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Climate Change, Irrigation and Pests: Examining Heliothis in the Murray Darling Basin

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Key Words: Resource Allocation, State Contingent Analysis, Stochastic Optimisation, Climate Change, Pests

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> 'The major uncertain factors in response are climate variables, though pest and disease effects may often be important. By their nature, the uncertain uncontrolled factors have to be brought to account through the probability distribution of yield' (Dillon & Anderson 1990, p. 160)

Abstract

Helicoverpa spp. (heliothis) are a major insect pest of cotton, grains and horticulture in the Murray-Darling Basin. Climate change is likely to make conditions more favourable for heliothis. This could cause regional comparative advantages in irrigation systems to change as management costs increase and yields decrease. Irrigation in the Murray Darling Basin produces 12 percent of Australia's total gross value of agricultural production. If producers fail to consider climate change impacts on heliothis they may misallocate resources.

Adamson *et al*. (2007 and 2009) have used a state contingent approach to risk and uncertainty to illustrate how producers could allocate irrigation resources based on climate change impacts on water resources. This is achieved by separating environmental risks and uncertainties into defined states of nature to which the decision makers have a set of defined responses. This approach assumes that the decision makers can achieve optimal allocation of resources as they have perfect knowledge in how they should respond to each state of nature (i.e. producers know how to manage heliothis now).

Climate change brings a set of new conditions for which existing state parameters (mean and variance) will alter. Consequently a decision maker will have incomplete information about the state

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description; and the relationship between state allocable inputs and the associated state dependent output, until they have experienced all possible outcomes. Therefore if producers ignore climate changes to heliothis they may lock in resources that may prove to be unprofitable in the long run.

The purpose of this paper is to suggest a framework that could be used for determining climate change impacts of heliothis (i.e. density), illustrate that management costs rise as density increases and how a stochastic function could deal with incomplete knowledge in a state contingent framework.

Adamson, D, Mallawaarachchi, T & Quiggin, J 2007, 'Water use and salinity in the Murray Darling Basin: A state-contingent model', Australian Journal of Agricultural and Resource Economics, vol. 51, no. 3, pp. 263-81.

—— 2009, 'Declining inflows and more frequent droughts in the Murray–Darling Basin: climate change, impacts and adaptation', Australian Journal of Agricultural and Resource Economics, vol. 53, no. 3, pp. 345–66.

Introduction

Helicoverpa spp. (hereafter Heliothis) are a major insect pest of the Australian cotton, grain and horticultural industries (Adamson, Thomas and Davis 1997). Its migratory behaviour and ability to rapidly develop insecticide resistance has forced industry wide adoption of area wide management strategies (Zalucki & Furlong 2005), forced production breaks in agricultural systems (e.g. tomatoes in Bundaberg) and in extreme cases limited production choices in areas, for example the collapse of the cotton industry in the Ord in 1975 (Longworth & Rudd 1975). Howden *et al.* (2003), Deuter (2008) and Zalucki *et al.* (2009) suggest that climate change will benefit heliothis: as rising temperatures could encourage both inter and intra-generational development; extend habitability in current temperate climate zones; and dependent upon changes to rainfall patterns, increase the initial population of migrating heliothis from inland Australia into the Murray-Darling Basin (hereafter Basin).

The uncertainty associated with the long term impacts of climate change are firmly within the policy setting agenda for both the resilience of agricultural production systems (Albanese et al. 2010) and water resources in the Murray-Darling Basin (Commonwealth of Australia 2008). Reductions in water supply, caused by climate change, will increase pressure on an already constrained resources ability to meet the needs of the: environment, urban water supplies; irrigators and other commercial activities (Khan 2008). Changes in temperature, rainfall patterns, humidity will have spatial and temporal impacts on productions systems, see Chakraborty *et al.* (1998) and Stokes & Howden (2008). Producers will actively respond to changes in climatic conditions by learning to adjust to new signals (Ash et al. 2007) and alter production systems accordingly to maximise their returns (Mallawaarachchi, Thilak & Foster 2009). One of these learning challenges will be how pests adapt to both the new climate conditions (Sutherst, Collyer & Yonow 2000) and modifications to productions systems. As Zalucki *et al.* (2009) discuss when producers alter commodity choices they directly provide stimulus, positive and negative, for new and existing pests, which can be expressed as changing management costs.

Adamson, Mallawaarachchi & Quiggin (2009) have used a state contingent approach to risk and uncertainty (hereafter state contingent analysis) to provide insights into how irrigators in the Basin may react to climate change from changes to water supplies. This work examined the impact: changes in the frequency of state events occurring (i.e. less floods and more droughts); and the state description (i.e. volume of inflows), had on irrigation investment patterns. These results suggest that as producers experience more droughts (i.e. change in the frequency of the states), they must alter investment patterns to maintain long run profitability. While a proportional reduction in water availability (i.e. a less water available within each state of nature) simply reduces the area irrigated. This suggests that as droughts increase, producers will transition out of both perennial commodities (i.e. pasture, fruit and grapes) and annual commodities (i.e. pasture for dairy, cotton and rice) that require large volumes of irrigation water in every state of nature, and into flexible production systems that do not require irrigation water in every state of nature (i.e. cereals and cotton production systems where limited or no irrigation occurs in the drought state of nature).

State contingent analysis allows for the climatic uncertainty to be considered as defined states of nature (e.g. normal, drought and wet) and the management response to that state of nature (e.g. what is the best allocation of my resources in the drought state of nature). This approach suggests that decision makers actively respond to alternative states of nature by changing their inputs to influence the final output. The decision makers choice is based on their past experiences and knowledge in order to meet their objective function (Chambers & Quiggin 2002). As Rasmussen (2006b) and O'Donnell & Griffiths (2006) discuss the benefit of the state contingent approach is that it separates production uncertainty from decision maker uncertainty.

This PhD aims to investigate the impact climate change has on heliothis and subsequently and reallocation of resources that may occur in the irrigation industry in the Murray-Darling Basin. To examine this thesis four hypotheses will be tested and the first hypothesis is.

Hypothesis One:

Climate change will alter the distribution and density of heliothis.

Hypothesis one will be tested by following an approach described in Adamson (1996) and (Sutherst, Collyer & Yonow 2000) where CLIMEX, a biological model that predicts the spatial suitability of landscapes based on climatic data, can be used to estimated distribution and density changes for species under climate change. This thesis will adapt the CLIMEX model for heliothis developed by Zalucki & Furlong (2005) to examine the changes to distribution and density of heliothis under four alternative climate scenarios for two periods (2050 and 2100), compared to the current climate. This thesis has used climate scenarios from the Garnaut Climate Change Review (Garnaut 2008) thus allowing the results to be adaptable to current policy debates. The four climate change scenarios all examine increased temperature but rainfall either increases or decreases. The scenarios also provide an examination of the benefits of climate mitigation (i.e. compare with and without mitigation strategies) to be consisted with Quiggin *et al.* (In Press). The four proposed scenarios are...

> "...Unmitigated Scenario 2 (U2)– Best estimate (median) business-as-usual scenario, usingA1F1 emissions path, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~4.5°C in 2100.
>
> Mitigation Scenario 2 (M2) – Best Estimate (median) mitigation scenario where stabilisation of 550 ppm CO2 equivalent (CO2 stabilised at 500 ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.
>
> Mitigation Scenario 3 (M3) –Wet mitigation scenario where stabilisation of 550 ppm CO2 equivalent (CO2 stabilised at 500 ppm) is reached by 2100, 90th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~2.0°C in 2100.
>
> Mitigation Scenario 4 (M4) – Best Estimate (median) strong mitigation scenario where stabilisation of 450 ppm CO2 equivalent (CO2 stabilised at 420 ppm) is reached by 2100, 50th percentile rainfall and relative humidity surface for Australia, 50th percentile temperature surface. Mean global warming reaches ~1.5°C in 2100." (Quiggin et al.2008)

As the density levels of pests change rational producers alter management costs following the concept of economic thresholds (Cox et al. 1991). We should then expect that if heliothis is responsive to climate change, as illustrated from the findings from testing hypothesis one, then the regional comparative advantage in production caused by increasing pest management costs and or reductions in yield caused by heliothis for each affected commodity will alter, ceteris paribus. This information leads to hypothesis two.

Hypothesis Two:

> *Density changes in heliothis will alter regional comparative advantages in production*

Hypothesis two will be tested by altering existing regional gross margin budgets that are used in the RSMG Water Allocation Model that is documented in Adamson, Mallawaarachchi and Quiggin (2007) (here after RSMG Water Allocation Model). This thesis will separate each existing state of nature describing water flow in the Basin (i.e. normal, drought and wet) to include four possible states of heliothis density (i.e. nil, light, medium, plague) to describe the possible impacts on comparative advantage for all affected commodities. Density impacts will be consistent with the economic thresholds concept in pest management and will describe per hectare cost changes, from both increased use of insecticides and their application, and residual yield loss which in part is based on the idea formulated in Adamson (2006) where the risk of biosecurity outbreaks could be described in state contingent terms. This separation of state of nature and density is important as because heliothis is migratory the final density in a 'normal rainfall' state of nature within the Basin is also depended on conditions outside the Basin (see next section). This approach then expands the approach used in both Adamson (1996) to describe climate impacts on pests and Adamson *et al.* (2009) where alternative conditions outside the Basin are not considered.

The analysis used by Adamson *et al.* (2009) used discrete values: to stipulate inflows in a state of nature; and the resource use and output obtained in each state and this suggests producers have complete information. Climate change is however, described when a new mean and or variance occurs (Pittock 2003). Consequently the movement from one climate to another could be described as a period of incomplete information. This premise raises the third hypothesis:

Hypothesis three:

> *The inclusion of stochastic functions within a state contingent approach will help explain periods of incomplete knowledge.*

Hypothesis three will be tested by introducing a stochastic function into the existing RSMG Water Allocation Model. A stochastic description will be applied independently to three key state contingent variables: the description of the state of nature; the inputs used in each state; and the outputs obtained in each state of nature. This approach allows for sensitivity testing of the data. These results will be compared and contrasted to the existing model to examine if this approach could provide a tool to help determine the impact of incomplete information sets.

Once this is reviewed this logically leads to the final hypothesis.

Hypothesis four:

> *Climate change influences on water availability have a greater impact on resource allocation than climate based changes on pest species redistribution and density.*

This will be achieved by running the four climate change scenarios for heliothis in the updated model (i.e. includes stochastic functions) to examine if changes in the optimal production systems occur. These results will be compared against the same climate change shocks on water viability.

The rest of this paper will initially provide greater background into why heliothis is a pest and the irrigation production in the Basin. Then methods that are planned to be used to determine the validity of the hypothesis are discussed. This is followed by a discussion of the progress that has been made towards the thesis so far. Then a proposed work plan is presented, this is then followed by a summary of the paper and finally a list of publications is provided.

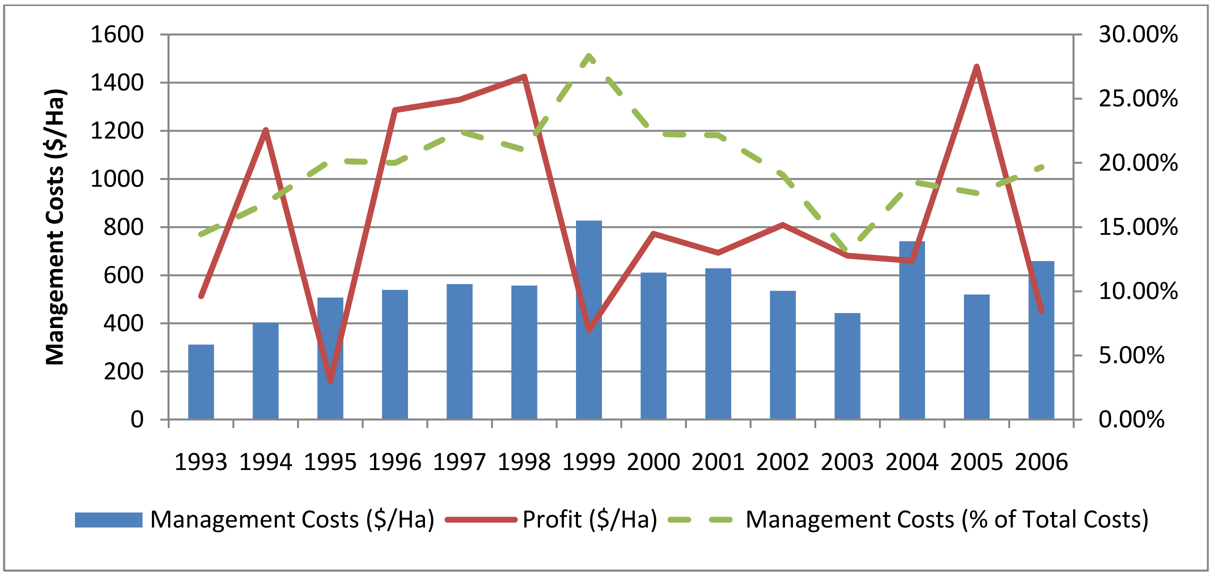
Background: Heliothis & Irrigation in the Basin

Adamson *et al.* (1997) estimated the annual production costs of heliothis for 30 commodities (cotton, grains and horticultural) throughout Australia. The data in this report suggested that producers in the Basin spent approximately $98 million on managing heliothis (chemicals, contractors and application) and residual production losses ranged from $63 million (range $26 to $125 million) per annum. Thus annual heliothis costs for the Basin were approximately $161 million (range of $124 to $223 million). At the time of this study these 30 commodities had a gross value of production of $1.2 billion. This report had followed other analysis by Alcock & Twine (1981) and McGahan et al. (1991) who estimated the annual production cost of heliothis in Queensland. These three estimations have a short time frame for relevance as they fail to deal with the dynamic nature of pests as they hold distribution and density constant (Adamson 1996).

