THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Restoring the Balance:
Water Reform & the Murray-Darling Basin Plan

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A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2014

School of Agriculture and Food Sciences

Abstract

The Murray-Darling Basin Plan (Basin Plan) is tasked with improving welfare by internalizing the negative externalities derived from the past 130 years of policy development which has over allocated water resources to irrigators in Australia's Murray-Darling Basin (MDB). As water scarcity increases these welfare losses are compounded. For example, during the Millennium Drought water could not be delivered to urban communities, critical environmental flow was not provided, and the typically elastic private demand for water transformed into an inelastic demand function exposing capital investment to climatic risk.

The Basin Plan utilizes the common property concept to internalize externalities by reducing the quantity of the privately held (irrigators) surface rights by 3,200 gigalitres (GL) and transferring these rights to an environmental steward. By restoring environmental flows, externalities are internalized as the environment gets a share, and the 'quality' of the water resources improves thus increasing economic welfare. To facilitate this transfer, an adjustment package has been designed that provides a net increase in groundwater and allocates over $10 billion in funding, split between two programs to purchase surface water. Some $3.1 billion has been allocated to purchase 1,500GL of property rights from irrigators while $5.8 billion has been allocated to gain 1,700GL by subsidizing investments in water use efficiency programs.

Water resources in the MDB are highly variable and are characterized by floods and droughts events. This variability is expected to increase as climate change is forecast to reduce supply and increase the variability of rainfall. Consequently the long run success of the Basin Plan will be dependent on the efficiency of these alternative strategies to source surface water for the environment subject to this inherent variability and increasing uncertainty.

By representing uncertainty about water supply within alternative states of nature (drought, wet and normal), the state-contingent approach (SCA) provides the capacity to examine how irrigators adapt to both the state of nature and alternative policy settings by changing inputs, production systems and transition towards opportunistically irrigating in favorable states of nature. By being able to model output and decision maker uncertainty separately,

the SCA approach then overcomes the limitations of other decision making approaches. By setting up the Basin Plan as an optimization question, the net change in national welfare from irrigation can be examined against the assurance that the Basin Plan objectives are achieved (i.e. policy constraints of minimum flow targets and quality improvements). This provides the capacity to illustrate how alternative climate scenarios could alter the possibility of meeting the water reform objectives listed in the Basin Plan.

The analysis reveals that: the increased groundwater access creates inequitable wealth for irrigators and shifts climate risk towards the environment; that the optimal bundle of property rights the environmental steward needs to purchase changes by spatial location and property right description in response to the climate scenarios; that irrigators could be locked in unsustainable levels of debt by investing in water-use efficiency technology; and the current design of the Basin Plan may not deliver lasting welfare benefits.

Declaration by Author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications During Candidature

Journal Articles

Adamson, D & Loch, A 2014, 'Possible negative sustainability impacts from ‘gold-plating’ infrastructure', Agricultural Water Management, vol. 145, Nov., pp. 134-44,

Loch, A, Adamson, D & Mallawaarachchi, T 2014, 'Role of hydrology and economics in water management policy under increasing uncertainty', Journal of Hydrology, vol. 518, Part A, pp. 5-16.

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Publications Included in This Thesis

Journal Articles

1. Adamson, D & Loch, A 2014, 'Possible negative sustainability impacts from ‘gold-plating’ infrastructure', Agricultural Water Management, vol. 145, no. Nov,pp.134-44.

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Loch, A.	Designed paper (10%) Wrote and edited paper (50%)

2. Loch, A, Adamson, D & Mallawaarachchi, T 2014, 'Role of hydrology and economics in water management policy under increasing uncertainty', Journal of Hydrology, vol. 518, Part A, pp. 5-16.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed paper (30%) Wrote the edited the paper (30%)
Loch, A.	Designed paper (40%) Wrote and edited paper (40%)
Mallawaarachchi, T.	Designed paper (30%) Wrote the edited the paper (30%)

3. Schrobback, P, Adamson, D & Quiggin, J 2011, 'Turning water into carbon: Carbon sequestration and water flow in the Murray–Darling Basin', Environmental and Resource Economics, vol. 49, no. 1, pp. 23-45.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed paper (40%) Modified model (30%) Model analysis (30%) Wrote the edited the paper (20%)
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4. Quiggin, J, Adamson, D, Chambers, S & Schrobback, P 2010, 'Climate change, uncertainty, and adaptation: The case of irrigated agriculture in the Murray–Darling Basin in Australia', Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, vol. 58, no. 4, pp. 531-54.

Contributor	Statement of contribution
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Chambers, S.	Designed paper (5%) Wrote the edited the paper (50%)
Schrobback, P.	Designed paper (5%) Wrote the edited the paper (5%)

Book

1. Quiggin, J, Adamson, D & Quiggin, D (eds) 2014, Carbon Pricing: Early Experience and Future Prospects, Edward Elgar Publishing, Cheltenham, UK and Northampton, MA, USA.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Editor role (85%)
Quiggin, J.	Editor role (10%)
Quiggin, D.	Editor role (5%)

Book Chapters

1. Loch, A, Wheeler, SA & Adamson, D 2014, 'People versus place in Australia's Murray-Darling Basin: Balancing economic, social ecosystem and community outcomes', in H Milber & V Squires (eds), River Basin Management in the Twenty-First Century: People and Place, CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 275-303.

Contributor	Statement of contribution
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2. Adamson, D, Zalucki, MP & Furlong, MJ 2014, 'Pesticides and IPM: Practice, practicality and policy in Australia', in R Pershin & D Pimentel (eds), Integrated Pest Management- Experiences with Implementation, Global Overview, vol. 4, Springer, pp 387-411.

Contributor	Statement of contribution
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Conference & Working Papers

1. Mallawaarachchi, T, Adamson, D, Goesch, T & Sanders, O 2010, 'Adapting to a water-limited environment: some observations and insights from the Murray-Darling Basin', paper presented to 54th Annual AARES National Conference, Adelaide, Australia, 10-12 February.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed paper (20%) Wrote the edited the paper (10%)
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Sanders, O.	Designed paper (5%) Wrote the edited the paper (5%)

Reports & Submissions

1. Adamson, D, Quiggin, J & Quiggin, D 2011, Water supply variability & Sustainable Diversions Limits: Issues to Consider in Developing the Murray-Darling Basin Plan, RSMG, School of Economics, The University of Queensland, Brisbane, Australia.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed report (90%) Modified model & analysis (100%) Wrote the edited the report (90%)
Quiggin, J.	Designed report (10%) Wrote and edited report (5%)
Quiggin, D.	Edited report (5%)

2. Mallawaarachchi, T, Adamson, D, Schrobback, P & Quiggin, J 2011, An economic analysis of the Impact of the National Water Initiative on the capacity and resilience of Australia's water management regime, RSMG, School of Economics, The University of Queensland, St Lucia, Brisbane, Australia.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed report (20%) Data collection (20%) Modified model & analysis (100%) Case study analysis (50%) Wrote the edited the report (5%)
Mallawaarachchi, T.	Designed report (75%) Case study analysis (50%) Wrote the edited the report (90%)
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Quiggin, J.	Designed report (5%) Wrote and edited report (5%)

3. Mallawaarachchi, T, Adamson, D, Chambers, S & Schrobback, P 2010, Economic analysis of diversion options for the Murray-Darling Basin Plan: returns to irrigators under reduced water availability: A commissioned study for the Murray-Darling Basin Authority prepared by the University of Queensland, Risk and Sustainable Management Group, The University of Queensland, Brisbane, Australia.

Contributor	Statement of contribution
Adamson, D. (Candidate)	Designed report (10%) Modified model & analysis (20%) Wrote the edited the report (5%)
Mallawaarachchi, T.	Designed report (90%) Modified model & analysis (80%) Wrote the edited the report (90%)
Chambers, S.	Data collection (50%) Report editing (2.5%)
Schrobback, P.	Data collection (50%) Report editing (2.5%)

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Apart from those authors directly acknowledged in the previous section there are no contributions by others.

Statement of Parts of the Thesis Submitted to Qualify for the Award of Another Degree

None

Acknowledgements

Well what do I say? I initially thought this was going to be a straightforward exercise and it has turned into one almighty slog especially over the last 6 or so months. I now understand why the acknowledgements are important, as it is not so much as thanking people for their input but to those who provided the capacity to allow the PhD to be undertaken and completed.

Right up and at the start I must thank both of my supervisors. Associate Professor Colin Brown has provided the perfect foil to Professor John Quiggin. Colin has been meticulous in the detail, he has challenged my statements, thinking, and my interpretation of the results thus driving me to deliver far greater clarity and refinement in my communication. Colin has also ensured that everything has progressed smoothly as possible when dealing with this part-time PhD student and bureaucracy. John has provided the capacity for this thesis to be written, the overarching critique of the approach, and the stick when required. Working with John has allowed me to experience a world of thinking that I didn't know existed and it has been a privilege. Hopefully this supervisory combination of big pictures teamed with fine detail has managed to make me deliver something of interest in the following pages and to both of you, thank you again for this opportunity to grow and develop.

I would also like to thank Nancy Wallace for her encouragement, kind words and ability to remind me and others that I was actually enrolled in a PhD and that I should be doing something about it. This reminds me, Dan Quiggin you had better finish your PhD as well and thanks for the help during this process.

Thanks must go to Dr Thilak Mallawaarachchi who has been my counterpart for a decade. Thilak has tried his best to teach me a number of things and I'm slowly getting there, I think? His way of implanting ideas into my brain, so that I would spend the next 20 minutes thinking and then needing to discuss the outcomes with him, did lead to a number of very long but profitable conversations.

To DECRA, Ian Davey, Dr Adam Loch speaks, it has been a hell of a lot of fun since meeting you at E-CREW. In 2013 we completed two papers, one book chapter, went to the

Belpasso Summer School, and that basically gave me the kick I needed to finish this PhD. Yes, I can now get to that other stuff on the desk.

To my other assorted co-authors and counterparts, thank you for the inputs, feedback (positive and negative), good luck to what you are completing now, and no doubt I'll see you around the traps sooner or later for a good debrief.

I would also like to thank my PhD thesis reviewers. They both provided some excellent critique that has improved the quality of the thesis.

To my parents, brother, sister, in-laws and other associated relatives, thank you for your encouragement and support during this time. Who knows if the thesis is accepted I might even attend the ceremony so we can all get together and celebrate.

To my family, Cathy, Rachel and Pippy (it's the dog), thank you for giving me the time, support and love to get this done. It has taken a lot of effort, long days, weekends and holidays for me to get to this stage and you have had to sacrifice a lot to provide me with this opportunity. Hopefully I can make it up to you over a long life together, love David.

Keywords

state-contingent analysis, water, property rights, Murray-Darling Basin, climate change

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 140201, Agricultural Economics, 45%

ANZSRC code: 140205, Environment and Resource Economics, 45%

ANZSRC code: 140104, Microeconomic Theory, 10%

Fields of Research (FoR) Classification

FoR code: 1402, Applied Economics, 100%

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List of Abbreviations Used in the Thesis

Abbreviation	Definition
$	Dollar
%	Percentage
ABARE	Australian Bureau of Agricultural Resource Economics
ABARES	Australian Bureau of Agricultural Resource Economics and Sciences (formerly ABARE)
ABS	Australian Bureau of Statistics
ACCC	Australian Competition and Consumer Commission
ACT	Australian Capital Territory
Basin Plan	Murray-Darling Basin Plan
BOM	Bureau of Meteorology
CDL	Current Diversion Limits
CEWH	Commonwealth Environmental Water Holder (now CEWO)
CEWO	Commonwealth Environmental Water Office (formerly CEWH)
CGE	Computerized general equilibrium
CMR	Catchment Management Regions
CO_2	Carbon dioxide
COAG	Council of Australian Governments
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DSEWPC	Department of Sustainability Environment Water Population and Communities (formerly SEWPaC)
EC	Electrical conductivity
GL	Gigalitres (=1,000 ML)
GVAP	Gross value of agricultural product
GVIAP	Gross value of irrigated agricultural product
Ha	Hectares
IIO	Irrigation Infrastructure Operators
IPCC	Intergovernmental Panel on Climate Change
km	Kilometers (=1,000 meters)
MDB	Murray-Darling Basin
MDBA	Murray-Darling Basin Authority

List of Abbreviations Used in the Thesis (continued)

Abbreviation	Definition
MDBC	Murray-Darling Basin Commission
ML	Megalitre (=one million liters)
m	Meters
mm	Millimeters
NMDB	Northern Murray-Darling Basin
NSW	New South Wales
NWC	National Water Commission
ppm	Parts per million
QLD	Queensland
RtB	Return the Balance
SA	South Australia
SA MDB	South Australian Murray-Darling Basin, a catchment in the MDB
SDL	Sustainable Diversion Limit
SEWPaC	Department of Sustainability, Environment, Water, Population and Communities
SIS	Salinity interception schemes
SMDB	Southern Murray-Darling Basin
SOI	Southern Oscillation Index
SRWUIP	Sustainable Rural Water Use and Infrastructure Program
T	Tons (1,000 kilograms)
VIC	Victoria

Foreword

It's no secret that I was employed by Professor John Quiggin in 2004 to help build the original version of the Murray-Darling Basin model that this thesis uses. Professor Quiggin planned to use that model to illustrate the benefits of a state-contingent approach to risk and uncertainty to help understand water property rights in the Murray-Darling Basin (MDB). Originally my input was rather like a dodgy apprentice builder working for an architect who had a vision but an incomplete set of plans. Let's just say building the initial model was an experience and I promised myself I would not quit until the model was completed.

During this time Dr Thilak Mallawaarachchi provided an enormous amount of encouragement, support, sanity, solutions and error checking during the initial build. Effectively Thilak was the builder that guided me through my apprenticeship as the model was constructed in two different platforms. By building a version of the model in GAMS (by Thilak) and a version in Excel (me) not only allowed for rigorous error checking but confirmed the initial findings. The combination of John's vision, the quality assurance by Thilak and my role as the goffer enabled the original model to be presented at the Australian Agricultural and Resource Economics Society Conference in February 2005. Well for the rest of 2005 and 2006 I spent my time playing with the model like a back yard car enthusiast stripping down the model and rebuilding it time after time to either fix (tweak) assumptions, update the data or add new features.

Sometime during that process I thought the model might have some merits. When the model was used in conjunction with Australian Bureau of Agricultural Resource Economics to review the increasing severity of drought and examine climate change impacts, it provided a ready understanding of what was occurring in the MDB. These results contrasted findings in other models. Primarily the results we provided suggested that irrigators would not increase investment in perennial horticultural activities as water scarcity increased.

The 2005 to 2007 phase in the Millennium Drought was a critical time and to put it simply all known rules in the MDB broke. Suddenly the prior information in regards to the value of water property rights, the reliability of those rights, water trade and environmental degradation and management responses became obsolete.

When the true value of high security entitlements in the Southern MDB was revealed, a combination of events occurred, Firstly, in the short run, the scarcity of water supply created price spikes in the water market as perennials producers rushed into the water market to protect their capital assets. This is a classic supply response to an inelastic commodity. Secondly, in the medium term, farmers' practices adjusted by switching inputs and outputs changing the nature of demand and supply in the water market. Those producers with annual commodities realized the opportunity cost of production and increased the volume of water in the market. For example, dairy producers changed their input mix by selling water and purchasing in supplements Perennial producers adapted their management strategies by reducing the area irrigated; purchasing water at different times in the season; using carry-over provision in dams; and altering existing water management systems. Consequently this change in demand and supply reduced the price of water in the allocation market in subsequent seasons.

The work undertaken in 2006 had predicted these adaptations and impacts. My faith in the model is and continues to be based on the critical assumption of the state-contingent approach that producers respond to states of nature and adapt by changing inputs and outputs. Ultimately the thesis highlights that further work on using a stochastic description of either water inputs or the states of nature is required to highlight imperfect state identification, learning and adaptation. Or as Goldstein and Gigerenzer (2002) discuss, decision makers rapidly adapt via utilizing 'ecologically rational' cognitive heuristics. In other words decision makers rapidly adapt to new information, they might not always get it right but they cannot be modeled as passive to change. This work is now on-going as this thesis morphed into a review of the Basin Plan.

The significant shift in social perception allowed the 2007 Water Act to appear overnight causing a massive public injection of cash into research allowing for new data to become available for modeling through time. About the same time another major shift in Australian public policy began, the Garnaut Climate Change Review.

In late 2007 John and the Risk and Sustainable Management Group (RSMG) were commissioned to work on the Garnaut Climate Change Review and the report was delivered in 2008. During this time I got thinking about the approach we were using. Centrally the results from the Garnaut model, illustrated that significant shifts in how water was used occurred when the frequency of the states of nature changed, so what if our data was wrong? So I started asking stupid questions and struggled to comprehend a couple of papers. My issue was simply this. What would happen if I didn't use discrete values in the model we built? And more importantly does it matter? It was about this time that Professor Quiggin suggested I do a PhD and Associate Professor Colin Brown agreed to be my principal supervisor, so here I am.

However, doing a part-time PhD over the same time as the Water Act was in process has proven interesting. A central part of the Water Act has been the development of the Basin Plan. The Basin Plan is designed to restore the balance between all consumptive water users in the MDB. While juggling the PhD and working on a range of issues, the RSMG held its first workshop on the MDB asking if we finally got it right. Well a lot has changed since the first Basin Plan was released and working for and debating the Basin Plan has shaped the final plan for the thesis.

The thesis has evolved as I have been allowed to explore, make mistakes and become aware of how much I still don't know. I have found this a rather humbling experience for a number of reasons and I think I now understand just how much of an opportunity I have been given to do this PhD.

1. INTRODUCTION

On 27 February 2014, after seven years of developing a strategy to deal with the problems associated with the over allocation of water to irrigators in Australia's Murray-Darling Basin (MDB), the implementation phase of the Murray-Darling Basin Plan (Basin Plan) was signed by all parties (Vidot 2014). There remains a small window of opportunity to influence both the final legislative agreement and the implementation review before Australia misallocates a large proportion of the $13 billion in public funds set aside to deal with water reform in the MDB. The Basin Plan proposes that the environment needs an additional 3,200 gigalitres (GL) and this will be sourced by purchasing 1,500GL water property rights from irrigators and obtaining 1,700GL of water via investing in water–use efficiency infrastructure programs. This thesis will argue that in light of water supply uncertainty derived from climatic variability and climate change, infrastructure investment programs will lock resources back into inefficient production areas and possibly create a legacy of rural debt and failure that may take generations to overcome, while providing little in the way of social and environmental benefits.

The thesis obtains these results by utilizing the state-contingent analysis approach to risk and uncertainty (SCA), developed by Chambers and Quiggin (2000) to help overcome the "profession[s] ... weak position to offer definitive policy analyses in matters related to risk" (Just & Pope 2003, p. 1255). It is SCA's ability to represent a decision maker's choice to optimally reallocate resources by type, place, date and by state of nature (Rasmussen 2003) that allows for risk strategies to be explored. By describing the future uncertainty about water supply within three alternative states of nature (i.e. droughts, normal and wet years) the decision maker's response to risk signals can then be examined by: altering the description of each state of nature; and the frequency of each state occurring. Policy can then be evaluated, to examine how: individuals' respond to risk from changes to their consumptive share of water resources (Basin Plan): and the threats climate change poses to all water users and policy outcomes. By reviewing how policy outcomes for all water users may be impacted by climate change, a discussion can then occur about how water reform policies could be adapted to maximize the benefits from public funding.

This thesis adapts the SCA model of the MDB developed by Adamson, Mallawaarachchi and Quiggin (2007) to examine, how the Basin Plan may change economic welfare, environmental flows and water quality. The model simplifies the definition of water quality as a measurement of salinity, which is the externality derived from consumptive water use. The partial-equilibrium model can determine the optimal private use of water resources, subject to a set of biophysical and policy constraints in the MDB via having a direct flow network that tracks changes to water and salt. The model has been adapted to provide a constrained economic welfare analysis of policy by examining the Basin Plan's twin metrics of success: a minimum water flow to the sea; and a specified salinity target.

The thesis examines each of the Basin Plan's approaches to obtain water for the environment separately and then tests how sensitive the solutions are to a changing climate. Firstly, as the Basin Plan utilizes the common property concept to negate externalities (Ciriacy-Wantrup & Bishop 1975; Ostrom 1990) the model has been adapted to incorporate Randall's (1975) arguments that changes in welfare can be determined from the reallocation of conjunctive water property rights to examine the private response to alternative institutional settings. The Basin Plan's intuitional settings are a new sustainable diversion limit (SDL), improved water quality and providing a minimum water flow target. This thesis then examines how the Commonwealth Environmental Water Office (CEWO) could purchase an optimal bundle of alternative water property rights (or portfolio) to achieve the Basin Plan objectives. This entitlement portfolio consists of a spatially explicit set of alternative water rights structures that must provide sufficient water security for the CEWO. Additionally the thesis also explores the mixed signals provided to irrigators from the Basin Plan's conjunctive (surface and groundwater) SDL to examine if the net change in the water available creates intra- and inter-generational wealth transfers.

The second Basin Plan implementation strategy involves subsidizing the cost of adopting water-use efficient technology to obtain water for the environment. The analysis examines the impact subsidized capital may have on irrigators investment patterns and the corresponding outcomes that investment has on future water security and water quality for all water users.

The analyses findings suggest that although the Basin Plan's design allows for water reform, that would benefit society, the Basin Plan's implementation strategy is flawed. The results suggests that the Basin Plan's implementation provides a direct short term wealth transfer to irrigators from purchasing used water, increasing ground water consumption and subsidizing capital investments. Additionally, by incentivizing water-use efficiency programs, water may become locked into regions and perennial commodities, which could reduce future water trading opportunities to mitigate drought risks. This loss of water trade to manage drought coupled with increased capital investment, could then expose irrigators, the urban community and environment to irreversible consequences if climate change reduces future water security.

1.1 **Background**

Over 14% of the Australian continent is located in the MDB (MacDonald & Young 2001) and it spans 13^{o} of latitude (24^{o} to 37^{o} South) and 13^{o} longitude (138^{o} to 151° East) (Thoms, Rayburg & Neave 2008) (Figure 1-1). The MDB includes large parts of New South Wales (NSW), Queensland (QLD), South Australia (SA), Victoria (VIC) and the entire Australian Capital Territory (ACT). The MDB has two major rivers systems: the Darling River, which runs north to south; and the Murray River including its significant tributary the Murrumbidgee River, which runs east to west. The length of the MDB river system is estimated to be 440,000 km and it facilities water delivery to agricultural and urban users, and to ecological assets (Murray-Darling Basin Authority (MDBA) 2010c).

The MDB conjunctive water resources are derived from surface runoff, groundwater aquifers and inter-basin transfers and these assets are expected to satisfy the increasing cultural, social, economic and environmental demands placed on it. However, like many watersheds in the world, water resources are currently over-allocated towards irrigation activities. This imbalanced water share, combined with the negative externalities derived from its overutilisation, reduces welfare (Connell & Grafton 2008; Crase 2008). With an incomplete specification of known and future conjunctive water resources supply, uncertainty exists over the total volume required to rebalance the system. The MDB has the second most variable inflows into a river basin in the world (McMahon & Finlayson 1991). Climate change is expected to reduce MDB wide river inflows and increase the severity and duration of drought events (Adamson, Mallawaarachchi & Quiggin 2009).

Over 10% of Australia's population resides within the MDB (Australian Bureau of Statistics (ABS) 2008c) and a further 5% of the Australian population (ABS 2010a), living in the City of Adelaide (Adelaide), relies on the MDB to supplement their potable water supplies.

There are over 30,000 wetlands in the MDB (MDBA 2010c), of which 16 are identified by the Ramsar Convention of Wetlands[1] as wetlands of international importance.

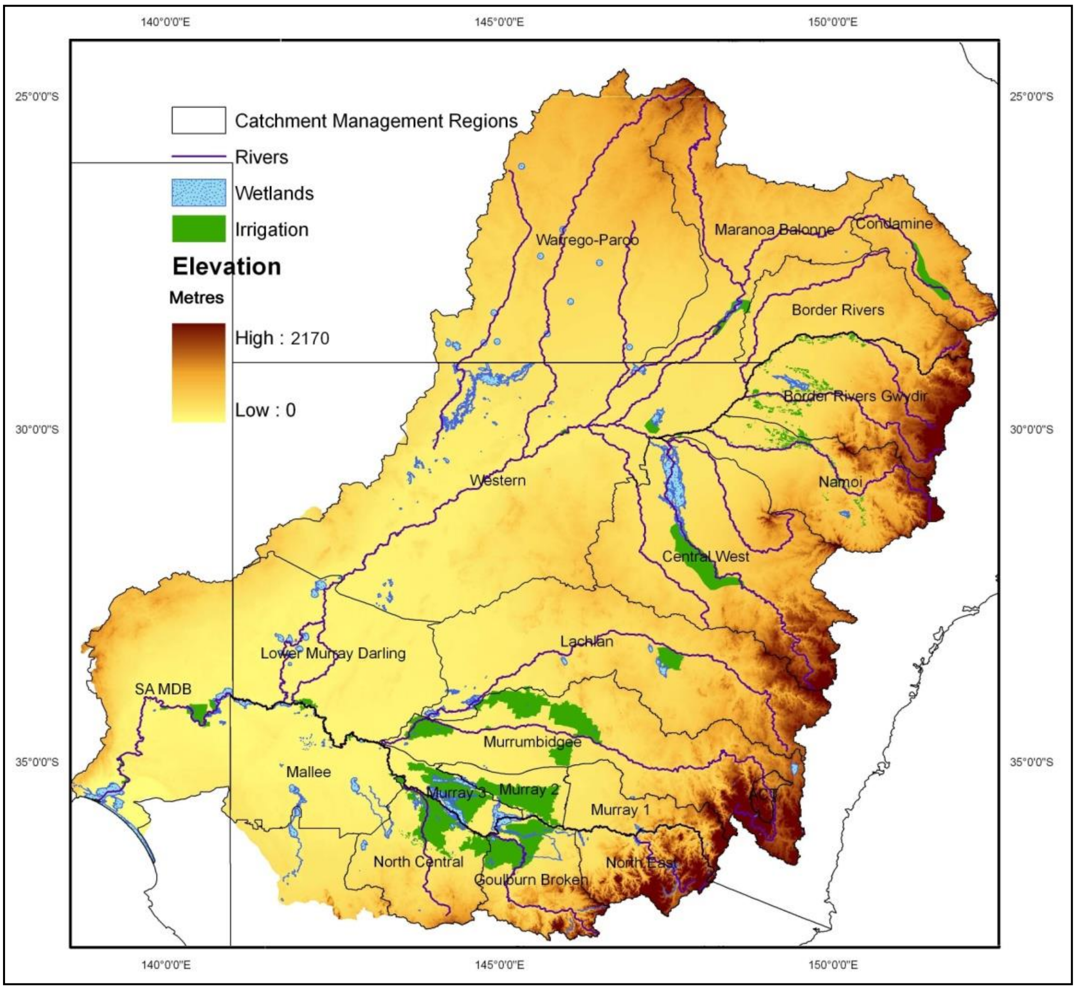

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Figure 1-1 The Murray-Darling Basin[2]

Over 41% of the nation's irrigators live in the MDB and approximately 65% of all irrigated land in Australia is located in the MDB. Approximately 80% of the MDB is dedicated to agricultural activity and the MDB produces between 35-40% of Australia's gross value of agricultural production (GVAP) and one-third of the GVAP is derived from irrigation activities, which utilize only 2% of the arable land in the MDB (ABS 2008c, 2008d). The level of irrigated output has been achieved by diverting over 60% of the MDB's conjunctive

[1] http://www.bom.gov.au/water/nwa/2010/mdb/context/physical

[2] Source Quiggin et al. (2008)

water resources[3] to irrigators. However, this level of water consumption has proven to be unsustainable and has reduced economic welfare in the MDB and Australia. Policies have continued to be designed to incentivize private water use and have failed to internalize the externalities derived from the use of that water. Consequently in response to the design and implementation of policy, private and public resource have been misallocated, water quality has been degraded and environmental assets have been irreversibly damaged or lost (Davidson 1969; Quiggin 1988).

The Basin Plan enacts the ‘common good’ approach (Ciriacy-Wantrup & Bishop 1975) to deal with externalities, by transferring a proportion of over allocated private water rights away from irrigators to be managed by a ‘public trustee’ tasked with improving the ‘quality’ (e.g. lower salinity) of the resource base. The Basin Plan proposes that the environment needs 3,200GL of surface water to rebalance the system (MDBA 2012c) and that the water will be managed by the CEWO. The Basin Plan stipulates two clear objectives for the environmental water: improve the ‘quality’ of water resources that are used for the urban community in Adelaide and provide a minimum flow to the mouth of the river (MDBA 2012c).

The 2007 Water Act (Commonwealth of Australia 2008) prohibits the compulsory acquisition of water from irrigators but rather utilizes two programs which are designed to encourage irrigators participation in the Basin Plan. The first is a direct market purchase of water entitlements rights via a $3.1 billion program known as Restoring the Balance (RtB). The second subsidizes off-farm storage/delivery infrastructure upgrades and on-farm irrigation water use efficiency strategies via a $5.8 billion program known as Sustainable Rural Water Use and Infrastructure Program (SRWUIP) (Crase & O'Keefe 2009). The final Basin Plan provided an additional $1.7 billion to purchasing additional water rights and addressing water delivery constraints in the MDB, and extended the final implementation timeline by five years to 2024 (MDBA 2012c).

1.2 The Economic Questions

The prior section raises four questions that require further investigation. First, what were the driving forces over the past 130 years of water resource development that have

[3] See Section 2.4 for a detailed description of the groundwater, surface supplies and inter-basins transfers that define the conjunctive water supply in the MDB.

encouraged an over-allocation of water resources to MDB irrigators? Second, how have policies and management evolved to deal with climate impacts on water supply security, and what relevant lessons are available for the Basin Plan? Third, how do the alternative Basin Plan implementation strategies alter intra and intergenerational welfare? Fourth, can the public funding allocated to the Basin Plan be justified?

1.2.1 Water Reform

Water reform in MDB has been locked in an on-going economic and policy debate. The combination of floods and prolonged droughts in the MDB, continues to expose policies that inadequately incorporate risk and uncertainty (Khan 2008). This policy design failure has encouraged private and public resource misallocation. The economic failure of policy occurs when there is a: misrepresentation how water scarcity transitions the production demand curve for water from elastic to inelastic (Randall 1981); misunderstanding how irrigators adapt to water supply shocks (Adamson, Mallawaarachchi & Quiggin 2009) ; and an inability to deal with the complex nature of trade-offs between all water users over time (Rostow 1959).

Section 2 will present an argument that for the last 130 years of State and Federal policy development within the MDB there has been political “romanticism and recklessness” (Cummins & Watson 2012) that has attempted to drought proof agriculture to promote regional economic development. By assuming that water supply is always available, the development of high input irrigation production systems is expected to facilitate regional economic development (Davidson 1969). In this political game, each State entity (see Section 2.1) has then attempted to maximize their economic gains by over-allocating water within their allocative boundaries.

This State based game comes at the expense of other States, requiring the Federal Government to appease disputes between all players (Cummins & Watson 2012). This approach to water resource development reduces welfare for: the inter- and intra-state based irrigators; dryland producers (Davidson 1969); the environment (Roshier et al. 2001; Young & McColl 2009); and rural communities (Buikstra et al. 2010). Thus the cycle of water reform has created the negative externalities that affect all water users within the MDB (Keating et al. 2002; MDBA 2011a; Quiggin 1988). However, welfare loss is not just contained within the physical boundaries of the MDB but to all who value its very existence (MacDonald et al. 2011).

This State Government based approach to water development in the MDB is evident over the first three stages of water resource development (i.e. exploration; expansion; and maturity, see Table 2-1). This development approach encouraged a continual policy reform cycle in the 1980's. Each new reform was sometimes correlated with an incremental step towards the problem resolution. However, each policy initiative created a legacy of obstacles and transaction costs (Mallawaarachchi et al. 2012) that inhibited swift and real reform (Cummins & Watson 2012). As these incremental policy steps failed to deal with the fundamental problem of resource misallocation, the duration between each new reform process contracted. This continual reform cycle entailed a new round of public expenditure to deal with the private and public transaction cost legacy.

The Millennium Drought (Section 3) forced a reevaluation of all known data about water security when the State based approach nearly caused the collapse of the entire river system (Chiew et al. 2011; Heberger 2011). In 2007, the Water Act (Commonwealth of Australia 2008) provided an alternative approach to deal with the water reform process, when the Federal Government assumed responsibility for developing a Basin Plan (Section 4). to 'restore the balance' between all water users (MDBA 2012c). This then shifted the State based welfare maximization process to a national welfare objective. The Basin Plan is the key component of the latest stage of water resource development , the 'contractionary' stage (Cummins & Watson 2012).

1.2.2 Water Policy Failure & Water Security

While the efficiency and transparency (Connell & Grafton 2011) of the institutions and governance frameworks (Crase, Dollery & O'Keefe 2011) enacted to overcome the legacy of past water reform vital for a successful Basin Plan, that is not the thesis focus. This thesis is a quantitative analysis of the Basin Plan's goals and implementation strategies and utilizes a state-contingent approach in an attempt to overcome the following applied policy problems.

> 'A problem with the advancement of applied policy advice on water markets is that theoretical models and empirical analysis usually bog down when faced with the

three scourges of quantitative institutional analysis: nonconvexity, irreversibility, and uncertainty' (Howitt 1995a, p. 1192).

In Sections 2, 3 and 4 it will be debated that Howitt's three modeling limitations of, non-convexity, irreversibility, and uncertainty, are derived from inadequately incorporating known and future water resource variability when allocating property rights. By providing the CEWO with a water entitlement portfolio, the Basin Plan then overcomes past allocation problems where the environment only received the residual flow once water had been allocated to the property right owners (Brennan & Scoccimarro 1999). As discussed in Section 2.2, the cycle of drought and floods in the MDB creates constraints and opportunities necessitating irrigator adaption (Adamson, Mallawaarachchi & Quiggin 2007). This adaptation occurs when the demand for water transitions from elastic (no scarcity) to inelastic (scarcity) which then creates non-convexity (Lee & Howitt 1996; Randall 1981). In periods of extreme drought, this non-convexity creates irreversible losses for all water users, especially for those users without defined rights. Complicating the policy problems with water scarcity is that climate change is expected to alter both the known mean and variance of the water resources available (Adamson, Mallawaarachchi & Quiggin 2007, 2009; Quiggin et al. 2010; Schrobback, Adamson & Quiggin 2011).

For the Basin Plan to provide lasting economic, social and environmental benefits, policy makers must explore both the variation of known supply, the future threats to that supply and gain an understanding of how water resources are used by all users so that the economic outcomes from changes to supply can be examined. Climate change is expected to have deleterious impacts on the MDBs future water supply (Garnaut Climate Change Review 2008; Gleick & Heberger 2012; Kingwell 2006). By understanding how water users adapted to past extreme drought events, policy can be designed to enhance the flexibility required to cope with future adverse climatic futures. By encapsulating a goal of resilience into the policy approach, ideally water reform should lead to a long run outcome that preserves the welfare gains derived from well allocated public expenditure (Chugh & Bazerman 2007; Grant & Quiggin 2013b).

1.2.3 Changes to Economic Welfare

For maximum economic benefits, policies designed to address natural resource externalities must have clear goals (Pannell 2009). Clear goals provide a mechanism to evaluate the achievement of a policy, but goals alone do not provide the necessary information about how a policy should be implemented. Decision makers need to: understand the inherent risks and uncertainty in achieving an outcome; the economic costs and benefits involved in adopting and implementing a policy; provide justification on why compensation is or was not offered; and be aware of how policy can change welfare in society.

The economic foundation behind the Basin Plan is the common property approach. The establishment of common property helps to internalizes externalities by improving the ‘quality’ of the resource base (i.e. water). Improvements in water quality are possible by transferring property rights away from private users and giving them to an institution who manages those water resources for the common good (Quiggin 1988). As property rights allow for neoclassical and institutional approaches to be adopted, a “…constrained utility maximization [approach] to predict individual and aggregate responses to existing and alternative structures of incentives” (Randall 1975, p. 731) can then be adopted.

This thesis divides water users and the utility they gain from water access into three groups: producers who gain economic rents from irrigating; society whose utility increases when water quality improves; and the environmental[4] gains accrued by improving the resilience of the ecosystem (see Section 2.6). By treating water as an input for social, environmental and economic activities the trade-offs between users can be modeled within Randall’s constrained profit maximization approach. Where profit is the net return from irrigation activates and the constraints are defined by the Basin Plan’s SDL limits and the policy goals of water quality and environmental flows. This approach then merges Randall’s framework for evaluating welfare changes derived from a reallocation of water resources and Pannell’s requirements to judge policy successes.

By setting up the constrained welfare maximization question in its dual form, the solution then can optimize economic returns from irrigation while achieving the Basin Plan objectives[5] at least cost. The scarcity value of water resource can be determined from alternative Basin Plan settings for the SDL, environmental flows and water quality goals.

[4] For this thesis, it is assumed that as quality of the environment improves, an associated increase in social welfare occurs. It is also assumed that everyone in society wants environmental quality to increase.
[5] To improve readability, the term Basin Plan objectives refers to the objectives that are listed in the Basin Plan.

Additionally by treating environmental gains and water quality as constraints (i.e. minimum acceptable standards), there is no need to monetize the environmental or social gains from improvements in water. Rather the joint-value of environmental gains and improvements can be determined by the dual value derived from the optimal solution. It is assumed that these standards (i.e. environmental gains and water quality) are consistent with social attitudes.

However, the above approach does not deal with the methodological problems associated with optimizing irrigation production under water scarcity. As discussed, to create lasting water policy, the risk and uncertainties associated with water supply need to be accounted for and debate over the appropriate way to internalize these problems into models poses two key issues.

> "First, there is a need to refine our understanding of the role of risk/uncertainty in agriculture. For example, the current prospects for climate change raise the issue of how farmers will react to it. This can involve "rare events" that have not been observed before. It creates two significant challenges: (1) rare events are difficult to evaluate empirically (suggesting an important role for "ambiguity"); and (2) the question is raised of the way decision-makers (including farmers) should adjust their management strategies in response to this new uncertainty.
>
> Second, our understanding of the farmers' decision-making process remains incomplete. While farm management studies have typically taken this issue seriously, difficulties in dealing with heterogeneous managerial abilities have limited our progress. The recent interest in behavioral economics appears to provide new opportunities for further explorations of this topic" (Chavas, Chambers & Pope 2010, p. 370).

The Millennium Drought highlighted how irrigators adapted to extreme drought conditions that were outside prior experiences (see Section 3). The modeling work by Adamson, Mallawaarachchi and Quiggin (2007; 2009) has illustrated that the state-contingent approach (Chambers & Quiggin 2000) provides a behavioral economic approach to deal with allocating resources under uncertainty about water supply.

The thesis then deals with the reallocation of property rights via a common property approach to maximize net social welfare described as changes from maximizing rent from irrigation subject to the institution goals of the Basin Plan. In such a manner, the trade-offs between economic rents and achieving social and environmental goals occurs at least cost via the use of dual optimization. By optimizing water resource allocation utilizing the SCA model (section 1.3.1), producers' adaption in respect to both alternative policy settings and the availability of water by state of nature can be determined. This approach then allows for climate change uncertainty to be expressed via changes to mean expected runoff availability in normal, drought and wet states of nature but also the frequency in which alternative states occur. This provides the capacity to compare and contrast the RtB and the SRWUIP to provide recommendations for the Basin Plan.

1.3 **Identifying & Dealing With Gaps in the Basin Plan Analysis Literature**

A significant number of economic analyses, discussions and theoretical analyses of the Basin Plan and climate change impacts on the MDB have been conducted prior to its formulation. Grafton and Jiang (2010) and Connor (2011) provide a literature review of the models and approaches that have been used to analyze water resources and the Murray-Darling Basin Plan and Grafton and Jiang (2011) provide a comparative study of outcomes from alternative models used to examine the MDB. The MDBA (2011e) details the economic models used, the analysis undertaken and the surveys conducted that provided economic guidance during the development of the Basin Plan. Many of these studies are discussed throughout the thesis but only the major studies and models are presented here to illustrate the remaining research gaps.

1.3.1 RSMG Model of the MDB (State-Contingent Analysis)

The SCA model developed by Adamson, Mallawaarachchi and Quiggin (2007) provided an example of how the SCA could be used to help bridge the gaps in understanding how decision makers adapted under uncertainty, which was an ongoing debate (Just & Pope 2003; Rasmussen 2003) and remains so (Chavas, Chambers & Pope 2010). The state-contingent theory is outlined in Section 5, the model is presented in Section 6 and the data sets used are documented in Section 7.

The model has been used to examine the possible impact a changing climate could have on MDB water resources (Adamson, Mallawaarachchi & Quiggin 2009). That paper examined how negative impacts on water resources could be modeled as either an increased frequency of droughts or a mean reduction in water availability across all states of nature. The authors argued that the greatest threat to irrigator's economic viability was not from a proportional reduction in water supply but from adverse water states (i.e. droughts) becoming more frequent. While irrigation adaption to steady reduction in the supply of water may be achieved with a proportional reduction in the area irrigated, as the frequency of droughts increases, irrigators are forced to adopt new production and management strategies to minimize the risk of negative returns on capital.

This thesis adds to the literature on climate change threats to water resources in the MDB from the addition of two papers (see Section 4.4). First Quiggin et al. (2010) used projected climate change scenarios (Garnaut Climate Change Review 2008) on water resources at catchment and not a basin scale to illustrate the spatial threats to water supply. Quiggin et al argued by adopting a carbon mitigation policy, the future private and public costs of adapting to the known and unknown consequences of climate change are lowered.

Second, Schrobback, Adamson and Quiggin (2011) provided an example of the unintentional consequences that could occur from investing in carbon mitigation policies. The paper argued that carbon farming incentives could result in large scale timber plantations being established. Due to their extensive root systems, trees have the capacity to intercept greater volumes of water as it flows across the surface, than many other landscapes. Additionally deep rooted trees can extract directly from the water table when required. Therefore plantations in high rainfall zones reduce the quantity of water available for downstream users. This unintended outcome from policy thereby creates a second round negative shock to water resources, and a substantial reallocation of wealth from irrigators to subsidized plantation owners. The lessons learnt from Quiggin et al. (2010) and Schrobback, Adamson and Quiggin (2011) have been incorporated into the SCA model used to evaluate the Basin Plan.

1.3.2 ABARES Two Stage Modeling Process (Positive Mathematical Programing & Computerized General Equilibrium)

Australian Bureau of Agricultural Resource Economics and Sciences (ABARES) utilizes a two state process for analyzing water issues in the MDB. The first stage is a partial-equilibrium model titled 'Water Trade Model' (Hafi, Thorpe & Foster 2009) to allocate resources. The 'Water Trade Models' results are subsequently used by a computerized general equilibrium (CGE) model titled 'AusRegion Model' (ABARES 2003). This process provides the capacity to optimize the interaction of water and landscape transformation within the MDB and then determine the wider economic impacts from changes to the landscape. ABARES provided input throughout the development of the Basin Plan and their last published contribution examined the 2011 version of the Basin Plan (ABARES 2011).

The 'Water Trade Model' has a directed flow network that can model water use on a monthly basis and determines salinity impacts yield. The model then mimics management decisions on how irrigation resources would be used based upon response to soil moisture via concave production functions. This is a traditional approach to representing climatic variability impacts on production (Section 5.3). To prevent large scale landscape transformation into and away from irrigation, the model provides "'smooth' responses to shocks as compared to sharp responses in models with Leontief production technology [such as (Adamson, Mallawaarachchi & Quiggin 2007)]" (Hafi, Thorpe & Foster 2009, p. 3).

The 'smooth' responses are an application of the positive mathematical programming (PMP) approach (Howitt 1995a, 1995b). The PMP approach relies on calibrating the production functions according to what has occurred in the past. All commodity areas then reduce proportionally rather than just the "least profitable activities responding" (Hafi, Thorpe & Foster 2009, p. 3). A smooth reduction in all commodity areas then implies that all resources are currently optimally allocated. Alternatively, this suggests that the current level of externalities is also both optimal and socially acceptable, which implies there is no economic or policy problem.

Doole and Marsh (2014) reviewed the use of PMP analysis when examining policy changes in response to nitrification problems in New Zealand's dairy industry. By critically analyzing the PMP process Doole and Marsh (2014) determined that "arbitrary results…[which are]…potentially implausibl[e]...[occur when the model is] applied outside of the calibrated baseline". These findings are consistent with the Heckelei and Britz (2000) and Heckelei and Wolff (2003) reviews of PMP which identified that PMP assumes that the current baseline is optimal. As discussed by Randall (1975), when the current returns from property rights are used in policy analysis, a bias towards the status-quo occurs devaluing the benefits from reallocating rights. This misunderstanding of the true economic return from water property rights, can be associated with methodological approaches that either use gross margin returns and not economic returns thereby failing to understand on-farm capital costs (Brennan 2006), or from using subsidized infrastructure costs (Davidson 1969).

This poses complex questions for the methodological approach of the partial equilibrium approach. If the calibration bias towards existing land allocations prevents the model from adapting to large shocks, then can it provide meaningful analysis once the baseline alters? As discussed, water supply during the Millennium Drought was outside known parameters (Section 3.3), and climate change is expected to alter both the mean and variance of rainfall. Climate change will then alter the profitability and feasibility of alternative production systems (Adams 1989; Adams et al. 1988; Crimp et al. 2008). If PMP is then used to predict climate change shocks, how can it be used to predict producer responses towards these new climate settings? The value of PMP results within the ABARES CGE framework must then be questioned.

1.3.3 TERM-H_20 (Computerized General Equilibrium)

TERM-H_2O is a CGE model which provides a detailed analysis of how a policy impacts on the local economy (e.g. labor, investment, income) flows through to macro-economic indicators (Dixon, Rimmer & Wittwer 2011). This second round analysis then helps illustrate the regional costs and benefits from policy changes, providing insight and clarity to the policy discussion. However, TERM-H_2O was not designed to model water flow but rather it uses predefined water volumes to be used in a given area.

It is the capacity of the partial-equilibrium model, described in Section 6, to represent water as it travels through the Basin that provides additional information. The dynamic constrained optimization nature of the model allows for the relationship between land use and water flow to be determined. Consequently, the model can be used to examine how climate change could alter the models optimal investment patterns. By holding land allocation constants and using the predicted climate change impacts to water supply, the model can examine if there is sufficient water flowing in a catchment to prevent the environmental and social constraints from being violated. These alternative approaches have been used to compliment other analyses where the SCA model has provided input into TERM-H_2O.

Consequently while the analysis work by Dixon, Rimmer and Wittwer (2011) and Wittwer and Dixon (2013) can determine the wider economic benefits of the implementation program and can reveal the wealth transfer to irrigators, TERM-H_2O cannot determine the bio-physical limitations of the implementation program.

1.3.4 The Analytical Gaps of the Basin Plan

The analysis of the Basin Plan and the evaluations of the Basin Plan implementation strategies have: concentrated on the practical limitations of the alternative approaches of the plan (Connell & Grafton 2008; Crase, Dollery & O’Keefe 2011; Crase, O'Keefe & Dollery 2009; Grafton 2007); discussed the cost-effectiveness of the alternative approaches to restore environmental flows (Grafton 2010), including alternative strategies utilizing trade solutions (Connor et al. 2013; Loch, Bjornlund & McIver 2011); provided strategies for optimizing the approaches but no solution (Crase & Gawne 2011; House of Representatives 2011); analyzed their second round impacts without optimizing on-farm and environmental water use (Dixon, Rimmer & Wittwer 2011; Hone et al. 2010; Wittwer & Dixon 2013), evaluated the farmer’s perceptions of the strategies (Cheesman & Wheeler 2012; Wheeler & Cheesman 2013); examined the impact that a general reduction in water availability would have on irrigated production rather than a specific implementation strategy (Grafton, Chu, et al. 2011; Grafton & Jiang 2011); discussed the limitations of the models used to evaluate the Basin Plan (Connor 2011); provided the analysis for an individual catchment (Qureshi et al. 2010) examined the RtB using a single water property right (Qureshi et al. 2010) or derived a solution for the Southern Murray-Darling Basin (SMDB) only (Qureshi et al. 2007). The partial-equilibrium analyses utilised the tradational stochastic function approach to modeling risk and uncertainty (see Section 5).

For example, the ABARES process has been used to investigate the impact of a uniform RtB (i.e. buy-back) strategy in the MDB. That analysis examined three buy-back strategies where 5, 6 and 7% of surface entitlements were purchased uniformly across the Basin. Critically, by assuming that all areas lose a fixed percentage of entitlements, the approach failed to determine efficiency gains from an optimal portfolio of entitlements for the environment. Consequently, the model was developed assuming that irrigators will passively adapt to the loss of water by reducing the area irrigated, despite predicting an increase in the price paid for water. Additionally the report suggests that the SRWUIP will "assist in offsetting the effect of the buyback on water availability for irrigation" (Hone et al. 2010, p. 61). However, they miss a logical question, if water-use efficiency is beneficial for irrigators, why do they need a subsidy?

Both Crase and Gawne (2011) and Nguyen, Goesch and Gooday (2013) furthered the discussion of why an optimal RtB strategy is required to maximize the environmental benefits, the authors do not derive a solution. The closest effort to optimize the RtB was by Qureshi et al. (2010) who also investigated the role of water-use efficiency to obtain environmental water for single catchment. Quershi et al.'s analysis used a single water entitlement with a constant reliability.

Therefore research has not examined how the Basin Plan's environmental targets could be achieved from purchasing an optimal portfolio of water property rights[6]. This thesis then updates and adapts Adamson (2012) to provide an optimal entitlements purchase strategy for the CEWO with fixed budgetary limits. By using the above constrained optimization approach, the model can be used to determine how CEWO's portfolio would have to be adapted to deal with alternative climate settings, while still obtaining the water needed to achieve the Basin Plan's goals

No quantitative analysis exists, of how the SRWUIP could be optimized to achieve the final Basin Plan's goals. However both Heaney and Beare (2001) and Qureshi et al. (2010) provide insight into the consequences to river flow from investing in water-use efficiency technology.

[6] Section 2.5.3 defines three alternative structures of surface property rights as high security, general security and supplementary water.

Heaney and Beare (2001) used an average water use model with passive decision makers in the SMDB and did not consider climate change impacts on water resources. Heaney and Beare (2001) highlighted the negative downstream impacts for all water users from changes in river flow and salinity levels derived from investment in water-use efficiency technology. This analysis helped generate debate about the merits of needing a set of trading rules by region. They argued that the economic problem stemmed from the lack of property rights associated with return flows. From this viewpoint it was argued that irrigators, who invested in water-use efficiency, should be penalized, either in the form of taxes or being forced to surrender the water gained from efficiency, and that increased salinity mitigation was required.

However, the strategies suggested Heaney and Beare (2001) are counterintuitive as they send the wrong incentives to producers. With irrigators having clearly defined property rights on water (see Section 2.5.3) and being responsible for non-point pollution of salt (see Section 2.5.2), why should society discourage an individual from optimizing their resources? By extending Heaney and Beare's argument in the opposite direction, society is now being asked to provide on-going farm support for inefficient producers. This strategy then fails to deal with the problem of over-allocation of water resources, as, if the gain from investing in water-use efficiency infrastructure is less than the penalty applied, farmers will continue to invest in efficiency programs.

Qureshi et al. (2010) examined the benefits from investing in water efficiency to obtain environmental flows in a single catchment. While the paper introduces alternative climatic states of nature, the model still expresses a passive producer who fails to reallocate resources by state of nature. Additionally by specifying a historic upper and lower area bounds for each of the 12 commodities the model framework then has a calibration issue like the ABARES 'Water Trade Model' as the area dedicated to a single crop cannot exceed past experiences which inhibits resource reallocations. While the use of a single catchment prevents minimizing, the transformation costs (private and public) that can be gained from a regional solution and downstream consequences on the quantity and quality of water from upstream of investment decisions cannot be determined (Heaney & Beare 2001).

While substantial work on climate change impacts on: future conjunctive water resources in the MDB (Jones & Page 2001; Pittock 2003), the environment (Roshier et al. 2001); the need for producer adaptation and adoption responses (Connor et al. 2012; Goesch et al. 2009; Marangos & Williams 2005); the threats to urban communities (Buikstra et al. 2010; Cooper, Rose & Crase 2012); estimations of catchment (Connor et al. 2009) and MDB wide economic impacts (Beare & Heaney 2002; Jiang & Grafton 2012), threats to existing MDB water sharing rules and water trade (Australian Competition and Consumer Commission (ACCC) 2008; Loch et al. 2012); the impact climate change will have on the Basin Plan (Connell & Grafton 2011; Grafton & Jiang 2010); and the economic benefits for the MDB from mitigating carbon emissions (Garnaut 2008; Quiggin et al. 2010; The Treasury 2008) exists, no substantial work exists in examining the impacts climate change will have on the alternative proposed approaches to obtaining water for the environment and the economic consequences of failing to take climate change into account for environmental targets, urban users or irrigator's sunk investments.

Lastly, this thesis is the only quantitative analysis of the final plan. The legislated Basin Pan has three major changes to the 2011 version of the Basin Plan analyzed by ABARES (2011) and Adamson, Quiggin and Quiggin (2011). First the Basin Plan's surface water SDL has been decreased, requiring more water to be returned to the environment. Second, the process in which the surface water SDL is to be reclaimed has been altered. The surface water SDL specifies both a catchment reduction and a SDL reduction in a trading region. The Basin Plan has expanded the total number of trading regions from two (Northern Murray-Darling Basin (NMDB) and the Southern Murray-Darling Basin (SMDB)) to five (NMDB, NSW, SA, VIC and SMDB). This increased disaggregation of the SMDB trading regions will introduce inefficiencies into obtaining the surface water SDL, as rather obtaining water from the least efficient SMDB producers, now the least efficient producers in each trading zone are targeted. Third, unlike the previous versions of the Basin Plan in 2010 (Mallawaarachchi, Adamson, Chambers, et al. 2010) and 2011 (Adamson, Quiggin & Quiggin 2011), the finalized Basin Plan increases the groundwater SDL up 929GL (Table 7-5). So while other authors may have examined the RtB and the SRWUIP, no other study has examined the outcomes for irrigators from the new groundwater SDL, nor analyzed the spatial changes to investment patterns from decreasing surface water use and increasing groundwater consumption.

1.4 The Objectives of this Thesis

This thesis utilizes the SCA model to build a constrained-welfare maximization solution of the final Basin Plan. To examine:

1. if the Basin Plan internalizes the externalities derived from the development of water resources in the MDB;
2. changes to welfare (social, economic and environmental);
3. the total adjustment package offered by the Basin Plan which includes increased groundwater resources, the price offered by RtB and the funds provided by the SRWUIP;
4. the alternative strategies for obtaining water to achieve the Basin Plan's goals by:
    a. deriving an optimal water right portfolio to achieve the Basin Plan's goal;
    b. undertaking a partial equilibrium analysis of the SRWUIP; and
5. the Basin Plan's resilience to a changing climate.

1.5 Summary

The failure to take account of the inherent climatic risk and uncertainty in allocating water resources within the MDB will continue to reduce welfare. The thesis aims to explore not only the causes of the uncertainty but how private individuals adapt to resource scarcity once it is revealed. By identifying the policy limits and the unintended consequences, the aim is to prevent another cycle of private and public resource misallocation.

2. THE DEVELOPMENT OF WATER RESOURCES IN THE MURRAY-DARLING BASIN

2.1 Introduction

Water resource development in the Murray-Darling Basin (MDB) is the culmination of 130 years of 'romantic and reckless' policy, which has created a legacy of obstacles that will inhibit swift reform (Cummins & Watson 2012). Policy romanticism and recklessness is neither the sole domain of water, nor is it unique to Australia (Chan 1982; Jairath 2003) but rather water policy is the outcome of a political game between rent seekers (Epstein & Nitzan 2002). This political game is an amalgamation of how well the game, correctly interprets current and future social preferences (Escobar 2013; Rostow 1959) and the design and implementation of the policy. Thus water reform is not only dependent on: the efficiency and effectiveness of policy makers to interpret the problem and its solution (Colebatch 2006); but how the policy is supported by the available institutions, frameworks and regulations required to implement policy (Brennan 2006; Garrick et al. 2009); and how the policy interacts with other social settings (Adamson, Zalucki & Furlong 2014).

But no matter how well the institutions and regulatory frameworks are designed, the success of natural resource policy is fundamentally depended on the supply of the resource in question and how demand responds to the allocated supply. This thesis will argue, that it is the highly variable nature of known water supply and the uncertainty surrounding future water supply in the MDB (Khan 2008), that drives Howitt's (1995a) non-convex demand responses and creates irreversible outcomes. However, the combination of transaction costs and policy incentives to treat water scarcity as a temporary phenomenon, it can encourage decision makers to wait for rainfall rather than transform production systems to mitigating non-convex responses.

Past policy has attempted to deal with the uncertainty associated with water supply by: investing in large scale storage solutions of offset supply variability (Davidson 1969; England 1960); designing private water allocations rights to reflect the alternative levels of water security (Colby 1990; Loch et al. 2012); allocating drought funding to offset income loss; and provide structural support (Productivity Commission (PC) 2009). This process has evolved into a continual cycle of public support and adjustment mechanisms (Bromley

2007; Grafton 2007, 2010) designed to retain water resources within communities (Lopez-Gunn et al. 2012; Musgrave 2008), at society's expense (Scheierling, Young & Cardon 2006). Past policies, built upon prior social acceptances, have shaped the expectations and investment patterns of private individuals (Mallawaarachchi et al. 2012). These at 'risk' private irreversible losses (Clark et al. 1979) have stimulated the continuing cycle of reform. Past reform embraced engineering solutions to deal with supply variability and water quality, rather than economic solutions to deal with water resource over allocation (Olmstead & Stavins 2007). Despite policy makers talking about improving the environment, they have introduced signals encouraging irrigated production to expand (Connell 2007).

This attitude of providing assistance, 'until it rains' approach, is only viable in the short-run. In the long run once the realized, or the potential, irreversible losses exceed public acceptance, policy reform 'should' be altered to reflect the new social settings (Rostow 1959). However, each new policy reform stage, must take time to traverse the private and public legacy of prior reform (Crase, Dollery & O'Keefe 2011) in an effort not to make things worse and minimize the adjustment process cost (Grafton 2010; Quiggin 2012).

Cummins and Watson (2012) divide the historical social acceptance of the MDB water resource development into four incremental learning stages: exploration, expansion, maturity and contraction (Table 2-1). The exploration stage consisted of learning about the natural variability of water resources supply; the expansion stage attempted to increase the volume and reliability of supply; the maturity stage occurred when policies' started shifting from engineering solutions towards market solutions; and finally the contraction stage, where net quantity of water rights owned by private individuals will be reduced. The Murray-Darling Basin Plan (Basin Plan) is the key component of the contraction stage and is the focus of this thesis.

This thesis concentrates its analytics on the threats that variability and uncertainty about future water supplies pose to the implementation of Basin Plan. However, it must be conceded that other risks such as political interference, institutional failings and operational barriers may also prevent the Basin Plan from achieving its objectives. This section then pays homage, although briefly, to how past reform has shaped the development of water resources in the MDB water resources. For a detailed discussion about the historic MDB reforms and their limitations, please consult Connell (2007), Connell and Grafton (2011), Crase, O'Keefe and Dollery (2013), Davidson (1969), Musgrave (2008) and Randall (1981). However, before embarking on a brief tour of 130 years of rent seeking in the MDB, a quick discussion about how the supply and demand for water impacts on private users is required.

2.2 The Private Demand Response Function to a Given Supply of Water

In its simplest terms, water economics is about understanding the nature of water supply and the consumer's demand response to the quantity of water available. Again, in its simplest terms, water policy is about altering demand and supply curves towards the socially desired levels of impounded supply and consumption. Figure 2-1 provides the simplified description of a private individual's short-run demand response to a specified allocation of water.

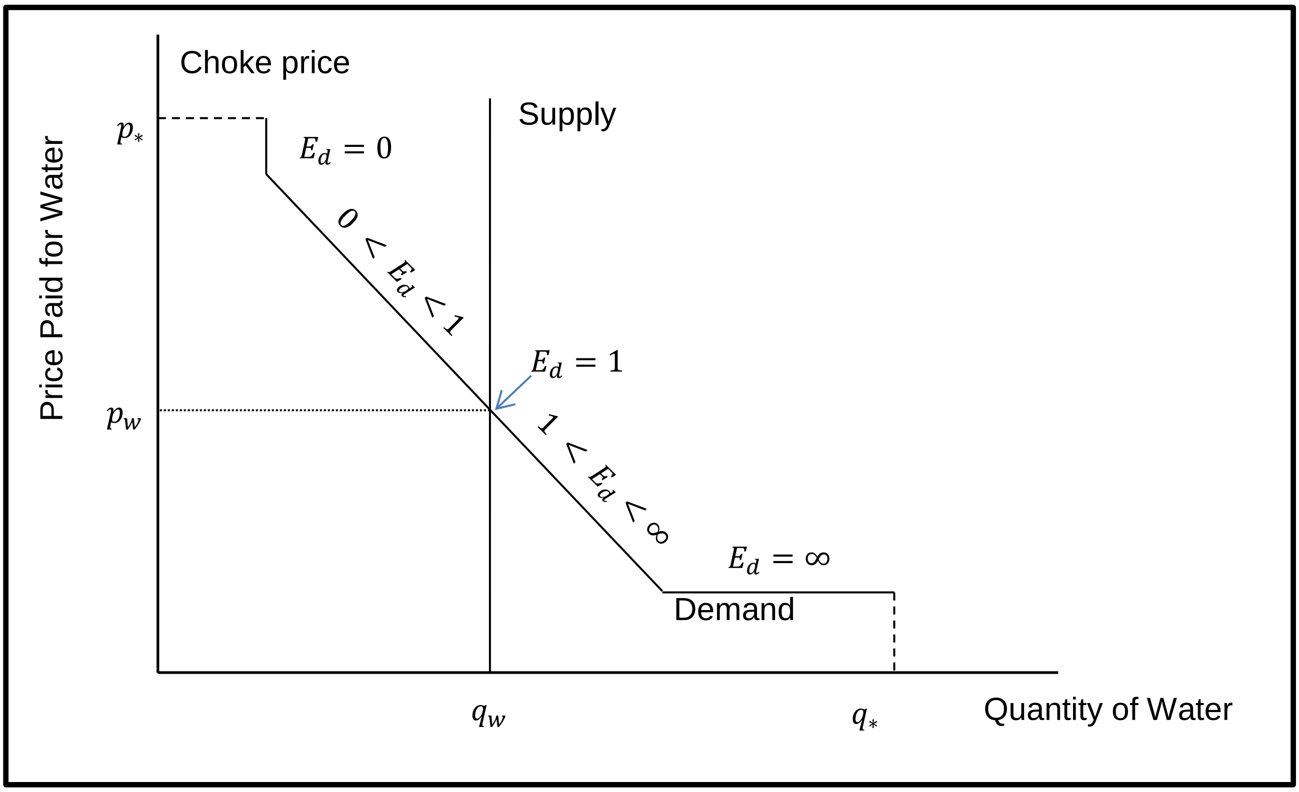

Figure 2-1 Private Demand Response to Water Supply

At equilibrium, the supply of water q_w meets the needs of the producer, who is willing to pay p_w to access this water, which provides the unitary of demand (i.e. (E_d) = 1). When the water supplied to the producer contracts to the left of q_w, then the producer is willing to pay

$\geq p_w$ to obtain water from the market to meet their demand for water. When water becomes scarce, the price paid for water becomes relatively inelastic (i.e. $0 < E_d < 1$) (Randall 1981) as producers attempt to keep commodities alive. Under periods of extreme scarcity, prices can become inelastic. However with insufficient water for all users, irreversible losses must occur as either the price exceeds their ability to purchase water (i.e. Olmstead and Stavins (2007) 'choke price' at p_*) or there is no water to purchase. When the supply of water expands to the right of q_w, the price of water falls. When water is no longer scarce its price becomes a relatively elastic good. As prices fall, producers can opportunistically enter the market and purchase additional water to engage in productive activities. Under perfectly elastic demand, consumption continues up until the point at which, the consumer cannot either store or utilize any additional water q_* with existing infrastructure.

Past water policy has attempted to influence both the long run demand for and supply of impounded water. By engaging in nation building exercises to drought proof economic activity in the MDB, policy has shifted the supply of water to the right. As the true cost of developing and supplying water was never passed on to irrigators, the demand for water also rapidly increased (Davidson 1969).

2.3 **The Four Stages of Water Resource Policy in the MDB**[7]

Table 2-1 aligns the key historical water initiatives into a summarized version of Cummins and Watson (2012), four distinct phases of water resource development and the discussion pertaining to the detail of the fourth stage are explored in Section 4. Table 2-2 builds upon Randall's (1981) work, which outlined the economic characteristics associated with the first three stages[8] of water resource development and are treated as separate due to the economic signals they provide to consumers.

[7] This section draws heavily from work published in Loch, Adamson and Mallawaarachchi (2014) and Loch, Wheeler and Adamson (2014).

