity cost of trading allocation water*

In the Riverina, water trade allows licence holders to buy or sell water at any time. While permanent trade involves the sale or lease of water entitlements, the temporary trade of allocation water is seasonal (MDBA, 2019b). We consider the opportunity cost (OC) of trading allocation water, or the potential benefit a farmer loses when using the water for irrigation over selling it (Mallawaarachchi et al., 2020). We calculated OC as the difference between the return on the option not chosen (water sale) and the return or IRR of the chosen option (water purchased for crop irrigation). The return on allocation water sale was calculated as the product of temporary water price and annual water allocated to the farm for irrigation – both drawn from long-term distributions – along with a seasonal factor. In addition, a fallow was assumed to replace the crop in the water sale option, incurring only a low weed control cost (assumed a single spray at a cost of $15/ha).

2.6. *Net value of adaptation and system profit gap*

An irrigation investment is considered viable if the present value of the benefits is greater than the present value of the costs (i.e., NPV > 0). The principal economic criterion to compare irrigation scenarios is the net value of adaptation, which is calculated as the difference between the NPV of future cash flows of each adaptation scenario and the NPV of future cash flows of the *Baseline*.

Using economic currency to aggregate contrasting crops and irrigation allocations, we define irrigated system profit gap as the difference between the largest net value of all scenarios considered here and the *Baseline* under consideration.

2.7. *Risk analysis*

For each scenario, the frequency distribution of the discounted annual cash flow was fitted based on the AD test to characterise profit volatility using @RISK. The PDF with the best fit was used to determine risk metrics.

2.7.1. *Downside risk and probability of break even*

A useful measure of downside risk is the Conditional Value at Risk of the lowest 20% of possible outcomes (CVaR0.2), i.e., the mean of the lowest 20% of discounted cash flows or, in other words, the risk of extreme financial loss associated with unfavourable events. In addition, the probability of positive returns ($P(\pi \geq 0)$) is used to measure the likelihood of breaking even over the 30-year period of the analysis, and the coefficient of variation (CV = standard deviation/mean) provides a measure of dispersion of a probability distribution (discounted cash flows). The CVaR0.2, $P(\pi \geq 0)$ and CV capture long-term yield, price and financial risk underpinning the irrigation investment across the whole irrigation system.

2.7.2. *Farmer risk aversion*

We use a risk premium (RP, $/year) – the minimum amount of money one is willing to pay to eliminate risk exposure – to calculate risk-adjusted profit (or certainty equivalent, CE) ($\pi - RP$) ($/year) (DiFalco et al., 2007). Risk premium captures the cost of risk measured through

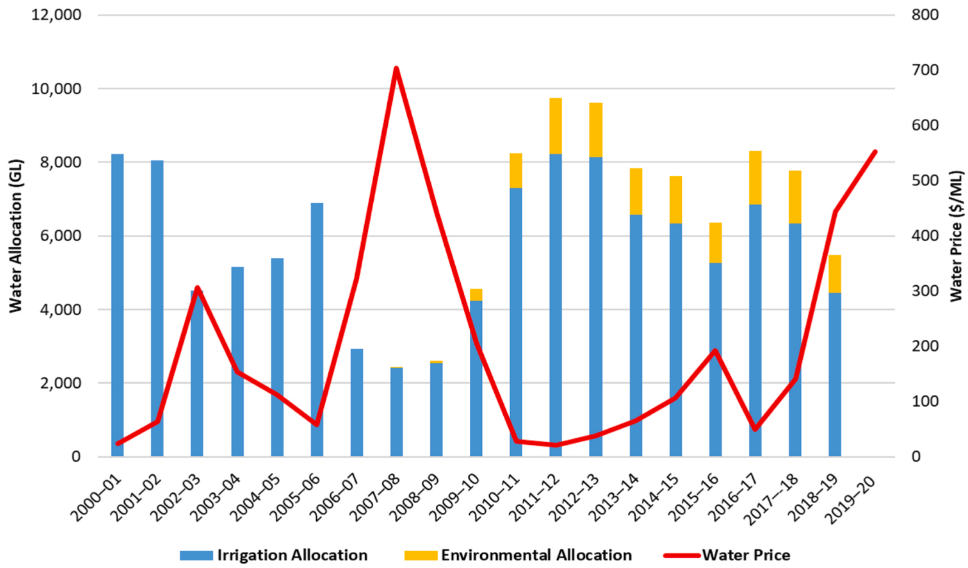

Fig. 1. Annual allocation of water for irrigation (blue bars) and environment (yellow bars) and average annual allocation water price (red line) in the combined regions of the southern Murray-Darling Basin from 2000 – 01–2019 – 20.
Source: adapted from Westwood et al. (2020).