As Zalucki & Furlong (2005) discuss the annual heliothis population is the Basin is highly variable and depended upon: September's migration into the Basin; and Basin wide emergence of overwintering individuals around October. The size of the September migration is dependent on rainfall and favourable climatic conditions in inland Australia. This migration is dominated by H. *puncigeria* (95 percent) and the local October emergence is H. *armigera* dominated. Between September and April, four to five generations of heliothis will develop during which H. *armigera* becomes the dominate species found. The timing of local emergence is depended upon temperature. Under warmer than average conditions, heliothis enter diapause latter and emerge sooner (Murray 1991) thus they spend more time feeding on crops. Warmer than average years also encourages the rate of larval development (Allsopp et al. 1991). Deuter (2008) has suggested that these two temperature responses (i.e. active for longer and faster development) could lead to an extra generation of heliothis being produced in a year. This is likely to aid their rate of insecticide resistance development (Daly 1993). Drake (1994) discuses argues that climate change could: negate temperature limitations on insect activity in temperate regions; alter population sizes due to rainfall availability; and alter wind based dispersal patterns.

Variability in population size and resistance development alters annual management costs. Table 1 provides a 13 year time series analysis of cotton insect management costs and about 90% of these costs can be attributed to heliothis (Adamson et al. 1997). Here the columns provide management costs, the dotted line determine the management costs as a proportion of total costs (including operator labour, excluding depreciation) and the solid line illustrates profit per hectare. The proportion of management costs of total costs ranges from approximately 13% (2003) to 29% (1999) and although these have direct implications on returns other non heliothis factors (price and yield) may provide larger shocks, however, the difference between 1998 and 1999 can in part be explained by an increase of over $200 per hectare costs. It is impossible to determine the negative impact heliothis has on yield from this data.

Table 1 Management Costs and Profit in Cotton[2]



Heliothis' impact on yields and management costs has negated choice in cropping systems, for example after 10 years (1964-65 to 1974-75) cotton was driven from the Ord (Bureau of Agricultural Economics 1972). As Davidson (1982) explains the cotton bounty incentives allowed the Ord to develop into a cotton monoculture for seven years. This landscape modification, combined with poor tactical use of insecticides, primarily DDT and Endrin (Thomson 1962) and heliothis' resistance levels rendered chemical control impractical (Michael & Woods 1980) and the removal of the bounty negated economics returns from cotton (Longworth & Rudd 1975).

Despite the adoption of the industry wide resistant management strategies for cotton, Heliothis has developed resistance to every insecticide introduced for its control. Zalucki *et al.* (2009) provide a historical timeline of resistance detection and this timelines can in part explain part of achieved cotton yields, illustrated in Chart 1. Here apart from the collapse of the Ord, the other most notable shock to production occurred in 1983-84 due to the industry wide failure of pyrethroids (Bureau of Agricultural Economics 1984, p. 18). This occurred despite significant investment in..

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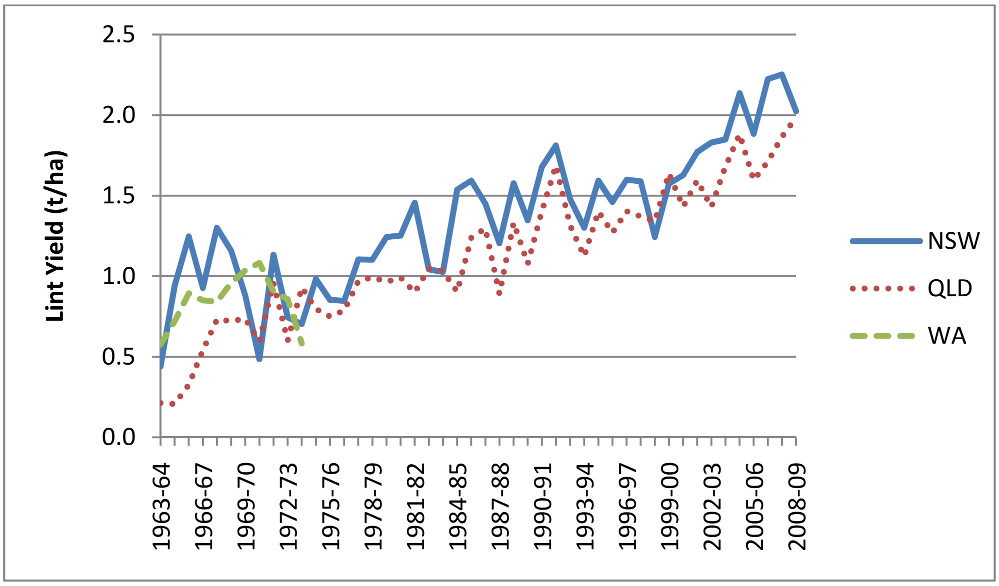
[2] Adapted from Boyce Charted Accountants et al (2004) and (2007)

> “..new cotton varieties with Heliothis-resistant traits have been breed by CSIRO and should be available to growers in 1983. A computer-program-based pest management system has been introduced, initially to New South Wales growers” (Bureau of Agricultural Economics 1982, p. 27).

Chart 1 Cotton Lint Production by State



Source(ABARE 2009) and (Bureau of Agricultural Economics 1972)

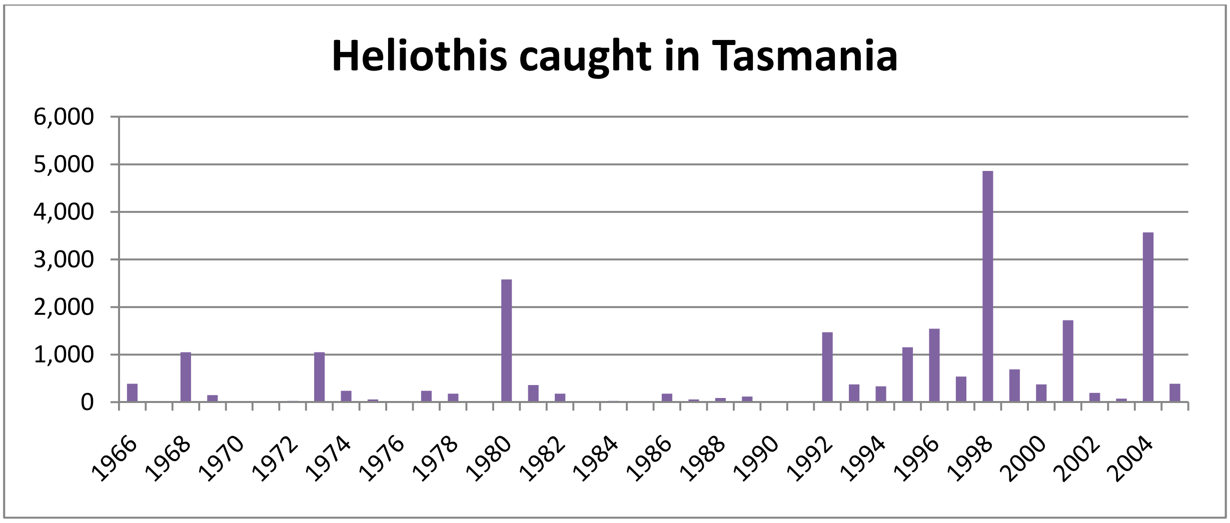
Recently heliothis resistance has plateaued and in fact reduced due to the adoption of genetically modified (GM) cotton in Australia. It has been suggested that GM cotton could act as a heliothis population sink but argument exists if this is purely due to GM cotton or perhaps a combination of weather patterns and reduced areas of cotton (Zalucki, Adamson & Furlong 2009). As Back & Beasley (2007) discuss the economics of GM cotton are skewed in favour of potential social and environmental benefits and not farm returns. However, it is very likely GM cotton will not be the final solution for heliothis as recent resistance management studies looking at the active ingredients for GM cotton we find that the ..

> “...2007/08 combined data set from CSIRO and Monsanto however indicates that Cry2Ab resistance alleles in H. *armigera* are significantly higher than previous years. CSIRO have also

> detected a significant increase over time in Cry2Ab resistance alleles in H. *punctigera* using the F2 screen method" (Downes 2009)

Part of the weather patterns discussion deals with Tasmania. As Tasmania does not provide suitable conditions for overwintering (diapause) consequently annual light trap data figures, illustrated in Figure 1, are therefore dependent upon migration and subsequent generations. The consistent increased interception since 1992 (GM cotton introduced in Tasmania raises a number of questions about natural variation versus response to changes in climate that at this stage cannot be answered.

Figure 1 H. punctigeria individuals caught in light-traps in Tasmania by year



Data adapted from (Zalucki, Adamson & Furlong 2009)

The Basin is as Australia's food basket due to production intensity of high value commodities on irrigation land and comparative advantage in dryland production systems, therefore if heliothis becomes more prevalent then economic loss may occur. The Basin produces 39 percent of Australia's gross value of agricultural production (hereafter GVAP) with only 20 percent of Australia's total agricultural land (ABS 2008). However, irrigation alone with two percent of agricultural land in the Basin yet it generated 12 percent ($4. 6 billion) of Australia's GVAP in 2005-06 (see Table 2 (ABS 2008)). In 2005-06 the major irrigation commodities produced were: dairy; fruit; cotton; and grapes worth approximately $938 million, $898 million, $797 million and $722 million respectively.

Table 2 GVAP in the Basin 2005-06 ($'million)

Commodity group	**Basin**			**TOTAL Australian**	**Basin's Value as % of total Australian Production**		
	Irrigated	**Dryland**	**Total**		**Irrigated**	**Dryland**	**Total**
Dairy farming	938	234	1,172	3,603	26%	6%	33%
Other livestock	132	4,093	4,225	10,987	1%	37%	38%
Rice	274	0	274	274	100%	0%	100%
Cereals (excl. rice)	92	3,344	3,436	7,320	1%	46%	47%
Cotton	797	64	861	933	85%	7%	92%
Grapes	722	55	777	1,377	52%	4%	56%
Fruit (exc. grapes)	898	213	1,111	2,627	34%	8%	42%
Vegetables	530	72	602	2,923	18%	2%	21%
Other agricultural commodities	193	2,340	2,533	8,494	2%	28%	30%
Total agricultural commodities	**4,576**	**10,415**	**14,991**	**38,541**	**12%**	**27%**	**39%**

Data derived from (ABS 2008) Tables 4.21 and 4.22

During 2000-01 to 2007-08 (see Table 3) irrigation production systems in the Basin have responded to water scarcity caused by the drought and price signals by either switching commodities produced or altering their management strategies (Mallawaarachchi, Thilak. et al. 2010). Part of the adaptation strategy has included the transition out of perennial high water use commodities (pasture, fruit and grapes) and annual high water use commodities (pasture, cotton and rice). This adjustment in irrigated commodities is broadly consistent with the results in Adamson *et al.* (2009). In those results flexible cotton production system are described as when producers switch to dryland cotton in drought years and back into irrigated cotton when season are good. Although the grow in dryland cotton did not occur in 2007-08, as other crops were planted, the 2008-09 cotton plantings "more than doubled to 159 thousand hectares following increased availability of water for irrigation" (Australian Bureau of Statistics 2010, p. 5)

Table 3 Area Irrigated by Commodity type ('000 Ha)

Commodity group	**2000-01**	**2001-02**	**2002-03**	**2003-04**	**2004-05**	**2005-06**	**2006-07**	**2007-08**
Pasture for dairy and other livestock	760	707	551	669	703	717	761	365
Rice	178	145	44	65	51	102	20	2
Cereals (excl. rice)	260	354	416	340	324	329	266	291
Cotton	405	394	218	174	258	247	126	53
Grapes	84	86	89	87	92	106	112	106
Fruit (excl. grapes)	59	62	74	59	63	75	78	71
Vegetables	37	35	31	40	35	32	26	28
Other agriculture	41	34	43	67	62	46	52	42
Total Agriculture#	**1 824**	**1 817**	**1 466**	**1 501**	**1 588**	**1 654**	**1 101**	**958**

Source: (Mallawaarachchi, Thilak. et al. 2010)

Totals may not equal the sum due to multiple cropping practices and errors in estimates

Zalucki *et al.* (2009) discuss that as Australia producers have moved away from wheat to canola and grain leagues, the real cost of pest management per hectare has increased. This statement is consistent with the concepts of economic thresholds and the opportunities for pests under landscape modification as discussed in Buckley *et al.* (2007). In 2006-07 Australian farmers spent over $1,574 million on weed control and a further $768 million on pest control (Australian Bureau of Statistics 2008). So if, the model by Adamson et al. (2009) is correct and, under climate change irrigation commodities in the southern Basin transitions towards grain crops (which include grain legumes) and principally out of dairy and, as discussed, heliothis activity increases in southern areas, will the long run pest response to landscape modification negate the benefits from adaptation? This thesis aims to provide insight into this question.

This section has raised questions concerning climate change influences on both heliothis and irrigation commodity mixes in the future. It suggests that producers will need to consider the implications from changing climate on pests in their adaptive plans to the climate change response. The next section outline the research methods that are proposed to be used to provide a framework for addressing heliothis response and adaptive irrigator management decisions to a changing climate

Research Methods

In order to understand how a changing climate may alter species distribution and density and ultimately the comparative advantage of commodities a series of approaches are planned to be used. Firstly an introduction into the biological and environmental factors involved in pest species distribution is presented so that the benefits and limitations of CLIMEX, a scientific model that predicts the suitability of areas for species survival, can be presented. Then a discussion of how CLIMEX results can be used in this thesis is presented in conjunction with the need to apply economic thresholds to the CLIMEX results. Then an introduction into how resources are allocated under risk and uncertainty is provided. Here the use of state contingent analysis is discussed in light of how a stochastic representation can be introduced to include greater understanding of resource limits.