[8] The economic characteristics of the fourth stage of water reform are presented in Table 4-1

Table 2-1 Evolution of Governance Mechanisms for MDB Management

Year	Initiative	Stage
1880	Water and Conservation Act provided riparian rights to access water resources	Exploration
1886	Irrigation Act provided states with the power of veto on private water rights and to manage and use water in the riverine system	
1901	The Constitution provided the states 'reasonable use' of water assets (Section 100) and the Federal Government retained the powers to ensure free trade between States (Section 98)	
1905	Water Act nationalized the riverine system and replaced irrigation trusts with central control to ensure urban and irrigation supplies	
1915	River Murray Waters Agreement; water sharing between New South Wales (NSW) & Victoria (VIC); and entitlements for South Australia (SA)	Expansion
1917	River Murray Commission established to implement the 1915 agreement	
1949	Snowy Mountain Scheme (Snowy Scheme) begins	
1982	River Murray Waters Agreement amended to allow management of environmental problems	Maturity
1985	Murray-Darling Basin Ministerial Council established to provide integrated planning and management of water, land and environmental resources	
1987	Murray-Darling Basin Agreement	
1989	First Interstate Environmental Agreement to address salinity and drainage	
1992	Murray-Darling Basin Commission (MDBC) established (replacing River Murray Commission)	
1994	Council of Australian Governments (COAG) Water Reform Framework	
1995	MDB States and territories agreed to define an upper limit on extractions in the MDB, the starting basis for the CAP	
1996	Commonwealth National Heritage Trust established in response to crisis in water quality	
1997	The CAP arrangements put into place, if not fully agreed to or signed by all States and Territories	
2002	The Living Murray Initiative; identify projects to improve river health and establish icon sites in the Basin	Contraction
2004	National Water Initiative; improved management of water and increased compatibility between states to facilitate expanded water trading	
2007	Water Act; established Murray-Darling Basin Authority (MDBA) to create MDB Plan (replacing MDBC)	
2008	Water for the Future plan; referred some state powers to the Commonwealth	
2010	Water for the Future Initiative: 10 year plan to balance water needs of farmers, communities and the environment.	
2010	Guide to the Proposed Basin Plan released	
2012	Basin Plan passes through Federal Parliament into law	
2014	Basin Plan implementation phase signed by all parties	

Adapted from: Loch, Wheeler and Adamson (2014), Musgrave (2008), National Water Commission (NWC) (2011c), State Library of South Australia (2013) and The Senate (2010)

2.3.1 The Exploration Stage of Water Resource Development

Prior to Federation in 1901, the formal structures and policies provided to coordinate the management of MDB water resources during the exploration stage of water resource development were either rudimentary or non-existent. The primary focus at this time was to ensure that there was sufficient water to meet the needs of rural communities and livestock. Each individual State had the ability to allocate a ‘reasonable use’ within their state, they were locked in “self-interest and political gamesmanship” (Clark 1971, p. 11) attempting to gain the largest share of the MDBs water resources. The Australian Constitution split water resource allocation between States and the Federal governments. The State’s ability to allocate a ‘reasonable use’ of water assets was reconfirmed by the Constitution. However, in an effort to ensure free trade between all States, the Federal Government obtained powers to provide sufficient water to enable navigation rights along the river (Table 2-1). This divergence in allocative power is a recognition of the state versus national welfare debate.

Due to a lack of storage and delivery infrastructure water resources, irrigation communities established during the exploration stage suffered from water insecurity (Table 2-2). Drought events exposed that this lack of water security increased the competition and conflict for water resources between all water users (Cooper, Rose & Crase 2012). The notable droughts of the establishment stage included: a series of dry years in the 1890s; the Federation Drought (1901-02); and again in 1912 (Loch, Wheeler & Adamson 2014). These drought events stimulated the politic ‘necessity’ to provide water supply security (Cummins & Watson 2012). The political debate focused its attention on the need to provide water for unlimited urban growth and prevent economic downturns in a rural based economy as “irrigation was the cure for drought” (Davidson 1969, p. 49). However, it was the 1914-15 drought that provided the political catalyst needed for the River Murray Water Agreement (MDBA 2010c) and heralded the start of the expansion stage of water resource development in the MDB.

Table 2-2 The Economic Characteristics of the Four Stages of Water Resource Development

Market characteristic	Exploration	Expansion	Maturity	Contraction
Long run supply of impounded water	Elastic	Elastic to Inelastic	Inelastic	The idealistic economic characteristics of the contraction stage are revealed in Section 4.5
Demand for delivered water	Minimal, Often no or minimal charge to access water. Elastic at low prices, inelastic at high prices.	Low but growing demand. Demand is elastic at low prices and inelastic at high prices.	High and increasing demand. Elastic at low prices; inelastic at high prices.	“ “
Physical condition of impounded and delivery system	Little to no infrastructure. All infrastructure new.	Infrastructure is in good to new condition.	Aging infrastructure in need of expensive upgrading or repair.	
Competition for water between all users	Nil, only during extreme droughts.	Increasing but minimal. Can occur during droughts creating a new round of investment in long run supply.	Intense apart from during floods.	“
Non-Convexity	No	No	Yes	“
Externalities	Nil	Minimal	Extensive externalities	“
Social cost of subsiding increased water use	Zero to very low	Fairly Low	High and rising	“

Adapted from Randall (1981) and Cummins and Watson (2012)

2.3.2 The Expansion Stage of Water Resource Development

The River Murray Water Agreement provided the governance structure required to deal with the divergent State attitudes towards the quality, availability and use of water resources (Craik & Cleaver 2008). The River Murray Commission (Table 2-1) implemented the River Murray Water Agreement and it facilitated the rapid expansion phase by utilizing public investment to develop the water resource infrastructure network that is still in use (MDBA 2010c).

Despite the expectation that farmers would be willing to pay for water security, the true cost of water was never passed on (Davidson 1969). With social approval, public funds were allocated to engineering solutions to mitigate supply variability and deal with water quality management issues. This social acceptance of on-going subsidization of water, then negated the need for price solutions to deal with supply uncertainty (Connell 2007). The presiding social belief was that, a secure water supply for livestock and food production were national priorities (Davidson 1969). Randall (1981) suggests that during this stage the combination of low costs for impounding water (dams) and, as the negative externalities from water resource use have not been realized, society was rational. With the cost of dams remaining low due to the availability of “favorable sites” (Randall 1981, p. 195), the economic debate was concerned with determining the appropriate rate of impounding future water supply and not about the economic efficiencies associated with developing water use (Randall 1981).

With the perception that the social costs to build infrastructure were low and with a political desire to develop regional and urban Australia, public policy was used to stimulate the demand and supply of water. For example, post the 2nd world war, commodity subsidization schemes were used to encourage participation in soldier resettlement irrigation schemes and work started on Australia’s largest water storage and supply system, the Snowy Hydro Scheme (Duane 1960; England 1960). In 1954, Adelaide’s water security fundamentally changed when the pipeline linking it to the Murray River was completed, as in drought periods the pipeline has provided up to 90% of potable supplies (Connell 2007).

It is estimated, that from 1940 to 1980 a tenfold increase in the storage capacity of the MDB occurred (Figure 2-2) and in response, diversions steadily increased to allow up to 65% of the impounded water resources to be accessed for consumptive use (NWC 2011c). However, the 1980's spelt the end the expansion stage of water resources in the MDB.

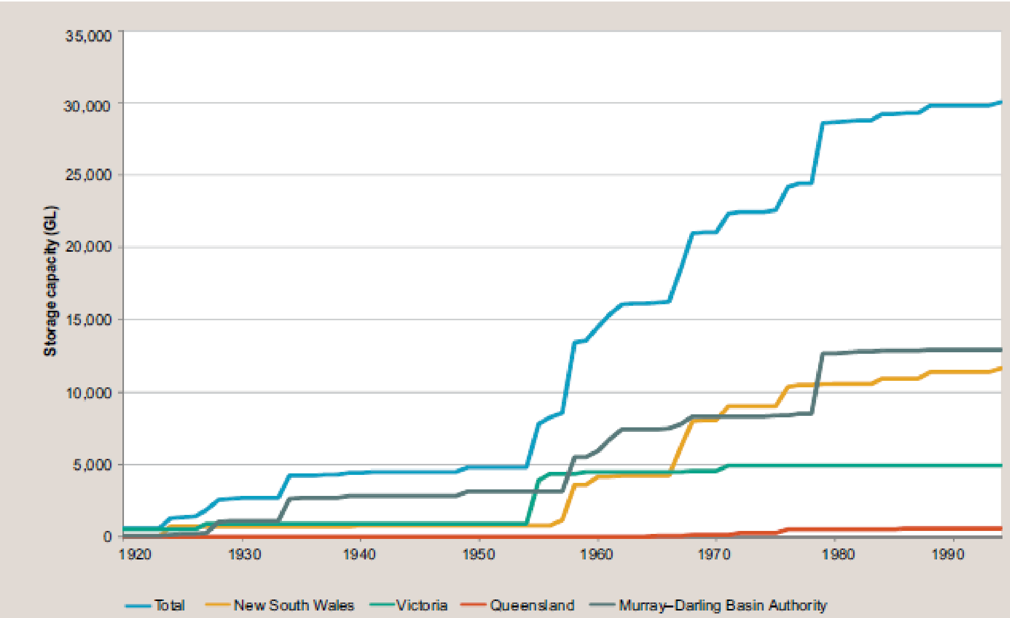

Figure 2-2 Development of public water storage capacity in the MDB[9]

2.3.3 The Maturity Stage of Water Resource Development

By exhausting all of the favorable low cost dam sites in the maturity stage of water resource development, all future public investments in water storage then faced an inelastic and incremental cost function (Table 2-2). As Randall (1981) notes, the maturity stage is also characterized by: the social realization that national welfare is reduced by failing to internalize the negative externalities from water use; that the competition between all water users has become intense during drought periods; and that public infrastructure needs to be upgraded. As the maturity stage continues, even in periods of normal rainfall, the combination of modifying the river's flow, over-allocating irrigation supplies and return-flows from irrigation, results in increasing river salinity and frequent algal blooms (MDBC 2007a).

[9] Source (MDBA 2010b)

With increasing public awareness and economic questioning about the net benefits of water resource development (Davidson 1969), the political justification of continuing to allocate public expenditure on developing new water resources becomes increasingly difficult (Connell 2007). Decision makers then refocused away from increasing supply and towards improving the water quality, as represented by the 1989 interstate agreement on salinity and drainage (Table 2-2). This strategy then allowed public funding to be refocused towards dealing with externalities (salinity) and in some cases this was combined with a moratoria on the granting of further consumptive extraction rights (Loch et al. 2013). By improving the quality of water (Section 2.5.2), irrigators could now develop water rights which had remained underutilized due to the externality of salt. Consequently, the improvement of water quality in one area then essentially transported the externalities of over-utilization to downstream users (Quiggin 1991).

The economic debate over who should pay (i.e. polluter or society) for ameliorating the negative externalities from water use (Chan 1982) helped change the global social awareness about sustainable nature of water resource management in river basins (Sitarz 1993). These discussions shifted policy focus away from utilizing direct regulations (e.g. water quality targets and water allocations) towards market-based instruments (e.g. property rights and trade) in an attempt to achieve environmental objectives (Jordan, Wurzel & Zito 2005; MDBC 2007a). The benefits of this approach had already been discussed, by Randall in 1981 when he proposed that the development of transferable water entitlements and an efficient market, would allow the true price of water use to be determined (i.e. inclusive of the cost of externalities). Randall hypothesized that price discovery would efficiently reallocate water property rights and that the costs of irrigation modernization would then be borne by the water user. Thus, price discovery would prevent the need for public funds to upgrade existing infrastructure.

In 1994, a critical step within the mature water resource development stage occurred when the MDB States and Territories agreed that an upper bound on surface water extractions needed to be established to deal with water use externalities (Table 2-2). This 'CAP' on extractions was based on recommendations to limit diversions to 1994 levels by the 'Audit of Water Use' (MDBC 1995)[10] and was enacted in 1997.

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[10] For consistency with latter discussion, the CAP in the mature stage of development is interchangeable what is later termed the Current Diversion Limit (CDL).

The CAP had four critical features. First, it defined the scarcity of private surface water resources within the basin. Second, the CAP failed to deal with groundwater resources (Connell & Grafton 2011). Third, it started the process of decoupling water and land rights to facilitate permanent trade (Bjornlund 2003). Fourth, despite debate arguing that net benefits would be accrued by society (inclusive of higher water costs for irrigators) by increasing environmental allocation, the CAP failed to established environmental rights (Crase 2008).

Ultimately, by defining a maximum water offtake, the value of water rights was revealed. This awareness of value provided incentives for private individuals to gain rent from selling or activating property rights that were either undeveloped ‘sleeper’ and or infrequently used ‘dozer’ rights (Crase, Dollery & O’Keefe 2011). Consequently, water use increased and compounding the externalities the CAP was designed to mitigate (Cummins & Watson 2012; MacDonald & Young 2001). Additionally, Randall’s hypothesis that true price discovery would occur, could not be tested as a series of market impediments including: trading rules; regional export limits; termination fees; and other administrative costs, were established (Australian Competition and Consumer Commission (ACCC) 2008; Roper, Sayers & Smith 2006).

Critically the CAP resulted in the residual environmental share of water being penalized by water managers attempting to preserve ‘private rights’ (Mallawaarachchi et al. 2008) and this environmental penalization was highlighted during dry periods. The on-going nature of over allocation of water and resultant externalities allowed the economic discussion to return towards debating the need to reduce private water consumption. This discussion then helped debate the need to establish environmental rights, which is the central objectives of the fourth stage in water reform (Connell & Grafton 2008).

These prior stages of water resource development, then built the infrastructure (see Figure 2-3) designed to manage the variable nature of conjunctive water supply in the MDB and mitigate water quality issues. These stages also locked policy makers into a series of transaction costs and in many cases policy solutions refocused water resources back into inefficient areas via on-going subsidies (Crase & O'Keefe 2009)

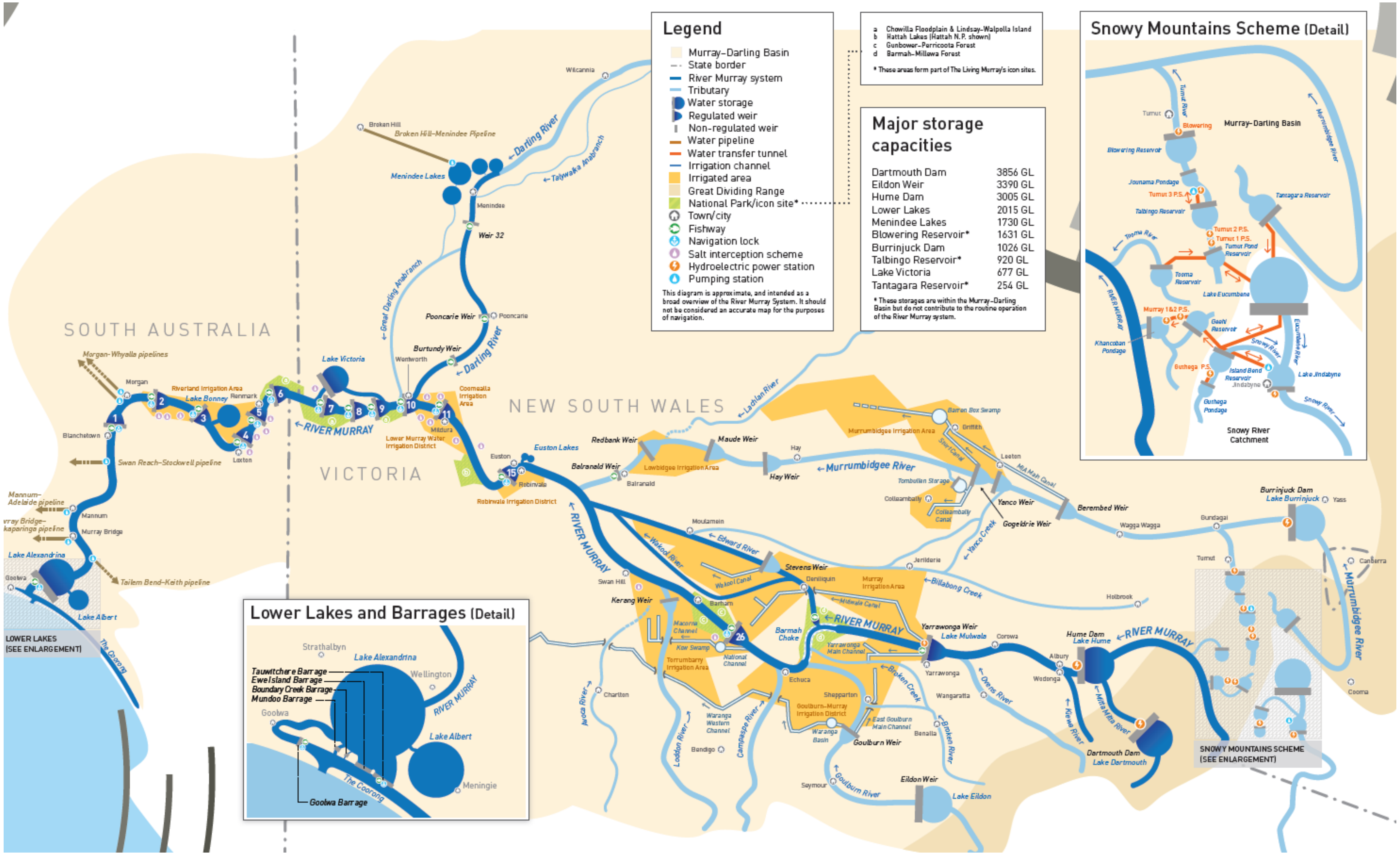


Figure 2-3 The Modification of the MDB[11]

[11] Adapted from http://www.mdba.gov.au/sites/default/files/river-murray-system-poster.pdf

2.4 **Conjunctive Water Resources in the MDB**

The total average annual conjunctive water supply available in the MDB is 25,467 gigalitres (GL). Of all water sources rainfall is the largest and accounts for 22,925GL; then groundwater extractions of 2,373GL; and Snowy River hydro transfers 1,118GL of water into the MDB (Table 7-1).

2.4.1 The Spatial and Temporal Distribution of Rainfall

Rainfall in the MDB has summer-dominant patterns in the Northern Murray-Darling Basin (NMDB) and winter-dominant patterns in the Southern Murray-Darling Basin (SMDB) (Figure 2-4). The Australian Bureau of Statistics (ABS) (2008b) estimates that the highest long term average annual patterns occur in the south-eastern corner where 900–1,200 millimeters (mm) falls, eastern areas receive 400–900mm, and precipitation steadily declines in the western and north western part of the MDB where only 100–400mm is expected. These average rainfall patterns provide the MDB with 530,000GL of rainwater resources. However, on average 94% of all rainfall is absorbed by the soil and 2% of rainfall recharges groundwater aquifers, only 4% of rainfall becomes runoff (i.e. inflows into the river system of 22,925GL).

Water averages are misleading in the MDB. Not only is the rainfall to runoff value contingent on natural and modified landscape features, but the MDB experiences severe droughts and floods. The conversion of rainfall into runoff is a complex relationship which includes variables, including but not limited to: the intensity, duration and temporal nature of the rainfall event; and the natural and human induced spatial characteristics of the landscape over which the rainfall event occurs (Jones et al. 2001 & 2008; Preston & Jones 2008; Schrobback, Adamson & Quiggin 2011).

Changes in the El Niño Southern Oscillation (ENSO) weather patterns bear a statistically significant relationship to quantity of rainfall that falls in the MDB (Kamruzzaman, Beecham & Metcalfe 2013). The ENSO is measured by the Southern Oscillation Index (SOI) and it has three phases: the El Niño phase classified by negative SOI values and the La Niña phase characterized by positive SOI values; and a neutral phase. The La Niña is associated with generating above average rainfall, the El Niño signals that large-scale droughts are possible, especially in the SMDB, and the neutral phase is associated with average rainfall patterns (Bureau of Meteorology (BOM) 2012).

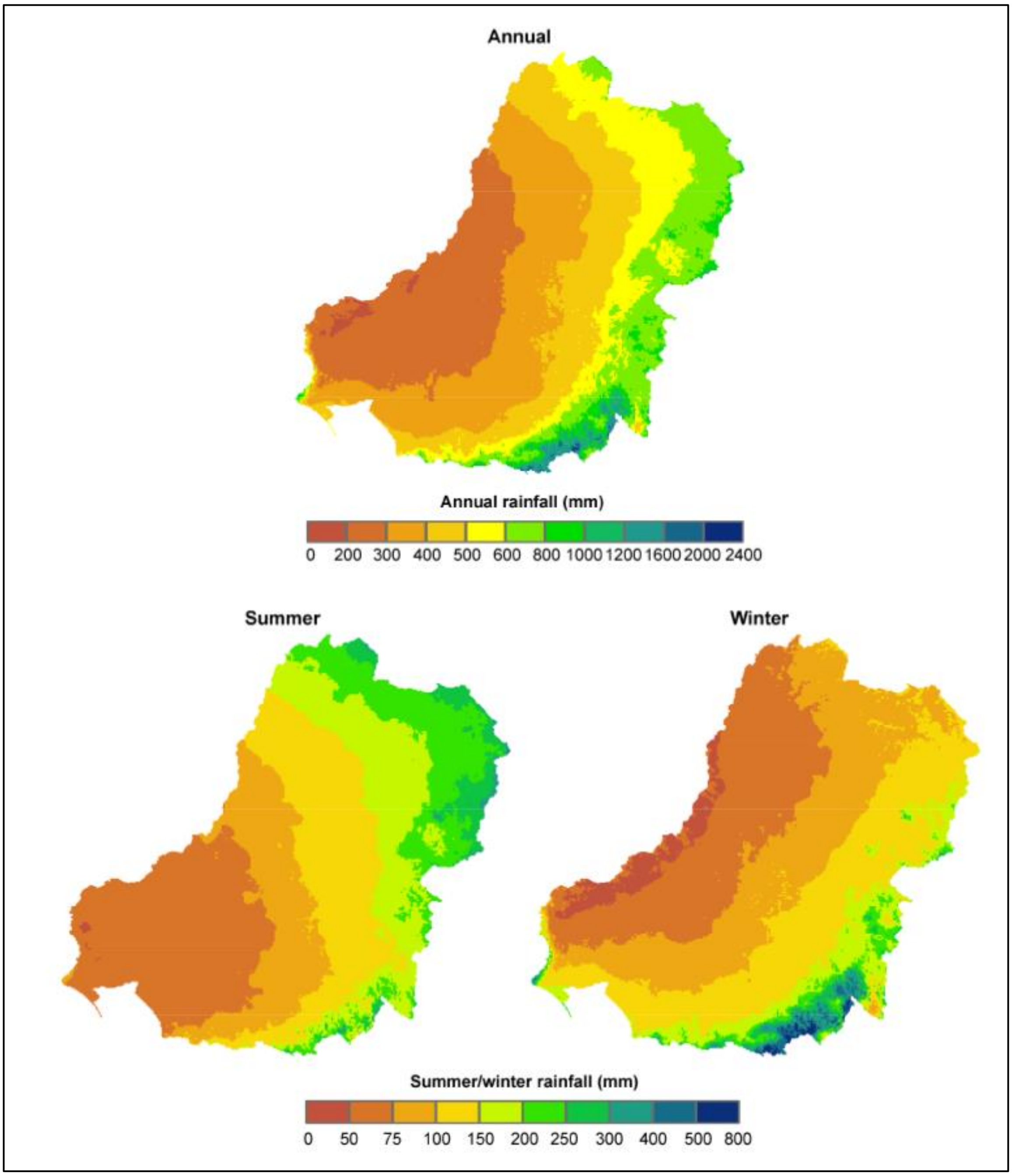


Figure 2-4 Long-Term Average Rainfall [12]

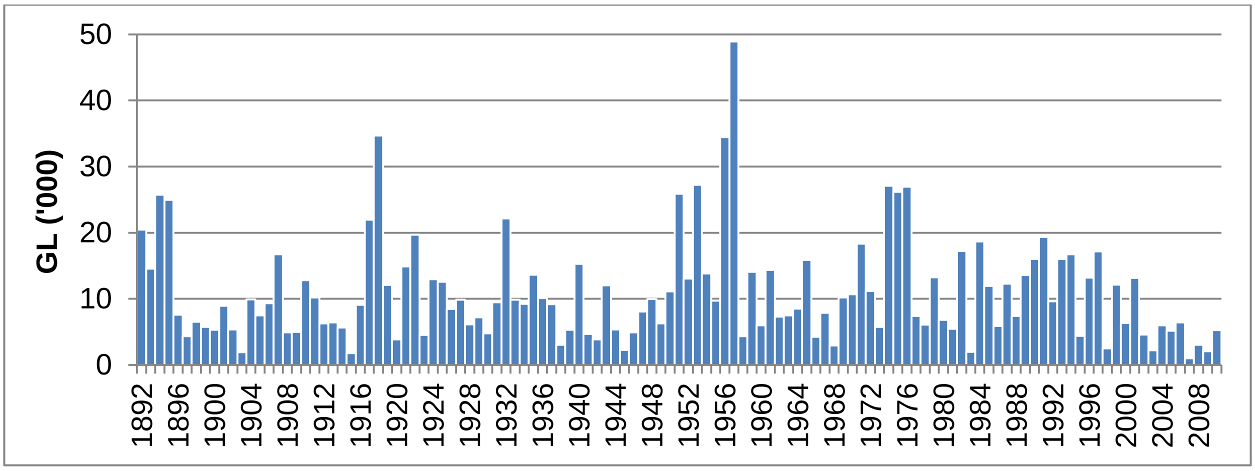
The cycle between the La Niña and El Niño phases results in the MDB having the second most variable water supplies in the world (Khan 2008). This variability of water supply determines agricultural output (Podbury et al. 1989). Rainfall variability across MDB is not

[12] Source Chiew *et al* (2008)

uniform. This is typified by the Darling River, which has the most variable inflows in Australia (Khan 2008). The impact of ENSO on rainfall is illustrated in Chart 2-1 and Chart 2-2 where the inflows into the Murray River and Menindee Lakes[13], over the period 1982 to 2010 are presented respectively.

An analysis of the data used to construct Chart 2-1 reveals that the Murray River has a mean inflow of 11,000GL, a median inflow of 9,000GL and a standard deviation of 7,800GL. The maximum recorded inflow into the Murray River occurred in 1957 when 49,000GL arrived and the minimum inflow was 1,000GL in 2007. The data depicted in Chart 2-2 indicates that the Menindee Lakes have a mean inflow of 2,000GL, a median inflow of 850GL and that the standard deviation exceeds 3,000GL. The maximum recorded inflow into the Menindee Lakes exceeded 18,500GL in 1957 and its minimum inflow was just 35GL in 1920. These datasets highlight the importance that rainfall events in the south eastern MDB (Figure 2-4) have in providing the largest proportion of inflows into the MDB and the role that La Niña and El Niño events have on the reliability of those inflows.

Chart 2-1 Inflows into the Murray (GL '000)[14]



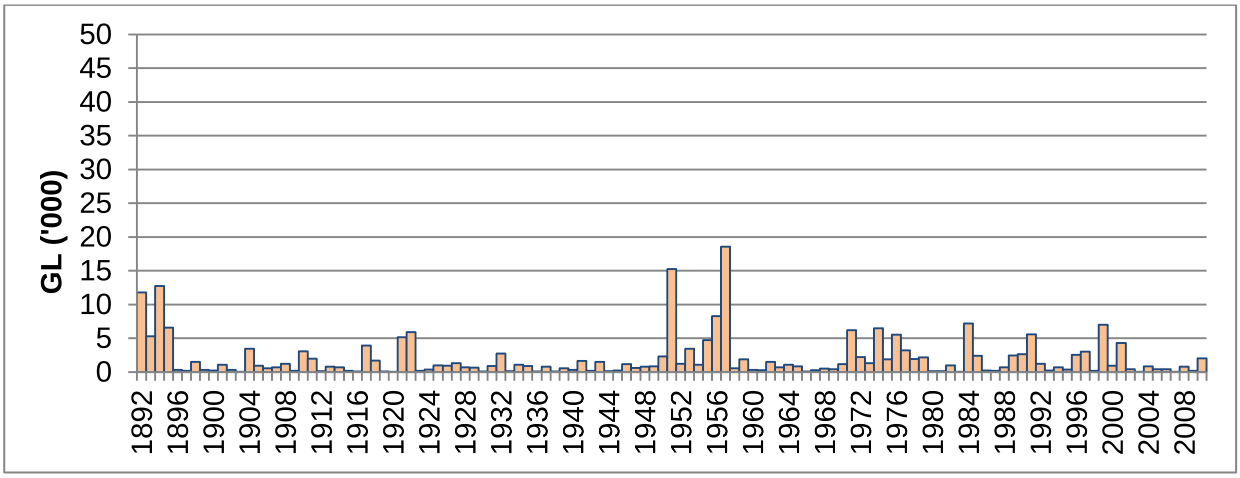
Estimating the total conjunctive available water resources in the MDB is complex due to the lack of time series and uniformed data collection methods. For example, Chart 2-1 and Chart 2-2 provide some of the best available information for water management in the

[13] Please consult Figure 2-3 for the spatial location of both the Murray River and the Menindee Lakes, which is along the Darling River.

[14] Source MDBA *pers. comm.* Jim Foreman, January 2011

MDB but all data until 2009 is derived from modeled outputs. Decision makers must take care with modeled outputs in case the model design prevents the tail of distributions being fully explored (Section 4.3.1). Connell (2007) states, that this lack of data and knowledge about water resources and their use in the MDB has prevented real water reform.

Chart 2-2 Inflows into Menindee Lakes (GL '000)[6]



2.4.2 Groundwater

As aquifer recharge zones can lie outside the geographical boundaries of water basins, the rate at which groundwater reserves recharge may have no correlation with local rainfall events. As depicted in Figure 2-5, irrigators in the NMDB access groundwater from the Great Artesian Basin, whose recharge zones include the Gulf of Carpentaria (Smerdon et al. 2012).

This spatial disaggregation between the recharge and consumption of groundwater can help mitigate localized drought events (Kirby et al. 2014) provided that water managers manage the groundwater extraction rate carefully. If the groundwater extraction rate exceeds the time required to replenish the aquifer, then groundwater can become a depletable resource (Crosbie et al. 2008; Loáiciga 2003). High groundwater extraction rates can degrade water quality and the structural stability of the aquifer. Once the aquifer is compromised (Knapp & Baerenklau 2006), its natural ability to recharge may be impaired or permanently prevented (Brunke & Gonser 1997).

In this thesis, the conjunctive extractive value of groundwater has been set to the current allowable extractions and not the total resource base. This assumes that the rate of groundwater consumption is sustainable. This thesis therefore cannot determine the long term sustainability of groundwater resources but it can raise questions about its use and value under alternative climate settings.

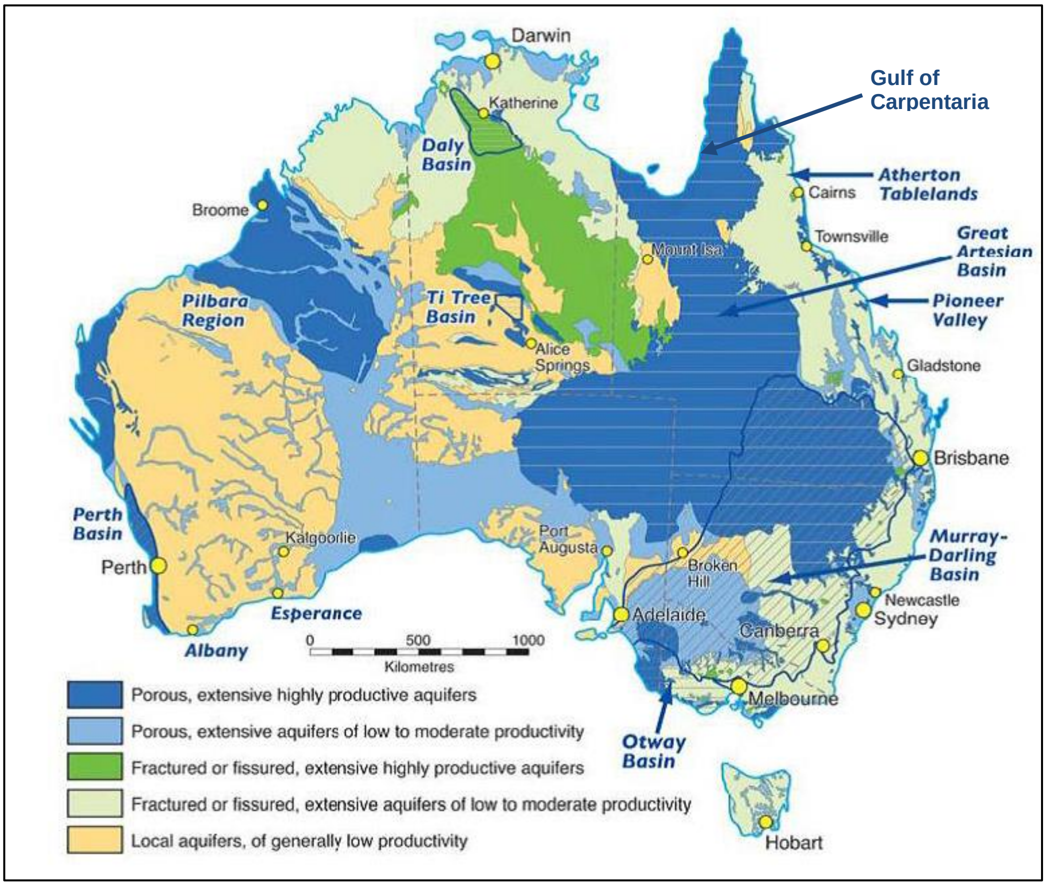


Figure 2-5 Australian Groundwater Resources[15]

2.4.3 Inter-Basin Transfers

The Snowy Mountain Scheme provides the capacity to transfer water, into the Murray River and the Murrumbidgee River (England 1960) from the Snowy River Basin[16]. These inter-basin transfers provide the SMDB with 1,118GL (Table 7-1) of high quality water (e.g. low salinity) which dilutes MDB derived water supplies thus benefiting all water users in the SMDB (Bell & Heaney 2000). These Inter-basin transfers were designed to shift water from areas with a relative elastic demand function for water ($1 < E_d < \infty$) to areas of

[15] Source Deloitte Access Economics (2013)

[16] Figure 2-3 provides the location of the Snowy Hydro-Electric Scheme

relatively inelastic demand $(0 < E_d < 1)$. However, these inter-basin transfers created ecological (MacPhee & Wilks 2013), economic and social harm (Pigram 2000) in the Snowy River catchment.

The restoration of Snowy River flows remains the subject of on-going debate. If climate change alters both the total volume and variability of inflows into the Snowy River catchment (Quiggin et al. 2008), then this inter-basin debate for an equitable share of water resources will intensify. Restoring flows to the Snowy River then…

> "…implies that flows to the Murray-Darling Basin must be reduced. Even if restoration of flows to the Snowy is accompanied by the implementation of water–saving initiatives, the opportunity cost of diverting flows from the Murray-Darling remains relevant.
>
> Reduced flows to the Murray-Darling Basin could have a variety of consequences relating to the opportunity costs associated with restricting available water for electricity generation and for the irrigation for arable land. Reductions in flows could change the biophysical condition of the catchments downstream and the quality of drinking water for Adelaide (Pigram 2000)". (Wagner, Quiggin & Adamson 2008, p. 1).

To prevent policy confusion, this thesis does not examine the impacts on returning flows to the Snowy River.

2.5 Managing the Supply and Quality of Water Resources

The delivery of water and its quality is subject to: hydrological realities, a complex set of regulations and management rules; and the capacity of the natural river system and capital infrastructure to supply water where needed (Crase, Dollery & O'Keefe 2011; Cummins & Watson 2012). The hydrological realities of water supply and its quality are dependent on rainfall, bushfires, landscape changes and ground-surface water connectivity (Young & McColl 2009).

Approximately 60% (15,700GL) of the total conjunctive water resource base is diverted for consumptive use. The Current Diversion Limits (CDL) is comprised of 13,345GL of surface water and 2,370GL of groundwater extractions (Table 7-1). In practice, CDL are estimates due to unmetered groundwater extractions, consumption by river pumpers, livestock consumption, and other uses (MDBA 2012d). Additionally measurement errors exist and in 2010-11 diversions were estimated at 6,311GL, ± 14% (i.e. 899GL) as…

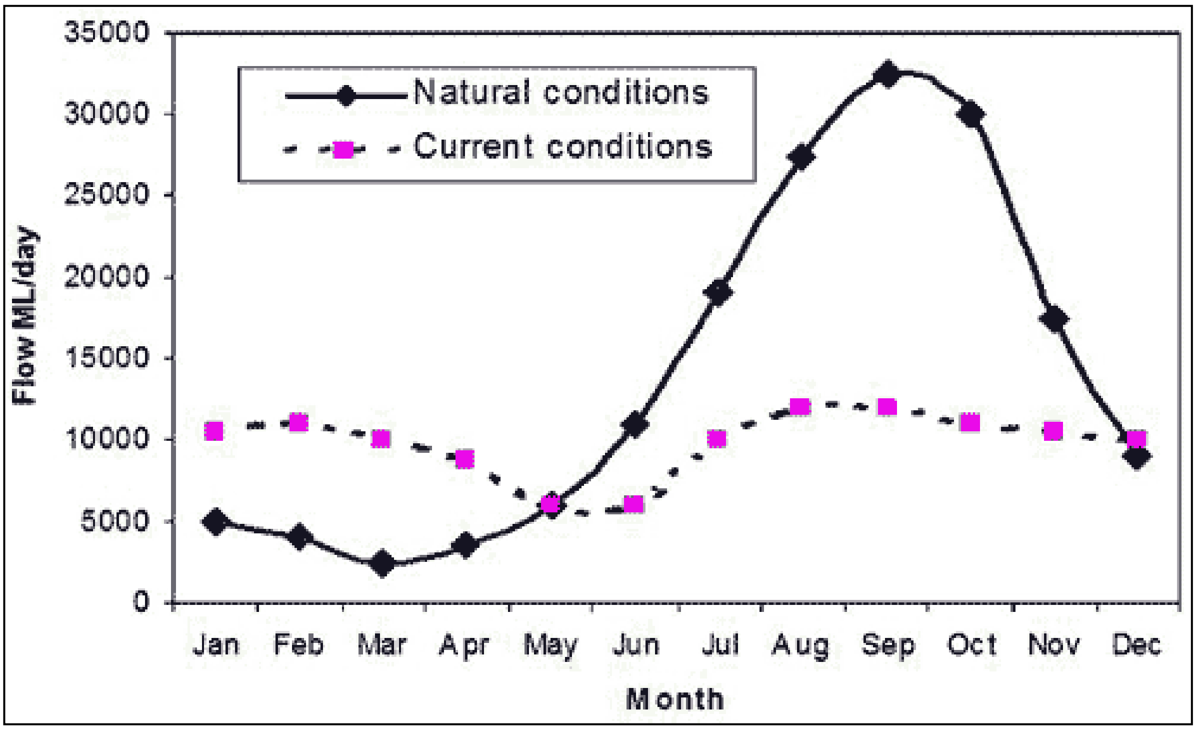
> "…metered diversions have been assumed to have an accuracy of ± 5%, regional surveys ± 20% and user returns ± 40%. Accuracy for individual valleys has been calculated by volumetrically weighting the accuracy of bulk offtakes (direct diversion points) in that valley" (MDBA 2012d, p. 9).

The capacity to deliver water at a given point in time is dependent upon the water diverted for consumption, the bundle of local and traded-in property rights, the capacity of the infrastructure network to deliver water, and the conveyance loss from transporting water along the river system (Adamson, Mallawaarachchi & Quiggin 2007). Historically, two management approaches for dealing with water supply variability have been adopted. The first option has been to penalize the residual water claimant, (i.e. the environment) in the short run, with the notion of providing compensation flows at some point in the future. Second, announcements concerning the percentage of allocation to be delivered to irrigators, subject to the description of the entitlements risk, are made throughout the year (Adamson, Quiggin & Quiggin 2011).

2.5.1 Flow Modification

Without a NMDB version of the River Murray Waters Agreement, the investment in public infrastructure in dams, locks, barrages and systems to facilitate inter-basin transfers has been concentrated in the SMDB (Figure 2-3). These public investments provide the capacity for water managers to meet peak consumptive irrigation demands in the spring and summer (Adamson & Loch 2014; Brennan & Scoccimarro 1999; Davidson 1969; Kingsford 2000). The later establishment of the NMDB and the way the CAP has been implemented (Mallawaarachchi, Adamson, Goesch, et al. 2010; MDBA 2010b) has allowed some on-going private investment to harvest overland flows in the NMDB to continue until recently (MDBA 2012d).

Chart 2-3 Change in Flow in the Southern MDB



Source MDBC (1995)

2.5.2 Managing Water Quality & the Salinity Interception Scheme (SIS)

The Basin Plan (MDBA 2012c, pp. 80-1) lists nine monitored threats to water quality: salinity; suspended matter (e.g. river turbidity); water temperature; nutrient levels (including phosphorus and nitrogen); toxins derived from biological systems (e.g. toxins from blue-green algae[17]); toxins derived from human activity (e.g. pesticides and heavy metals); pathogens (e.g. Cryptosporidium and Giardia[18]); acidity; and dissolved oxygen levels (e.g. black water events[19]). Apart from subsequent sections that discuss the direct environmental harm from irrigation, this thesis constrains the discussion pertaining to water quality to just salinity. This limitation in discussing water quality is due to the design of the model described in Section 6.

[17] Blue-green algae is a cyanobacteria, which is an algae like bacteria, that release toxins into the water (DSEWPC 2012).

[18] Pathogens are transported into the river via animal waste (Environment Protection Authority 2005).

[19] Black water events occur after flooding when high concentrations of organic matter are transported into the river system and decay. During the decomposition process, the organic matter releases tannins which darken the water and depletes the level of dissolved oxygen in the water. This deoxygenated water poses a health threat to aquatic species (MDBA 2012e).

Salinity in the MDB has two distinct but correlated forms, dryland salinity and water quality. Dryland salinity is primarily an externality associated with the removal of deep rooted vegetation. Extensive land clearing altered the water cycle and has allowed rising water tables to transport salt through the soil profile and up to the soil surface. When the water table falls, the salt remains behind. If subsequent rainfall events, fail to flush the salt away from the soil surface or vegetative root zones, economic harm can then occur to agricultural land, urban infrastructure and environmental assets (Keating et al. 2002). Irrigators can contribute to the dryland salinity problem by over irrigating and causing the water table to rise.

The quantity of dissolved salts within water is measured by the water's electrical conductivity[20] (EC). A river's EC is a function of the total salt load (natural salinity plus salt derived from irrigation activity) divided by the quantity of water in the river (Austin et al. 2010). Salt is naturally mobilized within the landscape from surface inflows and from saline groundwater rising into the river system in periods of low flow (Smitt et al. 2002). The act of irrigation removes water from the river contributing to low flow events, while unutilized irrigation water returns back to the river transporting more salt into the river, thus the river's salinity is concentrated further degrading water quality.

Salinity is actively managed within the landscape at a farm, regional, state and national level to deal with its point and non-point pollution characteristics. Irrigators adapt to the point pollution problem (i.e. quality of water arriving to their farm) by altering commodity choices and over-irrigating to flush salt away from the root zones when required (Connor et al. 2012). However, over-irrigating to combat pollution on farms in turn contributes to the non-point social problem of salinity if irrigators fail to adequately manage saline drainage water (Smith & Maheshwari 2002) or allow the water table to rise.

By monitoring water quality, active management can take place in an attempt to achieve 'end of valley' targets. A major water quality target is ensuring that the water reaching Adelaide's pipeline, at Morgan, is less than 800 EC, 95% of the time (MDBA 2012a; NSW Government 2000). Water quality monitoring then allows for salt to be managed within channel and before it reaches the river system. The active within channel management strategies include: diverting pulses of highly saline water (e.g. salt slugs) into dams or

[20] EC is a measurement of water's ability to conduct an electrical charge.

lakes; and using infrastructure to breakup and dilute salt slugs (MDBA 2011c). The monitoring of river quality helps determine the quantity of salt that needs to be extracted by the salinity interception schemes (SIS). For example, due to increased flows in the river, the quantity of salt removed by the SIS fell from 489,100T in 2009-10 to 324,000T in 2010-11 (MDBA 2011a, 2012a).

The SIS is an engineering solution designed to prevent groundwater salt from entering the river system and they consist of a borefield, pipeline and disposal option. Salt is removed …

> "…by constructing borefields that create a zone of pressure in the target aquifer that is equal to or slightly less than the pressure at the river. This creates a gradient where groundwater flow is towards the borefield rather than towards the river" (Telfer, Burnell & Charles 2012, p. 7)

This water is then pumped from these borefields along pipelines towards impervious aquifers and surface storage systems. These naturally or conducted systems then impound the salty water or allow to it be evaporated. However, the success of the SIS encouraged more water to be used and required on-going investment in the SIS. Just like impounding water, the initial SIS had low social costs but now faces rapidly increasing costs depending on their location and construction (Figure 2-6).

Initial SIS sites at Mildura-Merbein and Buronga, were able to target highly saline groundwater supplies and utilize natural disposal options (Telfer, Burnell & Charles 2012) keeping their costs lower than subsequent developments. The cost to remove each unit of EC in the initial SIS sites is estimated to be approximately $0.5 to $1.5 million. By utilizing existing disposal sites and pipeline infrastructure works, other SIS sites including Bookpurnon, Waikerie 2L and Pike were able to remove each unit of EC for between $1 to nearly $2 million. However, sites without access to existing infrastructure, or need to construct disposal basins (e.g. Mallee Cliffs); or intercept increasingly less saline groundwater, then face increasing costs to remove each additional EC. For example, the cost for the Upper Darling was estimated to exceed $4.5 million per EC (Department for Water 2011; Telfer, Burnell & Charles 2012).

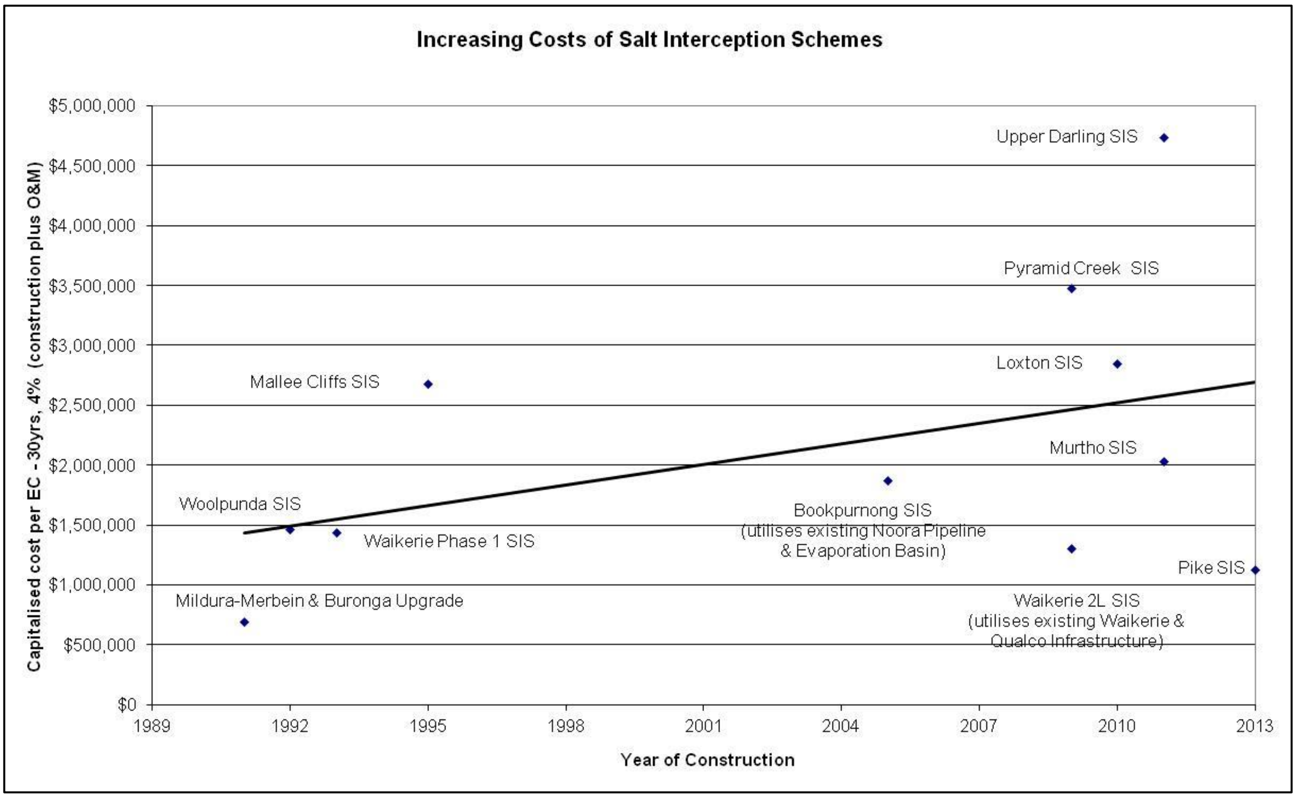


Figure 2-6 Capitalized Cost of Salinity Mitigation ($)[21]

The success water quality program has been determined by reviewing the water quality arrived at Morgan (Table 2-3). The data suggests that the quality target of providing water at 800 EC, 95% of the time for Adelaide has been achieved. It was only during the initial period (25 years) that the peak salinity levels exceed the 800EC. Therefore as a goal, the program has been a success but this is not an economic justification of the SIS as other more cost-effective strategies may exist.

Table 2-3 Salinity Levels at Morgan, South Australia (EC)

Period	Time interval	Average	Median (EC)	95th Percentile(EC)	Peak	%time >800EC
1 year	July 2010-June 2011	309	331	419	466	0%
5 years	July 2006-June 2011	432	426	696	785	0%
10 years	July 2001-June 2011	444	430	693	785	0%
25 years	July 1986-June 2011	511	484	797	1160	5%

Source MDBA (2012a, p. 11)

[21] Figure 2-6 was provided by MDBA *pers. comm*. Phil Pfeiffer**,** December 2013. Note without the raw data used to construct Figure 2-6 an analysis of the methodology and data used in its construct could not be undertaken.

2.5.3 Water Diversions, Water Property Rights, Water Allocations & Water Trade[22]

Water property rights are used to define the level of water security provided to irrigators in the MDB (Brennan & Scoccimarro 1999; PC 2003; Randall 1975). The MDB has both surface and groundwater entitlements.[23] In decreasing levels of security, surface water rights can be divided into three entitlement structures: high security, general security and supplementary. It is this variable nature of security by entitlement class that allows for a total of 16,890GL of surface property rights to exist on paper in the MDB (BOM 2011), despite the total surface CDL being only 13,345GL (MDBA 2012c). To model the mixed signals provided by the Basin Plan, this thesis has deliberately assumed there is only one entitlement class for groundwater (Section 8).

The initial allocation of water a farmer receives in a season is dependent on; the available water in storage; the management rules within an irrigation district; and the bundle of alternative water rights they own. As the season is revealed, allocations can increase in response to supply, but once allocated, water cannot be taken away from a farmer (Loch et al. 2012). Therefore water rights are an ownership of water entitlements and the allocation is the quantity of water an individual's rights receives. Therefore a direct positive correlation exists between a right's reliability and its purchase price (Randall 1975) .

The perceived annual reliability of these property rights has shaped the development of specific irrigation industries. For example, …

> "[t]he different irrigation crops in the various States are reflected in the States' policies on security. In South Australia, where horticultural crops predominate, entitlements are effectively 100 per cent secure. In Victoria, irrigators' entitlements are divided into water rights which are very secure (99 years in 100) and additional sales water which is allocated as a percentage (up to 120 per cent) of water right and which is less secure" (MDBC 1995, p. 29).

To minimize risk on capital investments perennial production systems (vine and tree commodities) require access to highly secure water supplies. Perennial production

[22] The terms 'property rights' and 'water entitlements' are interchangeable within this thesis.

[23] This thesis does not disaggregate groundwater rights into alternate structures. The issues pertaining to the Basin Plan allowing trading between surface and groundwater are discussed in Section 8.6.

systems are long run investments due to their upfront costs and delays in reaching production maturity. Therefore adverse impacts on prices and yields can expose perennial capital investments to unsustainable levels of risk. The failure to provide sufficient water to perennials can result in reduced in yield and prices. Prices decrease as water constraints reduce the size of the fruit and degraded their quality. In periods of severe water shortage, the root stock can die resulting in capital loss (Carr 2012). Consequently, high security water provides as insurance against adverse climatic variability.

Surface water rights provide less security (Clark 1971; MacDonald & Young 2001) and are utilized by producers who can: access other sources of water to augment their requirements; adjust the area under irrigation to match allocations (e.g. cotton and grains); or sell their water on the market (Mallawaarachchi & Foster 2009). Water trade in the MDB has two forms, permanent and allocation. Permanent trade is the transfer of a water entitlement from one individual to another (i.e. capital investment by trading a property right). Allocation trade occurs when an individual only trades the water they have been allocated in that season (i.e. akin to leasing the entitlement).

This imbalance in property rights and CDL can also occur when producers have an inability, or reluctance to trade (Crase, Dollery & O'Keefe 2011; Crase & O'Keefe 2009) and/or lack the funds to fully develop water entitlements. In this case, water may only be used occasionally (i.e. dozers), or may have never been used (i.e. sleepers). However, by encouraging trade, underutilized resources can be engaged within a productive capacity.

2.5.4 Complexity in Water

The complex nature of property rights and hydrological realities creates a series of practical considerations, management rules and legal questions when dealing with water entitlements. For example, it is only once rainfall becomes run-off, that water property rights exist (Clark 1971). Once runoff enters a river system, at which point does a given water asset transition from an open access resource, to a common property resource and to a private right (Carruthers & Ariovich 2004)? The water flowing in a river system is a combination of both the used and unutilized irrigators' entitlement portfolio, urban entitlements, defined environmental entitlements, open access (e.g. riparian rights for stock) and residual unallocated water. When water is diverted for consumptive use, it can have either private irrigation rights (Ditwiler 1975), or community rights for potable water, and/or common property rights for environment. When water returns into the river system from consumptive use, then questions can be asked about who owns the reflow and who is responsible for negative impacts on water quality (Heaney & Beare 2001). Additionally there can be instances where irrigators, (can accidentally or deliberately) source water from the wrong entitlement structure. For example, Young and McColl (2008) identified instances where bores, operating beside rivers, were accessing surface water resources rather than groundwater resources.

2.6 Examining the Trade-Offs Between Water Users

The supply of water at a given scale and scope creates utility for farmers, rural communities, the environment and society as a whole. The allocation of water rights creates a legal framework governing water's ownership and creates a "transfer of rights to wealth" (Castle 1978, p. 2). As the utilization of water creates externalities (i.e. salinity), an efficient allocation of water rights, between all users then allows for the conditions to maximize net social welfare[24] to emerge (Ditwiler 1975). This level of welfare then embodies the socially acceptable level of pollution or trade-offs that society is willing to accept for resource use (Coase 1960).

Australia's social welfare has been reduced due to the historic water development stages that have been over allocating water resources for consumptive use. Not only have irrigators gained wealth at society's expense, but irrigators have also received subsidies to misallocate resources, in efforts to gain wealth. However, the value of water is neither constant by user group, nor through time (Quiggin 2001). Consequently as society has become aware of the losses in wealth, society's values for water and the socially acceptable levels of pollution have changed. This has allowed the new 'politic' necessity to transfer water rights between users to emerge. When these rights transfer, a change in wealth will occur, facilitating the need for ethical debate about compensating those who generated wealth at society's expense (Randall 1975).

[24] Where social welfare is defined as: the economic gains from private water use; sufficient water supplies to meet social activities; and enough water to meet the environmental health standards that are consistent with society's current expectations.

2.6.1 Urban, Social & Cultural Issues

15% of Australia's population is directly dependent on the MDB to provide all or part of their water needs and water is an integral part of the social and cultural framework required to create sustainable communities (Buikstra et al. 2010). Water is a social input which facilitates the community's ability to: survive (i.e. need water to live); undertake household chores; promote economic activities; provide recreational activities; and meet the social and cultural values found within alternative communities (Halcrow 1978). Although this thesis fails to develop the complex issues surrounding indigenous Australian's rights to water[25], it acknowledges that these rights exist. This thesis treats all parts of society as one group and considers water as an essential input for human and community health.

The total consumptive allocation to urban users within the MDB is estimated at 615 GL (MDBC 2007b) or 2% of the conjunctive water resources. This thesis assumes that the quantity of water allocated to urban areas is a fixed requirement when allocating water resources between competing users (Section 6.7.6). However, trade-offs between consumptive users still exist, when the quality aspect of water is considered.

Research has revealed that communities within cities (Viscusi, Huber & Bell 2008) and rural areas (Cho et al. 2005) are willing to pay for increased water quality, including being willing to subsidize farmers to reduce nonpoint pollution (Hite, Hudson & Intarapapong 2002). Therefore within this thesis, it will be assumed that all improvements in water quality, increases urban water users' utility.

2.6.2 Environment

The irrigation sector has been in direct competition with the environment for land and water resources. In some cases, irrigation settlements have been developed on wetlands to take advantage of their biophysical attributes. The MDB has approximately 30,000

[25] To develop an understanding of indigenous cultural values associated with water in Australia, the following four references provide an introduction into this complex area. See Jackson et al. (2012) and Mooney and Tan (2012) for a discussion on cultural values and debate concerning the need for engaging with ingenious cultures when undertaking water planning. Bark et al. (2012) discuss the internalization of cultural claims into the basin wide planning process when reallocating water shares. Nikolakis, Grafton and To (2013) deliberately contrast indigenous and non-indigenous values in water markets to develop policy approaches to prevent inequity in water resource shares from arising.

wetlands, fragmented across 25,000km^2 (MDBA 2010b). Wetlands provide habitat, for a diverse range of resident and migratory fauna and flora, including 95 endangered species (MDBA 2010b).

The developing of water for irrigation purposes has: reduced the flow to the sea from 13,000GL to 5,000GL per annum (MDBC 2006a); altered river flow patterns (Chart 2-3); and degraded both the within-channel and extensive riverine environments. While the infrastructure network provides the capacity to meet peak agricultural demands for water it has come at the expense of the environment. By changing river flow patterns, the river's morphology has changed as the natural patterns of sedimentation and erosion were lost. Infrastructure and flow management have also damaged the environment, when large scale dam water releases occur. By releasing water from a dam the river's turbidity, sedimentation and the water temperature can rapidly alter, causing further environmental harm (Sherrick et al. 2004; Walker 1985). Additionally further river channel degradation occurs when return flows transport: biological wastes (Smakhtin 2001); chemical nutrients (Doole & Pannell 2011); and salts (Lester et al. 2011) back into the river. Some of these biological wastes contribute to the development of blue green algae in low flow events (MDBC 2007a).

Kingsford (2000) identified three extensive wetland riverine degradation issues derived from water resource development. First, there is a reduced movement of genetic material between wetlands. Second, the total area of wetlands has contracted. Third, by using wetlands as storage facilities, the lack of a natural drying cycle has provided opportunities for invasive species. Additionally these changes to wetland inundation and drying patterns has led to the development of acid sulfate soil that can irreversibly degrade the ecosystem habitat (MDBA 2010c). These issues then prevent wetlands and their dependent local and migratory biota to withstand other and future adverse shocks

Davies et al. (2008) reviewed the impact irrigation has had on the MDB environment (Table 2-4). This study examined twenty-three catchments in the MDB environment and examined four indicators: ecosystem health; fish stock; macoinvertebrate health; and hydrology. A five point scale from good and decreasing to extremely poor was then used to evaluate the indicators. In total only eight 'good' ratings were awarded across the four indicators and only one of those was awarded for 'ecosystem health' in the Paroo catchment. The remaining seven 'good' ratings were awarded to the indicators evaluating the connectivity of the river's hydrology. Overall Davies et al. judged that the river's hydrology appears in better shape than the: health of the ecosystem (20 times rated poor to very poor); fish stock (20 times rated poor to extremely poor); and macroinvertebrates[26] (20 times poor to very poor).

Table 2-4 Ecosystem Health in the MDB

	Ecosystem Health	Fish	Macoinvertebrates	Hydrology
Good	1			7
Moderate	2	3	3	11#
Poor	7	9	18	5^
Very Poor	13	3	2	
Extremely Poor		8		
Total	**23**	**23**	**23**	**23**

8 of these catchments were described as moderate to good
^ 1 of these catchments was described as poor to moderate
Source: Davies et al. (2008)

Some species have taken advantage of landscape modification to offset the loss of natural habitat (Adamson, Zalucki & Furlong 2014). For example, rice production systems can provide temporary on-farm wetland habitats for water birds (McIntyre et al. 2011; Roshier et al. 2001). Additionally infrastructure conveyance losses and irrigation return flows have facilitated the development of new persistent wetlands but these wetlands are now under threat from public investments in water efficiency programs (Heard 2009).

2.6.3 Agriculture and the MDB Economy

Nix and Kalma (1982) identify four distinct climatic zones in the MDB: sub-tropical, temperate, cool-temperate and semi-arid to arid. Soil moisture is an important factor in determining land use patterns in Australia followed by topography, the original vegetation cover and soil fertility (Davidson 1967). These biophysical constraints have favored the development of low-input, low-output production systems in Australia (Keogh 2009). However, as irrigation provides supplementary moisture, it negates the primary land use production constraint associated with dryland agricultural systems, creating opportunities to diversify into other activities and allowing for input intensification. It is this associated

[26] Macroinvertebrates are freshwater crayfish, crustaceans and insects.

increase in off-farm inputs that has created a political desire to use the irrigation industry to help develop regional economies (Davidson 1967).

In 2005-06, 18,634 or 31% of all farms in the MDB were directly involved in irrigation practices and these irrigators purchased goods and services from the wider MDB community. It is estimated that there are 65,472 businesses in the MDB and that 32% of them are identified as operating in the agricultural, forestry and fishing sector. Additionally 10% of the MDB's labor force is directly employed in agriculture or its support industries (ABS, Australian Bureau of Agricultural and Resource Economics (ABARE) & Bureau of Rural Sciences (BRS) 2009).

The gross value of irrigated agricultural product (GVIAP) provides up to one third of the MDB's total GVAP (i.e. GVIAP component of GVAP in Chart 3-6). The three major irrigated commodities produced in the MDB, in 2010-11, were pasture (375,000 hectares (Ha)), cotton (332,000Ha) and cereal crops (excluding rice) (165,000Ha). MDB produced the entire Australian rice crop and the majority of the nation's cotton crop (ABS 2012b).

Over the last decade, the area irrigated has fluctuated from 0.9 million to 1.8 million Ha per annum, Table 3-1. When the total area irrigated contracted, irrigators expenditure patterns for production inputs, casual labor and discretionary spending altered (Kirby et al. 2014). Droughts create negative second round impacts on the economic activity and employment in regional communities (PC 2009). Persistent droughts eventually force structural change in the irrigation sector altering a region's economy (Buikstra et al. 2010; Dixon, Rimmer & Wittwer 2011). Consequently, proposed downward changes to the quantity of water available to irrigators, created wider public discussion (House of Representatives 2011; Quiggin, Mallawaarachchi & Chambers 2012) as a net reduction in water rights can be perceived as either a permanent drought or a permanent water trade out of a region. In this case some individuals fail to consider the wider benefits of reallocation and only concentrate on their perceived losses (see Section 8.1 for a continuation of this point).

2.7 **Summary**

The development of water resources in the MDB has focused on using impounded water storages to offset rainfall deficits (i.e. drought) so that irrigators have water when required. However, the realized spatial and temporal variability in rainfall continues to pose allocation problems for water managers, forcing irrigators to adapt. As realized rainfall patterns have generally occurred within known bounds, the engineering solutions to reduce climatic variability have provided a degree of capacity to adapt within these bounds. The Millennium Drought illustrated that rainfall bounds are not fixed and that existing engineering and management solutions fail once critical threshold have been reached, forcing transformation.

3. FUTURE THREATS TO WATER SUPPLY: THE MILLENNIUM DROUGHT EXAMPLE

3.1 Introduction

To prevent problems associated with non-convexity uncertainty, and irreversibility, water managers must understand the variable nature of water supply and how water is used by society. This includes: determining the total conjunctive supply at the disposal of water managers (Young & McColl 2008); acknowledging the temporal and spatial aspects of water supply (Ditwiler 1975); recognizing the non-linear relationships which exists between the conjunctive sources of supply (Chiew, McMahon & O'Neill 1992; Moore 1979; Noel, Gardner & Moore 1980); and identifying the future known risks (Crase, Dollery & O'Keefe 2011; Pulido-Velazquez et al. 2011) and uncertainties which may alter future water supply (Carey & Zilberman 2002; Randall 1981).

By learning to adapt to water insecurity (Ash et al. 2007; Henzell 2007) by changing inputs and outputs, Ashton and Oliver (2012) found that irrigators could generate a positive return on capital and acquire off and on farm capital holdings. This capital portfolio diversification then provides farmers with greater resilience to other adverse events (Blank et al. 2004).

However, water managers' predictions about the future availability of water are often based on models that are built with historic data or in the case of the Murray-Darling Basin (MDB) with limited and fragmented data (Connell 2007). The complexity and limitations associated with determining the Murray-Darling Basin Plan's (Basin Plan) Sustainable Diversion Limits (SDL) are detailed in Section 4.3.1 but to summarize, societies skills in predicting future rainfall is incomplete (Chiew et al. 2011) and models can only provide guidance on what may occur, and not will occur, in the future.

