Investments and Uncertainty: Cost-Benefit Analysis and Water-Use Efficiency

David Adamson[†] and Adam Loch[†*]

[†] Centre for Global Food and Resources, University of Adelaide, South Australia, Australia

[*] Corresponding author: email adam.loch@adelaide.edu.au | tel. +61 8 8313 9131

Abstract

Long run investments in water capital are risky, particularly where water is required as a secure input to production systems. State of nature representations of water supply outcomes assist with our increased understanding of the vulnerability of capital, and water users, to adverse events. In an example, by coupling the cost-benefit analysis framework to a state contingent analysis approach we are able to explore the riskiness of water-use efficiency (WUE) investment payoffs and cash-flow outcomes when frequencies of states of nature change over the course of that investment. Critically, this approach also allows us to represent decision-maker adaptation in the face of risk and uncertainty. Finally, dividing WUE investment options into their key components—at the farm scale in this instance—adds clarity to the debate surrounding policy options to address future water scarcity challenges. In particular, our results illustrate: i) why private investment in water-use efficiency is lower than we should expect; ii) the role that public subsidies therefore play in distorting price signals, investment choices, and the socialisation of risk; and iii) the vulnerability to extreme shocks of any subsidy-transformed production systems toward high-value perennials.

Keywords: water-use efficiency, cost-benefit analysis, uncertainty, states of nature.

Investments and Uncertainty: Cost-Benefit Analysis and Water-Use Efficiency

1. Introduction

The world's supply of water is finite and uncertain. Historic misallocation of finite water resources has created insecurity, inequality, and negative externalities. Current public policy has needed to address historic misallocation in response to increased water demand associated with providing food security, urban/rural economic development, and/or alternative uses (e.g. environment). This motivates water managers and policy-makers to seek efficient and effective uses. A common strategy has been to adopt or invest in efficient water-use technology. Water-use efficiency is desirable, as it may allow society to produce the same quantity of a desired output with less of a specific input (i.e. water) by substituting other non-binding factors of production (land[1], labour, capital) (Arrow et al., 1961). By increasing technical or allocative efficiency in the extraction, delivery and consumption of water, welfare-enhancing (economic, social and environmental) investment opportunities are then possible. Importantly, a full accounting for current water resource use should pre-empt any such investment.

However, the combination of increased water demand and uncertain supply can amplify private capital investment risk exposure that, when scaled, can result in larger irreversible losses of public, social, and natural assets. In this paper, we define risk as a known-known described with some certainty via a probability distribution. We further define uncertainty (i.e. known-unknowns or unknown-unknowns) as outcomes that fundamentally change (identify) existing (new) probability distributions, and require altered management responses. In a water management context, an example of risk is our current understanding of the reliability of water supply (droughts and/or floods), while an example of uncertainty is a fundamental change to future water supply (positive or negative) requiring an adaptive management response. When

---

[1] Where land defines all-natural factors of production (i.e. inputs) including water.

such positive/negative water supply is realised, water demand may be dramatically altered (e.g. non-convex management solutions) under a motivation to protect capital investments. Thus, the greater the uncertainty (i.e. unknown-unknowns), the risker a future investment becomes.

The purpose of this paper is to explore a possible strategy to mitigate capital risk exposure at multiple scales by combining the state contingent analysis (SCA) approach with cost-benefit analysis (CBA). The strategy enables an alternative representation of uncertainty, coupled with an improved understanding of how private investors adapt to realised water supply, to enhance our appreciation of why water-use efficiency investments may fail.

2. Risk, Uncertainty and Cost-Benefit Analysis

Cost-benefit analysis (CBA) explores different trade-offs from allocating factors of production (land, labour and capital) between status-quo (i.e. existing system) and alternative (e.g. more efficient) investments. The quantification of future cash flows (expenditure and income) over the life of an investment option and discounting them back to a net present value, allowing for comparisons between investment choices.

The net present value (NPV) is the sum of the expected net return from the investment $(E[Y])$ over the project duration in years $(t = 0 \ldots n)$, divided by a discount rate r (Equation 1). The result provides a key metric for evaluation. $E[Y] = (Y - K)$, where K is the capital invested and Y is the net annual return derived from the investment. Further, $Y = (v - c)$ where: revenue (v) is a multiplication of the output (z) and price paid per unit of output (p) so that $v = zp$; and costs (c) account for both fixed and variable expenditures.

$$NPV = \sum_{t=0}^{t=n} \frac{E[Y]_t}{(1+r)^t} \tag{1}$$

If $NPV = 0$, then the project has broken even. When $NPV > 0$ the project is profitable. Finally, when $NPV < 0$, the project is expected to make a loss. However, it is logical to assume that both risk and uncertainty occurs when estimating the generated output, prices paid/received, or costs of investment. Therefore, representing and quantifying the negative and positive impacts derived from risk and/or uncertainty estimates on any single capital investment is crucial for understanding the opportunity costs of a full set of investment choices.

The risk/uncertainty debate surrounding CBA estimations of investment choices takes three major forms. First, what is the appropriate discount rate to reflect the values associated with unknown-unknowns, a precautionary principal, or the intra- and/or inter-generational benefits from realigning society towards alternative outcomes (Arrow and Lind, 1970; Baumol, 1968; Dietz and Stern, 2008)? Second, what is the appropriate way to represent risk/uncertainty to quantify the costs and benefits used in the analysis? Third, it has been argued that the very nature of the uncertainty problem prevents CBA from reflecting unknown-unknowns, as those events either fundamentally change the nature of the scenarios used to describe outcomes, or result in realised outcomes (e.g. output or prices) that have never been previously experienced (Horowitz and Lange, 2014; Tol, 2003). In what follows, we can ignore the first debate issue, as we will ultimately be dealing with a private investment choice over a fixed time-period. However, below we address the second and third debate issues via an initial discussion of the limitation of mean-variance representation of outcomes, and then illustrating the power of combining state contingent analysis (SCA) approaches to dealing with unknown-unknowns to a slightly modified CBA framework.

2.1. Risk and uncertainty within a traditional CBA framework

Within a CBA framework, risk/uncertainty is primarily included via sensitivity analysis that explore the mean and variance of a probability distribution of variables which positively/negatively impact costs/benefits (Merrifield, 1997). We can illustrate this using a

Just-Pope production function (Equation 2) that explores output from the use of a single input (e.g. water):

$$z = g(x) + h(x)_{\varepsilon} \tag{2}$$

The Just-Pope production function describes both additive risk $g(x)$, where output distribution is not derived from the use of inputs, and multiplicative risk $h(x)_{\varepsilon}$ where output distribution is directly linked to the use of inputs. In this case, the error term (ε) is frequently based on past data, where the known mean and variance parameterise a probability distribution function in a Monte-Carlo simulation. This allows for a series of outcome-runs to determine how often an investment fails to break even.

However, Just and Pope (1978, 1979) challenge the use of mean-variance approaches to stylise risk and/or uncertainty in their reviews of stochastic production functions. Prior to this, Rothchild & Stiglitz (1970, 1971) noted four limitations of relying on the mean and variance by illustrating the outcomes (i.e. identification of a riskier variable) from choosing between variables that had the same expected value, but different distributions. One critical finding, commonly known as *Mean Preserving Spread*, concerns how a failure to understand how alternative weights in the distribution of tails can result in investors choosing to invest in riskier rather than safer investments.

While the notion of representing risk and/or uncertainty as a deviation around a mean number is appealing within partial equilibrium analysis, this approach assumes that the decision-maker remains passive to the signals provided by the source of risk and/or uncertainty. In other words, the analysis assumes the investor (e.g. farmer) to be ‘dumb’, refusing to adapt in the face of required change—no matter the uncertainty signal. For example, in the case of irrigated cropping, the model represents a refusal to adapt as continuing with the same irrigated crop, even when no water inputs are available. Finally, Rothenberg and Smith (1971) explored how uncertainty alone impacted resource allocations within a general equilibrium model. The adoption of the general equilibrium approach allowed for an exploration of feedbacks on the allocation of capital to maximise profits (e.g. prices and labour), in response to uncertainty. They applied two different models representing uncertainty as i) a variable labour supply and ii) a fixed labour supply; but where the uncertainty is represented by a production function with a random parameter. Of their four key findings (ibid., p 458), three are particularly important for long-term capital investment outcomes. First, short-run production flexibility provides the greatest protection against uncertainty. Second, national income falls if the production function has a random variable with diminishing returns, but increases when a 'plausible' production function has a multiplicative random parameter. Third, while uncertainty decreases aggregate income, there will be both income winners and losers in the economy. Put another way, inputs can be risk-increasing, risk-decreasing, and shared inequitably dependent on the nature of the capital investment.

This nature of risk increasing and risk decreasing inputs of production are consequently concerned with their variability and how they change the net return of an/or between asset(s). However, what is not considered, is what occurs if the investment occurs and inputs can't be reliably sourced (i.e. there is no water).