Biological & environmental factors influencing pest spread

Pests are either indigenous or introduced (deliberate or accidental) but both can be invasive (Hone 1994). The success of an individual pest species, measured as density and distribution through time (Industries Assistance Comission 1985), is dependent upon the interrelated and interdependent characteristics of: spatial references (i.e. local, regional and interregional) (Mayer, Atzeni & Butler 1993); temporal (i.e. daily, weekly, seasonal and multi-seasonal) (Shea et al. 2002); biological (i.e. thresholds (Økland, Skarpaas & Kausrud 2009), dispersal mode (Jeger 1999), fecundity (Fitt 1990) and adaptation (Hoegh-Guldberg et al. 2008)); natural environment (i.e. topography (Brown, JH 1984), climatic variables (Drake 1994), and predator-prey relationships(Harper 1991)) and influenced environment (i.e. landscape modification (Buckley, Bolker & Rees 2007) and the direct and indirect influence of private and public management strategies (Auld, Menz & Tisdell 1987)). In a steady state, under active management, the combination of individual pest species success then defines a baseline pest level in temporal and spatial terms to which we can estimate the economic cost. These costs help determine the allocation of resources based on comparative advantage of production. It is proposed that any change to the steady state pest level will have a corresponding positive or negative economic signal, which if significant will case resource allocation in the long run. So what could happen to heliothis distribution and density under climate change?

The heliothis diapause model developed by Dr Dave Murray determines the proportion of the *H. armigera* population entering diapause and emerging from diapause by date and by location and based on historic climate data. Full details about the model can be found at http://cottassist.cottoncrc.org.au/DIET/. The data presented in Table 4 is obtained by interpreting the results charts produced using Namoi West Post Office climate data. The data examines the expected daipause and emergence date can compares it to a plus or minus 3^{o}C temperature change. The actual emergence data has also been included for 2009.

Table 4 Impact of Temperature Variation on Heliothis

	Diapause					**Emergence**			
	50%	**Days**	**90%**	**Days**		**55%**	**Days**	**88%**	**Days**
Average	2-Apr		30-Apr			7-Nov		16-Nov	
Average – 3^{o}C	16-Mar	-16	3-Apr	-27		3-Dec	-26	13-Dec	-27
Average + 3^{o}C	20-Apr	18	20-May	20		17-Oct	20	24-Oct	22
Actual 2009 Data						2-Oct	35	20-Oct	26

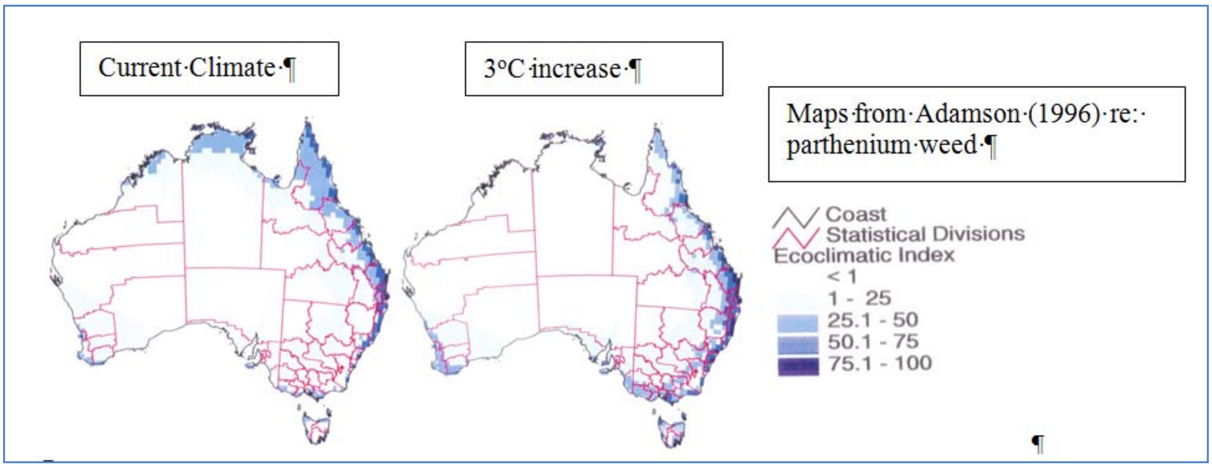
In Table 4 50% and 90% of the population is expected to go into diapause by the April 2 and 90% of by April 30 respectively. If temperatures are 3^{o}C cooler, then 50% of the population will be is diapause 16 days earlier (i.e. March 16) and 90% will be in daipause 27 days earlier than normal. However, if temperatures are 3^{o}C warmer then heliothis have an additional 18 days and 20 days before 50% and 90% of the population go into daipause. During this additional time they could be causing crop damage or increased management costs. This trend continues for the predicted emergence date then with increased temperatures heliothis emerge earlier than normal and latter in cooler years. By examining what actually occurred in 2009 it is estimated that 55% of the population emerged 35 days earlier than a normal year. If we consider that generational peeks are between 35-42 days (Zalucki & Furlong 2005) , then Deuter (2008) concerns' of an extra heliothis generation in a year could be possible. As temperature is the limiting factor in the southern temperate basin, then increasing temperatures are likely to extend the time heliothis are active. While in northern regions the time spent in the over wintering diapauses phase could be considerable reduced.

(Talpaz et al. 1978) provides one of the first bio-economic models that incorporate temperature and humidity variables to illustrate the boil weevil's development and the environment in which it operates. As ultimately the data is to be used in the RSMG Water Allocation Model which considers annual resource use, such daily estimates of pest development are not required rather it needs an estimation of the density pressure in a year.

CLIMEX is a tool for modelling species spread and has been used by Adamson (1996) to illustrate the impact a changing climate could have research investment by illustrating density and distribution changes associated with parthenium weed (see Figure 2). Please see Sutherst (2008) for listing of publications based on CLIMEX results throughout the world including climate impacts of fruit fly in

Australia (Sutherst, Collyer & Yonow 2000). CLIMEX uses spatial climatic data to match which areas are suitable for the species based upon their response to light, moisture and temperature (Kriticos & Leriche 2010)

Figure 2 Illustration of CLIMEX Results



Adamson (1996) determined the changes in density though time by using the Ecoclimatic Index a combination of the growth and stress indices and then applied a proportional change in management costs and yields. This approach ignores the concept of economic thresholds and is something that this thesis aims to address. Other actual physical changes to species i.e. leaky gut (Wilson & Mellor 2008) are not be considered in this thesis.

Pest Management and Economic thresholds

The key to understanding pest impacts on economic productivity is the difference between the concepts of: economic injury (i.e. the point at which pests start impacting on the commodity Stern *et al.* (1959) and Stern (1966)) and economic threshold (i.e. point at which cost and benefits from management are equal (Headley 1972)). This means that there is always a background pest level at which it is uneconomic to manage.

Using Norton & Mumford (1993) definition of economic thresholds is outlined of Equation 1. Where: C is the cost of management per unit dependent upon Ø the density of the pest attack at a given time of both the pests' life cycle and the development stage of the commodity at risk; P is price of the commodity at risk per unit; D is the damage coefficient associated with the corresponding levels of Ø; and K defines the success that control has on Ø. This definition then allows for the determination of optimal management by D or C, the evaluation of alternative management systems by Ø and/or K, and determination of threat alternatives species pose.

$$C = \O PDK \qquad \text{Equation 1}$$

Headley (1972) is credited for providing first economic threshold equation and this framework then allowed Hall & Norgaard (1973) to introduce bio-economic modelling to optimise both the timing and quantity of insecticide. Hueth & Regev (1974) then outlined optimisation subject to developing pest resistance. Gershon (1979) provides suggestions into how risk and uncertainty can be formulated into the economic threshold concept although many authors including Longworth & Rudd (1975) had already discussed the complex issues of risk uncertainty in light of pest management and the associated externalities. These and other works provided the platform to introduce greater sophistication including: Hall & Moffitt (1985) inclusion of inter-year economic thresholds; (Lazarus & Swanson (1983) introduced combining multiple management options; Lazarus & Dixon (1984) illustrating the benefits of area wide control versus individual management efforts; and Boggess *et al.* (1985) modelling of intergenerational ages structure models of multiple species. Work in this area continues providing greater specification of how density and area under threat (i.e. distribution) impact on economic return on a range of emerging issues, for example Davis *et al.* (1992) work on public control for private benefits and Laxminarayan & Simpson (2002) work on refuge strategies for transgenic crops. The refinement and complexity of analysis is due to the advancement in computation power which previously limited the use of nonlinear and dynamic assumptions Talpaz *et al.* (1978). What is surprising is that this literature is generally not carried over into the issues of sanitary and photosanitary risk analysis in international trade (Adamson & Cook 2007).

Carlson (1970) describes a pay-off matrix that specifies that alternative pests densities can be described as an individual by state of nature as a complete list of management responses (i.e. inputs used) to that state can be derived. Using the pay-off matrix the maximum expected utility can be determined from Bayesian principles. The combination of economic thresholds and the pay-off matrix under alternative states of nature (see state contingent section) allows this paper plans to illustrate that under existing climatic conditions Helicoverpa costs (management and production) are known by commodity, by region for alternative climate and density levels.

Need to understand the distribution (L) and density (Ø) by state of nature. If we accept the current management costs in the RSMG water allocation model provide the medium density state (see below) then by using these collected GM budgets we can assign changes to cost by density levels generated from CLIMEX. This can either be represented as: a change in the number of sprays, decrease in yield or a combination of both. Care has to be taken as when producers engage in management/protection of their enterprise their response has multiple impacts on multiple species. Although primarily attempting to control the negative impacts of one target species they are impacting on a range of non-target species. The question for producers is under climate change will management systems have to alter in response to, existing and new, pest species response to that given climate change and producer commodity adaptation.

The migratory nature (i.e. outside Basin influences), population dynamics and management of heliothis therefore suggest that heliothis density within the Basin to be highly variable and not directly correlated with the defined states of nature for water supply in the RSMG Water Allocation Model. Therefore it is proposed to introduce states of heliothis density within each water supply state of nature. The density states are proposed to be (i.e. no density, light density, medium density and plague proportions) for each state management response and yield loss will correspond accordingly to the Ecoclimatic Index. The frequency of the states will be defined via CLIMEX's Grown Index where based on the number of years historically the density would have actually been achieved.

An important step in this evaluation is the division of the existing cotton commodities into GM cotton and conventional cotton. As discussed in Norton (1985) GM cotton is in effect a form of calendar management rather than integrated pest management (IPM) because rather than tactically working out the economic threshold the bulk of the management costs are allocated in the licence fee. This division should help illustrate why some producers may switch out of GM cotton and into conventional cotton, dependent on density, as already alluded to.

By directly incorporated state densities and frequencies of heliothis pressures changes in the capital investment decision caused by climate change scenarios can be determined. As in the short run many exotic invaders will only temporally reduce the expected economic return of an investment. If however, they become endemic and require changes to management expenditure by state then resources may be reallocated. This is expanded in greater detail in the next section of resource allocation under risk and uncertainty where the state contingent approach is detailed.

Resource allocation under risk and uncertainly

The allocation of resources under climatic variability is a source of rich and detailed literature within Australian research. Either dealing with: the classification and determinates of climatic variability especially in Australian literature see Williams (1946), Davidson (1965) and (1969); the theory of economic climatic variability Anderson *et al.* (1977); the impacts of variability in Anderson (1979); examples in modelling climatic variability (McArthur & Dillon 1971); the management strategies for dealing with risks by Australian producers in Makeham and Malcolm (1981), Ritchie et al. (2004) and

Nguyen et al.(2005); and analysis of policies dealing with climate variability see Hughes et al. (2009). These practical applications above effectively use the expected utility approach which determines optimal choice as a function of the payout and derived utility of that payout (Rae 1994).

The problem with this approach unlike state contingent analysis is that it does not...

> ... "consider the interaction between the uncontrolled (uncertain) variables and the decision variables controlled by the decision maker. Furthermore, although Dillon and Anderson (1990) realized the basic need for modelling this kind of interaction, they did not derive criteria for optimal production that went beyond maximizing utility, defined as a function of expected value and variance of profit" (Rasmussen 2006b).

State Contingent Approach to Risk & Uncertainty

The re-examination of the state contingent approach to risk and uncertainty is due to Chambers and Quiggin (2000) who built upon the foundations described by Arrow and Debreu (1954) and Debreu (1959). The approach suggests that decision makers actively respond to alternative states of nature, by changing their inputs to influence the final output, based on past experiences and knowledge in order to meet their objective function. The benefits of a state contingent approach is that it allows for production and decision maker uncertainty to be treated separately (Rasmussen 2006a). This division removes the blurring of ambiguity found in other decision support systems where production and management inefficiency cannot be separated (O'Donnell & Griffiths 2006). So contrary to other approaches it assumes the producer is intelligent and is capable of adaptation to unforseen events and complements the discussions provided by (Ash et al. 2007; Hayman et al. 2007; Mallawaarachchi, Thilak & Foster 2009) .

The hinging component of state contingent analysis is that all possible outcomes can be described within a state of nature (i.e. rainfall can be represented by a 'normal' state, a 'drought' state and a 'wet' state). Within each state the decision maker has the ability to allocate their resources to produce a state specific output (Quiggin, John & Chambers 2000).

When we compare existing economic analysis of climate change in the Basin between the expected utility approach used by Beare and Heaney (2002) and Goesch et al.(2009) versus the state contingent approach Mallawaarachchi et al. (2008), Quiggin et al.(2008) and Adamson et al. (2009) we see some significant differences in the outcomes. By having the ability to explicitly model a drought state of nature and the risks associated with water supply in that state we find that production system move away from commodities that require water in all states of nature (i.e.

perennial horticulture) and opportunistic irrigation occurs when water resources are available. While in the expected utility approach, water resources move towards perennial horticulture. What was recently witnessed in the Basin was that there was not enough water to meet the needs of perennial horticulture (Mallawaarachchi, Thilak & Foster 2009).