The Millennium Drought (Section 3.3), reminded decision makers in the MDB that like any natural system, future rainfall events are not restricted to a draw from a known and complete dataset. Even if climate change is ignored, the future realized rainfall events in the MDB will inevitably set new minimums, maximums and patterns that will alter basin wide inflows. The Millennium Drought reset all known records regarding the severity and longevity of a drought event. Such was the contraction in water supply, it has been compared to an adverse climate change shock and it forced irrigators to adapt and transform their production systems (Chiew et al. 2011; Criak & Cleaver 2008; Grafton & Jiang 2010; Heberger 2011; Mallawaarachchi, Adamson, Chambers, et al. 2010; Quiggin et al. 2010). This thesis regards the Millennium Drought as a 'Black Swan' event (Taleb 2007) as new basin wide flow and water management models have been commissioned to overcome the limitations of past models (Murray-Darling Basin Authority (MDBA) 2010a). By understanding how irrigators adapted to this 'Black Swan' or 'rare events' (Chavas, Chambers & Pope 2010) it provides insights into how producers may reallocate resources in response to a changing climate.

Climate change is expected to adversely impact both the supply and the quality of water (Preston & Jones 2008; Quiggin et al. 2010). The realized outcomes from climate change have the capacity to alter both the temporal and spatial security of alternative water entitlements (Crase & Gawne 2011; Randall 1981). These new rainfall patterns and changes to water security will subsequently force managers to adapt beyond past experiences (Mallawaarachchi et al. 2012). As the constrained-welfare approach (Section 1.2.3) is dependent on understanding the private and institutional response to changes in their allocative water share, future threats to water shares need to be examined in order to develop policy outcomes that are resilient to future changes (Crase, Dollery & O'Keefe 2011). To this end, we need to understand what has, and what could occur to water resources and their management in the MDB.

3.2 Future Threats to Water Supply

We can classify future problems and their contingencies into three levels of increasing unawareness white swans, grey swans and black swans (Taleb 2007). White swans are problems with known possible outcomes and contingencies (i.e. complete awareness). Black swan problems involve unforeseen contingencies (i.e. totally unaware) and can be created by models that are constrained by bounded awareness heuristics (Chugh & Bazerman 2007) and traditional approaches in modeling distribution tails (Chichilnisky 2010). Once realized, black swan events shake the foundations of decisions and cause non-linear responses in awareness. In this regard, despite droughts being a frequent event in the MDB, the Millennium Drought can be perceived as a black swan event as the realized outcome was outside bounded heuristics and it forced non-linear behavioral change in irrigators, water managers and policy development (Ashton & Oliver 2011, 2012; Heberger 2011; Hooper & Ashton 2009; Mallawaarachchi & Foster 2009).

Climate change is neither a white swan nor a black swan but rather it is a grey swan. A grey swan is a situation where the problem is known and we are aware that the complete set of outcomes and contingencies is unknown. Grant & Quiggin (2013b) discuss that via inductive reasoning, decision makers become aware of needing to deal with unknowns concerning grey swan problems. Thus the Millennium Drought (realized black swan) provides guidance to understanding climate change (grey swan) and how decision makers may adapt to future 'rare events'. However, climate change is not the only other threat to future water resources.

3.2.1 Climate Change impacts on water supply[27]

Water, is a crucial input to agricultural production. The Intergovernmental Panel on Climate Change (IPCC) (2007b) concludes that, for the world as a whole, the negative effects of climate change on freshwater systems outweigh its benefits. In addition to raising average global temperatures, climate change will affect the global water cycle. Globally, mean precipitation (rainfall and snowfall) is projected to increase due to climate change. However, this change will not be uniform, and projections are subject to substantial uncertainty, as discussed later.

Climate change is projected to increase the variability of precipitation over both space and time. It is predicted that average precipitation will increase in high rainfall areas and decrease in most arid and semi-arid areas (Millet et al. 2005). Where precipitation increases there are likely to be more frequent events involving very high rainfall, such as monsoon rain associated with tropical cyclones (IPCC 2007a). Severe droughts are also likely to increase by multiples ranging from two to ten, depending on the measure (Burke et al 2006), particularly in the temperate zone between 30 and 60 degrees latitude. In addition, higher temperatures will lead to higher rates of evaporation and evapotranspiration, and therefore, to increased demand for water for given levels of crop production (Döll 2002). Water stress (the ratio of irrigation withdrawals to renewable water resources) is likely to increase in many parts of the world (Arnell 2004).

[27] This section draws heavily from Quiggin et al. (2010, p. 534)

The evidence from 15 different climate change models suggests that the MDB will become hotter, drier and droughts may become more frequent (Chiew et al. 2011). The climate change scenarios used in this thesis are presented in Section 4.4.

3.2.2 Other Shocks

Climate change is not the only issue to confront future conjunctive water supply. Other unknowns include, but are not limited to: the continuing investment in on-farm water harvesting in the Northern Murray-Darling Basin (NMDB); other sources of landscape modification that interact with water supply; and the outcomes to the conjunctive water resource base from policy signals. For example, Schrobback, Adamson and Quiggin (2011) modeled an unintended and negative policy shock to water resources, from carbon farming. Here the mitigation or adaption response to a changing climate provided incentives for irrigators to invest in silviculture, creating a second round negative impact on future water resources. The arguments presented in that paper were[28]…[w]e assumed that for-harvest forestry is only economically viable on productive land rather than on less productive land in order to achieve high carbon and timber yields.

Based on the assumptions, data sets for commodities and the model used in [that] study the simulation results demonstrate that a carbon emissions permit price of at least $100 per ton of carbon dioxide (CO_2) will be required for land users in order to create a price incentive for large scale forest plantations to be established in the Basin's south-eastern catchments. This result holds both for baseline climatic conditions and for a climate change scenario representing the implications for water availability of the stabilization of atmospheric CO_2 levels at 550 [parts per million] ppm. For the climate change scenario we found that larger areas are turned into forestry compared to the baseline climate scenario. This is due to decreased runoff interception and changes in the irrigation water requirements of forests compared to perennial commodities. However, the assumptions made for runoff generation in the model are extensive, in particular the linear relationship between water-soil-biomass regimes. This bears some modeling uncertainties which may affect the results presented here.

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[28] The remained of this section is a quote from Schrobback, Adamson and Quiggin (2011, pp. 37-8).

Subsequent to changes in land use patterns towards forestry we found that water use and water quality decreased overall with an increasing carbon permit price. The water quality in the drought state of nature declined so extensively in both climate scenarios that Adelaide's water quality target of 800 electrical conductivity (EC) was exceeded at a carbon permit price of $100. Furthermore, the environmental flows at the end of the system decreased so significantly with increasing carbon permit prices in the dry state of nature that the health of the Coorong was jeopardized.

The results from this study suggested that the contribution of forestry establishments in the south-eastern catchments of the Basin to emission mitigation will remain modest even under high carbon permit prices. It is also to be noted that under current policy settings, a permit price of $100/ton is unlikely to be realized in the medium term. Although the establishment of plantations in the region examined in this study may be a profitable alternative to conventional agriculture in the medium term, it seems likely that carbon sequestration through forestry will be commercially viable in other parts of Australia at significantly lower prices (Harris-Adams & Kingwell 2009).

However, in the light of uncertainties about carbon yields due to spatial and climatic characteristics and the future carbon price risks in a market that is subject to development, farmers may opt for more conservative agriculture land allocation decisions.

Future research on the impact of a carbon price incentive on land use changes and associated water yield impacts may investigate water allocation regimes that do not account for the water interception of plantations as previously recommended by Young & McColl (2009).

In such a setting, water could be extracted from foresters without purchasing water entitlements which could be an additional incentive for farmers to reallocate irrigated agricultural land to forestry. This would illustrate a situation where a national policy and regional water policy are not corresponding. Results of such a scenario are likely to reveal more severe negative social and economic externalities than reported in the present study.

In conclusion, the analysis reported here suggests that the option of carbon sequestration through forestry is unlikely to displace irrigated agricultural production of the Murray–Darling Basin to a significant extent in the short or medium term.

3.2.3 Adapting to Future Water Supply Shocks

Australian agricultural producers have continuously engaged in the process of adaption since European settlement to deal with, or take advantage of, policy signals, the biophysical attributes, technological opportunities, market forces, and diversification strategies (Donald 1982; Henzell 2007; Powell 1982; Shaw 1982). One key biophysical driver of adaptation has been learning to deal with the alternative phases of El Niño Southern Oscillation (ENSO) (Section 2.4). Producers have leant to maximize their returns under climatic variability (Hayman et al. 2007) based on their experience, management skills and ability to use alternative information sources (Ash et al. 2007) to help guide their final decisions with varying degrees of success (Mallawaarachchi & Foster 2009).

Producers are continually learning to adapt to the inherent variability in the system (Byerlee & Anderson 1982). However, a producer's ability to respond to a future event may be limited by their prior relevant experience to the event (Goldstein & Gigerenzer 2002), their ability to recognize or predict the event (Lindner & Gibbs 1990; Makeham & Malcolm 1981), their past management success in dealing with the event; any biophysical, financial and capital investment constraints on the farming enterprise; and factors outside of their control which constrain their choice sets (Mallawaarachchi et al. 2012).

By reconsidering the above decision in a state-contingent approach (Section 5), a manager's bounds (e.g. experience and management response) may reduce their awareness about all outcomes in states of nature (e.g. solutions to deal with a lack of water availability) and the description of each state (e.g. just how extreme can a drought be). Changes to the problem set (e.g. water availability in a drought or climate change) can result in resource misallocation occurring until new successful solutions are determined by the decision maker. As Grant and Quiggin (2013b) discuss, when decision makers' experiences are 'ecologically rational' (Goldstein & Gigerenzer 2002) cognitive heuristics rapidly improve their awareness, which increases their welfare. To this end, once a decision maker has experienced a state of nature (i.e. drought), the decision maker is more likely to make a better decision next time. However, if the time period between the adverse events occurring, can be classified as the long run, then changes to the irrigation property (e.g. new crops and new infrastructure) may decrease the value of past experiences to help guide solutions to the current adverse event.

Irrigators will continue to adopt and adapt the risk mitigation strategies learnt during the Millennium Drought. These strategies included: strategically over irrigating commodities to manage salt (Connor et al. 2012); engaging in both the temporary allocation (Loch et al. 2012; Loch et al. 2013) and permanent water trade markets (Mallawaarachchi & Foster 2009) to either purchase more water or obtain funds; strategically purchase additional water rights in anticipation to counter, future changes to the security alternative water rights provide (Beare & Heaney 2002); utilizing water carryover strategies (Sanders, Goesch & Hughes 2010); increasing their reliance on groundwater (Jiang & Grafton 2012); and adapting to short and long run supply scarcity by altering the commodity produced, the total area irrigated, or their production system to align with the revealed climate to maintain or improve their economic viability (Adamson, Mallawaarachchi & Quiggin 2009). Adaption will continue in the future and as knowledge is gained, farmer's responses to new and unforeseen problems will continue to exhibit non-linear characteristics (Barucci & Landi 1998).

3.3 Using the Millennium Drought to expose the Grey Swan

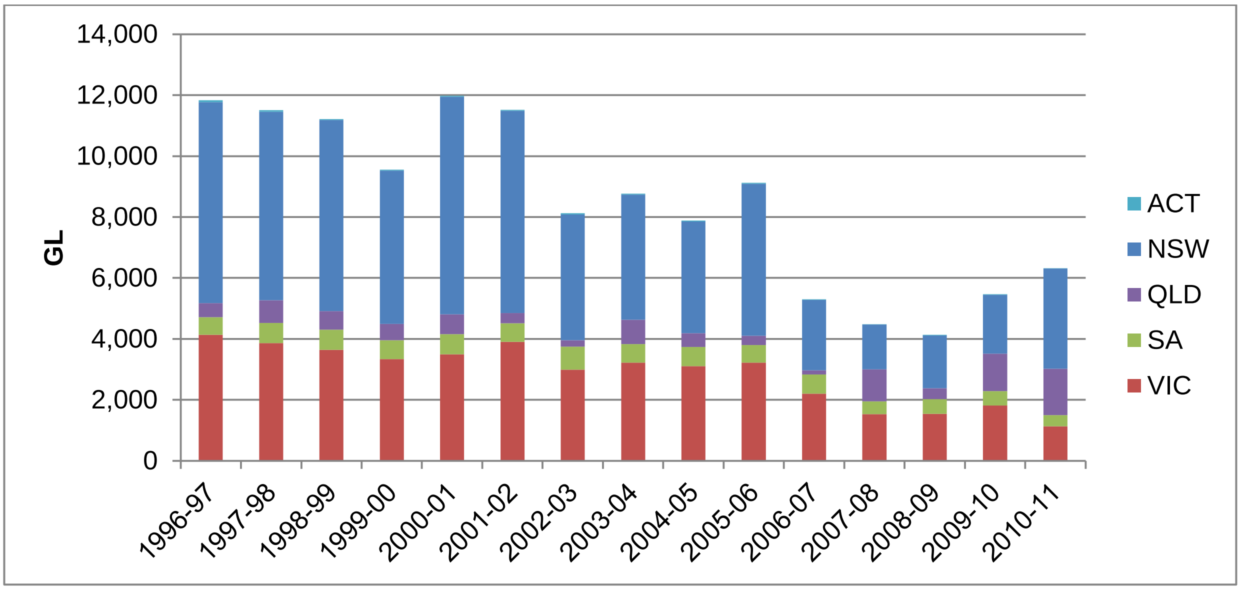
The longevity and severity of the Millennium Drought surpassed all recorded water availability history in the MDB's (Heberger 2011; Kirby et al. 2014). The drought started in the mid-1990s and lasted until 2010 (PC 2009; Leblanc et al. 2012). This drought exposed the short-run nature of supply management strategies; changed irrigators' expectations about both the future reliability and the value of alternative water entitlements (Wheeler, Zuo & Bjornlund 2013); and it provided the emphasis to shift water resource policy development away from a state level focus to a national focus (Connell & Grafton 2011; Crase & O'Keefe 2009).

This thesis divides the Millennium Drought into four stages: business as usual; the white swan; adapting to the black swan; and the recovery stage. It will be argued the first two stages of the drought could be modeled as a white swan as the reduction in water supply and the management response was known with some degree of certainty. However, the adapting to the black swan occurred as the longevity and severity of the drought exceeded past experiences and resulted in new management responses. The recovery stage, is defined by the breaking of the drought in the Southern Murray-Darling Basin (SMDB). The discussion concerning the drought is primarily built upon the amount of water that was diverted for consumptive purposes (Chart 3-1), the area irrigated (Table 3-1), and volume of water provided to the environment which in simplistic terms is represented by the level of water in Lake Alexandrina[29].

3.4 Business as Usual (Mid 1990's till 2001-02)

Despite low rainfall from 1997 (Chiew et al. 2011), the Millennium Drought did not alter the quantity of water diverted in the MDB (Chart 3-1), with the exception of 1999-00 when diversions in Murrumbidgee and Murray were low. The early stage of the drought in 2000-01 to 2001-02 had negligible impacts: with over 1.8 million Ha being irrigated (Table 3-1); and flows to Lake Alexandrina (Chart 3-2) show little variation, until October 2001.

Chart 3-1 Total Water Diversions in the MDB (GL), By Territory, By Year



Source MDBA (2009b, 2010d, 2011f, 2012d) and Murray-Darling Basin Commission (MDBC) (1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006b, 2007b, 2008)

This decreased flow to Lake Alexandrina appears to be a consistent management strategy of penalizing and compensating environmental flows. The decreased flows are consistent

[29] Lake Alexandrina is the largest lake in the Coorong wetland system. The Coorong is the terminal point in the river system before the Murray River flows into the sea and a series of barrages prevent the sea from intruding along the river system during periods of low, as illustrated in Figure 2-3.

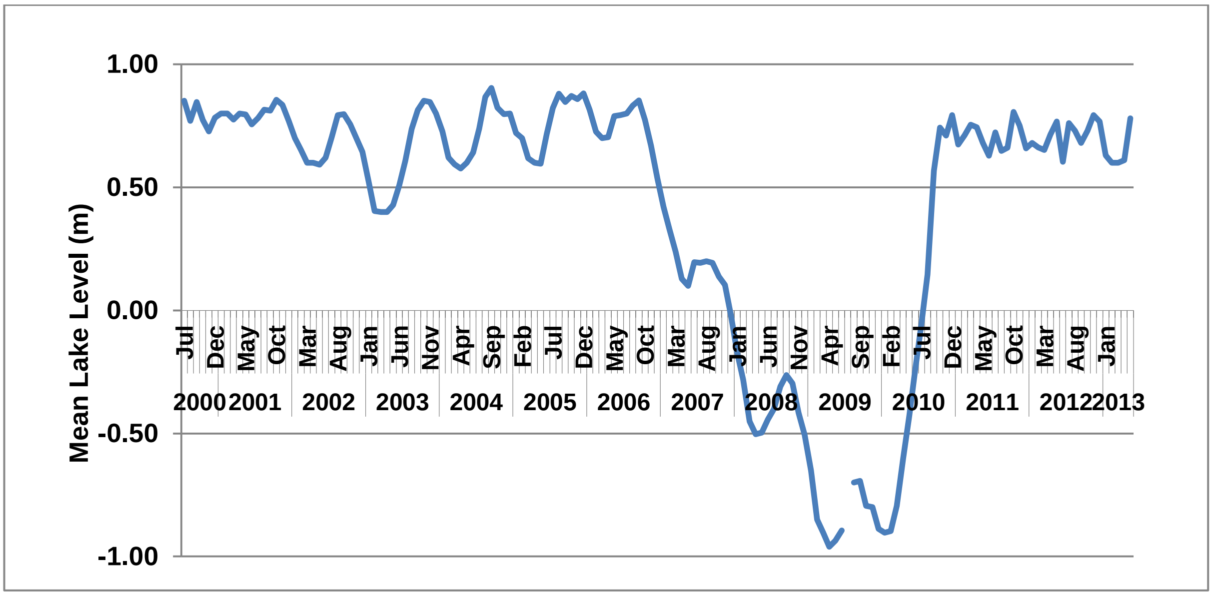
with ensuring peak private demands for water in spring and summer demands and compensation flows being provided to Lake Alexandria during the 2002 winter period. The business as usual stage then suggests that the water storage infrastructure and water management rules were capable of dealing with this level of water scarcity.

Table 3-1 Area Irrigated in the MDB by Commodity ('000 Ha)

Commodity group	2000-01	2001-02	2002-03	2003-04	2004-05	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11
Pasture for livestock	760	707	551	669	703	717	446	365	267	393	375
Rice	178	145	44	65	51	102	20	2	7	19	74
Cereals (excl. rice)	260	354	416	340	324	329	266	291	291	216	165
Cotton	405	394	218	174	258	247	126	53	128	138	332
Grapes	84	86	89	87	92	106	112	106	102	96	94
Fruit (excl. grapes)	59	62	74	59	63	75	78	71	69	79	80
Vegetables	37	35	31	40	35	32	26	28	25	25	32
Other	41	34	43	67	62	46	26	35	35	8	3
TOTAL Irrigation#	**1,824**	**1,817**	**1,466**	**1,501**	**1,588**	**1,654**	**1,101**	**958**	**929**	**976**	**1,201**

#totals vary due to rounding errors and double cropping. Double cropping is when the same area of land produces more than one crop during a year (e.g. a single hectare is used to produce both a summer and a winter crop).
Source Australian Bureau of Statistics (ABS) (2008c, 2008d, 2009, 2010b, 2011b, 2012b)

Chart 3-2 Water Level in Lake Alexandrina (meters (m))



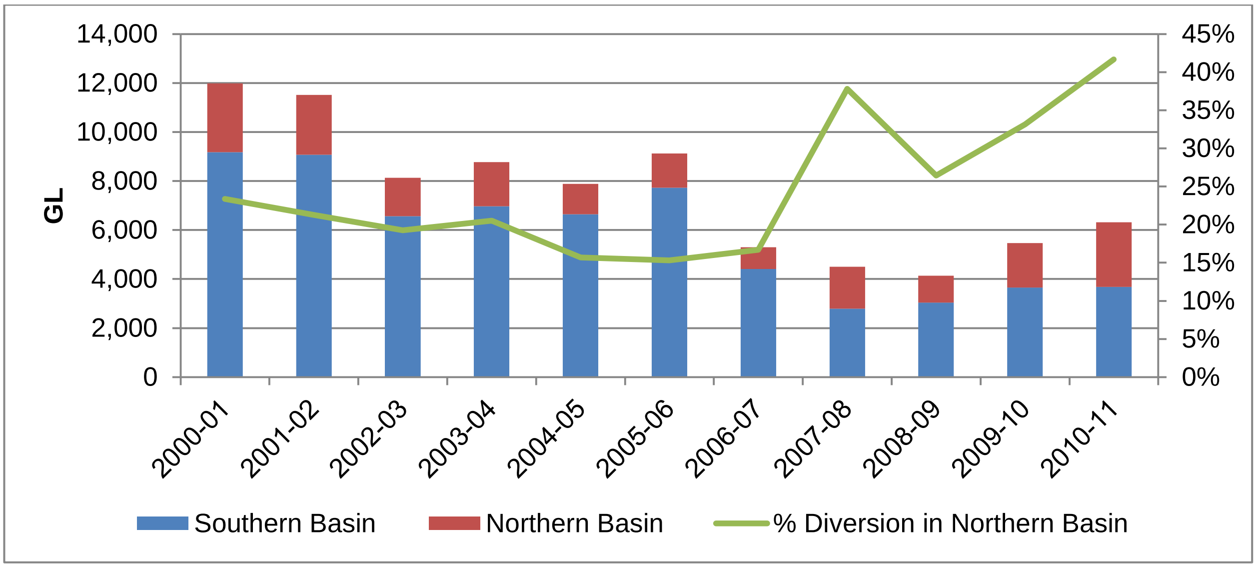
Data Source from MDBA pers. comm., Aftab Ahmad August 2013

3.5 **The White Swan (2002-03 till 2005-06)**

The second stage of the drought is marked by a decrease in average diversions, from the 1996-97 to 2001-02 period, of 11,267GL decreasing to 8,474GL over the 2002-03 to 2005-06 period (Chart 3-1). This 25% decrease in the water diversions only reduced the area dedicated to irrigation by 15% (Table 3-1).

Between 2001-02 and 2002-03: the quantity of water diverted in New South Wales (NSW) fell by 2,505GL (a 38% reduction); 23% less water was diverted in Victoria (VIC) (909GL); diversions in Queensland (QLD) contracted by 128GL (38% less); and in South Australia (SA) increased diversions by 145GL (a 24% increase). On a regional scale diversions in the SMDB and NMDB reduced by 2508GL and 883GL, respectively (Chart 3-3). As a percentage these regional diversions reduced by 36% and 28% respectively in the NMDB and SMDB. Irrigators reduced the area allocated to pasture, rice and cotton and increased the area dedicated to perennials and cereals (Table 3-1). Unlike the 'business as usual' stage, the time taken to restore the water level in Lake Alexandrina began to increase (Chart 3-2).

Chart 3-3 Water Diversions, NMDB Compared to SMDB (GL)



Source MDBA (2009b, 2010d, 2011f, 2012d) and MDBC (2001, 2002, 2003, 2004, 2005, 2006b, 2007b, 2008)

Without understanding the system, the data for 2005-06 can be misleading as when compared to 2004-05, the total volume of water diverted increased, the area irrigated increased and flows to Lake Alexandria have improved, the real situation is different. By

2005-06, the continuing lack of rainfall resulted in the security of all entitlements being re-evaluated. In the Goulburn Broken high security entitlements that had an historic reliability of receiving their entire allocation in 99 years out of 100 (MDBC 1995, p. 29) were only devalued by 70% (National Water Commission (NWC) 2011a)[30]. The reality was, the system was approaching a crisis.

3.6 **Adapting to the Black Swan (2006-07 to 2009-10)**

In 2006-07 all known water management rules in the MDB ceased to apply when only 5,270GL of water could be diverted. During this period (2006-07 to 2009-10) water diversions averaged only 4,852GL and this represents only 43% of diversions during the business as usual stage. It was within this period, that social preferences changed, forcing policy action in an attempt to deal with the on-going social, economic and environmental cost of the drought (see Section 4.2).

Past investments in infrastructure (i.e. barrages, see Figure 2-2) prevented large scale salt water intrusion along the river system. However, protecting the river system from salt water intrusion, the barrages also allowed the prioritization of private rights to initially continue and the water level in Lake Alexandria fell to nearly one meter below sea level, from 2008 until July 2010 (Chart 3-2). The continuing penalization of environmental flows, nearly caused the total collapse of the marine and avian populations in the Coorong due to rising river salinity and the exposure of acid sulfate soil (Kingsford et al. 2011). The changes to water policy (Section 4.2) forced by the drought, did result in change. By late 2009, arguably for the first time ever, iconic environmental assets along the MDB received water before irrigators to prevent total ecosystem collapse (Australian Government Department of Sustainability Environment Water Population and Communities (SEWPaC) 2010; MDBA 2011d).

By 2007-08 the lack of water combined with the opportunity costs associated with water sales (Wheeler et al. 2012), effectively ruled both rice (2,000Ha) and cotton (53,000Ha) out as a viable farming system. On-going water shortage continued to contract the area irrigated and by 2008-09 only 900,000 Ha was irrigated, which was half of the area

[30] In other words for each ML of high security entitlement owned, irrigators only received 0.3ML.

irrigated in 2000-01 (Table 3-1). The single largest reduction in area was pasture where between 2000-01 to 2008-09, over 500,000Ha had transitioned out of irrigation.

In December 2007, significant rainfall broke the drought in the northern MDB. This rainfall arrived too late for the cotton crop but producers were able to irrigate an additional 300,000Ha of sorghum compared to the previous season (ABARES 2010). The NMDB continued to receive above average rainfall from 2007 to 2010 and as a proportion, diversions in the NMDB increased from 20% of MDB diversions to over 40% (Chart 3-3). The NMDB rainfall also provided critical flows for the entire river system (MDBA 2011f).

The area dedicated to perennial horticulture (grapes and fruit) in the MDB continued increasing up until 2006-07. But in 2007-08, the area dedicated to perennials started contracting in response to: decreased water security; adoption of adaptive water management strategies including efficiency gains and timing (Connor et al. 2012); and responding to the water prices (Section 3.6.2).

3.6.1 Adapting with outputs and inputs

Despite the reduction in area, especially for annuals, a corresponding reduction in GVIAP is not evident, as illustrated in Table 3-2 and in Chart 3-6 where the GVIAP component of the GVAP is provided. This GVIAP data although informative, does not reflect how producers adapted, for four reasons. First, gross value is income and not profit and this prevents examining the changes to inputs and outputs. Second, it does not stipulate if the commodity was partly or fully irrigated. Third, homogenous prices and default rules are used for estimating production yield. Fourth, the processes of calculating GVIAP have changed through time (ABS 2008b).

Attempts have been made to determine the impacts droughts have on output prices to correlate back to producer responses. For example, Kirby et al. (2014) used a formula that assumed all changes to price were derived from the drought. However, with 70% of Australian agricultural GVAP derived from export sales (ABARES 2013), a high Australian dollar (PC 2013b), an oversupply of produce in some sectors (e.g. process fruit (PC 2013a)), locked in forward selling contracts (e.g. dairy), and efforts to preserve the capital investment in perennials, the use of a single relationship between output prices and drought may be misleading. Although Kirby et al. (2014) do identify that output per Ha did increase, and this is likely to be due to less efficient producers selling water to more efficient producers.

Table 3-2 Value of Irrigated in the MDB by Commodity ($'million Ha)

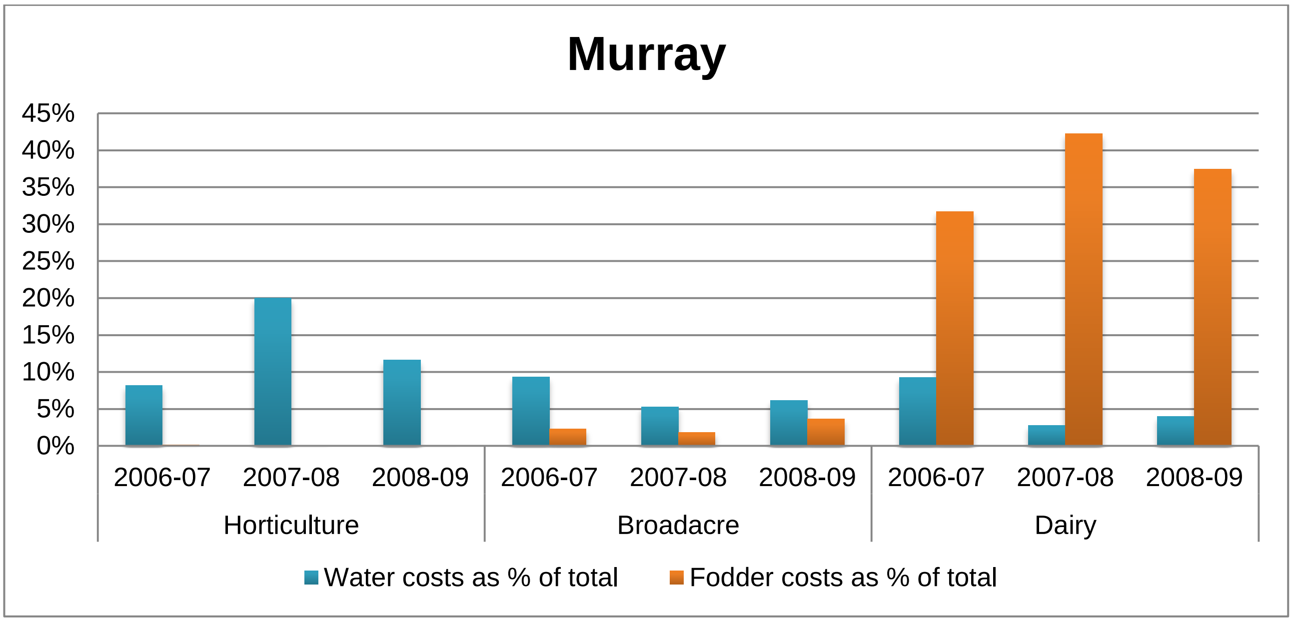
Commodity group	2000-01	…*	2005-06	2006-07	2007-08	2008-09	2009-10	2010-11
Hay & silage	80	…	161	176	139	80	97	66
Rice	349	…	274	55	7	34	89	171
Cereals (excl. rice)	149	…	180	191	269	279	122	140
Cotton	1,111	…	798	457	193	562	617	1,505
Grapes	785	…	721	651	1,104	598	719	671
Fruit (excl. grapes)	701	…	1,011	1,207	1,182	1,032	1,081	1,285
Vegetables	468	…	555	556	718	564	539	615
Dairy	804	…	901	763	961	791	624	836
Other Livestock Production	508	…	736	723	258	234	340	505
Other	90	…	150	129	247	119	139	151
TOTAL Irrigation#	**5,085**	…	**5,522**	**4,922**	**5,079**	**4,349**	**4,386**	**5,944**

#totals vary due to rounding errors
*data is not available from the ABS over the period of 2001-02 to 2004-05
Source ABS (2008a, 2011a, 2012a)

Arguably the preservation of MDB wide income was in part due to the changing net return per ML from alternative enterprises and the ability of irrigators to switch between inputs to produce alternative outputs in response to climatic and price signals. For example, Chart 3-4 examines changes in water and feed input costs as a percentage of total costs for the horticulture, broadacre and dairy industries from 2006-07 till 2008-09.

The data in Chart 3-4, suggests that for a horticulture producer water costs as a percentage of total costs increased in 2007-08, from less than 10% to 20%. The demand for water increased water prices in both the temporary (Chart 3-5) and permanent water market. These price signals then allowed dairy producers to adapt by selling their water and purchase fodder (Ashton & Oliver 2011; Ho et al. 2007). Chart 3-5, illustrates the dairy adoption, where the expenditure on water fell by about 5% and fodder costs increased by about 10% from 2006-07 to 2007-08. This adaption of responding to signals, by altering inputs is a key feature of the SCA model (Section 6). Irrigators then rapidly adjusted to water price signals by altering their water purchasing strategies and the water requirements of their production systems.

Chart 3-4 Water & Feed Costs as a % of Total Costs by Irrigation Farm



Source Ashton & Oliver (2011)

Adaption has proven to be influenced within regional economies, for example …

> "[t]he discussions with local industry in northern Victoria provided a contrast to the MIA region, in particular due to the significant adjustment taking place in the dairy industry, both in response to reduced water availability and reduced farm gate prices for milk. Evidence indicates that water trading has facilitated this adjustment, by allowing dairy farmers to substitute purchased feed for irrigation water, and allowing some dairy operators to switch over to producing feed (silage and hay) to supply the feed requirements of remaining dairy producers. Low rainfall and water allocations in 2008-09 have increased the dependence on bought-in supplementary feeds. Increasing feed costs and decreased income due to dairy price step downs have created cash flow pressures, forcing many producers to make significant changes to their operations. Uncertainty regarding their operations has increased and the seasonal conditions, irrigation water availability and grain prices have been the critical factors impacting on the viability of enterprises for most producers in the region. These observations are consistent with other available evidence (Khan et al. 2010; Murray Dairy 2010)." (Mallawaarachchi et al. 2011, p. 23).

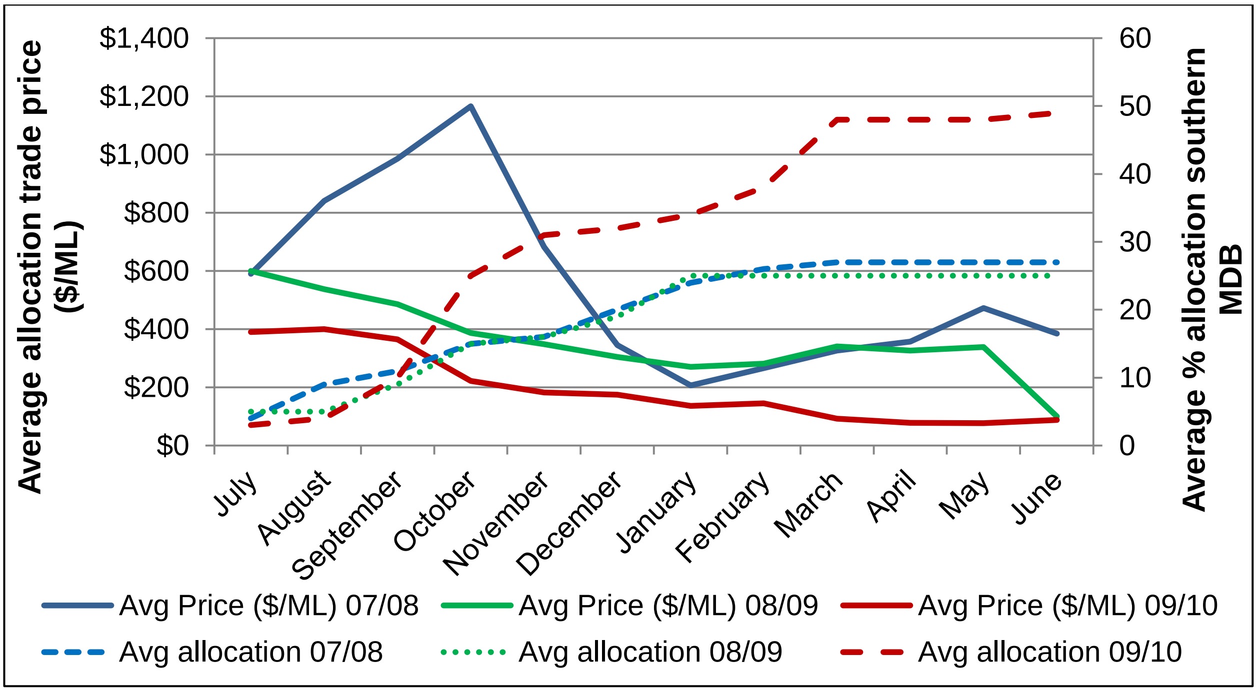
3.6.2 Water Trade, Water Prices and Adaption

Singh, Bari and Flavel (2008), detail that the average price paid per ML for water on the allocation markets during 2004-05, 2005-06 and 2006-07 in the Murrumbidgee was $80, $37 and $170/ML, respectively and in the Murray and Lower Murray-Darling it was $58, $42 and $187/ML respectively. However, the rapidly increasing prices during 2006/07 were only a precursor of the price that irrigators were willing to pay for water.

On July 2007, the average price paid for water on allocation market reached $600/ML in the SMDB (Chart 3-5) when only 9% of irrigator's entitlements were allocated. The price paid for water continued to increase throughout the spring period when it nearly reached $1,200/ML in October 2007, when only 15% of allocations were provided.

Irrigator's were willing to pay this price for water to preserve their capital investment in perennial root stock (Wheeler et al. 2012). However, despite the allocation announcements in 2008/09 almost mirroring the 2007/08 season and the initial allocation announcements in 2009/10 being lower than 2007/08, the average price paid for water on the allocation market fell (NWC 2009, 2010).

Chart 3-5 The Average Monthly Price of Water on the Allocation Market in the SMDB ($/ML)



Source Loch (2011)

The 2007-08 price signals forced a response in producer behavior. Both water purchasers and water sellers, rapidly adjusted and adopted intra- and inter-seasonal strategies (Loch et al. 2012). As Goldstein and Gigerenzer (2002) discussed, once decision makers have experienced new extremes, their use of differential learning allowed them to rapidly adapt and improve their welfare (Grant & Quiggin 2013b). In this case, high water prices encouraged irrigators with annual commodities to maximize their welfare from water use by selling water to other irrigators. By increasing the supply of water in the allocation market, downward pressure was placed on the price paid for water (NWC 2011a). Secondly to maintain long run viability irrigators engaged in a variety of alternative management options including: decreasing their demand for water by either reducing the area of perennial crops; or adopting alternative irrigation strategies (Mallawaarachchi & Foster 2009); or lowering their expected irrigation costs by purchasing water and carrying it over for the 2008-09 season (Loch *et al*. 2013). Consequently by October 2008 the price of water was only $387/ML, a decrease of nearly $780/ML compared to the previous year.

As farmers continuously adapted to the black swan, their experiences changed the swan's color to grey. This transformation was evident as by 2009-10, despite initial allocations being less than both previous years, the opening price in the allocation market was $200 less (Chart 3-5). Water trade and the removal of water trade barriers (Australian Competition and Consumer Commission (ACCC) 2008; NWC 2011a) provided the capacity for irrigators to adapt to the Millennium Drought and the clear price signals within the market allowed decision makers to rapidly adapt (Grafton, Libecap, et al. 2011). The price for water continued to fall throughout 2009/10. In December 2010, the drought finally broke in the SMDB and it was correlated to a La Niña phase (BOM 2012).

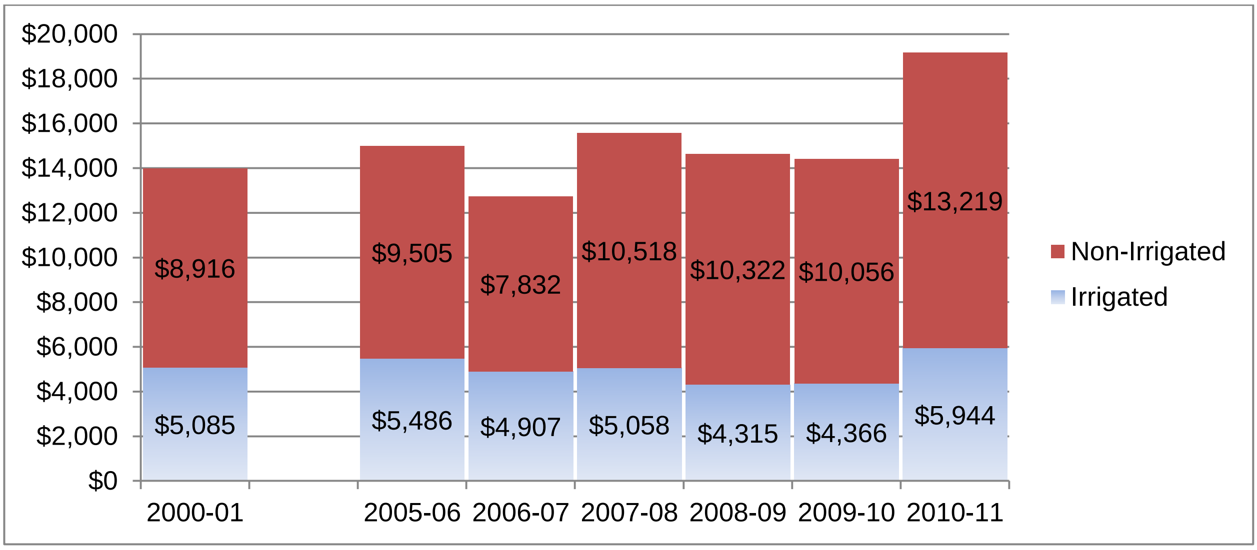
3.7 **The recovery**

The breaking of the drought is evident in Chart 3-6, where in 2010-11 both the income obtained from dryland and irrigated activity increased by over $5 billion when compared to 2009-10. Farmer adaption is still continuing in the recovery phase. For example, in the dairy industry as..

> …[i]t seems likely that the system is now facing significant challenges. Increased water allocations in the 2010-11 season has virtually dried up water allocation trades thus denying dairy farmers access to a supplementary income. While on the other hand, improved seasonal conditions have greatly improved the feed supply

situation, and the price of fodder has collapsed leaving reduced income prospects for feed growers. Moreover, those who took advantage of the seasonal conditions to grow grain crops are also facing prospects of grain quality downgrades or crop losses due to continuing rain (Mallawaarachchi et al. 2011, p. 23).

Chart 3-6 MDB GVIAP Component of GVAP ($ million)



Source ABS (2008a, 2011a, 2012a)

Adaption will continue in the MDB. Initial adaption may not provide a feasible solution and short term failure to identify the threats exists, the rapid nature at which managers alter their response to on-going problems has proven to be swift.

3.8 Summary

The over allocation of water is exposed once resource shares are allocated and water cannot be supplied. Water resources in the MDB are highly variable and their future supply is uncertain. When the total volume of rights exceeds the capacity of the system to deliver water, a non-convex response occurs, creating irreversible economic, social and environment losses. Irrigators, society and the environment can adapt up to a point when water scarcity occurs, but when facing continuing and increasing pressure individuals must transform existing strategies (i.e. learning to adapt to the black swan, makes it a grey swan). By dealing with the risks and uncertainty associated with conjunctive water resources, the adverse consequences from non-convexity and irreversibility may be reduced.

The Millennium Drought highlighted that in the mature stage of water resource development, irrigation production systems and river management strategies are tuned to expected or known variability of water. Consequently under prolonged drought periods water resource scarcity causes significant economic loss via irrigation capital exposure, environmental degradation and reduction in water quality. This fragility is exposed when both the mean and variance of water supply change (Adamson, Mallawaarachchi & Quiggin 2009).

Risk (Crase, Dollery & O'Keefe 2011) and uncertainty (Carey & Zilberman 2002; Randall 1981) associated with future temporal and spatial water resource scarcity (Ditwiler 1975) will continue to pose resource allocation problems for all water uses. Knowledge about the future climate is incomplete, but it is expected that there will be less water and droughts may become more frequent. Therefore how irrigators adapted to the Millennium drought may provide guidance on future adaption strategies. The information presented above revealed that irrigators actively adopt strategies to deal with water scarcity. It is acknowledged that the authors own subjectivity and heuristic bounds (Sections 4 to 7) will prevent the full range of possible adaption strategies to the grey swan from emerging. These bounds then constrain the value of the analysis in Sections 8 to 10.

The constrained welfare optimization model then has to incorporate how a redistribution of property rights alters the behavior of individuals to aggregate reduction in supply and how those individuals reallocate resources to deal with variability in the known supply and shocks to future water supply. The analysis also needs to consider if the reallocation of water rights can meet the policy objectives (i.e. contestants) and determine if future climate events alter the cost-effectiveness of alternative approaches to achieve these objectives.

4. THE CONTRACTION STAGE OF WATER RESOURCE DEVELOPMENT AND HYPOTHESES INVESTIGATED IN THE PHD

4.1 Background

The conception of the contraction stage of water reform was initiated within the maturity stage of water resource development (Section 2.3.3) and The Living Murray Initiative (Table 2-2) heralds the first policy attempt at returning water to the environment. However, it was the Federal Government's response to the Millennium Drought, the 2007 Water Act that is the major policy platform of the contraction stage of water resource development. As the 1914-15 drought provided the impetus for the River Murray Agreement, the Millennium Drought provided the opportunity for the Federal Government to take over the responsibility for developing a national approach to water reform in the Murray-Darling Basin (MDB).

The purpose of this section is to introduce the contraction state of water resource development and discuss the economic theory behind the approach used. This section also provides a discussion of the idealistic characteristics the contraction stage should have. These idealistic characteristics help frame a series of hypotheses used to test if the Murray-Darling Basin Plan (Basin Plan) utilizes public funding efficiently and effectively to provide long term welfare improvements.

4.2 Changing Social Preferences, Policy Steps and Millennium Drought[31]

In April 2002, the Living Murray Initiative was introduced to restore the environmental health of the river system. This initially involved transferring two key Murray-Darling Basin Commission (MDBC) programs to the Living Murray First Step, the Salinity Interception Scheme (SIS) and the Native Fish Strategy. The aim of the Native Fish strategy was to restore the population of native fish to 60% of pre-European levels by developing fishways[32] and by returning snags into the river (Craik & Cleaver 2008). Additionally the aim of the Living Murray was to increase environmental flows and scientific advice

[31] This section extensively draws from work published in Loch, Adamson and Mallawaarachchi (2014).

[32] Fishways are designed to allow fish to by-pass the dams, locks and barrages are designed to regulate river flow.

suggested that to have a ‘high’ probability of success, 3,350GL of water was needed to restore the rivers health (Connell & Grafton 2011). These return flow recommendations were not accepted by the government but in 2003, $500 million was allocated to provide water for six icon sites along the Murray River (Murray-Darling Basin Authority (MDBA) 2011b). However, as Cummins and Watson (2012) argue, the Living Murray is more akin to a transition process between the third and fourth stage of water resource reform. As the Living Murray provided greater rationality in its debates concerning the environment and the value of water-trade, the process for restoring environmental flows concentrated on subsidizing on and off-farm water use efficiency, rather than market based instruments (Cummins & Watson 2012).

As the drought progressed, the Council of Australian Governments (COAG) water reform agenda was extended when the National Water Initiative (NWI) was established in 2004. The NWI was developed to promote market based systems to improve water security. This included redefining the legal definitions of alternative property rights structures, providing the framework to help unbundling water and land property rights, removing other policy and regulation impediments to water trading (Australian Competition and Consumer Commission (ACCC) 2008), and promoting the development of comprehensive water plans to protect all water users and hydrological systems (Connell & Grafton 2008). The COAG approach incentivized State jurisdictions to work co-operatively towards a national framework by using Federal funding (Crase & O'Keefe 2009).

However, by 2006 Basin environmental conditions had deteriorated rapidly, and media attention increased public awareness about over-allocation problems, leading the Federal Government to act. Fuelled by environmentalist claims and severe drought effects, a *National Plan for Water Security* was formulated with limited economic or scientific analysis. Essentially, perceived changes in social preferences communicated through mass media and collective action of interest groups brought about policy change aimed at maximizing net social welfare.[33] Initial reaction from the beneficiaries of the status quo was to oppose government redistribution of rights to water resources, and the government‘s challenge was to communicate to the public that the change was, in fact, welfare

[33] Net social welfare occurs via maximizing private rents subject to environmental and social standards. Notably, this policy change both strengthened consumptive (irrigation) property rights and increased their relative value due to a reduction in future supply uncertainty from continued over-allocation. This created private welfare gains. Consumptive water users would also be expected to benefit from further private welfare gains from enhanced environmental public good values and sustainability.

increasing, taking all benefits and costs into account. This challenge was complicated by difficulties in identifying and implementing appropriate instruments to achieve this policy change, such that the total implementation costs did not exceed the perceived benefits, and that the original policy intent remained intact. However, as noted, heightened public concerns spurred the Australian government to enact a national Water Act (2007) which, among others, provided for the creation of the Basin Plan to achieve large-scale water reallocation and implement sustainable levels of extraction. A target figure of 3,200GL of surface water will eventually be reallocated to the environment—although access to an additional 929GL of groundwater resources (Table 7-5) will be provided by way of economic and social compensation.

4.3 The Basin Plan & the Contractionary Stage of Water Resource Development

In 2008 the Water Act was renamed Water for the Future (Crase & O'Keefe 2009). This initiative provided the framework to establish the Murray-Darling Basin Authority (MDBA), which was given the responsibility of determining the quantity of the water the environment needed, and the Commonwealth Environmental Water Office (CEWO)[34], which was given the responsibility of managing this environmental water.

Key to restoring the balance was that the MDBA had to improve water security for all water users in the MDB by determining a Sustainable Diversion Limit (SDL) to replace the existing CAP. As the reform process is designed "to promote the use and management of the Basin water resources in a way that optimises economic, social and environmental outcomes" (Commonwealth of Australia 2008, p. 3), it had overcome a key impediment to the decision making process experienced in the Living Murray Initiative, a lack of reliable data (Connell 2007).

The Water Act legislated the roles of: the ACCC to monitor and report on water charges and water trading rules (ACCC 2008); the Bureau of Meteorology (BOM) to develop a set of National Water Accounts (BOM 2011); and the National Water Commission (NWC) to audit the progress of reform and the state of water markets (NWC 2009, 2011b, 2011c). The MDBA was allowed to commission external parties to fill knowledge gaps. A principal knowledge gap was undertaken by the Commonwealth Scientific and Industrial Research

[34] The CEWO was originally known as the Commonwealth Entitlement Water Holder (CEWH).

Organisation (CSIRO), who were given the responsibility for determining the MDB's sustainable water yields, and quantifying the risks climate change posed to the SDL (CSIRO 2008).

The separation of the CEWO and MDBA, allowed the CEWO to actively engage in restoring environmental flows in the absence of the Basin Plan. The institutional opportunities and limitations are not a focus of this thesis. However, articles by Crase and O'Keefe (2009), Connell and Grafton (2011) and Crase, Dollery and O'Keefe (2011) examine the implications from separation of the design of the Basin Plan and the implementation of the Basin Plan, and provide detailed discussion concerning the development of institutions and regulations associated with the contractionary state of water resource reform. This thesis explores how uncertainty about future water supplies could alter the effectiveness of the Basin Plan and the tools for implementing the Basin Plan to improve welfare.

4.3.1 Theoretical Underpinnings of the Basin Plan

The Basin Plan aims to purchase 3,200GL of water from irrigators and give it to the CEWO in order to 'restore the balance' between all water users in the MDB. The Basin Plan provides an example of the common property approach to deal with the externalities associated with over allocation of natural resources (Ciriacy-Wantrup & Bishop 1975; Ostrom 1990; Ostrom & Ostrom 1972). The development of common property (i.e. 3,200GL), counters natural resource exploitation problems created by private individuals who have high discount rates. By transferring water property rights away from private individuals and providing those water rights to organizations who operate with a 'public trusts doctrine' (i.e. CEWO), less water is consumed. With more water within the river system and potentially less salt returning via irrigation return flows, the 'quality' (i.e. salinity) of the resource base improves, which provides benefits for the wider public. This 3,200GL of common property or pool of common water resources will also be used by the CEWO to manage environmental flows…

> "… for the purpose of protecting or restoring the environmental assets of the Basin so as to give effect to relevant international agreements. The Commonwealth's aim in using environmental water is to maximise environmental outcomes for the Basin" (CEWO 2013).

4.3.2 Obtaining Water Rights from Irrigators

Two contrasting approaches have been designed to obtain the 3,200GL of water required for the CEWO, a…

> "…(i) market purchase of agricultural water rights through an AUD$3.1 billion programme known as Restoring the Balance (RtB); and (ii) off-farm storage/delivery infrastructure upgrades and on-farm irrigation technical efficiency improvements through an AUD$5.8 billion programme known as Sustainable Rural Water Use and Infrastructure [Program (SRWUIP)] (Crase & O'Keefe 2009)[35] A target reallocation figure of 2750GL from these intervention programmes by 2019 was established through a Basin-wide Plan, inclusive of a minimum 650GL/pa total flow to the River Murray mouth at the Coorong (MDBA 2012c).[36] Recently, a further AUD$1.7 billion was committed to purchasing additional water rights and addressing water delivery constraints in the MDB (Department of Sustainability Environment Water Population and Communities (DSEWPC) 2013). Consequently, reallocation targets for environmental outcomes have increased by 450GL to 3200GL and the completion timeframe by five years to 2024" (Adamson & Loch 2014).

When evaluating the Basin Plan the contrast between the theoretical foundation of the Basin Plan and the contrasting strategies employed to implement the Basin Plan must be noted. As although the Basin Plan may be rational and have solid theoretical foundations, the success of the Basin Plan is also dependent on both the institutions supporting the Basin Plan and how the Basin Plan is implemented. A common risk to the design, the institutions and the implementation of the Basin Plan is uncertainty associated with future water supply and the determination of the environments share.

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[35] For the purposes of this paper, we apply a definition of water use efficiency consistent with Perry (2011), which differentiates between total water use efficiency (i.e. production yield per unit of total water used) and irrigation water use efficiency (i.e. production yield per unit of irrigation water applied). Herein, the concept of technical efficiency is consistent with the total water use efficiency definition above.

[36] The Coorong, located near the mouth of the River Murray in South Australia, is an iconic National Park and wetland environmental area which has been identified as a key bird-breeding and species habitat management site in the Basin Plan.

4.3.1 Complexities in Modeling SDLs for the Basin Plan[37]

Effective water management principally entails adequate comprehension of the variability inherent in each component of the connected supply system. Arguably, one of the highest stake responsibilities of the hydrologist-economist is to provide a number that goes into policy formulation. The complexity of any conjunctive water use system, which draws on surface and groundwater and relies on return-flows from irrigation and other uses, means that the inherent variability around target numbers is quite often lost once leaving the hands of the analyst. Simplicity requirements for mass communication usually demand a single number, whereas complexity [suggests that the use of single number is] often meaningless. Yet, single values, drawn from seemingly unrelated distributions, then become the building-block upon which further analysis is conducted and public opinion gauged; regardless of its reliability or whether limiting assumptions are clearly (and most discouragingly, especially when such limitations are emphatically) acknowledged. The MDB example provides ample evidence for this practical aspect of public policy-making.

Despite a century of water reform, the necessity of obtaining coherent and consistent data was a central part of the *Water Act* (2007) to overcome shortcomings in MDB information sets. As individual states or territories retain responsibility for the management and collection of data for the river sections within their political boundaries, significant water resource data fragmentation, disparate calibration techniques and varied modeling approaches prevented an understanding of available water resources, how data was used, and how the possible implications of climate variability and climate change were assessed (Horne 2012; Sandeman 2008).

Inconsistent data sets across state/territory agencies often provided a key barrier to transparency in the formation of policy decisions at a federal scale. For example, state and territory political boundaries are subdivided into surface water management areas and groundwater management areas that do not align. Meanwhile, the management of these areas was based on models, from which allocation and delivery decisions were subsequently drawn, as well as final audits to ensure compliance with objectives were conducted. In some unique cases the modeling methodologies, data standards, reporting errors and inherent model biases created difficult issues to resolve. In an attempt to

[37] This section has been published in Loch, Adamson and Mallawaarachchi (2014)

address such issues, the (CSIRO) sustainable yields project had the unenviable task of merging available data into a consistent framework, using hydrological boundaries to define their catchments. Despite their best efforts, inevitable limitations in the data occurred. They can be attributed to: misconstrued complexity of the issues; unreliability in the underlying data sets; and the timeframe set to achieve requisite outcomes (Young et. al. 2011). Fundamental improvements in the data and estimation of the sustainable water yield occurred. But an original emphasis on the complexity, variability and uncertainty associated with the water recovery recommendation (range) was lost once it was compressed to a single recovery target number (i.e. 3,200GL).[38]

The estimation of future MDB sustainable diversion limit (SDL) figures is not simply dependent on available data and how that data is collected, but also on the modeling methodologies used to estimate water supply and water requirements (Penton & Gilmore 2009). If SDL estimates are optimized for efficiency, then redundancy and flexibility must also be encapsulated in both the estimations of supply and the demand for alternative uses to accommodate future unknowns. As Young and McColl (2009) discuss, when institutions are incompatible with a highly variable hydrological system, decision makers must continually reform policy. Future water supply is not a fixed number, nor has it been in the past. 'Machine-learning' directed (modeled) historic Basin water use figures, provide comfort to policy-makers and (some) confidence to modelers.

But the complex association between rainfall, run-off and groundwater recharge cannot be described within a single variable (Chiew et al. 2011). In addition, landscape changes such as forestry (Schrobback, Adamson & Quiggin 2011) water harvesting (MDBA 2012b), and adaptation measures by all water users including the natural environment, in response to known and unknown triggers, will vary beyond grasp. Infiltration rates, ecosystem requirements and the ability of water to reach river systems, as acknowledged in the models, are only one of many possible representations equally probable in an unknown distribution. Despite these realities, an often-adopted approach is to separate target figures from system variability and uncertainty in order to parameterize secondary models following a hierarchy of aggregation. In given cases, a simple normal distribution will be attributed to the final catchment level numbers, thereby exposing the solution to 'black

[38] Jones *et. al*. (2002) provide an earlier MDB example for the dangers associated with recommendations on recovery target ranges, despite clear communication of their variability. Once again, target figures were typically used as 'sound-bites' for different purposes by varying stakeholder groups, including governments.

swan events' (Taleb 2007) where modeled outcomes fail to deal with the distribution tails (Chichilnisky 2010). Inevitable failure to perceive new lows and highs, results in (inaccurate) 'dumb farmer' model responses to the data provided (Chugh & Bazerman 2007). In fact, MDB irrigators adapted quite readily to environmental, political and economic incentives during the Millennium drought (Wheeler & Cheesman 2013) providing further evidence of the need to structure modeling approaches carefully and accurately.

A secondary fragile aspect of the MDB recovery target was driven by the separation of several conjunctive management issues. The separate treatment of surface and groundwater resources allowed the MDBA to present future increases to groundwater access without wider public discussion or debate. However, this separation has significant hydrological and economic consequences. Not only are MDB water managers failing to recognize non-linear relationships between surface and groundwater resources (Chiew, McMahon & O'Neill 1992), but differential influences of climate change on surface and groundwater systems are also being ignored (Pulido-Velazquez et al. 2011). Failure to recognize the hydrological complexity of this target and the separation of interconnected resources also creates problems when implementing policy solutions, in particular future water management plans. Not only does the Basin Plan assume all water-users are passive to new information but it assumes that individuals are incapable of adopting appropriate management solutions to accommodate new policy settings. This violates the fundamental principles of adaptation.

In this case, failing to understand the hydrological, economic, environmental and social implications of alternative policy tools—as well as their sensitivity to risk and uncertainty—not only creates a second best solution, but may potentially compromise the efficiency of MDB irrigators to adapt. Such outcomes are exacerbated by uncertainty about future climate states, which have a strong influence on all system characteristics. The greater the complexity of a given water resource system, the higher the probability that fatal policy constraints towards achieving effective, efficient and socially acceptable water policy solutions will be realized. Where this occurs, an inevitable cycle between policy design, social opinion and rigorous analysis can occur as political ambitions transition from one policy reform process to another.

4.4 **Climate Change and the Basin Plan**

The Millennium Drought (Section 3.3) provided an insight into the possible adverse climate future and raised awareness that the posed social and environmental benefits from the Basin Plan may be short lived, if climate change was ignored. For example, Crase and Gawne (2011) noted that if the CEWO failed to anticipate climate change impacts on the water security provided by alternative water property rights, then it may be left with a portfolio of water rights (i.e. 'common property') that is unable to provide sufficient water to achieve the Basin Plan's objectives. This concern was picked up by other authors including Hone et al. (2010) and Loch, Bjornlund and McIver (2011) who discussed the potential and strategy required for the CEWO to either offset any reductions in the water supplied by 'common property' by engaging in water trade, and to develop an environmental watering prioritization process to maximize ecosystem assets.

In response to the uncertainty associated with climate change, the Basin Plan introduced four strategies for minimizing water supply risk: identify the impact climate change could have on water resources (MDBA 2012c, pp. 21-2); ensure the resilience of the environmental outcomes (MDBA 2012c, p. 52); continue to remove water market impediments to trade (MDBA 2012c, p. 26); and ensure that reviews of the process…

> "…must be undertaken having regard to the management of climate change risks and include an up-to-date assessment of those risks, and consider all relevant knowledge about the connectivity of surface and groundwater, the outcomes of environmental watering and the effectiveness of environmental works and measures" (MDBA 2012c, p. 31).

Evaluating these risks to the Basin Plan, are then central to this thesis and to simplify the discussion, the impacts of climate change on future water resources in the MDB have been defined in the next section.

4.4.1 Climate Change Policy

The Garnaut Climate Change Review (Garnaut 2008, 2011) provides the most comprehensive set of policy recommendations and economic arguments for Australia's transition towards a low carbon economy. The Garnaut Climate Change Review also provided a set of carbon-emission scenarios and corresponding impacts on rainfall to runoff for the MDB that are documented in Quiggin et al. (2008) and it is from that source that the climate change scenarios are derived. The Basin Plan is evaluated against a mitigation scenario as…

> "…[a]daptation is beneficial in every case. For the simulations presented here, adaptation and mitigation are complements. That is, the benefits of adaptation are higher in the simulations with mitigation than in the "adaptation only" simulation.
>
> The complementarity relationship between mitigation and adaptation reflects several features of the projections and simulations considered here. First, in the absence of mitigation, the supply of water is so limited by 2100 that there is little scope for adaptation. This point is potentially applicable to a wide range of ecological and agricultural systems affected by climate change.
>
> Adaptation is a useful response to moderate rates of climate change. However, where climate change produces a rapid and radical change in conditions, adaptation of existing ecosystems and human activities may not be feasible. Instead, the systems in question will be unsustainable. New systems will ultimately emerge, but stable adaptation may not be feasible until the climate itself has stabilized at a new equilibrium.
>
> For the more moderate climate changes projected for 2050, the complementarity between adaptation and mitigation reflects more specific features of the projections. In the "adaptation only" simulation, the increased frequency of drought reduces the set of adaptation options, and precludes most high-value horticultural activities and opportunity cropping based on irrigation in wet states only. By contrast, in the simulations where both adaptation and mitigation take place, the effects of reduced water availability in all states of nature are less severe and leave open a wide range of adaptation opportunities" (Quiggin et al. 2010, pp. 546-7).

For this thesis, the 450 scenario from the Garnaut Climate Change Review has been used to define the future climate. The 450 Scenario is described as the strong mitigation scenario, in which CO_2 equivalents are stabilized at 450 parts per million (ppm) by 2100. At this level, mean global temperatures are expected to increase by ~1.5°C and the rainfall, relative humidity and surface temperatures across Australia, have been set to the

50th percentile projections (Garnaut Climate Change Review 2008). This thesis examines the outcomes for water resources in two time periods, 2050 and 2100, which equates to approximately an average decline in water resources of 10% and 20% respectively.

As discussed in Section 3.1, climate change will alter both the problem and solution set for water. In this thesis, the future climate change problem set is defined by the 450 scenario and the solution set is expected to be similar to those exhibited by all water users during the Millennium Drought. By maintaining the existing water security provided by the set of water rights, the impact climate change has on: producer's strategic transformation and management adaption to maximize wealth; the benefit the CEWO water resources provide to the environmental and society; the net change to the residual environmental share; and their correlated impacts on water flows and salinity throughout the MDB have on the Basin Plan's objectives can be examined.

4.5 The Desired Characteristics for the Fourth Stage of Water Development

The MDBA was given an objective to develop a Basin Plan which included defining a SDL that is socially acceptable and will continue to provide welfare benefits despite any future adverse climate impacts on water supply (Connell & Grafton 2011). For the Basin Plan to provide social and economic benefits, it is anticipated that the welfare reducing characteristics evident in the mature stage of water resource development, are either no longer evident or reduced where possible. Subsequently Table 4-1 places these desirable characteristics from contraction stage against the characteristics of the prior three stages of water reform.

In the absence of new low-cost technology or the discovering of favorable sites, the costs of building dams in the contraction stage should have the same inelastic tendencies as the maturity stage. Additionally, despite the development of a SDL that provides a new upper bound on private water diversions, the private demand for water will have similar characteristics as the maturity stage (Section 2.2). However, as the SDL decreases the number of water rights owned by irrigators, the value of water rights should increase in the market. The combined effect from the increased market price for water and irrigators adaption to the Millennium Drought (Section 3.6), should then prevent the price paid for water in a future drought, not to have the same inelastic tendencies as in the maturity stage (Section 2.2).

Table 4-1 The Four Stages of Water Resource Development, Examining the Contraction Stage

Market characteristic	Exploration	Expansion	Maturity	Contraction
Long run supply of impounded water	Elastic	Elastic to Inelastic	Inelastic	Inelastic
Demand for delivered water	Minimal, Often no or minimal charge to access water. Elastic at low prices, inelastic at high prices.	Low but growing demand. Demand is elastic at low prices and inelastic at high prices.	High and increasing demand. Elastic at low prices; inelastic at high prices.	High but stable demand. Elastic at low prices; inelastic (but not perfectly) at high prices.
Physical condition of impounded and delivery system	Little to no infrastructure. All infrastructure new.	Infrastructure is in good to new condition.	Aging infrastructure in need of expensive upgrading or repair.	Infrastructure maintained by user.
Competition for water between all users	Nil, only during extreme droughts.	Increasing but minimal. Can occur during droughts creating a new round of investment in long run supply.	Intense apart from during floods.	Reallocation reduces competition between all users.
Non-Convexity	No	No	Yes	Yes (decreasing frequency of occurring)
Externalities	Nil	Minimal	Extensive externalities	Reduction in externalities
Social cost of subsiding increased water use	Zero to very low	Fairly Low	High and rising	Nil
Sustainable in the long run	No	No	No	Yes

By encouraging the removal of trade impediments, the Basin Plan should also facilitate the water market price to approach the true price of water (Randall 1981). In the absence of subsidies, as the gap between the market and true price for water closes, irrigators would maintain their own infrastructure to maximize water-use efficiency

As the SDL reallocates water rights between users, the CEWO gains a portfolio of entitlements that should provide the environment with a secured minimum flow. In this case the competition between water users should be reduced. However, the SDL does not alter the existing pressure on the unsecured or residual environmental allocation. Consequently, it is assumed that this residual flow will still be penalized in the future, to preserve the water security of entitlement owners (i.e. CEWO and private individuals)[39]. Additionally, the peak demand for environmental versus irrigation supplies may be different and this may create some tension between users as changes to the river systems conveyance losses may occur.