2.2. An alternative approach

We propose that the combination of state contingent analysis within a slightly modified CBA framework is an effective alternative approach. Note that original studies used the term 'states of nature' when discussing investment choices under risk/uncertainty. The earliest work was undertaken by Arrow (1953) and Debreu (1959), providing a capacity to represent how decision-makers respond to realised alternative states (e.g. drought/flood events). For example, Graham (1981) explored farmers willingness to pay for a public dam project that provided water supply in dry states of nature, and flood mitigation in wet states. However, it was

Hirshleifer's (1965, 1966)[2] work that carefully articulated the differences between using the dominant mean-variance approach and the state of nature approach to represent risk/uncertainty to inform investment choice theory. According to Hirshleifer (1965), the state of nature approach removes the *"vagueness"* (p534) associated with other uncertainty methodologies, as it allows the decision-maker to precisely identify both the natural endowments provided in a given state, and the factors of production required to obtain an output in that state.

Chambers and Quiggin (2000) subsequently extended the state of nature approach by merging it with dual optimisation to illustrate how resources can be can be used to optimise input use in all states, by time, place and type[3] (Rasmussen, 2003). Following this work, the state of nature approach becomes the state-contingent analysis (SCA) approach.

In the SCA approach, nature (Ω) defines the complete uncertainty space, and Ω can be divided into a series of states of nature (s) that define real, and mutually-exclusive sets (S) to describe that uncertainty ($\Omega = \{1, 2, \dots, s, \dots, S\}$). Importantly the decision-maker has no ability to influence which s occurs. Further, the decision-maker's subjective belief about the frequency/probability ($\boldsymbol{\pi}$) of each s occurring is a vector described by ($\boldsymbol{\pi} = \pi_1, \dots, \pi_s$). However, for each s the decision-maker does have a set of management options for each alternative production system (technology). This can be represented (Equation 3) by a "continuous input correspondence, $X: \Re_+^S \rightarrow \Re_+^N$, which maps state-contingent outputs into input sets that are capable of producing that state-contingent output vector" (Chambers and Quiggin, 2002a, pg. 514):

$$X(\mathbf{z}) = \{x \in \Re_+^N : \mathbf{x} \text{ can produce } \mathbf{z}\}\,. \tag{3}$$

---

[2] Note Hirshleifer (1965) uses the term 'state-preference' rather than Arrow's (1953) states of nature.

[3] Refers to three input types: i) ***non-state-specific (or state-general)*** inputs that must be allocated *ex-ante* to the s being realised, and which influence z in all s; ii) ***state-specific inputs*** that are applied *ex-post* to the realisation of s and which influence z in only that s; and iii) ***state allocable (flexible) inputs*** (costs) that are applied *ex-ante* to s being realised, but where benefits accrue once s is realised.

For each s, the vector of inputs $\mathbf{x} = (x_1, .., x_N)$, their prices $\mathbf{w} = (w_1, .., w_N)$, and output prices p are known so that revenue can now be represented as:

$$v_s = z_s p_s \qquad\qquad \forall_s \in \Omega, \tag{4}$$

while costs are also now represented as:

$$c_s = w_s x_s \qquad\qquad \forall_s \in \Omega, \tag{5}$$

and expected net profit across nature Ω is:

$$E[Y] \; = \sum_{s \in \Omega} \pi \, (v - \mathbf{c}) \, . \qquad\qquad \forall_s \in \Omega. \tag{6}$$

Under the above conditions where inputs, input prices and output prices are fully known, and where the decision-maker’s management responses to alternative s does not alter, the total nature set Ω can be collapsed.

Therefore, once s is realised, there should be no vagueness in how decision-makers should respond. In such cases, not only is the risk/uncertainty completely described, but the decision-maker should then actively respond to that risk/uncertainty by reallocating inputs to obtain known returns. This combination of completely describing the risk/uncertainty and its outcomes limits the positive/negative impact of unknown-unknowns. We can express this another way. When parameterising risk/uncertainty unknown-unknowns can only be either greater than, or less than, the chosen parameter. For example, in the case where total supply of water (i.e. quantity of water) is the source of risk/uncertainty, the outcome can only result in more or less water than was expected. However, the severity of the realised water supply outcome may suggest better technologies for adoption in response. Consequently, sensitivity analysis could play a role in determining the thresholds at which existing technologies fail. At those failure points, if new technologies emerge over time, then a new set of s may be required, expanding the original total nature set Ω.

Importantly from the previous discussion, Equation 6 slots seamlessly into Equation 1, allowing for the combination of CBA and SCA frameworks; as earlier suggested by Hirshleifer (1966) and Graham (1981). In this paper then, we posit two hypotheses: *H1* that if we examine water efficiency from an alternative perspective we can achieve a better understanding of water as a production input and its vulnerability to shocks; and *H2* that incorporating risk and uncertainty enables robust modelling of water production inputs and efficiency impacts, and a better understanding of private capital investment decisions. Before we test these hypotheses, the next section details the value water inputs have to production systems, and the riskiness of capital investments in water.

3. Water resources in a production system

Recall that we discussed the Just-Pope production function (Equation 2) that specifies output as a function of inputs (e.g. water). Water inputs in the Just-Pope production function included both additive and multiplicative risk. Chambers and Quiggin (2002b) respecify the Just-Pope production function into an SCA format as $z_s = g(x) + h(x)_{s,\varepsilon}$, highlighting how stochastic information can be represented to explain adaptive responses to revealed states of nature and their outcomes. Mallawararchchi et al. (2017) modify Chambers and Quiggin's equation into $z_s = \zeta_s + h(\boldsymbol{x})_{s,\varepsilon}$, where all variability derives from the natural resource base (land quality) ζ_s, and the use of a multiplicative risk derived from a vector of inputs (including water) to explain dairy farmer adaptation during drought. Also thinking about drought adaptation, Adamson et al. (2017) explore the behavioural responses of different irrigator types (perennial and annual) to protect their capital investments. By developing a two period SCA game against nature where irrigators bet against receiving their water entitlement (i.e. the uncertainty), the authors explain how and why water prices transition from inelastic, unitary elasticity to elastic in response to water supply uncertainty. They achieved this by separating water into two distinct input types: i) water used to generate output z, and ii) water used to maintain perennial production systems (i.e. keep them alive)—although they did not specify this mathematically. However, if we merge the concepts from Mallawaarachchi et al. (2017) and Adamson et al. (2017), we can re-represent the SCA production function as Equation 7:

$$z_s = \zeta_s + g(x)_{s,\varepsilon} + h(x)_{s,\varepsilon}. \tag{7}$$

The equation now represents how z is produced, in each s, on a given area of land, using a combination of additive risk from natural soil fertility (ζ) and two multiplicative risk signals for water inputs (x): that is, those inputs required to keep the production system alive (g), and water inputs required to generate outputs (h).[4] Note, $g = 0$ for all annual crops. The addition of an error term for g beyond Chambers and Quiggin's original equation is deliberate to account for the decision-makers' unawareness of maintenance inputs required in each state.

This separation of water into g (maintenance water) and h (productive water) illustrates that an inability to meet $g(x)$ units of water results in irreversible losses of capital directly invested in that production system (e.g. rootstock, trellising, and some irrigation equipment). Separation also illustrates the opportunity costs of bringing forward perennial production system replanting expenditure. Adamson et al. (2107) argue that to avoid irreversible losses perennial producers may be willing to pay a price for water that leads to short run losses, if on average (in the long-run) the investment in the crop at least breaks-even . However, the problem investors may face is that there is no future water to access—although annual producers may provide access via market mechanisms, as they do not require g water between years. This highlights the differences between annual production systems that require water in the relevant state outcome (risk decreasing—short arrows Figure 1a), and perennial production systems that

---

[4] Plant physiologists discussing crop water consumption may use the terms basal evapotranspiration (ET), or the ET that happens before any useful yield, and productive ET which is associated with biomass formation. These two elements are analogous to our g and h; but our g represents the water needed to maintain a perennial crop for production in the following year.

require water across all states of nature (risk increasing—long arrow Figure 1b). For simplicity, *g* is always required as an input for perennial production systems.