When critically reviewing the state contingent model used for these analysis we find that key variables are deterministic in nature. Rasmussen (2006a) illustrates that outcomes (yields and prices) are in fact consequences of states of nature. This fact implies that a state of nature can in fact be described a stochastic function. If we can infer that state outputs (yield and price) are state dependent then logically resource inputs (water use, labour and capital) and even how we describe the individual states of nature (i.e. natural resource bounds e.g. total water availability due to climatic conditions) can also be stochastic in nature. An example of applying the stochastic nature of states can be found where 'input decisions have to be made before uncertain outputs are known' (Chavas, 2008, p 444).

This then opens up a range of opportunities to examine climate variability and resource allocation. Not only can we highlight the reliability of state conditions or what we expect within a state (i.e. quantity of rainfall in a drought state of nature) but we can also illustrate production heterogeneity within the model (i.e. variable yields in a given state of nature), the amount of input required by state (i.e. water requirements by commodity by state of nature) and importantly the management response to said conditions (i.e. variation with a state decreases through time via learning). Now not only can we represent climate change by altering the frequency of states occurring but the increased variance from exasperated climatic variation a manager may expect from alternative changing states of nature can be represented.

By stochastically describing states, input requirements and outputs we are in effect attempting to bring the best aspects of each approach together.

State contingent analysis versus discrete stochastic programming

Cocks (1968) outlines the theory of discrete stochastic programming, which has been used by Brown and Drynan (1986) and Kingwell et al.(1992) to determine optimal resource. However, as discussed in Quiggin *et al.* (In Press) although sharing some similarities the ability of the state contingent analysis overcomes the discrete stochastic programming problems of constraint diagonalisation and need for a recourse solution (i.e. optimal solution only found after partial realisation of the state of nature). This is achieved by not using a default commodity rather a state specific commodity that is treated differently (inputs and outputs) for each state of nature which has its own set of constraints. Further work is planned on clarifying this differentiation during the thesis.

Summary

This section has provided a introduction to the proposed approaches to be used. The next section will provide an examination of the work that has already been carried out to investigate the nature of stochastic state representation in the RSMG Water Allocation Model.

Progress on the Thesis

Introducing Stochastic States

From (Chambers & Quiggin 2000) a stochastic production function can be represented as Equation 2 where random output Z is obtained from using a vector x of inputs and ε is a vector of randomly occurring states.

$$z = f(x, \varepsilon) \qquad \textbf{Equation 2}$$

While a state contingent production function is represented in Equation 3. Here z_s is the output obtained in state s, and $f_s(x)$ are the inputs required by state s, to produce z_s and S equals the total number of states.

$$z_s = f_s(x) \qquad (s = 1, \dots\dots S) \qquad \textbf{Equation 3}$$

What Equation 3 is effectively saying is that I know the state and the resources needed to produce a given output for that state of nature, this is perfect knowledge. If we acknowledge that a decision maker often has incomplete information (in this case the impact of climatic variability on all possible enterprise options) we can then combine Equation 2 with Equation 3 to obtain Equation 4. Here we see that the random function has been re-introduced to signify that either the representation of the state, the input requirements or output obtained was within the range of possible outcomes that satisfied their decision making process.

$$z_{s,\varepsilon} = f_s(x, \varepsilon) \qquad (s = 1, \dots\dots S) \qquad \textbf{Equation 4}$$

This random function can be represented in the simplest form by a triangular distribution. Here ‘c’ is the expected value and ‘a’ and ‘b’ its bounds which provides some degree of certainty about the range. For example, a wheat producer knows that for a given area, in a normal year, with this combination of resource inputs, a yield of 2.2 to 2.5 tonnes of wheat per hectare should be obtained. This is represented by Equation 5.

$$z_{s,\varepsilon} = \begin{cases} \frac{2(x - a_s)}{(c_s - a_s)(b_s - a_s)} & \text{if} a_s \leq x \leq c_s \\ \frac{2(b_s - x)}{(b_s - c_s)(b_s - a_s)} & \text{if } c_s \leq x \leq b_s \end{cases}$$ **Equation 5**

Note that the distance between the bounds could be associated with either: the number of priors a decision maker has for that state; the variability of rainfall in that state and the implications from not receiving anticipated volumes; the input requirements (i.e. irrigation ML/Ha) for each state; and the producer's attitude to risk. The triangular distribution is easy to communicate and illicit information about bounds from third parties. For example, if producers know that they have 5 ML of water to irrigate with then they may expect a yield of 4 tonnes plus or minus 10%. Or alternatively to produce 4 tonnes of commodity 3 to 4 ML of water is required. It is then the range between the bounds that specifies the producers risk and/or believed knowledge about the state when they are allocating resources. The actual outcome is how well in fact they interpreted the state and ability to react to other unforseen events. The next section illustrates how to incorporate this approach into the model.

Modification of the RSMG Water Allocation Model

The model presented here updates that presented in Adamson et al. (2009). This version determines the optimal national benefit from utilising irrigation water anywhere in the provided that the volume used does not exceed the CAP and that water quality arriving at Adelaide meets the 800 EC condition. This equation representation is then the global solution and not the sequential as presented in Adamson et al. (2007). Equation 6 provides the objective function for the model which states that we aim to maximise economic return for irrigation in all catchments (k) in the basin. Economic return E[Y] is derived from the area A of commodity R grown in each region multiplied by the return of that commodity by the probability of that state (S) of nature occurring πS. Where return is based on the yield (Q) multiplied by price (P) net the total costs (C) of production in each region of the basin.

$$E[Y] = \sum_{R} \sum_{S} \pi_S \left[A^R \times Q_S^R \times (P - C)_S^R\right]$$ **Equation 6**

Subject to:

$$\sigma_S^{30}/0.64 \leq 800 \text{ EC}$$ **Equation 7**

$\sum \mathrm{K_s \pi_s} \leq \mathrm{CAP}$ **Equation 8**

wks ≤ fks **Equation 9**

$\mathrm{A_k R_{1..5}} \leq \mathrm{AHort_k}$ **Equation 10**

$\mathrm{A_k R_{1..27}} \leq \mathrm{Atotal_k}$ **Equation 11**

$\sum \mathrm{L_{rk}} \leq \mathrm{L_k}$ **Equation 12**

This is subject to Equation 7 where Adelaide's water quality must be less than 800 EC in each state of nature. The volume of water used in the basin must be less than the CAP on average (i.e. as long as the average CAP is not violated you may used more than under the CAP in a given state of nature) as in Equation 8 . Equation 9ensures that water use in a catchment must be less than or equal to the flow in that catchment. Equation 10 states that the area dedicated to horticulture in any catchment must be less than equal to the horticultural constraint in that area. While Equation 11 ensures that total area dedicated to irrigation in any region must be less than the total area available in that region. Equation 11 allows broadacre activities to expand over horticultural area if required. Equation 12 ensures that there is sufficient operator labour to undertake the irrigation activity mix in a region.

As πS Is the probability of the state occurring, $\sum \mathrm{\pi_s} = 1$ (i.e. every state is identified), where $0 < \pi \leq 1$ (the states are real. The three states of nature (S) are modelled which are represented by alternative Basin wide inflows. These states are Normal (the expected long term average inflows derived from (MDBC 2006)), Drought (0.6 * Normal Inflows), and Wet (1.2 * Normal Inflows). The model uses a conjunctive approach to water resources consequently total water inflows are dependent upon inter-basin transfers' surface supplies and ground water supplies. Here π1to3 = (0.5, 0.3, 0.2). The model uses a directed flow network where the Basin is divided into 31 catchments (K) which consists of 29 irrigation areas plus Adelaide and the Coorong.

The description of the state is where the first parameter distribution is examined. Traditionally we have used a normal runoff of 517 G, 308 GL in the drought state and 621 GL of runoff in the Wet states for the Condamine catchment. By using a triangular distribution (equation 4) and the parameters listed in Table 6, the normal state now receives runoff somewhere between (362, 517, 672) GL, a drought runoff distribution of (92, 308, 524) and a wet distribution of (466, 621, 777) GL. The overlapping bounds can illustrate that alternative producers will classify different states of nature form the same information. What this is saying is that as a producer I know that if runoff may range between alternative levels of 'a' and 'c', then for this runoff I adopt the specific management option. When undertaking the analysis each stochastic representation is run independently to avoid multiplicative uncertainty.

The area of production by catchment is defined by A which is a matrix of production systems $(\mathrm{K} \times \mathrm{R}) \times \mathrm{S}$. There are 27 production systems (R) consisting of 25 irrigation activities plus Adelaide Water plus a dryland production system. Catchments are based on disaggregated Catchment Management Regions (CMRs) to help model the directed flow network (water and salt) as illustrated in Appendix 1. Here water flows (fks) out of a given catchment are equal to inflows (net of evaporation and seepage) less extractions (net of return flows). Extractions are determined endogenously by land use decisions as described below, subject to limits imposed by the availability of both surface and ground water. This structure allows for the determination of total irrigation use, the flow to the Coorong and water quality arriving at Adelaide.

The second critical factor in describing A is the matrix R where the state contingent production systems are defined. Each state of nature for each r will derive an independent representation of yields (Q), prices (P), costs of production (C) and input requirements (N) and each matrix has a form of (31 X 29). The production systems are derived from$(\mathrm{K} \times \mathrm{M}) \times \mathrm{S}$, where M represents commodities. A commodity is a single enterprise in a given state in a given catchment. This data is based on a series of regional gross margin budgets that provide the data for the five inputs modelled ((N= water, land, labour, capital and cash input). This version of the model has 15 distinct commodities (M) plus urban water for Adelaide and water for the Coorong. Consequently there are (M+2)×S distinct state-contingent commodities see Table 5.

Some commodities are produced using more than one technology (i.e. capital intensive water saving irrigation investment such as drip systems versus low capital investment systems such as flood irrigation) and this is outlined in the third column of Table 5. The fourth column represents commodities for which irrigation practices change in the drought states to low or no water use. The fifth column illustrates production systems where only in the 'Wet' state of nature does irrigation occur. This describes 'opportunity irrigation' which occurs when large volumes of general security water rights are actually met. The final column illustrates which commodities can be mixed and matched to build new state production systems and obviously this can not apply to perennial commodities. This combination of technologies and ability to develop state contingent data production sets allows M to increase to R.

Area is divided into two classifications horticulture and broadacre (including pasture) for each k based on irrigated area in 2001 which was considered the last normal year in the Basin (ABS 2004) .

The model allows for irrigation expansion by allowing a 45% increase for R horticulture activities (see Table 1) and a maximum increase of 80% in total area irrigated. Area in k is constrained by equations 9 which ensure that horticultural productions systems can only be grown on horticultural land and equation 10 where the total area of land irrigated must not exceed maximum area. These two equations then prevent the model being dominated by horticultural R and allow broadacre R to expand into horticultural area if profitable.

Table 5 Production Systems in the Model

Classification	Commodity	Multiple Technologies	Flexible & Fixed Rotations	Wet Water use	Multiple Combinations
Horticulture	Citrus	Yes			
	Grapes				
	Pome Fruit				
	Stone Fruit	Yes			
	Vegetables		Yes		
Broadacre	Cotton		Yes	Yes	Yes
	Grain Legume				Yes
	Oilseeds				Not activated
	Sorghum				Not activated
	Oilseeds				Not activated
	Rice		Yes	Yes	Not activated
	Wheat				Yes
Pasture	Dairy	Yes			
	Beef				Not activated
	Sheep				Yes

Yield (Q) has a matrix of $(K \times R) \times S$ and represents the output derived by state of nature and here is where the second distribution parameter is entered. Traditionally we assume that cotton in the Condamine catchment produces 8.8, 3.2 and 8.8 bales/Ha in the normal, drought and wet states of nature. Here in the drought state a dryland crop of cotton in produced. We know that actual yield achieved in any year is a combination of environmental attributes (i.e. soil type, soil moisture, localised rainfall events, commodity varieties) that greatly influence production within a paddock let alone a catchment Bramley & Hamilton (2003) and Bramley (2005). So based on Table 6 the range of yield produced by a flexible cotton rotation in the Condamine in a normal year is between (7.9, 8.8, 9.6) bales/Ha, in the drought (2.7, 3.2 and 3.6) bales/Ha and in a wet year (7, 8.8, 10.5) bales/Ha. To model this, yield (Q) changes to Qε when the simulations are undertaken while everything else is held constant.

Net return per hectare is described in the model as (P-C). P is price paid for output is a matrix of $(M \times S)$ dimensions. For simplicity it has been assumed that the price paid in all regions for each commodity is uniform by state of nature. In this version of the model we have set the price of water reaching the Coorong to $0. Production costs are represented by (C). Here cost for producing one hectare of commodity R for each K in each S can be written as the sum of capital costs (i.e. capital costs do not change by state of nature and are a annual cost) plus operator labour costs (LC) (i.e. hours multiplied (L) by a constant price (LP)) plus variable costs (VC) as in Equation 13. Equation 14 details variable costs which are derived from the sum of casual labour (CL) (i.e. hours multiplied by a constant price) plus contractor costs (Con) plus machinery costs (Ma) plus chemical costs (Ch) plus water use (W) times by water price (Wp) plus other costs (O).

$$R_{ks} = \sum(CC_k + LC_{ks} + VC_{ks})$$ **Equation 13**

$$VC_{ks} = \sum(CL_{ks} + Con_{ks} + Ma_{ks} + Ch_{ks} + (W_{ks} \times Wp_{ks}) + O_{ks})$$ **Equation 14**

Here is where we examine the impact of the third stochastic distribution water use (W). As for yield the actual water required to produce a given unit of output is in fact the combination of the same environmental factors. In the base version of the model, in the Condamine catchment each hectare of flexible cotton is 5, 0, 5 ML/Ha in the normal, drought (commodity switches to a dryland crop, therefore no irrigation) and wet states respectively. So based on Table 6 the range of water required per hectare in the Condamine in a normal year is between (4.5, 5, 5.5) ML/Ha, in the drought (0, 0, 0) ML/Ha and in a wet year (4.3, 5, 5.8) ML/Ha. To model this, water use changes to Wε when the simulation is run while everything else is held constant.