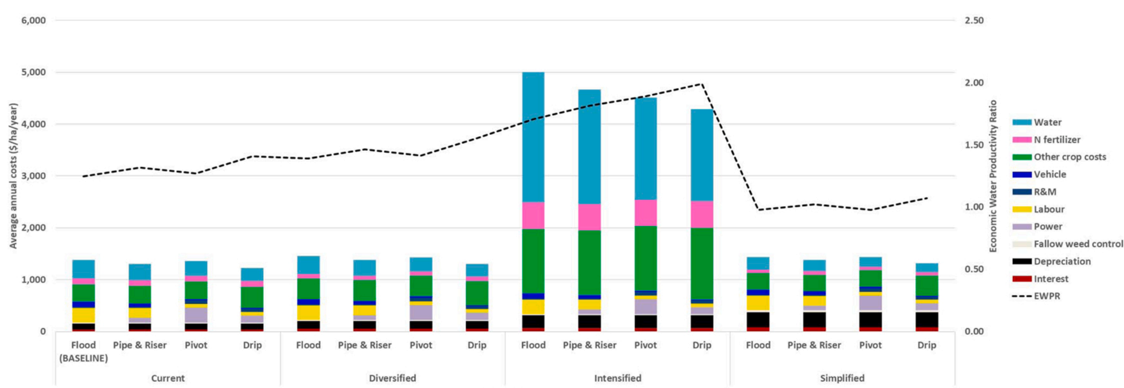

Fig. 2. Disaggregation of the annual costs of irrigation (left axis) and Economic Water Productivity Ratio (EWPR, right axis) for 16 scenarios combining four agronomic systems and four irrigation infrastructures for a Riverina farm, based on 30-year average costs and crop benefits across the system.

mean, variance, and skewness of profit distributions, and can be approximated as:

$$RP = 0.5 \times \frac{r}{\pi} \times V \tag{3}$$

where r is a coefficient of relative risk aversion (described below), π ($/year) is the mean net profit based on discounted annual cash flows and V ($/year) is the variance of the mean net profit for each adaptation scenario. The risk attitude range of farmers is typically measured by a unitless risk aversion coefficient, measuring either absolute or relative risk aversion, based on the magnitude and spread of the distribution of net returns (Hardaker et al., 2015). A scale of 0–4 was used for r in this study, assuming 0 = no risk aversion (i.e., risk-neutral decision maker); 1 = low risk aversion; 2 = moderate risk aversion; 3 = high risk aversion; 4 = very high risk aversion (Gandorfer et al., 2011). The analysis was run for each of these r to capture the full spectrum of attitudes to risk. A risk-adjusted profit value was calculated for each of the five levels of risk aversion. The difference between risk-neutral profit ($r = 0$) and risk-adjusted profit at the maximum level of risk aversion ($r = 4$) is the maximum cost of risk aversion.

2.8. Statistical analysis

Additional statistical tests were performed on the 16 factorial scenarios to assess the influence of agronomy, infrastructure, and their interaction on financial outputs. Using ANOVA (two-factor with replication), data were analysed for all scenarios with focus on: (i) varying the agronomy system for each infrastructure option, and (ii) varying irrigation infrastructure within each agronomy system. Discounted Annual Cash Flow outputs over 30 years were used as replicates.

3. Results and discussion

3.1. Profitability of the irrigated system

Profitability was highest for *Intensified* (Table 3, Fig. 3). *Diversified* was generally more profitable than *Baseline/Current*, while *Simplified* proved less attractive, especially under pressurised irrigation (*Pivot, Drip*). Surface irrigation, mainly *Pipe & Riser*, was relatively more profitable in most agronomic systems. Note that the downward trend in discounted annual cash flows relates to the discount rate, which is used to allow valid comparisons of benefits and costs that occur at different times (Fig. 3). The higher the rate the lower the present value of future

Table 3
Water use and profit-risk results from the Discounted Cash Flow analysis and risk analysis for the 16 adaptation scenarios combining agronomic system and irrigation infrastructure for a 700-ha farm in Riverina over 30 years (1989 –2018).

Agronomic system	Irrigation Infra structure	Mean annual water use (ML/ha/yr)	Net Present Value (million $)	Annual equiv. benefit per ha ($/ha/yr)	Annual equiv. benefit per ML ($/ML/yr)	Internal Rate of Return (%)	Payback period (yr)	CV of disc. cash flows	Prob. of break even P ($\pi \geq 0$) (%)	Downside risk after 30 years (CVaR0.2) (thousand $)	Net value of adaptation relative to Baseline (million $)
Current	**Flood (BASELINE)**	**2.6**	**3.4**	**162**	**62**	**11.8**	**8.4**	**2.30**	**73**	**-317**	**0.0**
	Pipe & Riser	2.3	3.5	166	72	9.1	9.2	2.30	73	-356	0.1
	Pivot	2.0	2.2	105	51	4.9	14.4	2.58	71	-399	-1.2
	Drip	1.8	2.9	138	75	5.2	13.3	2.40	72	-436	-0.5
Diversified	Flood	2.6	6.5	310	121	22.8	4.4	1.10	80	-255	3.1
	Pipe & Riser	2.2	6.6	314	140	17.2	5.4	1.44	81	-270	3.2
	Pivot	2.0	5.3	254	127	11.4	7.4	1.55	80	-312	1.9
	Drip	1.8	6.0	287	160	10.7	8.5	1.57	80	-355	2.6
Intensified	Flood	18.3	12.6	479	26	26.8	3.1	1.64	79	-520	9.2
	Pipe & Riser	16.0	12.9	491	31	21.2	5.6	1.65	79	-557	9.5
	Pivot	14.3	12.4	474	33	16.6	6.7	1.69	78	-604	9.0
	Drip	12.9	12.8	490	38	15.3	6.5	1.75	78	-673	9.4
Simplified	Flood	1.8	2.5	240	134	18.6	5.3	2.02	75	-234	-0.9
	Pipe & Riser	1.6	2.4	231	147	13.2	7.6	2.01	75	-251	-1.0
	Pivot	1.4	1.9	180	129	8.5	10.5	2.27	73	-286	-1.5
	Drip	1.3	1.7	165	131	6.4	11.3	2.10	74	-291	-1.7

