A Systems Approach to Improve Water Productivity and Environmental Performance at the Catchment Level

Amgad Elmahdi

Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy

2006

Department of Civil and Environmental Engineering
The University of Melbourne
ABSTRACT

(Less than 350 words)

Presented in this dissertation is an investigation of changing seasonality of flows in the Murrumbidgee catchment to improve water productivity and environmental performance. Also proposed is a methodology to investigate measure and quantify the economic and environmental impacts of various supply and demand options for irrigation and improved seasonal and environmental flows under different climatic conditions.

The study focused on the main three options identified by stakeholders. These options are irrigation demand management by changing crop mix, conjunctive water use management and surface water substitution by ground water. Water banking, together with conjunctive water use management options, was also tested.

A comparatively detailed integrated hydrological, economic and environmental modelling framework (NSM) was developed using system dynamics approach (Vensim™ software tool). The main objective of NSM model is to assess and evaluate the current economic outcomes and environmental performance. NSM is linked with a crop decision optimisation module (CDOM) and water trading module (WTM) to capture farmers’ cropping decisions and water trading. These modules and the NSM model were calibrated and validated using seven performance criteria.

Six scenarios, including the base case scenario representing various options of altered supply and demand, were tested. Economic and environmental impacts were evaluated using several indicators representing land and water resource use, economic indicators, environmental indicator and efficiency indicators. The results show clear tradeoffs between agricultural income, environmental performance and water use under each scenario. The most feasible and cost-effective options were, in increasing order of performance: changing crop mix, crop mix with water banking under infiltration and the all-option scenario, and conjunctive water use with the water banking under infiltration method.

In conclusion, modelling has shown that options do exist which have the potential to improve seasonal flows, restore environmental flow and enhance water security and potentially save water. Better irrigation demand management has the potential to increase the amount of water available for restoring some of the natural river flow regime, with increased productivity and regional return without reducing water security of irrigators and others users.
BIOGRAPHICAL SKETCH

Amgad has an extensive academic history spanning many faculties as well as countries. A brief summary of his achievement includes:

- **Bachelor of Science**, 1993, (Botany & Chemistry) Mansoura University, Faculty of Science, Biology Department—Egypt.

- **Masters of Science** in Limnology (Algae) 1997, Botany Department, Faculty of science New Damietta-University of Mansoura—Egypt entitled ‘Ecological Studies on Phytoplankton and Water pollution relationship in Triangle region of Manzala Lake- Damietta- Egypt’.

- **Masters of Science** in Land & Water Management 2000, CIHEAM- MAIB Mediterranean Agronomic Institute of Bari-Italy entitled ‘Amalgamation of GIS and Environmental indicators for decision making in Water resources management’. In Frame of the Italian and Egyptian Project.

- **DSPU** (Diploma special of Postgraduate universities of Environment Conservation and Renewable Resources) 1998, from Mediterranean Agronomic Institute of Chania—Greece.

Amgad has eleven years experience in various aspects of hydrology and water management. After obtaining a Masters of Science in Water-Ecological Studies in Egypt, Amgad went on to study environmental conservation in Greece and completed a Masters degree in Land and Water Management in Italy.

In 2003, Amgad received an award from the Ministry of Water Resources and Irrigation, Egypt, for Best Master Thesis in Water Resources Management. In August that same year he commenced his PhD at the University of Melbourne.

The research project under CRC irrigation future focuses on ‘Improved Seasonality of Flows through Irrigation Demand Management and System Harmonisation™’. It aims to identify opportunities to manipulate irrigation demand and supply in a way that optimises the social, environmental and economic outputs from all available water resources within a catchment.

Amgad’s thesis focuses specifically on the Murrumbidgee River to establish new knowledge to link irrigation demand and conjunctive water use management with environmental outcomes at the irrigation area scale in the Murrumbidgee catchment. The research is expected to assist with understanding how to improve the environmental quality of the Murrumbidgee River through better irrigation demand management and water banking approach.

The major driver for understanding the link between irrigation demand, conjunctive water management and water banking, with environmental outcomes, is to locate and measure the change in economic output and environmental impacts of various allocations and demands from irrigation on improved seasonality of flows.

Amgad has published a number of papers on his research, and in 2006 year he received confirmation of acceptance for four journal articles.

Aside from his research endeavours, Amgad has had a number of personal achievements. The father of two boys was elected as a Postgraduate Council member and Activities and Communication Officer for Melbourne University’s Postgraduate Association in January 2005, and in December he helped organise the ERE Conference in Hobart and in October 2006 helped organise the CEE (Civil and Environmental Engineering annual conference) in Melbourne.

In December 2004, Amgad was awarded the prize for the best student presentation for his paper in World Conference on Natural Resource Modelling. It was held under the auspices of the Resource Modelling Association (RMA) and partially sponsored by the Australian Mathematical Sciences Institute (AMSI) and the Centre of Excellence for Mathematics and Statistics of Complex Systems (MASCOS). There were 90 registered participants from many countries across the globe.

In April this year Amgad was named and awarded DIMIA and SBS’s Australian Harmony Hero 2006 for his work in promoting cross-cultural understanding and dissolving cultural barriers amongst students at the University of Melbourne.

In Decembers 2006 Amgad was awarded the prize for the best paper and presentation at environmental research event ERE conference, 10-14 Dec, Macquarie University-Sydney. In January 2007 Amgad was started his position at CSIRO land and water as Research Scientist- Water System Analysts. In October 2008 Amgad was awarded the ICID WatSave award 2008 for his PhD research.
DEDICATION

This thesis is dedicated to the memory of my beloved father, the late

And to my sons, Eyad and Zeiad and my wife Haidi; the three people who inspired
me the most toward the achievement of my PhD.

My mother, sister, brother and nephews, who always supported me to realize my
objectives during my life.

This is the proper plan of study and life: Reading, reflection and regular application in life.

Study is work inquiry into the value and applicability of what is studied is worship.

The experience of validity and value of the practice is wisdom.

The education is not for a mere living but for a fuller and meaningful life.

Never ignore family, friends, study, and your social life

Amgad Elmahdi
DECLARATION

This thesis is submitted in total fulfilment of the requirements of the degree of Doctor of philosophy to the University of Melbourne, Australia.

This is to certify that:

1. The thesis comprises only my original work towards the PhD except where indicated in the preface,

2. Due acknowledgement has been made in the text to all other material used,

3. The thesis is less than 100,000 words in length, exclusive of figure, tables, equations, footnotes, references and appendices.

Amgad Elmahdi

2006
ACKNOWLEDGEMENTS

Writing a thesis is singularly hard work, but is far from being a solo effort. First I would like to thank GOD for his almighty, guideless peace, and for the blessing of living such a beautiful life, and especially for having such a beautiful family.

I would like to take this opportunity to thank a number of people who have made the completion of this thesis possible. First of all, this study would not have been completed without the kind assistance, guidance, inspiration, encouragement and personal support and advice of my principal academic supervisor, Associate Professor Hector Malano. I especially thank him for making time for me when he had very little of his own. I am honoured to have studied and taught under his supervision. His support through the entire process of my research started by defining the problem, conceptualising discussion and writing the thesis was invaluable. He was patient in answering my questions and in the teaching of his vast knowledge.

I also wish to express my deepest gratitude to my academic co-supervisor, Dr. Teri Etchells for her valuable, impressive and insightful suggestions and comments for my study. She led me towards the better structure and writing of this engineering research thesis and paper. I would like also to present my sincere thank to Professor Shahbaz Khan as associated external supervisor for providing me primary and secondary data and supporting my study.

I would like to acknowledge the Department of Civil and Environmental Engineering of the University of Melbourne and CRC for Irrigation Futures for providing financial support for my research and study over the three years. Furthermore, I wish to thank the staff of my department and CRCIF for providing me with the necessary support and facilities throughout my study. I am grateful to the academic, computer and the administrative staff and my fellow PhD candidates in the civil and environmental engineering department who have made my stay and study such a pleasant and meaningful experiences.

Special thanks goes to these people (without any specific order), for their kind inspiration supports and most important their friendships, Dr. Evan Christine (CSIRO, Land and water), Dr. Xevi Emmanuel (CSIRO, Land and water), Dr. John Wolfenden (CEEWPR, UNE, University of New England NSW), Mr. Redha Beddek (SKM-Consultant) and Prof. Enrico Feoli (ICS-UNIDO-Italy).

I would like to extend a very special thanks to the UMPA (University of Melbourne Postgraduate Association) council and staff for sharing their great knowledge and confidence in my competence. Being a member at UMPA’s Council and also office bearer (Activities officer), providing and promoting my personnel and decision making experiences for $3.4 million/year.

Finally, I wish to express my deep gratitude and love to my dearest wife, Haidi. Her love, patience, moral support and constant encouragement enabled me to complete this study, my wish for her and support to pursue her PhD research. A special thanks to my two sons (Eyad and Zeiad) for their funny/lovely time they have given to me. In the end, I am thankful to my Mom for her love, pray and support during my study.
PREFACE

This dissertation is submitted for the degree of Doctor of Philosophy at the University of Melbourne, Melbourne, Victoria, Australia. The work described in the thesis carried out by the candidate during the years 2003–2006 in the Civil and Environmental Engineering Department under the academic supervision of Associate Professor Hector Malano, and Dr. Teri Etchells, and industry supervision of Professor Shahbaz Khan.

Several papers have been written by the candidate and the work has been presented at internationally esteemed and peer reviewed conferences. At present, a number of papers are still in preparation. Also, the thesis included eight chapters, each chapter or two been transferred into reviewed publications (journal or conferences) full references of the papers published as follow:

A- Chapter Two, Three and Five:


B- Chapter Four and Seven


C- Chapter Five

D-Chapter Six


E-Chapter Seven and Eight


Under preparation


# TABLE OF CONTENTS

## CHAPTER 1: INTRODUCTION

1.1 Introduction ................................................................................................................................................. 1
1.2 The Scope and Objectives of this Study ........................................................................................................... 4
1.3 Outline of the Dissertation ............................................................................................................................. 9

## CHAPTER 2: CASE STUDY AND LITERATURE REVIEW

2.1 Overview of the Murrumbidgee Catchment (Case Study) ............................................................................... 11
   2.1.1 Murrumbidgee valley irrigation areas ........................................................................................................ 15
   2.1.2 Groundwater hydrogeology and use ............................................................................................................. 17
   2.1.3 Water allocation ......................................................................................................................................... 23
   2.1.4 Environmental flow rules ............................................................................................................................ 25
2.2 Critical Issues Related to the Research Problem (Australian and Murrumbidgee Contexts) ......................... 26
   2.2.1 Economic use of irrigation water .................................................................................................................. 27
   2.2.2 Water environment and economic viability and reliability ........................................................................ 32
   2.2.3 Tools for reallocation: cap and trade ........................................................................................................... 34
   2.2.4 Trading pattern ........................................................................................................................................... 38
   2.2.5 Water availability and scarcity .................................................................................................................... 40
2.3 Catchment and its Interaction with Irrigation Management Concept ............................................................. 40
2.4 Modelling of Irrigation System (A Systems Approach) .................................................................................... 44
2.5 Summary and Conclusion ............................................................................................................................... 53

## CHAPTER 3: MANAGEMENT OPTIONS AVAILABLE

3.1 Seasonality of Flows ....................................................................................................................................... 55
3.2 Regulated River and its Effects ......................................................................................................................... 57
3.3 Potential Management Options and Seasonality of Flows ............................................................................. 60
3.4 Irrigation Demand Management and Crop Mix ............................................................................................... 65
   3.4.1 Tools for demand management .................................................................................................................... 66
3.5 Conjunctive Water Use .................................................................................................................................. 68
   3.5.1 Groundwater use ....................................................................................................................................... 69
   3.5.2 Groundwater conjunctive management and related issues ......................................................................... 70
3.6 Water Banking (Underground Dam or Storage) ............................................................................................... 72
   3.6.1 Water banking and related issues .................................................................................................................. 76
   3.6.2 Water banking and water trading .................................................................................................................. 78
3.7 Summary and Conclusion ............................................................................................................................... 80

## CHAPTER 4: SCENARIO DEVELOPMENT

4.1 Base Case Scenario .......................................................................................................................................... 82
   4.1.1 Surface and groundwater allocation ........................................................................................................... 83
   4.1.2 Water and land use ..................................................................................................................................... 84
4.2 Scenario Development ..................................................................................................................................... 89
   4.2.1 Scenario modelling ..................................................................................................................................... 91
   4.2.2 Demand management .................................................................................................................................. 93
   4.2.3 Conjunctive water use .................................................................................................................................. 94
   4.2.4 Climatic conditions .................................................................................................................................... 97
4.3 Scenarios Assessment Indicators ................................................................................................................... 97
4.4 Scenarios Drivers and Uncertainty .................................................................................................................. 98
   4.4.1 Rainfall and evaporation uncertainty .......................................................................................................... 99
   4.4.2 Environmental flows .................................................................................................................................. 100
   4.4.3 Flow and seasonality ................................................................................................................................... 101
   4.4.4 Dam operations ......................................................................................................................................... 101
   4.4.5 General drivers ........................................................................................................................................... 101
# Table of Contents

4.5 SUMMARY AND CONCLUSION .......................................................................................... 102

CHAPTER 5: NSM MODEL STRUCTURE .............................................................................. 104

5.1 SIMULATION MODEL .................................................................................................... 104
5.2 LIMITATIONS OF THE MODELLING .......................................................................... 108
5.3 MODEL COMPONENTS .................................................................................................. 111
  5.3.1 Water component .................................................................................................... 113
  5.3.2. Economic component .......................................................................................... 124
  5.3.3. Environmental component .................................................................................. 125
  5.3.4 Crop component (Crop Decision Optimization Module CDOM) ............................. 126
  5.3.5 Water trading approach ......................................................................................... 130
  5.3.6 Water trading module (WTM) .............................................................................. 135
5.4 CDOM MODULE VALIDATION ................................................................................... 140
5.5 WATER TRADING MODULE VALIDATION AND RESULTS ........................................... 141
5.6 SUMMARY AND CONCLUSIONS .................................................................................. 145

CHAPTER 6: NSM MODEL CALIBRATION AND VALIDATION RESULTS ...................... 146

6.1 CALIBRATION METHODOLOGY ................................................................................ 146
  6.1.1 Parameter identification and data .......................................................................... 150
  6.1.2 VENSIM™ Powell’s Optimiser ............................................................................. 150
  6.2 MULTI OBJECTIVE FUNCTIONS AUTO-CALIBRATION ............................................... 152
  6.3 ASSESSMENT CRITERIA FOR MODEL PERFORMANCE ............................................. 154
  6.4 NSM CALIBRATION AND VALIDATION RESULTS .................................................. 157
  6.5 SUMMARY AND CONCLUSION .................................................................................. 173

CHAPTER 7: SCENARIO ANALYSIS .................................................................................. 176

7.1 INTRODUCTION ........................................................................................................... 176
7.2 SUMMARY OF SCENARIOS AND PERFORMANCE MEASURES ................................. 177
7.3 COMPARISON OF SUB-SCENARIOS ......................................................................... 182
  7.3.1 Best Scenario analysis .......................................................................................... 188
  7.3.2 Water use analysis ............................................................................................... 188
  7.3.3 Gross margin analysis .......................................................................................... 189
  7.3.4 Water saving analysis .......................................................................................... 190
  7.3.5 Environmental impact analysis ............................................................................ 191
7.4 SENSITIVITY AND UNCERTAINTY ANALYSIS ........................................................... 192
7.5 COMPARISON OF MANAGEMENT OPTIONS ............................................................. 196
7.6 LIMITATIONS OF THE STUDY .................................................................................... 201
7.7 SUMMARY AND CONCLUSION .................................................................................... 203

CHAPTER 8: CONCLUSIONS AND FURTHER RESEARCH .............................................. 205

8.1 RESEARCH STATEMENT, QUESTIONS AND METHODOLOGY ................................. 205
8.2 KEY MESSAGES AND FINDINGS ............................................................................... 207
8.3 FUTURE RESEARCH .................................................................................................... 212

CHAPTER 9: REFERENCES .................................................................................................. 214

APPENDIXES ...................................................................................................................... 227

APPENDIX A: MURRUMBIDGEE ENVIRONMENTAL AND RIVER FLOW OBJECTIVE ........ 227
APPENDIX B: CATCHMENT DEFINITIONS ........................................................................ 232
APPENDIX C: GENERAL SCENARIO DRIVERS ................................................................ 233
APPENDIX D: WATER MONTHLY FLOW DATA ML .......................................................... 241
APPENDIX E: RIVER REACH WIDTH AND WET PERMITTER ........................................ 243
APPENDIX F: WHAT’S BEST 7.0 STATUS REPORT ............................................................ 248
APPENDIX G: BASE CASE AND CROP MIX SCENARIOS RESULTS .............................. 249
APPENDIX H: SCENARIOS RESULTS ............................................................................... 251
LISTS OF FIGURES

Figure 2-1 Murray Darling Basin Modified from MDB (Murray Darling basin Commission) ............. 12
Figure 2-2 longitudinal Section of the Murrumbidgee River (observed data source: Khan S., et al., 2004) 14
Figure 2-3 Zonal Division of the Murrumbidgee Catchment (modified from NSW agricultural 1996).... 15
Figure 2-4 Location of irrigation areas on the river reaches ............................................................ 16
Figure 2-5 main off-take canals and irrigation areas ........................................................................ 16
Figure 2-6 Hydro-geological map of the Murrumbidgee catchment ................................................. 18
Figure 2-7 Observed annual ground water allocation and usage in the mid-Murrumbidgee area ......... 20
Figure 2-8 Overall Changes in deeper groundwater levels between Narrandera and Hay from 1990 to 2003 (modified from Khan et al., 2004a). ................................................................. 21
Figure 2-9 Observed lower Murrumbidgee groundwater use and surface water allocation ............. 21
Figure 2-10 Observed groundwater entitlements and use in the Lower Murrumbidgee.................... 22
Figure 2-11 Observed deep groundwater levels at downstream of Narrandera and Hay ................. 23
Figure 2-12 August Allocation percentage with different water regulations (observed data http://www.dnr.nsw.gov.au). ........................................................................................................ 25
Figure 2-13 Monthly Water Allocation from July – Feb (observed data http://www.dnr.nsw.gov.au) .... 25
Figure 2-14 Natural and current flow in the upper reaches of the Murrumbidgee river (measured data, source MDB). ................................................................................................................... 30
Figure 2-15 Median monthly current and natural flow (measured data, source MDB). ....................... 30
Figure 2-16 Gross margins with and without environmental flow rules (Modelled data, Source: Rohan J. et al., 2001). ...................................................................................................................... 32
Figure 2-17 The operation of the Cap on Murray Darling basin Diversions Source: MDB (2004) .... 34
Figure 2-18 Temporary trading in NSW regulated Rivers (1989–97) (observed data source DLWC, 1998), 35

Figure 2-19 Increase in temporary and permanent trading in the MDB (observed data Modified from source Thompson, 2005). ...................................................................................... 36
Figure 2-20 Water allocation versus water trading in and out from CIA irrigation area (Observed Data source CIA report 2004). .................................................................................................. 37
Figure 2-21 Observed CIA evaporation and annual volume trade- in (Data source: CIA environmental reports). ............................................................................................................................ 39
Figure 2-22 Observed monthly allocation and monthly water trading price in the Murrumbidgee Valley (Data source: CIA environmental reports). ........................................................................ 39
Figure 2-23 Growth in water use in Murray Darling Basin Source: MDB, (2004). ................................. 41
Figure 2-24 System feedback loops ................................................................................................ 49
Figure 3-25 Regulated and unregulated rivers in NSW (Data source DLWC 2000) ............................. 57
Figure 3-26 Schematic diagram of Murrumbidgee River with flow volume GL (observed data year 2000/2001) .................................................................................................................... 59
Figure 3-27 Total observed monthly diversion of the Murrumbidgee River .................................. 66
Figure 3-28 Observed groundwater use in the MDB since 1999/00 to 2003/04 (source: NSW-EPA, 2001) 70
Figure 3-29 Water available for banking ......................................................................................... 76
Figure 3-30 Long-term water bank management ............................................................................. 78
Figure 3-31 Water banking and water trading conceptual diagram ............................................... 79
Figure 4-32 Observed groundwater use pattern in lower Murrumbidgee (1983–2004) compared with surface water allocation ............................................................................................................. 85
Figure 4-33 Observed net temporary water trading of the main irrigation areas MIA and CIA .......... 88
Figure 4-34 Scenarios and modelling implementation ...................................................................... 92
Figure 5-35 General framework of the model .................................................................................. 107
Figure 5-36 Conceptual Structure of the simulation model ............................................................. 112
Figure 5-37 Schematic diagram of subcomponents views and its links ........................................... 113
Figure 5-38 shows the river schematic equation .............................................................................. 116
Figure 5-39 Crop calendar .............................................................................................................. 122
Figure 5-40 Crop Decision Optimization Module CDOM components ........................................... 127
Figure 5-41 Water trading behaviour .............................................................................................. 135
Figure 7-90 Average gross margins per ML under both recharge methods for Scenario three ............ 257
Figure 7-91 Environmental Index for Scenario three and its variations compared to base case Scenario 258
Figure 7-92 Average total water use for Scenario four and its variations compared to the base case...... 259
Figure 7-93 Annual ground water use for Scenario four and its variations compared to the base case ... 259
Figure 7-94 Average gross margin per ha and ML for Scenario four and its variations compared to the base case ................................................................. 260
Figure 7-95 Environmental index for Scenario four and its variations compared to the base case .... 260
Figure 7-96 Average total water use for Scenario five and its variations compared to the base case.... 261
Figure 7-97 Annual ground water use for Scenario five and its variations compared to the base case .... 262
Figure 7-98 Average total gross margin of Scenario five and its variations compared to base case Scenario under infiltration and injection recharge methods................................................................. 262
Figure 7-99 Average gross margin per megalitre of Scenario five and its variations compared to base case Scenario under infiltration and injection recharge methods........................................ 263
Figure 7-100 Environmental index for Scenario five and its variations compared to the base case .... 263
Figure 7-101 Average annual water use under different conditions..................................................... 265
Figure 7-102 Environmental index.................................................................................................. 265
Acronyms and Definitions

- **NSM**: Network Simulation model
- **CDOM**: Crop Decision optimisation module
- **WTM**: Water trading Module
- **NRM**: Natural resource management
- **WSP**: Water sharing plan
- **SD**: System Dynamics
- **NSW**: New South Wales
- **GM**: Gross margin

**Crop mix**: changing crop mix area using different cropping pattern systems resulting from CDOM and WTM (see section 5.3 for details).

**Water banking**: simply redirecting surface water during winter (low demand) to the underground aquifer for storage and re-abstracting groundwater during high demand periods (summer).

**Conjunctive water use**: managing surface and groundwater resources as single water source by using and pumping groundwater as substitute for surface water.

**Water trading**: Allowing water trading between surface and groundwater using the water bank as a mechanism for intermediate storage.

**Shifting dam release**: Shifting the surface water released from the two main dams (outflow with the same level of delivery to irrigators) by six months to try to mimic the natural flow regime.

**Surface water restrictions**: reducing surface water use by 10% and directing this saved water to the environment (it could be stored and released according to environmental needs, or released each month).

**Environmental performance**: Satisfying environmental flow at end of the system. If the irrigation allocation is more than 80%, 300 ML/day flow should pass the Balranald weir while, if the irrigation allocation is less than 80%, 200 ML/day flow should pass to the Murray River. This is one of the key measures used in this study to evaluate successful conditions.

**Seasonality of flows**: is the alteration in the characteristics or behaviour of the flow with different periodic time based on climatic conditions.

**Irrigation efficiency**: is measured on a system scale as a ration between delivery and water diversion.

**Agricultural productivity**: is the system revenue per area.
Chapter 1: Introduction

1.1 Introduction

Water is a key resource to sustain life and, while only 50 litres of water per day per person is the recommended minimum for household use, 70 times as much is needed to produce food for one person (SIWI, IFPRI, IUCN, IWMI, 2005). Significant problems of water shortage and deteriorating water quality are contributing to a growing water crisis in many countries. Therefore, sustaining growth in the human population and environmental flow require even more water to be available. Water availability is falling and conflict over water use and other water-related environmental problems are rapidly increasing in many parts of the world, including Australia.

Water scarcity is one of the principle problems in the Murrumbidgee Catchment, one of Australia’s major irrigation regions, and is exacerbated by rising demand for water for intensive summer dominant crop production, a growing population, agricultural production, pressure for land, and environmental demand (Khan et al., 2004a). With increasing water scarcity, the allocation of water rights becomes critical and competition for rights increases. In turn, producers have tried informal and formal ways to obtain and secure access to water. As an example, according to DLWC (1998), in the Murrumbidgee river basin, irrigation extraction, intensive cropping systems and land clearing have had a major influence on the river environment and water availability. In addition, irrigation demand has changed the natural flow regime of the river and has induced significant environmental changes. Increased demand for irrigation water has led to reduced and alters river flows and a reversal of the seasonal flow patterns.

Declines in river health are the result of a number of factors and an altered flow is believed to be an important contributor to many of the changes that have occurred (Acreman M. and Dunbar M. J., 2004). These include increasing algal blooms, declines in native fish populations and increases in exotic species, a decline of wetlands with some wetlands suffering from lack of water and others from permanent inundation, decreased opportunities for fish migration and breeding during winter and spring in the river and its anabranches, decreased frequency and duration of flooding of low-lying wetlands of the mid-river, and variability of flow and its impact on natural food production and other processes in the river (INR Inland River Network, NSW 2000).
Increasing scarcity of water and high demand on existing supplies by agricultural and other users have placed river systems under great pressure (Lovett. et al., 2002). Healthy rivers are vital for many reasons (Murray Darling Basin Commission MDBC, 2002). Good water quality is essential for productive irrigation, for fishing and manufacturing industries, for recreation and for town water supplies. Economic, environmental, cultural and social values are also affected by the quality of the river. The Murray Darling Basin Commission MDBC (2002) reported that, without doubt, there is sufficient evidence that many of the Australian rivers are in poor condition that has affected irrigation productivity and environmental outcomes. Maintaining a healthy river environment through the allocation and management of water resources remains a big challenge.