When modelling water use three constraints are critical and are represented by Equation 6, 7 and 8. Dealing with them in reverse order it is the fact that the amount of water used in a catchment in a state of nature (Wks) cannot exceed the volume of water flowing in the catchment (fks). Then the total volume of water used in the Basin (∑KSπS) must be less than the Basin CAP. This equation allows for water to be carried over in low flow years. The Cap data for each k is derived from (MDBC 2008).

Equation 11 deals with the amount of operator labour (L) required producing ∑r in k. Here we ensure that the amount of labour in a region (derived from ABS 2004 data and based on number of farms * 2 people * 2,500 hrs/person) is adequate to meet the needs the chosen production systems.

Salinity is now modelled as a constraint rather than a dynamic impact on production negating the discontinuous function described in Adamson *et al.* (2007). Salt loads (tonnes) are represented in state contingent terms reflecting salt immobilisation in soil in drought times and mobilisation during the wet states. Salinity level (σ_s^k) is determined by the state contingent salt load (tonnes) entering the catchment and the flow at that catchment (see Equation 15). The constraint is based on the requirement that 95% of the time the EC at Morgan must be less than 800EC (MDBC 2007). In the Model Morgan is represented by Adelaide (k=30) and can be represented by Equation 7 where salinity level (mg/L) (i.e. Equation 15) is concerted into EC units.

Salt determined by

$$\sigma_s^k = s_s^k / f_s^k \qquad \text{Equation 15}$$

Because the model is solved on an annual basis, the process of capital investment is modelled as an annuity representing the amortised value of the capital costs over the lifespan of the development activity. This provides the flexibility to permit the modelling of a range of pricing rules for capital, and to allow the imposition of appropriate constraints on adjustment, to derive both short run and long run solutions.

New Solution Procedures

Each of the three new parameters are tested in isolation to negate the problem of multiplicative and additive uncertainty as found in many uses of stochastic production functions Chambers & Quiggin (2002). There are two distinct ways of including the Monte Carlo simulation in the model either: ex-ante or ex-post of the state being revealed. In the ex-ante optimisation, the optimal allocation is chosen for the mean values of relevant parameters, and then the parameters are drawn from a stochastic distribution. In other words producers know that their technology is stochastic, but can't adjust inputs and land allocations after stochastic variation is realised (i.e. a simulation of the optimisation results obtained). In the ex-post optimisation, the parameters are drawn from a stochastic distribution and the optimal allocation is chosen. Here producers can adjust inputs and land allocations after stochastic variation is realised. Now the model is optimisation investment patterns taking the stochastic variation into account.

For the ex-post evaluation, a number of modelled constraints have to be adjusted to assist with the optimisation. In this case, Equation 7 to Equation 10 have to be adjusted to meet the constraints 95% of the time due to the nature of the non-linearity within the model's water flow as illustrated in Equation 16to Equation 18. This then changes the optimisation from unconstrained to a chance constrained optimisation.

$$VaR_{0.95}\,(\sigma_s^{30}/0.64 \leq\ 800\,EC) \qquad \text{Equation 16}$$

$$VaR_{0.95}(\sum K_s\pi_s \leq CAP) \qquad \text{Equation 17}$$

$$\mathrm{VaR}_{0.95}(\mathrm{wks} \leq \mathrm{fks}) \qquad \text{Equation 18}$$

The model was solved in Microsoft Excel 2007 using the Risk Solver Platform from Frontline systems version V9.5.10. Here we used a Monte-Carlo approach to simulation method using 1,000 trials for a single simulation is used in combination with the Large-Scale GRG Engine. The bounds of the parameters for each variable tested are presented in Table 6. The mean values have not been illustrated due to space reasons as the state description has a matrix of $(K\ \times\ S)$ and the state inputs and outputs have a matrix of $(K\ \times\ R)\ \times S$.

Table 6 Simulation Bounds

Parameter	Normal Bounds		Drought Bounds		Wet Bounds	
	Lower (a)	Upper (b)	Lower (a)	Upper (b)	Lower (a)	Upper (b)
State description (Inflows)	-20%	+20%	-60%	60%	-15%	15%
State Inputs (Water Use)	-20%	+20%	-60%	60%	-15%	15%
State Output (Yield)	-20%	+20%	-60%	60%	-15%	15%

These parameters have been used for illustration only. Significant work on determining the actual stochastic function and parameters are needed. .

Preliminary Findings

Throughout this discussion the Base refers to the current modelling approach which has deterministic values; the ex-ante provides a stochastic simulation on the results; and the ex-post is the new approach where the model optimises resources using a Monte-Carlo description of the state variable in question. Each parameter is examined independently to negate multiplicative uncertainty and analysis firstly examines: the description of the state; then the impact of state outputs (yield); and finally state inputs (water use).

The interpretation of the Base results in Table 7 are as follows. The first column refers to the catchment being examined, the second column refers to the total area irrigated in that catchment (and the specific commodities being irrigated is located in Table 8); columns 3 to 5 refer to the amount of water used for irrigation in that catchment by state of nature and column 6 refers to the average water used over time (i.e. irrigation use multiplied by frequency of the state occurring), columns 6 to 10 refer to the salinity level of the water in that catchment by state and then by average and finally columns 11 to 14 refer to the economic return that water used by catchment by state and by average returns. Here we can also see that for the Basin over 1,863,000 Ha is expected to be irrigated. This will require between approximately 7,500 GL in the drought to over 15,000 GL in wet year and on average over 12,000 GL will be used. The salinity arriving at Adelaide will range between 476 EC during droughts to over 529 EC in a normal year with an average EC of 471 EC, which is well short of the 800 EC constraints for Adelaide (see equation 6). This water use will return over $1.1 billion in a drought year to over $4 billion in wet years and on average approximately $2.8 billion. It is important to note that all results are single values.

The commodities irrigated in Table 8 are summarised from the model. Here citrus, stone fruit and dairy refer to both high and low security (see Table 5), cotton crops refer to flexible cotton, fixed cotton and the cotton-chickpea rotation, other grains refers to wheat, sorghum, oilseeds and the wheat legume rotation and beef/sheep refers to the number of hectares irrigated for grazing beef and sheep enterprises.

Table 7 Base Model: Resource Allocation & Return

Catchment	Irrigated Area ('000 Ha)	Water Use (GL)				Salt (EC)				Economic Return ($'m)			
		Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	Normal	Drought	Wet	Average
Condamine	101.1	510.7	22.4	515.1	414.4	21.3	17.8	17.7	19.5	$120.7	$43.0	$135.8	$109.7
Border Rivers QLD	99.0	399.3	67.0	480.1	357.0	30.6	25.7	25.4	28.1	$89.4	$15.5	$152.5	$93.6
Warrego Paroo	18.5	67.2	6.2	81.5	59.3	38.9	33.7	32.1	35.8	$16.3	$6.9	$15.3	$14.1
Namoi	155.0	743.2	3.8	893.8	640.5	141.8	119.2	117.9	130.1	$351.9	$104.0	$362.4	$305.5
Central West	126.1	695.7	57.9	839.0	611.1	75.6	64.3	62.7	69.4	$162.7	$102.6	$174.6	$154.3
Maranoa Balonne	71.2	321.4	14.8	324.4	261.0	77.7	19.2	56.8	59.7	$61.9	$32.1	$56.3	$54.3
Border Rivers Gwydir	179.0	489.3	4.3	1,405.7	667.2	30.8	13.4	27.6	26.4	$161.6	$84.5	$120.8	$134.0
Western	1.0	8.1	8.1	9.7	8.6	57,624.7	95.2	57,032.5	45,941.2	$9.8	$4.6	$14.8	$10.2
Lachlan	11.4	89.1	89.1	106.9	94.4	220.6	185.4	183.5	202.4	$83.1	$50.8	$131.1	$91.1
Murrumbidgee	361.0	2,738.6	1,913.4	3,343.7	2,755.1	77.6	65.3	64.5	71.2	$420.5	$90.8	$656.4	$425.4
North East	25.5	188.1	188.1	225.7	199.4	70.8	60.5	58.7	65.1	$33.3	$10.2	$89.8	$45.6
Murray 1	22.1	189.1	189.1	226.9	200.4	20.2	17.2	16.7	18.5	$40.4	$14.3	$60.9	$41.3
Goulburn Broken Res (GB)	9.4	78.0	78.0	93.6	82.7	13.1	11.0	10.9	12.0	$6.7	-$0.4	$22.9	$10.1
Murray Valley (GB)	56.6	508.1	508.1	609.7	538.5	64.8	59.0	54.1	60.4	$35.1	-$31.7	$156.8	$58.2
Shepparton (GB)	51.0	412.7	412.7	495.2	437.5	26.5	22.7	22.2	24.5	$32.9	-$39.7	$166.8	$58.5
Central Goulburn (GB)	113.1	904.3	904.3	1,085.1	958.5	73.1	76.5	62.2	70.5	$62.6	-$38.7	$292.0	$111.1
Murray 2	227.7	1,571.9	1,054.7	1,921.3	1,573.3	51.4	47.4	43.2	48.1	$162.7	$1.0	$232.5	$151.3
North Central Res (NC)	3.5	19.3	19.3	23.2	20.5	9.2	7.6	7.6	8.4	$17.0	$10.6	$28.9	$19.3
Campaspe (NC)	1.0	5.3	5.3	6.4	5.6	26.2	22.2	21.9	24.1	$5.1	$2.9	$8.6	$5.7
Rochester (NC)	0.9	5.1	5.1	6.1	5.4	129.0	172.9	110.0	132.1	$7.4	$2.8	$11.5	$7.7
Pyramid Boort (NC)	1.0	5.3	5.3	6.4	5.7	16.0	5.2	13.4	13.0	$10.9	$2.9	$16.0	$10.8
Torrumbarry (NC)	0.7	3.8	3.8	4.6	4.0	151.9	171.7	133.7	150.4	$10.8	$2.1	$15.3	$10.4
Murray 3	40.5	333.7	256.2	396.1	336.9	77.4	118.0	68.1	82.7	$38.2	-$1.7	$60.1	$36.8
Nyah Tresco (M)	36.1	285.6	211.6	342.6	287.9	177.9	245.7	157.4	185.3	$65.2	$14.8	$104.4	$66.9
Merbein Robinvale (M)	13.3	114.6	96.8	137.5	117.9	260.4	402.2	222.3	277.3	$38.8	$17.7	$65.7	$42.7
Mildura (M)	18.8	188.0	188.0	225.6	199.3	341.4	564.5	293.6	371.7	$95.1	$57.6	$166.5	$109.0
Mallee Res (M)	9.6	96.3	96.3	115.5	102.0	414.2	755.3	358.4	465.7	$49.0	$29.5	$85.6	$56.1
Lower Murray Darling	12.2	116.8	116.8	140.2	123.9	369.0	115.3	338.9	309.2	$58.0	$31.9	$106.5	$67.3
SA MDB	97.2	762.3	762.3	914.7	808.0	**529.5**	**317.6**	**476.1**	**471.1**	$287.0	$195.1	$465.2	$322.1
Adelaide		206.0	206.0	206.0	206.0	529.5	317.6	476.1	471.1	$103.0	$309.0	$103.0	$144.2
Coorong	**1,863.3**	**12,056.7**	**7,494.6**	**15,182.4**	**12,082.0**					**$2,637.1**	**$1,125.0**	**$4,079.1**	**$2,767.3**
ALL		4,795.0	1,076.7	6,829.7	4,661.7	778.7	776.1	680.1	748.6				

Table 8: Base Model: Area of Irrigated Production ('000 HA)

Catchment	Citrus	Grapes	Stone Fruit	Pome Fruit	Vegetables	Cotton Crops	Cotton Wet	Rice PSN	Rice Wet	Other Grains	Sheep Wheat	Dairy	Sheep /Beef	TOTAL
Condamine			3.5			97.7								**101.1**
Border Rivers QLD				6.4		66.5	11.2			14.9				**99.0**
Warrego Paroo						12.2	2.2			4.1				**18.5**
Namoi		0.6				132.0	22.3							**155.0**
Central West	7.4					101.2	17.4							**126.1**
Maranoa Balonne					0.0	61.3	0.0			9.9				**71.2**
Border Rivers Gwydir		0.7				69.3	109.0							**179.0**
Western	1.0													**1.0**
Lachlan	11.4													**11.4**
Murrumbidgee	37.1							317.4	6.5					**361.0**
North East		4.6										20.9		**25.5**
Murray 1	0.9											21.2		**22.1**
Goulburn Broken Res (GB)	1.0											8.4		**9.4**
Murray Valley (GB)				4.0								52.6		**56.6**
Shepparton (GB)				6.2								44.8		**51.0**
Central Goulburn (GB)				5.7								107.4		**113.1**
Murray 2	2.5							221.1	4.2					**227.7**
North Central Res (NC)		3.5												**3.5**
Campaspe (NC)		1.0												**1.0**
Rochester (NC)		0.9												**0.9**
Pyramid Boort (NC)		1.0												**1.0**
Torrumbarry (NC)		0.7												**0.7**
Murray 3	1.7					2.1		24.0				12.7		**40.5**
Nyah Tresco (M)	7.6							28.4						**36.1**
Merbein Robinvale (M)	6.4							6.8						**13.3**
Mildura (M)	18.8													**18.8**
Mallee Res (M)	9.6													**9.6**
Lower Murray Darling	12.2													**12.2**
SA MDB		44.9										52.3		**97.2**
TOTAL	**117.7**	**57.8**	**3.5**	**22.2**	**0.0**	**542.3**	**162.1**	**597.7**	**10.6**	**28.9**	**0.0**	**320.4**	**0.0**	**1,863.3**