The defined environmental water rights should reduce the irreversible consequences that derived from non-convex responses to water insecurity. Non-convex responses within each water-user group may still occur but the frequency in which non-convex events and irreversible losses occur should be reduced. By managing the defined environmental supply for the national benefit, externalities should be reduced, increasing welfare.

If trade between the CEWO and irrigators is allowed, then additional flexibility to manage droughts would further dampen the irreversible impacts that were evident in the maturity stage of water resource development. If the price paid on the allocation market is inclusive of the cost of any negative externalities associated with the use of that water, then additional welfare gains are possible. Provided that the defined upper bound of water consumption is correct, then to prevent any backsliding in the political policy process, permanent trade should only occur away from irrigation.

[39] Climate change may alter the security of alternative water rights in the future.

4.6 **Evaluating the Basin Plan (Contraction Phase)**[40]

To maximize welfare, externalities must be internalized within the decision making process. By knowing the urban demand for water and treating the environment as a social production choice, we can then model the water requirements of ecosystems along the MDB in identical fashion as an irrigator's production system and/or as a flow constraint and/or a fixed input requirement. This constrained welfare optimization approach then can provide guidance to help determine the least cost solution (i.e. to irrigated production) to achieve the current socially acceptable levels of pollution (Rostow 1959).

Let us consider a graphical representation of this social choice problem (Figure 4-1). Suppose social wellbeing from water use can be summarized by the net output from its use in irrigation and environmental services. Given available technologies (knowledge) that allow substitution between these services, the shaded area under the curve $E_w I_w$, [then bounds the attainable and efficient social opportunity set], represents potentially available benefits from different combinations of water use. Before the policy change was introduced, water was mainly directed to irrigation and the environment was the residual claimant, a position depicted by Q.

In this case, under prolonged drought conditions water use would gradually approach a situation corresponding with I_w at the lower right corner. At I_w, irrigation receives all water at the expense of the environment, and consequently irreversible losses to society (social, economic and environment) would occur. To prevent irreversible losses the share of water resources between all water users needs to be considered (Krutilla, 1967). This can be shown by a shift in water use from Q to Q^* reflecting a change in social indifference curves. In Figure 4-1, I and I^* represent changed social preferences communicating the need for this shift in policy. This shift in policy results in an economic reallocation to attain a new socially efficient output bundle. Moreover, changes in the relative value of inputs and outputs under new social preferences will also influence the way water is used in future production systems, creating a spiral of policy-induced technological change leading to an outward shift in the social opportunity set $E_w I_w$. However, complexity in natural resource systems, social and individual preferences, and the manner in which policy changes affect choices and patterns of behavior have the potential to create multiple equilibria, because

[40] This section draws heavily from (Loch, Adamson & Mallawaarachchi 2014)

such behavior is sensitive to random events (Marshall, 2013). Well-designed public policy needs to reflect not only the objectives of society, but also any trade-offs associated with constraining the hydrologic and economic dimensions of a system across scope, scale, time and space dimensions[41]. A single policy can create unintended consequences in social, economic and environmental domains outside its design brief on a local, regional, national and international scale.

One such policy problem is derived from incentives and subsidies which distort the price of water and water delivery infrastructure downwards allowing inefficient producers to remain within the industry.

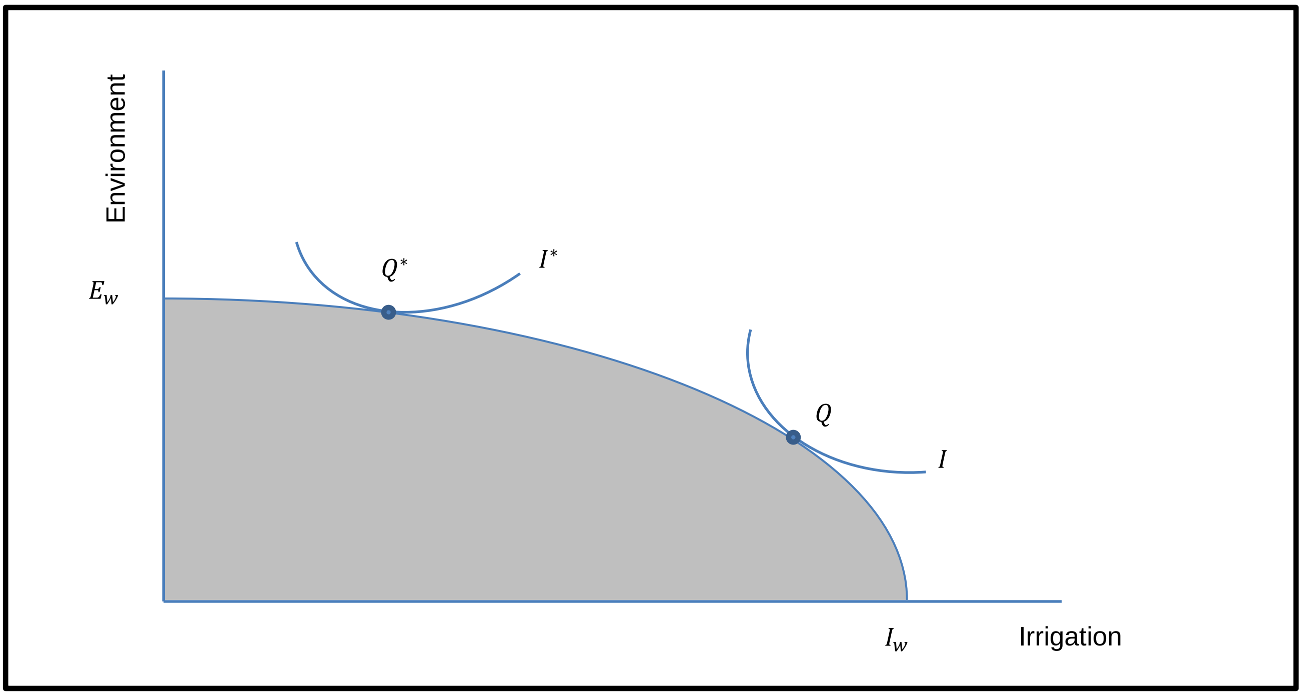

Figure 4-1 Welfare Effects in Water Allocation

4.6.1 Changes to Economic Welfare

Water policy is the outcome of a political game between rent seekers (Boyce 1998; Epstein & Nitzan 2002). This transfer of water from private to public ownership will create winners, losers and encourage rent seeking behavior as individuals and groups attempt to access as much compensation (money and groundwater) as possible. The formulation and implementation of the Basin Plan changes welfare by: internalizing externalities; allocating

[41] Scope describes the number of issues that are impacted by a policy, scale defines the institutional level at which those impacts occur and/or are managed, time sets the period over which the policy lasts, and space is the area over which the policy is enacted.

public funding to institutions and the commissioning of data, monitoring and enforcement of regulations, having $10 billion to purchase water from irrigators; and by increasing the groundwater SDL. Consequently, economic justification of the Basin Plan's implementation strategy is required to ensure that: the Basin Plan will increase net social welfare; public funds are used efficiently and effectively; and that the risks to welfare gains from a changing climate are minimized. If these criteria for economic justification are achieved then the Basin Plan should provide intergenerational benefits to society.

This analysis utilizes a "constrained utility maximization to predict individual and aggregate responses to existing and alternative structures of incentives" (Randall 1975, p. 731). Utility maximization will be defined as the economic return from using irrigation water on farm, and the institutional constraints are the SDL and the Basin Plan twin goals for environmental flows and salinity improvements. By examining the Basin Plan in this way, the trade-offs between consumptive and non-consumptive uses of water can be determined, which can then highlight "potential synergies and opportunities to maximize social returns from the government investment" (Mallawaarachchi *et al.*, 2010).

The thesis doesn't explore welfare changes from alterations to transaction costs, or from public expenditure on institutions and the commissioning of data.

Ho: *By internalizing externalities social welfare will increase.*

4.6.2 Is the Implementation of the Basin Plan Cost-Effective?

Public expenditure requires justification. By stating that compensation must occur it negates the ethical questions associated with rewarding the polluter (Randall 1975). The Basin Plan's direct compensation or adjustment package has two elements. First there is $10 billion to obtain 3,200GL of surface water for the CEWO and secondly groundwater extractions have been increased and each element needs to be examined to determine its cost effectiveness and determine the net welfare change in the MDB.

By shifting private demand and supply of goods and services towards the socially desirable levels of supply and consumption, externalities are reduced. To facilitate the development of common water property rights for the CEWO two alternative approaches (RtB and SRWUIP) will be used. However, the relative effectiveness of each program and the funding allocated to each program has been questioned (Crase & O'Keefe 2009; Grafton 2010; PC 2010).

The RtB is a direct market transaction of property rights between irrigator and the common property manager (i.e. CEWO). As the CEWO purchases water the supply curve shifts to the left from S_0 to S_1, reducing the quantity of water inputs used by $x_0 - x_{1,}$ in Figure 4-2, RtB. The second approach aims to obtain water by sharing the water saved via increases in water use efficiency and subsidizing the cost of this transformation. By shifting the production function to the left PF_0 to PF_1, less inputs are used to produce the same level of output Z. In this case, the environment gets $(x_0 - x_1) \times E$, where E equals the percentage share that the environment receives from the efficiency gain, where $0 < E < 1$. Current policy has set $E = 50\%$.

The comparative cost of each program in obtaining water for the environments can be expressed as

$$\sum C_{RtB}(x_0 - x_1) = \sum C_{SRWUIP}(x_0 - x_1)\, E\ . \qquad \textbf{Equation 4-1}$$

If the cost C of achieving the program objectives (i.e. water for the environment) is represented as $x_0 - x_1$ is identical under both the RtB $\sum C_{RtB}$ as the SRWUIP $\sum C_{SRWUIP}$ approaches then it does not matter which project gets funded, when only examining the first round impacts. Examining this relationship, as E approaches zero the SRWUIP program has to obtain more water than the RtB or alternatively the cost to obtain each unit of x must fall. This has three implications for the findings of these analyses to justify public expenditure.

First, to maximize the return from public expenditure a pre-selection bias towards existing and highly inefficient irrigation systems can exist. Such policy outcomes send signals that existing irrigation systems are correctly located within the river system but the pre-section bias fails to consider questions as to why irrigators are not taking advantage of the opportunities to act on their own. Randall (1975) argues that this bias is created when policy analysis uses the prices derived from existing property rights allocation. As irrigation development has been highly subsidized in the past, it then locks in the infant industry problems and ultimately prevents resources being used by those who can obtain rents without subsidies. The failure to consider the reallocation of rights then reinforces producers to remain inefficient, lowering net national welfare[42].

Second, when compared to the RtB, the SRWUIP is funded at a ratio of over $2.4:1. This then implies that for the SRWUIP to be of equal value when compared to the RtB, it must be responsible for upgrading infrastructure to obtain a total of over 4,500GL in savings, 50% of which is retained by irrigators (i.e. 2,250GL).

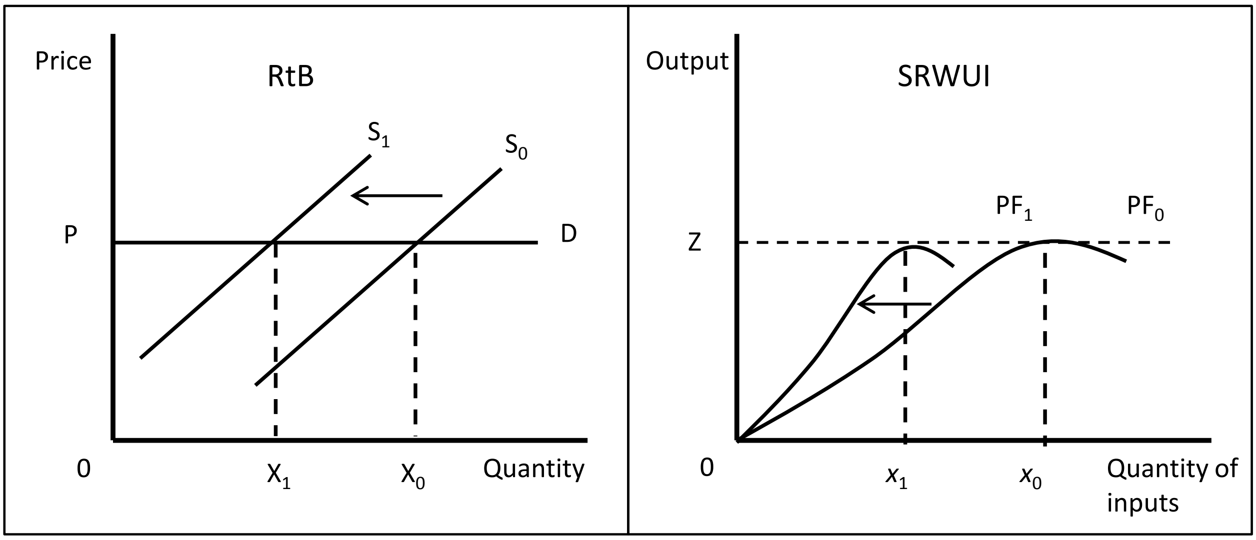

Figure 4-2 How Basin Plan Obtains Water

Third, as discussed in Section 2, if irrigation systems are already calibrated to the natural system, what are the implications to the agricultural, ecological and social systems from both the RtB and SRWUIP? These questions need to be asked in context of the demand for the conjunctive water supply which alternates between elastic and inelastic depending on current and future scarcity.

> **Ho:** ***The RtB provides the most efficient way to return water to the environment.***

[42] The development of irrigation areas has been mixed. Some irrigation areas failed to consider soil quality (Davidson 1969) and other areas took advantage of favorable areas. However, as only 2% of MDB agricultural land is dedicated to irrigation, soils are not considered a binding constraint in this thesis. Consequently it has been assumed that returns by commodity in each region are derived from being allocated on ideal soils and that based on each region's comparative advantage expansion can increase up to a predetermined level as discussed in Section 6.7.1.

The second component of the Basin Plan compensation package consists of increasing the groundwater SDL, especially in the Northern Murray-Darling Basin (NMDB) (Table 7-5). As the groundwater SDL has increased and the Basin Plan has four strategies to deal with the risks from climate change (Section 4.4) it has been assumed that groundwater is a highly reliable entitlement. With the NMDB primarily having general and supplementary water entitlements, the Basin Plan's net change on conjunctive water availability needs to be examined.

Ho: *The change in conjunctive water resources creates wealth.*

4.6.3 Solutions Resilience to Climate Change

If the policy signals designed to obtain water for the Basin Plan fail to adequately address the risk climate change poses on future water resources then the non-convexity, irreversibility and uncertainty that has hindered applied water policy will continue. Adamson, Mallawaarachchi and Quiggin (2009) illustrated that the SCA model can be used to determine if a proposed reallocation of resources (i.e. derived from the optimized solution) can be resilient to a changing climate. By adapting those findings, this thesis will examine the implications from: a decision maker being aware (*ex-post*) or unaware (*ex-ante*) about climate change; and examine two alternative approaches to model how climate change could alter water supply. First, examine how a climate change scenarios alters mean rainfall patterns. Second, examine what may occur if the frequency of El Niño events increases..

The *ex-ante* simulation is used to test if the current climate's optimal allocation of resources is still feasible, if the climate changed. This is tested by fixing resource allocations and altering the water inflow data to the new climate change parameters. If the river flow constraints (Section 6.7.2) and Basin Plan objectives are still satisficed, then the current allocation of resources would be able to survive a climate change event according to the model. However, if the river flow constraints do not hold (i.e. river flow < 0). then there would be insufficient water within the river system to meet irrigators demands and this would expose private capital to unacceptable risk. Correspondingly if the objectives of the Basin Plan do not hold then society and the environment may be worse off under a changing climate. This then represents an individual who adapts to the Basin Plan without considering the implications of climate change. In this approach, the implications of attempting to utilize the same resources in a new climate, then identifies both the invested capital at risk and examines if the Basin Plan's institutional goals could still be achieved. Note an *ex-ante* analysis of the increasing drought state is not required as the generated results have full knowledge about a drought state of nature. In this case an *ex-ante* analysis of a drought will reduce economic returns only.

In the *ex-post* optimization, decision makers have complete information about climate change and the constrained welfare maximization model uses the data from either approach for modeling climate change. The *ex-post* or aware decision maker then optimizes resource use so that investments will now be optimal once the climate change event occurs. This approach then ensures that the Basin Plan's twin institutional goals of water flowing to the Coorong and the salinity targets for Adelaide are achieved via a new redistribution of private capital throughout the MDB.

These contrasting approaches then help examine how future water scarcity may impede the objective of the Basin Plan and identify risks to all water users. Information concerning the RtB and SRUIP ability to provide water under alternative climatic events for the institutional requirements can then be determined. By using the SCA model to examine the alternative strategies for purchasing water, and using the *ex-ante* and *ex-post* approach to determine resilience to climate change, long term impacts on welfare can be explored. Modeling alternative levels of awareness helps identify policy makers' attitudes towards future risk. If policy makers provide greater incentives to adopt one mitigation strategy over another and incentives misallocate resources towards private and public risk, then welfare losses should be expected (Arrow & Fisher 1974).

> **Ho:** ***The failure to incorporate climate change risks into the Basin Plan solution will reduce long run economic welfare gains.***

4.6.4 Is the Basin Plan a Contractionary Phase of Water Development?

In order for the Basin Plan to be considered a true reflection of a contractionary phase of water resource development, it must have features consistent with the desired characteristics of the fourth stage (Table 4-1). However as Cummins and Watson (2012) commented, the Basin Plan has to counter over a 130 years of policy built upon ‘romanticism and recklessness’ that has left a legacy of obstacles that will inhibit swift reform. They argue that…

> “[g]iven the uncertainties confronting environmental policymakers, it is unlikely that we will ever ‘get it right’, but we can, and should, keep getting better. The hundred-year experiment will continue for many years yet” (Cummins & Watson 2012, p. 32)

This thesis reviews the three key signals that are evident within the contraction stage of water reform. First, the RtB is willing to use markets to purchase water from irrigators. Second, the SRWUIP is willing to subsidize the cost of water-use efficiency technology. Third, the groundwater SDL has been increased. Each incentive mechanism will be examined to determine if it achieves the prerequisites of a contractionary phase of water resource development.

Ho: ***The Basin Plan has some, but not all, characteristics of the contractionary phase of water resource development.***

4.7 Summary

Well-designed public policy, reflects both the social preferences and the trade-offs society is willing to accept. The Basin Plan is reflective of changed social preferences and it uses the economic concepts of common property to overcome the externalities derived from an over-allocation of private property rights. The CEWO will act as the ‘public trustee’ by managing 3,200GL of surface water in the national interest, which in this thesis is defined as achieving a minimum flow target and a maximum allowable salinity target (i.e. quality). The CEWO’s 3,200GL of water is to be obtained from irrigators and there are two mechanisms (RtB & SRWUIP) designed to facilitate this transfer of property rights. The RtB and the SRWUIP provide different incentives for producers and different outcomes for water resources in the MDB. With $10 billion set aside to obtain water for the CEWO, rent seeking is to be expected. Additionally the net change in the conjunctive SDL has the potential to create wealth for some catchments.

By representing climate variability and climate change as biophysical constraints, comments can be provided on irreversible decisions associated with: institutional strategies for purchasing alternative bundles of property rights structures; private outcomes from subsidizing capital to invest in water efficiency; and outcomes for the Basin

Plan's objectives. It is however, the fundamental complexity and uncertainty associated with the conjunctive water resources that will determine the long run success of the Basin Plan.

Critical to understanding the solution is the use of an appropriate methodology in examining the nature of decision making under increasing risk and uncertainty and this is explored in the following Section.

5. A STATE-CONTINGENT APPROACH TO PRODUCTION

5.1 Introduction

If the true outcome of alternatives choices and the decision maker's preferences are known, then decision making is a relatively straight forward procedure. With complete information about all possible outcomes obtained from alternative levels of input use and knowing the decision maker's utility function, the optimal allocation of resources can be determined with certainty (Anderson, Dillon & Hardaker 1977). Certainty provides clarity to the economic debate as it removes ambiguity to illustrate concepts, providing opportunities to explore existing bounds of knowledge and facilitate communication.

However, risk and uncertainty abound in decision making. Despite seminal work by Just & Pope where in 1978 they highlighted how the stochastic production function approach can be used. In 1979 Just & Pope then demonstrated why the stochastic production function can provide misleading results. However, the use of stochastic production functions still dominates the literature of risk and uncertainty when allocating resources. By 2003, Just and Pope in a review of modeling and production risk lamented that….

> "[w]e conclude that understanding of why risk response occurs is very limited. As a result, after decades of research, the profession remains in a weak position to offer definitive policy analyses in matters related to risk" (Just & Pope 2003, p. 1255).

This 'weak position' for policy analysis, in part, stems from attempting to oversimplify complex trade-offs: that include non-stochastic processes (Young et al. 1996); that represent passive decision makers; or attempt to smooth out discontinuous functions (Doole & Marsh 2014). Therefore, if we create abstractions and "…tools developed in this abstract world [that] don't even approximately apply in the real world, then one must question the value of this abstraction" (Chambers & Quiggin 2000, p. 3). The state-contingent approach proposed by Chambers and Quiggin attempts to explain the decision making dilemma under risk and uncertainty.

5.2 **What are States of Nature?**

Nature is the term used to describe the state-space $S \in \Omega$ of uncertainty. Nature is an exhaustive set of mutually exclusive events (a state of nature s) that describe all salient features of the uncertainty in question. So when s is revealed, all ambiguity is removed allowing for the traditional approaches used to solve certainty to be applied.

Critically, the decision maker has *no ability to control* which state of nature is realized. Once s occurs the decision maker adopts specific s based strategies to maximize their objective function. Alternatively, reinforcing this point, no matter the action undertaken by the decision maker in a preceding state of nature, the next realized state is independent of their action. However, the decision maker's action in a prior state may leave a legacy (negative or positive) to which they need to adapt once the state is realized.

As the state-contingent approach deals with production under uncertainty, the total size of the state-space can be kept small, as similar states with identical management actions can be condensed. Therefore, yields, prices and costs are an outcome of the state of nature and are not states themselves (Rasmussen 2006). This then allows for both output z and decision maker uncertainty to be treated separately, removing the ambiguity found in other decision support systems where production and management inefficiency cannot be separated (O'Donnell & Griffiths 2006).

The state-space approach was initially examined by Arrow (1953), Arrow and Debreu (1954) and Debreu (1959) where they provided the approach of transcribing all possible outcomes $(s \epsilon \Omega)$ from uncertain events across alternative states s. They discussed how decision makers actively responded to states of nature, by changing their inputs x to influence the final z, based on past experiences and knowledge to manage risk. The foundation for this approach is derived from the notion that "in the real world the allocation of risk-bearing [for a decision maker] is accomplished by claims payable in money, not commodities" (Arrow 1953, p. 91). Arrow's insight suggest that the objective function of the producer does not solely concentrate on the production of a single commodity but rather the net return y from all commodities contingent upon both the commodities payout by state of nature and the probability π of the states occurring $(s \epsilon \Omega)$.

5.2.1 State-Contingent Approach to Risk and Uncertainty

The real advancement into decision making under uncertainty provided by Chambers and Quiggin was that they merged Arrow and Debreu's work on the state-contingent approach with dual optimization (Rasmussen 2003). This insight then provided the capacity to determine the optimal conditions for resource usage to be derived "by type, place, and date, but also by a fourth dimension, the state of nature at the (future) time when the good will become available" (Rasmussen 2003, p. 449).

SCA then provides the capacity to model an active decision maker who responds to traditional economic and policy signals of price and quantity but also reallocates inputs to produce outputs in response to the state space (e.g. environmental signals). This provides insight into why traditional approaches that model production and uncertainty can provide misleading results as they assume that the decision maker remains passive to state signals. Section 3 highlighted that water resource scarcity during the Millennium Drought transformed the demand for water from elastic to inelastic and created a management response by producers to alter inputs and outputs in response to water availability and water price.

To illustrate the divergence in approaches Chambers and Quiggin (2000) compare the conventional stochastic production approach to a state-contingent approach to highlight the misrepresentation of risk and response by decision makers.

5.3 **Production: Conventional Versus State-Contingent**

Output from a traditional production technology is a function of input and can be written as

$$z = f(x, \varepsilon)$$

Equation 5-1

where $\varepsilon \in \Re^{s}$ is a random variable describing alternative states of rainfall, where 1= drought, 2 is good rainfall (Figure 5-1, Part A). Here a combination of inputs x^{*} is allocated before the state of nature is realised and in the absence of any additional inputs or management, obtains output $f(x^{*}, 1)$ in state 1 and $f(x^{*}, 2)$ in state 2. In this approach uncertainty impacts on technology are then disembodied so that a shift from A to B represents a transition to a new production function and represents an efficiency gain, rather than the presence of soil moisture. When a shift from B to A occurs, it is considered technical inefficiency, or management failure, rather than a lack of soil moisture. In this case a rainfall event which is outside the control of the decision manager can be either perceived as technological adjustment or management ability but not a state of nature being realized. In a stochastic representation B and A are then the expected upper and low bounds of output subject to the allocation of x^* inputs.

The state-contingent representation of output derived from the same 2 states of nature is provided by the dot (●) on Part B of Figure 5-1. As before, the combination of inputs x^* is allocated before the state of nature is realised and output $\left(f(x^*,1), f(x^*,2)\right)$ is obtained and $\left(f(x^*,2) > f(x^*,1)\right)$. This dot represents the state-contingent output set given by x^*: and in this case technical inefficiency does not exist. This separation of output by state of nature then prevents the problems associated with traditional stochastic approaches dealing with events that create change like a prolonged El Niño cycle or climate change (Doole & Marsh 2014).

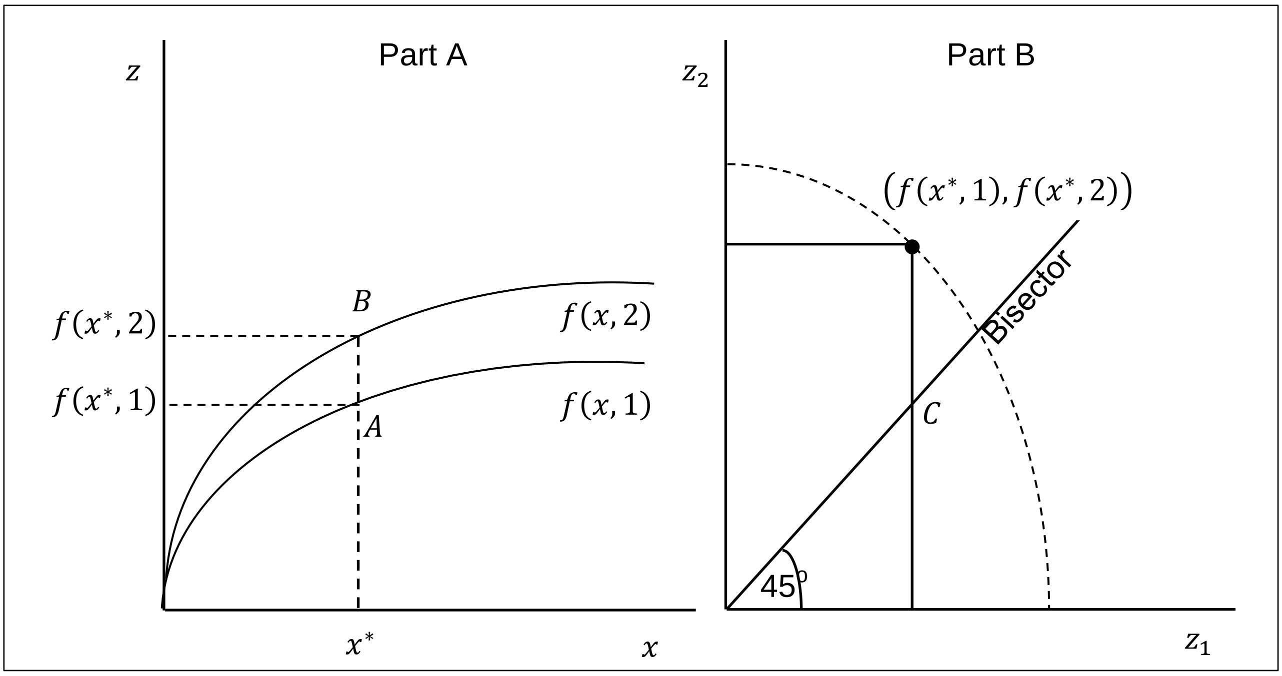

Figure 5-1 Stochastic Versus State-Contingent Production and Disposability[43]

The state-contingent production possibility frontier (or transformation curve) is the dotted line, Part B of Figure 5-1, and represents alternative outcomes in each state of nature dependent on the quantity of x allocated. By relaxing the efficiency assumption then $f(x^*,2)$ provides the upper bound of production in state 2 given x^* inputs. Free

[43] Adapted Chambers and Quiggin (2000, p. 35 and 8)

disposability of output is then the producer's rational choice to produce less than the upper bound once x^* is committed. Likewise in state 1 once x^* is committed then $f(x^*, 1)$ is the upper limit of production. Therefore everything within the rectangle defines the production possibility set once x^* is committed and the producer only operates on the frontier line when it is advantageous. The rectangle then represents the stochastic output set for x^* inputs. State-contingent production is defined as

$$\mathrm{z_S} \leq f_{\mathrm{s}}(\mathrm{x}, \varepsilon)\ \mathrm{s} \in \Omega = \{1, \ldots, \mathrm{S}\}\,. \qquad \textbf{Equation 5-2}$$

The bisector line, Part B of Figure 5-1, is the riskless outcome where output in state1 and state 2 are identical (i.e. $\left(f(x^*, 2) = f(x^*, 1)\right)$, which is the certainty equivalence (CE) between these 2 states of nature. Any point above the bisector line represents where $\left(f(x^*, 2) > f(x^*, 1)\right)$ and any point below the bisector line $\left(f(x^*, 2) < f(x^*, 1)\right)$. If the decision maker decides to operate on the bisector, they do so at the choice of producing less output in state 2. As states are separate, any choice to lower production in one state will have no impact on the other state of nature. This is then the basis for state-contingent technology.

5.4 State-Contingent Technology

State-contingent technology can be represented by a "continuous input correspondence, $X: \Re_+^S \to \Re_+^N$, which maps state-contingent outputs into input sets that are capable of producing that state-contingent output vector" (Chambers & Quiggin 2002)

$$X(\mathbf{z}) = \{x \in \Re_+^N : \mathbf{x} \text{ can produce } \mathbf{z}\}\,. \qquad \textbf{Equation 5-3}$$

The properties of these state-contingent output and inputs sets are listed below.

5.4.1 Properties of Output Sets

There are four key features of state-contingent technology.

1. $X(z)$ is closed for all $\Re_+^S$.

   Logically production of z from x is not finite and there are defined upper and lower bounds to the output set. The use of output-cubical technology is used to illustrate this in Figure 5-2 and explained. $X(z)$ is convex for all z.
2. $X(0_s) = \Re_+^N$ (no fixed costs), and $0_N \notin X(z)$ for $z \geq 0_s$ and $z \neq 0_s$ (no free lunch).

In this case the decision maker has a real option of not undertaking an action but if they decide not to respond, costs are still incurred in order to obtain a positive output.

3. $z' \leq z \Longrightarrow X(z) \subset X(z')$.

   There is free disposability of state-contingent outputs. In this case, a state-contingent set of inputs can always be used to produce a smaller set of state-contingent outputs than the specific set is designed to produce.

4. $x' \geq x \ \in X(z) \Longrightarrow x' \in X(z)$.

   Inputs have non-negative marginal productivity. Shankar (2012) determined that these input sets are weakly disposable when

   $x \ \in \ X(z) \Longrightarrow \forall\lambda \geq 1, \lambda x \in \ X(z)$

   and strongly disposable if

   $x \ \in \ X(z)$ and $x^* > x \Longrightarrow x^* \ \in \ X(z)$.

5.4.2 Properties of Input Sets

The dual to the input correspondence is the cost function where the cost of input is **w**, so

$$c(\mathbf{w}, \mathbf{z}) = \min_{x}\{\mathbf{wx}: \mathbf{x} \in \mathbf{X}(\mathbf{z})\} \ \ \mathbf{w} \in \Re^{N}_{++} .$$ **Equation 5-4**

When the input correspondence satisfies properties X, then the cost function satisfies the following 6 conditions:

1. $c(\mathbf{w}, \mathbf{z})$ is continuous on $\mathfrak{R}^{S}_{+}$ and positively linear homogeneous, non-decreasing, concave and continuous on $\mathfrak{R}^{N}_{++}$.
2. Shephard's lemma applies so that indifference curves are convex allowing for a unique cost minimization point.
3. $c(\mathbf{w}, \mathbf{z}) \geq 0, c(\mathbf{w}, 0_s) = 0$ and $(\mathbf{w}, \mathbf{z}) >$ for $\mathbf{z} \geq 0_s, \mathbf{z} \neq 0_s$.
4. $\mathbf{z}^0 \geq \mathbf{z} \Longrightarrow c(\mathbf{w}, \mathbf{z}^0) \geq \mathrm{c}(\mathbf{w}, \mathbf{z})$.

   Both 3 and 4 provide a complete representation of the cost function.

5. $X(\mathbf{z})$ is closed for all $\mathbf{z} \in \mathfrak{R}^{M}_{+}$**.**

   Which prevents production systems from using unlimited inputs.

6. Standard duality theorems apply so that

$$X(\mathbf{z}) = \cap_{\mathbf{w}>0}\{\mathbf{x}: \mathbf{wx} \geq c(\mathbf{w}, \mathbf{x})\} .$$ **Equation 5-5**

The state-contingent approach details three alternative forms of inputs to prevent the free disposability of output representing inefficiency: state allocable (redefined as state flexible by Rasmussen (2011a)), state general and state specific. Dependent on their specification, inputs can increase output, have no impact on output, or in given situations be a transaction cost between states of nature. The transaction cost may be incurred if inputs like technology are purchased, and treated like a fixed cost, to maximize output in given states of nature (normal or wet) and the inaction of technology in drought states reduces the income from output in that state.

5.4.3 Output-Cubical Technology

The output-cubical technology is described by Equation 5-2, illustrated in Figure 5-2, and "it is a special but restrictive type of state-contingent technology as it does not allow substitution between outputs realized in different states of nature" (Shankar 2012, p. 603),

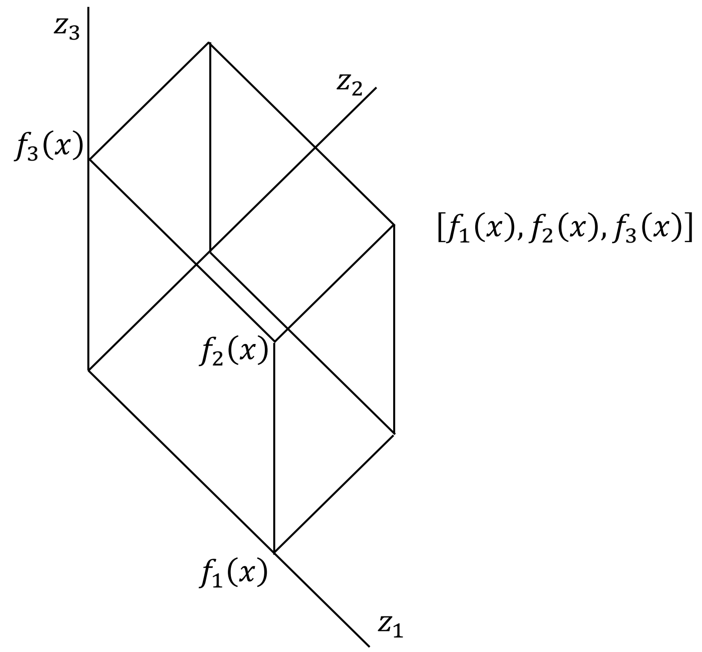

Figure 5-2 Output-Cubical Output Set [44]

The state-space below is a representation of where we have both inputs managed by a producer and ε_s being a random outcome beyond the control of the producer to describe uncertain production processes. When the random vector is $\epsilon = (\epsilon_1, \dots, \epsilon_s) \in \mathbb{R}_+^s$ then the following describes the stochastic functions relationship between input and output

[44] Adapted from Chambers and Quiggin (2000)

$$z_s \leq f(x, \in_s), \text{where } f: \mathbb{R}_+ \times \mathbb{R}_+ \rightarrow \mathbb{R}_+ . \qquad \textbf{Equation 5-6}$$

The output-cubical input correspondence associated is

$$\begin{aligned} X(\mathbf{z}) &= \{\mathbf{x}: z \leq f(\mathbf{x}, \varepsilon_s), s \in \Omega\} \\ &= \bigcap_{s \in \Omega} \{\mathbf{x}: z_s \leq f(\mathbf{x}, \varepsilon_s)\} \\ &= \bigcap_{s \in \Omega} \{\bar{X}(z_s; \varepsilon_s)\} \end{aligned} \qquad \textbf{Equation 5-7}$$

where $\bar{X}(z_s; \varepsilon_s)$ is interpreted as the ex post input set associated with the production function for a given realization of the random variable (Chambers & Quiggin 2002, p. 515)

The stochastic production function specification of the dual cost structure is then

$$c(\mathbf{w}, \mathbf{z}) = \text{Min}\left\{\mathbf{wx}: \mathbf{x} \in \bigcap_{s \in \Omega} \{\bar{X}(z_s; \varepsilon_s)\}\right\} \qquad \textbf{Equation 5-8}$$

which satisfies

$$c(\mathbf{w}, \mathbf{z}) \geq Max\{\bar{c}(\mathbf{w}, z_{1;}\varepsilon_1), \ldots, \bar{c}(\mathbf{w}, z_{s;}\varepsilon_s)\} \qquad \textbf{Equation 5-9}$$

where $\bar{c}(\mathbf{w}, z_{s;}\varepsilon_s)$ is the ex post function dual to $\bar{X}(z_s; \varepsilon_s)$.

5.5 State-Contingent Decision Making

Following Rasmussen (2003) the state-contingent terminology and concepts are defined as:

States of nature:	$\Omega = \{1, 2, \ldots, s, \ldots, S\}$		**Equation 5-10**
Probabilities:	$(\pi_1, \ldots, \pi_s \ldots, \pi_S)$		**Equation 5-11**
Cost:	$c = \mathbf{wx}$		**Equation 5-12**
Technology:	$\boldsymbol{T}(\mathbf{x}, \boldsymbol{z}) = 0$		**Equation 5-13**
Output:	$z_s = max\{z_s: \boldsymbol{T}(\mathbf{x}, \mathbf{z}) \leq 0\}$	$\forall_s \in \Omega$	**Equation 5-14**
Revenue:	$r_s = z_s p_s$	$\forall_s \in \Omega$	**Equation 5-15**
Net Return:	$y_s = r_s - c$	$\forall_s \in \Omega$	**Equation 5-16**
Preferences:	$W = W(y_1, \ldots, y_s)$		**Equation 5-17**

The producer's choice can be described as a two period game against nature. In this case the producer in period 1 allocates $\mathbf{x}$, a vector of inputs $\mathbf{x} = (x_1, .., x_N)$, with corresponding input prices of $\mathbf{w} = (w_1, .., w_N)$, *ex-ante* the state being revealed which provides a cost of $c = \mathbf{wx}$. The decision maker's subjective belief about the subsequent states of nature is $\boldsymbol{\pi}$ a vector described by $(\boldsymbol{\pi} = \pi_1, \dots, \pi_s)$. When the state is revealed in period 2 then all ambiguity is removed and output from allocated inputs and costs is derived from the transformation function of $T(x, \boldsymbol{z})$ where $\mathbf{z} = (z_1, .., z_s)$. With prices $\mathbf{z}$ being a vector of $\mathbf{p} = (p_1, .., p_s)$, so revenue is described as $\mathbf{r} = (z_1 p_1, .., z_s p_s)$ allowing for net return to be $\mathbf{y} = (y_1, \dots y_s) = (z_1 p_1 - wx, .., z_s p_s - wx) = (\mathbf{r} - \mathbf{c})$. To maximize their utility W, a producer then selects the input bundle $\mathbf{x}$ so that

$$MaxW[Y] = \sum_{s \in \Omega} \pi \, (\mathbf{r} - \mathbf{c})\,. \qquad \textbf{Equation 5-18}$$

The closure of input and output sets by state of nature then allows for the complete description of inputs and outputs by mutually exclusive states of nature. The benefit of this approach is illustrated in Figure 5-3, where the relationship between two states of nature, the frequency of the states occurring, the income derived in each state and the decision maker's preferences are provided. In this case the production system x, when produced in state 1 is y_1, and when produced in state 2 is y_2 and they provide an income of y_{s1} and y_{s2}, respectively when that state of nature occurs. $y = (y_1, y_2)$ is the income derived when a state of nature occurs and the indifference curve is illustrated by the convex utility derived from production $W(x)$.

As per the discussion above, the bisector line (or certainty equivalence (CE) (Hirshleifer & Riley 1992)) is where income is independent of the state of nature, i.e. $y_{s1} = y_{s2}$. All points along the fair-odds line, slope of $-(\pi_1/\pi_2)$, describe when returns have the same expected value. So only when the Fair-odds and the bisector line cross is the decision maker operating in a riskless environment. In this case then a risk adverse producer operates at $\bar{y} = (\pi_1 y_{s1} + \pi_2 y_{s2})$.

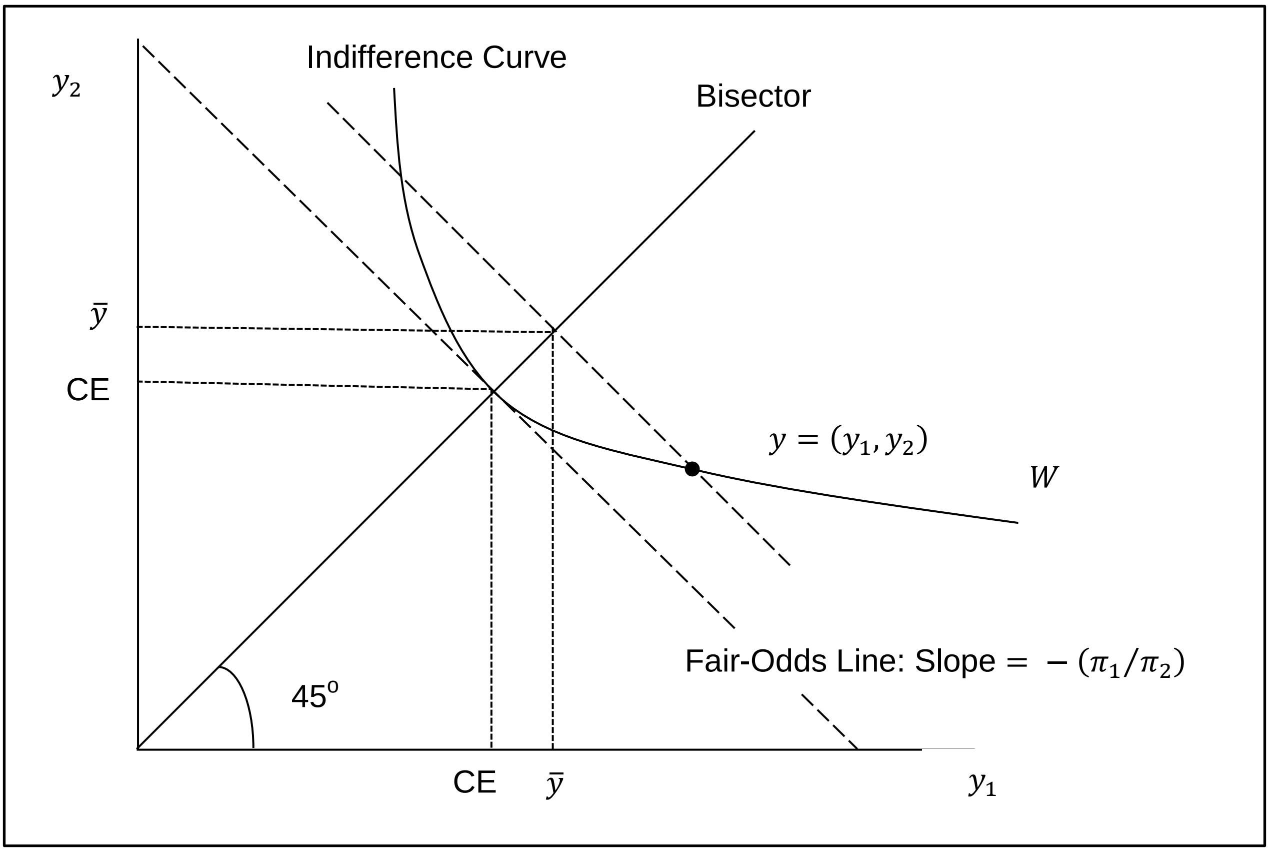

Figure 5-3 Key Concepts in SCA[45]

5.6 State General Input

The formal presentation of a state-general input x_n is

$$\frac{\partial f_s(\mathbf{x})}{\partial x_n} \neq 0 \text{ for one or more states } s \in \Omega \text{ for some level of } x_n$$

A state general input increases outputs in all states of nature. Assume there is one input of water allocated at the start of a season x^1 or x^2 or x^3. This water must be allocated before the state of nature is known, and water trade does not exist and the yield is z. In this case the production of citrus in the wet state s_3 is $z_3 = f_3(x)$ and the production in the drought state s_2 is $z_2 = f_2(x)$. In order for maximum possible yield to be obtained both rainfall and irrigation are required to obtain the optimal level of soil moisture. In this case, despite the quantity of inputs x^1, x^2, x^3 being equal in each state $z_3 > z_2$, $S \in \Omega$. The transformation curves for the 2 different states of nature production functions and their input use are illustrated in the third chart in Figure 5-4. Here production point O occurs when there is no water applied to the crop and yield is derived from residual soil moisture only. The application of x^1, x^2, x^3 provides a joint production z^1, z^2, z^3 respectively. The slope of the

[45] Adapted from Rasmussen (2003)

transformation curve for points $0, z^1, z^2, z^3$ can be calculated by determining the quantity of z_3 that could be produced by producing one less unit of z_2. Thus maximum efficiency from using z^3 water inputs in: drought state of nature is z_2^3 and there is no more water available; and a wet state of nature is z_3^3 and in this case the addition of more water does not increase yields. Therefore the production transformation curves …

> "…are lines at right angles with the corner point which corresponds to the state-contingent outputs associated with the chosen input volume in question. And, in fact, it is only such corner points that are interesting to the producer" (Rasmussen 2011a, p. 38).

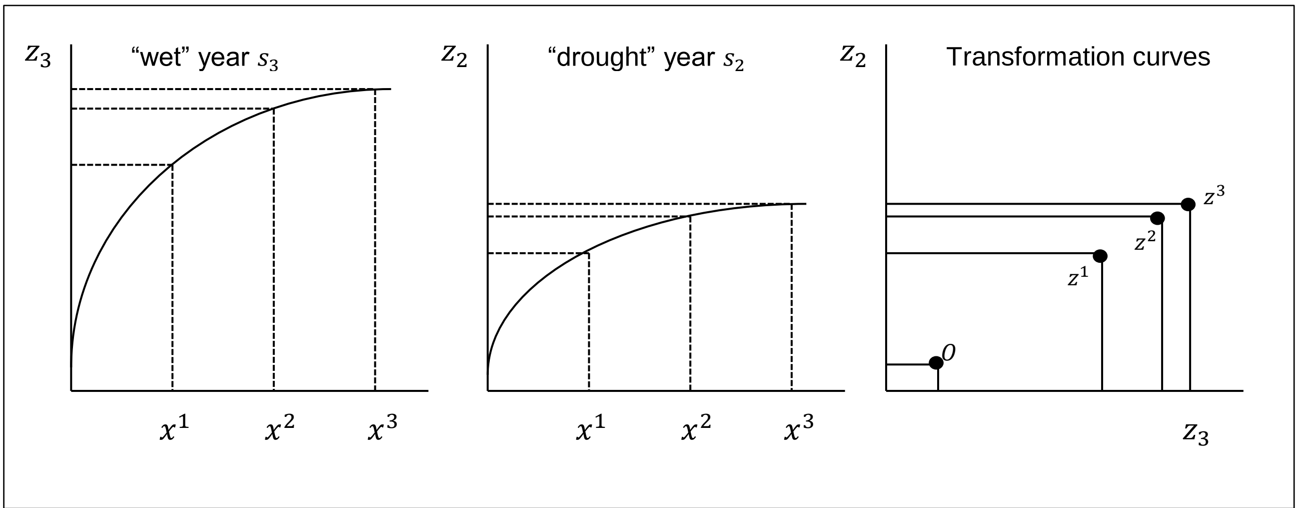

Figure 5-4 The Transformation Curve for State-General Inputs[46]

5.6.1 Representation of State General Inputs

Output written as a function of inputs is then

$$z_S = f(x_1, \dots, x_S, \varepsilon_s) \; s \in \Omega = \{1, \dots, S\}$$ **Equation 5-19**

and the output correspondence is

$$Z(x_n) = z = (z_1, \dots, z_s): x \sum_{s \in \Omega} X_s$$ **Equation 5-20**

where each $X_s \subseteq \mathbb{R}_+$ state-allocable input technology can also be expressed by the output correspondence as

$$Z(x_n) = \left\{ \mathbf{z} = (z_1, \dots, z_s): \sum_{s \in \Omega} x_s \leq x \right\}.$$ **Equation 5-21**

[46] Adapted from Rasmussen (2011a)

For each $z_s \subseteq \mathbb{R}_+$, the state general input x_n increases output in more than one state of nature z_s.

5.6.2 Criteria for Optimizing State-General Inputs

Optimizing problem for a state-general input is:

$$\underset{x}{\text{Max}}\, W(y_1, \dots, y_s) \qquad \textbf{Equation 5-22}$$

where

$$y_s = f_s(\mathbf{x})p_s - \mathbf{wx} \;\; s\epsilon\Omega \qquad \textbf{Equation 5-23}$$

by setting the first derivative of Equation 5-22 to zero the optimal use of input $x_n$is then

$$\frac{\partial W}{\partial x_n} = \sum_{s=1}^{S} W_s(\mathbf{y})\left(p_s \frac{\partial f_s}{\partial x_n} - w_n\right) = 0 \;\; (n = 1, \dots, N)\,. \qquad \textbf{Equation 5-24}$$

For a risk neutral producer this can be reduced to

$$\sum_{s=1}^{S} \pi_s p_s \left(\frac{\partial f_s}{\partial x_n}\right) = E\left(p_s \frac{\partial f(x)}{\partial x_n}\right) = w_n \;\; (n = 1, \dots, N) \qquad \textbf{Equation 5-25}$$

and Rasmussen (2011a) defines *E* as the ‘expectation operator’. This implies that a risk neutral producer increases the application of x_n as long as the input price is less than the expected value of the marginal product. The expected value of the marginal product is important here as by acknowledging that the production function and price are state specific, then the marginal rate of return in state *s* and state *t* are different and are expressed as

$$\left(p_s \frac{\partial f_s(\mathbf{x})}{\partial x_n} - w_n\right) \neq \left(p_t \frac{\partial f_t(\mathbf{x})}{\partial x_n} - w_n\right) \;\; (s, t \in \Omega)\,. \qquad \textbf{Equation 5-26}$$

Therefore by reexamining Equation 5-24 and Equation 5-25 in given states, the application of input x_n can be greater than or less than optimal but overall it will be optimal[47].

5.7 State Allocable (Flexible) Inputs

The formal presentation of a state-allocable input is x_n is

$$\frac{\partial f_s(\mathbf{x})}{\partial x_{ns}} > 0 \;\text{ for two or more states } s \in \Omega \;\text{ for some level of } x_{ns}$$

[47] See Rasmussen (2011a) pages 464-467 for a discussion concerning the allocation of inputs between a risk adverse and risk neutral producers.

Chambers and Quiggin (2000) use the example of allocating labor inputs (effort) x between two alternative activities, flood mitigation and repairing an irrigation system. By redefining the output in state 2 as dependent upon the labor inputs invested in flood mitigation works x^2 and output in state 1 dependent on the effort placed in repairing the irrigation system x^1, then $x = x^1 + x^2$. In this case, the decision maker has to determine how to allocate inputs between these 2 options (i.e. state allocable inputs). This choice is represented by Chambers and Quiggin's (2000) "breaker" diagram, Part A in Figure 5-5, where the left vertical axis represents output produced in s_1 and the right vertical axis is output obtained in s_2. Effort is the horizontal axis. As effort moves right to left, increased labor inputs towards fixing the irrigation system have diminish marginal productivity. When effort moves left to right, more labor is allocated towards flood mitigation work with diminishing marginal productivity.

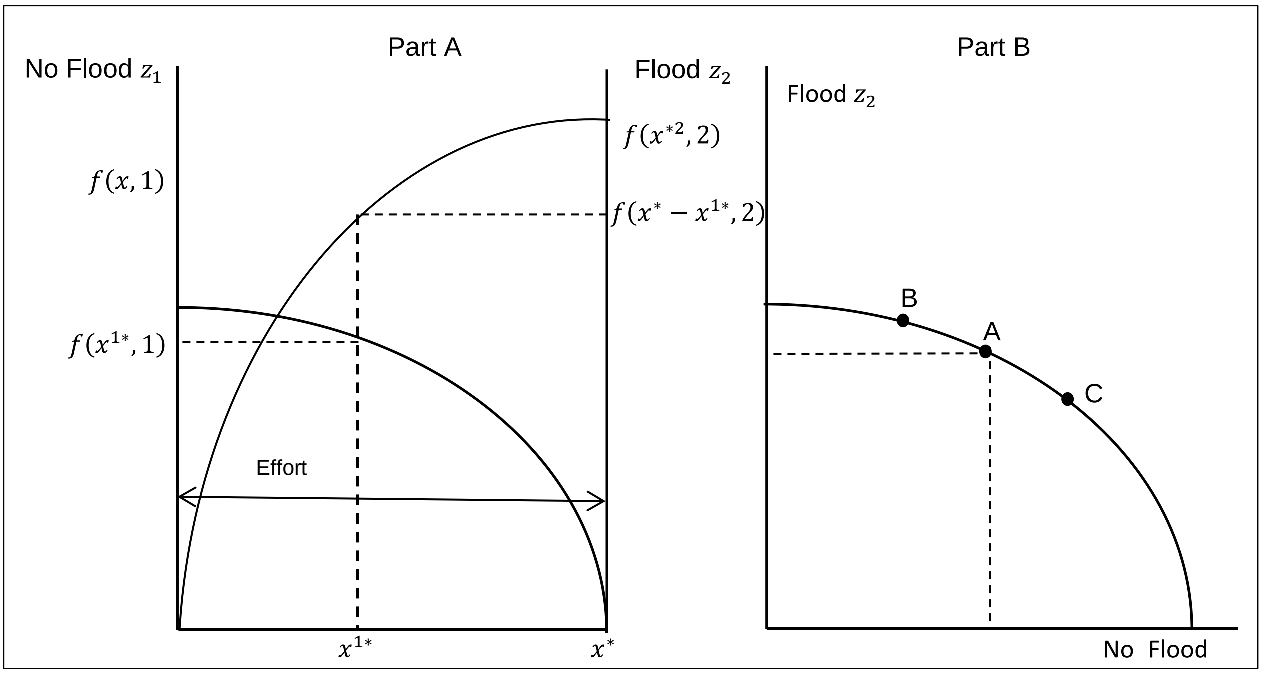

Figure 5-5 Effort Allocable Across States and the Production Transformation Curve

If x^{1*} effort is allocated to flood mitigation, then residual effort is utilised to repair the irrigation system. If state 1 occurs then output is $f(x^{1*}, 1)$ and if state 2 occurs then output is $f(x^* - x^{1*}, 2)$ and this provides the corresponding state space of A in Part B of Figure 5-5. The shift from A to B then indicates increased effort towards flood mitigation and a shift from A to C represents a greater allocation of effort towards fixing the irrigation system.

All points on the curve in Part B can be considered as the state-contingent product-transformation curve which identifies the state-contingent marginal rate of transformation. The negative slope is concave to the origin and reflects that, in order to increase production in one state of nature, output in the second state of nature is lost. All points of production below this line represent technical inefficiency.

5.7.1 Representation of State-Allocable Inputs

Output written as a function of inputs is then

$$\mathrm{z_S} \leq f(x_s, \varepsilon_s) \; \mathrm{s} \in \Omega = \{1, \dots, \mathrm{S}\}$$ **Equation 5-27**

with an input correspondence of

$$X(z) = \sum_{s \in \Omega} X_s(z_s)\,.$$ **Equation 5-28**

Here each $X_s(z_s) \subseteq \mathbb{R}_+$ state-allocable input technology can also be expressed by the output correspondence as

$$Z(x) = \left\{\mathbf{z} = (z_1, \dots, z_S) \colon \sum_{s \in \Omega} x_s \leq x\right\}$$ **Equation 5-29**

where each $z_s \subseteq \mathbb{R}_+$.

The output produced with output-cubical technology (Figure 5-2) is dependent on the total inputs used x, the output produced by a state allocable technology z_s is determined by the quantity of inputs used in that state x_s.

5.7.2 Criteria for Optimizing State-Allocable Inputs

The optimizing problem of the state-allocable input technology is

$$\max_{x_{n1}, \dots, x_{nS}} W(y_1, \dots, y_S)$$ **Equation 5-30**

where

$$y_s = f(\mathbf{x})p_s - w_n(x_{n1} + \cdots + x_{ns}) - \mathbf{w}'\mathbf{x}' \; (s \in \Omega)\,.$$ **Equation 5-31**

$x_{ns} \geq 0$ is use of input x_n designed to increase output in state s. $\mathbf{w}'\mathbf{x}'$ are the fixed costs of purchasing the remaining inputs is $N - 1$. By assuming that x_n is unique by state of nature (i.e. x_{nt} is state specific input for state t), the optimal application of x_{nt} is identical to state-specific inputs (Section 5.8) and is represented by

$$W_t p_t \frac{\partial f_t(\mathbf{x})}{\partial x_{nt}} = w_n \sum_{s=1}^{S} W_s \quad (t \in \Omega)$$ **Equation 5-32**

and Rasmussen (2011a) reduces this to

$$\pi_t \left(p_t \frac{\partial f_t(\mathbf{x})}{\partial x_{nt}} \right) = w_n \quad (t \in \Omega)\,.$$ **Equation 5-33**

This implies that a risk neutral producer will keep increasing the application of x_{nt} provided that the input price w_n remains less than the marginal product multiplied by the probability of state t occurring.

5.8 **State Specific Inputs**

The formal presentation of a state specific input is x_n is

$$\frac{\partial f_s(\mathbf{x})}{\partial x_n} > 0 \text{ and } \frac{\partial f_s(\mathbf{x})}{\partial x_n} = 0 \text{ for } s \neq t \text{ for some level of } x_n \ (t, s \in \Omega),$$

thereby making state-specific inputs a special form of the state general input set, as in this case, the use of inputs only increases outputs in a specified state of nature (i.e. only 1 state of nature). By returning to the state-general example and relaxing the need for both rainfall and irrigation to achieve optimum soil moisture, we can then argue irrigation provides no additional production in 'wet' states but irrigation is a vital input for production during 'drought' states. So if a producer has to allocate irrigation inputs before the 'wet' state of nature is realized, inputs of irrigation $0, x^1, x^2, x^3$ results in production of $0, z^1, z^2, z^3$, as illustrated in Figure 5-6.

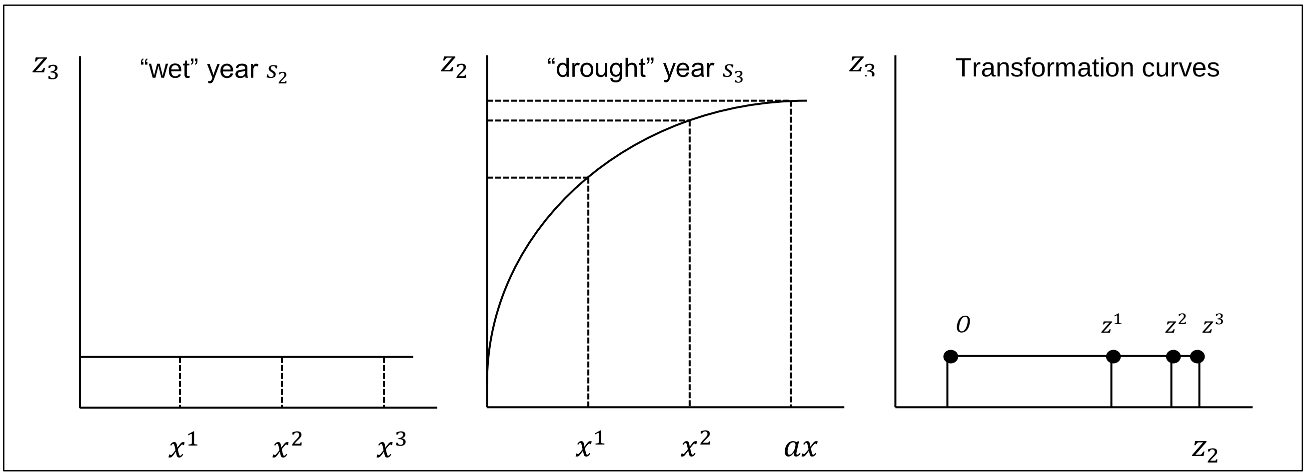

Figure 5-6 Transformation Curve for State-Specific Inputs[48]

[48] Adapted from Rasmussen (2011a)

5.8.1 Representation of a State-Specific Input

As the state-specific inputs are a special case of the state allocable inputs they can be represented by Equation 5-27 to Equation 5-29, Shankar (2012).

5.8.2 Criteria for Optimizing a State-Specific Input

The optimizing problem for a state-specific input is different to that of state-allocable inputs and can be expressed as:

$$\underset{x}{\text{Max}}\, W(y_1, \dots, y_S) \qquad \textbf{Equation 5-34}$$

where

$$y_t = f_t(\mathbf{x})p_t - \mathbf{wx} \qquad \textbf{Equation 5-35}$$

$$y_s = k_s - \mathbf{wx} \text{ for } s \neq t \qquad \textbf{Equation 5-36}$$

and k_s is a constant.

By setting the first derivative of Equation 5-34 with respect to x_n $(n = 1, \dots, N)$ to zero the optimal use of input $\mathbf{x}$ is

$$W_t p_t \frac{\partial f_t(\mathbf{x})}{\partial x_n} = w_n \sum_{s=1}^{S} W_s \;\; (n = 1, \dots, N)\,. \qquad \textbf{Equation 5-37}$$

For a risk-neutral decision maker this can be simplified to

$$\pi_t p_t \left(\frac{\partial f_t(\mathbf{x})}{\partial x_n} \right) = w_n \; (n = 1, \dots, N)\,. \qquad \textbf{Equation 5-38}$$

Which implies that a risk neutral producer increases the application of x_n provided that the input price w_n remains less than the marginal product gained in that state multiplied by the probability of state t occurring. Note, that as $\partial f_s(\mathbf{x})/\partial x_n = 0 \text{ for } s \neq t$, Equation 5-38 is equivalent to Equation 5-33.

5.9 **Optimal Production of Output**

The objective function of a producer who maximizes output is

$$\underset{z_1,\dots,z_S}{\text{Max}}\; W(y_1, \dots, y_S) \qquad \textbf{Equation 5-39}$$

and to maximize the income generated in a state of nature, production costs must be minimized

$$y_s = p_s z_s - c_s(\mathbf{w}, z_s)\,. \qquad \textbf{Equation 5-40}$$

Adapting Equation 5-4, the cost function objective to minimize the cost of production can be determined. By using the output-cubical technology, output and inputs in each state of nature are independent of other states of nature. Therefore, the costs function has the simple additive form of

$$c(\mathbf{w}, \mathbf{z}) = \sum_{s=1}^{S} c_s\,(\mathbf{w}^s, z_s) \qquad \textbf{Equation 5-41}$$

where $\mathbf{w}^s$ is the sub vector of prices corresponding to the production of z_s. By differentiating with respect to each element in the vector $\mathbf{z}$ (i.e.$(z_1, \ldots, z_S)$ and setting each derivate equal to zero the following optimal conditions for S are

$$W_s p_s - \sum_{s=1}^{S} W_t MC_s = 0 \;\; \forall_s \in \Omega \qquad \textbf{Equation 5-42}$$

> "…where MC_s is the marginal cost with respect to z_s; that is the derivative of the cost function c in [Equation 5-41] with respect to $z_s \ldots$ [W]eighting MC_s by the marginal utility in all states of nature is a result of the fact that the cost of producing a marginal unit of output in state s is the same, no matter what state of nature occurs. However, the marginal income(p_s) only occurs in state s. For a risk-neutral decision-maker [Equation 5-42] reduces to…"(Rasmussen 2003, p. 472).

$$\pi_s p_s = MC_s \;\forall_s \in \Omega \qquad \textbf{Equation 5-43}$$

implying that, provided the marginal cost of production is less than or equal to the product price in state s multiplied by the frequency of state s occurring, a risk neutral producer will continue to increase production in state s. The conditions for increasing production across all states of nature are defined by

$$\sum_{s=1}^{S} \pi_s p_s = \sum_{s=1}^{S} MC_s(\mathbf{w}^s, z_s) = E(p)\,. \qquad \textbf{Equation 5-44}$$

So a risk-neutral decision maker will increase output provided that the cost of producing that output is less than or equal to the expected product price $E(p)$ across all states of nature.