These pressures have resulted in significant competition for water, and water allocation issues between irrigation and environment are particularly controversial (water sharing plan, 2004). Current practice has maintained flows for upstream irrigation in preference to increasing flows for downstream users who are demanding that irrigation allocations be reduced to maintain flows and reduce river salinity levels. The main question is how, and from where, should this environmental water be provided? Answering this question requires creative solutions to achieve sustainable water resource management. Integrated water management in irrigated agricultural areas could be the best strategy to optimise the use of the available water resources (Beddek, et al., 2005).

The Cooperative Research Centre for Irrigation Futures (2005) reported that scientists have recommended three different approaches to meeting environmental water demand and targets; (i) obtain it from irrigators’ allocations; (ii) buy it by purchasing water on the open market; or (iii) save it by better demand management or by improving infrastructure to reduce losses/evaporation from supply systems. All of these approaches sound reasonable but need more study to assess their social, economic and political costs. In addition, environmental cost and benefit analysis may be used to assess management of environmental flows, particularly by applying the first two approaches. However, the third approach may be a potential and valuable approach for recovering or restoring environmental flow targets.

It is possible to achieve better environmental outcomes by using a different demand management approach to minimise the peak demand for irrigation water during summer cropping activities, so saving water for the environment (Langford and Ben-Mechlia, 2005). Furthermore, reintroducing natural flows and level characteristics through water management planning will reduce the ecological impacts of the system infrastructure.
There is a growing volume of literature on the potential environmental impacts of irrigation demand and which is developing in parallel to the research on environmental flows. However, studies researching the potential of better irrigation demand management to affect economic and environmental outcomes are few and of limited scope. Moreover, there are many models for water management systems, but there is a knowledge gap in linking bio-economic objectives and environmental constraints with the optimum use of water resources under conflicting demand (Xevi and Khan, 2005). The few existing models or tools suggest that irrigation demand management from programming models could provide a long-term analysis and view (see Letcher, R., 2005). Policy and decision-makers need better understanding and estimates of what management actions could assist in the short- to medium-term. Furthermore, most models only consider one objective or first-order impacts, such as maximising the gross margin, e.g., on farms or irrigation districts. Also, in general, the impacts on regional economies and environmental performance have not been taken into consideration.

Finding ways to meet irrigation demands and to achieve positive environmental and economic outcomes requires innovative policy initiatives. However, given the complexity of river questions, modelling tools are required to analyse the effectiveness of alternative demand, allocation and policy scenarios. These scenarios seek to assess the effects of options for the allocation and use of limited water resources (surface water and ground water) between agricultural production and the environment.

This research aims to assess new proposals against environmental and economical outcomes in the Murrumbidgee irrigation area of Australia. Furthermore, this project aims to help develop an understanding of how to improve water productivity and the environmental performance of the Murrumbidgee River through a range of demand management options, or opportunities suggested by stakeholders and irrigation communities. In particular, this research seeks to understand what could be achieved by linking irrigation demand and conjunctive water use management with water banking to improve the management of surface and groundwater in irrigated catchments and restore the environmental flow requirement.

The key environmental concerns in this research are expressed in terms of seasonal flows of water or environmental flows requirements. This research adopts end of system flows rule or requirement as one of the measurement of environmental performance of the river. If the allocation is more than 80%, 300 ML/day flow should pass the Balranald weir while if the
allocation is less than 80%, 200 ML/day flow should pass to the Murray River. This is one of the key measures used in this study to evaluate successful conditions. However, greater flow at the right time—higher in spring and lower in summer—could be considered a measure of beneficial environmental impact in future if the volumetric data become available. Ecologists are still attempting to determine the amount and timing of water flows, since simply increasing flows does not always lead to more flora or fauna. Similarly, more dollars do not always result in greater happiness and utility. The returns from agriculture are expressed in terms of net returns and gross margin per hectare and megalitres.

In the second section of this chapter, the research problem and objectives are described and discussed. Using a system theory dynamics approach, the objectives focus on evaluating the effectiveness of decisions on resource use, reallocation of water, and irrigation demand management, for improving seasonality of flows and environmental flow requirements. In the last section of this chapter an explanation of the outline of the dissertation is presented.

1.2 The scope and objectives of this study

The overarching objective of this research is to better understand the link between irrigation demand, conjunctive water use management and water banking, with environmental outcomes. This will be done by measuring the change in economic output and environmental outcomes in response to various allocations and demands from the irrigation sector, in particular, the impact on improved seasonality of flows and environmental flows. This project focuses on the Murrumbidgee catchment since this area provides a clear example of the difficulties in jointly achieving economic and environmental objectives. Environmental objectives in this study are represented by end of system flow. Additionally, there is already a great deal of knowledge and information that can facilitate research of this kind.

The two main irrigation areas in Murrumbidgee catchment (see Chapter Two section 2.1 for details) are the Murrumbidgee irrigation area (MIA) and Coleambally irrigation area (CIA) plus other small areas pumping directly from the Murrumbidgee River. The MIA and CIA use more than 70% of total irrigation water from the Murrumbidgee catchment. Irrigation demand is greatest during the summer season in all irrigation areas due to summer cropping which leads to changed river flows temporally and spatially (time and volume).

The reliability of irrigation supplies and the historically conservative nature of surface water allocation announcements by the Department of Land and Water Conservation DLWC are likely to have a significant influence on the crops grown by irrigators. The
implication is that farmers would be unlikely to base their farm plans solely on announced allocations at the beginning of the season (August and September). The most important factors that affect water allocations are rainfall, the amount of water in storage (or dams) and the state’s allocation rules or policies. For example, an important issue has arisen from environmental flows that has had the effect of reducing allocations by 4–10% (Khan et al., 2004b). Furthermore, the combined operation of the two main head dams Burtinjuck and Blowing, and water diversion, has had substantial effects on the flow regime (DLWC, 2000):

- seasonal patterns have changed to satisfy the irrigators; requirements, particularly in the middle river reach
- flow variability has reduced, particularly upstream of the irrigation areas
- the average discharge of water at the end of the system in the river downstream of the major irrigation areas is now much less than 40% of the total flow.

The frequency of high flows is now only about half the natural frequency, and average flows between June and October have dropped by a third (DLWC, 2000). At the downstream end of the system (Balranald weir) average flows are now about one third of their natural level (Khan et al., 2004b). Consequently, uncertainty in water allocations, environmental flow requirements (target) and innovative cropping systems are required to achieve a different and better seasonal distribution of water to satisfy consumptive and in-stream environmental demands.

This research is based on the hypothesis that better water demand management would result in optimum productivity of irrigation areas and better management of river flow: in particular, management strategies which consider system constraints on water conveyance and losses in conjunction with environmental requirements or constraints. This research seeks to improve information about better irrigation water demand management strategies to inform decision making for overall water management.

Given the problems with reduced water allocation and increased demand for water, the Murrumbidgee catchment could experience critical water scarcity, and thus regional economic performance will reduce (Jayasuriya R., 2004). If the current situation continues, it is expected that river health will decline, which will in turn reduce social and economic wellbeing. While the amount of water varies from year to year, the number of uses and total quantity consumed is increasing. Khan et al. (2004) reported that it is predicted that with global climatic change, the size of Australia’s water resources will decline and consumption
will grow. This situation would lead to reduced water availability for downstream users and a consequent decrease in crop yields and regional prosperity.

Better economic productivity and environmental performance may be achieved by spreading irrigation demand, by changing demand (volume and time), or by changing the time of supply through irrigation area storage facilities (water banking approach) or changing stock such as dam releases, water trading and change in cropping pattern. The seasonality of flows could be improved by using a number of options. These can be categorised into three main groups:

1. **Management:**
   - better irrigation demand management by changing the cropping pattern
   - water banking and conjunctive water use management
   - surface water substitution by ground water pumping
   - allowing water trading between surface and groundwater
   - market-based approach to reducing surface water demand.

2. **Storage:**
   - temporary water trading between the irrigation areas for storage purposes
   - storing water on-farm and off-farm during low season
   - wetland restoration and storage
   - new storage on tributaries of the upstream reach between the existing dam wall and Wagga Wagga.

3. **Policies and new technology:**
   - keeping land idle, with the incentive for improved ecosystem services
   - reduced evapotranspiration and seepage along the irrigation system to increase system and end-use efficiency
   - removable environmental barrage.

The focus of this study is on the first category (management) with the analysis focusing on three management options: irrigation demand management by changing the crop mix; surface-ground substitution with water trading between surface and ground water; and design interventions such as water banking with conjunctive water use management that would effectively influence the dynamics of water use, allocation, management and quality. This is the main contribution of this research. Therefore, the general research questions this study will address are:
• How can the available knowledge be integrated within a model in an effective way to provide a useful understanding of the current system’s economic outcomes and environmental performance (end of system flows) at catchment and irrigation area scale?
• What management options can be used to improve water productivity and river environmental performance to achieve satisfactory end of system flows?
• What are the implications (economic and social) of these management options (different demand and supply managements including water banking)?

From the previous discussion, the observed trend of the water problem is an increasing demand for water or diversions as well as a decreasing supply of this commodity and the consequent decline in river health and regional economics. Therefore, the major drive for this research is to develop a better understanding of the trade-off between water productivity, agricultural income and environmental performance by looking at the link between irrigation demand, conjunctive water use management and water banking; quantifying the economic and environmental impacts of these options.

This project will address the previous questions through the following three objectives:
• Develop or propose an integrated (hydrological–economic and environmental) modelling framework that incorporates hydrological, economic and environmental constraints. This will be designed to simulate and optimise irrigated areas’ demand management by considering both demand side and different water resource options.
• Evaluate and analyse the current economic and environmental performance by employing the developed integrated framework on three levels of analysis (crop/field, irrigation area and catchment levels) within the Murrumbidgee catchment.
• Assess and compare the economics and environmental impacts of the proposed future management scenarios under different climatic conditions.

The approach is based on system dynamics (system theory) and an optimisation approach that includes economic and environmental factors that influence irrigation demand, conjunctive water use management and water banking activities. The integrated model is expected to be able to effectively reflect the complexities of irrigation demand management systems temporally and spatially, and provide the desired compromise between different
objectives at the irrigation area or whole catchment level. The key indicators are
environmental flows at the end of the system and the gross margin per area and per water
used. In addition, several other indicators are observed which represent water use, water
productivity, area production, economic, and area welfare.

It is clear the present water reforms and policies in Australia and in the Murrumbidgee
catchment have political and social dimensions. This research will not investigate or consider
the political and social debate about environmental flow targets, or compensation and
incentive issues. Instead it will focus on developing a tool to investigate recommended
options from stakeholders and to aid policy-makers and other stakeholders with some
recommendations for water policy and management. It should be noted that this study is
limited to the assessment of options from a policy perspective and does not seek to
undertake an engineering assessment of the feasibility of certain proposals. Certainly, further
work would be required to ensure the engineering feasibility of preferred policy initiatives.

The model as an aid tool will help understand how to improve environmental
performance of the Murrumbidgee River through better irrigation demand management and
conjunctive water use management, and water banking approach. It can be used to test and
identify potential option to improve river water productivity and environmental
performance. It can also used to identify those reaches of the river where water banking can
improve seasonality of flows. Although this research will consider modelling the effects of
environmental flow rules, groundwater pumping rules and temporary water trading between
irrigation areas on improving the seasonality of flows, it will not thoroughly investigate every
aspect, for example, environmental impacts, legal and political issues and long-term policy
ramifications. Various demand-side and supply-side options will be examined and tested to
find the best policy options for improving economic productivity and environmental
performance through the integrated modelling framework. The expected project outcomes
will address policy scenarios for improving the Murrumbidgee River’s agricultural
productivity and restore environmental flows at the end of the system. Furthermore, it will
investigate the enhanced water security and expansion of irrigation leading to broader
environmental and economic outcomes. Finally, the integrated modelling framework
developed can offer useful policy and planning tools to catchment managers, water supply
authorities, policy and decisions makers and irrigators.
1.3 Outline of the dissertation

The three major steps developed in this research include systems analysis of the study area, development of several scenarios for different water use patterns based on different cropping patterns under different climatic conditions, and construction of the Network Simulation Model (NSM). Interim steps include the introduction of a conjunctive water use and water banking approach as a major component of the model and development of the Crop Decision Optimisation Module (CDOM) to capture farmers’ behaviour and their crop plan, followed by development of Water Trading Module (WTM) which will both feed the NSM model by input data. These steps are followed by verification and validation of the CDOM and WTM and then, calibration and validation of the NSM model. The system analysis of the study area involves two aspects, characterisation of the study area and analysis of the decision-making criteria and constraints on which the model is based.

This thesis is divided into eight chapters plus the bibliography. Following this introductory chapter, a review of the research problem background and critical issues pertaining to it are presented. The study area and the history of development of environmental flow rules are examined in Chapter Two, together with a general background on modelling irrigation system using the system approach. The literature on the system dynamics approach and theory is also reviewed. The chapter ends with a summary of the main findings.

Chapter Three looks at available management options and proposes, with a focus on irrigation demand and crop mix, a conjunctive water use and water banking approach. This chapter includes a discussion of the concept and the underlining issues related to water banking, a summary of water trading literature and water trading rules in NSW, followed by a description of groundwater and temporary water trading modelling. Also in this chapter, seasonality of flows pattern and definitions are presented.

Chapter Four explains the base case and scenarios used for testing, along with the variations to be tested. A discussion is presented about what indicators are appropriate for assessing the results from the recommended scenarios. Then, issues of uncertainty related to the scenarios analysis, drivers and implementation are examined, followed by a summary and conclusion of the main points.

In Chapter Five, this chapter describes how system dynamics can be applied to the irrigation system on irrigation area level with an emphasis on the development and conceptualisation of the integrated modelling frame work, NSM. Moreover, development of
the crop decision module, CDOM, is discussed in terms of its structure and constraints planning. In addition, this chapter explains the development of the water trading module, WTM, and its purpose, structure and objective. The validation and verification of these modules are then presented. This chapter ends with a summary and conclusion of the main findings.

Chapter Six explains the calibration and validation methodology of the overall NSM integrated model including model parameters identification, the selected Powell optimiser and the model performance criteria used to evaluate the calibration and validation results. In addition, this chapter ends with a conclusion about the significant findings of this chapter.

Chapter Seven presents the results of the scenarios compared to the base case. This chapter starts with a summary of the six scenarios and their variations (sub-scenarios). Then the overall performance of the sub-scenarios is assessed. This chapter is also discusses and presents a sensitivity and uncertainty analysis and integrates these findings to interpret the results. This is followed by a comparison of the main management options and limitations of the study. This chapter ends by with a summary and conclusion of the best options to improve the seasonality of flows and the balance between environmental and economic outcomes.

The thesis concludes in Chapter Eight with a summary of the interpretation of the model’s results and possible implication results of the findings. This chapter ends with recommendations for future research to be considered with ideas about future inter-disciplinary research.
Chapter 2: Case Study and Literature Review

This study focuses on investigating alternative options to improve Murrumbidgee River water productivity and environmental performance. Moreover, it seeks to provide understanding of the link between irrigation demand and conjunctive use of surface and groundwater combined with aquifer water banking. This chapter presents an overview of the study area, critical issues concerning the research objectives and a literature review on modelling irrigation systems from a system approach perspective.

In this chapter, an overview of the study area of the Murrumbidgee catchment is presented in section 2.1, which includes a quantitative and qualitative description of water and irrigation systems, their location, and general features. This study argues that the environmental flow demand and irrigation demand conflict with each other and so the rules for managing environmental flows are presented. A discussion of irrigation and environmental demands, water allocation and groundwater hydrogeology and use in the catchment is presented. This section will also investigate the balance between consumptive use and in-demand use in achieving economic benefits. Section 2.2, the critical issues of economic productivity, environmental impacts of river regulation, trading and allocation rules related to the research area are described in Australian and Murrumbidgee contexts. Section 2.3 summarizes the arguments for and against irrigation demand management with environmental and economic outcomes related to the catchment, and its interaction with irrigation system management. Section 2.4 includes a brief overview of the irrigation system complexity and a brief review of the existing Murrumbidgee water allocation and management models. It presents possible techniques that can be used to model such a complex irrigation system. As the study uses system dynamics modelling and multi-objectives optimisation, this section also includes a brief description of the system dynamics simulation approach, which is a type of simulation modelling. In the last Section 2.5 a brief conclusion of the key messages from the literature and the research problem is presented.

2.1 Overview of the Murrumbidgee catchment (case study)

The Murray Darling Basin covers most of inland south-eastern Australia. It includes much of the country’s farmland and a population of over 2 million people (MDBC 2004b). Located in south-east Australia, the Murray-Darling Basin covers 1,061,469 km\(^2\), equivalent to 14% of the country's total area see Figure 2-1. The Basin extends over three-quarters of
New South Wales, more than half of Victoria, significant portions of Queensland and South Australia, and includes the whole of the Australian Capital Territory (MDBC, 2000) see Below Burrinjuck Dam, the river flows initially through a narrow reach and then a widening valley near Gundagai. The Tumut River joins the Murrumbidgee River upstream of Gundagai. The total catchment area of the Tumut River is 4000 km$^2$ (Khan et al., 2004a). Blowering Dam is the major storage on the Tumut River; it stores both natural river flows and water that has been released from the Snowy-Tumut Section of the Snowy Mountains Hydro-Electric Scheme. The overall capacity of Blowering Dam is 1,632,000 ML.

Table 2-1. The Murrumbidgee River is one of the most regulated rivers in the Murray Darling basin (MDBC 2001), with a catchment area of around 84,000 km$^2$ and a length of 1600 km from its source in the Snowy Mountains to its junction with the Murray River. The Murrumbidgee River has two main head dams that regulate its flow: Burrinjuck and Blowering Dams. The total catchment area above Burrinjuck Dam is 13,000 km$^2$ its storage capacity is 1,026,000 ML.

![Figure 2-1 Murray Darling Basin Modified from MDBC (Murray Darling basin Commission)](http://www.mdbc.gov.au/naturale/users/natresources/basin_stats/statistics.htm)
Below Burrisnuck Dam, the river flows initially through a narrow reach and then a widening valley near Gundagai. The Tumut River joins the Murrumbidgee River upstream of Gundagai. The total catchment area of the Tumut River is 4000 km² (Khan et al., 2004a). Blowering Dam is the major storage on the Tumut River; it stores both natural river flows and water that has been released from the Snowy-Tumut Section of the Snowy Mountains Hydro-Electric Scheme. The overall capacity of Blowering Dam is 1,632,000 ML.

### Table 2-1 State shares of the Murray-Darling Basin

<table>
<thead>
<tr>
<th>State</th>
<th>Total area of states (km²)</th>
<th>Area in Basin (km²)</th>
<th>Percentage of states in Basin</th>
<th>Percentage of the area of the Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>New South Wales</td>
<td>802,081</td>
<td>599,873</td>
<td>74.8%</td>
<td>56.6%</td>
</tr>
<tr>
<td>Victoria</td>
<td>229,049</td>
<td>130,474</td>
<td>60.0%</td>
<td>12.3%</td>
</tr>
<tr>
<td>Queensland</td>
<td>1,776,620</td>
<td>260,011</td>
<td>14.6%</td>
<td>24.5%</td>
</tr>
<tr>
<td>South Australia</td>
<td>984,395</td>
<td>68,744</td>
<td>7.0%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Australian Capital Territory</td>
<td>2367</td>
<td>2367</td>
<td>100%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Totals</td>
<td>3,794,512</td>
<td>1,061,469</td>
<td>28%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

According to Khan et al., (2004b) in the river section between Burrisnuck Dam and Wagga Wagga the following unregulated tributaries flow into the Murrumbidgee River: Jugiong Creek (catchment area: 2200 km²), Muttama Creek (catchment area: 1200 km²), Adelong Creek (catchment area: 520 km²), Billabong Creek (catchment area: 1200 km²), Hillas Creek (catchment area: 520 km²), Tarcutta Creek (catchment area: 2000 km²) and Kyeamba Creek (catchment area: 700 km²). These tributaries are the main source of gain within this river reach between the dams and Wagga Wagga.

Downstream of Gundagai, the Murrumbidgee River flows through flat alluvial plains towards its junction with the Lachlan and Murray Rivers. In certain reaches of the river, the conveyance capacity is limited e.g., the Tumut River and the Gundagai Choke. Under average flow conditions this results in flows away from the main river through streams such as Yanco Creek downstream of the town of Narrandera. Yanco Creek flows south-west for about 180 km to its junction with Billabong Creek, a tributary of the Murray River.

The Murrumbidgee River has a very steep slope upstream of Gundagai to its confluence with the Tumut River. This is illustrated by Figure 2-2, which shows a longitudinal section of the river, and distances and elevations between major centres. In addition it gives travel times for different reaches of the Murrumbidgee River for medium to large floods. Due to flat slopes, the travel time of around 30 days from Narrandera to Balranald is around three
times the travel time for a similar distance upstream of Narrandera. The system includes some major floodplain lakes, e.g., Lake Mejum near Narrandera and Yanga Lake near Balranald. The main flow constraints in the Murrumbidgee system include the limited conveyance capacity of the Tumut River (<9000 ML/day) and the Gundagai Choke (<32,000 ML/day) (Murrumbidgee Catchment Board, 2003). The catchment is subdivided into three zones based on climate and hydrology (Figure 2-3). The research focused on zones 1 and 2, which include the main irrigation areas (Murrumbidgee irrigation area and Coleambally irrigation area) in the Murrumbidgee catchment plus the private irrigation areas. These two irrigation areas use more than 70% of available water.

Figure 2-2 Longitudinal Section of the Murrumbidgee River (observed data source: Khan S., et al., 2004)
2.1.1 Murrumbidgee valley irrigation areas

Major irrigation areas and districts in the Murrumbidgee Valley are concentrated on the riverine plains, especially in the region now managed by Murrumbidgee Irrigation (MI) and Coleambally Irrigation Cooperative Limited (CICL). This region is collectively known as the Murrumbidgee Irrigation Area (MIA) and includes the Yanco and Mirrool Irrigation Areas, located on the northern side of the Murrumbidgee River and the Coleambally Irrigation Area (CIA) located on the southern side of the Murrumbidgee River Figure 2-4.

These two main areas, MIA and CIA, were developed by the government to foster regional development through irrigation (Jayasuriya R., 2004). Technically, the MIA and CIA no longer exist, as they have been reformed as cooperative irrigation companies. However, since the terms MIA and CIA are still in common usage, this dissertation will continue to refer to them. Irrigation also occurs along the length of the Murrumbidgee River through private diverters which will be referred to as PRD 1, PRD 2, PRD 3 and PRD 4 based on their location to the river reaches (Figure 2-5), including a number of the river’s pumped
zones. This figure (Figure 2-5) shows the schematic spatial distribution of the 12 irrigation demand nodes involved in the case study of this research and their locations on the river reaches (Table 2-2).

Figure 2-4 Location of irrigation areas on the river reaches

Figure 2-5 main off-take canals and irrigation areas

The MIA and CIA are the largest areas of irrigation production, accounting for 180,000 and 77,000 hectares approximately of irrigated area respectively (Jayasuriya R., 2004). There are around 1940, 368 and 835 irrigation farms in the MIA&D (Murrumbidgee Irrigation Area and districts), the CIA and along the regulated river reaches respectively; comprising
both broad acre and perennial horticulture farms. The major irrigated agricultural enterprises in these areas include annual crops such as rice, oilseeds, cereals, vegetables and pasture supporting livestock enterprises including prime lamb, wool and beef production, to perennial crops such as wine grapes, citrus and stone fruit.

Table 2-2 Irrigation area location, area and water licence

<table>
<thead>
<tr>
<th>Irrigation area</th>
<th>Location</th>
<th>Farm area</th>
<th>Water Licence</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD 1 irrigation node</td>
<td>located between dam walls and Wagga Wagga weir</td>
<td>11,134 ha</td>
<td>102 GL</td>
</tr>
<tr>
<td>PRD 2 irrigation node</td>
<td>located between Wagga Wagga to Narrandera weir</td>
<td>44,614 ha</td>
<td>201 GL</td>
</tr>
<tr>
<td>PRD 3 irrigation node</td>
<td>located between Narrandera to Hay weir</td>
<td>66,571 ha</td>
<td>165 GL</td>
</tr>
<tr>
<td>PRD 4 irrigation node</td>
<td>located between Hay to Balranald weir</td>
<td>18,452 ha</td>
<td>154 GL</td>
</tr>
<tr>
<td>Coleambally irrigation area (CIA)</td>
<td>has been divided into three irrigation nodes based on their soil suitability (CIA 1, CIA 2 and CIA 3)</td>
<td>(60,347 ha, 6,112 ha and 11,160 ha) farm area respectively</td>
<td>total water licence 482 GL</td>
</tr>
<tr>
<td>Murrumbidgee irrigation area (MIA)</td>
<td>has been divided into five demand nodes (Yanco, Mirrol, Benrembah, Tabbita and Wah Wah)</td>
<td>(Yanco and Mirrol) 110,950 ha farm area (Benrembah and Tabbita) 42,827 ha farm area Wah Wah 28,016 ha farm area</td>
<td>583.7 GL water licence 225 GL water licence 120 GL</td>
</tr>
</tbody>
</table>

According to Khan et al., (2004b) Gogeldrie Weir, some 50 km downstream of Berembed, was completed in 1959 to enable the diversion of extra water to the MIA and associated districts and later to the CIA. Sturt Canal leading north from the Gogeldrie Weir was constructed to supply parts of Mirrool Irrigation Area, Benrembah Irrigation District and the Coleambally Canal leading south. The principal summer crops grown in the MIA and CIA are rice, corn, and soybeans, while winter crops include wheat, barley, oats, and canola, and horticultural products (grapes, prunes, vegetables). These crops are the main source of irrigation demand in the area studied in this research.

MIA and CIA, as mentioned above, are served by water from the Murrumbidgee River, particularly the middle three reaches: Wagga Wagga-Narrandera, Narrandera-Darlington point and Darlington point to Hay. These reaches support the off-take main canals known as the Murrumbidgee main canal, Sturt Canal and Coleambally canal.