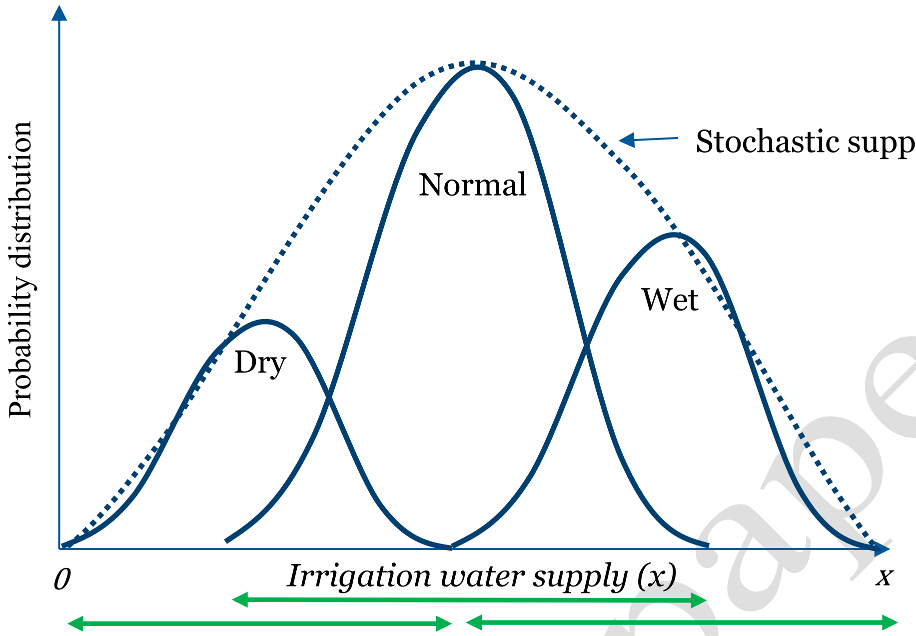

Figure 1a: water as a risk decreasing production input, annual systems

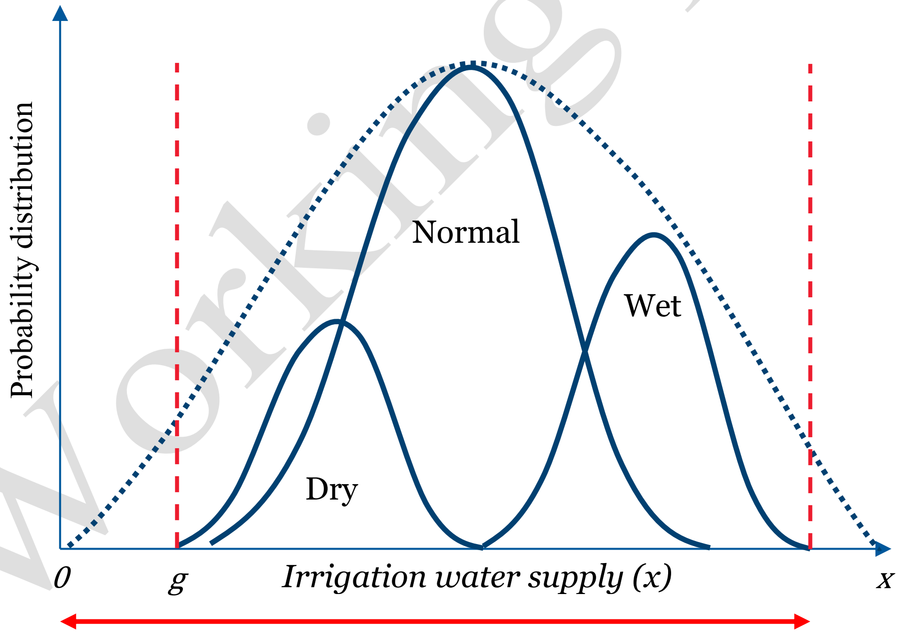

Figure 1b: water as a risk increasing production input, perennial systems

One common policy approach to reduce the risk associated with water capital investments is water-use efficiency (WUE). While debate about the value of WUE continues among scientists, water managers and policy-makers, a less-discussed issue is whether or not WUE actually provides greater capital investment protection in the face of rising risk and uncertainty.

3.1. Water-Use Efficiency as a risk-reducing strategy

Broadly, WUE focuses on innovating the use of water resources. Engineering innovations may reduce losses in water delivery systems. Agronomic innovations may increase outputs per unit of water applied. Economic innovations may maximise returns per unit of water applied. Perry (2007) defines different discipline terminologies as: *field application efficiency* (engineering) which is the ratio of crop irrigation water requirements and water delivered to a field; *irrigation efficiency* (agronomic) which is the ratio between water consumed by crops and water diverted; and *water-use productivity* (economic) which is the dollar value of water produced per unit of water applied. Alternatively, we could consider a *water-use index* (WUI), which is the crop yield (z) per unit of water diverted (Barrett Purcell & Associates, 1999).

However, these alternate terminologies can add to confusion and debate in the WUE space. We suggest, similar to Lankford (2012), that WUE should focus on understanding how total water delivered to the farm gate is utilised. In this context, system inefficiencies inside the farm gate are within the farmers' ability to manipulate through investments or management strategies. Everything beyond the farm gate is outside the farmers' control. Thus, to maximise the net economic returns from innovative investment or strategic decisions about WUE we must account for all water diverted at the farm gate, where the decision-maker will only invest if profitable inclusive of total costs. We therefore first specify *water-use productivity* (or economic WUE) as $E[Y]/ML$, which is the total expected income $E[Y]$ generated from all diverted water at the farm gate ML; or more simply the net profit made from all water. Next, the alternative WUE investment choices can also be redefined using the common denominator ML:

- *field application efficiency* defined as (ML'/ML), or the quantity of water required to provide sufficient input to irrigate a production system (ML') per ML;

- *irrigation efficiency* defined as (ML^{*}/ML), or the water consumed by crops ($ML*$) per ML;
- *Water Use Index* (WUI) defined as (z/ML), or the output produced z per ML,
    - where $ML > ML' > ML^{*} > WUI$.

This allows us to examine how: farmers reallocate all resources to maximise profits by understanding the opportunity costs of investments in WUE, determine if water is the binding constraint, and/or identify alternative (better) investment choices. Consequently, we can simplify WUE investment choice sets into three groups (Figure 2). First, **farm design choices** $(m = ML - ML')$: this explores the costs and benefits of alternative infrastructure systems to store/deliver water around the farm (e.g. channels from the farm gate, on-farm dams, and pipelines to/from paddocks). Second, **application technology choices** (a); these are the capital/practice options used to irrigate paddocks (e.g. flood, drip, sprinkler irrigation). Third, the **SCA production system choices** $[g(x)_{s,\varepsilon} + h(x)_{s,\varepsilon}]$, which account for both the capital invested in the commodities, and how and when watering occurs via technology investments (m) and (a) above.

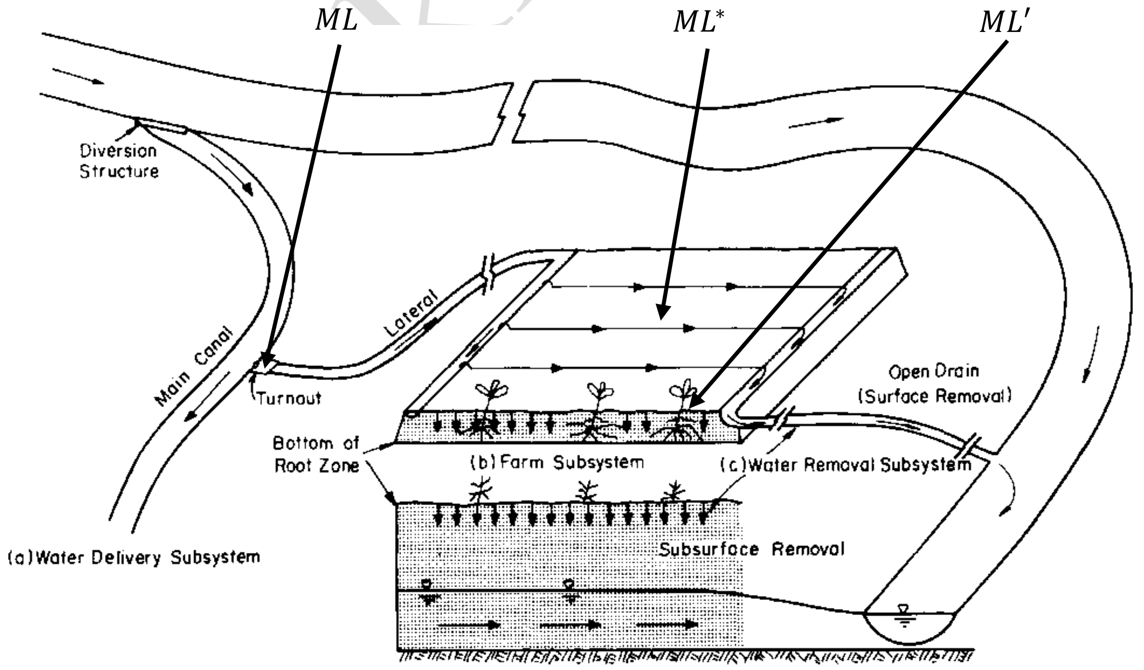

Figure 2: Post farm gate investment/management choices (adapted from Skagerboe, 1983)

Using this approach, we can now explore the risk to alternative investment and/or management strategy decisions associated with farm design, application technology, and SCA production system choices. Most importantly from a risk/uncertainty perspective, we are better able to represent and explore WUE investment/strategic management decision outcomes when water inputs are not available.