By using the assumption that there is no price uncertainty and only production uncertainty (the relationship between output in state s and state t), the optimal production can be derived from Equation 5-42

$$\frac{W_s}{W_t} = \frac{MC_s}{MC_t} \quad \textbf{Equation 5-45}$$

where the slope of the indifference curve, illustrated in Figure 5-3, is equal to the ratio defined by the marginal cost of production in state s and state t.

Equation 5-45, then highlights why the state-contingent model can illustrate how decision makers change production systems in response to climate change where droughts become more frequent. In this case as the decision maker's perceptions about future states occurring change, the slope of the indifference curve alters, which encourages resource (input) reallocation between states of nature in an effort to maximize future profit. This aligns with Arrow's (1953) arguments that for a decision maker "risk-bearing is guaranteed to be viable only if individuals have attitudes of risk-aversion" (Arrow 1953, p. 91) thus the switching of resources to maximize rent as the frequency of states is an optimal risk minimization strategy.

5.10 **Summary**

By considering the output of technology and the inputs required to produce that output as closed sets in each state of nature, the optimal use of capital by type, place, date, and by state of nature can then be derived. This separation between states then overcomes the limitations of stochastic representation of production under uncertainty, as the tails of the distribution are now directly examined as states of nature, this preventing the development of black swans in models (Chichilnisky 2010).

6. THE RSMG MURRAY-DARLING BASIN MODEL

6.1 Introduction

The RSMG Murray-Darling Basin model was developed by Adamson, Mallawaarachchi and Quiggin (2007, 2009) to provide a partial equilibrium example of the state-contingent approach (SCA). By integrating a river flow network that incorporates salinity, the model can then track how alternative spatial irrigation practices respond to alternative states of water availability (drought, flood and normal) and subsequently change both the quantity and quality of water available for downstream users. By altering the model's biophysical and economic constraints, the model can then be used to examine the optimal consumer behavioral (i.e. irrigator) response to maximize economic rent from water use at either a catchment or national level.

The RSMG model was the first economic simulation model of the entire Murray-Darling Basin (MDB) since the retirement of the Australian Bureau of Agricultural Resource Economics (ABARE) 'SALSA Model' (Beare & Heaney 2002). All other models had constrained the economic irrigation landscape to either, examine a single catchment or multiple catchments but only the Southern Murray-Darling Basin (SMDB) (Hall, Poulter & Curtotti 1994; Heaney & Beare 2001) had used alternative partial and general equilibrium techniques with a varying degree of success (Griffith 2012).

The model presented in this section has been formulated to reflect the constrained welfare optimization evaluation strategy. In summary, this evaluation is based on Randall's (1975) arguments, that to understand net changes in property rights, a constrained welfare optimization approach is required. By optimizing economic rent derived from irrigation at a national level, the trade-offs between economic returns, water quality and water flow targets pre and post Murray-Darling Basin Plan (Basin Plan) implementation can be determined.

Figure 6-1 provides a flow diagram of the model. The state of nature provides certainty by revealing the total volume of water to be traded-off between consumptive use and institutional goals. Irrigators maximize income by allocating resources across three states of nature (temporal aspects). The opportunity cost between irrigators in the MDB is determined by the spatial consumption of water and net changes to salinity from its use (i.e. reduced rivers flows and return flows transporting salt back into the river system) and subject to the institutional goals which seek to prevent irreversible harm in the MDB. Note, variables have been redefined in this section so that w is related to issues with water rather than input costs and state-contingent production systems are defined as x.

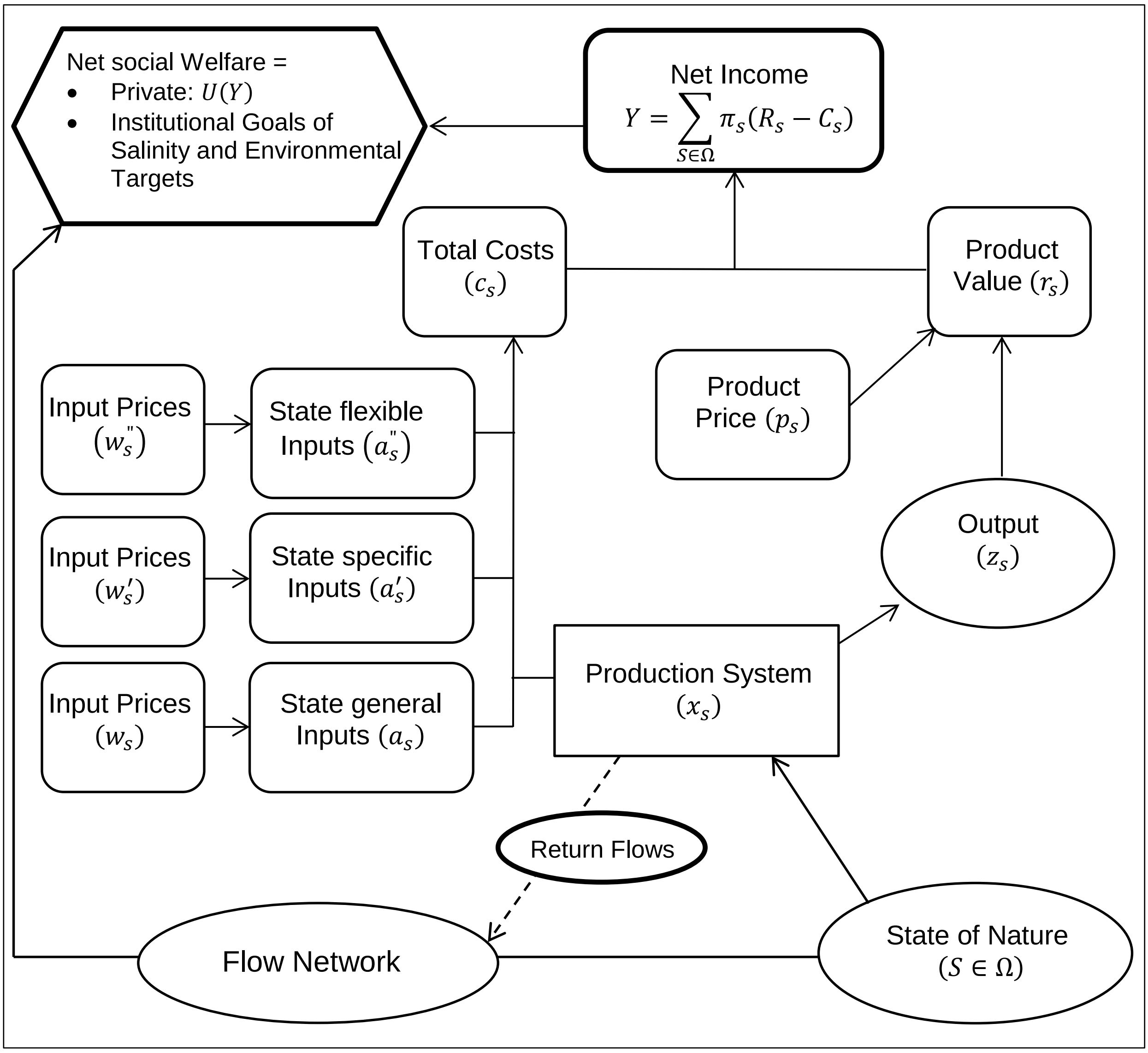

Figure 6-1 The RSMG Model of the MDB

6.2 Background to the Model

Quiggin (1988) provided the genesis for the model developed by Adamson, Mallawaarachchi and Quiggin (2007, 2009). The 1988 model was developed to evaluate policy options for salinity managing in the SMDB. The model optimized economic returns from allocating four production inputs (land, water, operator labor and other) between four crops (stone fruit, citrus, grapes and pasture) across six catchments. Salinity impacts on production output were derived by using a negative linear relationship. This relationship was discontinuous in nature as salinity did not reduce output until a threshold salinity level had been reached. The model included a directed water and salt flow network that allowed for policy mitigation of salt and downstream impacts from water-use to be incorporated.

Figure 6-2 illustrates the critical difference between the expected value (EV) approach used by Quiggin (1988), (Part A in Figure 6-2), and the SCA approach used by Adamson, Mallawaarachchi and Quiggin (2007), (Part B Figure 6-2). By separating water variability into states of nature, the SCA approach can allow for management response to adapt to alternative levels of water security that can create non-convex demand responses. In Part A only a single water supply of 620GL is expected to occur all the time and the decision maker always applies the identical management solution. Whereas in Part B, the decision maker is modeled as being aware that: for 50% of the time, only 620GL of water available; for 20% of the time, droughts provide only 358GL of water; and for 30% of the time inflows will provide 803GL of water.

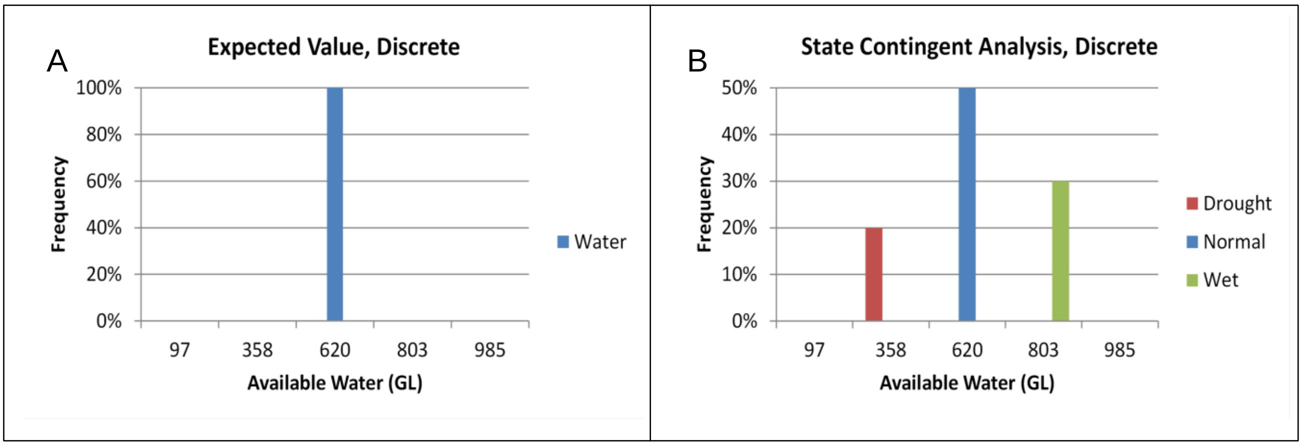

Figure 6-2 Outcome of Flow Variability[49]

By modeling the probability of alternative states and having complete information about each state of nature, decision makers can then maximize their returns across all state of nature. So the design of the SCA model then prevents land allocations from attempting to over utilize water in a drought and allows for the area irrigated in a wet state of nature to

[49] The data represented here is the conjunctive water resources for the Condamine from Table 7-1.

increase. While the EV model choses only a single land allocation, consequently the decision maker is exposed to increased risk in a drought and fails to maximize economic returns in a wet state of nature.

If the modeler's heuristics (Section 4.3.1) suggested that the problem of allocating water in the MDB could be framed within the EV approach, then the narrow bounds of a discrete representation of water supply quickly limit the value of the model for dealing with scenarios outside the initial specifications (Chugh & Bazerman 2007; Grant & Quiggin 2013a). Even if a stochastic production function (Chavas, Chambers & Pope 2010; Just & Pope 2003) is used to incorporate risk and uncertainty about future water supply, then the role that droughts and floods play in the decision making process for allocation production inputs is ignored (Mendelsohn & Dinar 2003).

This heuristic approach is evident in Quiggin (1988) where the results could create a Black Swan outcome. Quiggin's (1988) suggested that the optimum strategy to deal with climate risk in irrigation, was to allocate all water towards perennial horticulture. However, in Section 3.3 it was argued that the area irrigated in the MDB expands and contracts in direct response to La Niña and El Niño climatic events (Table 3-1) and that capital invested in perennials is compromised under increasing variability in water supply. Consequently, Quiggin (1988), although technically correct in the economic theory of the solution to deal with salinity externalities, has suggested a production mix that is inflexible once water supply variability is taken into account. Quiggin (1988, 1991) acknowledged this limitation when dealing with risk and uncertainty.

6.3 **Formal Model Description**

The model is used to examine the problems of allocating water resources between all water users. Private individuals are represented by irrigators and the institutions are responsible for ensuring social and environmental goals (i.e. provide the constraints on private choice). Uncertainty or nature in this case is the volume (supply) of water available to share between both groups. The state-space is divided into 3 states of nature ($S = 3$). Where:

- s_1, normal state where the quantity of water is the expected value θ;
- s_2, drought state is a period of water scarcity, 0.6θ; and
- s_3, surplus (wet) state where water supply exceeds the expected value by 1.2θ.

By adapting Figure 2-1, to obtain Figure 6-3, we can simply represent that alternative water states of nature (i.e. $0.6\theta, \theta, 1.2\theta$) can then align with producers adapting to those state signals by using output-cubical technology (Section 5.4.3).

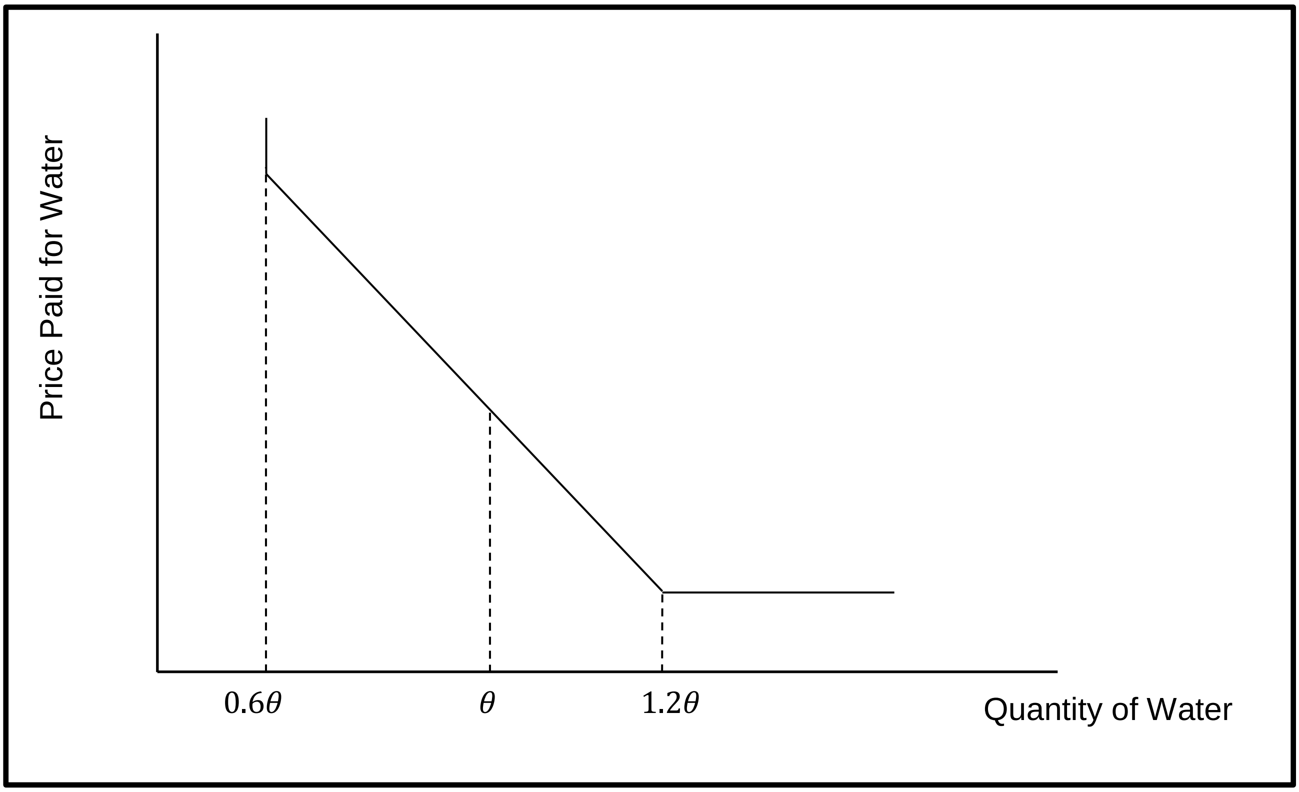

Figure 6-3 State of Nature and Management Response to Water Supply

Therefore, when the normal state of nature occurs, producers utilize the appropriate technology for that state of nature. When the drought state occurs, producers reallocate inputs and management strategies knowing that their demand for water is inelastic. In the wet state of nature, the abundant water relaxes supply constraints experienced in the normal state so that the demand curve becomes elastic. The wet state then defines all reallocation of inputs and management opportunities to take advantage of extra water supply. The probability π of each state occurring is: $s_1 = 0.5$; $s_2 = 0.2$; and $s_3 = 0.3$, “and the associated inflow levels are calibrated to match the observed historical mean and variance of inflow levels” (Quiggin et al. 2010, p. 542).

Unlike Quiggin (1991) and papers based on the approach described in Adamson, Mallawaarachchi and Quiggin (2007) this model has deactivated the binding operator’s labor constraint for three reasons. First, on review it was identified that the operator’s labor constraint was too restrictive, for some k, and the area irrigated was well below known historic allocations, even in wet years. Second, it prevented new individuals from entering into irrigation to take advantage of economic opportunities that may emerge. Third, agriculture in the MDB continues to adopt by investing in labor saving technology or purchasing contract labor, allowing for individuals to increase their farm size (Boserup 1965; Keogh 2011).

6.4 **The Objective Function**

To maximize net social welfare, the model is solved as though a single benevolent individual, with prefect knowledge, is acting in the national interest. This is the "global optimization for the system as a whole (Adamson, Mallawaarachchi & Quiggin 2007, p. 272). In this case the individual maximizes social welfare Y (Equation 6-1) from allocating resources, throughout all K in the MDB, between alternative state-contingent production systems x which are subject to a series of production (Equation 6-5 and Equation 6-6), bio-physical (Equation 6-7) and institutional policy (Equation 6-8 to Equation 6-11) constraints. The objective function is

$$MaxE[Y] = \sum_{K}\sum_{s\in\Omega}\pi_s\left(R_{s,k} - C_{s,k}\right) \qquad \textbf{Equation 6-1}$$

where

Revenue $$r_{s,k} = z_{s,k}p_{s,k} \qquad \textbf{Equation 6-2}$$

Costs $$c_{s,k} = \boldsymbol{a}_{s,k}\boldsymbol{x}_{s,k} \qquad \textbf{Equation 6-3}$$

Output $$z_{s,k} = f(\boldsymbol{x}_k) \qquad \textbf{Equation 6-4}$$

Subject to

$$\boldsymbol{b}_{s,k}\boldsymbol{x}_{s,k} \leq B_{s,k} \qquad \textbf{Equation 6-5}$$

$$\boldsymbol{x}_s \geq 0 \qquad \textbf{Equation 6-6}$$

$$w_{s,k} \leq wf_{s,k} \qquad \textbf{Equation 6-7}$$

$$\sum_{K} W\pi_s \leq Cap \qquad \textbf{Equation 6-8}$$

$$wf_{s,21} \geq 650GL \qquad \textbf{Equation 6-9}$$

$$\sigma_{s,20}/0.64 \ \leq 800\text{EC} \quad \textbf{Equation 6-10}$$

$$w_{k20} = 206GL \quad \textbf{Equation 6-11}$$

The description of the variables used in Equation 6-1 to Equation 6-11 are provided in Table 6-1.

Table 6-1 Description of Variables

Symbol	Definition
$E[Y]$	Expected [Income]
K	Catchments in the MDB ($K = 1 \dots 21$)
S	States of Nature ($S = 1 \dots\ 3$)
π	Probability of state occurrence
R	Revenue
C	Costs
Z	Output
P	Price per unit of output
$\boldsymbol{x}$	Vector of state-contingent production systems
$\boldsymbol{a}$	Vector of input costs (land, fixed costs, variable costs, water)/Ha
$\boldsymbol{b}$	Vector of input requirements (land (l), fixed costs, variable costs, water)/Ha
B	Input constraints (land (L), water)
w	Volume of water used derived from $b_{s,k}x_{s,k}$
wf	Volume of water flowing in the catchment
Cap	The total constraint on the water use. Depending on run ether based on Current Diversion Limits (CDL) or Sustainable Diversion Limit (SDL) data, see Section 4.3.1.
σ	Salinity level in EC units

6.5 The Model Design

The MDB is divided into catchments $k = 1 \dots K$ and the river system is modeled as a directed flow network (Table 6-2). The decision maker allocates alternative bundles of inputs $\boldsymbol{b}$ (one hectare of land, a unit of fixed costs, a unit of variable costs and a specified volume of water in megalitres (MLs) between alternative production systems x by k to maximize income subject to a series of land and water constraints. As inputs are used along the river system, irrigation return flows provide a point source of pollution by transporting salt back into the river system, degrading the quality of water for downstream users. The decision maker must then allocate water resources so that their consumption does not prevent the social and environmental goals from being violated. As the relationships between water flow, water use, salt and salinity are non-linear the model as a whole is non-linear.

Table 6-2 The Directed Flow Network

K	Catchment Name	Cumulative Flow Structure
$k1$	Condamine	+Condamine
$k2$	Border Rivers QLD	+Border Rivers QLD
$k3$	Warrego-Paroo	+Warrego-Paroo
$k4$	Namoi	+Namoi
$k5$	Central West	+Central West
$k6$	Maranoa-Balonne	+Maranoa-Balonne + Condamine(Net)
$k7$	Border Rivers Gwydir	+Border Rivers Gwydir + Border Rivers QLD(Net)
$k8$	Western	+Western + Warrego-Paroo(Net) + Namoi(Net) + Central West(Net) + Maranoa-Balonne(Net) + Border Rivers Gwydir(Net)
$k9$	Lachlan	+Lachlan
$k10$	Murrumbidgee	+Murrumbidgee
$k11$	North East	+North East
$k12$	Murray 1	+Murray 1
$k13$	Goulburn Broken	+Goulburn Broken + ½(North East(Net) + Murray 1(Net))
$k14$	Murray 2	+Murray 2 + ½(North East(Net) + Murray 1(Net))
$k15$	North Central	+ North Central + ½(Goulburn Broken(Net) + Murray 2(Net))
$k16$	Murray 3	+ Murray 3 + ½(Goulburn Broken(Net) + Murray 2(Net))
$k17$	Mallee	+Mallee + ½(North Central(Net) +Murray 3(Net) + Lachlan(Net) + Murrumbidgee(Net))
$k18$	Lower Murray-Darling	+ Lower Murray Darling + ½(North Central(Net) + Murray 3(Net)) + Lachlan(Net) + Murrumbidgee(Net)) +Western(Net)
$k19$	SA MDB	+SA MDB + Lower Murray-Darling(Net)
$k20$	Adelaide	+SA MDB(Net)
$k21$	Coorong	+SA MDB(Net) – Adelaide Extractions

The model is solved on an annual basis, and examines what happens on each Ha of land in each k. To model the producer's investment choice, capital costs are treated as an annuity representing the amortized value of the capital over the lifespan of the development activity. The per Ha capital costs are derived from estimates of both the establishment costs and the equipment costs required to develop an irrigation farm producing a specified production system, (see Table 7-11), and then divided by the average farm size of that production system in each k, (see Table 7-12). The model therefore provides the flexibility to model a range of alternative pricing rules for capital and by incorporating capital costs it overcomes the limitations associated with using only gross margin budgets to determine the economic value of water.[50]

The state-contingent production systems highlight the nature of irrigator response to a given state of nature for a single Ha of land in each k. In given cases the production systems are a representation of an amalgamation of enterprises (i.e. oil seeds refers to a spatial mix of canola and sunflowers dependent on what is produced in each k) and not a specific commodity.[51] Only the production systems x relevant to k can be produced in k. For example, cotton cannot be produced in South Australia (SA) and rice is not grown in QLD. All data for production systems were derived from a series of regional enterprise budgets that are documented in Appendix B.

These production systems have two major rules pertaining to how the land is used and capital costs. First, as the production system defines what happens on a single Ha over time, the ability to change what commodity is produced by state of nature is limited to annuals. For example, if the cotton/chickpea production system is selected, then on that single Ha the irrigator produces a cotton crop in the normal and wet states of nature, and chickpeas in the drought (see Section 7.7.2 and Table 6-4). In this case the choice to produce annuals is not dependent on what is produced in a prior or subsequent state of nature. This highlights the producer ability to adapt to environmental signals by reallocating resources between production choices.

Unlike an annual system a perennial production system must always produce the identified perennial commodity on that given Ha. As perennials are a long term investment and take time to reach production maturity, they cannot be removed from that Ha as the state of nature changes. For example, for a given Ha of a production system the model ***does not*** allow a decision maker to produce citrus in the normal and wet states of nature and then replace it with a dryland crop, ***nor does*** it allow for substitution between perennial crops by state of nature, for example a citrus crop cannot be replaced by viticulture on the same Ha in the same model run. Only the specified perennial can be produced on a given Ha and it must always be produced in each state of nature. This then allows for the risk of capital

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[50] See Section 1.3 and this debate provided by Brennan (2006).

[51] See Table 6-4 and Section 7.6.4 for a detailed description of the SCA production systems within the model.

investment in each Ha to be determined and illustrates how management strategies differ between perennial and annual production systems.

Second, for the annual state-contingent production systems that specify that producers can swap production choices by state of nature, the production choice with the highest capital cost is used to define capital costs in all states of nature. For example, for the state-contingent production systems cotton/chickpea, described above, the capital costs required to produce cotton is greater than chickpeas. In this case, the opportunity cost of having cotton machinery idle must be taken into account when allocating resources and therefore, in this production system the capital cost to produce chickpeas is based on the per Ha capital cost from cotton. Capital is then a state-general input (Section 5.6).

6.6 Income

The maximum Y in the MDB is derived from allocating resources between all k, where irrigation occurs $(k_{1..19})$ subject to biophysical constraints (water flow, Equation 6-7) and b limitations in each k (land, water) and the policy setting for: Adelaide (k_{20}); the Coorong (k_{21}); and water use (Cap). Revenue/Ha $(r = z \times p)$, where output (z)/Ha has a dimension of $(k \times x \times S)$, price (P) has a dimension of $(M \times S)$, where (M) is a commodity. The transformation of $(M = 18)$, Table 6-3, into $(X = 23)$, Table 6-4, occurs by: the use of alternative irrigation technology; the management response to alternative states of nature by reallocating inputs between commodities; and or utilizing different bundles of inputs to produce a state specified output for that commodity.

Table 6-3 Commodities Used in the Model, $\boldsymbol{M = (1 \dots 18)}$

M	Commodity Name	M	Commodity Name
$m1$	Citrus	$m10$	Rice
$m2$	Grapes	$m11$	Wheat
$m3$	Stone-Fruit	$m12$	Legumes
$m4$	Pome Fruit	$m13$	Sorghum
$m5$	Vegetables	$m14$	Oilseeds
$m6$	Melons	$m15$	Sheep
$m7$	Fresh Tomatoes	$m16$	Dairy
$m8$	Cotton	$m17$	Dryland
$m9$	Chickpea	$m18$	Adelaide

The two alternative technologies for irrigation are: high irrigation technology (suffix -H) referring to intensive capital investment to reduce water use per Ha (e.g. drip lines); and low irrigation technology (suffix -L) referring to inexpensive capital investment (e.g. furrow irrigation). The data and description of the state-contingent production systems for converting bundles of inputs between commodities and for a given commodity are provided in Section 7.6. The matrix of total SCA production systems is $X \times K \times S$. Where $x = 22$ is a default dryland commodity to account for area permanently transitioning out of irrigation. $x = 23$ is the SCA production system required to ensure that the city of Adelaide receives its water. $x = 23$ has special b characteristics of requiring (0 units of land, 0 units of fixed costs, 0 units of variable costs and it needs 1 ML of water) so that allocating water to Adelaide does not interfere with production activities.

Table 6-4 State-Contingent Production Systems $\boldsymbol{X = (1 \ldots 23)}$

$\boldsymbol{X}$	**Production System Name**	**State-Contingent Crop**		
		Drought	**Normal**	**Wet**
$x1$	Citrus-H	Citrus-H	Citrus-H	Citrus-H
$x2$	Citrus-L	Citrus-L	Citrus-L	Citrus-L
$x3$	Grapes	Grapes	Grapes	Grapes
$x4$	Stone Fruit-H	Stone Fruit-H	Stone Fruit-H	Stone Fruit-H
$x5$	Stone Fruit-L	Stone Fruit-L	Stone Fruit-L	Stone Fruit-L
$x6$	Pome Fruit	Pome Fruit	Pome Fruit	Pome Fruit
$x7$	Vegetables	Melons	Vegetables	Fresh Tomatoes
$x8$	Cotton Flex	Dryland Cotton	Cotton Flex	Cotton
$x9$	Cotton Fixed	Cotton Fixed	Cotton Fixed	Cotton Fixed
$x10$	Cotton/Chickpea	Chickpea	Cotton Flex	Cotton
$x11$	Cotton Wet	Dryland Cotton	Dryland Cotton	Cotton
$x12$	Rice PSN	Rice PSD	Rice PSN	Rice PSW
$x13$	Rice Flex	Dryland Wheat	Rice PSN	Rice PSW
$x14$	Rice Wet	Dryland Wheat	Dryland Wheat	Rice PSW
$x15$	Wheat	Wheat	Wheat	Wheat
$x16$	Wheat Legume	Wheat Legume Dry	Wheat Legume	Wheat Legume Wet
$x17$	Sorghum	Sorghum	Sorghum	Sorghum
$x18$	Oilseeds	Oilseeds	Oilseeds	Oilseeds
$x19$	Sheep Wheat	Sheep Wheat Dry	Sheep Wheat	Sheep Wheat Wet
$x20$	Dairy-H	Dairy-H	Dairy-H	Dairy-H
$x21$	Dairy-L	Dairy-L	Dairy-L	Dairy-L
$x22$	Dryland	Dryland	Dryland	Dryland
$x23$	Adelaide Water	Adelaide Water	Adelaide Water	Adelaide Water

Notes:
H = intensive irrigation capital (e.g. drip lines)
L = low irrigation capital (e.g. furrows)

6.6.1 Revenue

Revenue is $(r = z \times p)$ and for simplicity P is held constant in each state of nature, except for (x_{22}) where the price paid in $s_1 = \$50, s_2 = \$0, s_3 = \$65$ which reflects the default income generated from a default dryland production system[52]. Output z_s is the yield/ha and is derived from the regional gross margin budgets and the production rules stipulated in Table 7-15 and Appendix B.

6.6.2 Costs

Cost (c)/Ha has dimensions of $(k \times x \times S)$. Costs are based on a vector of input requirements $\mathbf{b}$ and a vector of input prices $\mathbf{a}$ to produce each unit of x/Ha. As discussed $\mathbf{b}$ has four inputs: land; fixed costs; variable costs; and water, and they all have dimensions of $(K \times X \times S)$. All x requires 1 Ha of land, 1 unit of fixed costs, 1 unit of variable costs and the volume of ML (water) required to produce one Ha in each s. For simplicity, there is no cost to purchase land. Fixed costs are constant in every state of nature and cover the per hectare annuity repayment on capital, with dimensions of $(K \times X \times S)$. Fixed costs can be considered as *ex-ante* costs before the state is realized. Variable costs are the costs of producing x/Ha which include all traditional enterprise costs (i.e. seed, machinery, chemicals, casual labor, contractor costs, other costs, etc.) plus a payment for operator labor, dependent upon the time required for each SCA production system.

The cost of water is derived from the number of ML required in each state and all water is charged at \$25/ML. Cost to produce $z_{ks(x)}$ is then the sum of fixed costs plus variable costs plus water costs. All data for Y and water use for dimensions of $(K \times X \times S)$ are presented in Appendix A.

6.7 **Constraints**

The use of the dual optimization approach provides the ability to determine the economic implications of binding resource constraints. However, The nature of partial equilibrium models, prevents changes to investment from having endogenous dynamic responses on

[52] By assuming the small country assumption for Australia holds prices output prices are assumed independent of the state of nature.

prices of inputs and outputs, which may result in unrealistic investment patterns when compared to general equilibrium models (Janvry & Sadoulet 1987; Rothenberg & Smith 1971).

The constraints listed within this Section, attempt to place bounds on resource use so that the model approximates some form of reality by adhering to known parameters for realized land and water use (Erdem et al. 2005).

6.7.1 Resource Endowments

Equation 6-5, ensures that the total land and water resources used by the production systems do not exceed the resource endowments The model diverts land use between two types of SCA production systems, horticulture and broadacre. This diversion occurs to prevent unrealistic expansion in horticultural activities. The total area dedicated to irrigation commodity (m) in (k) is based on data from the 2000-01 production year (Australian Bureau of Statistics (ABS) 2004) as at the time of model development that was considered the last 'normal' year in the MDB, see Chart 3-1. Area (L) in (k) is allowed to expand as follows: the total area dedicated to horticulture in a catchment is allowed to expand by 50%, with the exception of $k1, k6 \text{ and } k11$ where the total area dedicated to irrigation has been allowed to increase by 150%, 200% and 100% respectively to bring data into line with known capacities, Equation 6-12. The total area dedicated to all irrigated activities, inclusive of area that does not enter irrigation $(x = 22)$, can increase by 100%, Equation 6-13. No irrigation activity takes place in Adelaide $(x = 23)$. This then allows the broadacre area to expand into horticulture area if required but the expansion of both irrigation and horticulture is capped. Any land not allocated to irrigated area is assumed to either remain or return to a default dryland enterprise, thus the model can represent irrigation expansion or contraction by catchment (k) based on opportunities for irrigators or responses to policy and biophysical stimulus.

$$L_k x_{k,x(1..7)} \leq 1.5 L_k m_{(1..7)}$$ **Equation 6-12**

$$L_k x_{k,x(1..22)} = 2 L_k m_{(1...16)}$$ **Equation 6-13**

As decision variables, SCA production systems, can be any real number. Equation 6-6 ensures that the optimization algorithm does not allocate a negative area into production. In this case $0 \geq x_k \leq l_k$.

The second part of the resource endowments constraints ensures that the water used for irrigation does not exceed the resource allocated and CAP (either CDL or SDL dependent on run). Water resource endowments are also constrained by the biophysical constraints on water flow to ensure that water used is not greater than the flow in the river system.

6.7.2 Biophysical Constraints of Water Flow

The model has a single biophysical constraint (Equation 6-7) to ensure that the volume of water used for production does not exceed the capacity of the system to deliver supply. Figure 6-4 provides an illustration of the flow network and Table 6-2 provides the mathematical representation of the network.

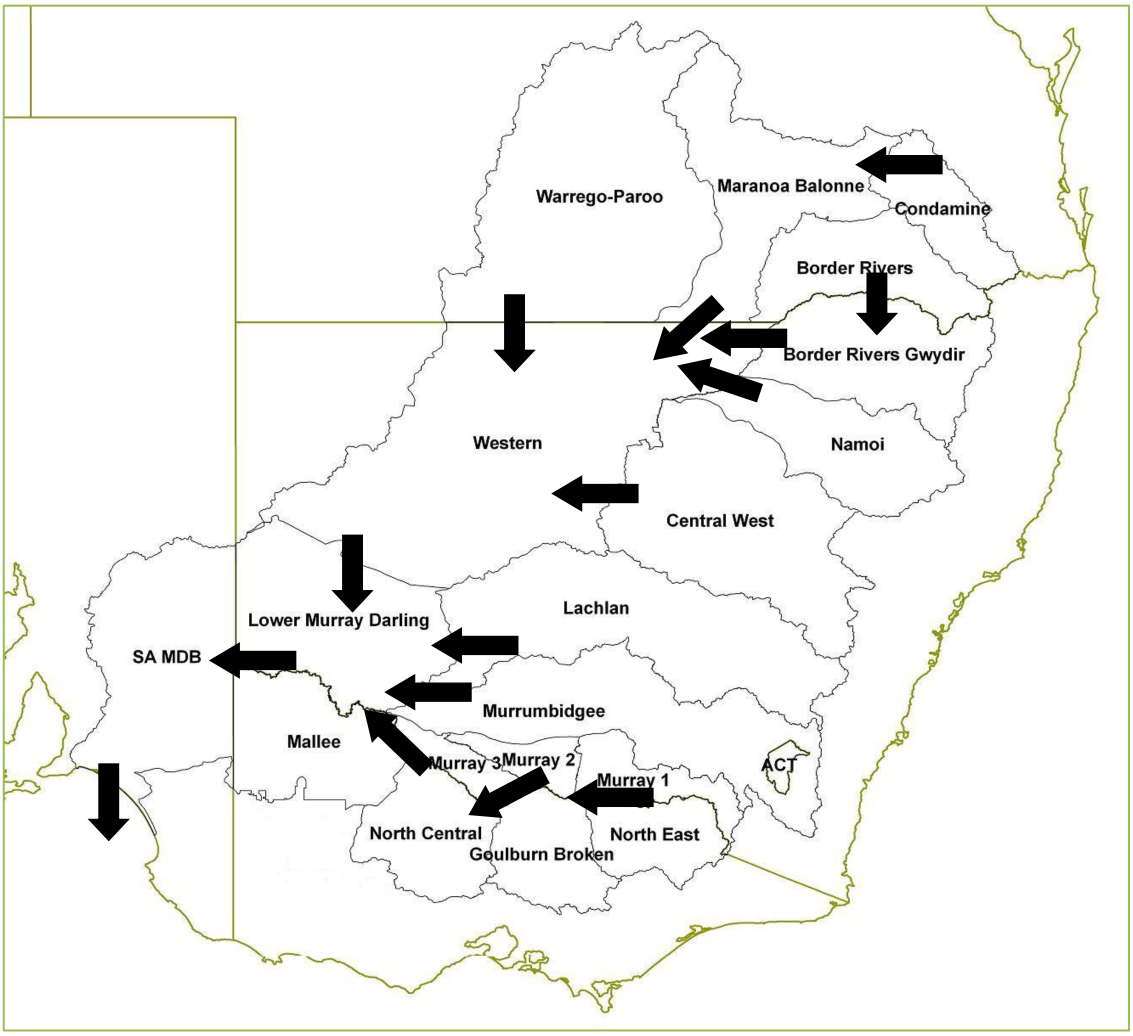

Figure 6-4 Representation of the Flow Model

The states of nature are defined by the available conjunctive exogenous water resources (θ): surface flows; groundwater extractions; and net inter-basin transfers. The flow leaving each catchment $wf_{s,k}$ is obtained from Equation 6-14, where flow is determined by the impact that conveyance losses (wc) have on water resources θ, minus water used (w) to irrigate less return flows (wr) from irrigation use. When this water reaches the next catchment it forms part of θ and conveyance losses are then applied. Equation 6-14 then allows for the trade-offs between spatial use of irrigation supplies and the environmental and social benefits to be determined.

$$wf_{k,s} = (\theta_{s,k} \times wc_{s,k}) - (w_{s,k} - wr_{s,k}) \qquad \textbf{Equation 6-14}$$

Each production system $(x_{s,k})$ then has a defined water use (ML/Ha) and reflow variable dependent on technology, -L or –H, which determines (wr) in each s.

6.7.3 Policy Constraints

There are three policy constraints in the model to describe the role of institutions on private use: total water use; environmental targets; and Adelaide's potable water supply. Extractions are determined endogenously by land use decisions as described above, subject to limits imposed by the availability of both surface and groundwater. This structure allows for the determination of total irrigation use, the flow to the Coorong and water quality arriving at Adelaide.

6.7.4 Total Water Used

The model defines the CAP as diversions for irrigation purposes, see Section 2. This then accounts for both water used for irrigation and the water used for transporting irrigation supplies. This assumption then allows for grains from trade to be quickly examined. The volume of water used in the basin must be less than the CAP[53] on average. This average then allows for carry over provisions to be modeled and in given cases it allows irrigators to use a volume of water greater than the CAP if profitable to do so. The model assumes that irrigators can access 100% of their entitlements on average (Equation 6-8) thus providing a basic modeling approach for carryover management response.

[53] CAP as in the limit on long term diversions. Here the term CAP is interchangeable with CDL or SDL depending on which scenario is run as demonstrated in Section 5.

Apart from Adelaide, which has a guaranteed water supply by Equation 6-9, all other potable supplies and estimations of livestock use defined under the CAP are subtracted from θ before the model is optimized. This approach ensures that these water shares are provided in all $S\epsilon\Omega$.[54]

6.7.5 Ecological Requirements

Without a detailed environmental plan in the Basin Plan, Equation 6-9 provides the only environmental target for this model. This simply ensures that 650GL of water arrives to the Coorong in all states of nature.

6.7.6 Salinity & Adelaide's Potable Water Supply

There are two constraints dealing with water quality and Adelaide's potable water supply. Water quality is simplified to reflect salinity (σ) as it is a binding policy constraint to ensure that the Basin Plan's requirement for Adelaide's water quality is achieved (Equation 6-10). This then allows salinity impacts on output to be modeled as a constraint on water consumption rather than a discontinuous function on yield.[55]

Equation 6-15 illustrates that σ is a ratio of the total salt load (G) and (f) and this provides salinity in milligrams per liter (mg/L):

$$\sigma_{s,k} = G_{s,k}/wf_{s,k}$$ **Equation 6-15**

The determination of the natural salt load utilizes the same framework as the directed river flow network. The total salt load $G_{s,k}$ is a combination of the naturally mobilized tons of salt that enters run off less the exogenous tons of salt removed via the salinity mitigation program, plus the endogenous salt transported with reflow determined by $\theta_{s,k}w_{s,k}$. The natural salt load is represented in state-contingent terms reflecting salt immobilization in

[54] If a defined indigenous cultural supply of water was to be allocated (Section 2.6.1), it could be modeled in one of three ways. First, the indigenous allocation could be removed from θ as per urban use in the MDB as assumed above. Second, as a defined volumetric constraint, as consistent with the way Adelaide's water supply is modeled (Equation 6-11). Third, as a portfolio of water property rights and this approach is illustrated in Section 8, for the CEWO.

[55] Adamson et al. (2007) did use discontinuous functions to model salinity impacts on output.

soil in drought times and mobilization during the wet states, where $(s_1 = 1.0, s_2 = 0.5, s_3 = 1.3,)$. σ is converted into EC by dividing it by 0.64.

6.8 **Model Platform**

The version of the model here was built in Microsoft Excel 2010 and uses the Risk Solver Platform V12.5.1.0 built by Frontline Solvers. The 'Large-Scale SQP Solver Engine' is used to deal with the non-linearity nature of the optimization problem (Frontline Solvers 2013).

6.9 **Summary**

By modeling water and salt interaction the externalities derived from its use can be tracked through spatial and temporal (states of nature only) terms. The direct representation of producer behavior towards alternative states is modeled via the adoption of a range of state-contingent production systems. Subsequent sections describes the data sources used in the model and then Section 8 and Section 9 define the changes to the model presented here to model both the Restoring the Balance (RtB) and the Sustainable Rural Water Use and Infrastructure Program (SRWUIP) approaches for returning the flow.

7. MODEL DATA & ASSUMPTIONS

The model described in Section 6 requires large amounts of specific data and assumptions that define the model's bounds. The data and assumptions presented in this section have been continually collected and modified since 2004 to reflect the availability of new data and refinements in the model. As discussed (Section 4.3), a key outcome from the contraction stage of water resource development has been the commissioning and collection of data to aid in determining the optimal allocation of water resources between all users in the Murray-Darling Basin (MDB) (Commonwealth of Australia 2008). Where possible, the data used in this thesis has been aligned to these new publically available data sets. However, some data has been provided by third parties during commissioned studies. All data and assumptions concerning the final Murray-Darling Basin Plan (Basin Plan), the Restoring the Balance (RtB) and the Sustainable Rural Water Use and Infrastructure Program (SRWUIP) have expressly been collected during this thesis.

7.1 Catchment Management Regions

To engage in the policy debate, The RSMG Murray-Darling Basin model (Section 6) disaggregates the MDB into catchments utilizing the Catchment Management Regions (CMR) classification system (represented by Part A in Figure 7-1). The CMR classification was chosen as it aligns with political boundaries but these boundaries can be at odds with the biophysical boundaries or hydrological realities. For example, the CSIRO Sustainable Yields Project (CSIRO 2008) (represented by Part B in Figure 7-1) clearly illustrates that hydrological and political boundaries may not harmonize.

Consequently all raw biophysical data sets have been modified to fit the CMR boundaries to engage in policy debate. Additionally, to enable greater accuracy in the directed water flow network and determine the opportunity cost between regional water users, the CMR boundaries were modified as follows. Due to a lack of surface and groundwater connectivity the Wimmera is not modeled[56]. The ACT is considered as part of the Murrumbidgee CMR. To provide clarity when determining the opportunity costs of utilizing

[56] Although the Basin Plan considers the Lachlan CMR as unconnected to the rest of the Basin, the model treats the Lachlan CMR as connected. This decision was made as the confluence of Lachlan Rivers is the Murrumbidgee River (Kemp 2010) and flows do connect in wet years and unlike the Wimmera CMR, the Lachlan CMR recharges groundwater reserves that can be used by the other CMRs in the MDB (Figure 2-5).

water resources along the Murray River, the New South Wales (NSW) Murray CMR was split into three sub catchments. As illustrated in Figure 6-4 and detailed in Table 6-2, Murray 1, Murray 2 and Murray 3 now correspond with the North East CMR, Goulburn-Broken CMR and North Central CMR.[57]

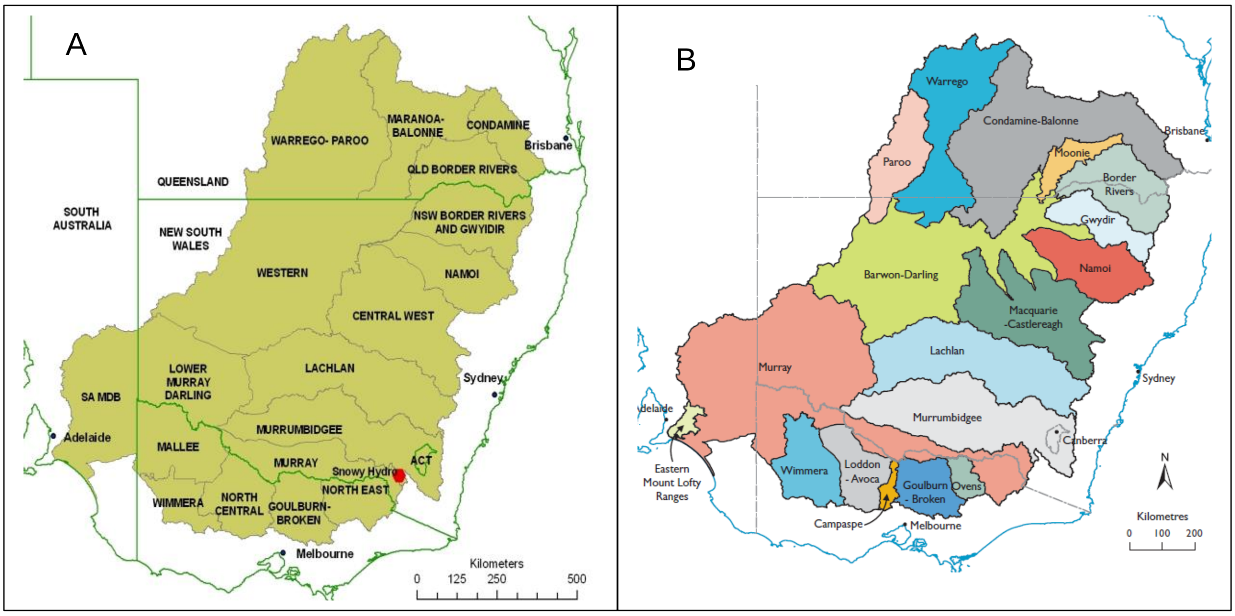

Figure 7-1 Difference in Data Gathering & Representation

7.2 Data for the Directed Flow Network

This section describes data sets for the exogenous variables required for the flow network: water resources θ, the conveyance losses wc and the natural salt load G. This data is also used in Equation 6-14 and Equation 6-15 to track the endogenous outcomes for water flow between catchments and salinity.

7.2.1 Conjunctive Water Resources in the Current Climate

Section 2.4 discussed that the MDB conjunctive water resources are derived from surface inflows, groundwater resources and inter-basin transfers and the data for each k is presented in Table 7-1. Under current climate settings, the MDB has a total of 22,925GL of runoff, 2,373GL of groundwater and 1,118GL of water transferred in from the Snowy River, providing a total of 26,418GL of conjunctive water resources. For any given catchment the total conjunctive water resources is the summation of the runoff, the groundwater

[57] For the remainder of the thesis the CMR definition is not used to describe catchments

resources available and any inter-basin transfers. For example, $k1$ has a total of 986GL in conjunctive water resources of which, 854GL is derived from runoff, 132GL of groundwater resources and there are no inter-basin transfers.

Table 7-1 The Basin's Conjunctive Water Resources (GL)

K	Catchment	Runoff[1]	Groundwater[2]	Inter-Basin Transfers[3]	TOTAL
$k1$	Condamine	854	132	0	986
$k2$	Border Rivers QLD	634	24	0	658
$k3$	Warrego Paroo	874	2	0	876
$k4$	Namoi	990	224	0	1,214
$k5$	Central West	1,536	99	0	1,635
$k6$	Maranoa Balonne	482	88	0	570
$k7$	Border Rivers Gwydir	1,442	108	0	1,550
$k8$	Western	205	79	0	284
$k9$	Lachlan	1,114	393	0	1,507
$k10$	Murrumbidgee	4,304	355	550	5,209
$k11$	North East	4,051	0	284	4,335
$k12$	Murray 1	1,626	6	284	1,916
$k13$	Goulburn Broken	3,368	486	0	3,854
$k14$	Murray 2	465	96	0	561
$k15$	North Central	501	0	0	501
$k16$	Murray 3	232	87	0	319
$k17$	Mallee	100	70	0	170
$k18$	Lower Murray-Darling	100	4	0	104
$k19$	SA MDB	49	120	0	169
$k20$	Adelaide	0	0	0	0
$k21$	Coorong				
	TOTAL	**22,925**	**2,373**	**1,118**	**26,418**

1 Data obtained from Mallawaarachchi, Adamson, Chambers, et al. (2010)
2 Data obtained from MDBA (MDBA 2012c)
3 Total transfers from MDBC (2006a), split by CMR from Wagner, Quiggin and Adamson (2008).

The runoff data is based on the CSIRO Sustainable Yields analysis and was modified to align to CMR's by Mallawaarachchi, Adamson, Chambers, et al. (2010). The groundwater extraction levels are based on the Basin Plan's Sustainable Diversion Limit (SDL) for groundwater (Murray-Darling Basin Authority (MDBA) 2012c). The Murray-Darling Basin Commission (MDBC) (2006a) provided the data for total quantity of inter-basin transfers, the assumption that these transfers into the MDB are evenly split between Murrumbidgee River and Murray River (North East and Murray1) was set by Wagner, Quiggin and Adamson (2008). Climate change impacts on water resources can then be modeled as a change to any or all of water conjunctive sources (Section 0), depending on the evaluation context.

7.2.2 Conveyance Data

As water flows along the MDB's river channels, a proportion of the water is lost to the ecosystem in the form of infiltration, evaporation, over-banking, dead-end gullies and billabongs (Grafton, Chu, et al. 2011; Lester et al. 2011; McMahon & Finlayson 1991; Smakhtin 2001). This conveyance loss wr is used in Equation 6-14 to alter θ as water flows between catchments. This adjustment defines the 'Net' flow (Table 6-2) and represents the maximum volume of water available to all users. The data provided in Table 2-1 was obtained from the CSIRO

Table 7-2 Assumptions Made About Conveyance Loss (%)

	Conveyance Loss (%)[3]		
$\boldsymbol{K}$	**Normal**	**Drought**	**Wet**
$k1$	0.35	0.37	0.30
$k2$	0.45	0.47	0.40
$k3$	0.83	0.85	0.78
$k4$	0.30	0.32	0.25
$k5$	0.59	0.61	0.54
$k6$	0.43	0.45	0.38
$k7$	0.08	0.10	0.03
$k8$	0.48	0.50	0.43
$k9$	0.30	0.32	0.25
$k10$	0.34	0.36	0.29
$k11$	0.10	0.12	0.05
$k12$	0.10	0.12	0.05
$k13$	0.08	0.10	0.03
$k14$	0.10	0.12	0.05
$k15$	0.25	0.27	0.20
$k16$	0.10	0.12	0.05
$k17$	0.02	0.04	0.01
$k18$	0.01	0.03	0.01
$k19$	0.07	0.09	0.02
$k20$	0.00	0.00	0.00
$k21$	0.03	0.05	0.01

MDBA data sets provided for Mallawaarachchi, Adamson, Chambers, et al. (2010)

Sustainable Yields project and converted by Mallawaarachchi, Adamson, Chambers, et al. (2010) during consultancy work on the Basin-Plan. The data presented illustrates the conveyance loss by $S \in \Omega$ by k and can be used as follows. In $k1$ in the normal state has a

θ of 986GL (Table 7-1) and if no irrigation occurred then the volume of water arriving into $k6$ from $k1$[58] would be $(1 - .35) \times \theta = 640.9GL$.

Compared to the normal state of nature conveyance losses increase in the drought state and reduce in the wet state of nature to reflect hydrological realities (Lester et al. 2011; McMahon & Finlayson 1991). As Adelaide $(k20)$ is modeled as a termination point in the model (Table 6-2), its impact on the Coorong's $(k21)$ water supply is modeled as a direct loss from the system (Table 6-2).

7.2.3 Salinity

The natural salt load, in tons (T) in the model is a combination of the naturally mobilized salt (Austin et al. 2010; Yaron & Bresler 1970), less the salt removed from the MDB via the SIS (Section 2.5.2). The term, 'natural salt load', is the quantity of salt in the river system before irrigation activities alter water quality (Equation 6-15). For simplicity, the model assumes that the SIS always chooses to extract 480,000T of salt in all states of nature (Table 7-2).

The quantity of mobilized salt has state-contingent properties to reflect the natural and management relationships between water and salinity. First, there is a natural and positive relationship between the quantity of rainfall and the amount of salt mobilized into the river system (Adamson, Mallawaarachchi & Quiggin 2007; Connor et al. 2012). Second, this approach recognizes that managers respond to the relationship between water and salt. For example: in drought periods irrigators can engage in deficit irrigation practices designed to use less water and maintain salt just below the root zones; and in wet states over irrigate to flush salt down the soil profile (Connor et al. 2012; Mallawaarachchi & Foster 2009). The model maintains constant endogenous variables for the rate at which salt returns to the river system (Section 6.7.6), by state of nature, to prevent salinity being double counted.

When compared to the normal state of nature, it was assumed that 50% of the salt remains immobilized within the soil in the drought state of nature and in the wet state of nature an extra 30% of salt is flushed into the river system (Table 7-2). The data then

[58] As Table 6-2 illustrates $k1$ (Condamine) flows into $k1$ (Maranoa-Balonne).

predicts that in a drought year over 450,000T of salt are mobilized; this increases to nearly 919,000T of salt in a normal state of nature and nearly 1.2 million tons of salt being flushed into the river system in a wet year.

Table 3 Data for the Natural Salt Load and Salinity Interception Scheme (T)

	Natural Salt[1]			
K	**Normal**	**Drought**	**Wet**	**Salinity Mitigation[2]**
$k1$	7,035	3,518	9,146	0
$k2$	7,818	3,909	10,163	0
$k3$	1,672	836	2,174	0
$k4$	67,452	33,726	87,688	0
$k5$	33,647	16,824	43,741	0
$k6$	7,035	3,518	9,146	0
$k7$	7,891	3,946	10,258	0
$k8$	0	0	0	0
$k9$	115,819	57,910	150,565	0
$k10$	160,000	80,000	208,000	0
$k11$	91,065	45,533	118,385	0
$k12$	20,000	10,000	26,000	0
$k13$	120,000	60,000	156,000	0
$k14$	35,000	17,500	45,500	0
$k15$	100,000	50,000	130,000	25,952
$k16$	45,000	22,500	58,500	0
$k17$	21,431	10,716	27,860	36,954
$k18$	20,091	10,046	26,118	188,203
$k19$	57,909	28,955	75,282	229,541
$k20$				
$k21$				
TOTAL	**918,865**	**459,433**	**1,194,525**	**480,650**

1 Source MDBC pers. comm. Andy Close August 2007 for the Normal State of Nature
2 Data from MDBA (2011a)

7.3 CAP Data

The term CAP data is used to define the maximum volume of surface water and groundwater that can be used for consumptive purposes (i.e. the cap on extraction) in each k and trading region. The CAP data will be used to model the Current Diversion Limits (CDL) or the Basin Plan's SDL (Section 4.1) and the new trading rules stipulated in the Basin Plan's.

7.3.1 Current Diversion Limits (CDL) Data

The current diversions in the MDB by k are presented in Table 7-4. $k1$ has a CDL surface CAP of 587GL, 132GL of groundwater providing a total CDL of 719GL to use on average. There is a total of 15,718GL of water diverted in the MDB.

Table 7-4 CDL in the Basin (GL)

	Current CAP (GL)		
K	**Surface Water**	**Groundwater**	**TOTAL**
$k1$	587	132	719
$k2$	404	24	428
$k3$	169	2	171
$k4$	508	224	732
$k5$	734	99	833
$k6$	391	88	479
$k7$	753	108	861
$k8$	198	79	277
$k9$	618	393	1,011
$k10$	2,554	355	2,909
$k11$	330	0	330
$k12$	54	6	60
$k13$	1,916	486	2,402
$k14$	906	96	1,002
$k15$	1,442	0	1,442
$k16$	815	87	902
$k17$	205	70	275
$k18$	97	4	101
$k19$	459	120	579
$k20$	206	0	206
$k21$			
TOTAL	**13,345**	**2,373**	**15,718**

Data adapted from MDBA (2012c)

7.3.2 SDL Data

The SDL by surface water and groundwater and the progress towards achieving this reduction are detailed in Table 7-5. The Basin Plan specifies changes to consumptive surface diversions by catchment (-1,613GL) and trading zone (-1,564GL) to obtain 3,194GL for the environment. The MDBA has identified that groundwater in the MDB are underutilized and that an additional 929GL should be consumed. Once the Basin Plan is implemented, the net contraction in conjunctive water extractions is 2,265GL.

Table 7-5 The Net Change in Extractions by Catchment & Region (GL)[59]

K	Trading Zone	Net Change in Volume		Volume Obtained	SRWUIP data
		Groundwater	**Surface Water**		
$k1$	Northern	62.8	-60.0	16.8	
$k2$	Northern	47.8	-8.0	5.0	
$k3$	Northern	132.0	-9.0	9.0	
$k4$	Northern	0.0	-10.0	10.0	
$k5$	Northern	8.6	-65.0	65.0	
$k6$	Northern	41.9	-40.0	11.2	
$k7$	Northern	128.7	-49.0	5.0	
$k8$	Northern	95.5	-6.0	0.0	
$k9$	Unconnected	123.3	-48.0	#65.0	
$k10$	Southern NSW	0.0	-320.0	173.0	
$k11$	Southern VIC	0.0	-32.9	32.9	
$k12$	Southern NSW	0.1	-7.9	7.9	
$k13$	Southern VIC	32.3	-369.3	369.3	
$k14$	Southern NSW	1.3	-131.0	131.0	
$k15$	Southern VIC	0.0	-194.5	194.5	
$k16$	Southern NSW	1.1	-117.9	117.9	
$k17$	Southern VIC	142.7	-30.4	30.4	
$k18$	Southern NSW	0.1	-13.2	13.2	
$k19$	Southern SA	111.3	-101.0	101.0	
	TOTAL	**929.2**	**-1,613.0**	**1,358.0**	
	Further Reduction Trading Zones				
Northern $(\mathrm{k} = 1 \text{ to } 8)$			-143.0		
Southern NSW $(\mathrm{k} = 10,12,14,16,18)$			-462.9		462.9
Southern VIC $(\mathrm{k} = 11,13,15,17)$			-425.3		425.3
Southern SA $(\mathrm{k} = 19)$			-82.8		82.8
Southern All $(\mathrm{k} = 10 \text{ to } 19)$			-450.0		450.0
Reduction in the Trading Zones			**-1,564.0**		**1,421.0**
TOTAL Surface Reductions*			**-3,194.0**		
TOTAL Net Change (Ground + Surface)			**-2,265.0**		

#Lachlan's proposed SDL reduction is 48GL but already 65GL has been returned.
*difference between Basin Plan and data set due to Wimmera not being modeled.
Data adapted from MDBA (2012c)

For a single catchment Table 7-5 can be interpreted as follows. $k1$ receives an increased groundwater SDL of 62.8GL and has a specified reduction in surface extractions of 60GL. However, due to the new trading rules the real reduction in $k1$ surface water may exceed 60GL, as $k1$ lies within the Northern trading zone ($k = 1 \; to \; 8$), that has an identified SDL reduction of 143GL. Therefore, $k1$ at a minimum must have a reduction in its surface diversions of at least 60GL and this may increase up to 203GL, dependent on: the opportunity costs for water used in production in $k1..k8$; biophysical constraints; and the Basin Plan's constraints. Ignoring trade reductions and by comparing Table 7-4 with Table

[59]The justification for not modeling the Wimmera CMR is presented in Section 7.1

7-5, the surface SDL for $k1$ is 424.2GL (i.e. 587 - 62.8), $k1$'s groundwater SDL is 192GL and $k1$ total SDL is 716.2.

As of 2012, the Commonwealth Environmental Water Office (CEWO) had already obtained 1,358GL of surface water for the environment. This leaves 1,836GL of surface water still to be obtained and the data suggests that this water will be predominately obtained from reductions in trading zones (1,564GL). Table 7-5 also provides assumptions concerning the SRWUIP analysis that is presented in Section 9.

7.4 **Water Property Rights**

It is identified in Table 7-6 that over 19,200GL of water rights have been allocated to private individuals in the MDB. This comprises of 2,371GL of groundwater entitlements and nearly 16,000GL of surface water rights. There are 3,582GL of high security rights, 7,230GL of general security rights and 6,081GL of supplementary rights (Section 2.5.3). For a given catchment the data can be interpreted as follows, irrigators in $k1$ have 132GL of groundwater licenses, 0GL of high security surface rights, 0GL of general security surface rights and 1,398GL of supplementary security rights. $k1$ has a total of 1,530GL of water entitlements. The middle set of numbers in Table 7-6, summarizes the publically available data for the RtB program (see Section 8). This includes the CEWO's willingness to pay for each alternative property right ($/Megalitre (ML)) by catchment The last set of numbers then transforms the RtB cost per ML into an annuity per ML to determine the annuity a producer would receive from the sale of surface entitlements by k (see Section 8.2.1). This data can be interpreted, as $k1$ no high or general security entitlements, the RtB could only purchase supplementary rights at a cost $860/ML (see Section 8.2 for greater discussion in regards to this data) and this would provide the irrigators with an annuity of $81 per ML.

Table 7-7 provides the estimated reliability of each surface entitlement by s and by k. This data was estimated against historic CAP diversions (Chart 3-1) and the assumption that high security water is 95% reliable on average, which is comparable to the 99% estimation provided in Section 2.5.3.

Table 7-6 Entitlements by Catchment, the Costs to Purchase Under the RtB and Their Annuity Value for Irrigators

	Entitlement Security (GL)[1]				Cost to Purchase ($/ML)[2]			Annuity from Water Sale ($/ML)		
K	Ground	High	General	Supplementary	High	General	Supplementary	High	General	Supplementary
$k1$	132			1,398			$860			$81.14
$k2$	24			587			$860			$81.14
$k3$	2			125	$0	$0	$161			$15.20
$k4$	224	5	286	255	$2,050	$1,593	$161	$193.51	$150.39	$15.20
$k5$	99	18	632	143	$2,050	$1,268	$161	$193.51	$119.69	$15.20
$k6$	88			932			$161			$15.20
$k7$	108	16	773	375	$2,922	$860	$161	$275.80	$81.14	$15.20
$k8$	79			196			$161			$15.20
$k9$	393	31	615	68	$2,050	$683	$161	$193.51	$64.47	$15.20
$k10$	355	377	1,888	697	$1,704	$914	$218	$160.85	$86.28	$20.58
$k11$	0	196	79	61	$1,933	$1,133	$193	$182.46	$106.95	$18.22
$k12$	6	6	50	20	$1,967	$1,133	$193	$185.67	$106.95	$18.22
$k13$	486	1,221	706	139	$2,059	$1,122	$196	$194.33	$105.89	$18.46
$k14$	96	96	834	334	$1,967	$1,133	$196	$185.67	$106.95	$18.46
$k15$	0	913	432	161	$2,065	$1,133	$199	$194.93	$106.95	$18.80
$k16$	87	86	750	301	$1,967	$1,122	$199	$185.67	$105.89	$18.80
$k17$	70	156	73	12	$2,066	$1,133	$199	$195.02	$106.95	$18.78
$k18$	4	11	111	275	$1,967	$1,107	$161	$185.67	$104.49	$15.20
$k19$	120	449	0	0	$2,099			$198.13		
TOTAL	**2,373**	**3,582**	**7,230**	**6,081**						

1 Data adapted from Bureau of Meteorology (BOM) (2011)
2 Data adapted from SEWPaC (2013)

Table 7-7 Estimated Reliability of Entitlements by Climate State (%)

	Normal			Drought			Wet		
K	High	General	Supplementary	High	General	Supplementary	High	General	Supplementary
$k1$			0.20			0.15			0.60
$k2$			0.40			0.30			0.60
$k3$			0.30			0.20			0.60
$k4$	1.00	1.00	0.40	0.75	0.40	0.20	1.00	0.90	0.60
$k5$	1.00	0.60	0.25	0.75	0.25	0.15	1.00	0.75	0.60
$k6$			0.20	0.75	0.20	0.15	1.00	0.80	0.60
$k7$	1.00	0.55	0.20	0.75	0.15	0.10	1.00	0.80	0.55
$k8$			0.50			0.20			0.60
$k9$	1.00	0.40	0.30	0.75	0.15	0.10	1.00	0.75	0.60
$k10$	1.00	0.80	0.35	0.75	0.40	0.20	1.00	0.90	0.80
$k11$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k12$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k13$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k14$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k15$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k16$	1.00	0.85	0.15	0.75	0.50	0.05	1.00	0.95	0.75
$k17$	1.00	0.70	0.15	0.75	0.40	0.05	1.00	0.80	0.75
$k18$	1.00	0.50	0.10	0.75	0.20	0.05	1.00	0.80	0.60
$k19$	1.00			0.80			1.00		

Authors own estimate, data matched to existing CDL.