2.1.2 Groundwater hydrogeology and use

Groundwater, in a broad sense, is all water that occurs below the land surface in aquifers. Aquifers occur in geological formations that are sufficiently permeable to allow water to move within them, allowing it to discharge or be extracted. According to the NSW State Groundwater Policy (1998), groundwater is usually categorised as occurring in:
1. Unconsolidated sediments—non-cemented sands and gravels commonly found in alluvial valleys, coastal plains and sand dune systems. Groundwater is contained within the pore space in these sediments.

2. Sedimentary rocks—consolidated or semi-consolidated formations such as sandstone, limestone, shales. Groundwater occurs both within the pore space in the rock matrix and also within fractures and joints.

3. Fractured rocks—volcanic and metamorphic rocks such as granite, basalt, shales and gneiss. Groundwater in these rocks occurs mainly within fractures and joints.

The Murrumbidgee catchment can be broadly divided into three major hydro-geological units (Figure 2-6).

- Upper Murrumbidgee Fractured
- Mid Murrumbidgee Alluvium
- Lower Murrumbidgee Alluvium

**Upper Murrumbidgee fractured aquifer**

Upstream of Narrandera the catchment geology mainly consists of hard consolidated rocks of Palaeozoic age. The useful groundwater pumping potential of the upper catchment is limited due to the low yielding nature of the fractured rock aquifers (Khan et al., 2004b). Most of these aquifers are made up of discontinuous local groundwater systems providing base flows to the upper Murrumbidgee creeks.

![Figure 2-6 Hydro-geological map of the Murrumbidgee catchment](image)

**Mid Murrumbidgee alluvium**

This is a deep V-shaped aquifer system called ‘Mid Murrumbidgee Alluvium’ between Gundagai and Narrandera (around 300 km in length). It overlies the weathered bedrock, and ranges in width from 1.5 km near Gundagai and 20 km upstream of Narrandera. According to Khan et al. (2004b), the mid Murrumbidgee alluvial aquifers are broadly classified as an
upper unconfined Cowra Formation and a lower confined Lachlan Formation (Wooley, 1972; Lawson et al., 1998). The Cowra formation consists of low yielding (<15 L/s) sands which vary in thickness from around 15 m near Gundagai to around 35 m near Narrandera. The Lachlan Formation is composed of well-sorted sands and gravels varying in thickness from around 10 m near Gundagai to about 125 m near Narrandera.

Khan et al. (2004b) reported that the pumping rates of current bores in the Lachlan formation vary from 5 L/s at Gundagai to over 150 L/s near Narrandera. From the mid-Murrumbidgee aquifer the town water supplies from the borefields for 1998–1999 were 21,190 ML (Gumly Gumly 3,650 ML, Wagga Wagga 12,932 ML). Aquifer salinity is low (less than 0.85 dS/m) near the river, indicating frequent recharge and discharge from the river, while aquifer salinity increases away from the river to levels greater than 5 dS/m according to irrigation water. Studies by Webb (2000) show a very strong hydraulic response between the mid-Murrumbidgee alluvial aquifer levels and river flow levels. Any reduction in seepage losses from the river in this reach will have a direct negative effect on groundwater availability. The total annual recharge to this aquifer is estimated to be around 127,000 ML (Webb, 2000). The current entitlements are around 55,000 ML, which gives potential for more extraction. The annual groundwater use and allocation in the mid Murrumbidgee ground water zone are shown in Figure 2-7.

*Lower Murrumbidgee alluvium*

Downstream of Narrandera, there are unconsolidated alluvial deposits of layers of sands, silts, clays and peat. These units are collectively known as the Lower Murrumbidgee Alluvium. This alluvial system contains three major aquifers: the shallow Shepparton, intermediate Calivil and the deep Renmark Formations (Brown and Stephenson, 1991). According to Khan et al. (2004a), the Shepparton formation is mainly formed by unconsolidated to poorly consolidated, mottled, variegated clays and silty clays with lenses of polymictic, coarse to fine sand and gravel, partly modified by pedogenesis. The Calivil mainly contains poorly consolidated, pale grey, poorly sorted, coarse to granular quartz and conglomerate, with a white kaolinitic matrix. The Renmark formation overlies the basaltic bedrock. The Renmark formation is distinguished from the Calivil formation by the presence of grey, carbonaceous sand (Webb, 2000).
The shallow Shepparton sediments were deposited by a series of prior streams over several million years. Below the Shepparton formation (20–60 m thick), the Calivil aquifer systems often extend to depths greater than 150 m. Water movement through the deep aquifers is generally from east to west, except in the area with major groundwater pumping around Darlington Point. Recharge of the deep aquifers is mainly from the Murrumbidgee River downstream of Narrandera and from the irrigation areas. The salinity increases from east to west, but is generally low. Deep groundwater with low salinity levels (<0.005 µS/cm) occurs over a large area extending between Narrandera and Hay. The shallow Shepparton aquifer is often very saline, especially under the irrigation areas where salinity levels can be high e.g. 0.02–0.12 µS/cm (Kumar, 2002).

According to Kumar (2002), the Lower Murrumbidgee Alluvium has been estimated to have 250,000,000 ML of low-salinity groundwater in storage, while the average annual recharge is estimated to be around 335,370 ML/year. In the last 10 years local imbalance between groundwater recharge and discharge has resulted in around 10–20 meters residual draw down in deep aquifers over large areas between Darlington Point and Hay, which gives the opportunity for artificial recharge (Figure 2-8). Overall groundwater use in the lower Murrumbidgee area has increased, while surface water allocation has decreased (Figure 2-9).
Figure 2-8 Overall Changes in deeper groundwater levels between Narrandera and Hay from 1990 to 2003 (modified from Khan et al., 2004a).

Figure 2-9 Observed lower Murrumbidgee groundwater use and surface water allocation.

Table 2-3 shows the groundwater use in the two main groundwater management zones in the Murrumbidgee catchment, and sustainable yield. In addition, the estimated annual recharge of the Middle Murrumbidgee aquifer is around 127,000 ML (Webb, 2000). The current entitlements are around 55,000 ML. While, the estimated annual recharge to the Lower Murrumbidgee aquifer system is 335,370 ML/yr, a ‘safe yield’ is 270,000 ML/yr (Kumar, 2002). Figure 2-10 gives an account of the annual groundwater use and entitlement for the lower Murrumbidgee catchment from 1981–1982 to 2000–2001. Although there is a rapid increase in the use of groundwater since 1994–95, the reported groundwater pumping is still less than the sustainable yield, (the maximum volume can be extracted). This is an opportunity for more pumping.
Table 2-3 Observed groundwater use.

<table>
<thead>
<tr>
<th>Murrumbidgee Groundwater Management Areas Water Use</th>
<th>Sustainable yield 650,000 ML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundwater use/sustainable yield</td>
<td>1999/00</td>
</tr>
<tr>
<td>Lower Murrumbidgee (D/S Narrandera)</td>
<td>248,417</td>
</tr>
<tr>
<td>Mid Murrumbidgee (U/S Narrandera)</td>
<td>1,459</td>
</tr>
<tr>
<td>Total Murrumbidgee source</td>
<td>249,876</td>
</tr>
<tr>
<td>SWA allocation</td>
<td>78%</td>
</tr>
</tbody>
</table>

The groundwater level of the deeper aquifers between Narrandera and Hay has suffered an overall decline (Figure 2-8). In the last 10 years, the deeper groundwater pressures have declined by 10–20 metres over most of the area. This is confirmed by individual deep piezometer trends downstream of Narrandera (draw down from −15 m to −31 m) and Hay (slight increase from −10.85 m to −10.65 m) see Figure 2-11 and Figure 2-8. Raised groundwater trends downstream of Hay could be attributed to an increased area of rice growing adjacent to the river and/or losses from the river. The declining groundwater levels may result in ingress of saline groundwater from shallow aquifers to deep aquifers and lateral movement of deep saline groundwater towards better quality groundwater. Residual groundwater draw down in deeper aquifers offers a potential for these aquifers to be artificially recharged; using good quality water from new dedicated bores or existing bores. This can help reduce salinisation of deeper aquifers as well as offer an evaporation free, secure underground storage ‘dam’ and could also work as an underground water bank. The
water banking approach and related issues are discussed in detail in the next chapter (Chapter Three).

![Graph](image)

**Figure 2-11 Observed deep groundwater levels at downstream of Narrandera and Hay**
(Data source: Khan *et al* 2004).

### 2.1.3 Water allocation

According to Khan *et al*, (2004a), water entitlements in the Murrumbidgee Valley in a given year depend on storage levels of dams and inflows as shown in Table 2-4. The water is allocated according to the following hierarchy:

1. environmental water provisions
2. basic rights requirements
3. licensed domestic and stock requirements
4. local water utility requirements
5. any water carried forward in water accounts
6. high security
7. general security.

NSW has two types of water licence for irrigators: high security and general security. The holders of the high security licence are guaranteed to receive 100% with a minimum of 95% of their licence during the water year, rather than the holders of the general security licence who are guaranteed a percentage based on annual allocations (general irrigator’s allocation—described in the next paragraph).
Table 2-4 Water Entitlements in the Murrumbidgee Catchment (Data source Khan S. et al., 2004a)

<table>
<thead>
<tr>
<th>Category</th>
<th>Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>basic landholder rights</td>
<td>4560 ML</td>
</tr>
<tr>
<td>native title rights</td>
<td>0 ML</td>
</tr>
<tr>
<td>local water utility access licences</td>
<td>23,403 ML</td>
</tr>
<tr>
<td>domestic and stock access licences</td>
<td>35,572 ML</td>
</tr>
<tr>
<td>high security</td>
<td>278,252 ML</td>
</tr>
<tr>
<td>general security</td>
<td>2,416,432 ML</td>
</tr>
</tbody>
</table>

The annual allocations are determined by the volume of water held in storage in the two major dams at the start of the water year (July 1), the minimum likely tributary inflow, and the likely contribution of water from the Snowy Mountain Hydro-electric Scheme. The amount of water required for environmental flows, essential requirements and carryover to the next year is evaluated and the amount of water that will be lost in transmission is established. Provisions for high security requirements are then made and the remaining water determines the general security allocations (irrigators’ allocation). If the allocations are below 100%, the system is monitored and if there are improvements in inflows to dams these allocations are progressively increased. So far, allocations in the Murrumbidgee have never reached 100% since the 2000 water year, which is after the introduction of the water cap and water sharing policy (Figure 2-12 and Figure 2-13).

Irrigators in the Murrumbidgee and Coleambally irrigation areas have historically received very reliable irrigation supplies. Coleambally Irrigation, CICL, (2000) reported that under normal conditions, irrigators could expect to receive their full allocations in all except the driest of years see Figure 2-12 and Figure 2-13. An initial allocation made at the commencement of the season is updated continuously during the season in response to rainfall. Historical allocation announcements show that initial allocations were either set at their maximum level (100% or higher) at the start of the irrigation season or set at a lower level and then considerably increased as the season progressed. Since 2000–2001 the surface water allocation the maximum end of seasonal allocation was 71% and 38% in 2001 and 2005 respectively. This end-of-season allocation is a major issue for irrigators and is a key metric for evaluating the effects of different water policy and allocation on the region’s economy.
2.1.4 Environmental flow rules

This is one of the major issues for this research: the dispute between environmental and irrigation water demand. The Murrumbidgee River Management Committee has developed a set of rules for the regulated Murrumbidgee River system for 1999–2000. These rules are designed so that water is shared between other users and the environment to improve river health whilst providing some level of water security to irrigators (water sharing plan, 2002). There are four flow rules in operation, as follows and in detail in Appendix A.
1. **Dam transparency**

‘Dam transparency’ refers to ensuring that the amount of water flowing into the dam is equal to the amount flowing out during certain periods.

2. **End of system flows**

This flow rule is aimed at achieving a certain flow target at the end of a river system. If the allocation is more than 80%, 300 ML/day should pass the Balranald weir while, if the allocation is less than 80%, 200 ML/day should pass to the Murray River. This is one of the key measures used in this study to evaluate successful conditions.

3. **Dam translucency**

‘Dam translucency’ means that part of the inflow is allowed to flow through the dam. The translucency rule takes effect from the moment the dam begins to store water.

4. **Environmental contingency allowance/provisional storage**

An ‘environmental contingency allowance’ is a quantity of water set aside for future use to meet environmental objectives. Provisional storage involves the retention of water in storages to meet future irrigation commitments.

These rules effectively affect the water supply by reducing the water allocation to irrigators. Khan (2004) pointed out that water entitlement for irrigators has reduced by approximately 4 to 5% of their total entitlement. Also, these rules relates to end-of-basin flow, more consideration need for intermediated river reaches and its implication which is beyond the scope of this study. Therefore, it is worthwhile to study the impact of environmental flow implementation on irrigation demand and regional economies. This study is adopting rule 2 (end of system flows) as the main measure factor or attribute of environmental performance of the river.

2.2 Critical issues related to the research problem (Australian and Murrumbidgee contexts)

Recently, agricultural research has expanded beyond its traditional focus on agricultural productivity to include the use of natural, environmental and economic resources. Irrigation is the largest water user worldwide (Rosegrant, and Ringler, 2000). Over the last decades irrigated areas have increased rapidly, helping to boost agricultural output and feed a growing
population (SIWI, IFPRI, IUCN, IWMI, 2005). Irrigation uses the largest fraction of water in almost all countries and this is certainly the case in the Murrumbidgee catchment.

Effective research addressing these issues requires an interdisciplinary approach to be able to study irrigation demand management whilst taking account of economic and environmental benefits. The demand for a more comprehensive approach to these problems is apparent as attempts are made to develop sustainable integrated water resources systems worldwide. Bio-physical simulation and optimisation models could be effective tools to analyse the complex relationships among natural resources in irrigation systems at the irrigation area levels. In the next sections, this chapter will discuss some critical issues for water problems from a global and Australian point-of-view, followed by a focus on the Murrumbidgee catchment area.

2.2.1 Economic use of irrigation water

The allocation and distribution of water in an irrigated agricultural system requires a comprehensive understanding of the complex interactions between physical, technical, socio-economical and organisational factors that affect each irrigation system. Increasing competition for scarce water resources has motivated researchers to examine the efficiency of water use in irrigation systems (e.g., Wichelns, 2002). In general, efficiency can be measured at the scale of a whole catchment, at the individual plant scale, and at almost any level in between. In this context, irrigation efficiency is measured on a system scale as a ration between delivery and water diversion, to account for system losses. In recent years, many researchers have found that many studies measure irrigation efficiency in policy settings without a corresponding economic analysis (e.g., to determine the optimal allocation of scarce resources (Willardson, et al., 1994; Wichelns, 2002)). According to some studies (e.g., NWSRU, 1996; Wichelns, 1999; Elmahdi, 2000), in Egypt, for example, the typical irrigation efficiency at the farm level is around 45–55%. While for the whole irrigation sector in one basin, it is around 75–82% due to interaction of irrigation and drainage systems. The remaining 18–25% is beneficial for other sectors such as the environment as it releases water to wetlands and the Mediterranean Sea. This efficiency ratio does not represent the economic performance at the farm level, which should include water cost, crop prices and water productivity.

Many authors have indicated the important role of economic analysis in irrigation management or water reallocation. For example, Keller et al. (1996, p.15) emphasised the examination of physical efficiency as well as the much broader concept of economic and
environmental efficiency. They recommend that ‘even if a closed irrigation system were operating at nearly a 100% overall efficiency, substantial economic gains could be made by reallocating water from lower to higher valued uses’.

Moreover, as Molden, and de Fraiture, (2000) pointed out, the problem with the concept of efficiency is that it refers only to physical quantities of water. It does not capture the difference in the value of water for alternative uses by obtaining more production per unit of water or by reallocating water from lower to higher valued crops. Economic analysis or economic efficiency is helpful and important in describing the effects of designing an irrigation policy for alternative water allocations and equitable distribution. Economic efficiency could be achieved when limited resources are allocated and used in a manner that generates the greatest net value, which incorporated variable and fixed costs.

As mentioned above, economical use of irrigation water is a universal problem for water allocation policies and water productivity. From a farming perspective, it is important to take into account economic analysis when formulating water allocation policy to generate high net values from limited water resources. According to Rosegrant and Ringler (2000), 70 percent of the freshwater diverted for human purposes goes to agriculture. Irrigation water demand is still increasing because the area being irrigated continues to expand. Meanwhile, industrial and domestic water demand has been increasing rapidly as a result of increasing economic development, population and urbanisation. In some regions water is already being transferred out of irrigation and into urban-industrial uses, putting additional stress on the performance of the irrigation sector (Rosegrant and Ringler, 2000). Although the achievement of irrigation in ensuring food security and improving welfare has been impressive, previous experience also indicates problems and failures of irrigated agriculture. In addition to high water use and low efficiency, environmental concerns are usually considered the most significant problem for the irrigation sector. The marked reduction in annual discharge of some of the world’s major rivers has been attributed in part to the large water depletion caused by irrigated agriculture, which in turn affects the river environmental health (MDBC, 2000). Water scarcity problems in developing countries could become more severe, and lead to a push to encourage people to migrate in search of water sources. This might lead to water wars in the future. People who experience this problem can be called water refugees.

Australia is one of the driest continents on the earth. Only 12% of rain runs off into rivers (MDBC, 2001). To compensate, Australia stores more water than any other country—
4 ML per person and 1.3 million litres per person per year. Australians are the second highest per capita consumers of water in the world (David F., 2004). According to David F. (2004), Australians have access to three times as much fresh water as the average Dutch citizen and 170 times as much as the average Jordanian. As reported by NLWRA National Land and Water Resource Audit (2000a), there is no reason to be complacent about the future of the key water streams in Australia. Some of Australia’s streams are considered to be very heavily allocated for irrigation and urban supplies and, in some cases, now have less than half of their natural flow available and even less in drought years. Studies such as (DLWC, 1998) estimate that Murrumbidgee River has less than 40% of its natural flow at the end of the system. This places the Murrumbidgee system under stress and reduces in a major way its capacity to deliver other services, not least the provision of a healthy environment.

Water scarcity, one of the principle problems in the Murrumbidgee Catchment, is exacerbated by the rising demands for water, such as in-stream demand, which reduces water allocation for irrigators by 5–10% (Khan, 2004b). This affects growth in population and agricultural production, and puts land and the environment under pressure. With increasing water scarcity, the allocation of water rights becomes a critical and controversial issue.

As many researchers have pointed out (Baumann and Boland, 1998; Grigg, 1996; Louks, 2000), modern societies face a water crisis. The fundamental factors of the water crisis are population growth; economic growth and urbanisation; rise in per capita water use; a finite supply of fresh water; pollution and contamination; and potential increase in the frequency and severity of droughts. Without a doubt, at the catchment level there are many competing water uses: water for agriculture, industry, domestic and for the environment. According to DLWC (1998), water is a finite resource and the signs are that it has reached the limit of reasonable use. For irrigation demand management, sustainability implies balance or equilibrium between crop water demands and in-stream demand. The traditional approach to managing water has been to build dams to provide a secure water supply for water users. According to Inland River Network IRN-NSW (2000), this approach has been wasteful and has had some devastating impacts on the environment such as cold water being released, which negatively affects fish breeding.

Over the last 100 years the Murrumbidgee River and associated wetlands and floodplains have changed significantly from their natural state with the use of water for agriculture, recreation, industry and domestic needs. These diversions of water—on average 50% of
natural flows—generate significant economic benefits, including about $343 million of irrigated agricultural products in the Murrumbidgee (Eigenraam et al., 2003).

There is clear evidence of increasing environmental stress within the river. For example, Figure 2-14 shows changes in flow, volume and seasonality along the Murrumbidgee River, particularly upstream of the irrigation area. Most of the irrigation diversion takes place in the upper river reaches and by the time the water reaches Hay and Balranald gauge stations, most of the summer releases have been removed and used. This has the effect of returning it to a natural seasonal flow pattern, but with a significantly reduced amount of water see Figure 2-15 (measured data, source MDBC). This situation has led to decreased breeding opportunities for native wildlife and fish populations and has increased the frequency of algal blooms (INR Inland River Network, NSW, 2000).

![Figure 2-14 Natural and current flow in the upper reaches of the Murrumbidgee river](image1)

![Figure 2-15 Median monthly current and natural flow](image2)
Consequently, the real challenge is to maintain ecological progress while continuing to supply agricultural and industrial enterprises, towns and stock, and domestic users with the water they need. Environmental flow rules for the Murrumbidgee River try to support some of the ecological processes specified by the water sharing plan WSP (2004) that will be discussed in more detail in the following section. Increased demand for water for agriculture and urban uses is putting the management of Australia’s rivers under scrutiny. Management must balance the various water use needs, providing also for in stream requirements, biodiversity and water quality.

There are clear hydrological, environmental and financial limitations to increasing the water supply for irrigation. Consequently, there has been emphasis on demand management (Winpenny, 1994). He mentioned four major demand management options, reduce waste and physical losses in distribution systems; increase recycling of water in all industries; treat water as an economic good and increase water prices; and reallocate the existing water supply more evenly and equitably.

This research will focus on the last management option (reallocate available water more evenly and equitably) recommended by Winpenny (1994), while examining treating water as an economic good on water reallocation. This option could tend to offer long-term solutions to water shortages and meeting increasing irrigation and environmental demands. In the last decade, water scarcity and a degraded water environment have become a significant problem. It has been proposed that future water management should be based on sustainable criteria and principles that take into account environmental and economic aspects. This research will address the environmental and economic benefits of irrigation demand management.

Water is required for different uses and users. It becomes a matter of competition for quantity, quality and timing. The seasonality of flow changes according to summer cropping activities, which moves the high peak flow from winter/spring to summer. Under natural conditions, there are high flows during the low water usage months from June to August, with the lowest flow during the peak water usage months of December to February. In addition, uncertainty of water allocations, environmental flow requirements and intensive cropping systems require a better understanding and distribution of the irrigation system in the Murrumbidgee catchment to improve the seasonal distribution of water to satisfy consumptive and in-stream environmental demands.
2.2.2 Water environment and economic viability and reliability

Water from the Murrumbidgee River supports a major portion of NSW’s irrigation industry and provides income and employment for thousands of people. As well as producing food for local consumption, it is also the source of hundreds of millions of dollars in exports for Australia. The long-term economic viability of the valley depends on the continued health of the River. Figure 2-16 shows how the gross margin for the two main irrigation areas has been affected after implementation of the environmental flow rules for one year. There is a slight difference before and after, but $2–4 million for irrigators and irrigation companies is of considerable importance. Furthermore, these have the effect of increasing opposition to environmental flow initiatives. Therefore, it is vital that the economic effects of management options are transparent so that communities can be confident about the impacts.

![Gross margin chart](chart.png)

Figure 2-16 Gross margins with and without environmental flow rules (Modelled data, Source: Rohan J. et al., 2001).

As well the river providing habitat for many species of fish and other wildlife; it also provides water for large areas of wetlands and floodplain forests. The waters of the Murrumbidgee are a finite resource and the signs are that they have reached the limits of reasonable use. To address the need for a better balance between river health and irrigation use, the NSW government introduced a water-sharing plan (2002) under the umbrella of the cap. The major targets were an achievement of more explicit and careful sharing of water between the environment and water users, and mitigation of the impacts of high summer flows for irrigation by release of environmental flows.
The Murrumbidgee River is regulated by two main dams and several weirs. The cold water released from dams affects fish (INR Inland River network, NSW, 1999). This problem of cold-water pollution (or temperature depression) has been recognised by fish biologists, professionals and recreational anglers. Water released from the bottom of dams during summer for irrigation is generally too cold for native fish by 10–15°C. Bottom-release water is generally 10–13°C, whilst most native fish require temperatures of at least 20°C to breed (INR Inland River network, NSW, 1999). River network, NSW (2000), reported severe downstream effects. Cold-water pollution has prevented breeding in several fish families over the past years. Also, declines in river health are the result of a number of factors; altered flow is believed to be an important contributor to many of the changes that have occurred including:

- increased frequency of algal blooms
- declines in native fish populations and increases in exotic species
- decline of wetlands, with some wetlands suffering from lack of water and others from permanent inundation
- decreased opportunities for fish migration and breeding during winter and spring in the river and its anabranches
- decreased frequency and duration of flooding of low-lying wetlands of the mid-river
- variability of flow and its impact on natural food production and other processes in the river.

It is suggested the effects of high summer flows for irrigation are to be mitigated and the full benefits realised from the release of environmental flows, which is one of the main river flow objectives. The main benefit of environmental flow releases is the reinstatement of greater natural flow variability to restore degraded environmental river quality (water sharing plan, 2002). Maintaining the flows for irrigation competes with increasing river flows for all downstream users, who are demanding that irrigation allocations be reduced to maintain flows and reduce river salinity levels. The Murrumbidgee catchment is facing severe and growing challenges in maintaining and meeting the rapid reduction in water allocations due to introduced rules and external factors such as climate change (see Figure 2-12 and section 2.1.3). In addition, water used for irrigation will likely have to be diverted from irrigation to meet the needs of other users (i.e., in-stream demand). In the same way, environmental and
other in-stream water demands become more important as economies develop. It is important to investigate other sources to satisfy environmental demand. These include water savings in irrigation areas and catchments. It is suggested that a large share of the water to meet new demands could come from water saved from existing uses through a comprehensive reform of water policy (Beddek et al., 2005).

2.2.3 Tools for reallocation: cap and trade

The MDB Cap was introduced to maintain water extraction in the MDB at 1993–94 levels. The Murray-Darling Basin cap is based on 1993–1994 levels of development (crop area, infrastructure, and management rules) adjusted for climatic conditions. The cap in New South Wales is not the volume of water that was used in 1993–94. Rather, the cap in any water year is the volume of water that would have been used with the infrastructure (pumps, dams, channels, areas developed for irrigation, management rules, etc.) that existed in 1993–94, assuming similar climatic and hydrologic conditions to those experienced in the year in question. Thus, the cap provides scope for greater water use in certain years and lower use in other years, as illustrated in Figure 2-17.