When water inputs are not available, we reveal the fragility of our three alternative investment choices. First, there is negligible risk exposure to farm design choices if water is not available. Some ongoing maintenance and refurbishment may be required, but there will be no irreversible capital loss. When water is not available, the capital risk exposure for application technology and SCA production system investment choices is context specific. For example, under a drip irrigation system if the rootstock dies, replanting will require replacement of the drip system. However, for flood-irrigated annual crops the risk exposure to application technology and production system capital choices is minimal in the absence of water inputs.

We account for risk exposure and total water input requirements via Equation 8:

$$z_{s,a} = \zeta_s + g(x_\varepsilon)_{s,a} + h(x_\varepsilon)_{s,a} + \mathrm{m}(x_\varepsilon)_s \tag{8}$$

In the new specification, output accounts for ζ, g, h, a and m and includes not only natural land endowments, but also how application technology choice (a) change both g and h input requirements. The water input losses from producing commodity outputs by application technology and delivery infrastructure (m) are also included. The combination of application technology and management practices influence both return flows and non-recoverable losses (Lankford, 2012).

Consequently, we can now explore: the returns to capital invested in g, h, a and m; the gains from increased WUE from changing the composition of g and/or h by commodity, and the possible gains from upgrading farm design. In the following section we describe the potential capital risk exposure from changing states of nature, which include outcomes where water is both reduced in supply, and not available at all. We describe the investment scenarios, the dataset/assumptions used, and then analyse outcomes via the combined CBA-SCA approach.

4. Scenarios & Data

The applied example is based on developing an almond production system in California's San Joaquin Valley. The decision-maker has the choice of how they allocate capital between five alternative production systems: the base case and four variations from that base by investing in $m,\ a,\ g$ or h. Each of these investments has different water use characteristics. To explore the vulnerability of these investment choices to supply shocks two alternative climate settings are explored: current and new climate. Finally, two subsidy settings (no subsidy and 50% public subsidy) are used to better understand the incentives required for private investments in WUE. This provides a total of 18 scenarios, where the base case for current and new climate is not explored using the subsidy setting. All scenarios are listed in Table 1—note that the scenarios do not include outcomes from upgrading a mix of investment options, or a portfolio involving all investment options.

Current climate water supply uncertainty $\Omega = \{1, 2, 3\}$ is represented by three s (normal, dry and wet) with a frequency 0.5, 0.2, and 0.3 respectively. Under a new climate, these frequencies change to 0.25, 0.75, and 0 respectively based on projections from the IPCC (2018). This new climate setting is harsh, and there is no wet state of nature, but the volume of water available in each s does not alter.

All values are in US$. In Table 1, under the Base case, the cost of m is estimated at $94,000, and in each s typical water losses are estimated at 10%, 15% and 10% of total water applied. For example, using Year 1 data presented in Table 3, total water losses $= m(g + h + a) =$

$10\%(12.36+0+3.09)=1.55\ ac\ in$. To achieve a 25% water saving in m, an alternative farm design will increase base case m costs by 50%. The water losses by m thus reduce to $10\%(75\%)(12.36+0+3.09)=1.16\ ac\ in$. Alternatively, a decision-maker could invest in standard field application technology a at a cost of $1,620/acre, or select high-quality technology to achieve 25% water savings at a multiplier of 1.5/acre. Finally, it costs approximately $8,070/acre to establish the crop (trellising, crop variety etc.). However, if the decision-maker was to invest in g or h crop varieties (respectively) by spending an additional 25% to gain the desired varietal attributes, then the respective g or h water requirements would fall by 10% per annum.

Table 1: Details of the 18 Scenarios

Scenarios	***m***	***a***	***g***	***h***	**Climate settings**		**Subsidy Setting**
Base	$94,000	$1,620	$8,072		Current (N= 05, D =0.,2, W = 0.3)	New (N = .25, D = 0.75)	With & without subsidy at 50% of choice cost
Invest in m	+50%						
Invest in a		+50%					
Invest in g			+25%				
Invest in h				+25%			

Water loss (%)	***m***			***a***			***g***			***h***		
	N*	**D***	**W***	**N**	**D**	**W**	**N**	**D**	**W**	**N**	**D**	**W**
Base	10	15	10	20	20	20						
Invest in m	-25	-25	-25									
Invest in a				-25	-25	-25						
Invest in g							-10	-10	-10			
Invest in h										-10	-10	-10

N= normal state of nature, D= drought states, and W = wet state of nature

For all scenarios, it is assumed that the decision-maker already owns 105 acres of land, of which 100 acres can be used for production, and the residual area is non-productive accounting for the homestead, sheds, and the water delivery system (m). The state-contingent production costs and outputs, costs of in-field technology choices (a) and crop variety establishment (g, h), and the cost of borrowing capital are derived from Yaghmour et al. (2016). The m costs were obtained from (https://www.homeadvisor.com/cost/landscape/drill-a-well/, data accessed 12 November 2018). Data has deliberately not been adjusted for inflation for two reasons: i) to improve the transparency of how the data has been used and modified, and ii) this study is not designed to provide financial advice, but rather explore water use-efficiency concepts. However, where Yaghmour et al. (2016) use a 23-year period to estimate the annual repayment of establishment costs, this study uses a 25-year period such that the costs fall from $581/acre to $558/acre. The full costs of m are summarised in Table 2.

Table 2: Estimation of farm design costs $(\boldsymbol{m})$

	Units	Cost/Unit	Cost
Well#	1000	$45	$45,000
125-Hp Pump#	1	$4,000	$4,000
2000 acre-foot reservoir *	1	$60,000	$60,000
Capital recovery at the end of life*			$15,000
Total Costs			**$94,000**

#https://www.homeadvisor.com/cost/landscape/drill-a-well/

*authors’ estimates

The cost of borrowing capital is 4.75% and it is assumed that the decision-maker borrows 100% of the capital required, and repays this investment back annually over a period of 25 years. Consequently, the annual repayment cost/acre of establishing an almond crop is then $735/acre (m + a + crop = $735 = $65 + $112 + $558). The investment period and repayment plan has been deliberately chosen to be identical to the productive life of an almond production system as it provides the opportunity to explore the residual debt if the crop dies in a given year, given by Equation 9.

$$Residual\ loan = \sum_{t=l}^{t} \frac{(a + crop)_t}{(1 + r)^t} \tag{9}$$

where l is the year of investment failure.

4.1. Nature and State-Contingent Production Systems

Like many areas of California, the water supply for this farm is derived from groundwater resources. Poorly metered and relatively low-cost access to groundwater resources makes them particularly vulnerable to over extraction. Drought and climate change increase the time required to replenish these resources (Famiglietti, 2014), exacerbating resource depletion rates. In response, well-depth increases along with pumping cost. Thus, it has been assumed that the true availability of water, and its access costs, change in response to state of nature (Scanlon et al., 2012). Groundwater resources in the southern San Joaquin Valley are particularly vulnerable both in terms of constrained recharge and subsidence. As a consequence of the 2007-10 drought, approximately 2% of California's aquifer storage has been irreversibly lost (Ojha et al., 2018). Thus, on-farm water supply is regulated by a reservoir (Table 2), but the groundwater cost and availability changes by s. In the normal (N) state, groundwater availability is 74 acre-in at a cost of \$22 acre-in; which generates 3000 lb/acre of almond meat. In the dry (D) state, groundwater restrictions reduce availability to 51 acre-in at a cost of \$26 acre-in; but only 2000 lb/acre of almond meat is produced. In the wet state (W), access to groundwater is unrestricted, allowing producer to pump up to 82 acre-in at a cost of \$21 acre-in, and the almond crop yields 3900 lb/acre[5]. The full description of how groundwater is used in each s by the vector of required inputs appears in Table 3. Importantly all data for the division of water by m, a, g and h are approximate. However, the sum of a, g and h for all years is based on Yaghmour et al.'s (2016) estimation of the total water applied per acre. The

---

[5] The data for the normal state of nature is from Yaghmour et al.'s (2016) Tables 1 to 3, while the data for the dry and wet state of nature is defined by Table 5.

data for m appears in Table 1, and as such the total groundwater expenditure differs from that of Yaghmour et al. For clarity, in a normal/wet year the sum of losses by m and a account for 27% of total water use per acre (e.g. in Year 1 for a normal state of nature (3.09+1.55)/17= 27%). In a dry year, losses increase to 30% due to higher evapotranspiration rates, etc.