This deliberate strategy is used in Section 8 to highlight the value of water security provided by each alternative property right classes. $k1$ Illustrates that, in the absence of high and general rights, no allocation is given for those rights but supplementary water rights are estimated to have a reliability factor of 0.2, 0.15 and 0.6 in the normal, drought and wet states of nature for each ML of water owned by irrigators. When multiplying the data from Table 7-6 and Table 7-7, $k1$ irrigators would be allocated 210, 280 and 839GL of water in the drought, normal and wet states of nature[60].

7.5 Climate Change Impacts on Water Resources

Section 4.4.1, discussed that The Garnaut Climate Change Review (Garnaut 2008, 2011) provided the initial policy platform on which Australia's response to climate change was founded (Quiggin, Adamson & Quiggin 2014). The data underpinning Table 7-8, was provided by The Garnaut Climate Change review and was first used by Quiggin et al. (2008). Despite advances in climate change forecasting and the determination of changes to runoff, the data has not been updated to provide a comparison to other papers (Quiggin et al. 2010) and reports (Adamson, Quiggin & Quiggin 2011)[61].

The data in Table 7-8 is based on The Garnaut Climate Change Review's '450ppm average scenario' (450 Avg)[62] (Garnaut Climate Change Review 2008), which is a strong policy response to climate change and offers an optimistic vision for the future. Despite proactive worldwide action to curb carbon dioxide equivalent (CO2-e) emissions, it is anticipated that…

> [c]hanges in rainfall will lead to twice the percentage change in runoff for catchments in wet and temperate climates, while the changes in runoff are even greater for catchments in more arid regions" (Austin et al. 2010, p. 608).

The data in Table 7-8, provide a weak representation of Austin et al. (2010) findings. The percentage reduction in runoff for arid catchments are generally less than or equal to 80% of current runoff levels and wetter catchments are expected to receive 80% or greater of

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[60] Section 8.3.2 discusses the limitation associated with these values and approach to determine the availability of water resources and their inherent value to irrigators.
[61] The limitations associated with converting runoff to rainfall were discussed in Section 2.4 and extended in Section 3.2 in regards to climate change.

[62] The 450 Avg Scenario was detailed in Section 4.3.1.

their current runoff values. However, it is the spatial patterns of climate change that have the greatest influence on runoff as despite both $k2$ (Border Rivers-QLD) and $k13$ (Goulburn-Broken) experiencing a 20% decline in runoff, the net loss in $k13$ (637GL) exceeds current runoff in $k2$ (6344GL).

Table 7-8 Current Surface Runoff (GL) & Impact of Climate Scenarios (%)

	Current Climate	450 Avg[1]	
$\boldsymbol{K}$	**Runoff (GL)**	**2050**	**2100**
$k1$	854	79%	78%
$k2$	634	80%	78%
$k3$	874	79%	78%
$k4$	990	83%	82%
$k5$	1,536	84%	83%
$k6$	482	79%	78%
$k7$	1,442	84%	83%
$k8$	205	82%	81%
$k9$	1,114	83%	82%
$k10$	4,304	84%	82%
$k11$	4,051	85%	84%
$k12$	1,626	82%	80%
$k13$	3,368	80%	78%
$k14$	465	82%	80%
$k15$	501	79%	77%
$k16$	232	82%	80%
$k17$	100	78%	77%
$k18$	100	81%	79%
$k19$	49	74%	72%
TOTAL	**22,925**	***18,858***	***18,590***
'*Snowy River Inflows'*	*1,118*	*86%*	*85%*
MDB	**24,043**	***19,818***	***19,543***
Reduction		*18%*	*19%*

1 Data provided by Garnaut Climate Change Review, the conversion of rainfall to runoff detailed in Quiggin et al. (2010)

Unlike Quiggin et al. (2010) which applied the climate change runoff reductions to all conjunctive water resources, this thesis assumes that groundwater extractions are resilient to climate change as the Basin Plan increases the groundwater SDL. As discussed, the Basin Plan was developed to rebalance the share of water resources and that climate change was a real threat to the success of the plan (Section 4.6.3). Thus the decision to increase groundwater SDL should not have been made without due diligence and it has been assumed that the new groundwater SDL should be resilient to a changing climate.

7.6 **Commodities**

Section 6.6 identified the 18 commodities that the SCA model uses to develop the state-contingent production systems. This section describes the datasets for these 18 commodities, how they were developed, modified and the assumptions used. The data presented in the sub-sections of this section includes, regional input and output data, estimations on capital costs, production area, and average farm size. From this point of the thesis, the label Adelaide is used to ensure that Adelaide receives 206GL of water annually and the term dryland provides a mechanism to track land as it transitions between dryland and irrigated land use when alternative scenarios are examined.

7.6.1 Commodity Inputs and Outputs

Regional gross margin budgets (GMB) were collected at a catchment level and all prices are provided in 2009 values. The GMB's were used to obtain estimates of yield (output), water used and input costs for each commodity (Table 7-9). The list of GMB collected is provided in Appendix B.[63]

Table 7-9 GMB Data Collected for Each Commodity

Column	Description
Catchment	Catchment name k
Yield	Average yield per hectare of the commodity in k
Price	Average real price of the commodity in the k
Labor	Average number of work hours per hectare for hired labor
Lab. Chg.	Average real hired labor costs per hour
Tractor Hr	Average number of machinery hours per hectare
Water	Average water volume (in ML) required per hectare
Water Price	Constant water price of $25/ML
Chemicals	Average real costs per hectare of total chemicals required
Contractor	Average real costs per hectare for contractors
Machinery	Average real costs of machinery per hectare
OVC	Average real other variable costs per hectare
VC Excl. Water	Total variable costs per hectare excluding water costs

Where GMB data was not available by k, a series of rules (Table 7-10) were established to fill data gaps and these rules were applied in descending order in an attempt to match the closest agronomic zones.

[63] The raw data for each $m \times k \times s$ is not provided in this thesis due to word limits but is available from http://www.uq.edu.au/rsmg/docs/2010_RSMG_Model_Documentation_11_Jan_2010.pdf

Table 7-10 Rules for Constructing Missing GMB Data

State	CMR	Data to use Options
QLD	• All QLD	1. Condamine Data 2. Average of NSW 3. Average of VIC 4. Average of SA
NSW	• Namoi • Border Rivers Gwydir	1. Equal to each other 2. Average of NSW 3. Average of QLD 4. Average of VIC 5. Average of SA
	• Western	1. Average of (Namoi+Central West) 2. Average of NSW 3. Average of QLD 4. Average of VIC 5. Average of SA
	• Lachlan	1. Average of (Central West+Murrumbidgee) 2. Average of NSW 3. Average of QLD 4. Average of VIC 5. Average of SA
	• Murrumbidgee Murray1 • Murray2 • Murray3	1. Equal to each other 2. Average of NSW 3. Average of VIC 4. Average of QLD 5. Average of SA
	• Lower Murray-Darling	1. Average of (Murray/Murrumbidgee/Lachlan) 2. Average of NSW 3. Average of SA 4. Average of VIC 5. Average of QLD
VIC	• ALL VIC CMRs	1. Average of VIC 2. Average of (Murray/Murrumbidgee) 3. Average of NSW 4. Average of SA 5. Average of QLD
SA	• SA MDB	1. Average of (Murray/Murrumbidgee) 2. Average NSW 3. Average of VIC 4. Average of QLD

This created GMB data was calibrated against known area production data (summarized for the MDB in Table 3-1, Table 7-13 and Table 7-12) to ensure that each k only produced crops that had a history of past production within that k. This calibration assumption prevents new commodities from being established but also prevents unrealistic expansion of cotton into SA and rice into Warrego-Paroo.[64]

7.6.2 Capital Costs

The capital cost required to operate one Ha of a given commodity is an annual repayment derived from the total cost to establish the commodity per Ha plus the total equipment capital required to run the farm divided by the total farm size (Table 7-11). It is assumed that all capital costs are repaid over a 20 year period at 7% interest. The sources of information used to determine average farm size in each k by commodity group is provided in Table 7-12. [65]

Table 7-11 Capital Costs by Commodity ($)

Commodity Name	Establishment Cost/HA	Equipment Required
Citrus-H	$23,056	$720,259
Citrus-L	$22,454	$720,259
Grapes	$16,125	$680,000
Stone Fruit-H	$34,184	$720,259
Stone Fruit-L	$34,184	$720,259
Pome Fruit	$34,184	$720,259
Vegetables	$2,765	$738,125
Cotton	$4,400	$3,083,000
Rice	$4,400	$999,500
Wheat	$2,000	$949,500
Dairy-H	$3,259	$2,445,496
Dairy-L	$3,259	$2,445,496
Sheep/Wheat	$2,630	$1,697,498

Data adapted from Australian Bureau of Agricultural and Resource Economics (ABARE) (2003), Falivene (2003), Hassalls & Associates (2000) Johnson (1998) and Queensland Department of Natural Resources Mines and Water (QDNRM&W) (2004a); (2004b, 2004c)

Although, the use of constant figures for establishment and equipment for each commodity in all catchments is simplistic, it rewards irrigators who have economies of scale in the Northern Murray-Darling Basin (NMDB) (Table 7-12). The model then also assumes that all irrigators specialize in one state-contingent production system (see next Section section).

[64] Past modeling experiments have allowed for the utilization of user-defined commodity datasets to reflect production opportunities associated with climate change.

[65] The assumptions concerning interest rates and farm size have remained fixed since 2010, allowing for comparison with prior studies. As the interest rate increases, fixed costs rise decreasing the net profit per Ha (Appendix A). As the area of land increases fixed costs decrease increasing profit per Ha.

Table 7-12 Default Farm Size in Basin by Catchment (Ha)

K	Citrus-H & L[1]	Grapes	Stone-Fruit-H&L	Pome Fruit	Vegetables	Cotton	Rice	Wheat[2]	Dairy	Sheep
$k1$	40	45	40	40	40	3,000	0	500	277	600
$k2$	40	45	40	40	40	3,000	0	500	277	600
$k3$	0	45	0	0	40	3,000	0	500	277	600
$k4$	40	45	40	40	40	3,000	0	500	277	600
$k5$	40	45	40	40	40	3,000	0	500	324	600
$k6$	40	45	40	40	40	3,000	0	500	277	600
$k7$	40	45	40	40	40	3,000	0	500	277	600
$k8$	40	45	40	40	40	3,000	0	500	277	600
$k9$	40	45	40	40	40	3,000	400	500	324	600
$k10$	20	45	20	20	20	500	400	500	342	600
$k11$	20	45	20	20	20	0	400	300	173	600
$k12$	20	45	20	20	20	500	400	500	215	600
$k13$	20	45	20	30	20	0	400	300	215	600
$k14$	20	45	20	20	20	500	400	500	215	600
$k15$	20	45	20	20	20	0	400	300	215	600
$k16$	20	45	20	20	20	500	400	500	215	600
$k17$	30	45	30	20	20	0	400	300	215	600
$k18$	20	45	20	20	20	300	0	300	215	600
$k19$	20	45	20	20	20	300	0	300	400	600

Data adapted from ABARE (2003), Alexander and Kokic (2005), McGuckian (2002), PC (2002, 2005), Patton and Mullen (2001), Hardman and Strahan (2000), URS Sustainable Development (2004), Unknown (2006), Alexander & Heaney (2003),Gordon (2004), Appels, Douglas and Dwyer (2004) and Wimalasuriya, Hamilton and Goldsworthy (2002) Brennan, JP, Sykes and Scott (2005)

1 Commodities cannot be produced in a catchment when they have a farm size of 0 Ha
2 Note all other broadacre crops use are assumed to be identical in size to wheat farms

7.6.3 Area of Production

Equation 6-12 and Equation 6-13 provided the upper bounds for structural irrigation investment patterns to change to horticultural production systems and the total area irrigated by k. The raw bounds for irrigation investment are detailed in Table 7-13 and Sections 8.2.2 and 9.3.3 describe how this data was altered to represent changes in investment patterns created by the alternative signals from policy.

Table 7-13 Area Irrigated (Ha)

K	Horticulture	TOTAL
$k1$	2,394	56,188
$k2$	4,394	58,335
$k3$	109	19,653
$k4$	423	94,152
$k5$	5,115	86,362
$k6$	214	29,709
$k7$	478	141,564
$k8$	715	34,930
$k9$	7,876	105,017
$k10$	25,577	305,212
$k11$	3,159	14,165
$k12$	616	12,269
$k13$	11,618	222,478
$k14$	1,688	152,286
$k15$	5,710	241,460
$k16$	1,189	111,740
$k17$	28,465	50,505
$k18$	8,394	18,477
$k19$	37,382	63,661
TOTAL	**145,517**	**1,818,162**

Adapted from Australian Bureau of Statistics (ABS) (2004)

7.6.4 Production Price Data

It has been assumed that due to the small country assumption that the price paid by state of nature remained constant for all irrigated commodities (Table 7-14). However, both Adelaide and dryland production systems use alternative prices by state of nature, as this then allows price to describe all salient features of those state-contingent production systems.

Table 7-14 Price Received per Unit of production

Commodity Name	State of Nature			Unit
	Normal	Drought	Wet	
Citrus	$600	$600	$600	T
Grapes	$950	$950	$950	T
Grapes	$1,600	$1,600	$1,600	T
Stone Fruit	$1,300	$1,300	$1,300	T
Pome Fruit	$720	$720	$720	T
Vegetables	$620	$620	$620	Bale + seed
Cotton	$260	$260	$260	T
Rice	$210	$210	$210	T
Wheat	$350	$350	$350	T
Grain Legumes	$600	$600	$600	T
Sorghum	$185	$185	$185	T
Oilseeds	$380	$380	$380	T
Chickpeas	$300	$300	$300	T
Dairy	$0.35	$0.35	$0.35	Liter
Fat Lambs	$45	$45	$45	$/DSE
Beef	$60	$60	$60	$/DSE
Adelaide	$1,000	$1,500	$1,000	ML
Coorong	$50	$0	$65	HA

Data based on past prices and data from the GMB datasets.

7.7 SCA Production Systems

The state-contingent approach examines how the state of nature (e.g. droughts and floods) influences the management strategy to alter the inputs used to produce state specific outputs. For example, shiraz grapes produced in periods of low water supply have more smaller berries than grapes produced with normal water supply. Smaller berries then increase the grape skin to moisture ratio and can produce a higher quality wine (Ojeda et al. 2002).

The transformation of commodities into SCA production systems, allows for irrigation management practices to be reflected both within and between states of nature. As similar state of natures, with identical outcomes, can be combined to keep the state space small, the model has merged similar commodities with similar management strategies into generic production systems (see Citrus below) to reduce the model size.

The description of each of the 23 state-contingent production systems x is documented below and Table 7-15 illustrates how the state-contingent production systems alter the inputs used and outputs obtained by state of nature. In Table 7-15, the multiplier for Z

alters output, the term 'water' is a multiple for the water used and the heading 'VC' either increases or decreases the variable costs per Ha by the described dollar value. The Citrus production system is used to illustrate, how the variables Z, 'water' and 'VC' are used to transform the normal states production data to production data for the drought and wet state of nature.

7.7.1 The Horticultural State-Contingent Production Systems

Citrus

The citrus production system is designed to reflect strategies used by grapefruit, lemon, lime, mandarin and orange producers to deal with changing states of water availability. Producers can utilize either –H or –L irrigation technology (Section 6.6) to produce citrus crops.

When compared to the normal state of nature, a Citrus-H producer operating in a drought state of nature, will allocate the same volume of water but receive a 20% reduction in output and face increased variable costs of $20/Ha (Table 7-15). When the wet state of nature is experienced, the producer increases water consumption by 120%, in part to help flush salt away from the root zone. Yield is expected to increase by 20% per Ha in a wet state of nature and this then requires an additional expenditure of $20/Ha to manage and harvest the crop (Table 7-15).

The paradox of water-use efficiency and management flexibility to deal with water scarcity was discussed in Section 9.6.2. The state-contingent production systems reflect this paradox via the reduction in output experienced in the drought state of nature. When compared to the normal state of nature, Citrus-L and Citrus-H output declines by 10% and 20% respectively when compared to the normal sate of nature.

Grapes

The grape production system reflects the changes in output (i.e. tons of grapes), water used and variable costs experienced by table and wine grape producers as they adapt to alternative states of nature.

Table 7-15 Data for the State-Contingent Productions

X	Production System Name	Normal	Drought Multipliers and Costs				Wet Multipliers and Costs			
		Commodity	Commodity	Z	Water	VC	Commodity	Z	Water	VC
$x1$	Citrus-H	Citrus-H	Citrus-H	0.8	1.0	$20	Citrus-H	1.2	1.2	$20
$x2$	Citrus-L	Citrus-L	Citrus-L	0.9	1.0	$0	Citrus-L	1.2	1.2	$100
$x3$	Grapes	Grapes	Grapes	0.9	1.0	$20	Grapes	1.2	1.2	$20
$x4$	Stone Fruit-H	Stone Fruit-H	Stone Fruit-H	0.8	1.0	$20	Stone Fruit-H	1.2	1.2	$20
$x5$	Stone Fruit-L	Stone Fruit-L	Stone Fruit-L	0.9	1.0	$0	Stone Fruit-L	1.2	1.2	$100
$x6$	Pome Fruit	Pome Fruit	Pome Fruit	0.9	1.0	$20	Pome Fruit	1.2	1.2	$20
$x7$	Vegetables	Vegetables	Melons	1.0	1.0	$0	Fresh Tomatoes	1.0	1.0	$0
$x8$	Cotton Flex	Cotton	Dryland Cotton	1.0	1.0	$0	Cotton	1.0	1.0	$100
$x9$	Cotton Fixed	Cotton Fixed	Cotton Fixed	1.0	1.0	$0	Cotton Fixed	1.0	1.0	$0
$x10$	Cotton/Chickpea	Cotton	Chickpea	1.0	1.0	$0	Cotton	1.0	1.0	$100
$x11$	Cotton Wet	Dryland Cotton	Dryland Cotton	0.8	1.0	$0	Cotton	0.9	1.2	$100
$x12$	Rice PS	Rice PSN	Rice PSD	1.0	1.0	$0	Rice PSW	1.1	1.1	$0
$x13$	Rice Flex	Rice PSB	Dryland Wheat	1.0	1.0	$0	Rice PSW	1.0	1.2	$100
$x14$	Rice Wet	Dryland Wheat	Dryland Wheat	1.0	1.0	$0	Rice PSW	0.95	1.2	$100
$x15$	Wheat	Wheat	Wheat	0.8	1.0	$0	Wheat	1.1	1.2	$50
$x16$	Wheat Legume	Wheat Legume Normal	Wheat Legume Dry	1.0	1.0	$0	Wheat Legume Wet	1.0	1.0	$0
$x17$	Sorghum	Sorghum	Sorghum	0.8	1.0	$0	Sorghum	1.1	1.2	$100
$x18$	Oilseeds	Oilseeds	Oilseeds	0.8	1.0	$0	Oilseeds	1.1	1.0	$0
$x19$	Sheep Wheat	Sheep Wheat Normal	Sheep Wheat Dry	1.0	1.0	$50	Sheep Wheat Wet	1.0	1.0	$0
$x20$	Dairy-H	Dairy-H	Dairy-H	0.9	0.7	$300	Dairy-H	1.5	1.2	$0
$x21$	Dairy-L	Dairy-L	Dairy-L	0.8	0.6	$300	Dairy-L	1.2	1.2	$0
$x22$	Dryland	Dryland	Dryland	1.0	1.0	$0	Dryland	1.0	1.0	$0
$x23$	Adelaide	Adelaide	Adelaide	1.0	1.0	$0	Adelaide	1.0	1.0	$0

H= intensive irrigation capital (e.g. drip lines).
L = low irrigation capital (e.g. furrows).

Stone fruit

Stone fruit production systems reflect the management systems used by apricot, cherry, nectarine, peach and plum producers as they alter their inputs by state of nature.

Pome Fruit

The pome fruit state-contingent production system detail changes in inputs and outputs by state of nature, for the apple and pear industry in the MDB.

Vegetables

The term vegetables is used to describe a range of regional irrigated vegetable production alternatives, including asparagus, beetroot, broccoli, cabbage, capsicum, carrot, cauliflower, eggplant, garlic, lettuce, onion, potato, pumpkin, rockmelon, sweet corn, tomato, watermelon and zucchini.

> "In the normal state, the vegetable production activity is represented by an average return from a range of alternative irrigated vegetable crops. In the drought state, water resources are conserved by planting only a dryland rockmelon crop. In the wet state, all resources are transferred to producing tomatoes for the fresh market" (Quiggin et al. 2010, p. 542).

7.7.2 The Broadacre State-Contingent Production Systems

Cotton (Fixed Rotation) or Cotton Fixed

> "To assist pest management, and sustain soil fertility, cotton is produced on a rotation system, represented here as allowing for two years of irrigated cotton production and one year of dryland agriculture over a three-year cycle. The simplest way of managing such a system is a three-field rotation, in which one-third of the land area is rotated out of irrigation each year" (Adamson, Mallawaarachchi & Quiggin 2007, p. 270).

Cotton (Flexible Rotation) of Cotton Flex

> "We also model an alternative rotation system in which the entire land area is allocated to dryland agriculture in dry years, and to cotton production in wet years. Since this activity requires more active management it incurs a cost penalty relative to the Fixed Rotation activity which has the same average yield. However, if

producers face variable state-contingent prices for water (or variable shadow prices associated with constraints), they may choose to adopt this activity" (Adamson, Mallawaarachchi & Quiggin 2007, p. 270).

Cotton/Chickpea

The cotton/chickpea state-contingent production system mimics the 'Cotton Flex' production option but instead of allocating resources to a dryland crop in the drought state of nature, inputs are allocated towards an irrigated chickpea crop.

Cotton Wet

The 'cotton wet' production system is designed to model opportunistic irrigation practices that occur in the NMDB when supplementary property rights are most secure in the wet state of nature (Section 7.4). For this production system…

"[t]he producer produces an irrigated cotton crop only in the wet state of nature. In other states of nature, dryland grain cropping is undertaken.(Quiggin et al. 2010, p. 542).

Rice PSN

The Rice PSN was designed to illustrate how rice is produced in the Southern Murray-Darling Basin (SMDB) and is similar in design to the cotton fixed rotation. This production system divides each Ha of Rice PSN, into 1/3 of the area planted to rice and the remaining 2/3 grows wheat, to reflect industry practices. In a normal state of nature, once the rice crop is harvested, farmers take advantage of residual soil moisture by producing a vegetable crop, and 10% of this production is assumed to be derived from the Rice PSN. In the drought state (Rice PSD) this vegetable crop cannot be produced and in the wet state of nature (Rice PSW), 15% of vegetable returns are due to the rice crop.

Rice Flex

The 'Rice Flex' production system was designed to mimic the 'Cotton Flex' system for the rice industry as it allows producers to allocate resources towards producing a dryland wheat crop in the drought state of nature.

Rice Wet

The ‘Rice Wet’ provides the opportunity for the rice industry to respond to years when water is plentiful. Like the ‘Cotton Wet’ system, irrigation only occurs in the wet state of nature and in all other states of nature a dryland wheat crop is produced. To reflect this opportunistic behavior by non-specialist producers, a yield penalty of 5% has been applied (Table 7-15).

Wheat

The wheat system produces an irrigated crop of wheat in every state of nature.

Wheat/Legume

Rotation cropping practices provide output benefits and greater efficiency of input use (McNeill & Penfold 2009); as each crop in the rotation requires different bundles of inputs, adaption to a state can be inferred if resources are reallocated. To represent this management option the Wheat/Legumes production system was created and ‘Legume’ is a default commodity derived from the available legume crops each k, which includes adzuki bean, chickpea, fava bean, mungbean, navy bean, peanut and soybean.

The farmer’s adaption to water availability is represented by altering the percentage of land dedicated to the wheat and legume crop in each Ha and to reflect the benefits of investing in rotation wheat output is increased by 10% in each state of nature. Land allocation between wheat and legumes occurs at a rate of 50/50, 100/0 and 30/70 for the normal, drought and wet state of nature respectively.

Oil Seeds

The oil seed production system provides the opportunity for irrigators to invest in producing canola and/or sunflowers, depending on what can be produced in each k.

Sheep/Wheat

> “This production activity represents a state-contingent production plan where producers allocate resources between sheep and wheat production in response to climatic conditions and market forces. The production mix between the two outputs is 50% wheat and 50% sheep in the normal state, 90% sheep and 10%wheat in the drought state, and 30% sheep and 70%wheat in the wet state. Effort is placed in

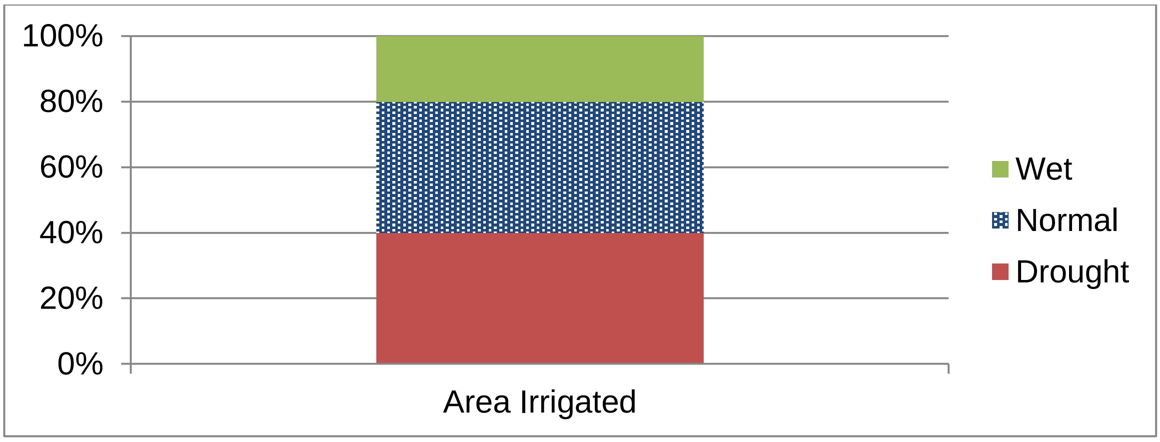
keeping the breeding stock alive during the drought state while in wet states there is plenty of fodder available on the non-irrigated pasture, and irrigated land can be allocated to wheat production"(Quiggin et al. 2010, p. 542).

Dairy

Section 3.6.1 outlined that during the Millennium drought, one adaption strategy employed by dairy producers was the trading of water to purchase feed. The 'Dairy' production system modeled here does not include the capacity to trade water in the drought state but rather assumes that all water is used on farm to reflect the ability of dairy producers to respond to water supplies by increasing or decreasing the total area irrigated within a property and compensating feed deficiencies by purchasing feed. The data used to construct Chart 7-1 to describe the changing area irrigated is for illustration purposes only.

A dairy producer has the choice of producing dryland or irrigated pasture on their farm. To represent the decision maker's response to the availability of water, the proportion of each Ha that is irrigated alters by state of nature. Using the data for Dairy- H (Table 7-15), the water multiplier for the drought and wet state of nature is 0.7 and 1.2, respectively. The impact of this state described water multiplier then means that in a drought state of nature only 40% of each Ha is irrigated, in the normal state of nature 80% of the Ha is irrigated and in the wet state of nature the entire Ha is irrigated (Chart 7-1). To compensate for the lack of feed in the drought state of nature, an additional $300 is spent per Ha purchasing supplements (Table 7-15) but despite feeding cattle, output decreases by 10%. But in a wet state of nature, no additional feed is required and output increases by 50%.

Chart 7-1 Proportion of a Hectare Irrigated by State of Nature (%)



7.8 Summary

This section has described the data and underlying assumptions used in this thesis and the RSMG Murray-Darling Basin model. To evaluate the net change in property rights, the RtB and the SRWUIP, some modification to the datasets and assumptions occurred and are documented in the subsequent sections.

8. OPTIONS FOR RESTORING THE BALANCE: PROPERTY RIGHTS

On one hand the Murray-Darling Basin Plan (Basin Plan) sends a strong signal that the Restore the Balance (RtB) program has $3.1 billion to purchase up to 3,200GL of water from irrigators for the Commonwealth Environmental Water Office (CEWO) and on the other hand the Basin Plan allows for an additional 929GL of groundwater to be used. This new conjunctive Sustainable Diversion Limits[66] (SDL) then creates mixed signals about water use, as in some catchments the conjunctive SDL has increased (Table 7-5).

To reinforce the Basin Plans' mixed signals on water use, this thesis has assumed that all new groundwater is 100% secure in all states of nature. This simplifying assumption has been made as it would appear to counter the design of the final Basin Plan, which as discussed is designed to deal with over allocation problems and is aware about climatic risks (Section 4.4). This increased access to a highly secure entitlement creates a contrast as the three alternative surface water entitlements have unique water security properties, by type and location, ranging from being up to 95% reliable, to only being allocated in wet years (Section 2.5.3). As value of water entitlements is positively correlated with their security, the Basin Plan may create a wealth transfer for some irrigators.

The spatial and temporal reliability of the alternative surface water rights will determine if the RtB can purchase an optimal bundle (a spatial mix of all three surface rights) or portfolio[67] of entitlements that can achieve the Basin Plan's social and environmental constraints, for $3.1 billion. However, the RtB was initiated before the Basin Plan was developed and its implementation created concern in both the wider rural community and the economics discipline (The Senate 2010). The objective of this section is to disentangle the mixed signals that are associated with the RtB purchasing surface rights from irrigators, yet increase the groundwater SDL.

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[66] Conjunctive SDL is the net change between the surface SDL and the groundwater SDL.

[67] For simplicity, portfolio can be used as either the RtB strategy for purchasing water or as portfolio of rights (i.e. common property) owned by the CEWO .

This analysis will therefore separate the groundwater and surface water used by irrigators. This approach then allows for the examination of the optimal portfolio characteristics (i.e. the spatial distribution and entitlements purchased from irrigators) that the RtB will need to purchase for the CEWO and a determination of how climate change may alter the characteristics of the portfolio. By knowing the required portfolio characteristics the RtB then sends clear signals to irrigators about their opportunity cost of utilizing water for irrigation or selling their surface entitlement to the CEWO. The separation of groundwater then provides transparent water security signals from all entitlements to emerge and the value of having increased access to groundwater can be determined.

To undertake the analysis, firstly a discussion concerning the irrigator's acceptance and the public uncertainty of the RtB impacts on communities is examined. This discussion also includes defining how the RtB was implemented and the conditions required for its optimization. The section then details how the SCA model, described in Section 6, was altered, and the datasets and assumptions needed to undertake this study were developed. Seven scenarios have been developed to examine how and why the development of the CEWO portfolio needs to anticipate climate change. These scenarios can also be used to examine if the CEWO's portfolio can provide the welfare gains that are anticipated from developing common property (Section 4.3.1). The results also examine how the characteristics of CEWO portfolio may adapt in response to the climate, and how wealth alters from the conjunctive SDL. A wider discussion on the results is used to explore the outcomes and limitations of the analysis. Final comments about the RtB process and the mixed water security signals are then provided.

8.1 The RtB, Its Acceptance, Its Operation and the Necessary Conditions for Optimality

Wheeler and Cheesman (2013) provide a comprehensive review of the irrigator's involvement in the RtB process. Their survey results suggested that, not only did irrigators actively engage in the RtB process but 80% of irrigators believed their decision to sell water to the CEWO, provided positive business outcomes. The 50% of irrigators who had been involved in the RtB process and who still had water to sell, believed that they would consider engaging with the RtB in the future (Wheeler & Cheesman 2013).

Concerns about the optimal allocation of public funding and the RtB process were raised when the CEWO announced that the RtB would have ‘no regrets’ in purchasing water (Adamson et al. 2010; Crase, Dollery & O’Keefe 2011). These concerns arose as: the RtB started purchasing water before work on the Basin Plan had commenced, raising concerns that the water rights purchased may not contribute to the environmental and social goals of the Basin Plan; and initial announcements about the buy-back process, were linked to examples where large sums of money were being used to purchase large corporate farms[68] along the drought affected Darling River. For example, $23.75 million was spent on purchasing Toorale Station, a 91,383ha property, which owned 14GL of low security water entitlements (Pittock, Finlayson & Howitt 2013).

The combination of the RtB process, the Millennium Drought and the willingness of irrigators to sell water to the CEWO, sparked community fears. Some in the rural community suggested that, the RtB would destroy rural communities as the process could facilitate the opportunity for both water and water sellers to reallocate out of local areas (The Senate 2010). These community concerns quickly filtered into the political process and resulted in reviews by The Senate (2010), the House of Representatives (2011) and The Auditor-General (2011). Ultimately the fear of irreparable community harm was proven baseless: with at least 90% of retirees either remaining on their farm and/or district; and those remaining in agriculture using the funds to retire debt, refinance loans or transform their production systems (Cheesman & Wheeler 2012).

Other fears raised in the political process included the: ‘Swiss cheese’ impact on infrastructure; the act of selling water would create social upheaval; and that banks were forcing debt ridden irrigators to sell water. In some irrigation systems the infrastructure is owned by irrigation infrastructure operators (IIO) and to prevent their

[68] At this stage water rights had not been recouped from land rights along the Darling River and this is an on-going issue in some parts of the MDB.

monopolistic power in determining prices for access and maintenance, regulations on charges are introduced in an attempt to provide equitable charges between water users (Roper, Sayers & Smith 2006). As the number of infrastructure users decrease, the allowable charges are redistributed back to the remaining users in the form of higher prices (Heaney et al. 2006). The 'Swiss cheese' effect is anticipated to occur when a group of irrigators suddenly exit in a patchwork pattern. Once these irrigators leave, the IIO reevaluate the viability of distribution channels and increase both fixed and variable costs to access and use water. These higher prices then make irrigation unprofitable and other irrigators shut down, creating holes in the infrastructure (i.e. Swiss cheese) (Heaney et al. 2006). However, by preventing individuals from selling assets, limiting water trade volumes or using exit fees to lock resources into specific areas, it prevents net social welfare gains associated with reallocating resources (Adamson, Quiggin & Quiggin 2011). The House of Representatives (2011) recommended that the RtB should be optimized to prevent number of 'Swiss cheese' incidents

The social upheaval argument was based on the notion that once irrigators sold water to the RtB, that all irrigation farms would become dryland enterprises. It was predicted that as the dryland transformation occurred, farmers would reduce their off-farm demand for production inputs and off-farm labor, which would contract regional economic activity and force people to leave the region. However, these suggestions of impending regional calamity from selling water are identical to any faming decision that alters the existing enterprise mix. For example, investing in labor-saving capital equipment, or acquiring additional land from neighbors to expand operations. As Wheeler and Cheesman (2013) found, the RtB provided a mechanism for irrigators to realize on-farm efficiencies and gain benefits from selling underutilized or surplus entitlements. Additionally what many public submissions ignored was that irrigators could always re-enter the water market and purchase water on their terms, which included purchasing water at lower prices (Wheeler & Cheesman 2013).

Other arguments raised in the political reviews, such as irrigator's being under undue pressure from banks to sell water entitlements are ignored in this thesis, purely as the pressure was from banks to adjust business activities and the RtB provided the best available price. Many submissions could simply be interpreted as, an effort to introduce some form of regional trade barrier to prevent perceived potential adverse implications for their communities.

However, by denying unfettered water, the maximum economic return on assets can never occur. It is an irrigator's choice to maximize their own objective function, by either utilizing water on farm or sell water to the RtB or to the open market. Wheeler and Cheesman (2013) note that as the government's willingness to pay exceeded the open market, it is logical that many farmers sold water to the highest bidder.

8.1.1 How Did the Buy-Back Work?

The RtB process is consistent with Schilizzi and Latacz-Lohmann (2013) description of a "budget-constrained, procurement-type auction" as the government fixed a budget of $3.1 billion and specified the conditions for purchasing water rights from irrigators for the CEWO. The RtB was widely supported by economists (Crase, O'Keefe & Dollery 2009; Dixon, Rimmer & Wittwer 2011) and economic institutions (PC 2010) as the most efficient way to obtain water for the environment due to its market approach to water reform.

The RtB used a multistage regional tendering system to purchase water rights directly from irrigators. In each tender round the government announced: which catchment/s it wanted to purchase water rights from; the total maximum budget it was willing to spend; a set of selling rules; a set of purchasing rules and a final date of submission. Irrigators who wished to participate, submitted non-binding expressions of interest stipulating the price they were willing to receive for a specified bundle of entitlements they were willing to sell (Hone et al. 2010). Once the submission date closed, the Government then was able to determine which tenders it would accept against four assessment characteristics of value for money.

1. "Priority of environmental assets that the water could be directed to.
2. The watering needs of the targeted assets, particularly the deficiency of current arrangements to provide adequate water, including any urgency to provide additional water.

3. The scope to which the entitlement acquisition would benefit the targeted asset such as the capacity to deliver environmental water to the target site, and the long term security of the property right.
4. The cost of the acquisition, including the price, transaction costs and costs of ongoing management and delivery" (Hyder Consulting 2008, p. 15).

This provided the government with complete temporal and spatial information to maximize environmental benefits (Latacz-Lohmann & Van der Hamsvoort 1997). On review all tenderers were notified of their outcome. This tendering process provided a mechanism for price discovery for both buyers and sellers, in four ways. First, as the procurement budget did not have to be exhausted the maximum price the government was willing to pay for water reform was discovered. Second, unlike the 'budget-constrained, procurement-type auction' irrigators could reject the offer, which revealed an individual's price for water. Third, by summarizing and publishing the prices paid for each water entitlement after each round, irrigators could then learn about the price the government was willing to pay. Fourth, this information could be used to guide future irrigators tender bids and/or reveal price changes through time.

8.1.2 Optimizing the Portfolio

To optimize the CEWO's portfolio: the complete description about the alternative property rights are needed, including: their location, their value and level of water security they provide (Randall 1975); and details about the river system, and Basin Plan are required. Crase and Gawne (2011) defined four key requirements to optimize the RtB process. First, the environmental goals of the CEWO's environmental strategy need to be clearly defined. Second, the transmission losses between the point of property rights purchase and environmental targets must be known. Third, the reliability of each water property right structure to provide water security under existing and future climatic settings must be incorporated. Lastly, the timing schedule of water rights to provide water at a given time should be known. The model described in Section 6, has the capacity to encapsulate all but the inter-seasonal timing issues due to its annual framework. Adamson (2012) added two further constraints to the RtB optimization process. The first was to ensure that the

CEWO's portfolio could provide the two institutional goals of the Basin Plan (environment and social) under all possible climatic outcomes and the second was to include the RtB's budgetary constraints.

8.2 **Modeling the Net Change to Property Rights and the Portfolio**

Adamson (2012) found that to examine the net welfare changes of the Basin Plan and the RtB process, irrigator's use of surface water and groundwater had to be modeled separately. This separation then clarifies the signals being provided to irrigators from having the opportunity to sell surface water and increase production from groundwater. The following section describes how the SCA model described in Section 6 was altered to include both the portfolio optimization process and the changes to irrigator welfare.

8.2.1 Modeling the Irrigator's Willingness to Sell to the CEWO

The irrigator's willingness to sell entitlements was modeled as an opportunity cost from either using water to irrigate or permanently selling water entitlements[69] to the CEWO. This was achieved by developing three new state contingent production systems ($x = 23\ to\ 26$), reflecting the total number of each alternative surface water entitlements in each catchment [$we_k^n, where\ N = (1, .., 3)$]. In this case $n(1,2,3)$ maps to $x(24,25,26)$ with a dimension of $(K \times N \times S)$.

Due to the annual nature of the model and as selling water is a permanent transition of water away from irrigation, the RtB price paid to irrigators by catchment was converted into an annuity to provide a constant return in each state of nature (ep_k^n). The water security provided by each entitlement by catchment by state of nature is defined by er_{ks}^n.

For $x = (24, 25, 26)$, the vector of all input prices, a were all equated to zero and the vector of input requirements $b\ (land, fixed\ costs, variable\ costs\ and\ water)$ per Ha are described as follows. For simplicity $b\ (1, 0, 0\ and\ er_{ks}^n)$ per Ha. Where land is used to track the total number of property rights being traded and there are no fixed

[69] Where trade implies a permanent trade of entitlements between a willing irrigator and the CEWO.

or variable costs to use the right once it's sold. By setting the reliability as the water required per Ha, it then allowed the output z to equal 1 and the price per unit of output to be ep_k^n.

To separate irrigators welfare changes in surface and groundwater from the Basin Plan, production systems were separated for that; surface water can only be used to produce production systems $x = (1\ to\ 26)$ and groundwater can only be used to produce production systems $x = (27\ to\ 48)$. It has been assumed that all SCA production data applicable to $x = (27\ to\ 48)$ align identically with $x = (1\ to\ 22)$, meaning that the irrigator receives the same return from producing commodities produced with either surface or groundwater[70].

8.2.2 Incorporating Land Used by Groundwater

By separating water used for irrigation into surface water and groundwater, the equations used to constrain production choice across the landscape were updated. Total available land can now be allocated to either SCA production systems produced with groundwater or SCA production systems produced with surface water. Consequently, Equation 6-12 and Equation 6-13 have been respectively replaced by

$$L_k x_{k,x(1\ldots7,27\ldots33)} \leq 1.5 L_k m_{(1\ldots7)}$$ **Equation 8-1**

and

$$L_k x_{k,x(1\ldots22,27\ldots48)} = 2 L_k m_{(1\ldots16)}$$ **Equation 8-2**

8.2.3 Changes to River Flow

River flow had to be updated to deal with the permanent trade of water to the CEWO and to deal with the separated groundwater and surface and their associated return flows from irrigation. To achieve this Equation 8-3 now replaces Equation 6-14 and the prior definition of θ has been altered. For the model to solve, θ now excludes the

[70] As $x = 23$ is Adelaide and $x = 24\ to\ 26$ are returns from selling water to the RtB, they are not required for modeling groundwater use.

groundwater SDL when determining inflows into a catchment, but the equation does pick up return flows from groundwater use[71].

$$wf_{k,s} = \left(\theta_{s,k} \times wc_{s,k}\right) - \left(w_{s,k} - wr_{s,k}\right) + wrg_{s,k} + we_{s,k} \qquad \textbf{Equation 8-3}$$

Now river flow is determined by the impact that conveyance losses wc have on water resources θ, minus water used w to irrigation less return flows wr from its use, plus the return flows from the groundwater used wrg and includes the volume of water purchased from the RtB program we. When this water reaches the next catchment k it forms part of θ and conveyance losses are then applied. Therefore conveyance losses are applied to water purchased for the CEWO, allowing for trade-offs between alternative regional entitlement prices and water security to be compared against the social and environmental constraints of the Basin Plan.

8.2.4 Basin Plan Objectives

To incorporate the new groundwater SDL and the specified surface SDL reduction by catchment and by regional trading zone as per specification in the Basin Plan (Table 7-5), Equation 6-8 was replaced with 6 new Equations. Where Equation 8-4 deals with the new catchments based SDL and Equation 8-5 to Equation 8-9 ensure that the regional based SDL are enforced.

$$\sum w^k \pi_s \leq \sum SurfaceSDL^k \qquad \textbf{Equation 8-4}$$

$$\sum w^{NTS} \pi_s \leq 143GL \qquad \textbf{Equation 8-5}$$

$$\sum w^{STV} \pi_s \leq 425.3GL \qquad \textbf{Equation 8-6}$$

$$\sum w^{STN} \pi_s \leq 462.9GL \qquad \textbf{Equation 8-7}$$

$$\sum w^{STS} \pi_s \leq 82.8GL \qquad \textbf{Equation 8-8}$$

$$\sum w^{STA} \pi_s \leq 450GL \qquad \textbf{Equation 8-9}$$

[71] By modeling increased groundwater access into θ nonsensical results were being generated.

where:

Symbol	Definition
$SurfaceSDL$	Total volume of surface water allowed for irrigation use
NTS	Water trading zones in the northern catchments ($k\ = 1 \ldots 8$)
STN	Water trading zones in the southern New South Wales (NSW) catchments ($k\ = 10, 12, 14, 16, 18$)
STS	The South Australia (SA) water trading zone ($k = 19$)
STV	Water trading zones in Victoria (VIC) ($k = 11, 13, 15, 17$)
STA	Water trading zones in all southern catchments ($k = 10 \ldots 19$)

Equation 8-10 was added to monitor the groundwater SDL and due to the specified spatial identification of new sources of groundwater Murray-Darling Basin Authority (MDBA) (2012c), it has been assumed that groundwater cannot be traded between. For simplicity, this analysis does not examine the opportunities for irrigators to convert surface water rights into groundwater rights.

$$\sum w^k\ \pi_s\ = \sum GroundSDL^k \qquad \textbf{Equation 8-10}$$

8.2.5 The RtB Program & the Basin Plan

The RtB budgetary constraints for the optimization process are provided by Equation 8-11. This equation ensures that the entitlement portfolio will on average provide, as a lower bound, sufficient water to meet the specified conditions of the SDL and the Basin Plan.

$$\sum_K (WE_K^N \times EP_K^N\ \times ER_{KS}^N)\,\pi_S\ \geq\ (SurfaceCDL - SurfaceSDL)\pi_S \qquad \textbf{Equation 8-11}$$

$$\leq \$3.1\ Billion$$

where:

Symbol	Definition
$(SurfaceCDL - SurfaceSDL)$	Total number of property rights purchased must provide sufficient flow to meet new SDL requirements
WE_K^N	Water entitlements by type $(N = 1,2,3)$ in each catchment
EP_K^N	Water price is the cost to purchase entitlements in each catchment
ER_{KS}^N	Entitlement reliability is the volume of water available in each state of nature

8.3 Data Used in this Analysis

The model uses the conjunctive water data set as presented in Table 7-1 and the Current Diversion Limits (CDL) and SDL data set from Table 7-4 & Table 7-5, respectively. The data for the 450 Climate Change scenario is found in Table 7-8. The location of all alternative property rights, the cost to purchase these rights for the CEWO, and the conversion of the RtB price paid into the annuity value is provided in Table 7-6. The water security provided by each water entitlement class by s and by k is located in Table 7-7.

8.3.1 The Value of Alternative Property Right Structures

The data concerning the prices paid during the RtB process is incomplete as: to ensure individual confidentiality, the RtB only published the average price paid per megalitre (ML) in a catchment (SEWPaC 2013); not all catchments were involved in the RtB process; and not all classes of property rights were sold. Consequently some catchment's data has been assumed to be identical to catchments along the same river section.

The price paid for water in both the Condamine and Queensland (QLD) Border Rivers catchments appears excessive. However, in the absence of detailed data, these prices have not been altered. These high prices may have occurred when the RtB purchased entire properties to overcome the pre-mentioned coupled nature of water and land rights along the Darling River.

The annuity value for water sales was calculated using the same assumptions as when determining the annual cost of capital (Section 6.6.2, Table 7-11), where returns are calculated over 20 years at 7%.

8.3.2 The Reliability of Alternative Property Right Entitlements

SEWPaC (2013) data concerning their estimations about the reliability of water purchased by the RtB process helped define the average reliability of each alternative property rights structure by catchment. To convert this average value into a specific reliability by state of nature, data from historic diversions was used (Chart 3-1).

These assumptions about the reliability of water rights are limiting as the time series is short. Additionally these assumptions about current reliability of water entitlements (Table 7-7) have been held constant to examine climate change impacts. This assumption will preserve the reliability of all property right owners (inclusive of the CEWO) into the future, this assumption then transfers all future climatic risk onto the residual unallocated water, which reflects the water management practices described in Section 2.5.

8.4 **Scenarios**

Seven scenarios are used to analyze the welfare issues associated with net change in ownership of all property rights (i.e. between surface and groundwater and from private individuals to the CEWO) and determine the optimal portfolio of surface water entitlements needed to achieve the objectives listed in the Basin Plan (Table 8-1). The CDL scenario provides the business as usual scenario for the MDB (MDB) (i.e. without the Basin Plan). The remaining six scenarios analyze the impact that the changes to the conjunctive SDL and the changes to property rights ownership have for irrigators and the CEWO. The SDL scenario provides an optimal RtB purchasing strategy and the constrained social welfare solution, under existing climatic conditions. As defined in Section 4.6.3, the resilience of the RtB portfolio to climate change is tested in the last five scenarios where, the RtB's purchasing strategy to purchasing a portfolio of property rights is made by decision makers who are aware (*'ex-post')* and unaware (*'ex-ante'*) about climate change impacts on water supply. Where climate change impacts on water supply occur in two ways the 450 Avg Scenario (CC) over two time periods 2050 and 2100, and where the frequency of the drought state increases (Droughts).

Table 8-1 Scenarios Examined

Model	Intervention	State probability	Climate assumption
CDL		(0.5,0.2,0.3)	Current
SDL	Buy-Back	(0.5,0.2,0.3)	Current
2050 CC, *ex-post*	Buy-Back	(0.5,0.2,0.3)	450 average, 2050
2100 CC, *ex-post*	Buy-Back	(0.5,0.2,0.3)	450 average, 2100
Droughts	Buy-Back	(0.5,0.3,0.2)	Current
2050 CC*, ex-ante*	Buy-Back	(0.5,0.2,0.3)	450 average, 2050
2100 CC, *ex-ante*	Buy-Back	(0.5,0.2,0.3)	450 average, 2100

8.5 Results

The results presented here suggest that the RtB had sufficient funding to purchase a portfolio of property rights (i.e. CEWO's portfolio) that would achieve all of the social and environmental objectives of the Basin Plan. However, the results from the scenarios illustrate that if the RtB process fails to take account of climate change and how the climate changes then the CEWO will be left with a portfolio that is unable to meet the Basin Plan goals. But by examining how the climate changes, a portfolio of entitlements can be purchased that provide on-going benefits for society and the environment.

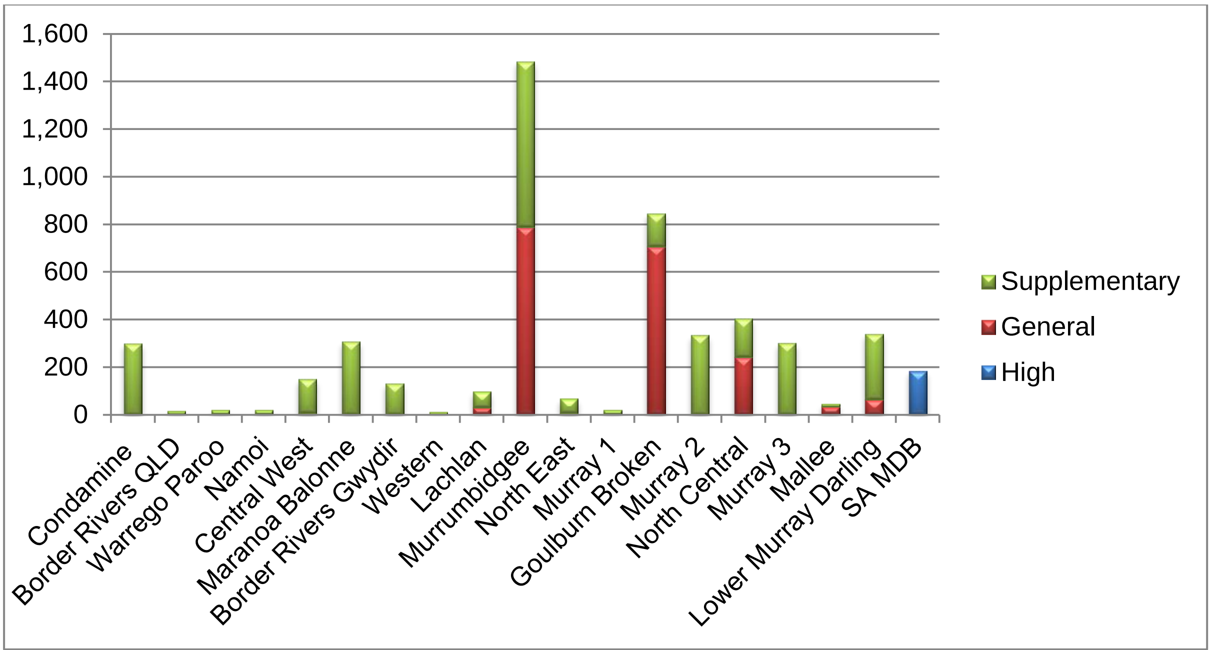
The results also indicate that for the MDB as a whole, the combination of selling $3.1 billion worth of water property rights and the increased groundwater access could lead to a situation where the net returns from irrigation increase for all SDL scenarios. The results are dependent on water reform continuing to encourage the removal of all impediments to water trade within the MDB.

8.5.1 Comments on the Optimal Portfolio

Table 8-7 illustrates the changes to optimal portfolio for the SDL and the three '*ex-post'* climate change scenarios. Chart 8-1, Chart 8-2 and Chart 8-3 are used to illustrate how the portfolio needs to change its strategic targeting by purchasing alternative classes of water entitlements and changing from which catchments it purchases water rights from, to meet the defined Basin Plan objectives, while maximizing irrigator economic returns.

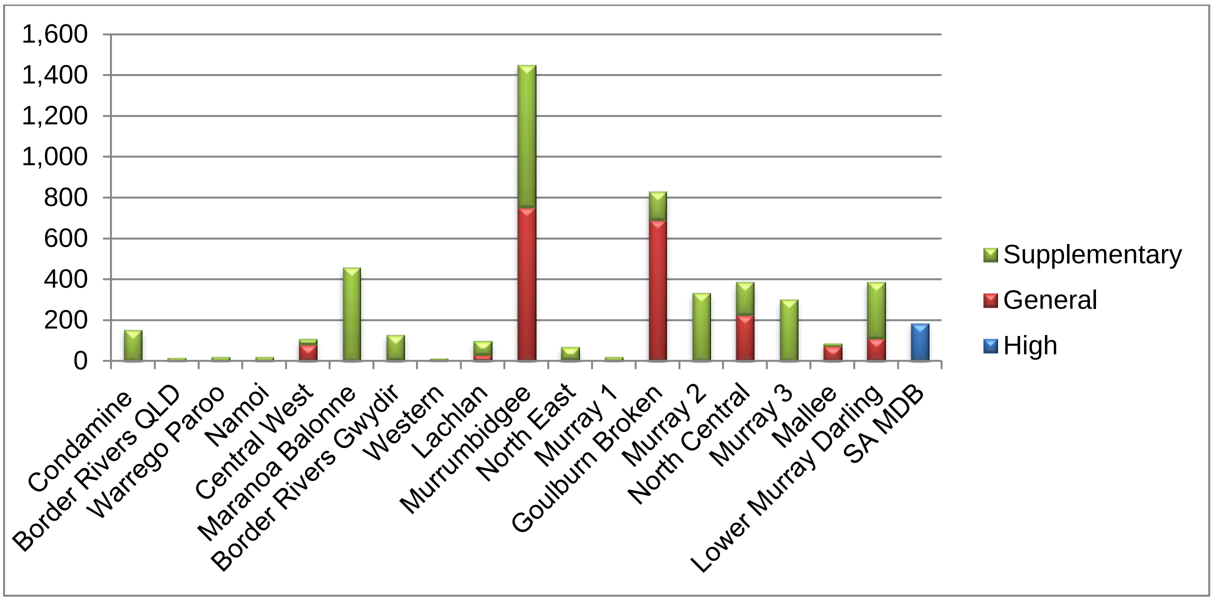
For $3.1 billion, the RtB could achieve the SDL scenario goals by purchasing 184GL of high security, 1,876GL of general security and 3,017GL of supplementary water entitlements (Table 8-7). To optimize the RtB portfolio all high security water would be sourced from the SA MDB (Chart 8-1) and the RtB would target the Murrumbidgee to provide the greatest number of entitlements under current climatic conditions.

Chart 8-1 Optimal Bundle of Entitlements by Catchment, SDL



However, the SDL scenario RtB portfolio fails to provide sufficient water for the CEWO if the climate changed. When the 450 Average Climate Change scenario is examined, the optimal RtB portfolio is still focused on purchasing water rights from along the Murrumbidgee but the portfolio would switch to purchase more general security rights (i.e. 1,976 versus 1,876 in the SDL scenario in Table 8-7) in order to provide sufficient water in the drought state of nature to meet the Basin Plan objectives (Chart 8-2).

Chart 8-2 Optimal Bundle of Entitlements by Catchment, *Ex-post* 450 Average 2050



However, if climate change is expressed by an increased frequency of droughts, the optimal portfolio remains very similar to the SDL strategy (Table 8-7) but the RtB would shift its focus towards strategically, purchasing water along the Murray River and not the Murrumbidgee River (Chart 8-3).

Chart 8-3 Optimal Bundle of Entitlements by Catchment, Droughts

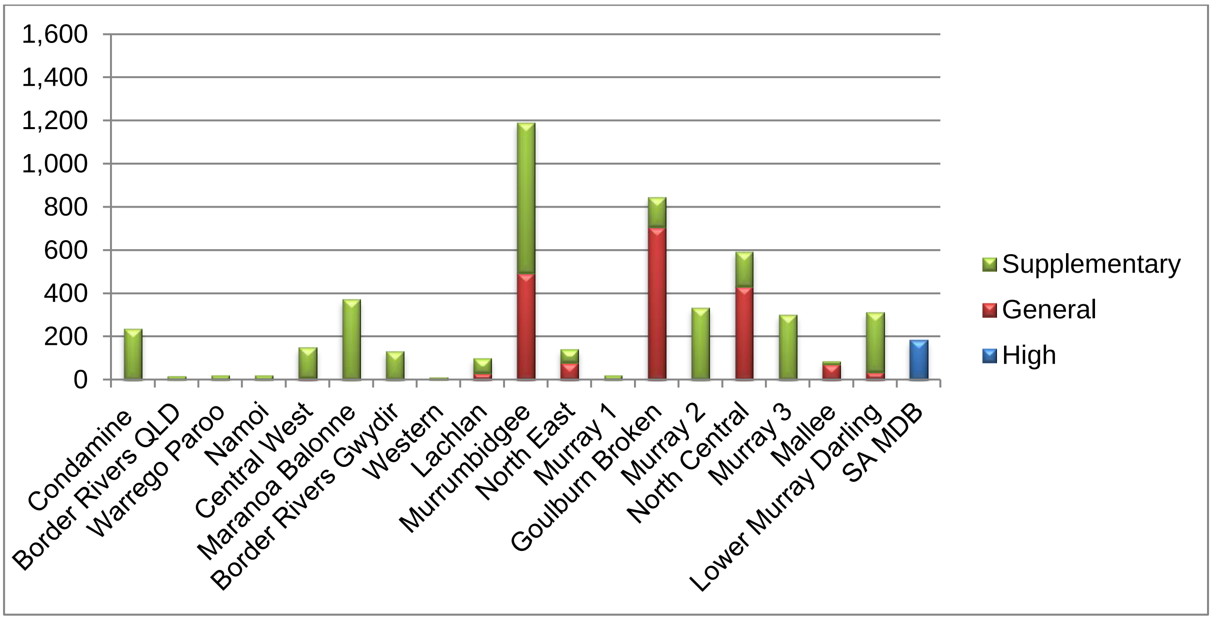
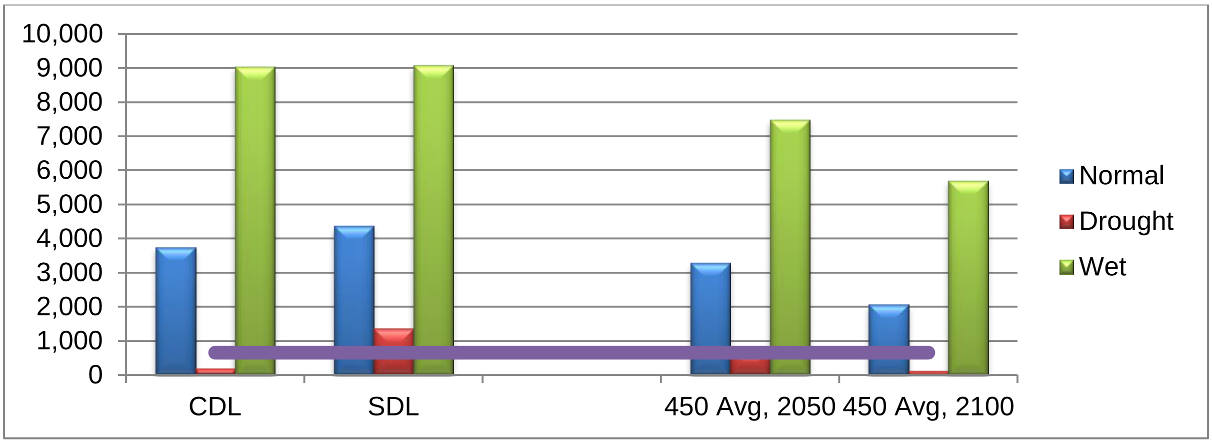


Chart 8-4 and Chart 8-5 are used to contrast the risks to the Basin Plan goals from failing to consider climate change[72] and how the climate changes (mean versus variability) when purchasing a portfolio of entitlements. The SDL scenario can clearly meet the environmental flow requirements to the Coorong (as represented by the horizontal line in Chart 8-4), the environmental flow benefits from the SDL are eroded through time under the new basin wide inflows that are predicted to occur under the 450 Avg Climate Change scenario in 2050 and 2100[73]. By 2100, flows to the Coorong are anticipated to be 65GL less in the drought scenario when compared to the CDL (Table 8-6) and Adelaide's water quality may be degraded by 210 EC on average.

Chart 8-4 Flow to the Coorong, *Ex-ante* Climate Change (GL)



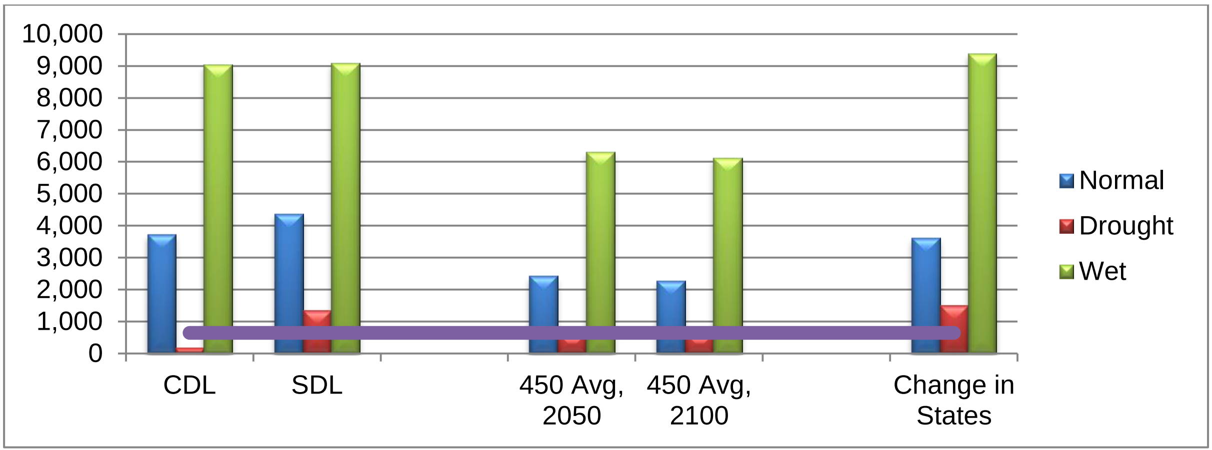
Compounding the SDL scenario's inability to meet environmental and social objectives under a changing climate, is that by reallocating irrigation resources in response to the RtB portfolio, the irrigator's demands for water can no longer be provided by the river. All shaded cells in Table 8-11, represent a situation where the river system would have a negative flow (i.e. irrigators demands exceed the biophysical constraints of the river system) and this would result in irreversible capital loss to irrigators, the ecosystem and society.

[72] Section 4.6.3 defined how the results for the *ex-ante* or unaware decision maker were determined.

[73] Note in scenario where the frequency of the drought increases this allocation of resources does not alter water flow (as it doesn't alter) but rather decreases economic returns for irrigators.

Chart 8-5 illustrates that by changing the portfolio (Table 8-7) to reflect the alternative climate risks[74] the CEWO would have sufficient water to meet the minimum flow requirements for the Coorong for the 450 Climate scenario in both 2050 and 2100. If the RtB strategically purchased its portfolio to maximize welfare and its objectives in a climate future where droughts are more frequent, the environmental flow threshold is exceeded.