![Image of graph showing water diversion over time](image-url)

**Figure 2-17 The operation of the Cap on Murray Darling basin Diversions** Source: MDBCA (2004)

Theoretically, in wetter or cooler years than 1993–1994, users should activate less water for use and trade. This water saved is climatic under use (or saving of above cap allocation) and may be used for the environment and to support resource reliability for water users. In a hotter or drier year than 1993–94 users are able to activate more water than in 1993–94 if the resource is available, because more water will be required for cropping in those years. The
cap is therefore a fundamental part of water access property rights in the Murray Darling basin. It is also consistent with the ability to maintain cropping levels and the opportunity to benefit from better use of water in the future, in the form of farm income or environmental improvements.

In addition, temporary transfer of water entitlements was permitted in the southern MDB since 1983 (Hall and Poulter, 1994). By mid-1990s, permanent intra-state transfers were allowed in state legislations, but interstate trading was not permitted until the end of the decade. However, trading was limited due to high transaction costs arising from restrictive transfer conditions (Pigram and Delforce, 1992). Water resource management in Victoria has often taken the lead compared to other Australian states, e.g., *Irrigation Act 1886* and progress with current water reforms (Smith, 1998). Only in the mid-1980s was the concept of transferable water entitlements raised (Howe et al., 1986). Eventually this was legislated for in 1990 (Pigram and Delforce, 1992). Temporary water trading (with legal recognition) officially began in Australia in the late 1980s. A more cautious approach to permanent trading has been taken due to the potential consequences for third parties and the environment. There are still major uncertainties over the status of existing water entitlements in over-allocated regions, due to the lack of clearly specified environmental flow requirements. Presently, permanent and temporary water trading is concentrated in the irrigation sectors of NSW (Figure 2-18) with some limitations to permanent water trading.

![Figure 2-18 Temporary trading in NSW regulated Rivers (1989–97) (observed data source DLWC, 1998).](image)

Across the Murray and Murrumbidgee Basins, both irrigated entitlements and allocations in regulated surface water systems are tradeable. Since the Council of Australian Governments (COAG) meeting in 1993–94 that resolved to encourage the separation of
water entitlements from land titles, there has been a considerable increase in water trading (Figure 2-19). The main reasons for allowing this were to encourage water use in locations and for practices that returned greater economic value, and to allow its transfer away from areas where use was causing unacceptable environmental problems, such as areas with a high water table or high salinity.

![Figure 2-19 Increase in temporary and permanent trading in the MDB](observed data Modified from source Thompson, 2005).

Water trading could serve as a way of solving water-sharing problems in the Murrumbidgee River, leading to a potential positive effect on the supply system and on seasonal flow. After the cap was introduced in 1994, trading has noticeably activated the water trading market and increased the water price, particularly during times with a low seasonal flow. As the volume of water entering the area decreased when compared to the previous years, the volume of water leaving the area increased as in CIA, this was reported in CIA annual environmental reports 2002 (Figure 2-20). This can be attributed to the low water allocation for the season and increased prices for temporary transfer, causing many farmers to opt for selling their water rather than growing summer crops. Water trading involves trade in water entitlement (permanent) and seasonal water allocation (temporary trading). Temporary trading involves transferring some or all of the water allocated to entitlements for the current irrigation season or an agreed number of seasons. Temporary water trading increases with reductions in water allocation to irrigators. Thus, permitting trade of seasonal allocation allows irrigators to reallocate water in reaction to climatic
conditions and water availability. Temporary water trading also diminishes the impact of reductions in irrigation water availability.

Figure 2-20 Water allocation versus water trading in and out from CIA irrigation area (Observed Data source CIA report 2004).

According to the MDBC Water Audit Monitoring Report 2002/2003 (2004), water allocations will fluctuate from year to year, depending on climatic conditions and constrained by the physical resources available. Moreover, the utilisation of the allocation will be higher in drier years and lower in wetter years. It is also expected that allocations would reduce and usage increase, if the allocation system was tightened to prevent growth in diversions under the cap. The water move or trade occurs when the buyers perceive positive returns and sellers are adequately compensated to maximise their return and sell their unused water.

The factors affecting trade within and between irrigation areas could be water allocation, water price changes, physical supply capacity (limitations on the volume of water which can pass), commodity or crop prices, water shortages (irrigation water availability minus crop water requirement schedule) and uncertain rainfall. According to Kirby et al., (2006), the water trading price goes up as the year gets drier. The benefits of introducing trading within irrigation areas are greater than further benefits of expanding trade between the irrigation areas with the additional benefits of lower environmental impacts and lower transaction costs (Appels et al., 2004). Whilst it would seem intuitive that the water-trading price increases as the water becomes scarcer and decreases when more water becomes available, Zaman et al., (2005) stated that this is not the case as different pool prices have been observed in wet seasons. This could be attributed to a higher commodity price or other seasonal conditions.
2.2.4 Trading pattern

On 25 June 2004, the Council of Australian Governments’ (COAG) agreed to a National Water Initiative for national water management. This initiative is intended, among other things, to expand water trade to bring about a ‘more profitable use of water and more cost effective and flexible recovery of water to achieve environmental outcomes’ (COAG, 2004).

In the three major irrigation districts of the southern Murray-Darling Basin (the Murray Irrigation district, the Murrumbidgee Irrigation Area, and the Goulburn-Murray Water district), gross trade in entitlements accounted for less than 2 per cent of total water allocations in 2002–03, while gross trade in seasonal allocations accounted for around 20 per cent (see Table 2-5). The demand for irrigation water is complicated by the fact that irrigators can also supply irrigation water to other irrigators. This makes management of the irrigation system more complex. Irrigators can sell part or all of their seasonal allocation or their underlying water entitlement, i.e., a farmer cultivating annual crops may choose not to plant his farm for a year if the expected return from selling or trading allocations, together with income from alternative land uses, exceeds the expected return from the irrigated crop.

| Table 2-5 Observed gross trade in seasonal allocation and entitlements to total allocation |
|-----------------------------------------------|---------|---------|---------|
|                                              | 2000-01 | 2001-02 | 2002-03 |
| **Murrumbidgee irrigation area**             |         |         |         |
| Ratio of trade in seasonal allocations to total allocations | 18.9     | 14.2     | 17.3     |
| Ratio of trade in entitlements to total allocations     | 0.3      | 0.6      | 0.6      |
| **Murray irrigation area**                    |         |         |         |
| Ratio of trade in seasonal allocations to total allocations | 14.2     | 6.9      | 28.6     |
| Ratio of trade in entitlements to total allocations     | 0.3      | 0.3      | 1.4      |
| **Goulburn-Murray water district**             |         |         |         |
| Ratio of trade in seasonal allocations to total allocations | 9.7      | 12.2     | 18.4     |
| Ratio of trade in entitlements to total allocations     | 1.7      | 1.7      | 2.5      |
| **Aggregate**                                   |         |         |         |
| Ratio of trade in seasonal allocations to total allocations | 10.9     | 11.1     | 19.5     |
| Ratio of trade in entitlements to total allocations     | 0.9      | 0.9      | 1.8      |

Source: Appels et al. (2004), Australia government Productivity Commission

Appels et al. (2004) claimed that seasonal conditions, uncertainty about future rainfall and the supply of irrigation water mean that some irrigators may choose to hold a greater water entitlement than required for a typical year as a means of reducing risk. In New South Wales, horticulturists are likely to hold high security water entitlements as an alternative means for managing risk, while the majority of annual croppers (including rice growers) hold general security water entitlements. Figure 2-21 shows the evaporation is in reverse trend with the total volume trade in CIA. Appels et al. (2004) concluded that water price is higher in dry years than in wetter years. In very dry seasons water companies may be unable to deliver the
full water entitlement and there will be strong competition for traded allocations. Figure 2-22 shows the trend of monthly water prices with monthly water allocation for 2003–04 and 2004–05 water year. Most irrigators with perennial pastures or crops will seek to purchase a traded allocation to augment their reduced seasonal allocation, while the supply for trade will come from irrigators with annual cropping (Qureshi et al., 2005).

Figure 2-21 Observed CIA evaporation and annual volume trade-in (Data source: CIA environmental reports).

Figure 2-22 Observed monthly allocation and monthly water trading price in the Murrumbidgee Valley (Data source: CIA environmental reports).

Understanding the market for seasonal allocation or temporary water trading is useful when considering irrigator’s responses to changes in price. Traded volumes can be large and prices can differ significantly from one irrigator, or district, to another and from irrigation season to irrigation season. The market for seasonal allocations is likely to reflect the
allocation decisions of water utilities, and seasonal conditions in both the headwaters of the catchment, and locally. For example, Brennan (2004, p. 14) highlighted the fact that the price of traded allocations is closely related to the percentage of seasonal allocation delivered by the utility. High prices for traded allocations correspond to seasons when allocations are low and lower prices with seasons when allocations are fully met.

From the above discussion, water trading could provide a mechanism for handling water sharing problems in the Murrumbidgee River, and can have a potentially positive impact on the supply system. Therefore, it is very important to study and understand the link between irrigation demand and water trading, taking account of environmental requirements (environmental flow legislation) and how a water-banking approach could facilitate and minimise the effects of water trading.

2.2.5 Water availability and scarcity

Given the problems with water allocation and demand management, the Murrumbidgee Catchment could experience critical water scarcity and a decline in river health if the current situation continues (Khan et al., 2008). While the amount of water available varies over the years, the number of uses, groundwater use and total quantity consumed is increasing. It is predicted that the amount of a resource will decline as consumption grows (Khan, 2004). This situation would inevitably conclude in an increase in groundwater use, lack of surface water for downstream and environmental users, and a consequent decrease in crop yields and in farm and regional incomes. The observed trend of the water problem is an increasing demand for water, or level of diversions, and a decreasing supply of this commodity and the consequent decline in river health. This trend in diversions over time is shown in Figure 2-23. In consequence, it is very important to analyse the effects of increased demand for water for irrigation and other uses, and the decreasing supply, on river health and irrigation area incomes.

2.3 Catchment and its interaction with irrigation management concept

Intensive cropping systems, a greater human population, agricultural development and economic growth are the main reasons for an increase in water demand in general, and irrigation demand in particular. This raises problems in the efficient and high profit use of this scarce resource. Water use efficiency involves much more than simply conserving water; it involves an agreement with society that water is its most valuable resource and that decisions on its use take place within a political climate (Brooks et al., 1994; Winpenny,
Brooks, et al. (1994) pointed out that most natural processes, such as water flow, landslides, erosion, fish migration and water pollution occur within catchment boundaries. Therefore, it is very important to highlight the catchment as the management unit for water resources.

![Figure 2-23 Growth in water use in Murray Darling Basin](source: MDBC, 2004).

Catchments are appropriate units for the analysis of the environmental impacts of water and land-use decision-making. This is because in the catchment context it is easy to understand how people affect, and are affected, by the interactions of water with other resources (see appendix B for catchment definitions). Brooks et al. (1994) pointed out that catchment-level analysis takes into account:

a) the interactions between different users and purposes as well as the availability of water resources as a limitation to what is feasible for development, such as the conflict between consumptive and non-consumptive water use

b) creates a framework within which allocations between competing users can be made in line with government priorities, (i.e., any modelling framework for water allocation must be aligned with the water sharing plan developed in the study area)

c) establishes operating rules for responding to variability from year to year and within each season and favours modifications of these rules as circumstances change and pressures on the resources amount (i.e. the results from the framework could be used as recommendations to influence the modification of water sharing rules and policy).

In this context, this research will deal with irrigation and environmental uses of water which compete in for quantity, time, and value. As the traditional approaches of developing
and using water resources could hardly support sustainable social and economic development, it is imperative to transform the existing ways of managing water resources (Wang, 1999 and 2003). Irrigation demand management is also a critical development issue because of its many links to agricultural productivity, water use, poverty reduction, improving health, industrial and energy development, and sustainable growth in downstream communities. But strategies to enhance agricultural productivity should not lead to further degradation of water resources or ecological services. Finding a balance between these objectives is important for planning and management and one of the main objectives of this study.

**Irrigation management**

In general, managing water resources is an integrated concept for a number of different water sub-sectors such as hydropower, water supply and sanitation, irrigation and drainage (Davis, D., 1996). An integrated water resources perspective ensures that social, economic, environmental and technical dimensions are taken into account in the management and development of these resources. Consequently, integrated irrigation water management in irrigated agricultural areas is the best strategy to optimise the use of the available water resources (Beddek et al., 2005). The main limiting factors for increased agricultural production are the availability of suitable land and water. In addition, water availability is falling and there is increasing conflict over water uses and other water-related environmental problems in many parts of Australia, and particularly in the Murrumbidgee catchment.

Irrigation management, by the simplest water and irrigation engineering definition, involves the transformation of natural hydrological resources into a managed resource to be used by the society for irrigation. In this context, two terms should be taken into consideration.

1. **Hydrological effects:** how the hydrological parameters such as rainfall, evapotranspiration, infiltration, and runoff are affected by climatic changes and hydro-meteorological changes.

2. **Water resources impacts:** how control, use and distribution of the available water supply for the use of irrigators and the protection of the environment are affected by changes in the natural catchment (Stakhiv, 1998).

The second term is the main focus of this study. The goal of irrigation demand management is to increase the reliability of water related services, and to mitigate the hydrological, seasonal and climatic extremes (such as floods and droughts). It should be a
self-adapting endeavour whereby the management system responds and adjusts to various challenges, such as climate variability, water availability, shifts in water uses and demand, demographic changes and public preferences, along with technological innovations and institutional requirements (Stakhiv, 1998). Additionally, irrigation demand management is being increasingly called upon to address water-related environmental and economic issues. This includes aquatic ecosystems, wetlands, endangered species, waterborne diseases, revenue, gross margin, water and economic productivity. Therefore, irrigation demand management is one of the main options considered in this study. There were several assumptions.

In meeting water resource challenges, a series of water sharing plans in New South Wales have been introduced to clarify the conditions of sharing water between different users, particularly in the Murrumbidgee catchment area. The Murrumbidgee River Management Committee was established in 1997 to advise on the environmental flow rules for this catchment. These rules are reviewed each year and provide the first phase of the environmental protection of the river.

There are provisions in the plan to provide water to support ecological processes and the environmental needs of the river, and direct how the water available for extraction is to be shared. The plan (water sharing plan, 2002) also sets rules that affect the management of water access licences, water allocation accounts, the trading of or dealing in licences and water allocations, the extraction of water, the operation of dams and the management of water flow. Implementing the water-sharing plan is considered one of the main effects on surface water allocation to farmers, and hence drives this study to quantify the economic and environmental changes at the irrigation area scale. These rules effectively affect the water supply by reducing the water allocation to irrigators. Khan (2004) claimed that the water entitlement for irrigators has reduced by approximately 4 to 5% of their entitlement. Therefore, it is worthwhile to studying the effects of different demands and allocations of irrigation water on environmental flow, seasonal flows and irrigators’ economics.

In view of the above, it is valuable to study the impacts of different allocations and demand from irrigation on improved seasonal and environmental flows at catchment level, taking account for hydrological, economic and environmental conditions. The next section (2.4) presents a brief overview of the complexity of the irrigation system and its implication on the modelling approach as a tool for studying irrigation systems. It focuses upon the
concepts, approach, principles and purposes of modelling and on the system modelling approach that can be used.

2.4 Modelling of irrigation system (a systems approach)

Irrigation systems are diverse in size, they range from field or farm systems to near farm, regional, basin and catchment systems; in character, they range from biophysical, environmental, and economic to social; and in duration, they range from hours for rainfall to centuries for soil erosion. Irrigation systems can be classified spatially, temporally, hierarchically or by subject matter (Fresco, 1994; Rhoades, 1998). In space, the hierarchy of irrigation systems ranges in scale from micro-level crop components to the field, to the whole farm, to irrigation areas and multiple irrigation areas, to large scales such as catchments. Some of the more complicated system environments lie at the intersection of different classes of boundaries, including the physical, biophysical and the environmental as well as social.

Irrigation systems also can be viewed or modelled statically or dynamically with respect to time. Dynamic systems include crop growth where time is central to evolutionary processes (Fresco, 1994; Fresco et al., 1994; Rhoades, 1998). Stability and sustainability systems are often of special interest in dynamic models (Conway, 1987). The inherent time lags are not explicit; although there is a relationship of predictive interest. An example of static process may be the cropping production decisions triggered by the type of year (i.e., in the study area, intimations of a dry year will trigger the planting of crops perceived to be appropriate for such conditions and require less water; a wet year will give chance to shift and select any crops).

Irrigation system demand is an inherently complex system with many interdependent variables across hydrological, agronomic, economic and environmental processes (Beddek et al., 2005). These variables must drive the processes across three infrastructure components: (1) source components such as rivers, canals, reservoirs, and aquifers; (2) demand components off-stream (irrigation fields, and areas) and in-stream (hydropower, recreation, environment); and (3) intermediate components such as treatment plants and water reuse and recycling facilities. Additionally, irrigation water demand management is strongly influenced by uncontrolled variables such as climate, and finally any additional segmentation arising from decentralised management must also be considered (e.g. where a natural resource management (NRM), or land and water management plan is decentralised and a
catchment is covered by several management bodies). An integrated modelling framework must allow for these layers of complexity.

In the Murrumbidgee River catchment (the case study), there is an ongoing examination of how to improve water policy since increased demands for water have led to reduced river flows and a reversal of the seasonal flow patterns (DLWC, 1998b). Based on the previous discussion about irrigation system studies and analysis, this study will rely on a simulation model to test potential policy initiatives. Importantly, this study will observe the practice outlined by Letcher et al. (2006) where it was stated that integrated models (such as this study) should not be developed as prediction tools, but as aids to understanding system responses to changes such as policy and option changes. Therefore, the model must be carefully designed to provide sufficient flexibility to offer insights yet a conservative approach to the range of application.

This model required for this study needs to focus on the irrigation area scale (sub-region scale: Murrumbidgee irrigation area divided into five sub-regions; Coleambally irrigation area divided into three sub-regions); and the river system at a whole-of-catchment scale. In terms of time scale, this study is concerned with irrigation area and catchment levels, biophysical-economic and environmental relationships on a monthly time scale (to be able to represent the seasonality of the system). In system and policy analysis, this study is focused on the first two components of the irrigation system ((1) source components such as rivers, canals, reservoirs, and aquifers; (2) demand components off-stream (irrigation fields, and areas) and in-stream (environment)) and their interactions. Within this study of the Murrumbidgee irrigation system, the components of the proposed model are hydrological, agricultural, economic and environmental.

Given the importance of integrated modelling, it is not surprising that a number of modelling tools have been developed for Murrumbidgee catchment in the field of water allocation and planning. These tools have been assessed to determine their suitability for this study (see Table 2-6).
<table>
<thead>
<tr>
<th>Model and Authors</th>
<th>Model Approach</th>
<th>Model objective</th>
<th>Shortcomings: model not suitable for this study objective</th>
</tr>
</thead>
</table>
| Xevi and Khan, (2003) modelled water management and sustainable water allocation | Multi-objective optimization approach | To maximizes production targets under a set of multidisciplinary constraints incorporating biophysical, economical and environmental factors. | - The model used two hypothetical irrigation demand node to represent the two main irrigation areas (Murrumbidgee irrigation area and Coleambally irrigation area)  
- The model use annual time scale to satisfy environmental demand by optimising the irrigation system demand.  
- The model is not dynamic, and does not capture the seasonality of the system.  
- Not represent dam release and the complete river network. |
| Hyde et al., (2003) modelled water resource decision making. | Multi-criteria decision analysis linked with multi-objective optimisation approach | To optimise water resource allocation by focused on the sensitivity analysis of weights coefficients used in the multi-criteria decision analysis. | - Time-scale is not sufficient to capture the seasonality of the system.  
- The model represents economic and environmental factors as constraints to the system rather than their interdependencies.  
- The model is not available for general application and is not able to represent the feedbacks relationship inherited into the system. |
| Singh et al., (2005) whole-farm model mainly for rice farm | Simulation model | To analyse the impact of water trading, with different levels of water allocation, on different crop rotations | - The model is on farm scale and represents only the rice crop farm  
- The model is not representing the irrigation area and the whole catchment scale.  
- The model is not able to represent the environmental factors. |
| (Khan, et al. 2005) forecasting water allocation for the Murrumbidgee Valley | Neural network model | To predict dam inflows and water allocation in irrigated Murrumbidgee catchment by using the sea surface water temperature | - The model is not representing the economic component of the system and can not determine economic impacts which can result from different estimated water allocation depend on the sea surface water temperature.  
- The model is not representing or estimating seasonal irrigation demand  
- The model is not for policy analysis rather than as prediction tool for water allocation and dam inflows. |
| (khan et al., 2004) numerical model | Simulation model | To simulate possible management scenarios for surface-groundwater interaction for the Murrumbidgee Irrigation Area | - The model is using the regional scale but not the whole catchment system  
- The model is representing only one irrigation area to determine the impact of increasing groundwater pumping on irrigation system.  
- The model is not representing the economic factors and the seasonal irrigation demand  
- The model is not able to represent the feedbacks relationship inherited into the system. |
<table>
<thead>
<tr>
<th>Citation</th>
<th>Model Type</th>
<th>Purpose</th>
<th>Issues</th>
</tr>
</thead>
</table>
| (Graham, 2004) | System dynamics | Simulation model | To explore alternative management scenarios for inundated wetlands | - The model is not representing the economic factors as it is out of the scope of the study.  
- The model treated the irrigation demand (diversion) as given.  
- The model is not representing the cropping and system variables. |
| Yu et al., (2003) | linear programming | “WRAM model” | To determine water reallocation and water trading in Murrumbidgee Catchment. | - The model is using annual time scale and not sufficient to capture seasonality  
- The model treated allocation as given to determine water trading and crop mix.  
- The model is not representing the hydrological network  
- The model treated the irrigation area as one node (not included sub-regions). |
| IQQM (Integrated quantity and quality modelling) (Hameed and O’Neill, 2005). | Simulation model | IQQM | To assess the impacts of water management policies at the whole-of-catchment scale by examining the proposed policy development in the river system using nodes and links. | - The model operates on a daily time step  
- The model is purely hydrological allocation model  
- The model is lacking from integration of economic and environmental factors at the regional scale,  
- The model is treating cropping system as given in simulation  
- The model is failure to represent crop water requirement and production functions. |

These models tried to model water allocation in Murrumbidgee catchment, IQQM is the most relevant model to this study objectives. However, its time scale and hydrological focus make it infeasible. The other models in Table 2-6 can not even consider for this study, because they have different model objective, temporal and spatial scale. In summary, the review of these existing models in Murrumbidgee catchment shows that, these models are suffered from two key problems which preclude their use in this study:

- Most of these models are focussed primarily on hydrological allocation and do not include sufficient economic or environmental variables to test the policy options in this study.
- Most of the models are annual and not able to represent seasonality or are too aggregated

The essential relations within each component of the irrigation system and the interrelations between them can be considered in an integrated assessment modelling framework (Letcher et al., 2004). There are several examples of integrated assessment models (IAMS) developed to examine water allocation or irrigation management (Letcher and Jakeman, 2003, Letcher et al., 2004, Lanini et al., 2004, Bazzani, 2005 and Letcher, 2005). To support these IAMS, hydrological and ecological models have been developed to provide
catchment flow processes at a level of complexity relevant to the scale of catchment being modelled (IHACRES: Croke et al., 2006; 2CSalt: Stenson et al., 2005).

In the study area (Murrumbidgee catchment system) where hydrology is dominated by surface water and groundwater flow, and changes in irrigation area management influence seasonal river flow and environmental flow (in-stream demand) over long periods of time, a more specific hydrological–environmental and economic system model is required. Therefore, there is need to adopt a tool or modelling approach that can integrate most of the available information (agricultural, economic, environmental, etc) and is able to represent most of the feedbacks inherited in such a system to better understand the effects and trade-offs of several policy options to improve river productivity and environmental performance.

Elshorbagy and Ormsbee (2005) identified seven characteristics for the best modelling approach needed. These characteristics are: (i) any hydrological system should be described in a simple fashion; (ii) the model should start simple, relying on available data and could be extended if more data become available; (iii) the model should be dynamic to handle the dynamic aspects of the system; (iv) the model should be able to represent both linear and non-linear functions; (v) it should have the ability to represent the feedback mechanism between different variables; (vi) an ability to measure and simulate human interference and any shocks in the system; and (vii) the ability to examine the alternative policy or scenarios. Although it might be impracticable or difficult to represent all these characteristics in one modelling approach; the emergence of system dynamics modelling within an object-oriented simulation approach makes it feasible (Elshorbagy and Ormsbee, 2005; and Simonovic and Fahmy, 1999). Rumbaugh, et al. (1991) stated that object-oriented modelling (system dynamics) is a way of thinking about problems using models organised around real world concepts.

System dynamics is a way to organise software as a collection of discrete objects that incorporate both data structure and system behaviour (Simonovic et al., 1997). Data are organised into discrete objects. These objects could be concrete (river gauge or reach) or conceptual (management or policy decision). According to Simonovic and Fahmy (1999), system dynamics is based on a theory of system structure and a set of tools for representing complex systems and analysing their dynamic behaviour (the system structure generates the system behaviour). The most important part of system dynamics modelling is to elucidate the endogenous structure of the system under study, to see how different elements of the system relate to one another and to test changing relations within the system when different
decisions are taken into consideration (Shi and Gill, 2005). Consequently, it is a feature of system dynamics that is able to deal with the feedback loops inherent in the irrigation water systems (see Figure 2-24). For example, when inflow increases, dam storage level will increase together with the area flooded. This will cause upstream flooding and increase releases that will in turn negatively affect the dam level. In context of this study, when river flow increases the amount of water diverted to irrigation, it will lead to decreased environmental flows which in turn decrease river flow. Thus, feed back loops are one of the most important features of system dynamics.

System dynamics modelling could be used to improve the efficiency of water allocation by incorporating a myriad of irrigation system constraints. The system dynamics approach allows different system components to be organised as a collection of discrete objects that integrate data, structure and function to simulate complex system behaviour. The main reason for the modelling of irrigation systems is to improve the knowledge of the system responses to given inputs. However, knowledge of any given irrigation system is often uneven. Areas where knowledge of the system is sparse or missing becomes apparent either 1) in the process of designing the model structure or 2) in the process of finding parameters that can make empirical model operational (Ford, 1999). Likewise, designing models often leads to revised priorities for future research, based on the data gaps that are identified. Data limitations are significant in modelling irrigation water systems. Frequently, the modelling requirements of decision-makers are difficult or impossible to meet given the data available. However, system dynamics offers an efficient approach to most effectively utilise available data and understand processes since it is using top-down approach to understand how the system behave, the model becomes more complex and detailed once more data become
available. Hence, systems modelling may provide value not just through the end-product model developed, but also through the development process itself (Van Dyne and Abramsky, 1975; Ford, 1999).