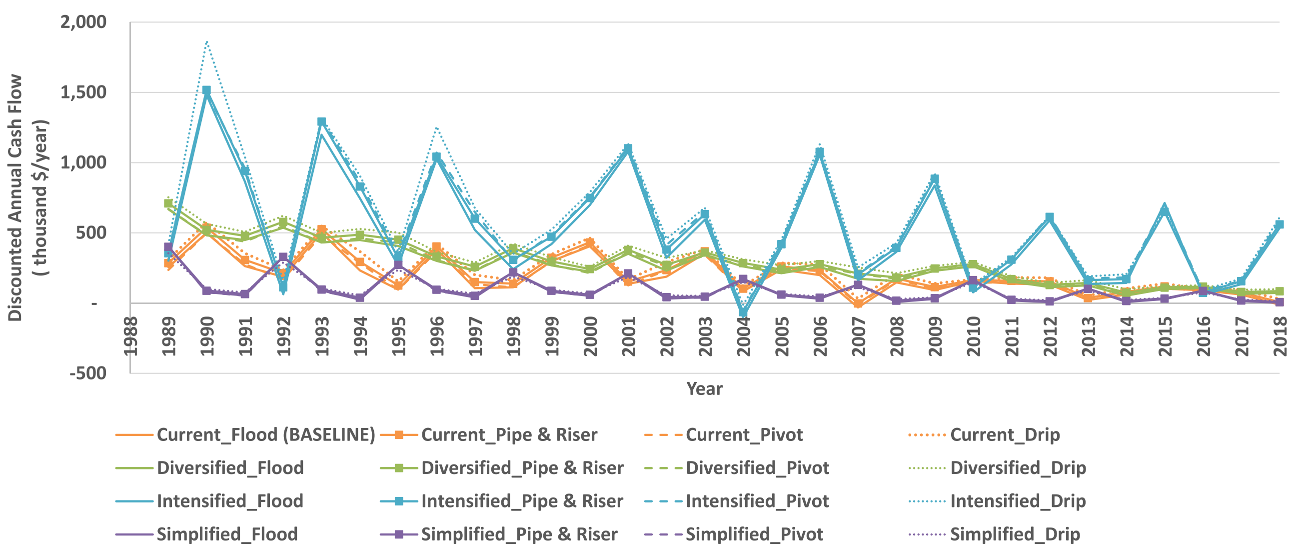

Fig. 3. Discounted Annual Cash Flow (thousand $/year) of the 16 adaptation scenarios combining agronomic system and irrigation infrastructure for a Riverina representative farm over 30 years (1989 –2018).

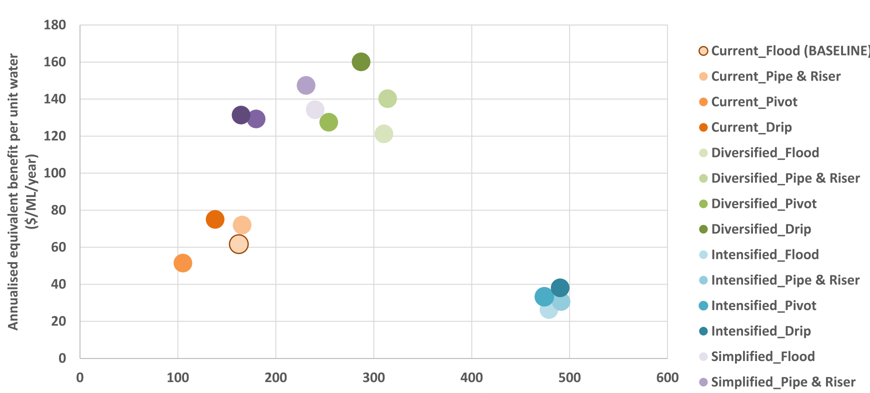

Fig. 4. Annualised equivalent benefit per unit area ($/ha/year) and per unit water ($/ML/year) for the 16 scenarios combining agronomic system and irrigation infrastructure for a Riverina farm over 30 years (1989 –2018). The Baseline scenario is outlined with a darker circle.

cash flows.

All scenarios generated a positive NPV, indicating a relatively profitable investment.