Table 3: Water use and cost of water by s, for all years

s	**Water (Acre-in)**	**Year/s**					
		1	**2**	**3**	**4**	**5**	**6-25**
Normal ($22/in)	g	12.36	21.96	22.40	24.00	25.60	25.60
	h	0.00	0.00	6.47	21.38	24.15	28.22
	a	3.09	5.49	7.22	11.35	12.44	13.45
	m	1.55	2.75	3.61	5.67	6.22	6.73
	Total	**17.00**	**30.20**	**39.70**	**62.40**	**68.40**	**74.00**
	Cost/ac	**$374**	**$664**	**$873**	**$1,373**	**$1,505**	**$1,628**
Dry ($26/in)	g	12.36	21.96	22.40	24.00	25.60	25.60
	h	0.00	0.00	2.59	8.55	9.66	11.29
	a	3.09	5.49	6.25	8.14	8.81	9.22
	m	2.32	4.12	4.69	6.10	6.61	6.92
	Total	**17.77**	**31.57**	**35.92**	**46.79**	**50.68**	**53.03**
	Cost/ac	**$462**	**$821**	**$934**	**$1,217**	**$1,318**	**$1,379**
Wet ($21/in)	g	12.36	21.96	22.40	24.00	25.60	25.60
	h	0.00	0.00	7.77	25.66	28.97	33.86
	a	3.09	5.49	7.54	12.41	13.64	14.87
	m	1.55	2.75	3.77	6.21	6.82	7.43
	Total	**17.00**	**30.20**	**41.48**	**68.28**	**75.04**	**81.76**
	Cost/ac	**$357**	**$634**	**$871**	**$1,434**	**$1,576**	**$1,717**

Table 4 provides all other variable and fixed costs of the production system. At full maturity, annual variable costs will range between approximately $3,560/acre in a dry state, and rise to $4,110/acre in a wet state. The difference in costs is due to groundwater use and costs, other operational expenses, and harvest costs.

Table 4: Variable Costs of Production by Stare of Nature and Fixed Costs

	Variable Costs	**Years**					
		1	**2**	**3**	**4**	**5**	**6-25**
Normal	Harvest Costs	$0	$0	$121	$202	$326	$421
	Irrigation	$374	$664	$873	$1,373	$1,505	$1,628
	Other Costs	$735	$767	$1,404	$1,569	$1,792	$1,873
	Total Variable Costs	**$1,109**	**$1,431**	**$2,399**	**$3,144**	**$3,623**	**$3,922**
Dry	Harvest Costs	$0	$0	$88	$152	$240	$366
	Irrigation	$442	$785	$893	$1,164	$1,260	$1,319
	Other Costs	$735	$767	$1,404	$1,569	$1,792	$1,873
	Total Variable Costs	**$1,177**	**$1,552**	**$2,386**	**$2,885**	**$3,293**	**$3,558**
Wet	Harvest Costs	$0	$0	$148	$234	$437	$471
	Irrigation	$357	$634	$871	$1,434	$1,576	$1,717
	Other Costs	$735	$767	$1,417	$1,615	$1,839	$1,925
	Total Variable Costs	**$1,092**	**$1,401**	**$2,436**	**$3,282**	**$3,851**	**$4,113**
TOTAL Fixed Costs		**$559**	**$445**	**$472**	**$570**	**$580**	**$562**

Finally, for simplicity the analysis assumes that: dry and wet state almond meat production increases proportionally in years 1-5 based on extrapolations of Yaghmour et al.'s (2016) data for the normal state; full crop maturity and almond production occurs from year six; the decision-maker is operating within a perfectly competitive market free of shadow prices, subsidies (unless tested); the actions of the decision-maker does not alter prices; and there are no barriers preventing industry growth.

5. Results

Table 5 provides the CBA outcomes from the Base scenario using an SCA framework to explore the risks from investing in almonds. The total cost of the investment is $18,390/acre, and $735/acre is paid off the debt every year for 25 years. The repayment includes all expenditure towards farm design, application technology, and the crop variety choice.

Table 5: CBA for the Base Case Scenario (state probabilities N=0.5, D=0.2, and W = 0.3)

Year	**Costs**				**Benefits**				**Cash Flow**			
	m	***a***	**Crop**	**Total**	**Normal**	**Dry**	**Wet**	**Average**	**Normal**	**Dry**	**Wet**	**Average**
1	$65	$112	$558	$735	-$1,668	-$1,757	-$1,651	-$1,681	-$2,403	-$2,492	-$2,386	-$2,416
2	$65	$112	$558	$735	-$1,876	-$2,033	-$1,846	-$1,898	-$2,611	-$2,769	-$2,581	-$2,634
3	$65	$112	$558	$735	-$1,530	-$2,001	-$1,153	-$1,511	-$2,265	-$2,736	-$1,889	-$2,247
4	$65	$112	$558	$735	-$1,048	-$1,712	-$342	-$969	-$1,783	-$2,447	-$1,078	-$1,705
5	$65	$112	$558	$735	$1,162	-$334	$2,589	$1,291	$427	-$1,069	$1,853	$555
6-25	$65	$112	$558	$735	$2,227	$316	$4,100	$2,407	$1,492	-$419	$3,365	$1,671
TOTAL	**$1,626**	**$2,800**	**$13,962**	**$18,387**	**$39,580**	**-$1,507**	**$79,597**	**$43,368**	**$21,193**	**-$19,895**	**$61,210**	**$24,980**

Once the almond crop is in full production, annual average benefits are estimated at around $2,400/acre. Income benefits range from a $300/acre return in a dry year up to $4,100/acre in a wet year. By the end of the 25-year investment, total income of $43,370/acre is expected; although if only normal years occur total income generated would fall slightly to $39,580/acre. The cash flow (benefits–costs) from the investment are therefore calculated to be $25,000/acre, ranging from net losses of $19,895/acre up to $61,210/acre profit. At a discount rate of 4.75% the NPV is $9,234/acre, the benefit-cost ratio is $1.87, and IRR is 13%.

The CBA results therefore reflect a typical minimum, maximum, and expected outcome analysis. However, it is the additional model representation of how the decision-maker responds to the revealed states that adds clarity. If the CBA had focused on an annual production system, the decision-maker could alter crop selections, reduce total area planted, and/or cease planting/irrigation entirely in response to water supply uncertainty. Perennial production systems do not enjoy such flexibility in their decision options. For perennial systems, net returns rapidly reduce when the state event frequency changes. Table 6 summaries the scenario results from changed climate outcomes, and differences between unsubsidised and subsidised (i.e. 50% funding assistance toward farm design, establishment and variety selection costs) production systems. In both new climate scenarios, all investment choices fail to generate positive returns.

Table 6: NPV outcomes for the 18 Scenarios

	No Subsidy		***Subsidy***	
Scenarios:	**Current Climate**	**New Climate**	**Current Climate**	**New Climate**
Base	$9,234	-$8,979		
Invest in $\boldsymbol{m}$	$9,194	-$8,926	$9,899	-$8,221
Invest in $\boldsymbol{a}$	$9,344	-$8,967	$10,559	-$7,752
Invest in $\boldsymbol{g}$	$9,340	-$8,758	$14,385	-$3,713
Invest in $\boldsymbol{h}$	$9,147	-$9,515	$14,192	-$4,470

Recall though that the current climate returns are not per acre-per annum; they are total over the life of the project. Therefore, while positive, they are not significant. This is reflected in Figure 3 by the NPV differential, compared to the Base scenario, which is slightly positive for investments in a and g at approximately $100/acre over the 25 years, but negative for all other options. Investments in g and h differ here because while the variety selection costs are similar, the water savings in dry events for g are higher. This illustrates why decision-makers may be relatively unwilling to invest privately in WUE options, even where the risk posed by uncertain water supply to inflexible production systems is clear.

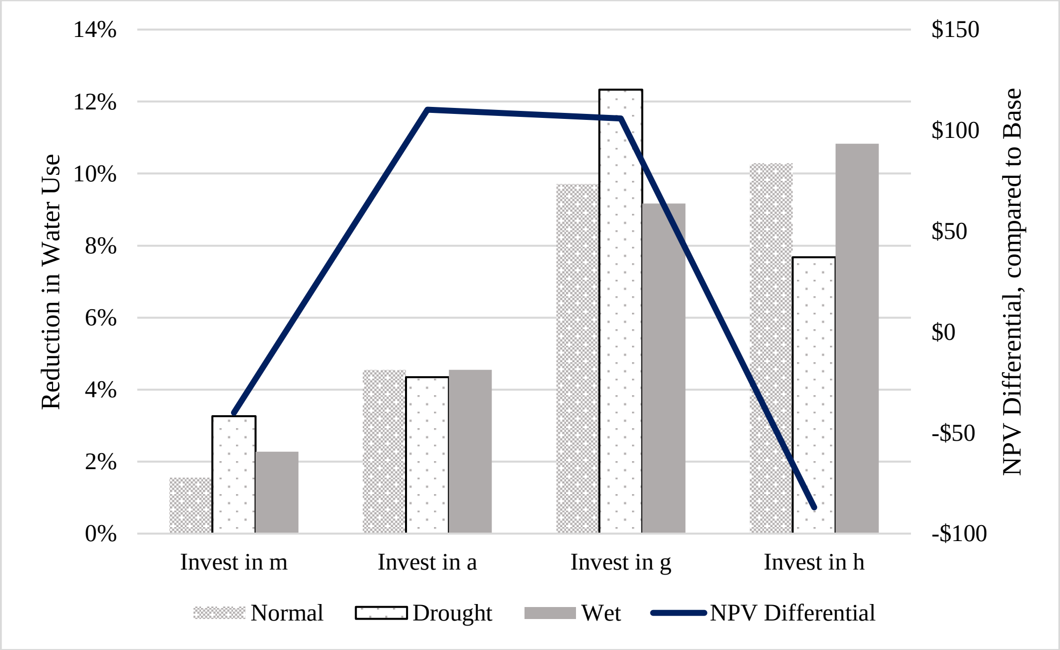

Figure 3: Change in water use and NPV compared to Base (Current Climate/No Subsidy)