Matthias and Frederick (1994) have used the system dynamics approach to model sea-level rise in a coastal area. Fletcher (1998) has used it as a decision support tool for the management of scarce water resources. Beddek et al. (2005) have used a system dynamics approach to model the economic impact of overuse groundwater system in Werribee irrigation district. Simonovic and Fahmy (1999), Simonovic et al. (1997), and Palmer et al. (1993) have used the system dynamics approach for long-term water resources planning and policy analysis for the Nile River basin in Egypt. A conceptualisation of hydrological models using this approach has been briefly outlined by Lee (1993), who indicated that the system dynamics modelling approach is an excellent tool for teaching and communicating hydrological modelling. System approach using such modelling techniques has affected the ways in which resource allocations at the farm, irrigation region and catchment level are evaluated (Wright, 1971; Doyle, 1990). A complete review of the use of the system dynamics simulation approach in integrated water resources management over the past 40 years with tracing of the theoretical and practical evolution of system dynamics application can be seen in Winz and Brierley (2007). The authors conclude system dynamics methodology offers prospects to enhance the resilience of the system as a whole. It provides a well-grounded, flexible and realistic approach to identifying and dealing with inherent uncertainties and complexities in water resources management.

Elshorbagy and Ormsbee (2005) claimed that the system dynamics simulation approach relies on understanding complex interrelationships between different objects within a system. This is achieved by structuring a model that captures the behaviour of the system and of farmers. The dynamics of the system could then be understood by simulating the system over time. Describing the system and its boundaries, by using the main variables and mathematical functions (that represent the physical processes) to generate the model behaviour, is one of the main steps of a system dynamics model.

From the above discussion, to meet most of the above listed best approach criteria in this study, a system dynamics modelling approach is proposed to develop the integrated model (discussed in detail in chapter five). A case study (this research) is provided that explore some of the capabilities of this technique in irrigation system management, particularly water reallocation policies. Therefore, this study uses a system dynamics modelling approach to
build the integrated hydrological–economic–environmental model linked with a crop decision optimisation module and a water trading module to better capture farmers’ decisions about their cropping mixes. This integrated modelling is discussed in detail in chapter 5.

Hence, this research project can be divided into three phases. The first phase integrates hydrological, economic and environmental constraints at a monthly time step for the irrigation areas. The second phase uses the integrated model to understand the current system situation and ensures that flows, storage volumes, releases, diversions, groundwater pumping, and environmental flows in the model reflect reality (actually a model validation and calibration step). The third phase before the evaluation of the proposed future scenarios uses the crop decision optimisation module to capture the decisions about the cropping plan. It also introduces the results of crop distribution to the integrated model while the water-trading module attempts to capture trading behaviour and volumes so as to be able to evaluate the effects of the proposed scenarios. Theses scenarios include irrigation demand, ground water pumping and water banking, options that will help to adjust and optimise, through objective functions and constraints, the irrigation demand and water allocation based on economic and environmental rationales.

Models can be classified according to the processes that they describe as either lumped or distributed; also being deterministic, stochastic or mixed (Elshorbagy and Ormsbee, 2005). Studying complex hydrologic problems, irrigation system and synthesizing different kinds of information have been made possible using models. According to Elshorbagy and Ormsbee (2005), models also can be classified into event based; continuous time, and large time scale models that may use analytical or numerical solution techniques. Additionally, models can be broadly classified into data-driven models and mechanistic models (Govindraju and Rao, 2000). Data driven models, sometimes called black-box models or empirical models, are usually based on relationships derived from raw data and their formulation may not be conceptually supported by the mechanism of the phenomenon under consideration. Alternatively, mechanistic models, occasionally called process-based models, can be highly data-intensive and are frequently over-parameterised. However, they have been found to be useful for a wide variety of applications related to surface water management (Donigan et al., 1995). A number of physical and process-based parameter values are often required for such modelling and the reliability of the results is questionable.
in the absence of large data sets such as is the case in this study (particularly water trading data).

From the above, models can be static or dynamic, mathematical or physical, stochastic or deterministic. One of the most useful classifications, however, divides models into two techniques, those that optimise versus those that simulate. According to Daene et al., (1999), these two approaches or techniques consider the principal approaches to irrigation system modelling: simulation of water resources behaviour based on a set of rules governing water allocation and infrastructure operation and optimisation of allocations based on an objective function and accompanying constraints.

In order to model the irrigation systems, there are diverse ways to characterise them by applying models that employ varying techniques (Van dyne and Abramsky, 1975; Ford, 1999). Optimisation models do not tell you what will happen in a certain situation. Instead they tell you what to do in order to make the best of the situation; they are normative or prescriptive models (Doyle, 1990). Many optimisation models suffer from a variety of limitations and problems, including difficulties specifying the objective function, unrealistic linearity, and lack of dynamics and feedback (Sterman, 1991). Some limitations of optimisation approaches in water resource management are: the system has inherited many non-linear relationships, has a limited ability to represent water quality, environmental values are modelled as constraints, input data are limited, they have a one-step time scale or steady time/state, a lack of dynamics, they have a simplified representation of groundwater use, and static behaviour. These limitations have been reported by several studies within the framework of a large-scale optimisation model called CALVIN for California Value Integrated Network (Jenkins et al., 2001; 2004). Applications of CALVIN in California include the economic values of conjunctive use (Pulido-Velazquez et al., 2004), impacts of dam removal in the Hetch Hetchy system (Null and Lund, 2006), and long-term climate change (Tanaka et al., 2006).

This study proposed using optimisation techniques integrated with simulation techniques (using system dynamics with feedback) to overcome most of these difficulties and capture most of the dynamics of the system. The optimum solution resulted from optimisation models can not fit for future planning or policy changes. There is no one policy or solution for long-term sustainable planning. Environmental value or performance is calculated rather than constrained in this study. Also, one of the research objectives is to test different management options which need what if approach ability (simulation technique).
2.5 Summary and conclusion

The introduction of the cap, the water-sharing plan, environmental flow rules, activation of sleeper and dozer licences, increased water trading, and dryer than average seasonal conditions have resulted in average allocations for general security falling by 30% since 1995. The average level of allocation has been reduced with irrigation allocation as low as 38% of entitlement in the 2002–03 irrigation season. The August 2003 general security allocation was 23% of entitlement, which is the lowest on record. For any water saving options, there is a requirement to take into account resource availability and climatic variability and its impacts on water allocation for consumptive and environmental purposes.

Moreover, irrigation demand management conflicts with environmental demand and outcomes. Irrigation demand in the Murrumbidgee River is dominant during the summer season due to summer cropping. Environmental outcomes could be achieved by a combination of development, management and manipulation of cropping patterns, conjunctive use and irrigation demand. In addition, improving irrigation demand to achieve better seasonal flow distribution could be possible through different management options:

1. better irrigation demand management by changing the cropping pattern
2. water banking and conjunctive water use management
3. substitution of groundwater pumping for surface water
4. trade water between surface and ground water.

Hence, the aim of this research is to investigate the possible management options for improving the management of surface and ground water resources in irrigated areas through better demand management to achieve environmental and economic benefits. The proposed approach to achieve the aims is based on a system dynamics and optimisation approach that includes economic and environmental factors that influence irrigation demand and farmer’s decisions. Various supply-side and demand-side options are examined and tested to identify the best policy options to meet the water productivity and environmental goals. Briefly, the major drive for understanding the link between irrigation demand, conjunctive water management and water bank with environmental outcomes is to measure and identify the change in economic output and environmental impacts of various allocations and demands from irrigation on improved seasonality of flows and environmental flow. This is one of the major original contributions of the research project. The model should be able to effectively reflect the complexities of irrigation demand management system temporally, spatially,
biophysical, economically and environmentally, as well as providing the desired compromise between different objectives at the irrigation area scale.

The next chapter (3) presents and discusses the potential options available to improve water productivity and river environmental performance through details such as, irrigation demand management, conjunctive water use, the innovative design such as the water banking approach and water trading rules in NSW.
Chapter 3: Management Options Available

This study focuses on understanding the link between irrigation demand, conjunctive water management and water banking with environmental outcomes. The outcome was evaluated by measuring and identifying the change in economic output as indicated by gross margin and the impacts of various allocations and demands strategies in the irrigation sector on improved seasonality of flows and environmental flows (end of system flows). Moreover, this study investigates the water banking approach by measuring the trade-offs between consumptive use and in-stream use.

This chapter begins with a brief discussion on the definition of the term ‘seasonality of flows’ and the current pattern of flows. Section 3.2 then presents and discusses river regulation and its impact on seasonal flows. Section 3.3 presents potential management options available to improve the seasonality of flows. In Section 3.4 discuss the first option, irrigation demand management by changing crop mix and its related issues. Section 3.5 presents the conjunctive water use option; groundwater system formation, use and critical issues in the Murrumbidgee catchment. Section 3.6 discusses the concept of water banking and related matters. It also presents the water trading facility with water banking as a mechanism that could be used to facilitate water movement between irrigation areas and help change demand and improve the seasonal flows. Section 3.7 ends with a brief conclusion and a summary of the options for improving the seasonality of flows.

3.1 Seasonality of flows

According to Salas and Obeysekera (1992), data generation and forecasting of seasonal flows are often needed for planning and managing water resource systems. Also, they have claimed that the modelling is more complex when dealing with time series of seasonal flows. The main reason is the inherent periodicity of several statistical characteristics that invariably lead to stochastic models with periodic parameters. Barberis et al. (2003) stated that seasonality of flows has always been investigated by using long-term records of monthly flow runoff that help to study high and low flow seasonal conditions both intra- and inter-year. In addition, they said that ‘the seasonality and year-to-year variations of streamflows can be catalogued to understand linkages between basins and regions and across time’. However, looking into changing the seasonality of flows by applying different management options is difficult and few. Therefore, the aim of this study is to investigate how to improve the seasonality of flows and environmental flows target by studying the options for managing
surface and groundwater resources in an irrigated area to achieve environmental and economic benefits. Consequently, this study seeks to maximise the economic returns of irrigation areas, subject to the physical constraints of the system, environmental targets, groundwater pumping and storage targets.

There is no clear definition of seasonal flow; rather there are several definitions that could be used to define seasonality of flow. Allister McGregor (2000) claimed that the rural economy is linked with seasonality and this can affect many people’s livelihoods. Seasonal drought can lead to high crop prices and high returns to some farmers, with negative impacts on other farmers. The seasonal flow can be defined, based on the changing availability of water resources or stream flow throughout the year (winter, summer, spring and autumn). Periodic climatic fluctuations, such as wetter winters or drier summers, could also produce variability in seasonal flow. From the above discussion, the seasonality of flow can be defined as being the alteration in the characteristics or behaviour of the flow over time, based on climatic conditions.

Natural seasonal flow is highly linked with climatic conditions. In wetter or winter seasons, high rainfall and low evaporation produces high stream flow or runoff. During summer, or drier conditions with low rainfall and high evaporation, low natural flow and runoff are expected. In the past, water resource managers built dams to capture excess runoff or high flow, storing them for use during dry seasons. The agricultural development and cropping systems found in the Murrumbidgee catchment, demand water mainly during the summer. This traditional management has led to water being supplied to irrigators in summer which, in turn, changed the seasonal flow (see Figure 2-14 and Figure 2-15 in Chapter Two-Section 2.2).

Regulated streams such as the Murrumbidgee River have the potential to capture seasonal floodwater. Captured wet-season floodwater is often stored and released for irrigation during the dry season (summer). This seasonal flow reversal can markedly affect aquatic ecosystems. Changing the pattern of water flow below dams or weirs may remove necessary stimuli or habitat requirements for fish spawning. With the water sharing plan, cap and environmental flow rules, the seasonal or river flow at any time during the year becomes equal to environmental flow plus irrigation deliveries. Comparatively, it is costly and difficult to change the river flows directly, but it is possible to change the left side of the river flow equation (see equation 1), which also includes tributary inflows, groundwater discharge,
evaporation, seepage, etc. This study only focuses on environmental flow and irrigation diversion.

\[
\text{environmental flow} + \text{deliveries} = \text{river flow} \quad \text{Equation 1}
\]

For example, during spring and winter, the objective is to increase environmental flow volume and decrease deliveries. This could be achieved by changing demand from irrigation, both in volume and time, which could be achieved by changing the crop mix, or changing the timing of supply by releasing water in winter to mimic natural flow and banking the water until it is needed during summer or high peak demand periods. These options need to be studied under different climatic conditions. In the next sections, the results of regulation are discussed in detail.

### 3.2 Regulated river and its effects

A regulated river is a river or stream where the flow has been controlled or modified from its natural conditions, mostly by a major dam. Most major rivers, such as Murrumbidgee River in NSW, are regulated to some degree (see Figure 3-25). Rivers are regulated for a number of reasons, including irrigation, hydro-generation, urban and rural water supply and diversion to other catchments.

![Figure 3-25 Regulated and unregulated rivers in NSW](Data source DLWC 2000)

According to the NSW State of the Environment Report 2003 (SOE, 2003), the rivers of NSW have highly variable flow regimes. They are often subjected to long periods of drought, interrupted by substantial floods. Regulated rivers, such as the Murrumbidgee River, suffer changes to their natural flow regime. According to NSW Fisheries 2001, the major cause of degradation of the aquatic ecosystem is river regulation. Furthermore, there are a number of other ways in which river regulation affects the river ecosystem and native
fish, such as altered flow, flood regime, seasonality of flow and quality of water. Constant flow occurs more frequently in regulated rivers used for irrigation or water supply than in unregulated rivers.

DLWC (1998a) stated that river regulation has also reduced the outflow of the Murray-Darling River system from a mean of 13,700 GL per year to 4900 GL per year, with ninety percent of the extracted water used for irrigation. The NLWRA (National Land and Water Resources Audit 2001b), assessed water use in Australia between 1983–84 and 1996–97, finding that surface water use in NSW rose by 52% over the period from 5932 GL to 9000 GL. This was the largest increase of any Australian state or territory. Most of the increase came from irrigation, which rose by 76% from 4910 GL in 1983–84 to 8643 GL in 1996–97, including the use of groundwater.

In addition, water storage areas in regulated rivers such as the Murrumbidgee, where water is captured in winter, stored, and then released for irrigation over summer, dramatically reduce the frequency of small floods that are particularly important for billabongs and other wetlands. In addition, constant flow also prevents natural drying of water bodies such as wetlands. Sudden rises and falls in river levels resulting from water release and subsequent extraction for irrigation can have an effect on riverbank stability, causing slumping, loss of riparian vegetation, erosion and sedimentation. One of the other most significant effects of regulation on water quality is cold-water pollution in the waterways downstream of many major dams. The NSW Fisheries (2001) reported that, bottom water releases from dams might be saturated with dissolved gasses that can cause gas bubble trauma in fish. Bottom water releases may also contain toxic levels of hydrogen sulphide, which can also lead to fish kill.

**Murrumbidgee River and the effects of its regulation**

The state of NSW implemented environmental flows in 2001, as discussed in the previous chapter, which are produced by releasing dam water to stimulate, maintain or restore natural flow patterns. It is impossible to restore flows across the river catchment to pre-regulation conditions. According to Gehrke and Harris (2001), the aim of environmental flow management is to mimic natural flow regimes, providing cues for key lifecycle events such as spawning and migration. Environmental flow management includes managing water level rise and fall; duration of a flow events; velocity of water in the channel; seasonality of flow; flood pulses or high flows; and protection of water levels during periods of low or no flow.
This can be achieved by modifying existing releases, increasing water use efficiency, restricting irrigation diversions and extraction, conjunctive water use management and by increasing allocations from large storage areas for the environment. The frequency of high flows is now only about half the natural frequency, and average flows between June and October have dropped by a third (DLWC 1998b and Ken et al. 2005). Figure 3-26 (simple water balance) indicates the average flows and diversions in GL along the Murrumbidgee River and at the downstream gauge station at Balranald for the water year 2000/2001, after the water sharing plan (WSP), where it is now about one third of its natural level (1195.8 GL and 2486 GL respectively) at the end of the system. It is very clear that most of the irrigation diversion is concentrated within the middle reaches between the Wagga Wagga and Hay gauge stations.

Figure 3-26 Schematic diagram of Murrumbidgee River with flow volume GL (observed data year 2000/2001)

Water demand in the Murrumbidgee catchment is dominated by summer crops that require high river flow, therefore altering the seasonality of flows. Furthermore, the combination of the regulation of the two main head dams (Burrinjuck and Blowering) and the water diversion has had substantial effects on the flow regime (described in Chapter two: section 2.2).

Increasing water scarcity and high demand for existing supplies have placed river systems under great pressure (Lovett et al., 2002). Maintaining flows for irrigation is competing with increasing river flows for downstream users and the environment, who are demanding that irrigation allocations be reduced to maintain flows and reduce the salinity level. The main objective is to enforce and enrich existing environmental flows rules, but also to try to improve the seasonality of flow.
3.3 Potential management options and seasonality of flows

Current management and polices often ignore the fundamental scientific principle that the integrity of flowing water systems (stream flow) depends largely on their natural dynamic character and, as a result, they frequently prevent successful river conservation or restoration. Stream flow quantity and timing are critical components of water quality and quantity, and the ecological integrity of river systems. Stream flow, which is strongly correlated with many critical physical parameters of rivers, can be considered a ‘master variable’ that limits the distribution and abundance of riverine species (Power et al., 1995; Resh et al., 1988). Poff et al., (1997) recognised the importance of considering river flow or stream flow as a regime, that is, a dynamic quantity that naturally varies over time in response to changes in many driving variables (precipitation, runoff, groundwater interactions, and evapotranspiration) that occur over broad spatial and temporal scales.

Flow regimes can be described in terms of five general attributes that characterise temporal patterns and invoke conceptual linkages to other ecological variables. These include flow magnitude (which is used to distinguish between low, normal, and high flow conditions), the timing of high and low flow events (the predictability of which may select for or against various life history characteristics of resident biota), their frequency and duration (which interact to define disturbance intensity), and the rate of change in flow conditions (which interacts with organism mobility and availability of refuge from intolerable physical conditions to further characterise the intensity and consequences of disturbance).

Acreman M. and Dunbar M.J. (2004) claimed that it is widely recognised that any alteration (abstraction, dam operation, etc) to a river flow regime (volume and time) will change the river ecosystem. The seasonality of river flow (volume and time) is considered to be one of the most important problems for consumptive use and in-stream demand, and the health of the river ecosystem. The seasonality of flow could be improved through management and other options presently under investigation. These options can fall into three categories: regulatory, structural and management. Regulatory options focus on changes to supply and demand regulations, and trading regulation between basin, irrigation areas and states. While structural options concentrate on changes to the delivery system and storage facilities (such as water banking), management options focus on changing crop mixes and the demand side of the system. All these options should intermesh to improve the seasonality of flows. This research will investigate the recommended options from a management perspective without detailed discussion of the regulation rules and structural
requirements, cost involved and political decision, since the regulation and structural aspects are beyond the scope of this study.

From the literature, several potential management options for water management were reported by NWAG National Water Assessment Group (2000) in response to climate change and other stresses as follows:

- Incorporate potential changes in demand and supply in long-term planning and infrastructure design.
- Improve capacity for moving water within and between water-use sectors.
- Identify ways to sustainably manage supplies, including groundwater, surface water, and effluent.
- Reduce agricultural demand for water by developing crops and changing farming practices to minimise water use, for example, via precision agricultural techniques that closely monitor soil moisture.
- Use pricing and market mechanisms proactively to decrease waste.
- Increase the use of forecasting tools for water management. Some weather patterns, such as those resulting from El Niño, can now be predicted, allowing for more efficient management of water resources.
- Enhance monitoring efforts to improve data collection for weather, climate, and hydrological modelling to aid understanding of water-related effects and management strategies.
- Encourage the development of institutions to confer property rights to water.
- Restore and maintain watersheds to reduce sediment loads and nutrients in runoff, limit flooding, and lower water temperature.
- Reuse wastewater, management of stormwater runoff, and promote the use of rainwater tanks.

Since this research study is one of the studies under the CRCIF (Cooperative Research Centre for Irrigation Futures) project ‘Improved Seasonality of Flows through Irrigation Demand Management and System Harmonisation™’, two consulting workshops were held with stakeholders, one in Leeton on April 2004 to develop draft criteria for assessing water demand management projects and ideas, and to assess the proposed ideas and options against the draft criteria (mainly to demonstrate potential water savings and a clear reduction in peak summer demand). The second workshop was held in the Griffith in March 2005.
The stakeholders who attended included irrigation farmers, representatives from Murray Irrigation Limited, the Murrumbidgee Catchment Management Authority, the Murray Catchment Management Authority, state government agencies, CSIRO and the Murray-Darling Basin Management Authority, and CRC for Irrigation Futures scientists.

At these two workshops, 25 stakeholders participated and agreed on criteria to assess the effectiveness of a water management project or option. The process used at the first meeting was to develop criteria against which to evaluate different options (using the workshop approach as described by Spencer, (1989)). This involved unstructured and uncritical generation of ideas from all participants (‘brainstorming’) by dividing stakeholders into five groups to consider the question (What criteria would you use to judge the effectiveness of a water management option?). Then, all collected responses were categorised under headings that reflected the responses. This resulted in several assessment criteria displayed in Table 3-7.

<table>
<thead>
<tr>
<th>No</th>
<th>Criteria</th>
<th>No</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>improved water use efficiency</td>
<td>7</td>
<td>equity, fairness</td>
</tr>
<tr>
<td>2</td>
<td>demonstrated influence on water availability</td>
<td>8</td>
<td>identify costs and cost minimisation</td>
</tr>
<tr>
<td>3</td>
<td>sound stakeholder processes</td>
<td>9</td>
<td>economic benefit</td>
</tr>
<tr>
<td>4</td>
<td>Feasibility</td>
<td>10</td>
<td>social benefits</td>
</tr>
<tr>
<td>5</td>
<td>Significance</td>
<td>11</td>
<td>environmental benefits</td>
</tr>
<tr>
<td>6</td>
<td>risk reduction</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Once these criteria were developed, the discussions centred on project ideas for improving flow seasonality. The stakeholders identified several options that are listed in Table 3-8. The options were assessed during the workshop by asking the stakeholders to rank the options in order of priority for investigation. Each group was asked to assign up to five points to each criterion, with five points being acceptable, and 0 points unacceptable. Adding the scores enabled the projects and options to be ranked. These options, which have been accepted by the community as the best possible demand management options for improving the seasonality of flows and environmental flows, can be summarised in six options:

1. market-based approach to reducing surface water demand
2. conjunctive water use (managed aquifer recharge (MAR) and aquifer storage and recovery (ASR))
3. better irrigation and spreading water demand with improved cropping mix
4. increase system efficiency
5. increase end use efficiency

6. substitute water use by using en-route storage.

### Table 3-8 Possible options to improve seasonality of flows

<table>
<thead>
<tr>
<th>No</th>
<th>Options</th>
<th>Management</th>
<th>Structural</th>
<th>Regulating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>* better irrigation demand management by changing the cropping pattern.</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>allowing water trading between surface and ground water under climatic conditions</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>temporary water trading between the irrigation areas for storage purpose</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>storage water on farm or on dams, and off farm during low season</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>removable environmental barrage</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>6</td>
<td>* water banking storage and conjunctive water use management</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>7</td>
<td>land idling with the incentive for improved ecosystem</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>wetland restoration and storage</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>* surface water substitution by groundwater</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10</td>
<td>new storage on tributaries upstream reach between existing dams wall and Wagga Wagga</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>11</td>
<td>market-based approach to reduction in surface water demand</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>12</td>
<td>reduced evapotranspiration and seepage along the irrigation system to increase system and end use efficiency</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

* These options are the focus of this study

These options are the more plausible and acceptable demand management options from irrigation community perspectives for improving the seasonality of flows. However, some of these cannot be easily applied, or it is unclear who will invest in their application. In addition, often both surface water and groundwater are used conjunctively but are managed individually. Surface water is always used when available and groundwater is used when the stream flow is too low. Therefore, in the next two paragraphs these options are critically discussed.

The first option assumes that the environmental manager will be able to buy water on an open water market, and allocate it to the environment. This disregards the farmer’s perspective. They might prefer to sell it or use it to irrigate new land and expand their farm business. Also, this option ignores the extra cost involved in improving environmental performance compared with buying water on the free market. This option needs further cost benefit analysis.
The second option allows storage of water when it is available in aquifers, by injection or infiltration and re-abstraction during peak demand. This will help to manage surface water and groundwater as one resource. This option is the core option of this dissertation. However, this water-banking approach to water planning would require a comprehensive study which is beyond the scope of this research. For instance, it would require matching the water quality and cost of different water sources. Investigating and presenting findings on the use of a water-banking concept to farmers and water managers is critical to its design and operation. This study tries to provide a critical understanding as to how to manage the conjunctive use of surface and groundwater combined with aquifer water banking in a regional context considering just the capital cost and annual operation cost (Pratt Water (2004a),) in the analysis. The costs of aquifer storage and recovery vary with location and depend on land acquisition, water pre-treatment, environmental regulations and permitting, design and construction and operation and maintenance costs (Khan et al., 2008b).

The third option is to change the crop mix, which can change the water demand curve and demand time. This emphasises winter crops rather than summer crops and could be promoted by an incentive policy and development of markets for winter crops.

The fourth option, an improvement in system efficiency, will decrease the system’s losses to leakage, evaporation and seepage, although it will not change the farmer demand. More water will be saved in the system by initiatives such as canal lining or concrete.

The fifth option is to increase end use efficiency by using different irrigation technologies to help save more water on farm. This is a controversial issue for farmers, who question why they should invest to improve their system efficiency, and involves other social factors. This could be encouraged by introducing land and water incentives for those investing in improving use efficiency.

The last option is to substitute water use by using en-route storage. This could provide the mechanism that could handle water distribution within the irrigation season. This option would require investment in en-route and on-farm storages.