However, the magnitude of the benefit varied widely, from $1.7 M (*Simplified_Drip*) to $12.9 M (*Intensified_Pipe & Riser*), compared with $3.4 M for the *Baseline* (*Current_Flood*). Annualised benefits per hectare of irrigated farm and per megalitre of irrigation water varied between $105/ha for *Current_Pivot* and $26/ML for *Intensified_flood* and $491/ha for *Intensified_Pipe & Riser* and $160/ML for *Diversified_Drip* (Table 3, Fig. 4). Annualised equivalent benefit per unit area strongly aligned with the annualised equivalent benefit and per unit water except for *Intensified* (Fig. 4), suggesting that intensification would be more suited to farmers targeting area-based rather than water-based returns. Taking infrastructure investment into account, the IRR was lowest for *Current_pivot* (4.9% return on investment, and 14.4 years to pay it back), whereas *Intensified_Flood* had the highest IRR (26.8%) and the lowest payback period (3.1 years). This result indicates that lower-input, lower-output systems would not justify high-cost investments.

Regarding the relative effect of key inputs on the NPV output mean, water price always ranked first, followed by grain prices and N price in all *Current, Diversified* and *Simplified* scenarios. In *Intensified*, water price had the largest effect, followed by a mix of grain and N prices. The price of N fertilizer had a relatively higher effect in most *Drip* scenarios. Tornado graphs for inputs ranked by effect on output mean for the 16 scenarios are shown in Supplementary Fig. S2.

Overall, the benefits of *Intensified* were accrued from large gains in crop gross margins – especially per irrigated area – which consistently offset the mounting costs, including additional water use, while *Diversified* was superior in mitigating risk across the system due to higher return per ML of irrigated water and more diverse sources of income (lower CV, higher CVar0.2 and $P(\pi \geq 0)$ (Table 3). The de-risking role of diversification with moderate input use was highlighted in lower rainfall years, such as 1992 and 2004, where restricted irrigation water impacted crop yields and system profitability (Fig. 3). This was also evident in the higher benefit per ML of water in *Diversified_Drip* compared, for example, to *Intensified_Drip* (Table 3 and Fig. 4).

3.2. Mitigating risk and uncertainty

Relative to the *Baseline* (*Current_Flood*), *Diversified* scenarios with surface and pivot irrigation and all *Simplified* scenarios reduced downside risk quantified with CVar0.2. The less costly albeit less efficient *Flood* and *Pipe & Riser* irrigation methods were the least risky in all scenarios. Over 30 years, compared to the *Baseline*, CVar0.2 was reduced for *Diversified* scenarios from 1% (*Diversified_Pivot*) to 19% (*Diversified_Flood*), but not with *Drip* (−12%). The probability of break-even, $P(\pi \geq 0)$, varied between 71% (*Current_Pivot*) and 81% (*Diversified_Pipe & Riser*), compared with 73% in the *Baseline*. The CV of annual discounted cash flows changed from 2.30 in the *Baseline* to a low of 1.10 in *Diversified_Flood* and a high of 2.60 in *Current_Pivot*, indicating a reduced risk or increased resilience in the former and an increased risk in the latter scenario (Table 3, Fig. 5). Our results partially support the proposition that, when water supply is limited, pressurised irrigation should be favoured for efficient water use, despite their high capital costs and higher energy requirements (Mantovani et al., 1995).

The results above assumed the farmer had a risk-neutral behaviour (i.e., nil risk aversion). Accounting for four levels of risk aversion (low, moderate, high, very high), we found that *Intensified* returned the highest risk-adjusted profit for the low and moderate risk aversion levels, followed by *Diversified*, especially with surface irrigation (Figs. 5 and 6). While all scenarios broke even in risk-neutral conditions, some were too risky for a more risk-averse farmer in this context, and *Diversified* was the least risky overall (Fig. 6). In comparison, for example Gandorfer et al. (2011) reported CE (or risk-adjusted profit) in the range from − 282–78 $/ha/year[2] in a study of risk associated with tillage and nitrogen fertilisation, and Monjardino et al. (2019) reported a maximum range from − 254–486 $/ha/year in risk-adjusted profit (or CE) for one site in a study of yield and profit gaps.

The maximum cost of risk aversion varied 3-fold from $0.27 M/year in *Simplified_Flood* to $0.75 M/year in *Intensified_Drip*, compared to $0.39 M/year in the *Baseline*. These results confirm that given sufficient water, crop diversification, particularly in combination with surface irrigation, could de-risk the system in a profitable way, at least for low to moderate attitudes to risk. When water is limited, simplifying the system is a risk-reducing strategy.

Quantitative evidence on approaches more likely to mitigate financial risk or boost profitability could increase the confidence of more risk-averse farmers to step away from conventional practices. The level of farmer risk aversion could be reflected in terms of the level of adaptation, choice of infrastructure, area of farm irrigated, crop type, and the willingness to pay for irrigation water, as well as opportunistic trade of water driven by the movement in the water market. Farmer risk aversion is particularly relevant in the context of near absence of government subsidies for Australian farm businesses – about 1.4% of gross farm income, in comparison to an average 18% for OECD countries, and larger subsidies in countries such as Norway (60%) and Japan (48%) (OECD, 2017).