A question therefore becomes whether the motivation to invest privately changes if there is some form of financial support available from external sources (e.g. government or NGO funding providers)? We test a scenario where 50% of the total farm design, establishment and variety selection costs are subsidised, and recalculate the CBA outcomes. In this case, all NPV differentials compared to the Base are positive across all investment choices, and crop variety options provide the highest saving/benefit returns (Figure 4). This highlights the relevance of subsidy support to private investment choices, reflecting reality in many water contexts.

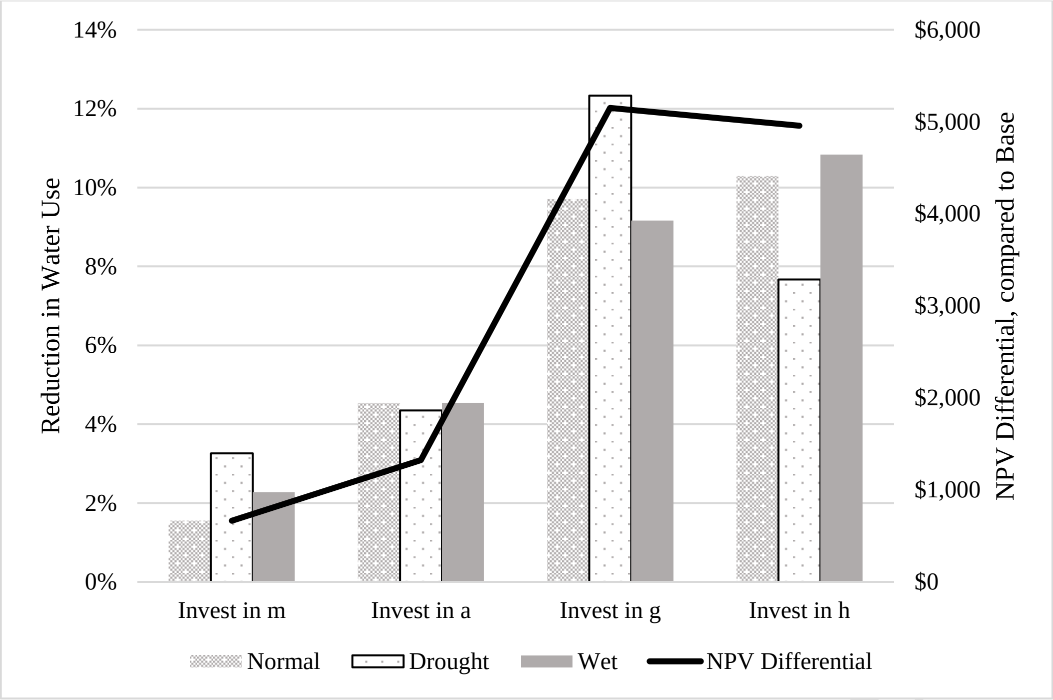

Figure 4: Change in water use and NPV compared to Base (Current Climate/Subsidy)

However, 25 years is a long period, over which we should expect to see some shift in climate conditions. Our new climate scenario tests what effects any water supply shock (e.g. drought) may have on investment outcomes, with respect to the unsubsidised/subsidised scenarios. The new climate settings shift the probability of drought occurrences to 0.75, which is extreme but comparable with expected outcomes reported by IPCC under business as usual arrangements resulting in 1.5° to 2.0° warming (IPCC, 2018). Under these conditions, we assume that the probability of Wet states also falls to zero. For farms that enjoy no subsidy support only investments in *g* technology will result in slightly positive returns; all other options result in neutral or highly negative NPV returns compared to the Base (Figure 5). Where 50% investment subsidies are available, the NPV returns compared to the Base becomes positive for all of the investment options, with *g* and *h* investments becoming initially sound (Figure 6). However, it is critical to return to Table 6 above, and note that total NPV returns over the life of the project are negative in all new climate scenarios.

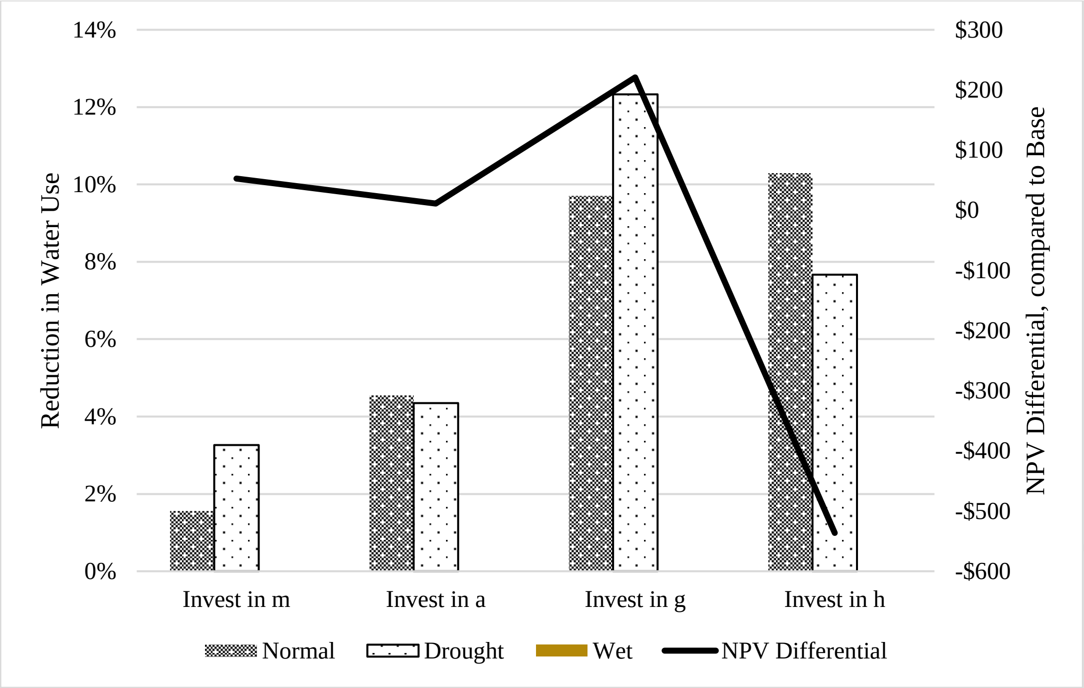

Figure 5: Change in water use and NPV compared to Base (New Climate/No Subsidy)

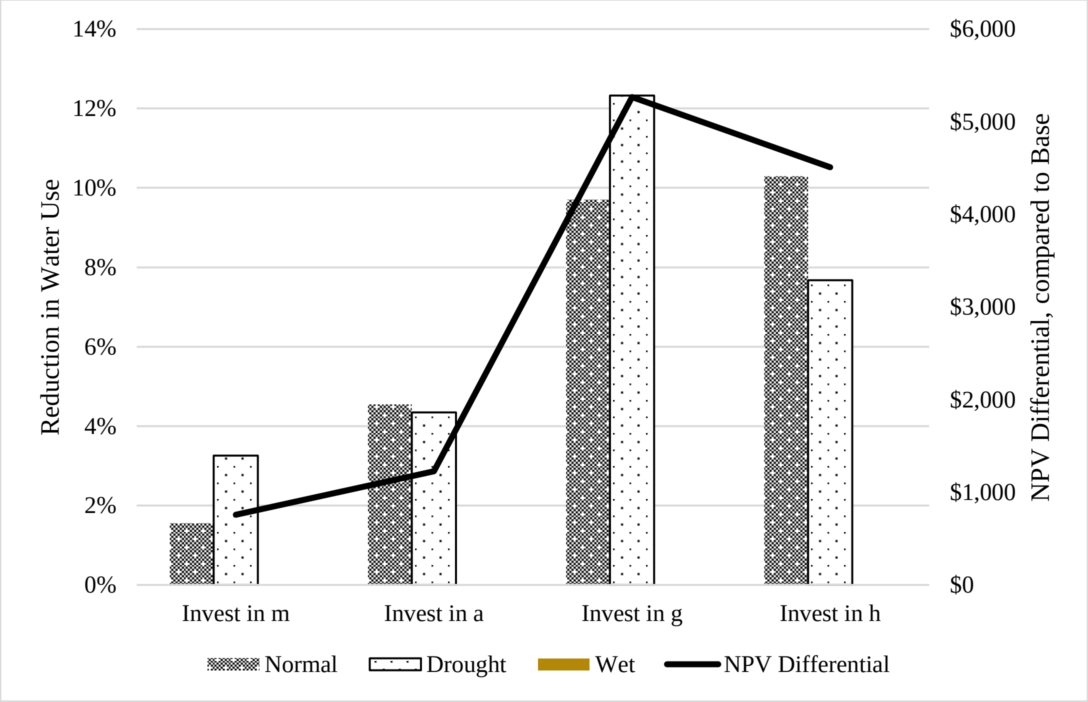

Figure 6: Change in water use and NPV compared to Base (New Climate/Subsidy)