However, the assessment and ranking results revealed there was clearly preferred idea in all five stakeholders groups. The highest priority, common and preferred options in decreasing order were: conjunctive water use, changing cropping mix, on-route storage and water trading. However, there is a need to consider the limitations of these results. The assessment criteria developed at the first meeting were only approximations and, although
the 25 participants represented most stakeholders, they were not a fully representative sample.

All these management options need to be properly analysed to better explain and understand how to link agricultural production and economic decisions with available water and environment requirements. Therefore, from the discussion so far, this research is focused on the three most appropriate options as recommended by stakeholders:

1. irrigation demand management (changing crop mix)
2. conjunctive water use management
3. structural interventions such as water banking (underground storage).

These options would effectively influence the dynamics of water use, allocation, management and quality under the uncertainty umbrella (climatic change) and other geophysical conditions. The next sections will discuss these three options in more detail.

### 3.4 Irrigation demand management and crop mix

Managing the water supply system is conceptually simple in terms of moving water within the physical constraints of hydrology and engineering principles; there is usually a clear link between an action and the reaction to it. Demand management on the other hand, depends on several variables linked to human needs and behaviour that change over time and space and cannot be easily constrained and managed. Moreover, irrigation water demand management is particularly difficult due to the presence of uncontrolled variables such as climate. In addition, more difficulties result when economic and environmental perspectives are integrated with biophysical processes in irrigation demand management.

Simply, water demand is the amount of water needed to satisfy user requirements. Integrated demand water management in irrigated agricultural areas is the best strategy to optimise the use of the available water resources (Beddek et al., 2005). Irrigation demand management can be considered to be a tool or mechanism that can modify the level or peak demand and timing of irrigation water demand. According to White and Fane (2001), demand management is intended to support conservation either through changes to consumer behaviour or changes to the supply of resources using technology or policy. The behaviour of consumers can be changed by education or by setting up polices and/or incentives. The analysis of policy is beyond the scope of this study, but changes to the supply of resources can be delivered with alternative sources of irrigation such as pumping, on- and
off-farm storages, rainwater tanks, increasing the efficiency of irrigation use, or by applying alternative management or policies.

Thus the main objective of irrigation demand management is to minimise the peak demand for irrigation water that will modify and improve the flow seasonality. The crop water demand of the irrigation areas in this study is greatest during summer months. Figure 3-27 shows the peak of the total monthly diversion after implementing the environmental flow in the Murrumbidgee River. It is clear the peak demand and diversion (over 200 GL/month) has been shifted, decreased and concentrated during summer months from October to March. This summer concentration of flow represents a significant change from the natural flow pattern of the river. One of the research objectives is to change and minimise peak demand during summer and free more water for the environment, without negative economic impacts on the irrigation areas and farmers. Water scarcity or decreasing water allocations encourage decision makers and water managers to look for improved management by changing cropping pattern systems. The value of water depends not only on its quantity but also on quality, reliability, time of availability and location.

![Figure 3-27 Total observed monthly diversion of the Murrumbidgee River](image)

3.4.1 Tools for demand management

Tools and techniques to promote demand management can be classified in many ways but the following four categories are convenient (Rosegrant, 1997). None of the measures are in reality as simple as they appear in the list below, even for surface water and, in almost all cases; they are even more complex for groundwater.
1. Institutions and laws

Supply and demand systems for water always exist within a set of water rights, land rights, environmental rules, social and civil institutions, and legal regimes. Some are formal and others informal; some modern and others traditional; some international and others local. Institutions in the Murrumbidgee River considered in this study are water cap, water sharing plan, environmental flow, water trading rules and the groundwater sharing plan.

2. Market-based measures

This is the world of water prices and tariffs, and of water subsidies, both of which appear in a variety of forms. Although pricing is currently favoured, analysts see it as a necessary but insufficient incentive for achieving efficiency, equity, and sustainability (Brooks, 1995; 2004). Most researchers argue that water tariffs should be designed to encourage conservation, not just to recover costs. In the Murrumbidgee River water users have fixed costs and licensed costs for their entitlement. Of course, any of these measures depend on the existence of a more or less sophisticated system for metering.

3. Non-market measures

An enormous variety of non-financial measures, including education and advocacy, can be used to manage water demand (Brooks and Peters, 1988). Information and consulting services can be provided; social pressure can be applied; and regulations can limit the time or quantity of use. Although regulations have a bad name, they are often both appropriate and efficient for managing water demand.

4. Direct intervention

Governments and water authorities can, of course, intervene directly by providing services, installing consuming or conserving equipment, fixing leaks by lining canals, adjusting pressure, providing drainage, etc. More fundamentally, they can also affect, if not control, land use by their decisions on the location and quality of water and soil, which is of course why these decisions are so politically sensitive.

To sum up, conserving water can improve both the economy and environment and it may even allow for more equity. Demand management options could be achieved through:

- increasing system efficiency by reducing system losses (seepage, leakage, evaporation) through initiative of lining canal or concrete channels which will make more water available to satisfy high summer peak demand and improve the seasonal flow
- introducing new irrigation systems (using new irrigation technologies or genetically modified crops with high productivity and lower water use) which will help farmers to achieve the same level of production with less water
- changing the crop mix, so helping to improve environmental outcomes and shift the irrigation peak demand.

Changes of crops both temporally and spatially could be used to reduce demand for water. Improving the crop mix by focusing on both winter and summer crops, but mainly on winter crops, could help to improve environmental outcomes and optimise water use. According to Durack et al. (2005), introducing or growing other crops on uplands or in rice fields have been defined as crop diversification, but need to take into account the economic return and involved cost. Thus, modelling of cropping mix should consider many variables such as new crop intensity, new crop water requirements, economic aspects, production, yield and long-term effects of new systems on soil quality. This study concentrates on testing different crop mix scenarios from winter, summer and perennial crops and their impacts on the peak demand and water diversion, taking into consideration economic and productivity aspects. Moreover, it studies other options such as conjunctive water use and water banking.

### 3.5 Conjunctive water use

Conjunctive water use is defined as combined use of surface and groundwater to optimise resource use and minimise the adverse effects of using a single source. Traditionally, these water resources have been seen and managed as isolated resources, even where there is high hydraulic connectivity. Recognition that the connectivity between these stores is an important part of river system function is growing, with significant implications for both water quantity and quality. Water flow regimes, water security, aquatic ecology, salinity and nutrient loading, can all be affected by the movement of water between the surface and aquifers. Surface stores and flows are therefore affected by the way aquifer stores and flows are managed, and vice versa. In-stream salinity is one classic example of a negative effect resulting from independent management of connected surface water and groundwater.

Thus, conjunctive water management is the management of surface water and groundwater in a coordinated way, such that the total benefits of integrated management exceed the sum of the benefits that would result from independent management of the surface water and groundwater components. Systems such as the Murrumbidgee system; with high river-aquifer connectivity are of particular interest. These may include aquifers
formed by alluvial deposits, coastal sands, fractured rock or sedimentary basins such as the Murrumbidgee River.

According to Fullagar (2004), conjunctive management is a logical step towards improved water management as it makes best use of the attributes of both surface water and groundwater systems. This should allow for a more efficient use of water for economic, environmental and/or social values. Therefore, conjunctive water management is an important component of future water management that deals with water quantity, water quality, the environment, and natural hazards—issues that grow in priority as demands on Australia’s water resources increase in the future. In the next section the groundwater system and its use in the Murrumbidgee catchment are discussed.

3.5.1 Groundwater use

Groundwater is a poorly understood resource in the MDB and particularly in the Murrumbidgee catchment. However, groundwater is important to rural and regional economies and communities, their ecosystems and the environment. Since the State of the Environment (SoE) report (NSW EPA, 1997), the use of groundwater in the MDB has increased, mostly in response to the drought and the need to have access to alternative supplies.

According to (NSW EPA, 2001), the drought and its associated effects such as blue-green algal blooms, reduced surface water allocation, and diminishing surface supplies leads to an increase in the groundwater use. Other factors such as the expansion of the irrigated agriculture industry, mineral water supply systems and a variety of other local and regional matters have helped pushed groundwater consumption in NSW to more than 1 million megalitres (ML) per annum, or 15% of the entire volume of water consumed in NSW each year. The level of groundwater use in NSW under the Murray Darling basin is much higher than other state in the MDB Figure 3-28.

According to DLWC (1998c; 1998d), the volume of groundwater available in NSW is estimated to be about $5,110 \times 10^6$ ML, enough to cover the state to a depth of four meters. Unfortunately this groundwater is not all of good quality or uniformly distributed, with less than $5 \times 10^6$ ML suitable or obtainable for use. Unlike surface water, groundwater can be found in most areas of NSW. However, it varies considerably in its recharge potential, vulnerability to pollution, and its connection to surface water and other ecosystems. Groundwater is a vital resource that has led, and now supports, agricultural and grazing
development over much of inland NSW, DLWC (1998d). Total consumption in NSW is about $1 \times 10^6$ ML a year, with more than 530,000 ML used each year for agriculture and stock purposes.

![Figure 3-28 Observed groundwater use in the MDB since 1999/00 to 2003/04 (source: NSW-EPA, 2001)](image)

The NSW SoE (2003) reported that in NSW nearly one fifth of the water used is groundwater. In many areas, groundwater is the only water source. But many aquifers are under stress from high levels of water extraction. In particular, areas of the MDB are affected adversely by continued over-extraction of groundwater. Groundwater users, other stakeholders and the NSW government agree that this situation cannot continue. Use of overused aquifers across the state must be kept within, or returned to, sustainable yields, which balance the water pumped and environmental requirements with recharge.

### 3.5.2 Groundwater conjunctive management and related issues

The Calivil and Renmark formation aquifer is classified as at risk of over-extraction (Murrumbidgee GW Sharing Plan, 2004). This means that, if everyone extracted water to the level of their licensed entitlement, there would not be enough water for all existing water users and the end situation will be one of an inability to protect these groundwater sources in the medium- to long-term. In addition, there are several problems with over allocation of groundwater licenses such as:

a. Australian catchments in general, and the Murrumbidgee catchment in particular, have an unpredictable and highly variable climate and rainfall. It is very difficult to predict long-term trends in available surface water and crop values. Thus at any time when surface water supplies are inadequate for biophysical demand, the use of groundwater increases steadily towards the full allocation.
b. With increasing regulation of surface water, groundwater may well become the preferred option for many users; this creates the potential for more allocation to be used (see Figure 2-9 Chapter two).

c. Sustainable or safe yields are simply an arbitrary amount, the total underground storage is unknown, and therefore, by allocating more than these apparently ‘safe’ amounts, there is a risk of stressing the aquifers further. Further research is required to better quantify the capacity of underground water storage systems, determine accurate sustainable yield as well as how the systems use their recharge water.

d. It is very difficult to take back water that has already been licensed. If full allocation has never been used (even in drought) then it would be far less painful to reduce allocation to a more precautionary level, and this is the case in Murrumbidgee catchment.

The second important issue is groundwater quality. The quality of groundwater has implications for public health, groundwater dependent ecosystems, industry, economics, social framework, soil and land quality and other sources of water. A precautionary approach for water injected into aquifers is required. Mixing groundwater with surface water of poor quality or of high salinity can lead to ecological, and economic and health impacts. Another aspect of groundwater quality is land use and the quantity of fertiliser, pesticide, herbicide, and fungicide that leaches downward either through the soil, or directly into a recharge bed to contaminate groundwater. Salinity is a major groundwater quality problem, which can lead to the devastating effects of dryland salinity.

The third major issue is groundwater dependent ecosystems. A third of the NSW government’s groundwater policy deals with groundwater dependent ecosystems (GDE), it is an area of enormous environmental importance as deep-rooted trees and other features (such as lakes, wetlands, native vegetation, etc) mainly depend on groundwater. It is an area of study that is relatively new to Australia, and thus is not well understood and is beyond the scope of this study. In response to GDE issues in the Murrumbidgee catchment, particularly for the lower Murrumbidgee ground water, ground water sharing plan have allocated water for environmental provisional, see Table 3-9.

The Water Management Act requires that water be allocated for the fundamental health of a water source and its dependent ecosystems as a first priority. The Shepparton formation aquifer, being shallower, is the main contributor to the GDEs in the area. Therefore 85% of the average annual recharge has been put aside for environmental purposes in the
Shepparton and 20% in the Calivil and Renmark. The proportion of recharge reserved for the environment may be varied from July 2008 after further studies of the GDEs recommended by the groundwater-sharing plan.

The last but not smallest problem is groundwater trading. This is very hard to monitor. In lower Murrumbidgee groundwater area, trading or local transferring of groundwater allocations is prohibited to or from water sources outside of the area according to quality. There are many problems associated with groundwater trading, from lack of knowledge about the aquifer systems to where trade would be coming from and going to.

### Table 3-9 Lower Murrumbidgee ground water-sharing plan at start of the plan
(Source Murrumbidgee Ground Water sharing plan 2004)

<table>
<thead>
<tr>
<th></th>
<th>Shepparton (ML/yr)</th>
<th>Calivil and Renmark (ML/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>average annual recharge</td>
<td>65,000</td>
<td>335,000</td>
</tr>
<tr>
<td>environmental water from recharge</td>
<td>55,000</td>
<td>65,000</td>
</tr>
<tr>
<td>basic landholder rights</td>
<td>3,000</td>
<td>1,000</td>
</tr>
<tr>
<td>local water utility share component</td>
<td>0</td>
<td>2,210</td>
</tr>
<tr>
<td>aquifer access share component</td>
<td>0</td>
<td>522,523</td>
</tr>
<tr>
<td>extraction limit</td>
<td>10,000</td>
<td>522,523</td>
</tr>
<tr>
<td>amended aquifer access share component from mid 2008-percentage of previous possible variation to extraction limit</td>
<td>not applicable</td>
<td>64% 230,000 to 390,000*</td>
</tr>
</tbody>
</table>

* Water available under supplementary water access licences will be included each year in the extraction limit. However, supplementary water will be progressively phased out over the term of the plan.

Climate and the level of recharge of these groundwater sources vary from year to year. The groundwater management plan therefore uses average annual recharge as the basis for sharing water. This estimated average annual recharge for each of these groundwater sources at the start of the plan. Further studies of the recharge have been recommended, and the figures may be varied from July 2008, which could have positive influence on the possibility of using this aquifer for water banking by asking for more annual recharge.

In summary, all these matters need to be considered in conjunctive water use management. However, this study focuses on climate, allocation and water trading issues. Groundwater quality and ecosystems are out of the scope of this study.

### 3.6 Water banking (underground dam or storage)

In this study, water banking refers to releasing water earlier than required and injecting it into a groundwater aquifer to be pumped when required. Water banking is also referred to as aquifer storage and recovery (ASR). The potential benefit of water banking is its ability to use and manage the available water sources (surface water, groundwater and water trading) as one single source. In the context of this research, the goal for water banking in general is
to efficiently allocate all water resources to meet economic demand while achieving environmental sustainability.

In the Murrumbidgee River basin, irrigation extraction, intensive cropping systems and land clearing have had major effects on the river environment (DLWC, 1998b). In addition, irrigation demand has changed the natural flow regime of the river, inducing significant environmental changes. Water banking is a new management approach to managing water resources with the ability to mitigate the effect of options for the allocation of limited water resources between agricultural production and the environment. In this research context water banking is defined as the use, store and management of all surface and groundwater water resources available, as one single resource using the aquifer as a storage system. In the literature, water-banking definitions are diverse, depending on the authors’ or owners’ perspectives, and the reasons for its use. The differences in definitions are clearly seen in a summary of water banking studies given in Table 3-10. In this table, the studies have been divided into those which could be classified as virtual water banking or physical water banking.

Virtual water banking refers to situations where a regulatory tool is introduced to facilitate water trading and to encourage the highest beneficial use of water. In this context, a virtual water bank finds buyers, sellers and facilitates water rights transactions. If the government enters the market to buy back water for environment, the term environmental water banks is sometimes used also.

Physical water banking has been used to describe situations where the water bank acts as storage system to secure water during the peak demand or dry period. For instance, the Water Bank Company (2004) in the United Kingdom has defined a water bank as an underground rainwater tank where rainwater is collected, filtered, stored and distributed for use in a variety of household and commercial applications. A water authority in Arizona (2004) defined a water bank as storing water in Arizona’s groundwater aquifer (SNWA-Southern Nevada Water Authority, 2006). The same definition was mentioned by Laurent et al. (2001) and The Washington State Department of Ecology (1999). Christine (2002) reported that, in the Klamath basin, irrigators plan to set up a water bank to be assured that they will have enough water during drought or dry years. This definition is considered the closet definition to this study.

In 1988, the United Nations in Thailand claimed that inadequacy of water sources, remoteness of villages, and lack of availability of appropriate technologies as some of the
major factors that constrain the sustainability of the rural water supply. An innovative water bank project has been devised by the Department of Health to provide safe drinking water to rural communities, particularly in areas subject to frequent droughts. Their water bank is a combination of three concrete container systems together with its own roofed catchment for rainwater.

<table>
<thead>
<tr>
<th>Table 3-10 Water banking definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Virtual Water banking</strong></td>
</tr>
<tr>
<td>Water banking study</td>
</tr>
<tr>
<td>(WaterBank Com., 2005)</td>
</tr>
<tr>
<td>Federal Wildlife and Related Laws Handbook and the Idaho Water Resources Board (1999)</td>
</tr>
<tr>
<td>IDIOLOGIC (2005), a US Federal Government Agency,</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical Water banking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water banking study</td>
</tr>
<tr>
<td>Water Bank Company (2004) in the United Kingdom</td>
</tr>
<tr>
<td>Christine (2002)</td>
</tr>
<tr>
<td>1988, the United Nations in Thailand</td>
</tr>
<tr>
<td>West Governors’ Association (2006)</td>
</tr>
</tbody>
</table>

West Governors’ Association (2006) stated that the goal for water banking in Kansas (Kansas Water Banking Act, 2001) is to efficiently allocate water resources to achieve economic growth while protecting the public interest by encouraging conservation and management of existing water rights. In many areas of the western states in the USA, water banks have been established for a variety of reasons (MacDonnell et al., 1994). These include the goal of moving water to where it is needed most, to create a reliable water supply for dry
years and ensuring future water supplies for people, farms and fish (Acton and Narayanan, 2000).

The water can be redirected to the aquifer by using artificial recharge through infiltration basin or injection reverse pumping. The Council for Scientific and Industrial Research (CSIR, 2000) in South Africa gave the preliminary results of a study into artificial groundwater recharge. These have shown that it is feasible to bank vast quantities of water underground for later use. Four pilot projects undertaken by CSIR, with funding from the Water Research Commission, have indicated that storing water underground could provide a cost-effective and reliable water source for semi-arid South Africa with different injection recharge rate ranged from 195–214 KILh⁻¹.

At the end, this study (Murrumbidgee catchment) adopts the following definition of water banking: releasing water earlier from dams than required and injecting it into a groundwater aquifer to be abstracted / pumped when required. In other words, redirecting surface water to subsurface water until it is required. Evaporation losses will by zero. In the Murrumbidgee catchment, Khan (2006) reported that there is a potential opportunity for artificial recharge to store and inject water in deep aquifers of about 200 GIL per year as the water level declines despite natural recharge. Artificial recharge also allows for the use of existing natural storages before opting for more elaborate and environmentally problematic storage facilities such as dams. Moreover, this form of storage can be used to supply water during peak demand periods, such as during summer months; or daily peak demand periods, when this water can augment the bulk supply system.

To sum up, the main objective of the water bank in the context of this research is to allocate all water resources to achieve desirable economic outcomes while protecting the water environment through different management options. Water banking has the potential to: i) add flexibility to conjunctive water management, ii) enhance in-stream flows that are biologically and ecologically significant, iii) reduce water use in over-allocated areas, iv) reduce the impact of water pumping on stream flows, and v) facilitate the legal transfer and market exchange of various types of surface, groundwater and storage entitlements. The extent of benefits will be tested by this study to understand how is water banking can add flexibility to conjunctive water use management.
3.6.1 Water banking and related issues

In this research context, the water banking approach means managing surface and groundwater resources in the Murrumbidgee catchment as one source. Also, it is a way or mechanism to satisfy increased water demand and resolve competition between irrigation and environmental demand see Figure 3-29. Water banking can create the opportunity to release water from the head dams at the beginning of the water year to mimic the natural flow. The water is stored in the aquifer (or deposit it in the water bank) and later released from the bank to satisfy the summer demand. The bank is then refilled after the peak demand season.

![Figure 3-29 Water available for banking](image)

Water banking has several constraints; one of the main issues is spatial constraints, where water might be banked behind dams, on stream, off stream and underground (aquifer). In this study, water banking considered only the opportunity for banking water underground. According to Khan (2004), Willem et al. (2005) and Pratt Water (2004a), the possibility for water savings within the Murrumbidgee River system from system losses is about 200 GL (after accounting for loss to groundwater). This potential water savings ranged from 12–14% river loss and 12–20% channel loss in the CIA and MIA (through channel lining and concrete), the two main irrigation areas in which it is possible to use the aquifer downstream. In the study, the loss will be modelled to represent the total loss from transmission, evaporation and seepage for each river reach (see chapter 5, section 5.3.1). Pratt Water (2004b) and Khan et al. (2005) found that deep groundwater pressures have declined by 10–20 m over most of the area (between Narrandera and Hay) and this drawdown will take more than 20–30 years to recover through natural recharge. This enables a potential for
water banking by artificial recharge, using good quality water with low salinity, through dedicated or existing bores. However, artificial recharge by injection is not a proven technology and still under investigation. Additionally, the cost is likely to be high and needs to be taken into account. This study tested the water banking approach under artificial recharge, injection and infiltration, and also under different climatic and management conditions. Also, this study assumed that water banking is managed by a water service provider (the main irrigation area) so individual farmers are not required to store water on their farm and suffer evaporation losses.

Climate variability is an important issue that imposes the greatest stress on the hydrological system and water availability. Expectations of available in-stream flow volumes and water-banking volumes should take this variability into account. This could be done by allowing management actions to be varied in response to climatic conditions. For example, it may not be beneficial to allow pumping from the aquifer during wet years when excess water is available and extra water may not be needed. In this situation, the wet conditions could be used to passively or actively recharge the aquifer for use during dry seasons. Groundwater could be a viable source of water during dry periods. During periods of pumping, groundwater would be removed from the storage or aquifer and water levels would decline. With the return of wet conditions, the groundwater system should be allowed to recover through natural or artificial recharge of water into wells during times of peak wintertime flow.

Water banking could be planned over the long term or short term according to climatic conditions. In the literature, it is recommended that water banking be tested on used on an annual basis, as each year’s conditions are highly variable. In order for water banking to function, there several issues must be taken into consideration, such as institutional arrangements to legalise short- and long-term release and delivery of banked water, adequate hydrological capacity to allow storage and delivery without significant water loss, economic and environmental validity and social considerations. Furthermore, the acceptability of water banking by irrigators is critical in its design and operation.

It is beyond the scope of this study to look at all the constraints and issues pertaining to water banking in aquifers. These include environmental implication and energy required to re-abstract water, water quality, salinity, recharge rate, entitlements, legal aspects and costs involved in re-pumping and operation and capital cost. There is already a large amount of literature on aquifer storage and recovery (ASR) that considers water quality and
contamination problems as well as water pump clogging (Pavelic et al., 2007; 2006; Lin et al., 2006; Dudding et al., 2006). However, literature on the practical introduction of water banking and likely implementation issues for farmers is sparse.

Also, this study suggests that with each year that passes, an improved scientific understanding of the hydrological system and the role and capabilities of the water bank can be developed. Strategies will require modifications and adjustments as the availability of water and its timing vary from year to year. Management schemes will require adaptation to continually improve the water banking activities in the basin by learning from each years operational plans. Figure 3-30 shows a suggested strategy for long-term water banking as the climate moves between dry and wet conditions. Water banking in the long term can be managed, based on a normal money market approach—as debit and credit based on supply and demand market theory. In wet years when supply exceeds demand, water banking can go into credit as the received water is stored. However, during dry conditions when demand exceeds supply, water banking can debit and release the water.

![Figure 3-30 Long-term water bank management](image)

### 3.6.2 Water banking and water trading

The water market is considered to be one of the best mechanisms to ensure the most economically efficient use of water, moving water from low value to high value crops. Although it has effects on the environment, with regulation and trade prohibited between basin and catchment, these effects could be minimised. In this research, water trading was tested in a water-banking scenario, to facilitate water movement between irrigation areas and water banks.
Figure 3-31 shows the water banking and water trading conceptual framework, assuming two main irrigation areas A and B (MIA and CIA) on both sides of the river. Each irrigation area has, or will develop, its own water bank, and is able to manage its water resources (surface and groundwater) as one system. In the case of water availability exceeding biophysical crop water requirements, the irrigation area will store water in its aquifer by using artificial recharge, while in case of biophysical crop water requirements exceeding the water available (surface and groundwater), this irrigation area will buy water from other area’s water banks, within system constraints such as groundwater pumping capacity, environmental flow rules, river channel capacity and trading limitations. This water trading mechanism can facilitate the water movement and achieve better management of the whole system (surface and groundwater) while achieving economic benefits.

Market-based reduction in water demand is often promoted as a cost-effective way of attaining environmental objectives. It can be used to provide financial resources to cover all the costs of providing water, and to foster the economically efficient allocation of water—to move water from lower to higher value uses (Ait et al., 2005). In addition, water needs for the environment can be obtained through an open market mechanism. Through the open market, an environmental manager can buy water for environment requirements at market
price and provide it to the river. If the water market works efficiently, then water can move between all water users such as industry, agriculture, and the environment. In the last decade, water trading has increased considerably, despite infrastructure and institutional restrictions, such as the restriction between Murray and Murrumbidgee River valleys, especially with the reduction in surface water allocations. The New South Wales water allocation plan 2003–2004 for the Murray and Lower Darling valleys stated: ‘Due to the low water availability in both the Murray and Murrumbidgee River valleys at the start of the 2003–2004 seasons, there will be no temporary trades between these valleys. This restriction may be relaxed with a significant improvement in available water resources’. (DIPNR 2003, p. 14)

The main reason for allowing water trading was to encourage water use in locations and practices that returned greater economic value and to allow its transfer away from areas where excessive water use was causing unacceptable environmental problems, such as high water tables and salinity. It is assumed that water trading, both for agricultural and environment requirements, will improve water productivity, promote the economic efficiency of the irrigation industry, and enhance environmental sustainability.