3.3. Closing the system profit gap and the opportunity cost of trading water

The net value of adaptation was positive for all *Diversified* and *Intensified* scenarios, but negative for most *Simplified* and *Current* scenarios (Fig. 7). This result summarises the financial performance of each scenario relative to the *Baseline* (*Current_Flood*) given all bioeconomic trade-offs considered in the analysis. Driven by cotton, *Intensified* generated the highest returns per area of irrigated farm and *Diversified* achieved the highest return per megalitre of irrigation water (Fig. 4). Surface irrigation (*Flood, Pipe & Riser*) had a relatively higher net value under most scenarios, while *Drip* outperformed in terms of return per ML of water under all scenarios except in *Simplified*. The largest net value of adaptation identified in this probabilistic analysis was just under $10 M for *Intensified_Pipe & Riser*, indicating the potential magnitude of the profit gap in this case study, given high water availability and a neutral attitude to risk. However, a more risk-averse farmer may prefer a less risky approach in closing a third of that profit gap by diversifying the system with a legume crop and flooding irrigation.

The relative profitability of each scenario correlated negatively with the opportunity cost of trading allocation water (Fig. 7). Given the relatively strong negative correlation ($r = -0.89$, $p < 0.05$) between historical water price and irrigation allocation, the likely opportunity cost of trading water varied from − 2% for *Current_Drip* and − 3% for *Simplified_Drip* and *Current_Pivot* to − 29% for *Intensified_Flood*, compared to − 13% for the *Baseline*. In this context, a positive opportunity cost means that a farmer is better off selling their allocated water whereas irrigating valuable crops is the more profitable option when the opportunity cost is negative or lower. In other words, simplification with costly irrigation is more likely to generate financial return from moving to less secure entitlement. Of note, farmers can smooth out annual variation in water availability not only by trading water in the market, but also through the carryover of unused water. Clearly the design of the systems (including crop rotation, crop inputs, irrigated area, water allocations, infrastructure options) bounded our results and conclusions; we did explore only a small sample of the profit and risk trade-offs associated with alternatives including more water-efficient but energy-intensive irrigation technologies. In any case, crop management can

[2] Converted from Euros

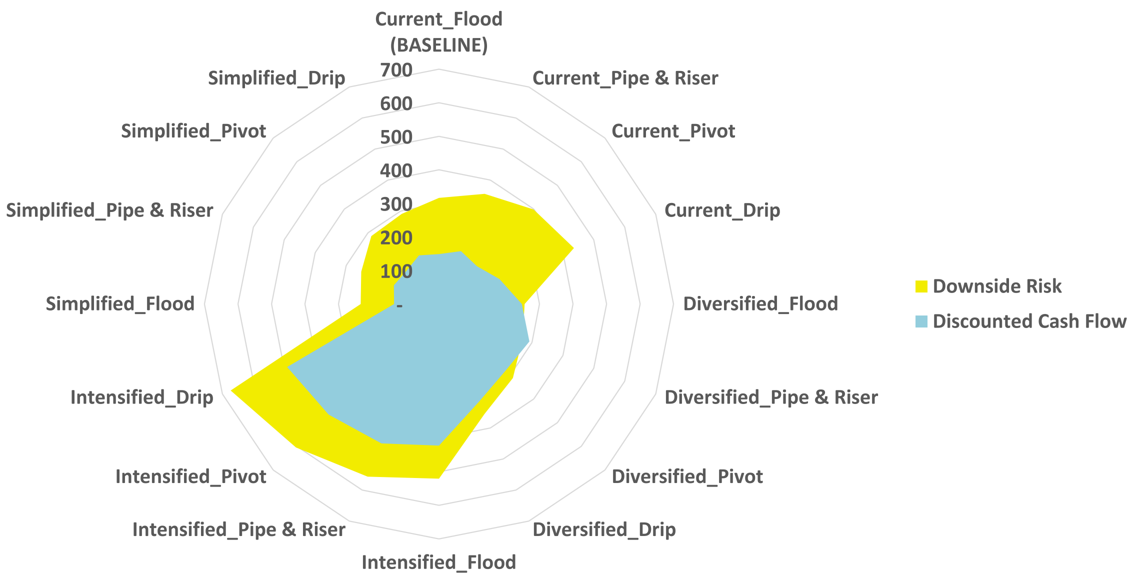

Fig. 5. Risk-return profile of 16 scenarios combining agronomic system and irrigation infrastructure for a Riverina farm over 30 years (1989 –2018). Discounted cash flow (blue) and downside risk (CVar0.1) (yellow) are in thousand $. For illustration purposes, downside risk is represented similarly to the cash flow (e.g., high values = high profit/risk, low values = low profit/risk). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