Chart 8-5 Flow to the Coorong, *Ex-post* Climate Change (GL)



As Table 8-7 suggests, these alternative portfolios of water may only provide water security of around 2,640GL for the environment and not the 3,200GL required by the Basin Plan and this is due to the water security of the portfolio and the design of the constraint. The CEWO will have to carefully manage its water over time, as the portfolio of rights (Table 8-7) does not deliver a constant supply of water but rather peaks (≈4,000GL in wet state of nature) and troughs (≈1,320GL in drought states). This pattern of water supply then alters the social benefits of reduced salinity as illustrated in Table 8-6. Adelaide's residents should expect an improvement in their water quality by 96EC on average (Table 8-6) for the SDL scenario and this improves water quality by over 53%.

[74] Section 4.6.3 defined how the results for the *ex-post* or aware decision maker were determined

All optimal portfolios[75] provide the CEWO with significant flexibility to manage drought events (Table 8-6), with at least a net increase in environmental flows of $\approx$250% when compared to the CDL. This flexibility would help negate Howitt's (1995a) applied policy limits and provide additional flows to help meet some additional environmental targets along the MDB, which are not included in this model.

8.5.2 Changes to Irrigator Welfare

Table 8-4 identifies the water used by irrigators for all scenarios by water type (i.e. groundwater and surface water), Table 8-5 details the economic returns from utilizing alternative sources of water for irrigation activities or selling it to the CEWO, and Chart 8-6 provides this data graphically. The results for SDL scenario suggest: that the extra 929GL of groundwater (Table 8-4) provides irrigators with increased economic returns of $336 million on average (Table 8-5); irrigators now use 2,488GL less of surface water, which reduces their returns by $416 million on average but they gain $293 million from selling water to the RtB. The data suggests that irrigators now use 1,599GL or 10% less water on average but their economic return has increased by $212 million or 7% on average.

The data in Table 8-4 and Table 8-5 shows that this trend of decreased water use and increased economic return was found in all scenarios. Therefore it can be suggested that the access to more groundwater, constant returns from water sold to the RtB and the ability to engage in trade, will provide the capacity for irrigators to offset any negative impact from the Basin Plan or a changing climate. These findings complement Dixon *et al.* (2011) who argued that the prices paid under the RtB for entitlements adequately compensates irrigators. Additionally as the increased economic returns are greatest in the drought states of nature (e.g. a gain of nearly $550 million is anticipated in the increasing droughts scenario, Table 8-5), some wider economic benefits could occur. The second round benefits of these findings are not quantified in this thesis, it could be anticipated that some of the irrigators

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[75] Ex-ante solutions are not optimal, they are the SDL scenario which passively reacts to the 450 Climate Change scenario.

increased economic returns may help delay the pressure on social services (PC 2009).

Chart 8-6 Economic Return by Scenario by State of Nature ($'m)

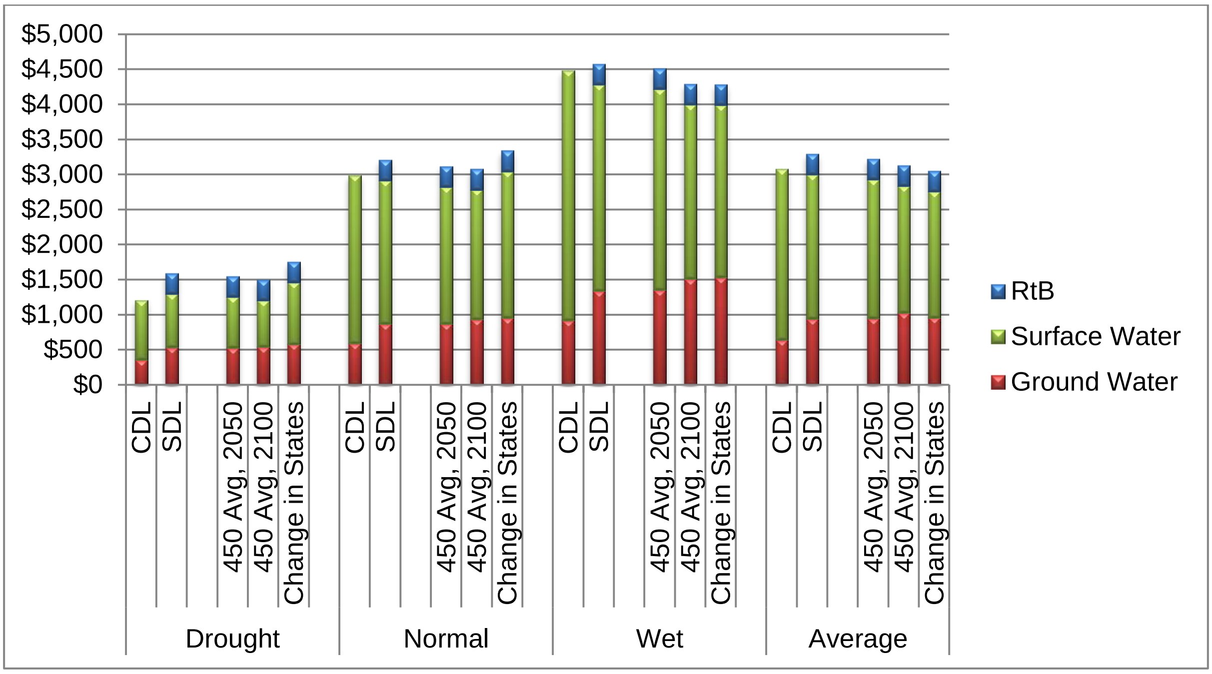
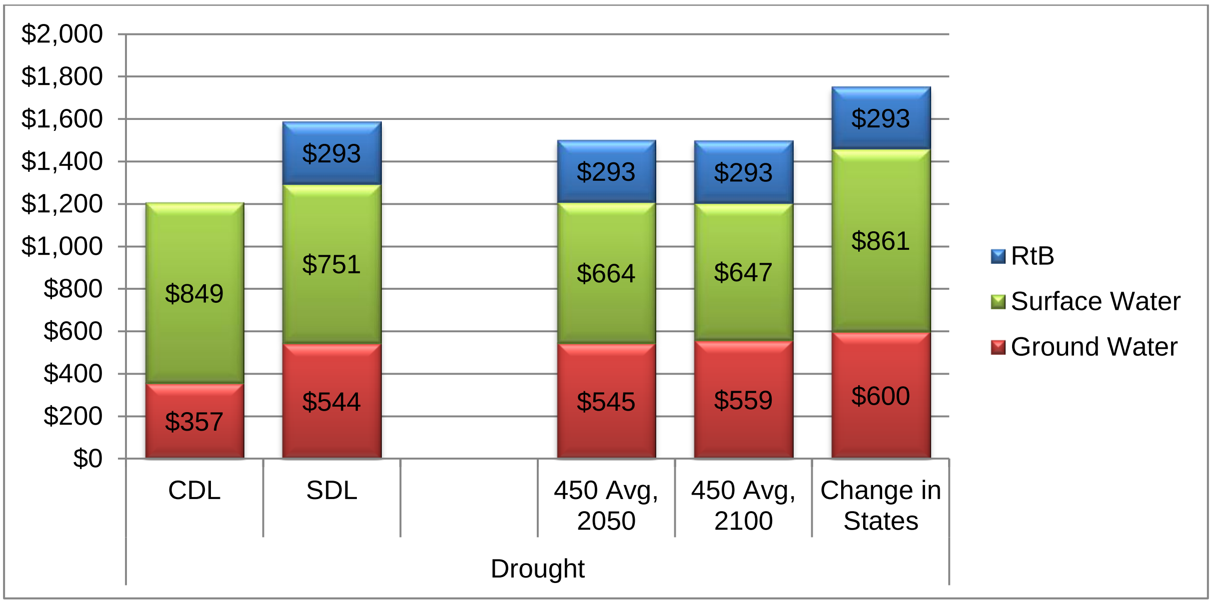


Chart 8-7 Economic Return in Drought States of Nature by Scenario ($'m)



However, welfare benefits are not uniform across the MDB. Table 8-12 illustrates the net change in total conjunctive water use and its value by catchment when the CDL and SDL results are detailed. The assumptions that groundwater security is guaranteed and that regional trade is possible, allows resources to be reallocated so that total water used in irrigation only decreases by 1,560GL and that economic returns from water use (excluding sales) decreases by $80 million. By disaggregating this water use and economic return data into the Northern Murray-Darling Basin (NMDB) and Southern Murray-Darling Basin (SMDB), these results suggest that the Basin Plan allows irrigators in the NMDB to be net winners and the SMDB irrigators lose. Irrigators in the NDMB gain an additional 451GL of water, increasing their economic returns by $50 million, on average. SMDB irrigators are expected to lose $130 million in economic returns on average when 2,000GL of surface water is removed from production. If the Basin Plan was solely a game of rent between NMDB and SMDB irrigators, the NMDB is a clear winner (Section 2.1).

The economic benefits of guaranteed groundwater security allow irrigators to return ≈$270/ML compared to $162/ML for surface water across the MDB, under the CDL (Table 8-2). The economic benefit to access groundwater ($/ML), increases both in response to an increased SDL, and due to climate change. Groundwater's economic benefit is due to the water security it provides into the future. Unlike groundwater the economic return generated by surface water is expected to decline.

Table 8-2 Value of Alternative Water Resources for Irrigators ($/ML), Compared to the CDL

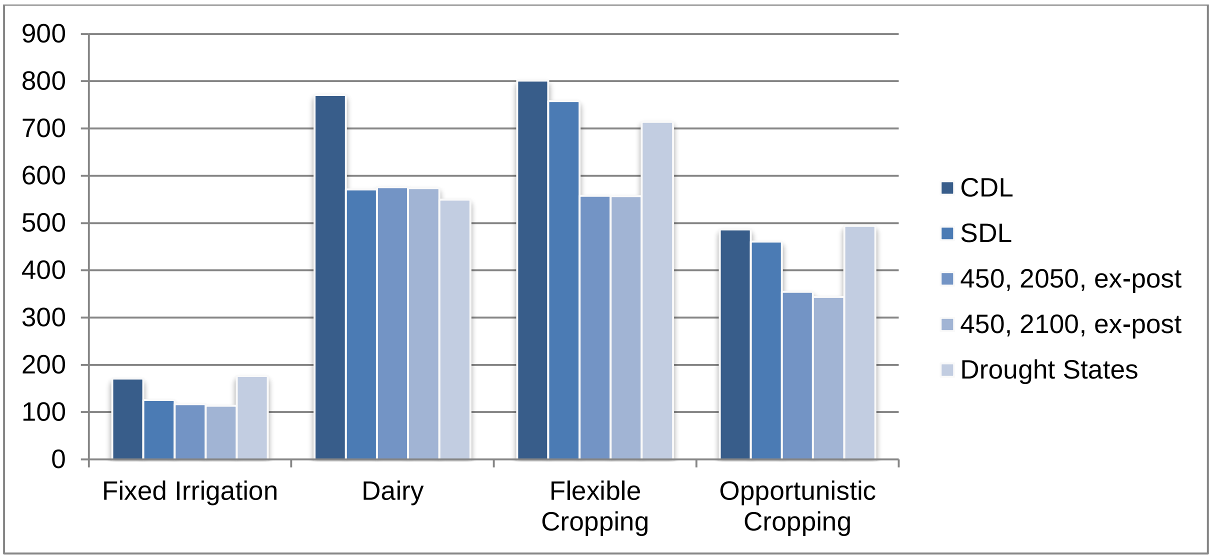
	Groundwater	Surface Water
CDL	$269.98	$162.22
SDL	$25.77	-$12.10
450, 2050, *ex-post*	$43.78	-$21.65
450, 2100, *ex-post*	$50.75	-$23.95
Drought States, *ex-post*	$59.38	-$28.11

As the economic returns from water use diverges between surface water and groundwater, the implementation of the Basin Plan will create wealth for owners of groundwater property rights. However, as discussed in 4.6.2, once the RtB purchases surface water rights, the supply curve shifts to the left (Figure 4-2) and the price of surface water rights may increase, which in the short term (i.e. before climate change occurs), may partially offset the divergence in values between groundwater and surface water. However, the value of the three surface entitlement classes should not be expected to increase uniformly. It should also be expected that these prices should also lead to greater on-farm adaption and adoption of water-use efficient technology.

The results in Table 8-8, Table 8-9 and Table 8-10 help illustrate how the increased economic returns are possible, as they detail: the area allocated by water source (groundwater or surface water); which commodities are produced by the alternative water sources; and a detailed catchment analysis of the land use change, respectively. Chart 8-8 is also used, to illustrate how the irrigators with surface water may adapt production systems compared to the CDL scenario. By increasing groundwater access, an additional 180,000Ha of irrigated land can be produced (Table 8-8) when the SDL is compared to the CDL. The new land irrigated with groundwater is expected to produce an additional 45,000Ha of horticulture, 74,000Ha of cotton and 61,000Ha of grain crops (Table 8-9). At the same time the area produced with surface water is expected to contract by 292,000Ha, for a net reduction in irrigated area of 112,000Ha (Table 8-8). As the area irrigated by state of nature is not constant, it is expected that in the wet state of nature there is 313,000 Ha less irrigated with surface water and the biggest single commodity loser will be dairy with 200,000Ha less of production (Table 8-9). The breakdown of the catchment based expansion and contraction in the area produced with groundwater and area produced with surface water is provided in Table 8-10, where the net increase in irrigated area for the NMDB is visible.

As illustrated in Chart 8-8, the area dedicated to dairy is anticipated to contract in comparison to the CDL for all scenarios listed. However, this contraction in dairy area is still less than the 500,000Ha which transitioned to dryland during the Millennium Drought (Table 3-1). Irrigators will actively transition out of irrigation under the 450 Climate Change scenarios, as evident by the reduction in both the flexible and opportunistic SCA production systems in Chart 8-8. In the scenario where droughts become more frequent, the area dedicated to both flexible and opportunistic cropping is expected to increase as producers respond to the marginal cost of production in state s and state t (Equation 5-45).

Chart 8-8 Production Management Adaptation in Surface Water (Area '000Ha)



This changing state-contingent marginal cost of production guides the RtB portfolio to purchase water from the Murray and not the Murrumbidgee in the drought scenario. Table 8-3, illustrates that the resulting change in economic return for the Murrumbidgee incentivizes the expansion of the rice industry at the expense of the wheat industry. In this case, the average return from Rice PSN increases from $75 to $85/ML and the return from wheat decreases from $85 to $76/ML.

Table 8-3 Impacts from Increasing Droughts in the Murrumbidgee ($/ML)

	Economic Return ($/Ha)			Current Climate	Increasing Droughts
	Normal	Drought	Wet		
Rice PSN	$768	$768	$58	$555	$626
Flex Rice	$303	$324	$58	$234	$261
Wheat	$358	$106	$434	$331	$298
			Water Used ML/Ha		
Rice PSN	7.5	7.3	7.5		
Flex Rice	7.5	0.0	7.5		
Wheat	3.9	3.9	3.9		
			$ Return/ML		
Rice PSN	$103	$105	$8	$75	$85
Flex Rice	$41		$8	$23	$22
Wheat	$92	$27	$111	$85	$76

Data summarized from Appendix B

Table 8-4 Total Conjunctive Water Used by Scenario, Compared to CDL (GL)

Scenario	Groundwater All states (GL)	Surface Water (GL) Normal	Drought	Wet	Average	TOTAL Diversions (GL) Normal	Drought	Wet	Average	% Change (Average)
CDL	2,373	12,013	6,899	17,632	12,676	14,386	9,272	20,004	15,049	
SDL	929	-2,449	-1,634	-3,122	-2,488	-1,520	-704	-2,193	-1,559	-10%
450, 2050, *ex-post*	929	-2,775	-2,134	-4,325	-3,112	-1,846	-1,205	-3,396	-2,183	-15%
450, 2100, *ex-post*	929	-2,768	-2,218	-4,410	-3,151	-1,839	-1,289	-3,481	-2,222	-15%
Drought States	929	-1,375	-1,838	-1,878	-1,619	-446	-909	-949	-689	-5%

Table 8-5 Economic Return from Conjunctive Resource use and Sales by Scenario, Compared to CDL ($’m)

Scenario	Groundwater Normal	Drought	Wet	Avg#	Surface Water Normal	Drought	Wet	Avg	RtB All	TOTAL Economic Return Normal	Drought	Wet	Avg	% Change (Avg)
CDL	$590	$357	$914	$641	$2,399	$849	$3,573	$2,441		$2,989	$1,206	$4,487	$3,082	
SDL	$300	$187	$495	$336	-$374	-$98	-$698	-$416	$293	$218	$382	$90	$212	7%
450, 2050, *ex-post*	$350	$188	$610	$395	-$540	-$186	-$1,085	-$633	$293	$102	$295	-$182	$55	2%
450, 2100, *ex-post*	$370	$202	$643	$418	-$573	-$203	-$1,134	-$668	$293	$89	$291	-$199	$43	1%
Drought States	$391	$243	$676	$447	-$334	$11	-$1,170	-$515	$293	$350	$547	-$201	$224	7%

avg = average

Table 8-6 Results for the Social Objectives, Flow to Coorong (GL) and Adelaide's Water Quality (EC), by Scenario, Compared to CDL

Scenario	Flow to Coorong (GL)				Adelaide Salinity (EC)				% Change (Drought)	
	Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	Coorong	Salinity
CDL	3,739	186	9,046	4,621	423	687	328	448		
Compared to CDL										
SDL	631	1,172	39	562	-49	-361	2	-96	629%	-53%
450, 2050, *ex-post*	-1,316	464	-2,733	-1,385	158	-246	113	63	249%	-36%
450, 2100, *ex-post*	-1,461	464	-2,913	-1,512	185	-250	123	79	249%	-36%
Drought States	-122	1,333	349	310	36	-393	-18	-66	715%	-57%
450, 2050, *ex-ante*	-459	589	-1,559	-579	54	-234	68	0	316%	-34%
450, 2100, *ex-ante*	-1,680	-65	-3,349	-1,857	266	114	180	210	-35%	17%

Table 8-7 Total Number of Property Rights to Purchase

	Property Rights Purchased			Water Obtained			
Scenario	High	General	Supplementary	Normal	Drought	Wet	Average
SDL	184	1,876	3,017	2,352	1,324	4,002	2,641
450, 2050	184	1,973	2,890	2,362	1,319	3,992	2,642
450, 2100	184	1,972	2,892	2,362	1,319	3,992	2,642
Drought States	184	1,859	3,017	2,356	1,349	3,998	2,647

Table 8-8 Land Allocated to Irrigation by Conjunctive Source by Scenario, Compared to CDL ('000Ha)

	Area Produced ('000 Ha) by									% Area Change (Average)		
	Groundwater	Surface Water				TOTAL				Ground	Surface	
Scenario	All states	Normal	Drought	Wet	Average	Normal	Drought	Wet	Average	Water	Water	Total
CDL	475	1,744	1,260	2,230	1,793	2,218	1,735	2,705	2,268			
SDL	180	-288	-271	-313	-292	-108	-91	-134	-112	38%	-16%	-5%
450, 2050, *ex-post*	246	-493	-437	-625	-521	-247	-191	-379	-275	52%	-29%	-12%
450, 2100, *ex-post*	250	-498	-451	-641	-532	-249	-202	-391	-282	53%	-30%	-12%
Drought States	136	-303	-397	-295	-319	-166	-261	-159	-183	29%	-18%	-8%

Table 8-9 Area of Production System, by Scenario, Compared to CDL ('000Ha)

	Maximum Area Produced with Groundwater						Maximum Area Produced with Surface Water					
Scenario	Horticulture	Dairy	Cotton	Rice	Grains	TOTAL	Horticulture	Dairy	Cotton	Rice	Grains	TOTAL
CDL	82	0	99	10	285	475	171	771	968	2	318	2,230
SDL	45	0	74	0	61	180	-45	-200	-40	-2	-26	-313
450, 2050, *ex-post*	54	0	38	0	153	246	-54	-195	-210	22	-188	-625
450, 2100, *ex-post*	57	0	36	0	156	250	-57	-197	-225	35	-197	-641
Drought States	64	0	79	10	-16	136	-64	-222	26	205	-241	-295

Table 8-10 Area Irrigated by Conjunctive Water Change from CDL to SDL ('000 Ha)

	Groundwater						Surface Water						Net Change					
	Hort#	Dairy	Cotton	Rice	Grains	TOTAL	Hort	Dairy	Cotton	Rice	Grains	TOTAL	Hort	Dairy	Cotton	Rice	Grains	TOTAL
Condamine			13			**13**			-13			**-13**						**0**
Border Rivers QLD	5				11	**15**	-5		6		-2	**0**			6		9	**15**
Warrego Paroo			5		71	**76**			-2			**-2**			3		71	**74**
Namoi						**0**			-2			**-2**			-2			**-2**
Central West			1			**1**			-13			**-13**			-12			**-12**
Maranoa Balonne			8			**8**			-8			**-8**						**0**
Border Rivers Gwydir			18			**18**			-7			**-7**			11			**11**
Western			28		-30	**-2**			2			**2**			30		-30	**0**
Lachlan					24	**24**			-3	-2	-2	**-7**			-3	-2	21	**16**
Murrumbidgee	17				-43	**-26**	-17				-3	**-20**					-46	**-46**
North East						**0**						**0**						**0**
Murray 1						**0**						**0**						**0**
Goulburn Broken					8	**8**		-89				**-89**		-89			8	**-81**
Murray 2						**0**		-2				**-2**		-2				**-2**
North Central						**0**						**0**						**0**
Murray 3					0	**0**		-102				**-102**		-102				**-102**
Mallee	7				19	**26**	-7				-19	**-26**						**0**
Lower Murray-Darling						**0**						**0**						**0**
SA MDB	17	0				**17**	-17	-6				**-24**		-6				**-6**
TOTAL	**45**	**0**	**74**	**0**	**61**	**180**	**-45**	**-200**	**-40**	**-2**	**-26**	**-313**	**0**	**-200**	**34**	**-2**	**34**	**-134**

#Hort = Horticulture

Table 8-11 Residual Flow leaving a Catchment (GL), Shaded Cells Indicate a Negative or Infeasible flow

	Ex-ante						*Ex-post*					
	2050			2100			2050			2100		
	Normal	Drought	Wet	Normal	Drought	Wet	Normal	Drought	Wet	Normal	Drought	Wet
Condamine	-58	239	-60	-122	202	-143	0	229	0	0	224	0
Border Rivers QLD	-35	9	-46	-76	-14	-99	0	151	0	0	148	0
Warrego Paroo	-16	62	-25	-33	53	-52	0	54	0	0	53	0
Namoi	-58	356	-75	-123	318	-158	0	323	0	0	318	0
Central West	-52	286	-70	-109	253	-147	0	256	0	0	252	0
Maranoa Balonne	-62	267	-84	-131	228	-178	0	212	0	0	208	0
Border Rivers Gwydir	1,241	717	-184	1,082	625	-389	1,148	781	0	1,135	771	0
Western	-182	912	-262	-307	800	-555	0	955	0	0	942	0
Lachlan	238	-38	-80	165	-81	-174	46	2	0	0	70	0
Murrumbidgee	1,675	865	2,070	1,383	695	1,693	1,696	979	2,070	1,662	959	2,026
North East	3,311	1,881	4,194	2,979	1,686	3,773	3,016	1,708	3,821	2,979	1,686	3,773
Murray 1	1,203	679	1,547	1,032	579	1,330	1,051	590	1,355	1,032	579	1,330
Goulburn Broken	2,264	995	3,240	1,676	653	2,480	1,716	875	2,534	1,649	836	2,447
Murray 2	-42	-138	144	-311	-294	-214	179	0	379	157	0	352
North Central	1,023	102	2,072	657	-106	1,568	863	131	1,803	824	115	1,750
Murray 3	1,736	556	2,875	1,328	325	2,316	792	116	1,662	737	91	1,589
Mallee	2,080	291	3,551	1,510	-29	2,778	1,494	151	2,852	1,415	152	2,764
Lower Murray-Darling	2,509	1,708	4,328	1,733	1,277	3,266	2,102	1,620	3,779	2,021	1,607	3,683
SA MDB	3,631	1,186	7,647	2,373	498	5,838	2,741	1,030	6,456	2,591	1,027	6,275
Adelaide	3,880	1,375	7,950	2,621	687	6,141	2,989	1,219	6,759	2,840	1,215	6,578
Coorong	**3,280**	**775**	**7,487**	**2,059**	**122**	**5,697**	**2,423**	**650**	**6,312**	**2,278**	**650**	**6,133**

Table 8-12 Estimated Change in Total Conjunctive Water Use (GL) & its Value ($m) CDL-SDL

Catchment	Conjunctive Water Use				Economic Value			
	Normal	Drought	Wet	Avg	Normal	Drought	Wet	Avg
Condamine	2.8	62.8	-0.6	13.8	-$2.9	$4.7	-$1.6	-$1.0
Border Rivers QLD	41.4	13.6	38.2	34.9	$8.9	$4.5	$8.9	$8.0
Warrego Paroo	126.0	132.0	120.0	125.4	$27.2	$13.2	$31.4	$25.6
Namoi	-8.0	0.0	-12.0	-7.6	-$3.9	-$1.2	-$4.3	-$3.5
Central West	-30.9	8.6	-81.9	-38.3	-$10.3	-$5.5	-$6.8	-$8.3
Maranoa Balonne	-1.4	41.9	0.3	7.8	-$2.0	$1.4	-$1.2	-$1.1
Border Rivers Gwydir	128.7	128.7	65.7	109.8	$9.1	$12.3	$12.3	$10.7
Western	142.6	95.5	98.4	119.9	$13.3	$18.7	$12.7	$14.2
Lachlan	93.8	111.9	54.7	85.7	$3.8	-$0.5	$12.2	$5.5
Murrumbidgee	-177.6	-177.6	-213.1	-188.3	-$14.5	-$3.1	-$16.8	-$12.9
North East	0.0	0.0	0.0	0.0	$0.0	$0.0	$0.0	$0.0
Murray 1	0.0	0.0	0.0	0.0	$0.0	$0.0	$0.0	$0.0
Goulburn Broken	-737.8	-457.2	-891.8	-727.9	-$40.6	$21.9	-$123.6	-$53.0
Murray 2	-20.8	-12.0	-25.2	-20.3	-$1.6	$0.2	-$3.1	-$1.7
North Central	0.0	0.0	0.0	0.0	$0.0	$0.0	$0.0	$0.0
Murray 3	-1,020.2	-611.7	-1,224.4	-999.8	-$60.6	$19.8	-$117.6	-$61.6
Mallee	0.0	0.0	-28.5	-8.6	$1.4	$1.4	$2.4	$1.7
Lower Murray-Darling	0.0	0.0	0.0	0.0	$0.0	$0.0	$0.0	$0.0
SA MDB	-58.5	-40.9	-92.4	-65.2	-$1.6	$1.0	-$7.1	-$2.8
TOTAL	**-1,519.8**	**-704.5**	**-2,192.7**	**-1,558.6**	**-$74.5**	**$89.0**	**-$202.3**	**-$80.1**
NMDB	*495*	*595*	*282.8*	*451.4*	*$43.2*	*$47.6*	*$63.6*	*$50.1*
SMDB	*-2014.9*	*-1299.4*	*-2475.4*	*-2010.1*	*-$117.5*	*$41.2*	*-$265.8*	*-$130.3*

8.6 **Discussion and Limitations Associated with the Analysis**

The constrained optimization approach of modeling the RtB and the changes to groundwater suggest that not only could the RtB be optimized to meet the objectives of the Basin Plan but as a whole, economic returns increase within the MDB. The combination of increased economic returns, improved water quality and meeting environmental objectives is what is expected when the ‘common property approach’ to internalizing externalities is adopted (Section 4.3.1). However, irrigator’s economic returns in this model only increase above the CDL returns, when increased groundwater access is included.

The increased economic returns are not uniform and the analysis suggests that the dual benefits from increasing the quantity and reliability of water assets in the NMDB provide the necessary conditions to facilitate an irrigation ‘boom’. It is anticipated that irrigators in the SMDB will be worse off, with the noticeable exception of the SA MDB, as the SMDB does not gain access to new groundwater reserves. This loss of economic returns in the SMDB may provide guidance into why the expenditure on the SRWUIP has a SMDB basis, for example the $1 billion investment in the northern Victorian ‘Food Bowl Modernisation Project’ (Crase & O'Keefe 2009). The economic justification of the SRWUIP is examined in the next section.

The increased water security offered by groundwater will continue to stimulate the discussion of transferring surface water entitlements into groundwater (Kirby et al. 2014). This conjunctive entitlement transfer of risk is possible and in 2011 (Grafton & Horne 2014) the National Water Commission (NWC) began establishing the rules for permanently trading entitlement rights between groundwater and surface water (NWC 2011b). However, while the Basin Plan reconfirmed these commitments to allow permanent trade between surface water and groundwater resources, they can currently only occur under strict conditions[76]. If these transfer conditions are maintained, this discussion of property right transfer between groundwater and surface water is unlikely to continue due to increased costs of accessing groundwater.

[76] These conditions are listed in sections 12.24 to 12.26 of the Basin Plan (MDBA 2012c, pp. 131-2).

The spatial and temporal water security offered by alternative rights can be optimized to purchase an optimal portfolio for the CEWO. However, climate change (mean and variance) alters both the spatial and alternative bundle of property rights purchased for the portfolio. With an uncertain future, it would be prudent for the CEWO to alter this portfolio over time in response to how the climate does change to maintain the benefits derived from having ‘common property’ managed in the nation’s interest. How, or if, the CEWO will interact with the water market (permanent and allocation) to gain additional flows is still to be determined, but in January 2014 the CEWO engaged in allocation water trade (via a tender system) by offering 10 GL of water to Gwydir valley irrigators (CEWO 2014). The role of water trade as a source of revenue has been recognized by the CEWO to offset both the management cost of the CEWO and the transaction and operation costs of managing its portfolio, and the water trade framework is yet to be finalized (CEWO 2013). It may be heroic to assume that this water trade framework will prevent both political pressure on the scale and scope of CEWO water placed on markets in drought periods, or that some irrigators assume that the CEWO’s portfolio can be used like a water overdraft facility.

From the data provided, the RtB could achieve the Basin Plan’s goals for $3.1 billion. Therefore despite the concerns that the government paid above existing market prices, the RtB provides welfare gains. Irrigators correctly speculated that the government would be willing to pay above existing market prices to encourage their involvement in the RtB process (Cheesman & Wheeler 2012). The Government’s willingness to pay a higher price for water can be justified as the RtB process: helped overcome irrigator’s transaction costs associated with existing trade barriers (NWC 2011a); stimulate participation in what had been thin trade in the permanent entitlement market (Adamson, Quiggin & Quiggin 2011); allowed irrigators to become aware of the ‘true’[77] social price of water (i.e. inclusive of the externality cost) (Randall 1981); and by managing the water portfolio in the national interest, both private water users and social gains are expected. Private water users are expected to gain welfare from improved water quality and increased property right values and society may gain from reallocating public expenditure which may have otherwise been required to ameliorate intra- and inter-generational externalities from water use.

[77] Where ‘true’ implies no political interference in the determination of the price paid.

As water quality improves, irrigators can diversify into saline susceptible commodities (Connor et al. 2012) and gain increased flexibility to manage droughts. Mallawaarachchi and Foster (2009) found that some irrigators were forced into selling their water during the Millennium Drought, as river salinity exceeding 38,000EC and was unsuitable for on-farm use. Additionally some irrigators may be able to free-ride on the CEWO's water 'quality' improvement by abdicating their current requirements to manage saline drainage water (Smith & Maheshwari 2002) without 'adversely affecting' end-of-valley targets. Improved water 'quality', will provide greater opportunity for salinity sensitive species to adapt to other unforeseen negative impacts derived from poor water quality (Kefford et al. 2006; Kingsford et al. 2011).

The RtB has achieved these water quality improvements at prices which are comparable with investing in the SIS (Section 2.5.2). The analysis of the SDL revealed that the net reduction in irrigation returns from surface water is $416 million and salinity is reduced by 96EC, which equates to a cost of $4.3 million in lost revenue per EC. This cost per EC is equivalent to the public cost of establishing a new SIS which cannot utilize existing infrastructure (i.e. >$4.5 million per EC in the Upper Darling SIS). If the cost differential between maintaining and operating the CEWO portfolio and SIS diverge in the future, and the true extent of climate change is understood, then future reviews of the salinity mitigation program may consider, all be it heroically, to mothball inefficient SIS assets.

However, care needs to be taken with these due to the limitations of the model and assumptions used. First, the optimal solution is derived from a benevolent individual acting in the national interest ,which is not the same as multiple agents acting in their own interest (Perry et al. 1989). For example in the CDL solution, the benevolent individual did utilize all water available as they had complete information about all states of nature. In this case, the model has deliberately underutilized or did not utilize some water rights (i.e. mimicked irrigators 'dozers' or 'sleeper' behavior) while maximizing welfare. This result could either reflect the true nature of irrigation practices or it is a construct of the model. As Wheeler and Cheesman (2013) found, the RtB allowed irrigators to sell underutilized water assets to the CEWO. Alternatively, the risk minimization behavior used within this SCA model is not applicable to all farmers (Rasmussen 2011b).

Second, all scenarios provide a blank slate free from any binding institutional legacy that hindered past water reform (Cummins & Watson 2012). This approach overcomes institutional barriers and helps illustrates gains from reallocating resources outside of established irrigation zones, it can create misleading outcomes. For example, the model ignores natural flow constraint barriers like the Barmah and Millewa Chokes (Kingsford 2000). Consequently, when these alternative theoretical optimized partial equilibrium solutions are compared, the errors can be compounded and are derived from the heuristics and bounds within the model. Therefore the optimal CEWO portfolio suggested by the model will differ to the realized portfolio due to: the model's bounds; the incomplete understanding of the current and future water security provided by alternative property rights; the CEWO not revealing the complete set of their environmental objectives; and changes to future irrigator willingness to sell water to the CEWO.

The use of a single known (assumed) variable to describe the reliability of alternative water rights allows the model to derive an optimal portfolio for the RtB process to target. In reality the reliability of these assets are not constant by state of nature and the adoption of a stochastic description of reliability of each alternative water right, by state of nature would help explore the environmental and economic return trade-offs in greater detail. This stochastic approach would change the portfolio's spatial targeting and the desirable mix of alternative property rights. This information could also be used to reveal the economic benefits of having adaptable and not hard environmental flow targets as Adamson, Quiggin and Quiggin (2011) discovered in an analysis for the MDBA (see Section 10.3 for greater discussion on this issue). This new portfolio may then increase the cost for the RtB above the current budgetary constraint. However, the RtB appears to offer a cost-effective solution to achieve the goals stipulated in the Basin Plan. Any funding shortfall is likely to be relatively minor when compared to the funding available for the SRUWIP. (next section) and policy makers would be advised to follow the PC's (2010) recommendation to transfer more funds to the RtB program, if needed.

How the CEWO uses its water to meet environmental watering plans and improve water quality will have direct impacts on the river flow. If the demand patterns between irrigators and the environment diverge, then conveyance patterns may alter, eroding potential gains from the CEWO and irrigators piggybacking on each other's water supply, resulting in changes to environmental, social and economic outcomes.

The area constraints on horticultural expansion may underestimate the true value of groundwater now and into the future. When the solutions are compared in Table 8-9, the area contracting out of horticulture being produced with surface water is identical to the expansion in the horticulture area irrigated with groundwater. The economic benefits from improving water quality for production have not been examined.

Debate has suggested that the second round losses associated with selling water would exceed any first round gain. However, Dixon et al. (2011) found that the wealth transfer to irrigators from the RtB has negated any real losses in the second round. If anything, a reduction in the number of private property rights, should increase their value and allow farm equity to increase (Section 10.2.2). This equity then provides the impetus for irrigators to invest in water saving technology, creating further wealth and this is where the RtB and the SRWUIP diverge in three critical features.

8.7 **Summary**

These results illustrate the benefits of modeling the conjunctive changes in property rights within a state-contingent framework to understand how private individuals adapt in response to a policy change to understand changes in welfare (Randall 1975). The state-contingent approach helps illustrate the ability of decision makers to adapt to climate and policy signals by changing inputs to produce state described outputs.

The analysis suggests that the $3.1 billion RtB program could achieve the stated Basin Plan's objectives under a changing climate. Even with the limits of the model, a net wealth transfer to irrigators is evident. This wealth transfer could be justified from a social point of view as the Basin Plan may have second round impacts that this analysis can not examine.

However, the correct optimization question the Basin Plan should have asked was,…

> …what optimal bundle of entitlements could achieve the social objectives at least cost under increasing climatic uncertainty?

As the climate continues to change, the future reliability of alternative surface water entitlements will be discounted further and the owners of the golden groundwater receive increasing asset values. This was a deliberate decision to illustrate that decision makers determined that groundwater resources are underutilized. Under a changing climate, the recharge rates to groundwater will reduce, leading to revised reliability rates in the long run, creating a call for further compensation. Until then a key adoption response for irrigators will be to take advantage of the ability to transfer surface entitlements in groundwater assets as allowed by the Basin Plan. This could create an over-exploitation of groundwater resources. Thus, as the Basin Plan directly tackles the visible consequences of over-allocated surface water by restoring surface flows, it may be creating externalities within aquifers (MacDonald and Young, 2001).

9. OPTIONS FOR RESTORING THE BALANCE: SRWUIP[78]

9.1 Introduction

By 2050, up to 3.9 billion people globally are expected to reside within river basins affected by severe water stress and supply scarcity (OECD 2012). Scarcity drives change, and consequently agricultural water within many of these basins has been targeted for reallocation to achieve multiple water use objectives (Saleth, Dinar & Frisbie 2011). Sustainable water use that maintains both agricultural production and the biophysical environment involves a complex trade-off between economic, social-cultural and ecological systems (Chiesura & de Groot 2003). One such example of complex economic, social and ecological water demand trade-offs can be found in Australia's Murray–Darling Basin (MDB). This trade-off relationship has motivated an implementation of costly and contentious intervention strategies to reallocate water from economic (e.g. irrigated agriculture) to ecological (e.g. basin river flow) and social uses. Major MDB intervention approaches involve: (i) market purchase of agricultural water rights through an AUD$3.1 billion program known as Restoring the Balance (RtB); and (ii) off-farm storage/delivery infrastructure upgrades and on-farm irrigation technical efficiency improvements through an AUD$5.8 billion program known as Sustainable Rural Water Use and Infrastructure [Program (SRWUIP)] (Crase & O'Keefe 2009).[79] A target reallocation figure of 2750GL from these intervention programs by 2019 was established through a Basin-wide Plan, inclusive of a minimum 650GL/pa total flow to the River Murray mouth at the Coorong

[78] The following section has been published as.

> Adamson, D & Loch, A 2104, 'Possible negative sustainability impacts from 'gold-plating' infrastructure', Agricultural Water Management, vol. 145 (November), pp 134-44, dx.doi.org/10.1016/j.agwat.2013.09.022

This section is presented as published, except for sections 9.3 to 9.6 which have been altered to discuss the modeling sections in greater detail and consistency with Section 8. In addition the section has also been edited for consistency with the rest of the thesis (e.g. SRWUI is now SRWUIP) and links to other parts of the thesis have been added. This results section has also been expanded.

[79] For the purposes of this section, we apply a definition of water use efficiency consistent with Perry (2011), which differentiates between total water use efficiency (i.e. production yield per unit of total water used) and irrigation water use efficiency (i.e. production yield per unit of irrigation water applied). Herein, the concept of technical efficiency is consistent with the total water use efficiency definition above.

(Murray-Darling Basin Authority (MDBA) 2012c)[80]. Recently, a further AUD$1.7 billion was committed to purchasing additional water rights and addressing water delivery constraints in the MDB (DSEWPC 2013). Consequently, reallocation targets for environmental outcomes have increased by 450–3200GL and the completion timeframe by five years to 2024.

These intervention programs constitute a transfer of public funds to purchase water from irrigators and subsidized capital payments to upgrade infrastructure owned by both on-farm and off-farm operators. Of the two intervention programs, SRWUIP represents the larger proportion of funding commitment (68%). However, water reallocation from this program may be limited to 40% of the 3200GL target if historic MDB water saving outcomes can be maintained[81]. As previous policy has divided water savings equally between irrigation and environmental uses, the total water reallocation from infrastructure projects may be as low as 20% of environmental needs. Further, climate change is predicted to reduce MDB surface water availability between 9% (northern MDB) and 13% (southern MDB) under the median 2030 scenario (CSIRO 2008). If accurate, this has important implications for future water saving outcomes from any executed SRWUIP projects between now and 2024. Finally, the MDB experiences high seasonal variability in surface water runoff into storage and delivery systems (Connor et al. 2012), which must factor into the environmental manager's capacity to deliver environmental objectives across a temporal scale. The uncertainties related to the SRWUIP include water returned from capital works, future climate change impacts and MDB seasonal inflow variability; all of which require flexible water management arrangements to achieve the objectives listed in the Murray-Darling Basin Plan (Basin Plan). The Basin Plan's environmental flow objectives include providing habitat refugia or rejuvenation, sediment or nutrient flushing from the system, and ephemeral connections between spatially diverse species

[80] The Coorong, located near the mouth of the River Murray in South Australia, is an iconic National Park and wetland environmental area which has been identified as a key bird-breeding and species habitat management site in the Basin Plan.

[81] The Living Murray (TLM) program invested AUD$1 billion in purchasing water and (predominantly) infrastructure upgrade projects between 2004 and 2009 to generate 225GL of water savings from technical efficiency improvements (MDBA 2009a). These savings were divided equally between agricultural, environmental and urban uses (Quiggin 2012). With no discount factor—an unlikely outcome given an expected diminishing availability of suitable infrastructure investment projects over time (Crase & O'Keefe 2009)—a further AUD$6 billion investment could generate ~6 × 225 = 1350GL water savings; or 40% of the reallocation objective. Water recovered via TLM does not contribute in any way towards meeting the current Basin Plan target.

populations while maintaining low levels of salinity (Connor et al., 2013). Investing in fixed capital projects across the MDB may therefore be inconsistent with a flexible management approach to counter the inherent variability and uncertainty associated with future flow patterns.

The size of the budget allocated to the Basin Plan requires careful scrutiny to justify public expenditure. This section reviews the SRWUIP program objectives and models the impacts subsidizing water-use efficiency could have for all water users under current and future climate outcomes. The technical efficiency gain implications are demonstrated using a modified version of the state-contingent MDB model developed by Adamson, Mallawaarachchi and Quiggin (2009). This model can also highlight the differences between variability and climate change within the basin to allow for proactive water user responses to environmental stimuli. Qureshi et al. (2010) provide a useful base examination of the interaction between MDB intervention approaches and return flow outcomes.

This analysis expands that study in three ways. First, a full-Basin model is optimized rather than focusing on a single-catchment example. Second, while the two studies share similar state of nature constraints, this study considers future risk and adaptation to both climate change and extended drought conditions. Third, where Qureshi et al. concentrate on return flow impacts from intervention, this section assesses capital work’s contributions towards achieving MDB Plan objectives (environmental, social and economic) to determine the net economic return from incentivized capital investments. Results suggest that increasing farm technical efficiency via capital investment may encourage production systems with reduced adaptive capacity to future water scarcity, thus exposing prevailing irrigation capital to unacceptable risk. Further, the modeling suggests that rather than freeing water for environmental use, the proposed technical efficiency investment creates second-best options for the MDB environment if changes to return flow are ignored. Finally, during climate change or drought-induced water scarcity, this approach results in significant reductions in the water supply available to achieve environmental, social and economic outcomes across the MDB. The remainder of this section outlines: general issues associated with technical efficiency improvement in the MDB; the modified state-contingent MDB model and its application in this context; results from the modeling process; and implications for water managers. This section concludes that federal basin water managers at multiple governance scales should avoid reallocation policy options that reduce the flexibility of managers to respond to the inherent variability and uncertainty associated with their systems.

9.2 **Technical Efficiency Issues**

The reallocation of water resources to the environment via investment in on-farm capital is based on an assumption of technical efficiency gains. In this paper, technical efficiency is expressed as both a reduction in the total volume of water required to produce (at least) similar original technology outputs, and a reduction in the rate of return flows (Cummins & Watson 2012). Irrigation water is applied to support plant growth and yield. The difference between applied water and plant uptake (return flow) then contributes water back into the hydrological system as irrigation runoff, seepage or evaporation. These return flows subsequently provide water for downstream water rights (Nieuwoudt & Armitage 2004). Thus, more efficient water use may result in reduced irrigation water use as well as less ‘excess’ water availability as return flows to the hydrological system (Grafton & Hussey 2007).

Negative impacts from reduced return flows include less surface water runoff and groundwater recharge (Young 2010) water quality impacts from increased pollutants (e.g. salt or phosphate) or turbidity (Grafton & Hussey 2007), and magnified consumptive irrigation use (Connell & Grafton 2008) reducing water for the environment. Extended drought, drainage collection improvements and altered on-farm water use practices have reduced MDB return flows since the early 1990s (URS Australia 2010). Return flow reductions from changed water use practices to manage variable water supply conditions under climate change are also reported by Connor *et al.* (2012).

The technical efficiency impacts explored herein are best highlighted through example. Where efficiency gain is expressed as both a reduction in the volume of water required to produce (at least) similar original technology outputs, and a reduction in the rate of return flows (Cummins & Watson 2012). Figure 9-1 illustrates efficiency gains for a perennial crop and follows notation from Section 3. Here the original production function PF (F(x) generated an output per hectare Z from water use WU. If more capital resources are invested, a new production function generates Z from a reduced water volume WU'. For simplicity it is assumed that neither the operational or maintenance costs increase. Under drought (climate change) conditions the available water will decrease proportionally for each production function to WUd/WUd' such that the reduction is equivalent ($WU - WUd = WU' - WUd'$). Farm output also falls from Z to $/Zd'$, where $Zd' < Zd$.

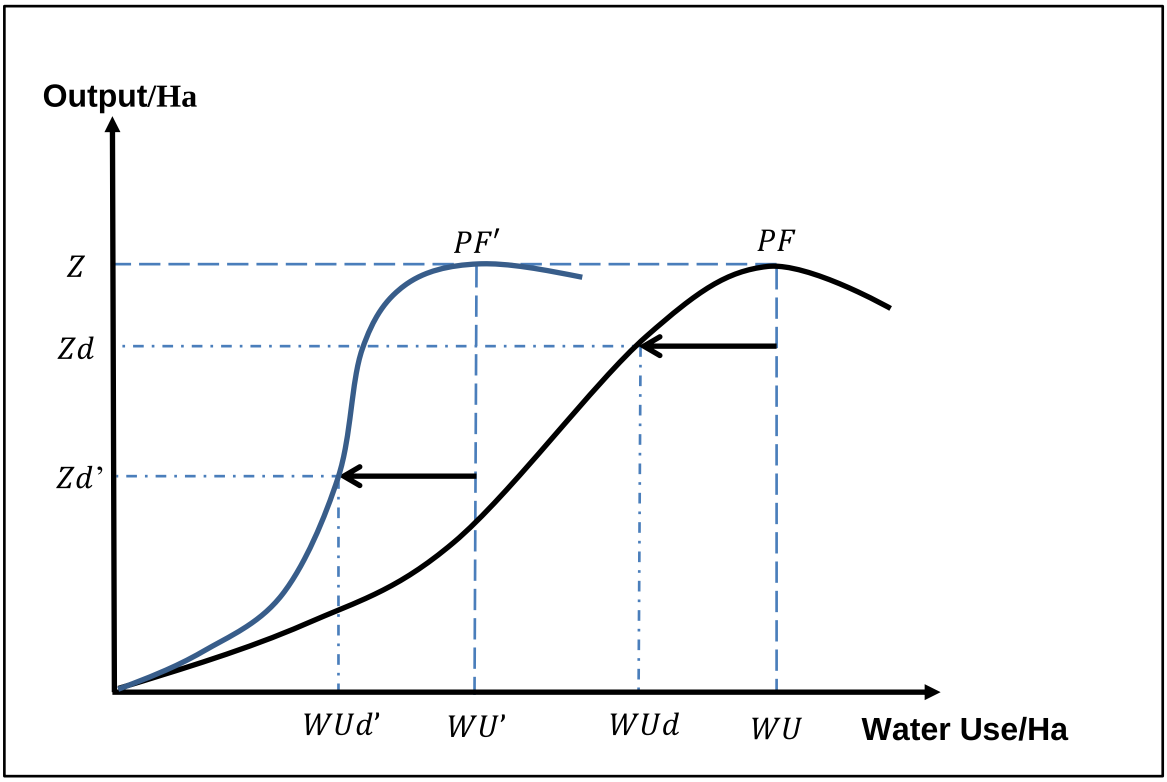


Figure 9-1 On-Farm Water Efficiency Gains

During drought supply conditions we assume all saved water from capital transformation has been applied to perennial horticulture production, resulting in a higher capital level exposure to risk than in the original production function context. Further, where the capital transformation has not increased water supply security, or where the water savings are not used to improve flexibility in farm risk management, then subsequent droughts will result in additional negative capital returns (e.g. the perennial crop asset may be lost). Young et al. (2002) suggest that, over 20 years, water efficiency savings following capital transformation could reduce net (return) flows by as much as 723GL per annum—or 23% of reallocation objectives under the 3,200GL target. Climate change could further reduce return flows in the southern MDB. Quantifying the impacts of changes to land and water use, and the subsequent return flow implications under inherent basin water supply uncertainties, motivates our application of a modified state-contingent model.

9.3 **Modeling the SRWUIP**

The SRWUIP analysis aimed to follow the RtB approach (Section 8), of examining how the SCA model (Section 6) could be used to represent how the SRWIUP could influence irrigator's profit maximizing behavior subject to the Basin Plan objectives and the cost constraints of the SRWUIP. However, after numerous attempts this approach had to be abandoned as no feasible solution could be found and these infeasibility problems are discussed in the results (Section 9.6). To obtain a feasible optimization solution for the SRWUIP both the model and approach were altered as follows.

First, severe restrictions were placed on how the SRWUIP program operated, including: restricting the SRWUIP to only spend funds in the Southern Murray-Darling Basin (SMDB); SRWUIP funding could only be used by horticultural producers; and the SRWUIP had to obtain only 971GL for the Commonwealth Environmental Water Office (CEWO). Second, a new set of perennial state-contingent production systems were developed to represent how the SRWUIP program altered: water-use requirements, capital costs; and variable costs. Third, irrigator behavior towards subsidized capital investment was represented by changing prior land use constraints on perennial producers. Fourth, the water reflow equations were modified to represent the difference between existing water-use technology and the new subsidized water-use technology. Fifth, additional constraints were introduced to ensure that both the SRWUIP and the Basin Plan objectives were obtained.

9.3.1 Placing Limits on the SRWUIP

After extensive testing, the SRWUIP has been limited to obtain the 971 GL of water from the southern connected system. This SRWUIP target value is then the summation of the Sustainable Diversion Limit (SDL) targets to be obtained from all southern trading zones (Section 7.3.2) (i.e. 971GL = Southern New South Wales (NSW) (462.9GL) + Victoria (VIC) (425.3GL) + South Australia (82.8GL) trading zones in Table 7-5). This approach then provided the SRWUIP with the flexibility it required to obtain water for the environment at least cost across regions. It is assumed that all other water required by the CEWO comes from the RtB but to prevent any signals from the RtB entering the model, no prices have been attached to the transfer of property rights to the CEWO.

9.3.2 New State-Contingent Production Systems

Due to a lack of published data about the expected on-farm water-use efficiency gains, it was assumed that the new capital intensive horticultural crops would experience a net reduction in water use of 20-30% depending on their existing technology settings (Table 9-1). In this case seven new horticultural commodities were developed $x = (24 \text{ to } 30)$. This assumption that SRWUIP funding is only allocated to horticultural crops, allows the model to examine if capital subsidies, could encourage irrigators to ignore existing drought management strategies. The horticultural production systems are divided into six perennial production systems $x = (24 \text{ to } 29)$ and an annual vegetable crop. The annual vegetable crop is described in Section 7.7.1, and allows it provides the opportunity for the irrigator not to irrigate in a drought year.

The following assumptions have been made for the SRWUIP program. Only 50% of the water efficiency gained from capital expenditure goes to the environment. A total budget of $7.6 billion exists (MDBA 2012c) to recover 971GL and the program only occurs in the Southern Basin. This then provides an annuity per megalitre (ML) of $367 at 9% over a 20 year period. By assuming that the capital is subsidized by the total volume of water returned to the environment per hectare, the reduced capital and by commodity by catchment is determined. The reduction in variable costs is determined by the total water efficiency gain multiplied by the price of water set at $25/ML as consistent with the model.

9.3.3 Modeling Irrigator Behavior to Subsidized Capital

The Base scenario described below, follows the same rules for horticulture and total land use as described in Equation 6-12 and Equation 6-13. However, this constraint was relaxed in the SRWUIP scenarios (Section 9.5) to deliberately illustrate perverse policy outcomes of how cheap capital could alter investment patterns. In this case, the subsidized production systems can expand into the total area irrigated (Equation 9-2) and expansion of unsubsidized, old horticultural technology, is still restrained by Equation 9-1.

$$L_k x_{k,x(1\ldots7)} \leq 1.5 L_k m_{(1\ldots7)}$$ **Equation 9-1**

$$L_k x_{k,x(1\ldots22,24\ldots30)} = 2 L_k m_{(1\ldots16)}$$ **Equation 9-2**

9.3.4 Modeling Changes in Reflow

Irrigation returns flows (wr) are one of the parameters required to determine water flow within the SCA model (Equation 6-14). As stated in Section 6.7.2, wr is determined by a s defined reflow variable for each production system (x_k) based on the technology used (-L or –H). The separation of the state-contingent production systems into those produced with and without SRWUIP funding, then allowed for the reflow variables used by $x_{k,s}$ to be altered to represent changed reflow rates due to subsidized technology. This approach then provided the capacity to model the spatial impacts of SRWUIP investment on water flow without having to modify Equation 6-14.

9.3.5 Basin Plan Objectives

However, to model the Basin Plan, Equation 8 had to be transformed into Equations 13 to 17 to model both the specified catchment and trading region SDL (Table 7-5). As discussed in Section 7.1, of the two defined unconnected catchments (MDBA 2011e), only the Lachlan (k = 9) is included within the model. These equations allow irrigation water can to be carried over between states of nature by only requiring water on average to equal the specified SDL.

$$\sum w^k \pi_s \leq \sum SurfaceSDL^k \qquad \textbf{Equation 9-3}$$

$$\sum w^{NTV} \pi_s \leq 143GL \qquad \textbf{Equation 9-4}$$

$$\sum w^{STV} \pi_s \leq 425.3GL \qquad \textbf{Equation 9-5}$$

$$\sum w^{STN} \pi_s \leq 462.9GL \qquad \textbf{Equation 9-6}$$

$$\sum w^{STS} \pi_s \leq 82.8GL \qquad \textbf{Equation 9-7}$$

$$\sum w^{STA} \pi_s \leq 450GL \qquad \textbf{Equation 9-8}$$

Symbol:	Definition:
$SurfaceSDL$	Total volume of surface water allowed for irrigation use
NTV	Water trading zones in the northern catchments ($k\ = 1 \ldots 8$)
STN	Water trading zones in the southern New South Wales (NSW) catchments ($k\ = 10, 12, 14, 16, 18$)
STS	The water trading zone in South Australia (SA)($k = 19$)
STV	Water trading zones in Victoria (VIC) ($k = 11, 13, 15, 17$)
STA	Water trading zones in all southern catchments ($k = 10 \ldots 19$)

For the SRWUIP program Equation 9-9 then replaces Equation 9-5 to Equation 9-7 to allow the model to find the best places within the southern connected system to undertake capital works to get 971GL for the environment.

$$\sum w^{CTZ} \pi_s \ = \ 971GL \qquad \textbf{Equation 9-9}$$

Where CTZ is the water from capital programs in southern trading zones ($k = 10 \ldots 19$).

Equation 9-9 can then record the water gained from investing in water-use efficient technology and the equation retains all water saved in the river. For example, each Ha of Citrus-H produced with SRWUIP technology uses 2.3 ML less water than Citrus-H produced with existing technology (Table 9-1), which then provides 1.15ML for the environment (i.e. 50% of 2.3 = 1.15ML). However, this approach then treats all environmental water as improvements in the rivers base flow and does not assign the environmental water gained from the SRWUIP with defined property rights (see Section 9.6.4 for a discussion on this assumption).

Another limitation in the approach is that the model considers that all water diverted is used on farm. The model therefore cannot track conveyance losses in built capital infrastructure.

9.4 Data Used in this Analysis

The data used in this analysis for SDL, climate change, and all production systems produced without subsidized capital can be found in Section 7. The data for the seven SRWUIP subsidized horticultural production systems developed are detailed in Table 9-1.

Table 9-1 How Capital Investment has Been Modeled to Influence Water Use, Return Flow Rates and Subsidized Capital Expenditure in the Murrumbidgee Only

X	Production System Name	Reduction in Water Requirements			Return flow Rates			Reduction in Capital
		Drought	Normal	Wet	Drought	Normal	Wet	
$x24$	**Citrus-H**	2.3	2.3	2.7	0.05	0.15	0.15	$828
$x25$	**Citrus-L**	2.0	2.0	2.4	0.05	0.15	0.15	$736
$x26$	**Grapes**	1.8	1.8	2.2	0.05	0.15	0.15	$677
$x27$	**Stone Fruit-H**	0.9	0.9	1.1	0.05	0.15	0.15	$331
$x28$	**Stone Fruit-L**	1.3	1.3	1.5	0.05	0.15	0.15	$474
$x29$	**Pome Fruit**	2.1	2.1	2.5	0.05	0.15	0.15	$773
$x30$	**Vegetables**	0.0	2.5	1.8	0.05	0.15	0.15	$904

Note: Half of the water reduction is estimated to go to the environment by state of nature
The reduction in water costs is reflected in the changes to variable costs under constant $/ML

9.5 Scenarios

The scenarios listed in Table 9-2, are used to analyze the outcomes from investing in water use efficiency to obtain 971GL of water for the environment, compared to simply removing the water away from irrigators. The Base scenario assumes that the water is simply taken away from irrigators without compensation. The WRF-100 scenario assumes that reflow rates do not change under increased efficiency gains and the two WRF-50 scenario assumes that reflow rates halve under increased efficiency. By comparing WRF-100 to the two WRF-50 scenarios, impacts on return flows and downstream users can be examined from subsidizing in water-use efficient technology. The WRF-50 *ex-ante* and the WRF-50 *ex-post* scenarios provide the difference between decision makers being unaware or aware of how a reduced reflow rates could alter the outcome for all downstream water users and investment s. The climate change (CC) scenarios are both *ex-ante* for the 450 Avg Climate shock in 2050 and 2100. These analyses examine what would occur if both a reflow reduction and climate change occurred after the subsidized investments were made. The Droughts scenario examines a new optimal strategy for strategically investing in the SRWUIP with perfect knowledge that droughts will become more frequent in the future. The increased frequency of the drought state occurring is identified in the fourth column and is consistent with Section 8.

Table 9-2 Model Runs

Model	Intervention	Return Flow	State probability	Climate assumption
Base	Full trade	100%	(0.5,0.2,0.3)	Current
WRF-100	Capital works	100%	(0.5,0.2,0.3)	Current
WRF-50 *ex-ante*	Capital works	50%	(0.5,0.2,0.3)	Current
WRF-50 *ex-post*	Capital works	50%	(0.5,0.2,0.3)	Current
2050 CC scenario	Capital works	50%	(0.5,0.2,0.3)	450GL average, 2050
2100 CC scenario	Capital works	50%	(0.5,0.2,0.3)	450GL average, 2100
Droughts	Capital works	50%	(0.5,0.3,0.2)	Current

9.6 Results

The Base model assumes what would occur if the SDL was achieved by simply trading the water away from irrigators. All other runs examine the SRWUIP and assume that 971GL of water must come from water savings via capital works. The Base scenario provide sufficient water to meet all defined objectives of the Basin Plan by using 10,127 GL of water to irrigate 1.8 million Ha of land. The Base model would generate average returns of $2.4 billion and this would require farmers repaying $1,674 million per annum on capital investments. On average, Adelaide's water quality is expected to be 282EC and the Coorong would receive 5,546 GL of water. Flows to the Coorong are expected to decrease to 1,164 GL in a drought state of nature (Table 9-3).

The WRF-100 results provided Coorong flows of 867GL under drought conditions while salinity was maintained at 308EC, meeting important constraints. By comparison, in the model where it was known that capital works would result in 50% return flow reductions (WRF-50 *ex-post*) constraints were still able to be met. That is, Coorong flows of 650GL were achieved in drought conditions with a moderate increase in salinity (348EC); providing a feasible outcome from the capital works program (see italicized Coorong flow volumes in Table 9-3). In the normal state, agricultural water use remained reasonably consistent between the Base and WRF-100/WRF-50 (*ex-post*) models, but economic returns increased dramatically (from $2,436 to ~$7,760 million) as the subsidization of capital investment transformed the southern Basin towards increased production of citrus and grape perennials. This transformation naturally involved corresponding increases in farm capital exposure to risk under different states of nature. However, to achieve this increased income the annual cost of capital would need to be $5,755 million.

Table 9-3 Summary Results from Model Runs

Model	Normal water use (GL)	Normal Coorong flows (GL)	*Drought Coorong flows (GL)*	Normal Salinity (EC)	Normal $ returns ($million)	Area under production ('000 Ha)	Annual Capital Repayments ($'m)
Base	10,127	5,546	*1,164*	282	$2,436	1,800	$1,674
WRF-100	10,120	5,565	*867*	243	$7,762	1,269	$5,755
WRF-50 (*ex-ante)*		4,841	*582*	277			
WRF-50 (*ex-post)*	10,133	4,832	*650*	280	$7,763	1,269	$5,756
2050 CC scenario		2,524	*0*	474			
2100 CC scenario		2,374	*0*	497			
Droughts	11,365	3,894	*650*	353	$8,336	1,348	$6,109

Note: Full outcome sets were not always calculated for each model where they involved minor alterations to previous runs (e.g. 2050 CC scenario effects based on WRF-50 ex post). This accounts for any missing values above.

The resilience of the optimized solutions was testing by examining what could occur to capital investments and environmental gains from a changing climate. The CC represents the 450 Avg Climate scenario in 2050 and 2100 (i.e. 2050 CC and 2100 CC, respectively). While 'Droughts' examines the impact on water resources from an increased frequency of the drought state occurring.

Although not optimized (*ex-ante)*, the models showed decreasing return flows in northern Basin catchments in normal and wet states, and large southern Basin catchment return flow reductions in the drought state of nature. In both models Coorong flows are reduced to zero, and salinity impacts range between 1,750EC (2050 CC) and 2,371EC (2100 CC). This suggests that any early environmental benefits derived from a MDB capital works program could be entirely undone by 2100 under climate change impacts. It also suggests a significant requirement for future MDB structural adjustment under a capital works intervention approach.

An increased frequency in drought states, encourages land use to increase across the Basin. Setting return flows at 50%, allows an additional 492GL of water use during the drought state and an additional 79,000 hectares of land is irrigated. In this case, southern Basin production mainly transforms toward annual vegetable crops (Table 9-4). This then provides the capacity for irrigators to adapt to drought conditions. However, in line with our technical efficiency discussion above, perennial crop production also decreases, suggesting negative capital returns for the Basin as a whole. Overall the model estimates an increase in economic returns under the drought state; rising from $957 million (Base) to $4,935 million (Drought). Notably, the annual capital repayment required to achieve this needs to increase to $6,109 million.

9.6.1 Implications for Water Managers

The capital works scenarios performed according to *a priori* expectations of water user behavior, within the context of severely relaxed Basin constraint parameters. Irrigators adopt subsidized capital works readily and adjust their water and land use to accommodate changed availability. However, this clearly has a number of implications for irrigators, water managers and projected MDB governance arrangements. Our findings indicate that full agricultural water reduction requirements cannot be achieved through capital works models, particularly in southern MDB catchments without significant relaxation of existing flow, trade and zone constraints. The use of capital works as a policy instrument appears to: (i) expose agricultural water users to increased economic risk under production transformations; (ii) decrease social wealth via large public to private transfers to achieve capital investment (relative to Base trade model results); and (iii) where capital investment results in return flow reductions, undermine Basin Plan environmental flow objectives. We detail each of these in turn.

9.6.2 Production Transformation

Generally, a public subsidization of private on-farm infrastructure will lead to suboptimal allocation of resources, with high net social costs. More specifically in the MDB, any transformation of production towards perennial cropping in response to subsidized capital works programs, possibly as a consequence of perceived water supply increases from efficiency, may drive a number of additional specific perverse outcomes. For example, if annual cropping production shifts towards higher rates of perennial production, reduced non-planting during scarcity will decrease future water flexibility and increase the need for water market allocation purchasing (Wheeler, Zuo & Bjornlund 2013). Further, although some irrigators improve their reliability of supply via the transformation of lower security licenses (e.g. general security licenses in New South Wales) into high security licenses, overall the reliability of water supply will not be improved via capital works. During a return to reduced supply conditions, increased on-farm capital investment will raise perennial irrigator exposure in the form of subsidized (public) or individual (private) risk. Where irrigators more generally choose to expand their irrigated cropping area in response to subsidized capital investment (i.e. shifts from IA to IA' in Figure 9-2), such that all 'saved' water is applied on-farm, they will also be exposed to increased levels of private risk during adverse states of nature.