3.7 Summary and conclusion

The aim of this study is to improve the seasonality of flows by studying the possible management options for surface and groundwater resources in irrigation areas to achieve environmental and economic benefits. This requires a decision tool to optimise economic and environmental outcomes from irrigation areas subject to the physical constraints of the system, environmental target flow, and the pumping and storage targets.

The seasonality of flows could be improved by testing the alternative management options investigated by this study. These options could be categorised into policy, physical and management options. Policy options include supply and demand and trading regulation between basins, irrigation areas and states. Physical options focus on delivery systems and storage facilities (water banking). Management options include changes to crop mix and selection. All these categories should interrelate to improve the seasonality of flows. This study focuses on several management options, irrigation demand by crop mix and water trading integrated with conjunctive water use management and design interventions such as water banking that would effectively influence the dynamics of water use, allocation, management and quality.
Holistic, accurate analyses of complex systems such as the irrigation systems under consideration in this study are almost impossible to test through experiment or observation. The application of system theory via models can help us to arrive at a better understanding of these systems. In the next chapter (four) the scenarios development and its rationale are discussed before model development in chapter five.
Chapter 4: Scenario Development

Scenario analysis is a mechanism used to study future potential water biophysical demand management and policy options, based on different assumptions, to examine possible outcomes and their likely benefits. The objective of this study is to evaluate and identify the changes in economic and environmental outputs of various supply and demand options to improve the seasonality of flows and environmental flows in the Murrumbidgee River. This is analysed by understanding the link between irrigation demand, conjunctive water management and water banking.

In this study different scenarios that take account of several demand and supply options under different climatic uncertainty conditions were examined relative to their impact on seasonal river flows, water productivity and environmental flows. This analysis was carried out in relation to the base case that is presented in Section 4.1. Section 4.2 presents the development of alternative scenarios, the definition of the scenarios and types, and discusses the modelling implementation of the scenarios and the rationale for each scenario under demand management, conjunctive water use and climatic conditions. Section 4.3 presents the assessment and evaluation of scenarios, using several indicators including water resources consumed (water use, crop water use and irrigation area use), production indicators (yield/ha and yield/ML), economic indicators (gross margin/ha and ML) and other indicators. Section 4.4 discusses scenario uncertainty and drivers. In the last Section 4.5 a brief summary and conclusion are presented.

According to Kepner et al. (2004), today’s environmental managers, catchment managers, and decision-makers are increasingly expected to examine environmental and economic problems in a larger geographical context such as catchment or irrigation area scale. Furthermore, Dunlop et al. (2002) identified three ways in which scenarios can be used to help develop better long-term strategies and policies: 1) They can be used to challenge policy makers’ mental models of the range of possible futures and extent of their time frame; 2) the lessons learnt during the cycle of scenario development and modelling can be used to highlight emerging issues and how they may vary among alternative futures; and 3) it can be used to test policy options. The first and third ways were used in this study. In short term strategies, when predictions are relatively robust, policies can be tested with various conceptual or analytical models by comparing a range of policy options to a base-case scenario.
In general, scenarios were developed to simulate actions or recommended changes from stakeholders or the irrigation community. The scenario-based approach could offer the decision makers, water authorities and/or irrigation companies a basis on which to explore decision analysis and alternative opportunities or actions that could improve water resource management at any scale. Scenario analysis offers several advantages, including the ability to intentionally investigate several future options (by forecasting or back-casting) or different points of view at one time. Therefore, scenario analysis requires that scenarios are possible, promising, plausible and applicable to be useful for decision-making.

In this study, scenarios were used to answer questions that relate to future management, uncertainties and development options with the view to managing human and environmental water use and growth patterns to minimise hydrological, economic and environmental impacts. The steps involved in scenario analysis process involve:

1. describing the base case and existing situation of the region
2. describing change patterns of development and significant processes that affect a region, particularly the Murrumbidgee catchment
3. constructing and calibrating a network simulation model (NSM) to simulate these processes and changes
4. simulating changes in the river flow and demand curve and evaluating the outcomes from these changes by using model indicators.

The first two processes are discussed in this chapter while the third process is discussed in chapters five and six. In chapter 7 the potential impacts from alternative scenarios are compared to the current conditions (base case).

4.1 Base case scenario

To better investigate and compare the potential management options, there is a need to understand and present the baseline conditions of the Murrumbidgee River catchment and its main irrigation areas. Hence, existing and pre-development information is presented here. Base-case information helps us to understand how surface water, groundwater and water trading have been used over the last ten years since the introduction of the MDBC cap regulation on irrigation diversion in 1993/1994. Aspects considered in this base case include:

- water allocation
- operational constraints
- water trading level
• groundwater and surface water use levels
• cropping system
• production and economic return
• environmental conditions.

The cap year was chosen as the base year because of the cap’s impacts on water allocation. These have not reached 100% since its introduction. This has led to several economic and environmental effects on the irrigation sector and the river system, as discussed in the previous chapters (chapter 2–section 2.2). Any alternative or potential scenario involves one or more changes from the base-case conditions of water availability or stock, demand, crop pattern and economic assumptions. The research methodology consisted of analysing a number of potential management scenarios and comparing them on the basis of the resources used as indicators (water use and land use), production indicators (yield/ha), environmental indicators (environmental flow) and economic indicators (gross margin per ha and ML).

This study mainly used primary and secondary data sources to evaluate the potential effect of different crop mixes, conjunctive water management and water banking on environmental and economic outcomes. In brief, the main data sources (see chapter 5 for details) included MIA and CIA information (both published and unpublished), CSIRO Land and Water’s published and unpublished reports, Australian Bureau of Agricultural and Resource Economics (ABARE), Department of Primary Industries (DPI), Australian Bureau of Statistics (ABS), Australian Bureau of Meteorology and Department of Infrastructure, Planning and Natural Resources (DIPNR).

4.1.1 Surface and groundwater allocation

According to Khan et al. (2004b), surface water allocations are based on the water level in the two main head dams, Burrinjuck and Blowering, at the start of the water year (July 1st), and the minimum historical inflows and water contribution from the Snowy Mountain Hydro-Electric Scheme. Water entitlements in the Murrumbidgee Valley have been allocated in a specific order, see chapter two for details (section 2.2, Table 2-4). The largest water entitlement is for general water security licences followed by the high-security water licences. General water security is allocated by percentage, which does not guarantee licence holders their full entitlements after ensuring essential water entitlements such as for environmental
flows, domestic and stock licences, local water utilities and high security licences are satisfied. High security holders are guaranteed a minimum 95% of their allocation.

On the other hand, groundwater systems in the Murrumbidgee catchment are also considered to be a large source of water for irrigation and domestic use. The Murrumbidgee Groundwater Management Committee (2000) stated in the lower Murrumbidgee groundwater management plan that there is over $5,100 \times 10^6$ ML stored in the state’s aquifer system, yet only $5 \times 10^6$ ML, or less than 0.1%, is suitable for consumptive use. As mentioned in Chapter Three (section 3.5), the groundwater system is divided into three main zones: upper, mid and lower Murrumbidgee groundwater systems. Table 2-3 (Ch.2–Section 2.2) shows the groundwater use in the two main groundwater management zones in the Murrumbidgee catchment and their sustainable yield. In addition, the estimated annual recharge of the middle Murrumbidgee aquifer is around $127 \times 10^3$ ML (Webb, 2000) and the current entitlements are around $55 \times 10^3$ML. The estimated annual recharge to the Lower Murrumbidgee aquifer system is $335.37 \times 10^3$ ML/yr and a ‘safe yield’ is $270 \times 10^3$ ML/yr (Kumar, 2002). Figure 4-32 provided an overview of the annual groundwater use for the lower Murrumbidgee catchment from 1981/82 to 2003/04. The announced allocation of surface water was reduced to less than 100% after 1993/94, which led to dramatic increases in groundwater use. Reported groundwater pumping is still less than the ‘sustainable yield’, and which indicates further opportunity for additional pumping.

![Figure 4-32 Observed groundwater use pattern in lower Murrumbidgee (1983–2004) compared with surface water allocation.](image-url)
4.1.2 Water and land use

This study focused on the main irrigation areas: the Murrumbidgee Irrigation Area (MIA), Coleambally Irrigation Area (CIA) and Private River districts (PRD). For the purpose of system representation, the MIA was divided into five main nodes, CIA was divided into three nodes and PRD was represented by four nodes, one for each river reach as described in Chapter two–section 2.1. The rationale behind this segregation is that each node has its own water entitlement and crop mix. The crop area for each irrigation area or node is changed every year due to water allocations and farmer crop planting decisions. The CIA crop area was obtained from the CIA annual environmental reports (2001–2005). Land use and net estimated potential crop water requirements (NCWR) of MIA, PRD and CIA under average climate conditions were obtained from different sources for the major crops (see Table 4-11).

Table 4-11 Crop area and estimated NCWR of CIA, MIA and PRD

<table>
<thead>
<tr>
<th>Crop</th>
<th>MIA</th>
<th>CIA</th>
<th>PRD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Area (ha)</td>
<td>NCWR (ML/ha)</td>
<td>Total Area (ha)</td>
</tr>
<tr>
<td>rice</td>
<td>46120</td>
<td>11</td>
<td>30440</td>
</tr>
<tr>
<td>wheat</td>
<td>39215</td>
<td>2.9</td>
<td>14276</td>
</tr>
<tr>
<td>oats</td>
<td>2896</td>
<td>2.6</td>
<td>1290</td>
</tr>
<tr>
<td>barley</td>
<td>3034</td>
<td>2.8</td>
<td>3299</td>
</tr>
<tr>
<td>maize</td>
<td>2924</td>
<td>6.4</td>
<td>116</td>
</tr>
<tr>
<td>canola</td>
<td>2685</td>
<td>1.7</td>
<td>2153</td>
</tr>
<tr>
<td>soybean</td>
<td>2881</td>
<td>6.4</td>
<td>4551</td>
</tr>
<tr>
<td>summer pasture</td>
<td>3929</td>
<td>11.5</td>
<td>0</td>
</tr>
<tr>
<td>winter pasture</td>
<td>24184</td>
<td>2.1</td>
<td>11998</td>
</tr>
<tr>
<td>lucerne (uncut)</td>
<td>2468</td>
<td>17.5</td>
<td>0</td>
</tr>
<tr>
<td>vines</td>
<td>13635</td>
<td>5.7</td>
<td>0</td>
</tr>
<tr>
<td>citrus</td>
<td>8700</td>
<td>7.9</td>
<td>0</td>
</tr>
<tr>
<td>stone fruit</td>
<td>934</td>
<td>9.7</td>
<td>112</td>
</tr>
<tr>
<td>winter vegetable</td>
<td>1500</td>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>summer vegetable</td>
<td>1500</td>
<td>5.9</td>
<td>0</td>
</tr>
<tr>
<td>lucerne (cut)</td>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>total</td>
<td>156605</td>
<td>68435</td>
<td>174835</td>
</tr>
</tbody>
</table>

Modified from Source: Khan et al., 2004

Among the major summer crops, rice is the dominant crop, followed by maize. Wheat is the most major winter crop, followed by barley and oats. Currently, grapes (vines) are the major fruit crop in the MIA, whereas there is no fruit grown in the CIA. The main crop
driving water demand during summer is rice, which in main reason why river flows have shifted to summer, causing environmental impacts. Seasonal Murrumbidgee River flows could be improved by altering the crop demand by using an alternative crop mix and encouraging farmers, through appropriate incentive policies, to adopt new crop mixes that include more winter crops.

**Crop on-farm prices, yields and variable costs**

Crop prices presented and used within the study were based on averages calculated over a three year period from 2000–01 to 2002–03 (see Table 4-12). Crop yields and variable costs were obtained from a number of sources, including researchers and extension staff of the various NSW Agriculture Department (Griffith) publications (Annual Farm Budget Handbooks and technical reports). In addition, yield and variable costs were sourced by soil type (sandy, loam, clay), irrigation technology (landformed, non-landformed, raised beds), and dryland enterprises. Also, Table 4-12 provided an overview of the current yield levels of major crops in the MIA and CIA. Khan *et al.* (2004a) indicated that yields have not yet reached their potential maximum and that there is room to increase the yield and farm profitability by improving water and nutrient management.

**Licensed entitlements**

The areas serviced by the Coleambally Irrigation Company hold a general security surface water entitlement of $482 \times 10^3$ ML. The areas serviced by the Murrumbidgee Irrigation Company hold a general security surface water entitlement of 928,748 ML, while the Murrumbidgee Valley holds a total general security surface water entitlement of 2,032,748 ML. The distribution of these water entitlements and the channel pumping capacity constraints are shown below see Table 4-13.

**Water Trading**

In the base-case scenario, water trading was based on existing water trading rules (as described in Chapter 3, Section 3.6) between the irrigation nodes. This water trading between the irrigation areas was adopted according to the existing trading rules. Figure 4-33 shows net annual temporary water trading at the irrigation area level. Negative values indicate greater volumes trading out than entering the area. It is very clear that the MIA is almost always an exporter. Twelve nodes represent the Murrumbidgee River valley, as shown in Table 4-14 and Figure 2-5 (Chapter 2, section 2.1). Each node is represented by its cropping system, water entitlement, crop water use, crop production and its land and water constraints. This will be discussed in detail in the next chapter.
### Table 4-12 Crop prices, yield and gross margin in the Murrumbidgee valley

<table>
<thead>
<tr>
<th>Crop</th>
<th>MIA Yield (kg/ha)</th>
<th>CIA Yield (kg/ha)</th>
<th>Average price between 2000-01 to 2002- ($/tonne)</th>
<th>Gross margin ($/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>rice</td>
<td>9.1</td>
<td>9.1</td>
<td>315</td>
<td>1753.5</td>
</tr>
<tr>
<td>wheat</td>
<td>5</td>
<td>5</td>
<td>150</td>
<td>375</td>
</tr>
<tr>
<td>oats</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barley</td>
<td>4.5</td>
<td>4.5</td>
<td>150</td>
<td>245</td>
</tr>
<tr>
<td>maize</td>
<td>10</td>
<td>10</td>
<td>220</td>
<td>1206</td>
</tr>
<tr>
<td>canola</td>
<td>2.6</td>
<td>2.6</td>
<td>370</td>
<td>404</td>
</tr>
<tr>
<td>soybean</td>
<td>3</td>
<td>3</td>
<td>450</td>
<td>524</td>
</tr>
<tr>
<td>summer pasture</td>
<td>N/A</td>
<td>N/A</td>
<td>7</td>
<td>180</td>
</tr>
<tr>
<td>winter pasture</td>
<td>N/A</td>
<td>N/A</td>
<td>7</td>
<td>215</td>
</tr>
<tr>
<td>lucerne (uncut)</td>
<td>8</td>
<td>8</td>
<td>75</td>
<td>187</td>
</tr>
<tr>
<td>vines</td>
<td>15</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>citrus</td>
<td>35</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>stone fruit</td>
<td>-</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>winter vegetable</td>
<td>30</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>summer vegetable</td>
<td>29</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>lucerne (cut)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>fallow ($/tonne)</td>
<td>N/A</td>
<td>N/A</td>
<td>165</td>
<td>100</td>
</tr>
<tr>
<td>annual</td>
<td>N/A</td>
<td>N/A</td>
<td>282.0</td>
<td>810</td>
</tr>
<tr>
<td>others</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>80</td>
</tr>
</tbody>
</table>

Source: Khan S. et al., 2004 and NSW DPI (2005 data sets) NA: Not available

### Table 4-13 Licensed surface water entitlement (GL)

<table>
<thead>
<tr>
<th></th>
<th>MIA Yanco+ Mirrool</th>
<th>BEN (includes Tabbita)</th>
<th>Wah Wah</th>
<th>CIA</th>
<th>Private diverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>surface water entitlement (GL)</td>
<td>583.748</td>
<td>225</td>
<td>120</td>
<td>482</td>
<td>PRD1 = 102</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD2 = 201</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD3 = 165</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD4 = 154</td>
</tr>
<tr>
<td>channel and pumping capacities (GL)</td>
<td>167.790</td>
<td>66</td>
<td>66</td>
<td>120</td>
<td>PRD1 = 50.179</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD2 = 200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD3 = 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PRD4 = 80</td>
</tr>
</tbody>
</table>


Figure 4-33 Observed net temporary water trading of the main irrigation areas MIA and CIA
Table 4-14 Irrigation nodes and names

<table>
<thead>
<tr>
<th>Irrigation Area</th>
<th>Node name</th>
<th>Allow to trade</th>
<th>Entitlement (GL)</th>
<th>Trading %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coleambally irrigation area</td>
<td>CIA 1 total water trading</td>
<td>yes</td>
<td>490.5</td>
<td>100</td>
</tr>
<tr>
<td>Coleambally Kerabury</td>
<td>CIA 2 total water trading</td>
<td>yes</td>
<td>413</td>
<td>75</td>
</tr>
<tr>
<td>Coleambally outfall drain</td>
<td>CIA 3 total water trading</td>
<td>yes</td>
<td>452.8</td>
<td>75</td>
</tr>
<tr>
<td>MIA - Yanco (1)</td>
<td>MIA 1 2 total water trading</td>
<td>yes</td>
<td>202.4</td>
<td>75</td>
</tr>
<tr>
<td>MIA – Mirrool (2)</td>
<td>MIA 3 4 total water trading</td>
<td>yes</td>
<td>23.4</td>
<td>75</td>
</tr>
<tr>
<td>MIA – Benerembah (3)</td>
<td>MIA 5 total water trading</td>
<td>yes</td>
<td>125</td>
<td>75</td>
</tr>
<tr>
<td>From dams to Wagga Wagga</td>
<td>PRD 1 total water trading</td>
<td>yes</td>
<td>102</td>
<td>100</td>
</tr>
<tr>
<td>From Wagga Wagga to Narrandra</td>
<td>PRD 2 total water trading</td>
<td>yes</td>
<td>201</td>
<td>100</td>
</tr>
<tr>
<td>From Narrandera to Hay</td>
<td>PRD 3 total water trading</td>
<td>yes</td>
<td>165</td>
<td>100</td>
</tr>
<tr>
<td>From Hay to Balranald</td>
<td>PRD 4 total water trading</td>
<td>yes</td>
<td>154</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2 Scenario development

Scenario analysis requires that scenarios must be possible, promising, plausible, and applicable to be useful for decision-making processes. In this study, scenarios were used to answer questions about system responses to alternative measures aimed at improving the seasonality of flows and end-of-system flows. The aim of this study was to study alternative options to improve seasonality of flows to meet production and environmental water demands.

Several options have been identified, both from the literature and from the two consultative workshops with stakeholders, held in Leeton (NSW) in April 2004, and in Griffith (NSW), March 2005. These were sponsored by the Cooperative Research Centre-Irrigation Future (CRC IF) scoping project entitled 'Improved Seasonality of Flows through Irrigation Demand Management and System Harmonisation™', and involved key stakeholders and the irrigation community. These included irrigation farmers, representatives from Murray Irrigation Limited, the Murrumbidgee Catchment Management Authority, the Murray Catchment Management Authority, and state government agencies, CSIRO, the Murray-Darling Basin Management Authority and the CRC for Irrigation Futures. They defined several options that can be categorised as regulatory, physical and management, as described in chapter three (Section 3.3).

These options need to be properly evaluated to better explain the adoption of agricultural production decisions and need to be studied under different climatic conditions and other drivers. Therefore, the scenarios should aim to ensure that the Murrumbidgee water system is managed for the greatest possible long- and short-term environmental and economic
benefit for all irrigation areas within the Murrumbidgee catchment. In addition, the key management scenarios for the Murrumbidgee catchment should take into account uncertainties, drivers of change, opportunities and challenges.

Thus, this study focuses on the three main options recommended and preferred by the stakeholders and irrigation community. They are based on the priority investigations criteria presented in Chapter 3 (Section 3.3). These preferred options are considered in order of precedence:

- conjunctive water use
- changing cropping mix
- substituting surface water use by groundwater.

To sum up, this study attempts to provide a strategy for the best use of available water resources (surface, groundwater and trading) for agricultural and in-stream demand using environmental and economic assessment criteria. This criterion examines the impact of the water banking approach (that would effectively influence the dynamics of water use, allocation, management, economics and environmental quality), with different crop mixes and conjunctive water use management options to improve the seasonal flow and satisfy environmental flow under climatic uncertainty conditions. Each scenario will try to answer questions such as what would be the consequences of a decision or action? and what policies might be necessary to reach or avoid a specific long- or short-term outcome? These three options are combined into six main scenarios that are developed as follows:

**Main scenarios**

- **Scenario 1**: Base case with the current conditions after the introduction of the water cap including surface, ground and trading water sources without water banking and conjunctive water management.

- **Scenario 2**: Base case with different crop mixes under different climatic conditions. Involves matching the crop area to soil type, irrigation technology, trading limits, water entitlements and seasonal water availability, increasing winter cropped area and decreasing summer crop area, to potentially save water.

- **Scenario 3**: The same as Scenario 2 (base case with different crop mix under different climatic conditions) combined with water banking under both recharge methods (infiltration and injection). This scenario also includes testing changes in the crop mix and conjunctive water use options.
• **Scenario 4:** Base case with conjunctive water use (surface water substitution by groundwater) under the assumption of reducing surface water by 10% and shifting dam releases six months earlier.

• **Scenario 5:** The same as Scenario 5 (base case with conjunctive water use) combined with water banking under both recharge methods (infiltration and injection), which allows water trading between surface and groundwater. This scenario also involves reducing surface water by 10% and shifting dam releases.

• **Scenario 6:** The same as base case with all previous options that include changing crop mix, water banking with two recharge options, conjunctive water use and shifting dam releases.

Table 4-15 shows a summary of the combination of the six main scenarios and the sub-scenarios arising from the base case. These sub-scenarios are discussed in detail in the next section. These scenarios were tested under three different climatic conditions to assess uncertainty (dry, wet and average). The changes from the base case scenario involved different crop mixes (summer, winter and reduction in high crop water requirements by 50%), different water sources (surface water, groundwater and trading water), and the presence or absence of water banking. These main scenarios were tested with different assumptions that led to several sub-scenarios or scenario variations. This matrix of scenarios, variations, time, water sources and uncertainty led to more than 50 scenarios. These scenarios can be categorised into two main categories: demand management and conjunctive water use, which were tested under climatic uncertainty conditions. These categories and climatic conditions are discussed in detail in the following sub-sections after scenario modelling and implementation are discussed in the next sub-section.

### 4.2.1 Scenario modelling

As discussed above, the suggested scenarios test demand management and deal with changing water demand or stocks. These scenarios need a flexible modelling tool (Clap and Fiorentino, 1997) and comprehensive hydrological-economic-environmental model that is able to implement the processes involved in them. As discussed in Chapters 2 and 3, the best approach to deal with this complex system is a combined system dynamics and optimisation approach. The model should be able to represent the network system from the two main head dams and account for the river flows at different points along the river. It must be able to capture the diversion effect from different demand scenarios, count the end-of-system...
flow as an environmental constraint, and measure economic return from each scenario. Figure 4-34 shows how these scenarios were built and implemented into the Network Simulation Model (NSM). The NSM concept and structure will be discussed in detail (with the three levels field, irrigation area and catchment see Figure 5-35 in the next chapter (chapter five).

Figure 4-34 Scenarios and modelling implementation

Under changing demand, one case was identified by changing crop mix as management option which can be built in two ways. One works directly on the crop module by adding more and new constraints according to general drivers to determine and drive the crop pattern that is to be shifted to summer or winter crops. In the second way, the user inputs the suggested crop pattern into NSM directly by changing the crop pattern to use a different mix of summer, winter and reduced crop areas. This case leads to a change in the demand from irrigation that can be used as proxy for stream flows and so on.

Three alternative water sources were identified for the scenarios: surface, groundwater and water trading. Under these cases two changes were tested, namely a reduction in surface water availability by 10% and a shift in the release from the dams (outflow) by one season. Under conjunctive water use, these changes test the use of groundwater as a substitute for
surface water, water trading between irrigation areas and the shifting releases from the main dams by one season. These variations are used to build and drive the NSM.

All the above scenarios and cases were examined considering the uncertainty of climate, which affects the NSM outputs by changing the rainfall and evaporation inputs. These will influence crop water requirements and in turn alter irrigation demand. These combination scenarios and cases were further combined with the availability of water banking. The main assumption of water banking, as discussed early in Chapter 3, is that each irrigation area has a water bank which can be used to analyse both short-term (one year) and long-term (several years) operations by storing water in the bank and releasing it according to irrigation needs.

4.2.2 Demand management

The concept of demand management involves modifying the level or time of a demand for a resource. This could be achieved by changing consumer behaviour or the resource stock by using technology (White and Fane, 2001). In addition, changing the stock of resources can be achieved by using other water sources and measures such as groundwater and water trading in conjunction with the main source (surface water) for irrigation, or applying new water banking approaches and/or increasing system efficiency. Furthermore, behaviour can be changed through education and adoption of new management practices. This is beyond the scope of this study. In general, the objective of demand management is to improve the management of surface and groundwater resources to satisfy environmental and consumptive demands in irrigation catchments with economic benefits. Irrigation demand has an impact on environmental flow and also on stream flow in general. Changing the crop mix could lead to changes in the irrigation demand, which in turn could have positive or negative influences on stream flows. Consequently, changing the irrigation demand curve could be used as a proxy measurement for changing the stream flow curve.

Crop mix

In the case of crop mix under the main scenario of irrigation demand several changes were examined, including:

1. winter crops, which involves increasing the area planted to winter crops such as wheat, winter pasture, barley and canola
2. summer scenario, which focuses on summer crops by increasing the area planted to summer crops such as rice, lucerne, maize and soybean
3. reduction scenario was examined to determine the consequences of reducing the crop areas of rice, wheat and lucerne by 50%

4. mixed cropping scenario examined different crop mixes of summer and winter crops with equal priority.