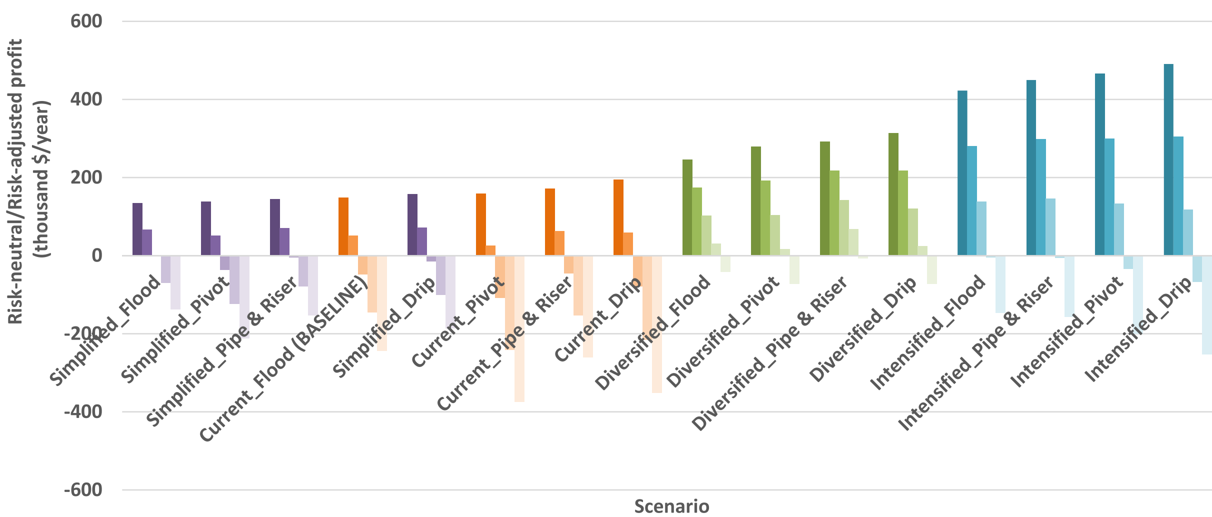

Fig. 6. Risk-neutral profit (darkest bars) and associated risk-adjusted profit for 16 scenarios combining agronomic system and irrigation infrastructure across four levels of farmer risk aversion (from low risk aversion–dark bars to very high risk aversion–light bars) for a farm in the Riverina over 30 years (1989 –2018). Scenarios are ranked by risk-neutral profit. Scenarios are *Intensified* (blue), *Diversified* (green), *Current* (orange) and *Simplified* (purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

hardly be optimised in the real world (Sadras and Denison, 2016).

The scenarios investigated here provide a benchmark for comparisons of alternative combinations of new and current agronomic practices and irrigation infrastructures. Sensitivity analysis is highly recommended around input costs, transfer efficiencies, and infrastructure costs. Likewise, further analysis is required to explore best use of water and land, and the potential role for deficit irrigation – i.e., more land cropped less intensively, with each hectare receiving less supplementary irrigation.

3.4. Implications for irrigation decisions

For the case study farm, intensifying the current irrigation system delivered the largest financial benefits over 30 years but diversification was superior in terms of risk mitigation across low to moderate farmer risk aversion, while also profitable. A system profit gap of up to $10 M was quantified for the irrigated farm area (max. 700 ha) over 30 years, compared to present practice if more profitable farm designs would be adopted. In addition, our study has confirmed that the capital cost of irrigation development is a key driver of investment performance, and consistently high crop gross margins are required to offset costs at a system scale.

Under the assumptions in our study, agronomic system had greater relative influence on financial performance than irrigation infrastructure. ANOVA's F-ratio – a measure of true variance between scenarios – varied between 0.15 for *Simplified* irrespective of irrigation methods and 0.83 for *Current* suggesting a low variance, with 14–56% confidence. The difference was larger for changes in agronomic system within the same irrigation infrastructure, with the F-ratio ranging between 16.33 for *Flood* and 21.30 for *Pivot* all with.

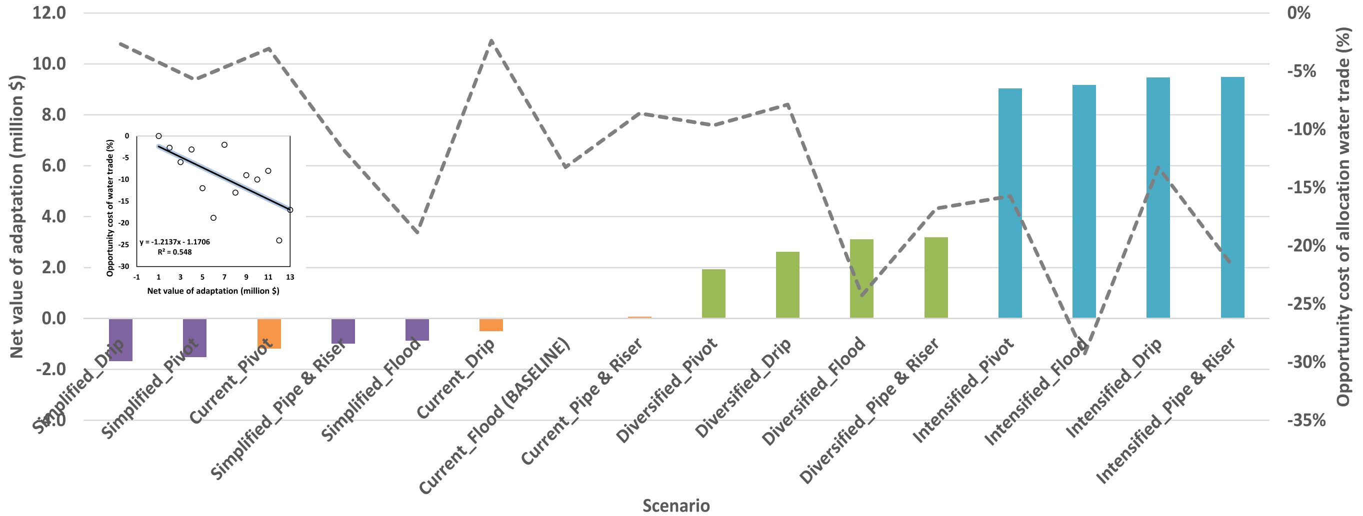

Fig. 7. Net value of adaptation (bars) and opportunity cost of water trade (dashed line) for 16 adaptation scenarios combining agronomic system and irrigation infrastructure over 30 years (1989 –2018) for a farm in the Riverina. Scenarios are ranked by net value of adaptation. Scenarios are *Intensified* (blue), *Diversified* (green), *Current* (orange) and *Simplified* (purple). Inset shows the negative correlation between the net value of adaptation and the opportunity cost of trading water for each scenario. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