An alternative way to illustrate the negative effects of extreme climate change from Table 6 above is to chart the cumulative cash flows in each of the 25 years of the project required to cover outstanding debt on a investments and crop variety choices. This reflects the number of years until break-even point on the project is reached, repayments are fully covered, and the project begins to make profits. In this analysis, m investments are excluded as the farm design is not adversely affected if the crop is irreversibly lost. Figure 7 shows the cumulative cash flow results for the subsidised scenario, across the current and new climate probabilities. In the current climate, subsidised investments in g and h achieve break-even in Year 12—all others require approximately three further years to break-even and cover costs. However, under the new climate scenario the project never achieves a positive return over the project life—even when subsidised.

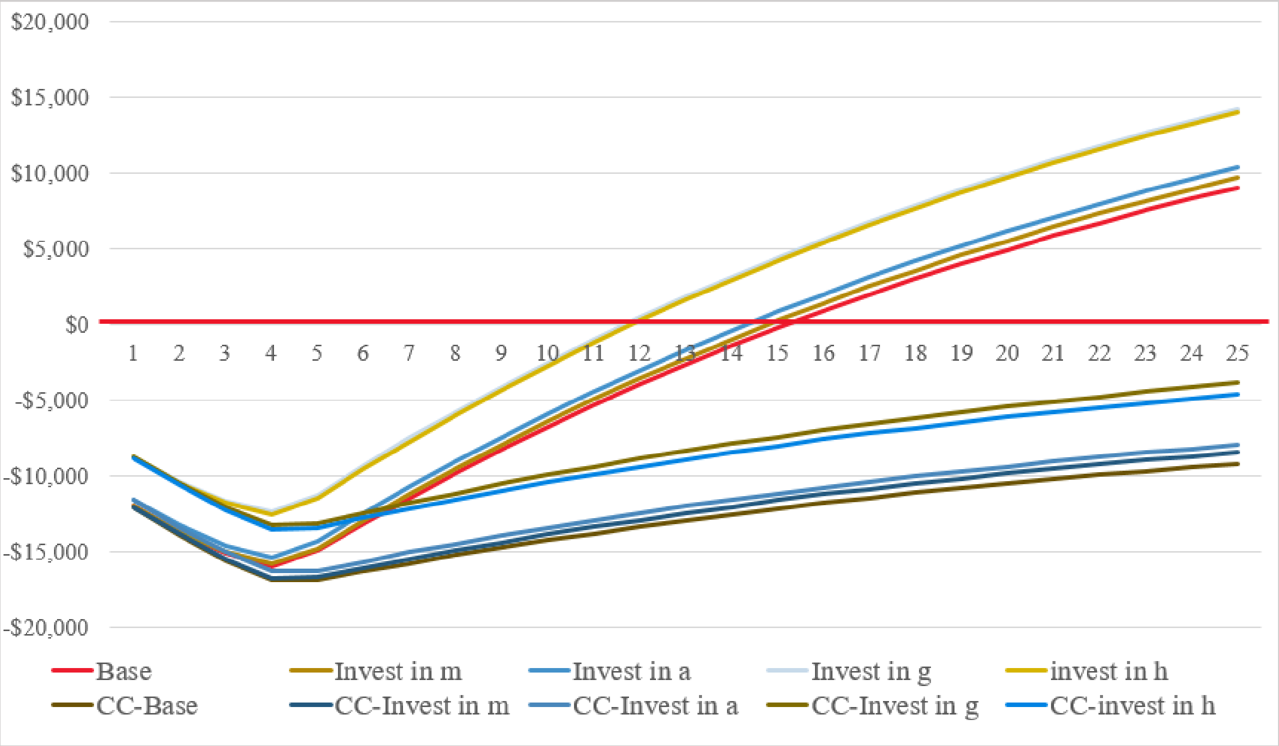

Figure 7: Years for cumulative cash flow to pay residual debt (Both climates/Subsidised)

6. Discussion

The contribution of this combined CBA-SCA approach can be emphasised by a few key discussion points:

6.1. Reluctance to reduce water supply risk privately

The analysis provides some insight as to why many contexts do not experience private (self) investment into WUE technology adoption. Most importantly, increased productivity may not necessarily equate with higher profitability. Typically, investment costs can be high, the savings difficult to measure, economic returns may be low, and future water use and/or supply risk may be unchanged (Ward and Pulido-Velazquez, 2008). Additionally, by quarantining their water-savings to create a supply buffer against extreme adverse states of nature, decision-makers may reduce their risk to capital loss. Models that fail to reflect alternative states of nature will allocate these idle resources back into production. Further, in practice decision-makers will perceive little benefit from leaving ‘saved’ water resources idle, leading to increased total irrigated area at risk, and negating efficiency savings (Adamson and Loch, 2014). Our realistic farm establishment and operation data, coupled with stylised assumptions regarding water savings, show that the appropriate technology investment would be water-smart varietals; although in reality decision-makers may perceive this option as less certain (riskier) when compared against engineering or physical technology investments (e.g. drip irrigation). Further, as we have shown here, investment in varietals only makes sense where the associated commodity returns are high and the supply of water is very reliable—two factors that most practical water users would be acutely sceptical about. Where private decision-makers appreciate these factors it will thus dissuade them from technological change on-farm, and this is reflected in our results.

6.2. Importance of subsidies

That is not to say that WUE technology adoption does not occur. As discussed by Pérez-Blanco (2017), WUE modernisation aimed at achieving higher farm incomes is widespread on the back of policy reforms and revised social water objectives. However, higher farm incomes are also typically associated with increased total water consumption and lower environmental flows, among other externalities. In many cases these negative externalities have resulted from public financial support toward WUE technology adoption (e.g. subsidies) that distort price signals for private investors, incentivise change at the farm level based on distorted returns to capital investments (as shown in our analysis), and create welfare transfers. From an economics perspective these outcomes are poor. However, where subsidised WUE adoption policy is a perceived panacea to scarcity challenges (Gomez et al., 2018), a future concern should be the resultant socialisation of risk. As illustrated by our SCA framework, any business as usual climate change outcomes may see severe future water supply shocks where private users—publicly incentivised to become more water-dependent and risk-taking (e.g. under associated transformations to high-value perennial cropping systems (Expósito and Berbel, 2017))—will be exposed to irreversible capital loss, and higher long-term income vulnerability. In such events, the public will likely be held responsible, and then further burdened with paying the costs associated with these capital losses and vulnerability impacts, as the insurer of last resort (Adamson and Loch, 2018).

Any consideration of WUE subsidisation must therefore appreciate the investment differentials between private investment objectives (e.g. profit, income, and/or productivity) and public investment objectives (e.g. return flows, food security, poverty reduction, and/or resource reallocation) before committing to policy or program implementation. For example, if we examine this from the single-user perspective, rather than the wider industry or sectoral view, we may miss important ramifications of industry-wide transformations (or societal expectations) under subsidy arrangements. This changes the risk-profile of the user(s); but also the reliability of water supply by state of nature and any second-round effects resulting from industry-wide transformations (Rothenberg and Smith, 1971). Policy/program designers would be well-advised to consider the scale of needed reforms, and the probability of future water supply shocks—or other shocks to productions systems (e.g. pests or disease, trade embargoes, political wavering etc.)—that could negatively affect investment returns before committing to subsidised WUE investments as a retort to future scarcity dilemmas. This advice applies equally to all contexts around the world, regardless of their stage of institutional, resource-use, policy reform, or rights establishment. Risk and uncertainty exist in all stages, and trigger (required) adaptation in response to dynamic change (Loch et al., 2019).