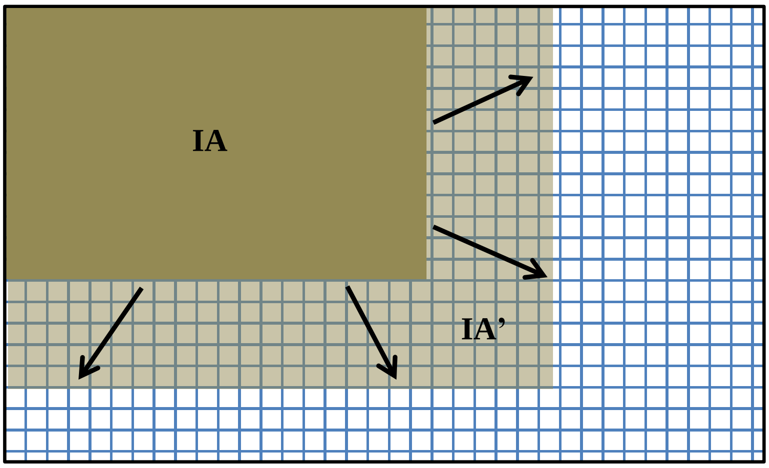


Figure 9-2 Possible Efficiency Gain Effects on Total Irrigated Area (IA)

The SRWUIP allows the Jevons Paradox (Alcott 2005; Jevons 1865) or rebound effect (Gómez Gómez, Blanco & Dionisio 2013; Gutierrez-Martin & Gómez Gómez 2011) in water-use efficiency to occur where instead of environmental gains (Huffaker & Whittlesey 2003), the demand for water increases and the area irrigated increases at the expense of national welfare (Scheierling 2011; Scheierling, Young & Cardon 2006). Unlike other studies, the combination of the SDL and the SRUIP obtaining a share of the water-use efficiency gain then helped curb the area expansion. However, this analysis expects up to 1.37 million Ha to be upgraded (Table 9-4) and in this case, as Connell (2007) discusses, the SRWUIP clearly represents a policy decision makers dream about production and not the environment.

One unintended consequence of dreaming about production is that the SRWUIP provides sufficient incentives to transform industries. In this case, if irrigators on mass converted annual production systems into perennial systems, then the past drought adaption of purchasing water from annual producers to keep perennials alive will be lost.

Table 9-4 Area Irrigated (‘000Ha)

	Subsidized			Non-Subsidized					TOTAL	
	Citrus	**Grapes**	**Veg**	**Hort**	**Cotton**	**Rice**	**Cereals**	**Dairy**	***Hort***	**TOTAL**
Base				201	792	420	33	208	*201*	**1,654**
WRF-100	402	867		31	792	57			*1,300*	**2,149**
WRF-50 (*Ex-post*), CC 2050 & 2100	402	867		31	792	59			*1,300*	**2,151**
Droughts	364	790	193	31	704	73	90	4	*1,379*	**2,249**

This increased exposure to risk is underlined in the climate change and drought models, where any future reductions in water supply will logically need to be borne by irrigators, the environment and society as a consequence of the capital works subsidy incentives. An example helps illustrate the link between efficiency improvements from capital works and possible perverse contributions to environmental flow objectives, Table 9-5.

In this example, a 30% efficiency improvement from the adoption of new technology reduces water use per hectare from 10 ML/Ha to 7 ML/Ha. Originally, return flows contributed 3ML/Ha in normal and wet states of nature, and 1ML/Ha in the drought. Savings generated from capital works lower return flows by 50%, but since water use is also reduced, this has a proportional impact on return flows. Consequently, return flows fall to 1.05ML/Ha in the normal and wet states, and 0.35ML/Ha in drought. If savings are shared on a proportional basis between irrigators and the environment then irrigators effectively receive 1.5ML/Ha for existing or increased use. This use contributes to return flows, and it does so at a reduced rate, resulting in 0.22ML/Ha relative environmental flow reductions during normal and wet states of nature. Note that in the drought state environmental return flow increases by 0.93ML/Ha as a consequence of the capital works, which may be considered positive. It should be noted that some irrigators might choose not to utilize their saved water in this way, electing instead to retain that water as a buffer for risk-management purposes, and thereby decrease their risk exposure (Wheeler & Cheesman 2013). However, if MDB environmental watering plan objectives seek to mimic natural conditions, then increased flows during dry periods may be at odds with management goals. This strategy of preserving water to minimize risk during dry periods is evident in the drought model where, instead of investing all subsidized capital into perennial crops that require water in all states of nature (see Table 9-1), investment in vegetables occurs (i.e. 193,000Ha, Table 9-6) where water is not needed in the drought state of nature. If irrigators are then not utilizing their water resources it may suggest that the recent drought may have left a permanent transition towards greater flexibility in the management systems.

Table 9-5 Water Efficiency Impacts on Environmental Flow

	Existing technology	New technology
Water use/Ha	10ML	7ML (= 3ML saving)
Return flows by state (normal, drought, wet)	100% return flows (0.3, 0.1, 0.3)	50% return flow (0.15, 0.05, 0.15)
Return flow outcomes	3.0ML, 1.0ML, 3.0ML	1.05ML, 0.35ML, 1.05ML (extra water)
Water saving split (50/50)		1.50ML (increased use)
Increased farm water use		2.55ML, 1.85ML, 2.55ML
Environmental supply	3.0ML, 1.0ML, 3.0ML	2.55 + (0.15*1.5) = -2.78, 1.85 + (0.05*1.5) = 1.93, 2.55 + (0.15*1.5) = -2.78
Difference:	3.0ML-2.78ML=-**0.22ML(N)**, 1.0ML+1.93=**0.93ML(D)**, 3ML-2.78ML=-**0.22ML(W)**	

Table 9-6 Change in Capital Investment by Enterprise, Comparing Climate Change

Production System Name	WRF-100, 2500 CC, 2100 CC	Drought Run
Citrus-H	402	366
Citrus-L		
Grapes	867	790
Stone Fruit-H		
Stone Fruit-L		
Pome Fruit		
Vegetables		193

9.6.3 Wealth Transfer Misallocation

The SRWUIP attempts to prevent the ‘Swiss cheese’ impacts by rewarding inefficient producers and locking capital into existing production areas. Thus the SRWUIP appears to have fallen into the methodological trap noted by Randall (1975). Randall argued that when the returns from the existing allocation of property rights are used in an analysis, a bias towards the status-quo occurs, preventing increased welfare.

Under the SRWUIP program a proportion of public expenditure will also be allocated to owners of large scale capital (i.e. those that manage diversions before allocating water to farmers). The limited public data on proposed MDB capital works prevents a breakdown on which group (i.e. irrigators or irrigation infrastructure operators (IIOs)) in the MDB would receive the funding. This prevents a clear understanding of whether rent seeking is occurring and, if so, whether the wealth transfer is equalized between the groups. However, it is possible that water savings are predominantly created by conveyance system improvements, not on-farm efficiencies. Therefore farm water use may not decrease (Table 9-2).[82]

Thus, although the policy intent may be to allocate wealth transfers across irrigators, IIOs will also be obtaining subsidies to provide environment ‘gains’. It is possible that once implemented, the SRWUIP may heavily favor IIOs to provide environmental water allowing for the development of ‘gold-plated’ water infrastructure. As a consequence, irrigators (in particular) and environmental water managers will be adversely impacted through exposure to higher infrastructure operating costs over time. Economically marginal irrigators may be forced to exit sub-systems, thus creating the ‘Swiss Cheese’ impact that the SRWUIP appears to be designed to negate[83].

In addition, the state of nature analysis highlights the importance of considering climate change impacts on capital investments (Kingwell 2006). Future climate trends are expected to place pressure on dryland and irrigated agriculture systems to relocate towards favorable areas. By refurbishing existing IIO infrastructure, the chance for redesigning the irrigation industry for maximum social benefit is ignored. This reallocation

[82] Contrary to the buyback recovery program, capital works creates net debt; whereas Wheeler and Cheesman (2013) show reduction of farm debt via buyback investment.

[83] Assuming no termination charges are applied.

of irrigation assets was witnessed in the results for the 2050 CC and 2100 CC scenarios where irrigated land use trended towards southern catchments. By rewarding the current inefficient owners of capital to remain where they are, results in further wealth transfers towards irrigators and IIOs.

Importantly, these irrigation water delivery schemes were originally public assets, which were increasingly privatized (New South Wales) or corporatized (Victoria) to meet reform requirements (Cummins & Watson 2012). If the economic benefits from water savings were obvious to MDB IIOs, we might expect them to finance capital works investments themselves. Since they are no longer public assets[84], private incentives to invest appear limited and industry privatization no longer enjoys the political support afforded it in previous periods (Sirasoontorn & Quiggin 2007). Questions should therefore be raised about why public investments are being undertaken to 'gold-plate' these assets where economic capital losses are likely in future. Affecting such a substantial public investment (i.e. $7.75 billion) to not achieve Basin Plan outcomes, as suggested in the results, indicates that capital works do not provide an appropriate economic intervention. This contention is detailed further below.

9.6.4 Inconsistency with Basin Plan Environmental Objectives

To maximize the volume of water to be returned to the environment, the SRWUIP must allocate funds towards areas that are highly inefficient in their water use. However, this rewarding of resource wastage via capital subsidy then negates one of the critical aims of the Basin Plan, the liberalization of trade. By subsidizing inefficient producers to take on more debt, this policy instrument then locks land, labor and capital resources back into existing land use patterns, which essentially fails to embrace the concept of maximizing resource rents via trade.

Unlike the RtB which purchased clearly defined property rights from irrigators, the property rights obtained from the SRWUIP are not clear. As Crase and O'Keefe (2009) argue that despite the rhetoric, the SRWUIP will not deliver the projected flows to the environment, due to the scheme being locked into the past history of mistakes including: the misunderstanding of the concepts, hydrology, and scale associated with river basins;

[84] Victoria is the exception as they are owned by the minister and in this case it's a wealth transfer to the Vic government.

questionable ‘rigor’ associated with the predicted benefits; and a lack of clear understanding of which property rights are being purchased. These concerns are well founded as the CEWO notes…

> “…SRWUIP water recovery is reported at the point at which water savings have been received, estimated or agreed in signed project works contracts. Until water transfer contracts have been exchanged however, these figures may be subject to change over time.”[85]

The model results show that, if water recovered for environment benefit is not fully stipulated, the short-term gains of the program will be potentially undone through significant water resource losses; especially via climate change impacts. Importantly, no capital works model is able to achieve the required Basin Plan full trade zone water reduction target. Further, if return flows reduce as a consequence of this investment, then we also jeopardize Basin Plan environmental objectives. This is because return flow reductions diminish supply reliability for downstream users, particularly the environment (Table 9-3). Within a reduced return flow context, failure to fully consider states of nature and climate change in Basin planning may result in over-investment in capital programs, leading to additional diminution of environmental gains from other policy approaches (e.g. buyback).

Finally, if we persist with previous proportional water saving sharing arrangements (50/50), we will likely reduce environmental flows even further. This implies that such arrangements may have to be reviewed to either alter share proportions to account for this imbalance (e.g. 75% environment, 25% irrigation), or scrap proportional sharing arrangements altogether.

Crase, Cooper and Rose (2014) provide an analysis which suggests that SRWUIP funds could be better used to adjust irrigators out of the industry. Their study suggests that VIC irrigators had a preference for having access to reduced termination fees. This may suggest that the termination fees are preventing some irrigators transitioning out of the industry or from having the opportunity to fully engage in the RtB process. So rather than using subsidized capital to trap irrigators back into an activity, they may prefer to leave.

[85] http://www.environment.gov.au/system/files/pages/16cfc337-7c02-4a77-ab57-fb0e8483b58b/files/water-recovered-under-rtb-and-srwuip.pdf

The SRWUIP funds could improve national welfare by reallocating these funds towards providing an exit strategy out of irrigation.

9.6.5 Implications from Model Limitations

Like all models there are limitations in the approach and assumptions. A major limitation is the use of discrete parameters in the optimization solution, which implies perfect knowledge about the future. If the model used stochastic information relating to the state of nature (i.e. total volume of conjunctive water) or the inputs required by state of nature (i.e. how much water is required to produce one hectare of a commodity), then the results would transition towards less area being irrigated and more water being saved to mitigate climatic variability in the drought state of nature and ensuring that the minimum flow and salinity levels are achieved.

At the same time, the use of stochastic descriptions of return flows would also highlight the problems with water scarcity in droughts. Secondly, although providing reasonable estimations of flow and conveyance loss throughout the system, the model is flawed by its scale and scope. By modeling at a catchment management region level, clear information about economic return along political boundaries is provided but political boundaries do not align with hydrological boundaries. Consequently, the data does not necessarily align well with other studies that use the CSIRO sustainable yields data and/or detailed models that are concerned with diversions versus allocations. However, at the same time this simply allows for additional fundamental questions to be asked: are we irrigating in the right areas; should we be irrigating at all; and what are the benefits from trade?

9.7 **Summary**

The intended MDB capital works program is at odds with the Basin Plan objectives in terms of economic, social and environmental outcomes. By subsidizing capital investment, irrigation farmers in the MDB will take the opportunity to modernize their water use arrangements, in turn increasing farm debt levels and reducing their flexibility to future water supply shocks. Further, the process of ‘gold-plating’ MDB irrigation infrastructure will not increase the reliability or security of water assets owned by irrigators or IIOs. This mixture of increasing risk exposure and over-investment in capital works will compound losses under a future return to drought states of nature, or climate change impacts. In that eventuality, irrigators (and IIOs) will: still have to cover the costs of maintaining that capital; and when the face value of entitlements is re-discovered under drought the pressure to meet new use charges and debt liabilities will likely require governments to again act as the final insurer. Capital investments may marginally increase: (i) on-farm water use efficiency; (ii) irrigators' capacity to improve farm viability and sustainability; and (iii) rural structural adjustment to water reforms through regional job creation resulting in reduced short-term political risk. However, there is a potential trade-off associated with return flows that requires greater investigation. These unknowns and increased on-farm efficiency may be exposed under climate change.

Thus, where climate change or drought-induced water scarcity present management issues for federal basin water managers, policy options should encourage flexibly manage inherent variability and uncertainty. Capital works investment policy solutions do not facilitate long-term flexible responses to future scarcity problems.

10. REVIEWING THE HYPOTHESES & CONCULUDING COMMENTS

10.1 Introduction

The 2007 Water Act was designed to ‘restore the balance’ between irrigators and the rest of the society, to improve national welfare. From a theoretical perspective the design of the contraction stage of water reform, utilizes the common property approach to improve welfare. The common property approach occurs as water is transferring water away from irrigators and provided to a ‘public trustee’ who manages the water resources for the benefit of all. This is achieved by, the Murray-Darling Basin Authority (MDBA) who are responsible for developing the Murray-Darling Basin Plan (Basin Plan). The Basin Plan defines the sustainable diversion limits (SDL), which cap the maximum amount of water that irrigators can own. The two metrics of a successful Basin Plan are defined by, an improvement in the ‘quality’ of the resource base and a minimum water flow target.

The change between Current Diversion Limits (CDL) and the SDL is then, the total quantity of common property provided to the Commonwealth Environmental Water Office (CEWO). The CEWO will manage this water in the national interest to improve water quality and achieve the water flow targets. Two alternative strategies have been funded to obtain water for the CEWO: the ‘Restore the Balance’ where property rights are purchased from irrigators; and the Sustainable Rural Water Use and Infrastructure Program (SRWUIP). The SRWUIP subsidizes the adoption of efficient water-use technology and the CEWO shares the water saved with the irrigator.

The economic debate about the Basin Plan has not focused on the economic foundations of the policy. Rather the economic debate has been centralized on: the institutional designs; removing barriers in water markets; exploring the impacts climate change could have on the SDL to critique if the balance will be restored; debating if the trade-offs from moving from the CDL to the SDL are justified; and justifying the cost-effectiveness of the alternative strategies for obtaining the CEWO water. This thesis has not explored the institutional questions but has explored the changes in welfare from the new SDL and alternative strategies for obtaining water for the CEWO. The thesis has also explored the welfare consequences of failing to consider climate change when attempting to implement the Basin Plan.

By using a constrained welfare approach this thesis has been able to define welfare as the economic return from irrigation and the constraints as the institutional goals of the SDL, minimum water flow objectives and a defined upper bound on water quality. Climate change impacts on each of the two implementation strategies have also been explored. The findings presented in Section 8 & 9 are re-examined in light of the hypotheses.

10.2 Discussion

The five hypotheses presented on evaluating if the Basin Plan was a true reflection of the contractionary stage of water reform were:

Ho: by internalizing externalities social welfare will increase;

Ho: the Restoring the Balance (RtB) provides the most efficient way to return water to the environment;

Ho: the change in conjunctive water resources creates wealth;

Ho: the failure to incorporate climate change risks into the Basin Plan solution will reduce long run economic welfare gains; and

Ho: the Basin Plan has some, but not all, characteristics of the contractionary phase of water resource development.

The SCA model of the Murray-Darling Basin (MDB) developed by Adamson, Mallawaarachchi and Quiggin (2007) was used to test the hypotheses. The model was used to determine a constrained welfare maximization solution to: determine an optimal portfolio of water rights for the CEWO; examine the impact increased groundwater supplies could have on future investment patterns; evaluate changes in irrigation investment patterns from subsidizing capital investments in water-use efficiency upgrades; and review how climate change may alter the three above questions.

10.2.1 Did Social Welfare Increase From Internalizing Externalities?

The thesis identified welfare as: the economic return from irrigation activity; water quality; and the volume of water reaching the Coorong wetlands. The analysis suggests that the RtB improves water quality and increases water flowing to the Coorong. However, as the results indicate the environment will not receive a net increase of 3,200GL but rather 2,600GL on average, as underutilized water entitlements may be developed. The reduction in the quantity of surface water owned by irrigators then contracts economic returns by around $416 million, but water quality is expected to improve by 96EC. This change in water and returns suggests that to obtain a 1 EC improvement in water quality, irrigator's economic returns fall by $4.3 million, which is equivalent to the current public cost of the Salinity Interception Schemes (SIS) at $4.5 million per EC. In this case irrigators and not society are paying for the improvements in water quality.

In the case of the SRWUIP, the evidence is less clear. Unlike the RtB evaluation, no feasible solution existed, where the SRWUIP could obtain all the water the CEWO needed, while achieving the Basin Plan's goals. Therefore the SRWUIP must be used in conjunction with the RtB program. The SRWUIP solution for the ERF-50 (*ex-post*) (Table 9-3) does suggest that that environmental welfare increases on average as water quality has improved by 2 EC, and there are sizable economic benefits ($5 billion) for irrigators. It creates a situation where water use has increased and there is less water flowing to the Coorong in a normal state of nature. This outcome of the SRWUIP increasing water use and economic returns, then suggests that policy implementation is still concerned with production and not the environment The SRWUIP results also suggested that the real beneficiaries of the wealth transfer may be irrigation infrastructure operators (IIO). The SRWUIP may leave irrigators investments exposed to climate shocks as they may have high levels of debts, increased fixed and variable costs to access water, and there may be less water available for trade if upgrades are directed towards perennial production systems.

The state contingent analysis (SCA) model cannot determine the second round impacts of water reform. However, Wittwer and Dixon (2013) analyzed the second round impacts of both the RtB and the SRWUIP using the TERM-H_2O CGE model (see Section 1.3) and determined that the SRWUIP (upgrades) provide...

> "…a windfall gain to the MDB regions at the expense of the rest of Australia. Upgrades represent an additional $3.5 billion NPV of funds transferred to the MDB region, meaning that *buyback plus upgrades* outperforms *buyback* only in the MDB region in terms of GDP" (Wittwer & Dixon 2013, p. 416).

Therefore any implementation strategy which is reliant on the SRWIP for obtaining the largest share of environmental water is likely to reduce net welfare gains for the wider community.

10.2.2 Was the RtB more efficient than the SRWUIP for obtaining the CEWO's portfolio?

Since the 2007 Water Act (Commonwealth of Australia 2008) it has been estimated that $13 billion (Vidot 2014) of public funding has been allocated to the contractionary state of water resource development. This thesis has limited the upper bound of the public expenditure as $10.6 billion (based on $3.1 billion for the RtB and $7.5 billion for the SRWUIP, as detailed Section 9.1). This simplistically implies that if all public expenditure was allocated to farmers, then each megalitre (ML) of water returned to the environment would have a social value exceeding $3,300/ML or alternatively each of the Basin's 18,634 irrigation farms would receive nearly $569,000 to forgo a proportion of their water rights.

The results suggest that the RtB could obtain all the water needed to implement the Basin Plan for $3.1 billion or for $969/ML. As the evaluation of the SRWUIP could only find a solution where the SRWIUP would be used to obtain 971 GL of water for the CEWO, then the SRWUIP would need to pay in excess of $8,000/ML. By assuming that the remainder of the water required for the Basin Plan is purchased at the RtB rate ($969/ML), an additional $2.159 billion would be needed, giving an average cost of $3,112/ML by using a joint RtB and SRWUIP approach. In this case, the RtB provides greater efficiency in obtaining the water for the CEWO.

In this analysis, as the alternative costs to recover water are paid to irrigators, this data suggests that a clear pricing signal has been provided to irrigators to embrace the SRWUIP.

10.2.3 Does the Change in Conjunctive Water Resources Create Wealth?

The Basin Plan specifies a surface and groundwater SDL and as the RtB, SDL analysis suggests, the Northern Murray-Darling Basin (NMDB) benefits from selling low security surface water rights to the CEWO and gaining access to highly reliable groundwater. To this effect, irrigators in the NMDB would have access to an additional 450GL of extra water resources and without the addition of new groundwater entitlements, irrigators in the Southern Murray-Darling Basin (SMDB) lose access to 2,010GL of water to irrigate with (Table 8-12). Overall the MDB experiences a contraction in water resources of 10% (Table 8-4) but the combination of greater access to groundwater and returns from selling water to the CEWO allows economic returns in the MDB to increase by 7% (Table 8-5). In the second round, those irrigators who own the water entitlements should gain increased wealth, as the value of water entitlements remaining in a productive capacity is expected to increase (Dixon, Rimmer & Wittwer 2011). Therefore, yes, wealth would increase across the MDB as a whole but some regions in the SMDB will be worse off.

However, a note of caution is required regarding the increased returns from groundwater, as there is no guarantee that irrigators will have access to all or part of the new groundwater entitlements. If the new groundwater entitlements are sold on an open market, other industries (e.g. mining and coal seam gas) or other users may place greater value on owning these resources and may out bid irrigators to purchase the rights. The development and utilization of water by other users may create negative externalities for irrigators (Davis & Hoffer 2012). Due to the complexity in determining sustainable levels of groundwater extraction (Section 4.3.1) and the optimistic assumptions about guaranteed reliability, the results may be misleading. It is possible that in the future both the SDL and reliability of the groundwater resources may need to be revised.

10.2.4 Is Welfare Reduced by Ignoring Climate Change?

The results presented within this thesis are consistent with the findings of Adamson, Mallawaarachchi and Quiggin (2009) where adaption to climate change has the following two patterns. First, the failure (i.e. *ex-ante* scenarios) to incorporate climate change into the decision making framework over allocates investments into perennials and exposes capital to excessive risk. In turn this could increase farm debt as if the demand for water exceeds the capacity of the river to deliver water, then capital investments will be lost (Table 8-11). Second, if decision makers incorporate climate change risk (i.e. *ex-post* scenarios) into their long term planning then structural transformation will occur in the MDB. The results suggest that the greatest transformation to irrigation practices in the MDB will be driven by changes to the variability of water supply (i.e. droughts become more frequent) rather than a mean reduction in water supply (i.e. the 450 Avg Climate Change Scenario). The adoption of flexible and opportunistic irrigating production systems will be favored by irrigators to help minimize the climate change risk posed to capital (Table 9-4). It is this ability of SCA to model strategic behavior responses to risk and uncertainty, by altering inputs to produce a specified output that provides insights into future adaption strategies.

The heterogeneity in temporal and spatial characteristics of future water supplies (Jones et al. 2008) will create uncertainty for the future reliability and values of alternative water property rights. The analysis here assumed that the security of alternative entitlements would remain constant into the future. This approach transferred all climate risk to the residual claimant on the water resources, the unpreserved environmental share. Consequently, the analysis highlighted how climate change impacts on water inflows altering the CEWO's optimal portfolio by structure (i.e. different combinations of rights) and spatial location (Chart 8-5).

Climate change is also anticipated to create a divergence in the value of rights by security between groundwater and surface water entitlements. As the reliability of water assets diverge, an inter and intra-generational wealth transfer occurs between the alternative water right owners. The results suggested that the NMDB will gain wealth from having greater access to more groundwater resources. Future changes to entitlement security could also change the quantity and quality of water in the MDB, furthering changing Australia's welfare.

The subsidization of capital to invest in water-use efficiency not only allows inefficient producers to remain within the irrigation industry but incentivizes producers into increasing the area irrigated. If large-scale landscape transformation occurs primarily into the production of perennial crops, then past drought adaptation strategies may no longer provide the capacity to deal with negative climatic change impacts on water supply. Under climate change, this combination of high debt, increasing fixed and variable prices to access water from 'gold plated' infrastructure, an inability to either pay for (i.e. choke price, Section 2.2) or access water, could result in a debt legacy and ultimately force wide-scale industry exit.

10.2.5 Is the Basin Plan a Contractionary Stage of Water Development?

Table 10-1 compares and contrasts the main features of the three key policy components of the Basin Plan: changes to groundwater; the RtB; and the SRWUIP, against the idealistic characteristics of the fourth stage of water resource development. This information is designed to examine if the signals provided by the key policy components are designed to help facilitate the transition towards the contraction stage of water resources development.

If the SDL for groundwater is correct, then aquifers provide a natural storage solution for water and the social cost for developing these resources are low. This combination of lows costs and increase storage then suggests that the development of sustainable groundwater levels resembles the expansion stage water resource development.

By defining the groundwater SDL, the demand for groundwater should be high due to its reliability and overall this should increase the quantity of water used in the MDB (i.e. expansion stage of water resource development). As groundwater is accessed at the point of use it has been assumed that the costs of upgrading and maintaining the infrastructure are assumed to be the responsibility of the private user. This demand for water and private maintenance of infrastructure are characteristics of the contraction stage of water reform.

The non-convexity for water use still exists but with the SDL being correctly set, no externalities should be associated with its removal from the aquifer (i.e. contraction stage). However, externalities may be generated if, new SDL for groundwater is incorrect or its use creates pollution for other users (i.e. coal seam gas). In summary the development of new groundwater exhibits the characteristics of both the expansion and contraction stage of water resource development.

The RtB provides a clear example of a contractionary stage of water resource development by meeting every idealistic characteristic of the contraction stage. There is a small proviso that if the RtB was used on its own, it is uncertain who would pay (private or public) to upgrade the degraded delivery infrastructure, but with clearer market signals, this cost should be borne by the water user.

Table 10-1 Comparing Key Components of the Basin Plan to the Stages of Water Development

Market Characteristic	Ideal Characteristics of the Contraction Stage	Basin Plan Components		
		Groundwater	**RtB**	**SRWUIP**
Long run supply of impounded water	Inelastic	Elastic in SR	Inelastic	Inelastic
Demand for delivered water	High but stable demand. Elastic at low prices; inelastic at high prices.	High but stable demand. Elastic at low prices; inelastic at high prices. Water use increases.	High but stable demand. Elastic at low prices; inelastic at high prices. Water use decreases.	High, potentially increasing demand in droughts. Elastic at low prices; inelastic at high prices. Water use may increase.
Physical condition of impounded and delivery system	Infrastructure maintained by user.	All infrastructures new and maintained by user.	On-farm infrastructure maintained by user, off-farm unknown	All infrastructure (on and off-farm) new and subsided.
Competition for water between all users	Reallocation reduces competition between all users.	Reallocation of groundwater towards irrigators.	Reallocation reduces competition between all users.	Reallocation reduces competition between all users but not to the extent of the RtB.
Non-Convexity	Yes	Yes	Yes	Yes
Externalities	Reduction in externalities.	No impact on externalities	Reduction in externalities and social costs	Some reduction in externalities but social costs remain high
Social cost of subsiding increased water use	Nil	Nil to very low	Nil	High and rising
Sustainable in the long-run	Yes	Depending on final water user	Yes	No
Component the stage resembles		**It has elements of the expansion and contraction stage**	**Contraction stage**	**It has elements of the expansion and maturity stage**
Resilient in the long run	Yes	Possibly yes	Yes	No

Cummins and Watson (2012) discuss that the Living Murray Initiative was trapped in an incremental step between the third and fourth state of water resource development when attempting to obtain 500 GL of water with water-efficient technology, the SRWUIP has embraced this approach to restore the balance. For the SRWUIP to obtain 1,700GL of water, it is not an incremental step in water reform progress but rather a regression back to a step between the expansion stage and the maturity stage of water reform, all be it with a limit on extraction. The SRWUIP then prevents society from tackling the economic, social and environmental problems with market reform but rather embraces the engineering solution. The subsidization of infrastructure effectively provides almost identical conditions of the maturity stage but with ‘good to new’ infrastructure and perhaps a slight reduction in externalities. The SRWUIP is not a mechanism for the immaculate conception of water but rather the SRWUIP is likely to cannibalize the water gained from the RtB.

Overall, the Basin Plan provides a conflicted stage of water resource development.

10.3 Areas of Further Study

The notion of bounded rationality in modeling to create unawareness (black swans) is discussed within the relationship of curbing the effectiveness of past reform. This thesis has also created its own black swans by the way the: economic problem was conceptualized; subjectivity defined the bounds around data sources, assumption and the choice of analytical programing tools; and from the way scenarios were defined and analyzed. By drawing attention to the key gaps, new future areas of study are revealed. The thesis has discussed a range of limitations during the application of the SCA to evaluate both the SRWUIP and RtB programs, see Section 9.6.5 and 8.6 respectively.

This section limits the discussion towards articulating three issues associated with the analyses presented in this thesis. The first discusses how optimization can create misleading results and why care in the interpretation of these results is required. The second explores how the model in Section 6 could be adapted to utilize stochastic rather than discrete parameters. The third discusses why there is a need to provide an expected value approach of the model described in Section 6.

10.3.1 Conceptual definition

The partial-equilibrium optimization approach used in this thesis examines a resource allocation at a future point time and is not bound by existing allocations of capital, historic investments in irrigation infrastructure, farmers' preferences, forward contracts and other binding policy requirements that decision makers face. By using a profit maximization function, resources are allocated towards a given production system until a binding constraint is realized (e.g. land in one catchment), then resources are allocated towards the next best production system and so on, until one or more binding constraints (e.g. water inputs in Equation 6-5, the river stops flowing Equation 6-7, or Basin Plan requirements Equation 6-8 to Equation 6-10) prevent the allocation of further inputs. Such an approach can lead to an unrealistic reallocation of resources towards a given farming system as the second round impacts on prices driven by an oversupply of output are not considered.

The policy analysis here has compared one theoretically optimal allocation of resources (i.e. CDL analysis) to an adjustment (i.e. Basin Plan). This then internalizes the error between the allocation of resources, *ex-ante* and *ex-post* derived from a change in policy or climate change event. However, the analysis does not provide a guide on how resources would transition from one investment pattern to another. A recursive optimization model could be used to illustrate how temporal transition could occur by states of nature and the state based decisions made through time, but the value of such a model would have to be thoroughly tested. This recursive optimization model should also consider the transaction costs of prior investment strategies.

On reflection, this thesis missed an opportunity by not illustrating the benefits of the SCA model against either a discrete expected value model or a stochastic expected value (EV) model. The only example of direct comparison between the SCA and EV approaches exists and that is by Rasmussen (2006) who compared the approaches to generate production functions. A key feature of the state-contingent approach is, illustrating why and how decision makers respond. The SCA then overcomes the limitations in other approaches to deal with risk and uncertainty as discussed by Keynes (1937) , Rothschild and Stiglitz (1970, 1971), Just and Pope (1978) and Just (2003), who all adding to the argument that...

> “…our understanding [and representation] of the farmers’ decision-making process remains incomplete” (Chavas, Chambers & Pope 2010, p. 370)

The state-contingent approach attempts to gain knowledge of how and why producers reallocate resources. By representing risks and uncertainty (known and unknown) into the decision making process, it illustrates not only how we adapt but helps explain why. The insight into the adaptation process under scarcity and towards the increased probability of droughts, provided by the state-contingent approach, highlights the dangers of the ‘immaculate conception of water’ that occur from traditional approaches to risk and uncertainty.

10.3.2 Technological limits

Despite the Water Act encouraging the collection and dissemination of data (Section 4.3) gaps in the available literature still exist and in many cases these gaps facilitate the need for assumptions. For example, the data concerning the property rights in Section 7.4; the complexity in obtaining current water data (Section 4.3.1), and the errors that occur when attempting to predict future water resources (see Sections 3.2 and 4.4). There are errors in data sets used.

Additionally, the model also assumes that all catchments experience the same state of nature at the same time and that expectations about the states are uniform in each catchment. There are numerous issues that this model could examine. For example: the decision makers’ choice between permanent and allocation trade (see Section, 4.5, 4.4); changes in the comparative advantage of production derived from drought resistant or saline tolerant species or alternative production systems; the optimal allocation of environmental water between ecological site; and the possible reallocation of resources in absence of restrictive SDL trade rules.

Experience and comparison between the GAMS version of the model and the Excel version of the model have been carried out. The GAMS version of the model provides a better and more robust optimization algorithm. However, the GAMS model cannot undertake the *ex-ante* analysis of climate change. Future model development should consider merging the two platforms to obtain the best features form each.

10.3.3 Analytical Conceptual constraints

The state-contingent model used in this thesis relies on discrete data and parameterization of the model. For example, the model uses a fixed volume of water to describe each state of nature (water flow), producers have complete knowledge about inputs (capital, water, labor and costs), output (yield) and prices for all production systems in each state of nature, and that all producers within a catchment are homogenous. The complete information not only applies to the decision maker being able to determine the state of nature but also having a complete knowledge about all possible management options from which to maximize their objective function. The model then ensures that the producer can operate on the state-contingent frontier line (or transformation curve), see Section 5.3. Therefore, based on the model's description for water flow and water use (see Equation 6-7), the model can allocate water resources up until the point that there is zero flow out of a catchment (as illustrated in Table 8-11). This poses a dilemma as we know that society has imperfect knowledge about the future water supply (see Section s 3.2, 4.3.1 and 4.4). Therefore, the model may be misrepresenting risk and uncertainty associated with future water supply by state of nature, which then has implications for how producers adapt to the water scarcity, and therefore the results may provide misguiding policy recommendations.

Section 5 discussed that it was the choice of the producer if they wished to operate on the transformation curve and the equations are stochastic in nature. Rasmussen (2006) adds to this discussion by reminding us that outcomes (yields and prices) are in fact consequences of states of nature. This opens up a range of opportunities to examine climate variability and resource allocation. For example, Chavas (2008) examined the role of the 'output-cubical' technology (Section 5.4.3) to explain ex-post allocation of inputs in the agricultural system in the United States of America.

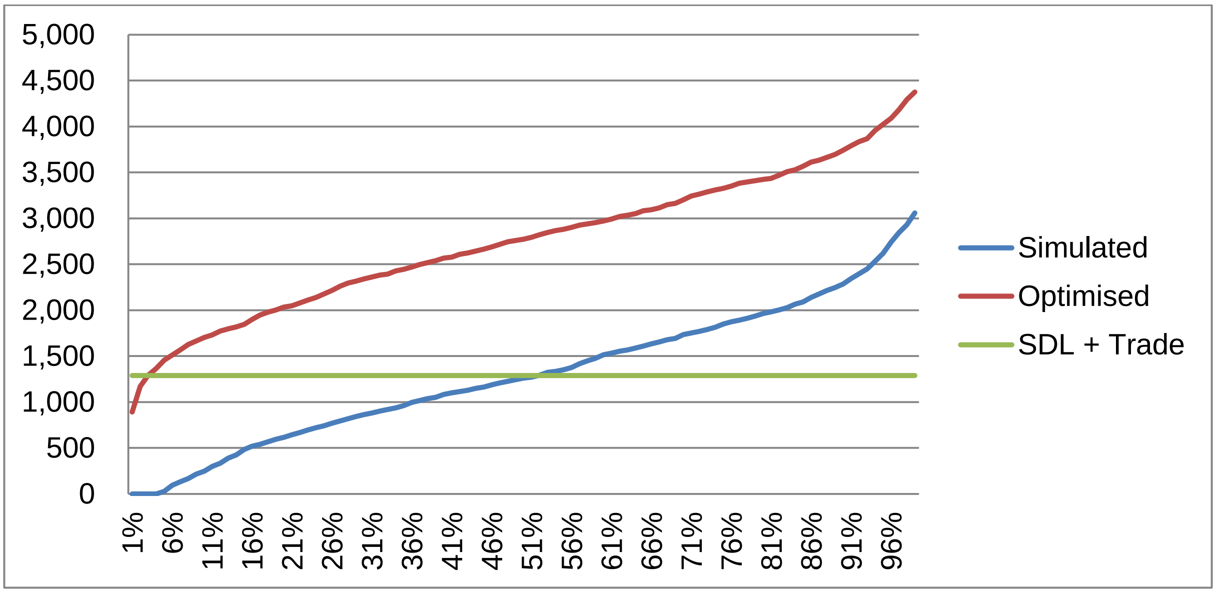
In a commissioned study, Adamson, Quiggin and Quiggin (2011) highlighted the risks to achieving the 2011 Basin Plan objectives by developing a version of the model that explored the role of stochastic states of nature (Chart 10-1). In 2011 the Basin Plan suggested that 1,000GL should arrive at the Coorong every year. The commission report developed a discrete model solution ('SDL + Trade') and compared it against a 'Simulated' solution and 'Optimised' solution.

The ‘Simulated’ solution is a case where ‘input decisions have to be made before uncertain outputs are known’ (Chavas 2008, p. 444). This approach utilizes the land allocation data from the discrete model run and then relaxes the information about the state of nature to examine the implications for river flow. This approach is then similar to the *ex-ante* climate solutions and highlighted that approximately 37% of the time, less than 1,000GL of water would reach the Coorong.

The ‘Optimised’ solution is similar to the ‘*ex-post*’ climate change solution. In this case by adapting the model to represent stochastic states of nature and introducing a chance constraint. The model can be optimized to ensure that the objectives listed in the Basin Plan objectives could be achieved, at least 95% of the time.

This strategy could then be used to examine: the water security provided by each water entitlement by state of nature; the associated risks to the CEWO optimal water rights portfolio; and examine new drought adaptation strategies. By carefully determining the stochastic description of the parameters and the bounds of the state-contingent input and output sets (see Section s 5.4.1 and 5.4.2), it would then allow for the level of risk associated with the state description and input use to be explored and perhaps overcome Rosser’s (2011) issues of fat tails and dealing with non-linear climate change events and unawareness.

Chart 10-1 Stochastic SCA and Environmental Targets (GL)



Source Adamson, Quiggin and Quiggin (2011)

In Section 3.2 unawareness was classified into three groups of swans: white, grey and black based on Taleb (2007). This thesis has modeled climate change as a white swan.. By representing white swan problems within a SCA, they can be solved using standard optimization techniques applied to problems not involving uncertainty (Chambers & Quiggin 2000).

However, Climate change is a grey swan as the problem is known, but a complete description of the data set and the decision maker's contingency plans are unknown. A stochastic description of a climate change within the SCA framework would provide a clear separation of signals and the management response to the signal. This would allow for increased examination of the tails of the distributions to explore tipping points in existing management options. This approach then opens up a range of other issues to be explored, including: how to internalize cognitive heuristics of decision makers to illustrate the rapid adaption of information generated from 'ecologically rational' (Goldstein & Gigerenzer 2002) (i.e. state of nature) experiences to bound the SCA input and output sets; optimizing strategies for broadacre and perennial producers when engaging in the permanent and allocation trade market; and exploring the value of property rights under a changing climate. By testing for tipping points greater awareness and knowledge could be gained. These insights may lead to better solutions. However, despite all best intentions the approach, in practice, is still limited by the eventual bounds on awareness of its user and the inevitable black swan.

10.4 Concluding remarks

Despite the identified limitations of the Basin Plan and its implementation, it must be remembered that this is still the largest transfer of water to the environment ever in Australia and perhaps in the world. In addition, unlike many of the other stages of water reform in the MDB, the Basin Plan has been well (perhaps too well) funded. Inevitably, like any large program there is always some form of resource waste when implementing a policy (Colebatch 2006; Ostrom 1990). Waste can occur from dealing with: the legacy from past policy (Connell & Grafton 2008), the nature and objective of the new policy design (Chambers 1992; Önal et al. 1991), the public and private transaction costs involved (Griffin 1991), dealing with rent seeking and compensation (Boyce 1998), combatting market failure (Bromley 2007) at the micro and macro level (Castle 1978) and the temporal life of the policy (Clark, Clarke & Gordon 1979).

The MDB is of economic, social and environmental significance to Australia and the recent embarkation towards the contractionary phase in water policy signifies that attempts to encapsulate externalities into the decision making approach is occurring. The adoption of common property provides the clear strategy to reduce the quantity of water rights held by private individuals. The establishment of the MDBA, the CEWO and the National Water Commission (NWC) has created a stimulus for the production of data and knowledge about the MDB that has stimulated significant public debate. However, this new data and knowledge has not altered the economic signals and recommendations that occurred before or during the early stages of the Basin Plan development but rather has provided clarity towards the final numbers.

The final Basin Plan, at first glance, suggested it was a contractionary stage of water resource development with the transfer of 3,200GL of water from private individuals to the CEWO. However by carefully reviewing the three key features of the Basin Plan, the RtB, the SRWUIP and change in groundwater SDL. It can be concluded that only the RtB is a clear application of a contractionary phase of water resource development. The access to groundwater may not necessarily be a contractionary stage as it expands irrigation. However, if the groundwater SDL is correct it provides production certainty under a changing climate. However, if the groundwater SDL is not sustainable or badly developed then externalities of development have been relocated from the surface to underground. The SRWUIP provides publicly funded upgrades of existing infrastructure and locks irrigation into the maturity stage of water resource development and although it may eventually provide some water to the environment its public costs cannot be justified.

To mitigate climate risk posed to future reliability of water property rights, irrigators could have traded what will become increasingly unreliable surface entitlements for high security groundwater entitlements. This transfer of climate risk away from irrigators to the CEWO was possible in the NMDB and will have been realized by informed irrigators. Unless the irrigators who took advantage of the SRWUIP incorporated flexibility into their water management strategy by either having water surplus to their production needs or allocated water towards an annual crop, then as the climate changes they face the real prospect of having to deal with a debt legacy created from lost capital invested in perennials.

The world is uncertain and the outcomes from decisions have known risks and unknown and potentially irreversible costs that impair the future perceived economic rents. But the failure to adequately encapsulate the variability in current runoff and the management response to that variability in the MDB, seams counterproductive when the opportunity costs of public resources is high (Wittwer & Dixon 2013). The state-contingent approach highlights the problems of supply scarcity and how irrigators respond. By developing a model that explicitly details the constrained economic welfare problem, externalities are reduced and threats to the Basin Plan by ignoring climate change have been discussed.

The thesis strongly suggests that the RtB on its own could obtain all the water required for restoring the flow for $3.1 billion. The combination of the RtB and the increased groundwater entitlements, adequately compensate the MDB community for any loss of welfare from reduced assess to surface water. To maximize social welfare the $7.5 billion in funding allocated to the SRWUIP, should be allocated elsewhere (Quiggin 2012; Wittwer & Dixon 2013).

Unfortunately, a political reply already exists to this funding reallocation choice. In February 2014, it was announced that the RtB could only purchase 1,500GL of water from irrigators (Vidot 2014). Therefore the SRWUIP strategy presented in Section 9 is a fair reflection of what could occur. As we enter the next 100 years of this on-going policy experiment in water resource development, the countdown to the next wealth transfer has begun. As the inevitable forthcoming drought will create a policy battle over rural debt derived from the SRWUIP while the environment and society remain penalized.

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APPENDIX A.PRODUCTION DATA

Table A-1 Economic Return, Normal State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$	-$3,820	-$3,764	$614	-$15,098	$1,965	-$4,856	$791	$1,166	$859	$1,166	$500	-$550	-$550	-$4	$351	$186	$501	$316	-$275	-$753	-$550
$k2$	-$3,820	-$3,764	-$5,672	-$15,098	$1,965	$2,346	-$687	$952	$678	$952	$500	$0	$0	-$4	$351	$252	$501	$310	-$275	-$753	-$551
$k3$	$0	$0	-$3,319	$0	$0	$0	-$687	$1,059	$769	$1,059	$500	$0	$0	-$4	$351	$218	$501	$269	-$275	-$785	-$658
$k4$	-$3,820	-$3,764	$4,314	-$23,373	$1,965	-$4,856	$8,783	$2,517	$2,004	$2,517	$726	-$550	-$550	-$89	$257	$173	$291	$135	-$321	-$913	-$728
$k5$	$4,972	$5,141	$4,314	-$16,714	$1,965	-$1,944	$5,030	$1,091	$790	$1,091	$726	$490	$490	-$53	$118	-$353	$291	$45	-$428	-$660	-$461
$k6$	-$3,820	-$3,764	-$3,319	-$4,856	-$4,856	-$4,856	-$687	$953	$678	$953	$500	$0	$0	-$4	$351	$247	$501	$310	-$275	-$803	-$678
$k7$	-$3,820	-$3,764	$4,314	-$23,373	$1,965	$2,346	$8,783	$1,092	$789	$1,092	$726	$0	$0	-$40	$257	$211	$291	$211	-$321	-$873	-$684
$k8$	$6,154	$6,449	$4,314	-$16,714	$1,965	-$4,856	$5,030	-$334	-$423	-$334	$726	$0	$0	-$4	$351	$247	$501	$310	-$275	-$803	-$678
$k9$	$6,154	$6,500	$4,314	-$5,552	$3,965	$2,346	$1,277	-$410	-$489	-$410	$726	$541	$541	-$40	$118	-$130	$314	-$42	-$348	-$749	-$564
$k10$	$4,417	$4,770	$4,314	-$14,446	$289	$671	-$440	$563	$255	$563	$248	$768	$768	$58	$358	$257	$336	-$130	-$180	-$1,079	-$370
$k11$	-$5,496	-$5,439	$4,314	-$14,446	$289	$671	-$440	$0	$0	$0	$0	$594	$594	-$157	$110	$9	-$439	-$247	-$198	$648	$640
$k12$	$3,649	$3,918	$4,314	-$14,446	$289	-$8,485	-$440	-$983	-$983	-$983	-$983	$588	$588	$58	$258	$120	$336	-$130	-$85	$1,108	$1,741
$k13$	$3,649	$3,918	$520	-$14,446	-$1,056	-$382	-$2,355	$0	$0	$0	$0	-$550	-$550	-$157	$110	$48	-$439	-$247	-$200	$327	$693
$k14$	$3,649	$3,918	$2,243	-$6,531	-$6,531	-$6,531	-$440	$563	$255	$563	$248	$712	$712	$58	$258	$120	$336	-$130	-$147	$320	$857
$k15$	$3,649	$3,918	$4,756	-$14,446	$1,619	-$13,459	-$440	$0	$0	$0	$0	$260	$260	-$157	$24	$19	$218	$55	-$239	$113	$455
$k16$	$3,649	$3,918	$2,243	-$14,446	$289	-$6,531	-$440	$563	$255	$563	$248	$588	$588	$58	$258	$120	$336	-$130	-$275	$177	$694
$k17$	$4,766	$5,035	$2,243	-$10,330	$1,406	$671	$4,560	$0	$0	$0	$0	-$550	-$550	-$157	$530	$303	$218	-$247	$9	-$19	$308
$k18$	$4,417	$4,678	$2,243	-$11,836	$1,406	-$6,531	-$440	-$545	-$739	-$545	-$134	$0	$0	-$157	$110	-$27	$218	-$247	-$240	-$2,267	-$2,465
$k19$	-$3,820	-$3,764	$614	-$15,098	$1,965	-$4,856	$791	$1,166	$859	$1,166	$500	-$550	-$550	-$157	$110	$9	-$439	-$247	-$201	$515	$517

Table A-2 Economic Return, Drought State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$	-$3,840	-$3,764	-$831	-$21,106	-$1,680	-$4,876	$7,680	$500	$859	$352	$107	-$550	-$529	-$4	$141	$804	$205	$88	-$224	-$1,142	-$1,099
$k2$	-$3,840	-$3,764	-$7,117	-$21,106	-$1,680	-$3,303	$7,680	$500	$678	$529	$107	$0	-$529	-$4	$141	$804	$205	$82	-$224	-$1,142	-$1,099
$k3$	-$20	$0	-$4,764	-$20	$0	-$20	$7,680	$500	$769	$437	$107	$0	-$529	-$4	$141	$804	$205	$41	-$224	-$1,151	-$1,106
$k4$	-$3,840	-$3,764	$2,377	-$29,153	-$1,680	-$4,876	$7,680	$726	$2,004	$75	$298	-$550	-$614	-$89	$26	$738	$39	-$57	-$200	-$1,268	-$1,221
$k5$	$1,489	$3,217	$2,377	-$23,720	-$1,680	-$7,164	$7,680	$726	$790	-$815	$298	$140	$160	-$53	-$92	$547	$39	-$153	-$300	-$1,033	-$989
$k6$	-$3,840	-$3,764	-$4,764	-$4,876	-$4,856	-$4,876	$7,680	$500	$678	$518	$107	$0	-$529	-$4	$141	$804	$205	$82	-$224	-$1,100	-$1,047
$k7$	-$3,840	-$3,764	$2,377	-$29,153	-$1,680	-$3,303	$7,680	$726	$789	$223	$298	$0	-$572	-$40	$26	$738	$39	-$17	-$200	-$1,237	-$1,191
$k8$	-$3,840	-$3,764	-$4,764	-$4,876	-$4,856	-$4,876	$7,680	$500	$678	$518	$107	$0	-$529	-$4	$141	$804	$205	$82	-$224	-$1,100	-$1,047
$k9$	$2,435	$4,445	$2,377	-$10,692	$320	-$3,303	$7,680	$726	-$489	-$138	$298	$210	$185	-$40	-$92	$547	$31	-$255	-$132	-$1,109	-$1,064
$k10$	$697	$2,715	$2,377	-$20,546	-$3,355	-$4,978	$5,963	$248	$255	$67	-$180	$303	$324	$58	$106	$888	$21	-$358	$38	-$1,472	-$922
$k11$	-$5,516	-$5,439	$2,377	-$20,546	-$3,355	-$4,978	$5,963	$0	$0	$0	$0	$161	$67	-$157	-$116	$579	-$439	-$475	$67	$23	-$425
$k12$	$83	$1,948	$2,377	-$20,546	-$3,355	-$13,804	$5,963	-$983	-$983	-$983	-$983	$204	$324	$58	$16	$758	$21	-$358	$311	$483	$676
$k13$	$83	$1,948	-$1,210	-$20,546	-$4,608	-$6,902	$5,963	$0	$0	$0	$0	-$550	-$689	-$157	-$116	$579	-$439	-$475	$63	-$217	-$194
$k14$	$83	$1,948	$513	-$6,551	-$6,531	-$6,551	$5,963	$248	$255	-$285	-$180	$329	$324	$58	$16	$758	$21	-$358	$198	-$215	-$12
$k15$	$83	$1,948	$3,026	-$20,546	-$2,117	-$17,578	$5,963	$0	$0	$0	$0	-$96	$67	-$157	-$194	$471	-$96	-$161	$46	-$409	-$384
$k16$	$83	$1,948	$513	-$20,546	-$3,355	-$6,551	$5,963	$248	$255	-$285	-$180	$204	$324	$58	$16	$758	$21	-$358	-$73	-$338	-$134
$k17$	$1,200	$3,065	$513	-$16,430	-$2,239	-$4,978	$7,963	$0	$0	$0	$0	-$550	-$689	-$157	$220	$1,195	-$96	-$475	$267	-$524	-$496
$k18$	$697	$2,623	$513	-$17,456	-$2,239	-$6,551	$5,963	-$134	-$739	-$524	-$562	$0	-$689	-$157	-$116	$579	-$96	-$475	-$9	-$2,567	-$2,765
$k19$	$83	$562	$4,337	-$20,546	-$9,665	-$4,978	$5,963	-$1,365	-$1,365	-$1,365	-$1,365	$0	-$689	-$157	-$116	$579	-$439	-$475	$83	$78	-$138

Table A-3 Economic Return, Wet State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$	-$3,840	-$3,864	$3,444	-$9,131	$9,154	-$4,876	-$12,183	$1,066	$859	-$1,734	$524	-$550	-$650	-$650	$406	-$198	$549	$430	-$616	$98	-$102
$k2$	-$3,840	-$3,864	-$2,842	-$9,131	$9,154	$13,584	-$12,183	$852	$678	-$1,948	$310	$0	-$100	-$100	$406	-$110	$549	$424	-$616	$98	-$103
$k3$	-$20	-$100	-$489	-$20	-$100	-$20	-$12,183	$959	$769	-$1,841	$417	$0	-$100	-$100	$406	-$155	$549	$383	-$616	-$452	-$510
$k4$	-$3,840	-$3,864	$8,128	-$17,633	$9,154	-$4,876	-$12,183	$2,417	$2,004	-$1,289	$1,699	-$550	-$650	-$650	$322	-$179	$318	$232	-$732	-$69	-$256
$k5$	$8,416	$8,889	$8,128	-$9,749	$9,154	$8,436	-$12,183	$991	$790	-$1,982	$415	$28	-$457	-$559	$173	-$838	$318	$143	-$807	$232	$26
$k6$	-$3,840	-$3,864	-$489	-$4,876	-$4,956	-$4,876	-$12,183	$853	$678	-$1,947	$310	$0	-$100	-$100	$406	-$117	$549	$424	-$616	-$209	-$309
$k7$	-$3,840	-$3,864	$8,128	-$17,633	$9,154	$13,584	-$12,183	$992	$789	-$1,984	$416	$0	-$100	-$100	$322	-$132	$318	$325	-$732	-$28	-$218
$k8$	-$3,840	-$3,864	-$489	-$4,876	-$4,956	-$4,876	-$12,183	$853	$678	-$1,947	$310	$0	-$100	-$100	$406	-$117	$549	$424	-$616	-$209	-$309
$k9$	$9,834	$10,510	$8,128	-$452	$11,154	$13,584	-$12,183	-$510	-$489	-$2,814	-$956	$71	-$419	-$523	$173	-$549	$356	$64	-$763	$81	-$104
$k10$	$8,096	$8,780	$8,128	-$8,386	$7,479	$11,909	-$13,899	$463	$255	-$2,737	-$157	$266	-$251	-$362	$434	-$167	$393	-$16	-$663	-$249	$62
$k11$	-$5,516	-$5,539	$8,128	-$8,386	$7,479	$11,909	-$13,899	-$100	$0	-$100	-$100	$119	-$375	-$481	$173	-$379	-$539	-$133	-$663	$2,617	$1,575
$k12$	$7,175	$7,758	$8,128	-$8,386	$7,479	$2,092	-$13,899	-$1,083	-$983	-$1,083	-$1,083	$108	-$390	-$497	$328	-$290	$393	-$16	-$625	$3,078	$2,675
$k13$	$7,175	$7,758	$3,920	-$8,386	$5,948	$12,598	-$13,899	-$100	$0	-$100	-$100	-$550	-$650	-$650	$173	-$335	-$539	-$133	-$665	$1,910	$1,459
$k14$	$7,175	$7,758	$5,643	-$6,551	-$6,631	-$6,551	-$13,899	$463	$255	-$2,737	-$157	$212	-$303	-$413	$328	-$290	$393	-$16	-$663	$1,878	$1,616
$k15$	$7,175	$7,758	$8,156	-$8,386	$8,991	-$5,281	-$13,899	-$100	$0	-$100	-$100	-$173	-$634	-$730	$84	-$339	$275	$164	-$702	$1,589	$1,174
$k16$	$7,175	$7,758	$5,643	-$8,386	$7,479	-$6,551	-$13,899	$463	$255	-$2,737	-$157	$108	-$390	-$497	$328	-$290	$393	-$16	-$733	$1,657	$1,422
$k17$	$8,292	$8,874	$5,643	-$4,270	$8,596	$11,909	-$10,899	-$100	$0	-$100	-$100	-$550	-$650	-$650	$635	-$217	$275	-$133	-$577	$1,409	$1,013
$k18$	$8,096	$8,688	$5,643	-$6,256	$8,596	-$6,551	-$13,899	-$645	-$739	-$3,397	-$1,178	$0	-$100	-$100	$173	-$435	$275	-$133	-$689	-$2,267	-$2,465
$k19$	$7,175	$6,371	$8,661	-$8,386	-$1,495	$11,909	-$13,899	-$1,465	-$1,365	-$1,465	-$1,465	$0	-$100	-$100	$173	-$379	-$539	-$133	-$668	$1,606	$1,072

Table A-4 Water Use, Normal State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$			5.0	3.3	6.4		4.0	5.0	5.0	5.0					1.5	2.6	4.0	4.0	4.8	9.0	10.0
$k2$			5.0	3.3	6.4	7.0	4.0	5.0	5.0	5.0					1.5	2.5	4.0	4.0	4.8	9.0	10.0
$k3$			5.0				4.0	5.0	5.0	5.0					1.5	2.6	4.0	4.0	4.8		
$k4$			6.1	5.0	6.4		5.9	5.6	5.6	5.6					3.4	3.0	2.9	3.0	5.7	12.6	14.0
$k5$	5.0	7.8	6.1	1.7	6.4	7.0	7.1	6.3	6.3	6.3		8.4	8.4		5.4	6.2	2.9	5.4	6.7	11.7	13.0
$k6$			5.0				4.0	5.0	5.0	5.0					1.5	2.5	4.0	4.0	4.8	13.5	15.0
$k7$			6.1	5.0	6.4	7.0	5.9	7.0	7.0	7.0					3.4	3.5	2.9	5.0	5.7	11.7	13.0
$k8$			5.0				4.0	5.0	5.0	5.0					1.5	2.5	4.0	4.0	4.8	13.5	15.0
$k9$	5.0	7.8	6.1	3.6	6.4	7.0	8.2	9.8	9.8	9.8		8.5	8.5		5.4	6.6	5.2	6.7	6.7	11.7	13.0
$k10$	7.5	10.0	6.1	3.0	6.4	7.0	8.2	10.3	10.3	10.3		7.5	7.5		3.9	6.3	7.5	8.0	6.0	8.1	9.0
$k11$			6.1	3.0	6.4	7.0	8.2					7.4	7.4		3.9	6.2		8.0	6.0	7.7	8.5
$k12$	7.5	10.0	6.1	3.0	6.4	7.0	8.2					7.0	7.0		3.5	5.9	7.5	8.0	5.8	7.7	8.5
$k13$	7.5	10.0	6.8	3.0	6.0	6.0	4.7								3.9	6.3		8.0	6.0	8.1	9.0
$k14$	7.5	10.0	6.1				8.2	10.3	10.3	10.3		7.0	7.0		3.5	5.9	7.5	8.0	5.8	8.6	9.5
$k15$	7.5	10.0	5.5	3.0	6.9	8.0	8.2					6.1	6.1		3.5	4.1	7.5	3.5	5.8	8.1	9.0
$k16$	7.5	10.0	6.1	3.0	6.4	0.0	8.2	10.3	10.3	10.3		7.0	7.0		3.5	5.9	7.5	8.0	5.8	9.0	10.0
$k17$	7.5	10.0	6.1	3.0	6.4	7.0	8.2								3.9	6.2	7.5	8.0	6.0	9.0	10.0
$k18$	7.5	9.6	6.1	3.3	6.4	0.0	8.2	10.1	10.1	10.1					3.9	6.5	7.5	8.0	6.0		
$k19$	7.5	9.9	6.5	3.0	10.5	7.0	7.4								3.9	6.2	0.0	8.0	6.0	9.0	10.0

Table A-5 Water Use, Drought State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$			5.0	3.3	6.4				5.0	3.8					1.5	1.7	4.0	4.0	7.4	6.3	6.0
$k2$			5.0	3.3	6.4	7.0			5.0	3.5					1.5	1.7	4.0	4.0	7.4	6.3	6.0
$k3$			5.0						5.0	3.6					1.5	1.7	4.0	4.0	7.4	0.0	0.0
$k4$			6.1	5.0	6.4	0.0			5.6	2.6					3.4	3.7	2.9	3.0	7.5	8.8	8.4
$k5$	5.0	7.8	6.1	1.7	6.4	7.0			6.3	7.0		7.1			5.4	5.9	2.9	5.4	7.7	8.2	7.8
$k6$			5.0						5.0	3.5					1.5	1.7	4.0	4.0	7.4	9.5	9.0
$k7$			6.1	5.0	6.4	7.0			7.0	3.5					3.4	3.7	2.9	5.0	7.5	8.2	7.8
$k8$			5.0						5.0	3.5					1.5	1.7	4.0	4.0	7.4	9.5	9.0
$k9$	5.0	7.8	6.1	3.6	6.4	7.0			9.8	7.8		7.3			5.4	5.9	5.2	6.7	7.7	8.2	7.8
$k10$	7.5	10.0	6.1	3.0	6.4	7.0			10.3	8.7		7.3			3.9	4.3	7.5	8.0	7.6	5.7	5.4
$k11$			6.1	3.0	6.4	7.0						7.1			3.9	4.3		8.0	7.6	5.4	5.1
$k12$	7.5	10.0	6.1	3.0	6.4	7.0						7.0			3.5	3.9	7.5	8.0	7.6	5.4	5.1
$k13$	7.5	10.0	6.8	3.0	6.0	6.0						0.0			3.9	4.3		8.0	7.6	5.7	5.4
$k14$	7.5	10.0	6.1	0.0	0.0	0.0			10.3	8.4		7.0			3.5	3.9	7.5	8.0	7.6	6.0	5.7
$k15$	7.5	10.0	5.5	3.0	6.9	8.0						5.6			3.5	3.9	7.5	3.5	7.6	5.7	5.4
$k16$	7.5	10.0	6.1	3.0	6.4	0.0			10.3	8.4		7.0			3.5	3.9	7.5	8.0	7.6	6.3	6.0
$k17$	7.5	10.0	6.1	3.0	6.4	7.0									3.9	4.3	7.5	8.0	7.6	6.3	6.0
$k18$	7.5	9.6	6.1	3.3	6.4	0.0			10.1	9.0					3.9	4.3	7.5	8.0	7.6		
$k19$	7.5	9.9	6.5	3.0	10.5	7.0									3.9	4.3		8.0	7.6	6.3	6.0

Table A-6 Water Use, Wet State of Nature

	$x1$	$x2$	$x3$	$x4$	$x5$	$x6$	$x7$	$x8$	$x9$	$x10$	$x11$	$x12$	$x13$	$x14$	$x15$	$x16$	$x17$	$x18$	$x19$	$x20$	$x21$
$k1$			5.0	3.3	6.4		6.0	5.0	5.0	5.0	5.0				1.5	3.2	4.0	4.0	3.5	6.3	6.0
$k2$			5.0	3.3	6.4	7.0	6.0	5.0	5.0	5.0	5.0				1.5	3.0	4.0	4.0	3.5	6.3	6.0
$k3$			5.0				6.0	5.0	5.0	5.0	5.0				1.5	3.1	4.0	4.0	3.5		
$k4$			6.1	5.0	6.4		6.0	5.6	5.6	5.6	5.6				3.4	3.0	2.9	3.0	4.8	8.8	8.4
$k5$	5.0	7.8	6.1	1.7	6.4	7.0	6.0	6.3	6.3	6.3	6.3	8.4	8.4	8.4	5.4	6.8	2.9	5.4	6.2	8.2	7.8
$k6$			5.0				6.0	5.0	5.0	5.0	5.0				1.5	3.0	4.0	4.0	3.5	9.5	9.0
$k7$			6.1	5.0	6.4	7.0	6.0	7.0	7.0	7.0	7.0				3.4	3.6	2.9	5.0	4.8	8.2	7.8
$k8$			5.0				6.0	5.0	5.0	5.0	5.0				1.5	3.0	4.0	4.0	3.5	9.5	9.0
$k9$	5.0	7.8	6.1	3.6	6.4	7.0	6.0	9.8	9.8	9.8	9.8	8.5	8.5	8.5	5.4	7.4	5.2	6.7	6.2	8.2	7.8
$k10$	7.5	10.0	6.1	3.0	6.4	7.0	6.0	10.3	10.3	10.3	10.3	7.5	7.5	7.5	3.9	7.4	7.5	8.0	5.1	5.7	5.4
$k11$			6.1	3.0	6.4	7.0	6.0					7.4	7.4	7.4	3.9	7.3		8.0	5.1	5.4	5.1
$k12$	7.5	10.0	6.1	3.0	6.4	7.0	6.0					7.0	7.0	7.0	3.5	7.1	7.5	8.0	4.9	5.4	5.1
$k13$	7.5	10.0	6.8	3.0	6.0	6.0	6.0								3.9	7.4		8.0	5.1	5.7	5.4
$k14$	7.5	10.0	6.1				6.0	10.3	10.3	10.3	10.3	7.0	7.0	7.0	3.5	7.1	7.5	8.0	4.9	6.0	5.7
$k15$	7.5	10.0	5.5	3.0	6.9	8.0	6.0					6.1	6.1	6.1	3.5	4.6	7.5	3.5	4.9	5.7	5.4
$k16$	7.5	10.0	6.1	3.0	6.4	0.0	6.0	10.3	10.3	10.3	10.3	7.0	7.0	7.0	3.5	7.1	7.5	8.0	4.9	6.3	6.0
$k17$	7.5	10.0	6.1	3.0	6.4	7.0	6.0								3.9	7.3	7.5	8.0	5.1	6.3	6.0
$k18$	7.5	9.6	6.1	3.3	6.4	0.0	6.0	10.1	10.1	10.1	10.1				3.9	7.7	7.5	8.0	5.1		
$k19$	7.5	9.9	6.5	3.0	10.5	7.0	6.0								3.9	7.3		8.0	5.1	6.3	6.0

APPENDIX B. GROSS MARGIN DATA SOURCES

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