100% confidence. These results provide useful insights to tailor agronomy to infrastructure, and vice versa. They also support the trend of farmers adapting to climate adversity and variable agronomic performance by employing technology, such as irrigation systems, to mitigate risk and maintain or increase profitability (Hughes and Gooday, 2021).

An important dimension beyond the scope of this study is the likely environmental impact of each adaptation strategy. For example, pressurised irrigation systems (e.g., *Pivot*) are more energy-intensive, surface irrigation (e.g., *Flood)* requires more intense vehicle and fuel usage, and micro irrigation (*Drip*) could increase the risk of agrochemical pollution and agricultural emissions from higher N fertiliser inputs (albeit lower herbicides). Options to minimise leakiness are desirable, both to reduce environmental damage and increase system efficiency – models such as APSIM can quantify these across a wide range of climates and soil types (Keating et al., 2002). While not presented here, the water balance components (evaporation, runoff, drainage) in this environment are proportional to water applied, from minimal amounts in the *Simplified* system, to the extreme of the rice paddy component within the *Intensified* system.

Our findings build on previous system-wide studies on the relative benefits of various adaptation strategies for irrigation, including for the critical management of soil nitrogen dynamics and greenhouse gas emissions (Kodur et al., 2019; Maraseni et al., 2021; Maraseni and Kodur, 2019; Mushtaq et al., 2015). In particular, Gaydon et al. (2012) concluded that farm-level strategy mainly depends on seasonal water availability, but did not account for new crops, contrasting irrigation infrastructure, farmer risk aversion, nor historical prices for key commodities such as grains, water and fertiliser. In contrast, while seasonal water availability was considered and provided useful insights for profitable adaptations to water-constrained systems, the broader implications for overall water allocations–including environmental flows and water recovery programs–fell outside the scope of this study. A follow-up study could explore how investments in on-farm irrigation infrastructure impact on the supply of irrigation water. Exchanging entitlements for irrigation infrastructure could lead to a reduction in water entitlements and allocations to irrigators (Goesch et al., 2020). However, as suggested by Goesch et al. (2020), "the impact of these investments on production is less than the purchase of an equivalent volume of water because they increase water use efficiency, increasing the effective supply of irrigation water. In addition, irrigators retain some of the savings from these investments."

Our results were strictly dependent on the modelling assumptions and simulated outcomes, and hence are intrinsically less variable than the field observations. For example, assuming average transfer efficiencies of 70%, 80%, 90% and 100% respectively for *Flood, Pipe & Riser, Pivot* and *Drip* means the benefit of *Intensified* with micro irrigation was likely over-estimated as some losses are expected to occur in the field. This is compounded by the fact that rice is commonly flood-irrigated, incurring field losses of 60 – 80%, not the assumed range of 70 – 100% associated with the four selected irrigation methods. It is worth remembering that all adaptation scenarios are assumed to rely on new investments, which may not always apply if farms are already equipped with alternative infrastructure or only require partial adjustments. Similarly, operational costs may change if other supplies such as groundwater are pumped through the system (An-Vo et al., 2015). Further sensitivity analysis on the capital and operational costs of irrigation is therefore recommended.

Altering the discount rate is expected to impact NPV – lower rates increase the present value of benefit, and vice versa. Determining an appropriate discount rate remains controversial and could warrant further testing (Abelson and Dalton, 2018). In a stricter financial analysis, using a modified internal rate of return (MIRR) could more accurately reflect the relative profitability of an investment. This is because it assumes that positive cash flows are reinvested at the cost of capital (instead of the IRR itself) and the initial outlays are financed at the financing cost rate suited to the business (Zhang, 2005).

Assuming a long-term water price – mean $138/ML drawn from a 20-year distribution –means the conclusions favouring *Intensified* would not hold in a drought context, such as in 2007 – 08, when the price of irrigation water exceeded $800/ML. The same applies to the price of N fertiliser – also drawn from a 30-year distribution – which would have been unfavourable to *Intensified* during N price spikes, e.g., up to $900/t of urea at the height of the global energy crisis in the late 2000 s. Furthermore, the impact of grain prices is significant; while cotton is one of the most profitable irrigated crops in sub-tropical Australia (Roth et al., 2013), high grain prices in 2008 triggered a record area of irrigated wheat in the region (Peake et al., 2014). Generally, the cost of crop production and decline in the terms of trade is a growing concern for farmers. For example, the open water market in the Riverina has favoured higher value, permanent crops like almonds, olives, citrus and grapes, but these industries are also adjusting to fast rising production costs and potential reduction in yield and quality from restricted water delivery in mid-season extreme heat (Githui and Goodwin, 2019;