6.3. Future climate shocks

As stated above, in many cases transformations to higher WUE in production systems are often coupled to higher reliance on access to secure water supplies. Yet the main benefit that private decision-makers receive from WUE investments is a net reduction in water use by s. As shown here, long-term investments to achieve water use reductions are risky, particularly where the major constraint to productivity and returns is water and actual water reductions remain uncertain based on poor data availability and limited baseline accounting (Lankford, 2012). In this context, it becomes critical to understand the production system ratio of $g(x)$ and $h(x)$ water input requirements to identify and explore the exposure of capital to risk in response to changing frequency of states of nature. Further, policy-makers and water managers should consider changes to the description of those states of nature via sensitivity analysis that explore where current WUE technology/management systems fail to deliver long-term benefits.

6.4. Study limitations

This is a farm-based example; we need case studies and data at other scales to build basin-scale, regional or even national analysis results. For example, Adamson (2019) is exploring the use of g and h at basin scales for environmental benefits. As our evaluations scale, unless the net change in water accounts are fully understood future investments will be exposed to increased risk if the net demand for $g(x)$ units of water increases. In the real world the size of a payoff from a long-run investment is rarely derived from a single risk or uncertainty, but rather a number of alternative futures associated with factors that both increase and decrease the rate of return on a given investment. Consequently, in this case as the time taken to breakeven is determined by which state of nature is revealed, and the ordering in which those states of nature occur, the repayment timeframe may be significantly altered. As the time required to breakeven increases, the possibility of some other 'bad' event (hail, disease management, output price collapse etc.) being realised also increases. More work is needed in the state-space to articulate and understand the risk-increasing and risk-decreasing nature of water inputs to production, which will only come from access to quality data and practical applications that assist us to define not only the number of states, but also their descriptions in a range of contexts.

7. Concluding Comments

Long run investments in water capital are risky, particularly where water is required as a secure input to production systems. State of nature representations of water supply outcomes assist with our increased understanding of the vulnerability of capital, and water users, to adverse events. In this example, we couple the cost-benefit analysis framework to a state contingent analysis approach to explore the riskiness of WUE investment payoffs and cash-flow outcomes when frequencies of states of nature change over the course of that investment. Critically, this approach also allows us to represent decision-maker adaptation in the face of risk and uncertainty. Finally, dividing WUE investment options into their key components—at the farm scale in this instance—adds clarity to the debate surrounding policy options to address future water scarcity challenges.

8. References

Adamson, D., 2019. Irrigating the environment, Centre for Global Food and Resources. University of Adelaide, Adelaide, South Australia.

Adamson, D., Loch, A., 2014. Possible negative feedbacks from 'gold-plating' irrigation infrastructure. Agricultural Water Management 145, 134-144.

Adamson, D., Loch, A., 2018. Achieving environmental flows where buyback is constrained. Australian Journal of Agricultural and Resource Economics 6, 83-102.

Adamson, D., Loch, A., Schwabe, K., 2017. Adaptation responses to increasing drought frequency. Australian Journal of Agricultural and Resource Economics 61, 385-403.

Arrow, K.J., 1953. Le rôle des valeurs boursières pour la répartition la meilleure des risques, Econométrie, 41–47, CNRS, Paris; translated as The role of securities in the optimal allocation of risk bearing,. The Review of Economic Studies 31, 91-96.

Arrow, K.J., Chenery, H.B., Minhas, B.S., Solow, R.M., 1961. Capital-Labor Substitution and Economic Efficiency. The Review of Economics and Statistics 43, 225-250.

Arrow, K.J., Lind, R.C., 1970. Uncertainty and the Evaluation of Public Investment Decisions. The American Economic Review 60, 364-378.

Barrett Purcell & Associates, 1999. Determining a framework, terms and definitions for water use efficiency in irrigation. Land and Water Resources Research and Development Corporation, Canberra, Australia, p. 26.

Baumol, W.J., 1968. On the Social Rate of Discount. The American Economic Review 58, 788-802.

Chambers, R.G., Quiggin, J., 2000. Uncertainty, production, choice, and agency: The state-contingent approach. Cambridge University Press, New York.

Chambers, R.G., Quiggin, J., 2002a. The state-contingent properties of stochastic production functions. American Journal of Agricultural Economics 84, 513-526.

Chambers, R.G., Quiggin, J., 2002b. The State-Contingent Properties of Stochastic Production Functions. The American Journal of Agricultural Economics 84, 513-526.

Debreu, G., 1959. The Theory of Value. Wiley, New York.

Dietz, S., Stern, N., 2008. Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. Review of Environmental Economics and Policy 2, 94-113.

Expósito, A., Berbel, J., 2017. Agricultural irrigation water use in a closed basin and the impacts on water productivity: The case of the Guadalquivir river basin (Southern Spain). Water 9, 136.

Famiglietti, J.S., 2014. The global groundwater crisis. Nature Climate Change 4, 945.

Gomez, C.M., Pérez-Blanco, D., Adamson, D., Loch, A., 2018. Managing Water Scarcity at a River Basin Scale with Economic Instruments. Water Economics and Policy 4, 1750004.

Graham, D.A., 1981. Cost-Benefit Analysis Under Uncertainty. The American Economic Review 71, 715-725.

Hirshleifer, J., 1965. Investment Decision under Uncertainty: Choice—Theoretic Approaches. The Quarterly Journal of Economics 79, 509-536.

Hirshleifer, J., 1966. Investment Decision Under Uncertainty: Applications of the State-Preference Approach. The Quarterly Journal of Economics 80, 252-277.

Horowitz, J., Lange, A., 2014. Cost–benefit analysis under uncertainty — A note on Weitzman's dismal theorem. Energy Economics 42, 201-203.

IPCC, 2018. Global Warming of 1.5°C, an IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. IPCC Secretariat, Geneva.

Just, R.E., Pope, R.D., 1978. Stochastic specification of production functions and economic implications. Journal of Econometrics 7, 67-86.

Just, R.E., Pope, R.D., 1979. Production function estimation and related risk considerations. American Journal of Agricultural Economics 61, 276-284.

Lankford, B., 2012. Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency. Agricultural Water Management 108, 27-38.

Loch, A., Adamson, D., Dumbrell, N.P., 2019. A fifth stage of water reforms: policy lessons for future natural resource management, Centre for Global Food and Resources Working Paper. The University of Adelaide, Adelaide, South Australia.

Mallawaarachchi, T., Nauges, C., Sanders, O., Quiggin, J., 2017. State-contingent analysis of farmers' response to weather variability: irrigated dairy farming in the Murray Valley, Australia. Australian Journal of Agricultural and Resource Economics 61, 36-55.

Merrifield, J., 1997. Sensitivity Analysis in Benefit Cost Analysis: A Key To Increased Use and Acceptance. Contemporary Economic Policy 15, 82-92.

Ojha, C., Shirzaei, M., Werth, S., Argus, D.F., Farr, T.G., 2018. Sustained Groundwater Loss in California's Central Valley Exacerbated by Intense Drought Periods. Water Resources Research 54, 4449-4460.

Pérez-Blanco, C.D., 2017. Water Conservation Technologies: from panaceas to actual solutions, Efficiency-oriented water management: From panaceas to actual solutions, Venice, Italy.

Perry, C., 2007. Efficient irrigation; inefficient communication; flawed recommendations. Irrigation and Drainage 56, 367-378.

Rasmussen, S., 2003. Criteria for optimal production under uncertainty. The state-contingent approach. Australian Journal of Agricultural and Resource Economics 47, 447-476.

Rothenberg, T.J., Smith, K.R., 1971. The effect of uncertainty on resource allocation in a general equilibrium model. The Quarterly Journal of Economics 85, 440-459.

Rothschild, M., Stiglitz, J.E., 1970. Increasing risk: I. A definition. Journal of Economic Theory 2, 225-243.

Rothschild, M., Stiglitz, J.E., 1971. Increasing risk II: Its economic consequences. Journal of Economic Theory 3, 66-84.

Scanlon, B.R., Faunt, C.C., Longuevergne, L., Reedy, R.C., Alley, W.M., McGuire, V.L., McMahon, P.B., 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proceedings of the National Academy of Sciences 109, 9320-9325.

Skagerboe, G.V., 1983. Agricultural water management and the environment, in: Biswas, A.K., Dakang, Z., Nickum, J.E., Changming, L. (Eds.), Long-Distance Water Transfer: A Chinese Case Study and International Experiences. Tycooly International Publishing Limited, Dublin, Ireland.

Tol, R.S.J., 2003. Is the Uncertainty about Climate Change too Large for Expected Cost-Benefit Analysis? Climatic Change 56, 265-289.

Ward, F.A., Pulido-Velazquez, M., 2008. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences 105, 18215-18220.

Yaghmour, M., Haviland, D.R., Fichtner, E.J., Sanden, B.L., Viveros, M., Summer, D.A., Stewart, D.E., Gutierrez, C.A., 2016. Sample Cost to Establish An Orchard and Produce Almonds: San Joaquin Valley South -2016. UC Agriculture and Natural Resources Cooperative Extension, Agricultural Issues Center, UC Davis Department Of Agricultural And Resource Economics.