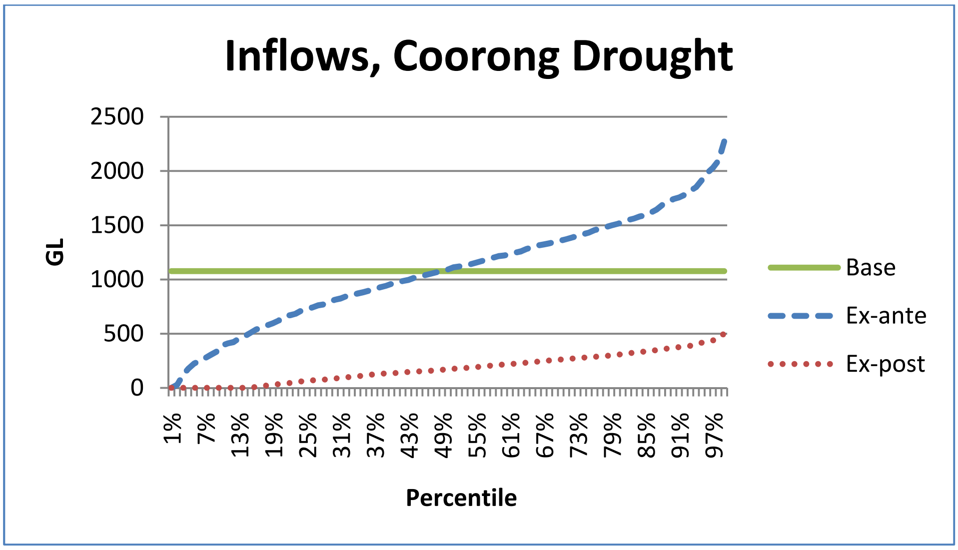
Evaluating the State Description of Inflows

Arguably the critical component in the model is the total volume of water available for irrigation as illustrated in Adamson *et al.* (2009) where a mean reduction in water in each state results in a reduction of area irrigated. The question we have here is if uncertainty exists about the actual volume of water available in each catchment by state of nature what can we learn. The direct comparison of the Base model and the Ex-post optimisation (Base – Ex-post) are in Table 9 (resource use) and Table 10 (area). Here we see that overall area of irrigation has increased by approximately 12,000 Ha, the total water used for irrigation has not changed on average but when the water is utilised has with far greater pressure placed on the system in drought states of nature. The salinity results are misleading as one result from a range and are for guidance only, please see Figure 5 for a description of results. The average economic return in the ex-post optimisation is $40 million less than the Base solution.

These results are caused by changing commodities principally away from cotton and rice. The model uses Murrumbidgee water to provide water to the lower catchments (i.e. Lower Murray Darling and South Australia MDB) and ensures Adelaide's water supply remains potable. As the Murray is highly connected the model suggests that the water should be used in the Murray Valley in the Goulburn region and in Torrumbarry and in the Murray 3 catchment at the expense of the Shepparton and Murray 2 region. The model moves productions systems towards using less water in the normal and wet states of nature but increases water use in the Drought state.

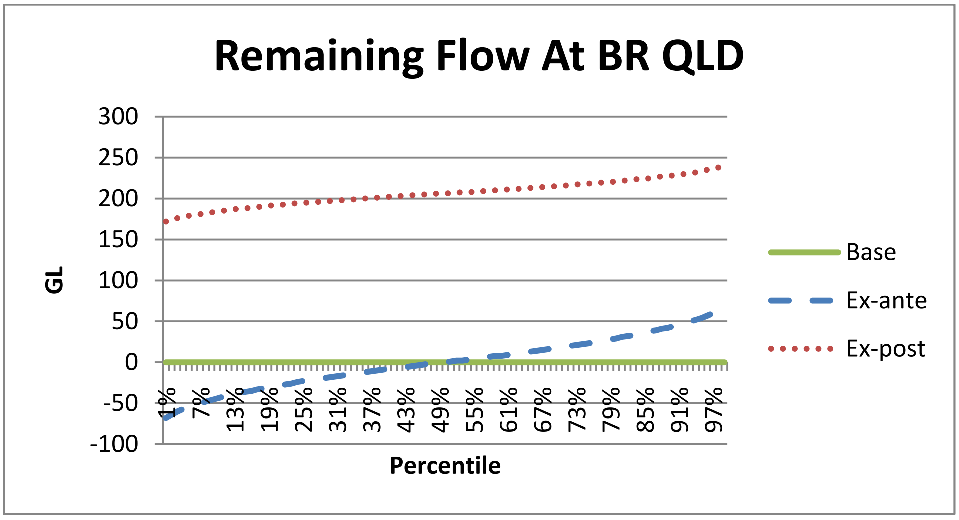
Figure 3 illustrates the results generated for both the ex-ante simulation and ex-post optimisation compared to the Base solution for the volume of water flowing to the Coorong in the drought state of nature. In the base model the answer is just over 1050GL. However, in the Ex-ante simulation, due to the uniformity in parameters selected in Table 6, 50% of the time this volume is either above or below the Base solution. There is a 1% chance that no flow will actually reach the Coorong. The Ex-post analysis suggests, in this scenario flow to the Coorong has no value, then about 15% of the time no flow would reach the Coorong and 50% of the time only 172 GL would reach the Coorong in the drought state of nature.

Figure 3 Comparison of Approach for Modelling the State Description



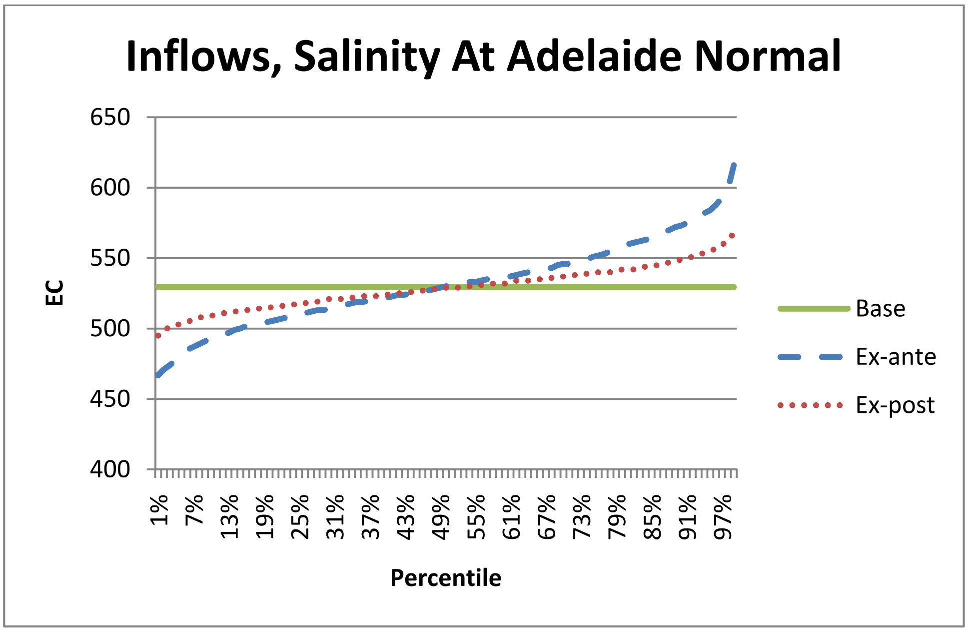
One very important finding of the ex-ante simulation is that it highlights limitation with the Base model as illustrated in Figure 4. By negating the inherent variability the Base model is allowed to utilise all water within a catchment (see Equation 9). The ex-ante simulation quickly picks up this limitation by highlighting the probability that in the Normal state of nature 50% of the time the optimal allocation of water resources of 399.3 GL (see **Table 7**) for the Border Rivers Queensland catchment not be met due to inflow variability. In order to cope with this problem the ex-post model adapts production systems by moving resources away from cotton to wheat which uses less water on average per Ha in all states. With the ex-post result only 193 GL is allocated for irrigation in a normal year and instead of $89.4 million being made in the catchment only $49.7 million is generated.

Figure 4 Highlighting resource limits



If we examine salinity arriving at Adelaide the Base model suggests that in the Normal state of nature we should expect an EC of about 530. The ex-ante suggests that actual salinity in the normal states could actually fluctuate anywhere from about 470 to over 600 EC in a normal year. What we see here is the limitation in reporting expected output in state contingent analysis as discussed in (Chavas 2008)[3]. The ex-post analysis then knows the bounds describing the states and consequently the new-optimisation easily falls within the bounds of the ex-ante approach (i.e. a compaction of the variance of outcomes).

Figure 5 Evaluating Salinity at Adelaide (EC)



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[3] Chavas (2008) really only investigates only the ex-ante solution.

Table 9 Base Model – Ex-post Inflow Model: Resource Allocation & Return

Catchment	Irrigated Area ('000 Ha)	Water Use (GL)				Salt (EC)				Economic Return ($'m)			
		Normal	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**
Condamine	0.0	29.1	0.0	-5.8	12.8	0.9	-0.6	-0.3	0.3	3.9	2.3	3.3	3.4
Border Rivers QLD	-6.0	206.4	-125.5	248.8	152.7	-0.7	-6.3	2.2	-1.0	39.8	22.6	26.8	32.4
Warrego Paroo	4.4	4.6	-25.3	18.2	2.7	-2.4	-5.5	1.7	-1.8	3.5	-0.8	2.7	2.4
Namoi	5.2	50.8		24.6	32.8	-10.5	-35.0	5.0	-10.8	19.7	5.4	15.1	15.5
Central West	13.4	47.5		91.8	51.3	-0.2	1.3	1.4	0.6	11.8	7.2	8.9	10.0
Maranoa Balonne	-0.8	-0.2	-1.6	-0.6	-0.6	5.7	-1.8	-0.1	2.4	-0.1	0.0	-0.1	-0.1
Border Rivers Gwydir	-52.7	-242.1		-394.0	-239.3	10.3	-10.1	9.6	6.0	-48.3	-30.5	-37.8	-41.6
Western	0.0	0.0	0.0	0.0	0.0	50,890.4	-43.8	48,928.3	40,114.9		0.0	0.0	0.0
Lachlan						2.1	-12.6	6.2	0.4				
Murrumbidgee	74.4	553.5	360.6	665.5	548.5	1.3	-7.6	-0.4	-1.0	51.0	-2.1	69.2	45.8
North East						-2.7	-14.4	-1.1	-4.6				
Murray 1						0.4	-0.7	0.3	0.2				
Goulburn Broken Res (GB)						1.0	-0.1	1.0	0.8				
Murray Valley (GB)	-58.4	-536.7	-536.7	-644.0	-568.9	-1.3	-6.1	0.0	-1.8	-19.0	17.6	-94.7	-34.4
Shepparton (GB)		12.7	12.7	15.2	13.4	1.0	-0.5	1.4	0.8	5.1	-0.1	-6.7	0.5
Central Goulburn (GB)						-11.3	-36.0	-7.6	-15.1				
Murray 2	35.7	246.7	164.2	299.7	246.1	-1.0	-7.9	0.4	-2.0	22.2	-0.6	31.1	20.3
North Central Res (NC)						0.0	-0.4	0.1	-0.1				
Campaspe (NC)						-0.2	-0.9	0.9	0.0				
Rochester (NC)						-12.0	-90.4	-5.4	-25.7				
Pyramid Boort (NC)						-0.2	-0.3	0.2	-0.1				
Torrumbarry (NC)	-21.7	-194.9	-194.9	-233.9	-206.6	-14.6	-78.7	-6.8	-25.1	-4.7	6.9	-34.0	-11.1
Murray 3	-5.6	-39.4	-48.6	-51.6	-44.9	-6.2	-100.1	-2.5	-23.9	-3.1	1.6	-6.0	-3.0
Nyah Tresco (M)						-26.1	-287.4	-14.0	-74.7				
Merbein Robinvale (M)						-5.7	-267.5	-0.9	-56.6				
Mildura (M)						-4.3	-443.5	1.8	-90.3				
Mallee Res (M)						-2.8	-846.1	4.6	-169.2				
Lower Murray Darling						6.9	-81.9	8.4	-10.4				
SA MDB						8.3	-347.0	12.9	-61.4				
Adelaide						8.3	-347.0	12.9	-61.4				
ALL	-12.1	137.7	-395.1	33.8	0.0					81.8	29.5	-22.2	40.2
Coorong		-161.3	1,005.5	-367.0	10.4	19.0	-10,802	24.4	-2,143.6				

A positive number means Base bigger than Ex-post Inflows (i.e. greater area, more water used, more profit in the Base solution) and the alternative applies.

Blank values indicate no differences. Except for Salinity (EC) as salinity in the ex-post is a range direct comparison in this manner is misleading.