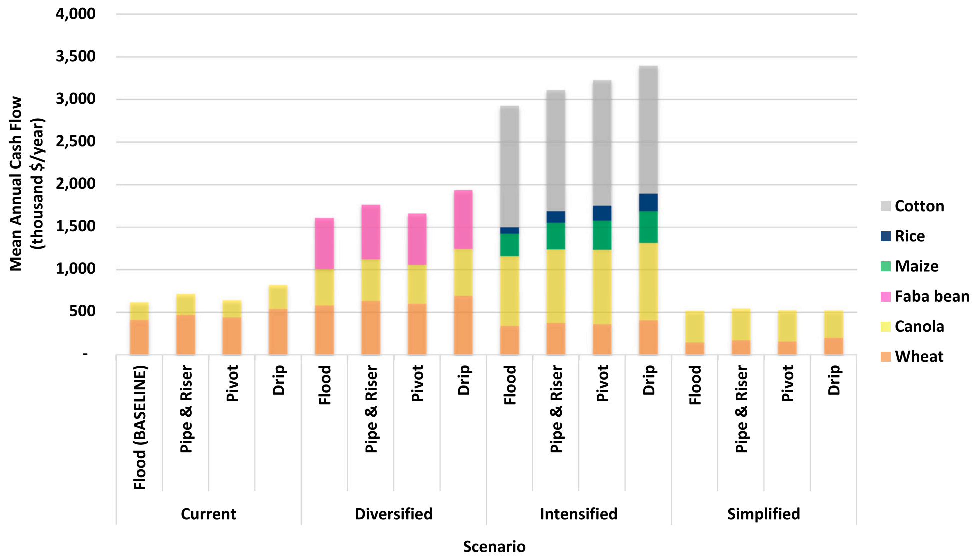

Fig. 8. Mean annual cash flow of each crop for 16 scenarios combining agronomic system and irrigation infrastructure over 30 years (1989 −2018) for a farm in the Riverina. Annual Cash Flow excludes the upfront capital cost of infrastructure.

Mallawaarachchi et al., 2020).

As illustrated in Fig. 8, cotton is the main driver of profitability in *Intensified*, followed by canola, with wheat, maize and rice performing relatively well, especially under *Pivot* and *Drip*. The higher profitability of *Diversified* relative to *Baseline/Current* was mainly attributed to the inclusion of a profitable grain legume in the rotation, along with the water and N implications of rotations flowing on to the wheat and canola. *Simplified* resulted in the lowest wheat profitability, although dryland canola was relatively more attractive in a water-limited system due to the significant savings in irrigation costs. If water security and affordability permit intensification, investing in pressurised irrigation favours more flexible rotations – including summer crops – and provides the opportunity to irrigate more strategically across larger areas.

Ultimately, the complex trade-offs between water scarcity, price volatility, irrigation investment, environmental impacts, and farmers' attitude to risk influence irrigation decisions, so insights from this study could inform pathways towards the closure of the irrigated profit gap. More broadly, knowing that saving 1% of irrigation water could be used to grow additional food and fibre worth $154 M per annum in Australia (CSIRO, 2020), points to the opportunity to design agronomic and irrigation systems to increase water productivity, whole-farm profitability and resilience.

Approaches that combine crop simulation, economics and finance, risk and uncertainty, such as the one used in this analysis, add value to agricultural systems research (Weersink and Fulton, 2020). While system interpretations of yield gaps have been limited to crop rotations, few have scaled the concept of yield and profit gap to the whole farm given logistical and economic concerns. A simplified version of the analysis described in this article was incorporated in the Investment App of WaterCan Profit www.watercanprofit.com.au. The tool is freely available to researchers, extension officers and agribusinesses. Potential exists for similar approaches to be applied to other irrigated crop production regions of the world with similar trends of dry hydrological conditions and limited water supply driving high water prices, such as California (NASDAQ, 2020), the Indo-Gangetic plains of India and Pakistan (Ali et al., 2016; Kirby et al., 2017), the Nile Basin in NE Africa (Oestigaard, 2012), the Yaqui Valley in Mexico (Fischer et al., 2022; Schoups et al., 2006), and the Iberian Peninsula in Europe (Rodrigues et al., 2021; Soto-García et al., 2013).

4. Conclusion

A framework of crop simulation and profit-risk analysis was used to investigate profit-risk trade-offs and farmer risk aversion in contrasting agronomic and irrigation scenarios. For this case study, scenarios of intensification with cotton were the most profitable, while crop diversification with a grain legume, along with moderate inputs and surface irrigation was superior for de-risking. Significant differences in the cost of risk aversion across scenarios confirm that attitudes to risk are likely to affect irrigation decisions and profit outcomes in riskier contexts underpinned by complex trade-offs. We demonstrated the potential to better understand and quantify where benefits may be greatest and where risk and uncertainty can most readily be mitigated in the face of high volatility in seasonal rainfall, water allocations and commodity prices, along with high capital costs of infrastructure. We advance a context-specific, system-based approach that aims to identify financially feasible irrigation systems design and decision making, with the goal to increase water productivity, whole-farm profitability, and resilience.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.107740.

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