Table 10: Base Model – Ex-post Inflow Model: Area of Irrigated Production ('000 HA)

Catchment	Citrus	Grapes	Stone Fruit	Pome Fruit	Vegetables	Cotton Crops	Cotton Wet	Rice PSN	Rice Wet	Other Grains	Sheep Wheat	Dairy	Sheep /Beef	TOTAL
Condamine						5.8	-5.8							0.0
Border Rivers QLD						66.4	11.2			-83.6				-6.0
Warrego Paroo						0.3	2.2			1.9				4.4
Namoi						9.1	-3.9							5.2
Central West						7.5	5.9							13.4
Maranoa Balonne					0.0	0.3	0.0			-1.1				-0.8
Border Rivers Gwydir						-34.6	-18.1							-52.7
Western												0.0		0.0
Lachlan														
Murrumbidgee								74.2	0.2					74.4
North East														
Murray 1														
Goulburn Broken Res (GB)														
Murray Valley (GB)												-58.4		-58.4
Shepparton (GB)														
Central Goulburn (GB)														
Murray 2								35.2	0.4					35.7
North Central Res (NC)														
Campaspe (NC)														
Rochester (NC)														
Pyramid Boort (NC)														
Torrumbarry (NC)												-21.7		-21.7
Murray 3						2.1		-5.2				-2.4		-5.6
Nyah Tresco (M)														
Merbein Robinvale (M)														
Mildura (M)														
Mallee Res (M)														
Lower Murray Darling														
SA MDB														
TOTAL	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**56.9**	**-8.5**	**104.2**	**0.6**	**-82.8**	**0.0**	**-82.5**	**0.0**	**-12.1**

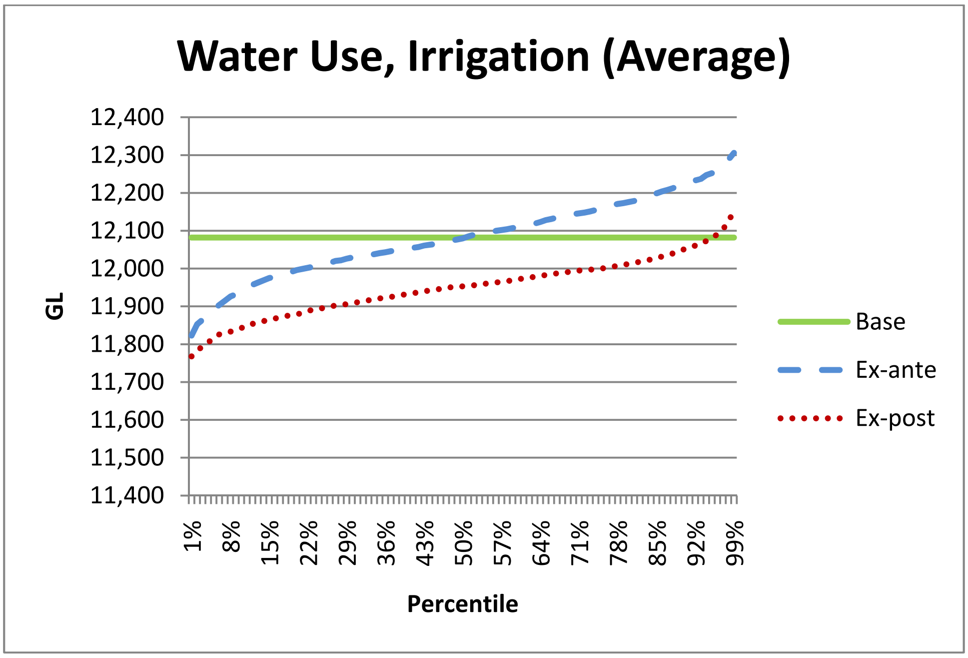
A positive number means Base bigger than Ex-post Inflows (i.e. greater area in the Base solution) and the alternative applies. Blank values indicate no differences. Here we see that there has been a move away from cotton crops to cotton wet. Cotton wet only irrigates in the wet state of nature. While the change in the Border-Rivers QLD away from cotton to grains uses more water in the drought state but frees up water to flow down the system in the normal and wet states of nature.

Examining the Description of State Inputs

Determining the impact of uncertain water requirements for a known output in a given state provides with greater issues to consider. The direct comparison of the Base model and the Ex-post optimisation (Base – Ex-post) are in Table 11 (resource use) and Table 12 (area). Here we see that overall area of irrigation has decreased by approximately 57,000 Ha, the total water used for irrigation has reduced (95%) of the time (see Figure 6). Overall salinity values are lower and the average economic return in the ex-post optimisation is $137 million less than the Base solution.

Here not only do we notice the resource constraints (remaining water flow in the catchment) potentially being reached (ex-ante) as in the examination of the state description but we also get a fundamental downward shift in water use (ex-post) to counter this as illustrated in Figure 6. This shift is caused as producers now have to build flexibility into their water supply to prevent perennial commodities being without water (ex-post).

Figure 6 Reduction in Irrigation Demand



As the demand for water during the drought is the key driver for commodity selection we find a shift away from commodities that require water in all states of nature (Rice PSN) to commodities that don't use water in the drought state of nature (flexible cotton production) or in fact only use water in wet years (Cotton Wet, Rice Wet), see Table 12. This production shift then explains Figure 7 where more water flows to the Coorong in the drought state of nature.

Figure 7 Flows to the Coorong, Drought State

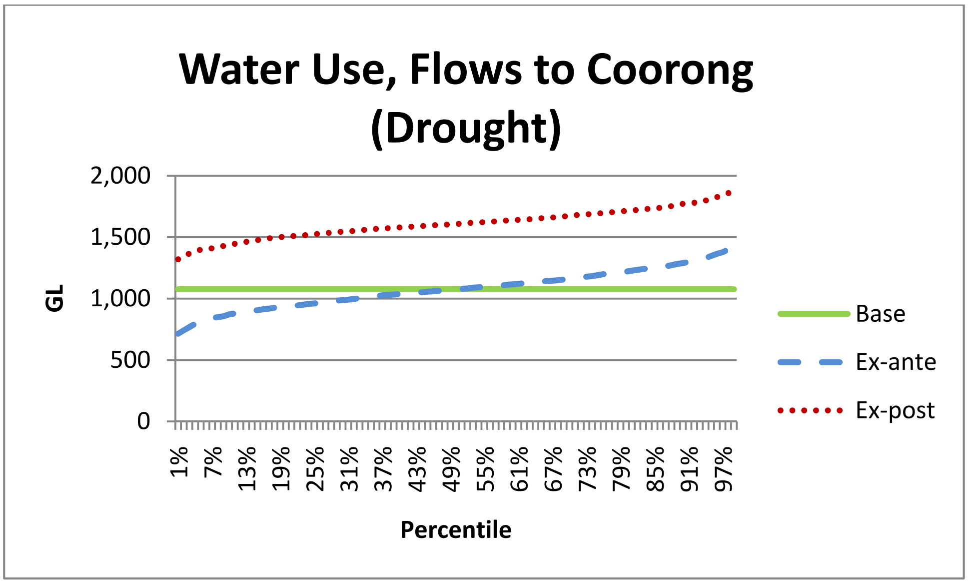


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Table 11 Base Model – Ex-post Inputs Model: Resource Allocation & Return

Catchment	Irrigated Area ('000 Ha)	Water Use (GL)				Salt (EC)				Economic Return ($'m)			
		Normal	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**
Condamine	3.4	102.9	1.7	-1.0	51.5					14.8	8.2	12.9	12.9
Border Rivers QLD	28.5	62.7	-1.1	158.1	78.5					20.6	9.6	15.5	16.8
Warrego Paroo	7.9	11.9	6.2	30.9	16.5					4.0	1.6	3.5	3.4
Namoi	25.4	133.3	-5.5	156.5	112.5					63.8	17.5	60.0	53.4
Central West	23.1	118.0	1.8	136.5	100.3					24.6	16.6	21.5	22.0
Maranoa Balonne	-0.8	-12.9	-2.4	-15.5	-11.6	15.7	0.1	-0.1	7.8	0.3	0.0	0.3	0.2
Border Rivers Gwydir	-17.7	-202.2	-0.5	-162.7	-150.0	3.2	0.0	6.0	3.4	-22.3	-17.4	-21.6	-21.1
Western		0.4	0.8	1.2	0.8	54,821.4	0.0	54,293.1	43,698.6	0.0	0.0	0.0	0.0
Lachlan	-32.8	-302.3	-159.8	-335.1	-283.7					-14.5	3.2	-22.2	-13.3
Murrumbidgee	48.5	131.9	1,027.9	268.0	351.9					70.5	-34.5	116.0	63.2
North East		0.8	-2.7	16.3	4.8					0.0	0.1	-0.4	-0.1
Murray 1		-5.9	-35.8	10.2	-7.0					0.1	0.9	-0.3	0.2
Goulburn Broken Res (GB)	0.6	9.9	11.1	6.4	9.1					0.0	-0.3	1.0	0.2
Murray Valley (GB)	-12.1	-137.6	-118.3	-236.5	-163.4	-0.1	-1.3	0.5	-0.2	-14.3	3.4	-4.1	-7.7
Shepparton (GB)	1.3	17.9	55.5	38.4	31.6	0.2	0.3	0.1	0.2	2.6	-1.4	-1.5	0.6
Central Goulburn (GB)		27.8	-12.5	55.6	28.1	-2.5	-3.2	-2.7	-2.7	-0.7	0.3	-1.4	-0.7
Murray 2	46.6	334.1	307.1	406.1	350.3	-0.1	-1.4	0.5	-0.2	42.8	-1.1	52.1	36.8
North Central Res (NC)		1.3	-1.3	2.1	1.1					0.0	0.0	-0.1	0.0
Campaspe (NC)		-0.1	-0.1	-0.8	-0.3	0.1	-0.1	0.1	0.0	0.0	0.0	0.0	0.0
Rochester (NC)		0.0	-0.1	0.0	0.0	5.0	14.8	3.7	6.6	0.0	0.0	0.0	0.0
Pyramid Boort (NC)		0.0	0.5	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Torrumbarry (NC)	-24.8	-205.0	-231.4	-274.8	-231.2	7.3	14.8	6.0	8.4	-5.8	8.1	-38.6	-12.9
Murray 3	-40.7	-236.1	-156.7	-264.2	-228.6	5.8	17.0	4.9	7.8	-19.1	3.9	-25.2	-16.3
Nyah Tresco (M)		5.5	19.3	-30.5	-2.6	-3.0	-25.0	-2.0	-7.1	-0.1	-0.5	0.8	0.1
Merbein Robinvale (M)		5.3	2.3	4.2	4.4	-11.4	103.2	-6.2	13.1	-0.1	-0.1	-0.1	-0.1
Mildura (M)		-0.7	-1.2	28.7	8.0	-17.8	165.0	-10.1	21.1	0.0	0.0	-0.7	-0.2
Mallee Res (M)		5.5	-6.1	-7.0	-0.6	-24.7	258.4	-12.4	35.6	-0.1	0.2	0.2	0.0
Lower Murray Darling		7.3	1.7	-10.6	0.8	0.1	15.2	7.9	5.5	-0.2	0.0	0.3	0.0
SA MDB	0.6	-8.7	62.2	59.6	25.9	-19.6	85.8	-4.7	5.9	0.7	-1.4	-0.4	-0.1
Adelaide						-19.6	85.8	-4.7	5.9				
ALL	57.0	-135.0	762.5	40.3	97.1					167.5	16.9	167.3	137.3
Coorong		178.6	-606.4	45.3	-18.4	-37.0	312.7	-4.9	42.6				

A positive number means Base bigger than Ex-post Inputs (i.e. greater area, more water used, more profit in the Base solution) and the alternative applies.

Blank values indicate no differences. Except for Salinity (EC) as salinity in the ex-post is a range direct comparison in this manner is misleading.

Table 12: Base Model – Ex-post Inputs Model: Area of Irrigated Production ('000 HA)

Catchment	Citrus	Grapes	Stone Fruit	Pome Fruit	Vegetables	Cotton Crops	Cotton Wet	Rice PSN	Rice Wet	Other Grains	Sheep Wheat	Dairy	Sheep /Beef	TOTAL
Condamine						20.0	-16.6			0.0				3.4
Border Rivers QLD						16.3	11.2			1.0				28.5
Warrego Paroo						1.7	2.2			4.1				7.9
Namoi						25.6	-0.2							25.4
Central West						22.8	0.2							23.1
Maranoa Balonne					0.0	0.4	0.0			-1.2				-0.8
Border Rivers Gwydir						-28.3	10.6							-17.7
Western														
Lachlan								-32.8						-32.8
Murrumbidgee						-117.8		188.8	-22.5					48.5
North East														
Murray 1														
Goulburn Broken Res (GB)												0.6		0.6
Murray Valley (GB)												-12.1		-12.1
Shepparton (GB)												1.3		1.3
Central Goulburn (GB)														
Murray 2						-13.6		76.7	-16.5					46.6
North Central Res (NC)														
Campaspe (NC)														
Rochester (NC)														
Pyramid Boort (NC)														
Torrumbarry (NC)												-24.8		-24.8
Murray 3						1.2		-54.6				12.7		-40.7
Nyah Tresco (M)														
Merbein Robinvale (M)														
Mildura (M)														
Mallee Res (M)														
Lower Murray Darling														
SA MDB												0.6		0.6
TOTAL	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-71.7**	**7.4**	**178.0**	**-39.0**	**3.9**	**0.0**	**-21.7**	**0.0**	**57.0**

Examining the Description of State Outputs

Determining the impact of uncertain yield outcomes from management decisions does not have as a dramatic impact on the base solution as either the description of the state or the inputs required by state of nature. The direct comparison of the Base model and the Ex-post optimisation (Base – Ex-post) are in Table 13 (resource use) and Table 14 (area). Here we see that overall area of irrigation has decreased by approximately 5,000 Ha, the total water used for irrigation has not changed on average but there has been a reallocation of water to the normal state with less water being used in the drought and wet states of nature. Overall salinity values have increased and the economic return is described in Figure 8. Here we quickly see as in Figure 5 the ex-post optimisation negates the lows and highs associated with the ex-ante simulation.

Figure 8 Impact of Uncertain State Outputs

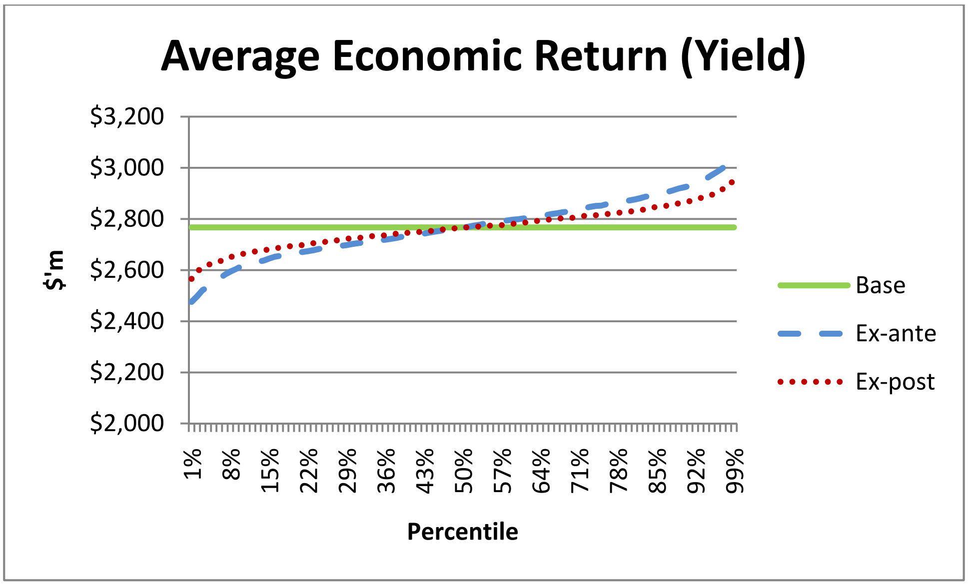

Table 13 Base Model – Ex-post Yield Model: Resource Allocation & Return

Catchment	Irrigated Area ('000 Ha)	Water Use (GL)				Salt (EC)				Economic Return ($'m)			
		Normal	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**	**Normal**	**Drought**	**Wet**	**Average**
Condamine										15.1	-22.6	-10.4	-0.1
Border Rivers QLD	1.5	0.0	3.5	0.0	0.7					-2.5	-8.7	57.8	14.3
Warrego Paroo	0.0		0.1		0.0					-0.2	-1.4	1.2	0.0
Namoi	0.0									-3.4	-10.6	95.2	24.8
Central West										9.0	-22.5	54.1	16.2
Maranoa Balonne	1.7	0.5	3.3	1.2	1.3					22.6	4.9	-34.5	1.9
Border Rivers Gwydir	-0.2	-0.5		-1.2	-0.6	0.0	0.1		0.0	-11.6	3.9	-43.8	-18.2
Western						0.0	0.8	0.0	0.2	-0.4	0.3	0.0	-0.1
Lachlan										2.8	5.3	26.1	10.3
Murrumbidgee	-4.9	-68.5		-52.8	-50.1					18.2	-41.2	265.7	80.6
North East										12.3	4.5	-1.4	6.6
Murray 1										3.1	4.4	-9.9	-0.5
Goulburn Broken Res (GB)	0.0	-0.3	-0.3	-0.4	-0.3					0.0	4.4	-4.7	-0.5
Murray Valley (GB)	-20.4	-185.4	-185.4	-222.4	-196.5					-2.7	-18.6	13.9	-0.9
Shepparton (GB)		-0.2	-0.2	-0.2	-0.2	0.0	0.0	0.0	0.0	-4.9	-14.8	-8.7	-8.0
Central Goulburn (GB)						-4.3	-8.4	-3.7	-5.0	-2.2	-57.6	-54.1	-28.9
Murray 2	-5.4	-68.6		-57.8	-51.6					-25.1	-19.3	35.1	-5.9
North Central Res (NC)										0.2	0.2	-0.7	-0.1
Campaspe (NC)										0.4	-1.0	2.6	0.8
Rochester (NC)						-8.6	-20.2	-6.6	-10.3	-0.2	0.4	-1.1	-0.3
Pyramid Boort (NC)										0.8	1.8	-1.6	0.3
Torrumbarry (NC)	-2.3	-20.5	-20.5	-24.6	-21.7	-10.7	-19.2	-8.5	-11.7	-0.9	1.6	-3.5	-1.2
Murray 3	6.4	51.5	20.4	57.6	47.1	-6.4	-20.2	-4.8	-8.7	2.2	-2.2	-2.2	0.0
Nyah Tresco (M)						-13.4	-37.6	-10.4	-17.4	3.6	13.5	-5.2	2.9
Merbein Robinvale (M)						-16.4	-47.8	-11.5	-21.2	-3.9	-2.6	13.6	1.6
Mildura (M)						-22.3	-74.8	-15.4	-30.7	-11.8	-15.1	-3.7	-10.0
Mallee Res (M)						-28.3	-122.6	-19.3	-44.5	-3.5	5.5	-10.8	-3.9
Lower Murray Darling						-17.0	-8.8	-12.0	-13.9	6.5	-15.1	10.5	3.4
SA MDB	28.5	256.6	256.6	307.9	272.0	-33.7	-39.7	-22.6	-31.6	36.7	69.0	91.0	59.4
Adelaide						-33.7	-39.7	-22.6	-31.6				
ALL	5.0	-35.4	77.5	7.3	0.0					60.3	-133.7	470.4	144.5
Coorong		6.7	-78.9	-21.6	-18.9	-18.8	37.5	-11.3	-5.3				

A positive number means Base bigger than Ex-post Inputs (i.e. greater area, more water used, more profit in the Base solution) and the alternative applies.

Blank values indicate no differences. Except for Salinity (EC) as salinity in the ex-post is a range direct comparison in this manner is misleading.

Table 14: Base Model – Ex-post Yield Model: Area of Irrigated Production ('000 HA)

Catchment	Citrus	Grapes	Stone Fruit	Pome Fruit	Vegetables	Cotton Crops	Cotton Wet	Rice PSN	Rice Wet	Other Grains	Sheep Wheat	Dairy	Sheep /Beef	TOTAL
Condamine														
Border Rivers QLD						-0.7	-0.1			2.3				1.5
Warrego Paroo						0.0	0.0			0.1				0.0
Namoi														
Central West														
Maranoa Balonne					0.0	-0.6	0.0			2.2				1.7
Border Rivers Gwydir						-0.1	-0.1							-0.2
Western														
Lachlan														
Murrumbidgee						-6.7			1.8					-4.9
North East														
Murray 1														
Goulburn Broken Res (GB)														
Murray Valley (GB)												-20.4		-20.4
Shepparton (GB)														
Central Goulburn (GB)														
Murray 2						-6.7			1.3					-5.4
North Central Res (NC)														
Campaspe (NC)														
Rochester (NC)														
Pyramid Boort (NC)														
Torrumbarry (NC)												-2.3		-2.3
Murray 3						2.1		4.2				0.1		6.4
Nyah Tresco (M)														
Merbein Robinvale (M)														
Mildura (M)														
Mallee Res (M)														
Lower Murray Darling														
SA MDB												28.5		28.5
TOTAL	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-12.6**	**-0.2**	**4.2**	**3.0**	**4.6**	**0.0**	**5.9**	**0.0**	**5.0**

Discussion

Both the ex-ante and ex-post approach provide a number of interesting outcomes that need to be considered when analysing any result from the base model which negates any uncertainty within the state description. Principally amongst these is the resource constraints as due to their inherent variability, especially water either as a state description or input requirement, may lead to an over allocation of resources. The combination of simulation and optimisation within a state contingent framework offers us number of interesting insights into how decision makers learn through time and adaptation strategies they may employ.

The shape and function of the distribution used to determine the randomness within each state will ultimately influence on decision on which commodities to invest in. Issues such as heat stress stifles yield or increases water use to a point where MC>MR will quickly alter capital investment in technology and is a critical component missing in this analysis.

Policy makers are starting to grapple with not only climate variability but climate change as well. Under climatic change previous information available to decision makers may no longer be as relevant. As the mean, median and variance of climate variables alter (i.e. rainfall, temperature, evapotranspiration, humidity and carbon dioxide) what are the consequences for irrigation in the Basin? What will happen to landscape heterogeneity of water flows, commodity yields and pest distributions from changes in climate? State contingent analysis of risk and uncertainty is one tool that may help disentangle the riddle if used correctly, as it allows for the separation of environmental factors and the management response to the given stimuli.

Understanding the true relationship between climatic variability, uncertainty and change relationship between the temporal and spatial aspects of rainfall and corresponding runoff is critical for the long term future of water allocations within the basin. The total supply of water will need to cater for environmental, agricultural and social needs. The movement towards more variability rainfall will force the reallocation of resources away from commodities requiring consistent annual supplies of water firstly by reducing the area of high water demanding perennial horticulture and move the water towards more flexible production systems that can adapt towards increasing variable allocations.

Where to from here & timelines:

This paper proposes a four step solution to modelling climate change impacts of pests and irrigation adaption. Firstly This paper will follow the same approach outlined in (Quiggin, John. et al. In Press) and compare two climate scenarios (450 and 550) identified in the Garnaut report for two time periods, 2050 and 2100 to the existing baseline climate. Secondly CLIMEX a model that determines the spatial suitability of species will be used to model heliothis distribution and density. The existing heliothis CLIMEX model by (Myron P & Michael J 2005) will be adapted for this purpose. Thirdly from these results a new gross margin budgets will be developed in line with the economic thresholds and the pay-off matrix that will examine changes to management costs and yields. Fourthly the RSMG water allocation model described in (Adamson, Mallawaarachchi & Quiggin 2007) will be adapted to include a stochastic representation of heliothis regional impact on production systems and the model will be run with and without climate change options to heliothis to determine if heliothis may have future impacts on irrigation resource allocation.

The proposed work schedule for this PhD is in Table 15.

Table 15 Proposed Work Schedule

Date	
Aug 2010	Revert work back to the simpler 21 catchment model
Sept 2010	CLIMEX Runs for Heliothis Completed
Nov 2010	Economic thresholds (ET)
Dec 2010	Modification of model for Heliothis and ET
Feb 2011	Paper ready for Melbourne AARES on Heliothis and Climate Change
April 2011	Finalisation of stochastic functions in the model
Aug 2011	Finalisation of all model simulation
Dec 2011	Thesis ready for submission

Summary

The thesis topic raises a number of issues concerning the impact of climate change and pests for irrigation investment. Heliothis has been chosen as it is a major pest that has had significant scientific investigation and it has already forced resource allocation (i.e. cotton out of the Ord). While the use of CLIMEX to determine climate change impacts on species distribution has already had investigation however, actually using economic thresholds in the analysis has not yet been undertaken correctly. Using the scenarios from the Garnaut Climate Change Review provides a solid grounding for policy review. The use of a stochastic representation of states, their input requirements and their output has already been illustrated to provide items for clarification in the RSMG Water Allocation Model especially in regards to the water flow constraints. There is still significant work in identifying the best stochastic function to deal with the complex issue of fat tails in the drought state of nature within the state contingent framework.

Publications and talks during the PhD process:

Published Journal Articles:

Zalucki, MP, Adamson, D & Furlong, MJ (2009), The future of IPM: whither or wither?, The Australian Journal of Entomology, vol. 48, pp. 85-96

Completed Reports:

Mallawaarachchi, T., Adamson, D., Chambers, S. And Schrobback, P. (2010), Economics Analysis of Diversion Options for the Murray-Darling Basin Plan: Returns to irrigation under reduced water availability: A commissioned study for the Murray Darling Basin Authority, RSMG, UQ Business School Commercial, The University of Queensland.

Adamson, D., Chambers, S., Quiggin, J. and Schrobback; P. (2009), Confidential report completed, at the current time no details can be given.

Adamson, D., & Quiggin, J. (2008), Climate Change & Irrigation in Renmark, Consultancy report developed for ARUP Consulting, September 2008, The University of Queensland.

ARUP (2009), Renmark Irrigation Trust Irrigation Modernisation Project, Stage 2 - Assessing the Current Situation & Predicting the Future, ARUP Pty Ltd, Adelaide.

Journal Articles and Book Chapters in Press

Quiggin, J, Adamson, D, Chambers, S & Schrobback, P (In Press), 'Climate change, mitigation and adaptation: the case of the Murray-Darling Basin in Australia', Canadian Journal of Agricultural Economics, vol. Special Issue “Water in the 21st Century”, manuscript No. SP10-08.

Adamson, D 2010, 'Quarantine and Food Safety', Ch x, in J Kelsey (ed.), No Ordinary Deal: Unmasking Free Trade and the Trans-Pacific Partnership Deal.

Submitted Journal Articles

Schrobback; P. Adamson, D., and Quiggin, J. (xxxx) ‘Turning Water into Carbon: Carbon sequestration and water flow in the Murray-Darling Basin’, paper submitted to Environmental and Resource Economics.

Papers under development

Adamson, D., Zalucki, MP, and Furlong, MJ () Climate change impacts and Heliothis

Proposed Papers

Adamson, D, Brown, C. and Quiggin J. 'Introducing Stochastic States

Adamson, Quiggin, Pannell, State contingent analysis versus Discrete Stochastic Programming:

Talks Given

Adamson (2010), 'Climate variability and irrigation investment in the Murray Darling Basin, AARES, Adelaide, 10-12 February, 2010.

Adamson (2009), 'Climate Impacts and Irrigation Investment in the Murray–Darling Basin, E-CReW, Charles Sturt University, Bathurst 3-4 November 2009.

Adamson (2009) 'From Apples to Zoonosis: Unpeeling the Myopia of Analysis', Invited Speaker to AARES Annual Symposium: Invasive Species and Biosecurity, 10-11 September 2009

Adamson (2009), 'SPS the Safe Sex of Trade', Invited Speaker to Fulbright Symposia: US-Australia Free Trade Agreement: the last five years, the next five years, 24-25 August 2009, Canberra

Adamson (2009), 'Modelling Regional Irrigation Impacts of Climate Change', Invited Speaker to PRSCO Conference, 19-22 July, 2009, Gold Coast

Adamson (2009), TPP & Agriculture, Invited speaker to TPP Colloquium 22-23 June 2009, University of Auckland, New Zealand.

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