The drivers considered when developing the crop mix scenarios are poor soil, the export market and international trade, new biotechnology and technology, efforts to increase water use efficiency, reduce recharge and improve the environment. All of these drivers are discussed in details in Appendix C and Table 4-16.

4.2.3 Conjunctive water use

Both surface water and groundwater are regularly used when they are available. However, they are managed individually. Surface water is used when available and groundwater when the stream flow is low or dry. Therefore, the conjunctive water use option involves testing the management of surface water and groundwater as a single source for short- and long-term time spans under different climatic conditions. This option was investigated through two cases as follows:

1. using groundwater with surface water
2. allowing water trading of surface water combined with water banking.

Under these water sources cases three variations were tested as follows:

1. assuming a 10% reduction in surface water use for irrigation which is replaced by groundwater
2. assuming new releases from the high dams by shifting the release by one season (six months) earlier, with the same level of delivery to irrigators with the possibility of storing water underground using water banking. Effects on hydropower, return flow, dam spill and storage level were not considered. The main assumption here is water banking is managed by water service provider and the incurred cost will be added on water cost, so the farmer will have equity in sharing water price.

The drivers of these sub-scenarios are summarised in Table 4-16 and are discussed in detail in Appendix C. All of these sub-scenarios were tested under different climatic conditions. These climate uncertainty conditions are discussed in detail in the following sections.
## Table 4-15 The main Scenarios and the changes involved from the base case

<table>
<thead>
<tr>
<th>Main scenarios</th>
<th>Sub-scenario (scenario variations)</th>
<th>Water sources</th>
<th>Crop mix</th>
<th>Climatic conditions</th>
<th>Water banking</th>
<th>Conjunctive use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Surface water</td>
<td>Ground water</td>
<td>Trading water</td>
<td>Actual</td>
<td>Winter</td>
</tr>
<tr>
<td>1- base case</td>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2- base case with different crop mix under different conditions</td>
<td>mixed cropping</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Xx</td>
<td>xx</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>X</td>
<td>xx</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>Xx</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>reduction</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td>3- scenario 3 (crop mix) with water banking under different assumption of recharge (infiltration and injection)</td>
<td>crop mix</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td>4- base case with conjunctive water use (groundwater substitute) under different assumption</td>
<td>reduce surface water by 10%</td>
<td>x</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>shifting dam release</td>
<td>x</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>x</td>
</tr>
<tr>
<td>5- scenario 5 (base case with conjunctive water use and water banking) with allowing water trading under different assumption of recharge (infiltration and injection)</td>
<td>reduce surface water by 10%</td>
<td>x</td>
<td>*</td>
<td>x</td>
<td>*</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>shifting dam release</td>
<td>x</td>
<td>*</td>
<td>x</td>
<td>*</td>
<td>x</td>
</tr>
<tr>
<td>6- scenario 6 all options (mixed cropping case with conjunctive water use and water banking) with allowing water trading under different assumption of recharge (infiltration and injection)</td>
<td>shifting dam release</td>
<td>x</td>
<td>*</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

* Base condition (no change)  x: the change involved in the scenario  xx: give priority for these crops
<table>
<thead>
<tr>
<th>Main scenario categories</th>
<th>Cases</th>
<th>Variations</th>
<th>Scenario issues</th>
<th>Scenario Drivers</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base case</strong></td>
<td>crop area scenario 1</td>
<td>do nothing</td>
<td></td>
<td>do nothing</td>
<td></td>
</tr>
<tr>
<td><strong>Irrigation demand management</strong></td>
<td>crop mix (scenario 2)</td>
<td>- winter - summer - reduction - mixed cropping</td>
<td>- environmental flow - flow and seasonality - climatic condition</td>
<td>- intensification - grain crops and yields - biotechnology - demand for agricultural products - information and precision agricultural - oil consumption - water resources and irrigation</td>
<td>- crops areas - water allocation - system constraints at Gundagai - system constraints at Tumut river - end of the system - irrigation efficiency</td>
</tr>
<tr>
<td><strong>Conjunctive water use management (groundwater substitute and water banking)</strong></td>
<td>crop mix with water banking scenario 3</td>
<td>- cut SW by 10% - shift dam release</td>
<td>- environmental flow - flow and seasonality - minimising losses - dams operations</td>
<td>- water resources and irrigation - conjunctive water use - ecosystem services</td>
<td>- system constraints at Gundagai - system constraints at Tumut River - end of the system - GW Pumping limits - trading rules - banking constraints 200 GL</td>
</tr>
<tr>
<td></td>
<td>groundwater substitute scenario 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>water banking and water trading scenario 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>crop mix with water banking and water trading scenario 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Uncertainty conditions</strong></td>
<td>dry</td>
<td>inc evap by 10%</td>
<td>- flow and seasonality - climatic uncertainty</td>
<td>- climatic change - water resources and irrigation</td>
<td>- minimum and maximum historical records of rainfall and evaporation</td>
</tr>
<tr>
<td></td>
<td>wet</td>
<td>INC RF by 10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>actual RF and evap</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2.4 Climatic conditions

The Murrumbidgee catchment experiences a variable climate with rainfall and evaporation differing from east to west. Thus all of the above scenarios were tested under different climatic conditions to study the effects of climate uncertainty. Three different cases were identified, using generated climatic data developed by using Stochastic Climate Library SCL (2004):

1. dry scenario: examines dry conditions and their impact on irrigation demand. This was examined by using future projections of evaporation and rainfall, which assume an increase in evaporation by 10% and a decrease in rainfall by 10%
2. wet scenario: examines wet conditions using maximum rainfall projections. Assumes an increase in rainfall by 10% and a decrease in evaporation by 10%
3. average climatic scenario: tests the average conditions of rainfall and evaporation.

The potential driver of these climatic cases is a global climate change. CO₂ concentration, land clearing and potential evaporation from the system are summarised in Table 4-16 and discussed in detail in Appendix C. Table 4-16 is comprised of the following elements: variations, issues, variables and drivers. Variations are the sub-scenarios that will be tested, issues represent the main issues and drivers affecting these scenarios, variables represent which variable inside the model will be changed while drivers are the most likely driver which could influence or lead to this situation under each scenario. Most of these will be discussed later.

4.3 Scenarios assessment indicators

Each of the proposed scenarios was evaluated using environmental, economic, water use and productivity indicators. According to Fairweather et al. (2003), water indices are generally a ratio of an agronomic or economic variable to a volumetric or depth measurement of the water applied to the root zone, transpired by the crop or available to the crop. In general, water use indices measure the productivity or profitability of the irrigation system. Five groups of water indices were used to evaluate the scenario outputs under this study as shown in Table 4-17:

1. water resources indicators (water use, crop water use and irrigation area used)
2. land and water productivity indicators (yield/ha and yield/ML)
3. economic indicators (gross margin/ha and gross margin/ML)
4. monthly environmental indicators expressed as percentage of desired end-of-system flow
5. physical efficiency indicators expressed as a percentage.

<table>
<thead>
<tr>
<th>Indicators category</th>
<th>Indicator</th>
<th>Calculation</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water resources indicators</strong></td>
<td>crop economic WUI</td>
<td>gross return/ ET</td>
<td>$/mm</td>
</tr>
<tr>
<td></td>
<td>crop WUI</td>
<td>yield/ET</td>
<td>Kg/mm</td>
</tr>
<tr>
<td></td>
<td>Irrigation area WUI</td>
<td>yield/irrigation water applied</td>
<td>Kg/ML</td>
</tr>
<tr>
<td></td>
<td>gross production economic WUI</td>
<td>gross return/total water applied</td>
<td>$/ML</td>
</tr>
<tr>
<td></td>
<td>irrigation area economic WUI</td>
<td>gross return/irrigation water delivered to the area</td>
<td>$/ML</td>
</tr>
<tr>
<td></td>
<td>water use per area</td>
<td>irrigation applied/area</td>
<td>ML/ha</td>
</tr>
<tr>
<td></td>
<td>overall WUI</td>
<td>water available to all crops in the region/water into regional bank</td>
<td>%</td>
</tr>
<tr>
<td><strong>Production indicators</strong></td>
<td>gross production over area</td>
<td>crop yield/area</td>
<td>tonnes/ha</td>
</tr>
<tr>
<td></td>
<td>gross production economic</td>
<td>yield/(irrigation applied + rainfall)</td>
<td>tonnes/ML</td>
</tr>
<tr>
<td><strong>Economic indicator</strong></td>
<td>gross margin per area</td>
<td>(T. income – T. variable cost)/Area</td>
<td>$/ha</td>
</tr>
<tr>
<td></td>
<td>gross margin per ML</td>
<td>(T. income – T. variable cost)/irrigation applied</td>
<td>$/ML</td>
</tr>
<tr>
<td><strong>Water efficiency indicators</strong></td>
<td>water bank efficiency</td>
<td>water released from bank/water into bank</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>conveyance system efficiency</td>
<td>water delivered to IA/water diverted to the IA</td>
<td>%</td>
</tr>
<tr>
<td><strong>Environmental indicators</strong></td>
<td>environmental flow satisfaction</td>
<td>no of months satisfy environmental flow/total number of months</td>
<td>%</td>
</tr>
</tbody>
</table>

*Water use indicator

However, for simple representation, this study used two main criteria (environmental performance and agricultural productivity/economics) to better understand the tradeoffs of each scenario (see details in Chapter Seven, section 7.2). To measure the performance of each scenario, a standard set of criteria was defined, comprising water use, water productivity, welfare and environmental measures. These criteria were selected to reflect the objectives of this study, namely changing the seasonality of flows and improving water productivity and environmental performance in the Murrumbidgee River. These criteria are not of the fail/pass type, but assess the performance of each scenario on a scale of economic, social and environmental outcomes.

### 4.4 Scenarios drivers and uncertainty

Recently, several water regulations have been introduced in NSW that have affected irrigators’ allocations, economics and environment conditions, particularly in the
Murrumbidgee catchment. These regulations, together with external environmental factors (such as climatic and rainfall uncertainty), have had several positive and negative impacts on water use and river health. Thus there is a need to test different scenario options while taking into account these uncertainties and their impacts on seasonal river flows. Potential effects of a number of scenarios developed in this study were compared to current conditions (base case) using the indicators outlined above. Several scenarios identified earlier in this chapter were used to test possible options for improving the seasonal flows and satisfying environmental flow requirements. These scenarios are affected by several sources of uncertainty discussed in the following sections.

4.4.1 Rainfall and evaporation uncertainty

Inter-annual climate variability is a significant feature of agricultural water policy and planning in Australia. Global climate change is likely to have significant effects on both water resources and agricultural productivity. Potential influences include changed rainfall patterns (average rainfall, the intensity of rainfall events, seasonality of rainfall), plant water use (\(\text{CO}_2\) concentration, potential evaporation) and catchment yields of surface water. In turn, these could affect the amount of water available for irrigation and environmental flows, crop and pasture growth. Although climate change research has developed in recent years, there are still high levels of uncertainty.

Rainfall in the Murrumbidgee catchment decreases from east to west and is very variable in frequency and intensity. The highest rainfall, up to 1500 mm, is in the upper part of the Tumut catchment. In the middle reach at Gundagai it is around 600 mm and in the lower reach between Darlington Point and Balranald it varies from 300 mm to 500 mm. Potential evapotranspiration varies from 1000 mm per annum in the east to over 1600 mm per annum in the west. January is the hottest month with average daily maximum and minimum temperatures of 32°C and 16°C respectively. In the upper parts, the average daily maximum and minimum temperatures are 21°C and 6°C. July has average maximum and minimum temperatures of 14°C and −4°C. Increasing scarcity of water (due to climatic change and drought) and high demand on existing supplies by agricultural and other users have placed river systems under great pressure (Lovett et al., 2002).

Climate change is expected to have significant impacts on the hydrological cycle at a regional scale. This will in turn, affect the availability of, and demand for, water resources and the way the resources are most effectively managed. According to Beare and Heaney
(2002), a number of future emission scenarios have been developed to explore the links between global warming and economic development, population growth and technological progress. Based on the IPCC report (2000), global warming scenarios, the Atmospheric Research Division of Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO) has run global and regional climate models to develop long-term projections for a variety of climatic variables such as precipitation, temperature and evaporation for Australia regions, particularly the Murray Darling Basin. They have concluded that the projected declines of rainfall in 2050 and 2100 are 5% and 5–10% respectively. In addition to precipitation, climate change affects other parameters such as evaporation. It is predicted that evaporation is likely to increase by 10–20% across the Murray Darling Basin. Climate change can also affect agriculture indirectly through any attempts to reduce greenhouse gas emissions. The major contributors to emissions are land clearing and animal production.

Although this study does not explore the influence of climatic variability, the scenarios developed were to quantify some effects of climate change on water availability and demand. These were tested by examining the impact of dry and wet conditions on irrigation demand and seasonal flows. Assumptions of a 10% increase in evaporation and a 10% decrease in rainfall were made to simulate extremely dry conditions. Assumptions of a 10% decrease in evaporation and a 10% increase in rainfall were made for extremely wet conditions.

4.4.2 Environmental flows

According to the water sharing plan for Murrumbidgee regulated river (2004), the state of NSW implemented environmental flows in 2001 by releasing dam water to simulate, maintain or restore natural and seasonal flow patterns. EPA (1997) stated that it is impossible to restore flows across the river catchment to pre-regulation conditions. Rather, the aim of environmental flow management is to mimic natural flow regimes, providing cues for key lifecycle events such as spawning and migration. It can also rehabilitate and improve ecosystems. This can be achieved by modifying existing releases (shifting the release one season), increasing water use efficiency, restricting diversions and extraction, conjunctive water use management, irrigation demand management and increasing allocations for the environment from large storages. The main source of uncertainty is change to environmental flow allocations due to a revision of environmental rules in 2008. Rules for surface water
flows and environmental flows for groundwater dependent ecosystems are still under investigation and revision. All of these have potential impacts on water allocation.

### 4.4.3 Flow and seasonality

According to DLWC (1998a) water is a finite resource and the signs are that it has reached the limit of reasonable use. The frequency of high flows is now only about half the natural frequency, and occurs during summer months instead of winter. Average flows between June and October have dropped by a third (DLWC 1995). Further downstream, end of the system average flows are now about one third of their natural level. Moreover, water demand in the winter rainfall dominated Murrumbidgee catchment is dominated by summer crops that require higher flow rates to pass through the upstream river reaches, therefore altering the seasonality of flows. These issues can be overcome through the changing crop mix, introducing incentives for winter crops and using a water bank approach. A further source of uncertainty is errors in flow measurements at different stations along the river. Pratt Water (2004a) reported that there is about a 33% error in flow measurements at downstream reaches of the Murrumbidgee River stations.

### 4.4.4 Dam operations

The operation of Burrinjuck and Blowering dams (two main headworks in the catchment) and associated water diversions has had substantial effects on the flow regime, causing changes to seasonal patterns and volumes, including a reduction in flow variability and in the average discharge of water downstream of the major irrigation areas. This could be relaxed by modifying the release from the dams, increasing water use efficiency, restricting diversions and extraction and conjunctive management of surface and groundwater.

### 4.4.5 General drivers

Each of the scenarios analysed in this study was the result of the actions of a number of drivers of land and water resources (see Table 4-18). These general drivers have several impacts on different components of the system. These general drivers, and their possible effects, are discussed in detail in Appendix C. The drivers include different landscape values, converting water to economic output and managing external impacts such as globalisation and intensification. The scenarios will help challenge presumptions about the future, but also identify constraints, trade-offs and issues that must be managed in future. The scenarios can also be used as groundwork for the analysis of different alternative strategies and policies.
Table 4-18 General drivers

<table>
<thead>
<tr>
<th>General Drivers</th>
<th>System component impacted</th>
</tr>
</thead>
<tbody>
<tr>
<td>water resources and irrigation</td>
<td>diversion, extraction, river operation, allocation, environmental flows</td>
</tr>
<tr>
<td>agricultural products demand</td>
<td>cropping system and irrigation demand</td>
</tr>
<tr>
<td>land use</td>
<td>crop mix, irrigation demand and diversion</td>
</tr>
<tr>
<td>information and precision agriculture</td>
<td>demand, irrigation use, surface and groundwater use, production</td>
</tr>
<tr>
<td>intensification</td>
<td>crop mix, environmental impact, fertlizer, herbicide use, production</td>
</tr>
<tr>
<td>technology</td>
<td>crop mix, irrigation area, water use, cost, production</td>
</tr>
<tr>
<td>biotechnology</td>
<td>crop mix, irrigation area, water use, production</td>
</tr>
<tr>
<td>grain crops yield</td>
<td>crop mix, irrigation area, irrigation demand and use</td>
</tr>
<tr>
<td>oil consumption</td>
<td>groundwater use, agricultural cost, crop mix</td>
</tr>
<tr>
<td>regional and research development</td>
<td>development, crop mix, irrigation use</td>
</tr>
<tr>
<td>ecosystem service</td>
<td>water policy, environmental allocation, flows</td>
</tr>
<tr>
<td>social issues</td>
<td>agricultural area, income, development and cost</td>
</tr>
</tbody>
</table>

The future will be affected by different numbers of drivers. Some drivers could be trends or forces, while others could be policies and actions that may take place in the future. The scenarios included in this study did not cover every possible variation and combination of possibilities, but included a few options considered more plausible. In addition, the scenarios themselves didn’t indicate what decision will be critical for ensuring positive long-term outcomes; rather they provide appropriately scaled information, context and models that might help in answering these kinds of questions.

4.5 Summary and conclusion

The main aim of this study is to improve the seasonality of flows by studying possible management options for surface and ground water resources in the Murrumbidgee catchment to achieve improved environmental and economic outcomes. This chapter presents and discusses the modelling scenarios used in this study, including the base case and other derived scenarios. Three main options were identified as the highest priority for further investigation by the stakeholders and irrigation community. These options are crop mix, conjunctive water use and water banking. This study focuses on providing one example of the best use of available water resources (surface, groundwater and water trading) for agricultural and in-stream water demand. It uses environmental and economic assessment criteria to examine the effectiveness of the water banking approach with different crop mixes, and conjunctive water use management options. This analysis was carried out to include several sources of uncertainty that are analysed in Chapter 7–section 7.4.

The six main scenarios developed and tested in this study are as follows:

- **Scenario 1:** Base case under the current conditions after introduction the MDBC-water Cap.
• **Scenario 2:** Base case with different crop mixes.

• **Scenario 3:** The same as Scenario 2 combined with water banking under infiltration and injection recharge methods.

• **Scenario 4:** Base case with conjunctive use (reduce/shift surface water release).

• **Scenario 5:** The same as Scenario 4 with water banking (under infiltration and injection recharge methods) with allowing water trading.

• **Scenario 6:** All options crop mix, conjunctive water use, water trading through water banking under infiltration and injection recharge methods.

Under changing demand, one case was promising: changing crop mixes. Under this scenario, four scenario variations (sub-scenarios) were identified: summer, winter, mixed crop and reduction. All these sub-scenarios were tested with and without water banking (under infiltration and injection recharge methods) and under different climatic conditions with the same water sources as the base case (surface, ground and trading water). This led to different levels of demand that resulted from changing the crop mix.

Under changing stock or water availability, two cases based on different water sources were found: conjunctive water use allowing groundwater pumping as a substitute water source, and water trading combined water banking. Under these scenarios, two scenario variations (sub-scenarios) were identified: a reduction in surface water by 10% and a shift in the dam release by one season earlier. All these scenarios were tested under different climatic conditions. This led to 64 scenarios that were evaluated based on several indicators such as land and water use, economic outcomes, productivity and environmental outcomes.

A model that is able to simulate all the processes involved in these scenarios and variations is necessary. As discussed in Chapters 2 and 3, one of the promising approaches for working with complex systems is through the application of system dynamics (SD) via models. This can help decision makers to arrive at some acceptable level of understanding. The model should be able to represent acceptable levels of agreement between the hydrological and economic aspects of the study area with some environmental constraints. The model concept and structure used in this study will be discussed in detail in the next chapter.
Chapter 5: NSM model Structure

In this chapter the research methodology is developed using a system analysis approach: an integrated hydrological-economic-environmental network simulation model has been constructed to assess and help better understand the possible effects of better irrigation demand. As mentioned in chapter 1, this chapter describes the approach to system analysis of the study area, construction of the model, calibration and validation of the model, and development of several Scenarios of different irrigation management systems. The objectives, assumptions and criteria used in the model are defined using a systems approach (Ford, 1999; Sterman, 2000).

The characterization of the study area, including a description of the geographical and agricultural production system, was discussed in chapter 2. The goals, problems and constraints are presented in chapter three. Section 5.1 of this chapter describes the model’s objectives, assumptions and criteria development. It includes the steps involved and provides the sources of information necessary to construct the model and the data sources used in the model. The system analysis of the study involves two parts: characterization of the study area (chapter two) and analysis of the criteria and constraints on which the model is based (chapter four). Section 5.2 discusses the limitations of the research and its applicability in informing broader irrigation systems decisions. Section 5.3 describes the Network Simulation Model (NSM) components and equations. In addition, this section describes the crop decision optimization module (CDOM) objectives, structures, data sources and parameter descriptions. The crop decision module tries to capture farmer crop planning decisions, which are the main driver of irrigation water demand. Furthermore, section 5.3, describes the incorporation of water trading into the NSM model through the water trading module (WTM). Section 5.4 describes the crop decision optimization module (CDOM) validation (the model calibration and validation processes are described in full in Chapter Six). In Section 5.5, water trading module (WTM) validation and results are described. Finally, Section 5.6 of this chapter briefly summarizes and concludes the main findings.

5.1 Simulation model

Based on a system analysis approach, a simulation model was constructed to describe irrigation system demand, resources constraints and water trading at field, irrigation area and
catchment levels in the Murrumbidgee catchment. The model’s objective is to provide better understanding and evaluating the impacts of irrigation demand management, conjunctive water use management and water banking approaches on environmental flows and the seasonality of flows. However, it is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly, further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.

This study uses a systems approach to develop a model that is able to examine the system behaviour, cropping system and water use. The art and science of systems analysis has evolved through developments in engineering, economics and mathematics. As the science of systems analysis has advanced over the last decades, and as the scale of modern irrigation projects has grown, systems analysis has found extensive application in irrigation business management. UNESCO (2002a; b) reported that systems analysis may be used to find the best acceptable solution. However, this is not its only purpose; often it may be used to structure a water resources project. Structuring involves drawing systems elements in a block diagram connected by means of logical statements and functions.

Since models are abstractions of reality, they do not usually describe all the features that are encompassed by a real world situation. Systems analysis, in a very broad sense, is concerned with the identification and description of models of reality which study the behaviour of different aspects of a system under different conditions. Furthermore, models may include the selection of a preferred course of action to influence systems behaviour. Consequently, systems analysis may include the field known as operations research.

Based on the methodology of the systems analysis proposed by Ford (1999) and Sterman (2000), the process of modelling involves the following steps:

1) description of the research problem
2) research question
3) construction of the model
4) testing the model (verification and validation)
5) exploration of different Scenarios.
Steps 1 and 2 are explained in detail in chapters 1 and 2, while steps 4 and 5 are presented in chapters 6 and 7. Step 3, involving the construction of the simulation model, is explained in this chapter.

The first step is to define the research problem. In this instance this involves identifying “reference mode behaviour”, the key variables affecting behaviour, and selecting the time horizon for the analysis. As previously mentioned in chapter 1 and 2, demand for water, and the competition between irrigation and environmental demand, is increasing while the supply and allocation of water is decreasing or uncertain in the Murrumbidgee catchment. The key principle variables include: 1) processes such as surface water, groundwater pumping and water trading; 2) production variables such as cropped area for different crops, crop production and yields; 3) economic variables such as gross margins, variable cost and net return; and 4) environmental variables and constraints such as environmental flows targets at the end of the system.

Modelling procedures were applied to describe the relationship between crop water demand, water allocation, climatic condition, groundwater and water trading with environmental outcomes. The model was developed using data from water provider companies, Department of Infrastructure, Planning and Natural Resources (DIPNR), river authorities and some data from local institutions in the study area such as CSIRO land and water. Data on agricultural systems were obtained from New South Wales Agriculture, whilst some data were from secondary information.

Qualitative conceptual models were formulated as causal loop diagrams (first understanding of the system). Causal loop diagrams are a convenient and powerful way to clarify and display various mental models of a system (Dudley, 2004). The proposed model can be used to directly address the conflict between irrigation water demand and environmental flows by fairly predicting the likely outcomes of a decision and its associated risks for alternative cropping patterns. Results from the simulation model may influence the decision making on irrigation systems. However, the model results should be interpreted within its uncertainty and model limitations as discussed later in this chapter and chapter 7.

Characterizing the crop–water system is the first and one of the most important steps for designing a model for studying the interactions within the crop–water system. This step helps to define the limits, problems and constraints of the system (ecological and economic) and should ultimately help to define the type of system and its behaviour (Thomton and
Herrero, 2001; Devendra, and Thomas, 2002). In this study, the model represents the two main irrigation areas with their sub areas, Murrumbidgee irrigation area and Coleambally irrigation area, plus the main private river diverters in the Murrumbidgee catchment. Using this model, the impact of different biophysical changes can be considered across each of the irrigation areas.

The general characteristics and the scope of the model are shown in Figure 5-35. The model combines the biophysical, hydrological, environmental and economic aspects of the irrigation system. The biophysical aspects of the irrigation areas are represented in the model structure by two components, crops and water.

Water is the central currency for the analysis of crop–water production systems at the field, irrigation area and catchment level, so the crop component is linked to the water component. Three hierarchical units of analysis are defined and interactions are included among the three levels. At the field level, crop, biophysical demand and variable cost are included. At the irrigation area level, crops and water components are included. And, at the catchment level, information on irrigation areas is incorporated regarding water availability from the main canals, diversions and environmental constraints.

![Figure 5-35 General framework of the model](image)

The water component is used to determine how much water is available monthly for irrigation and the environment, while the crop component determines the water needs of
each crop and the whole irrigation area. The yield under the specified conditions is then calculated. Irrigation requirements for crops in each irrigation area are calculated using the difference between precipitation and the crop’s water requirement over a specified period of time. Everything is linked to the water component because water is the core of the model and the model is driven by cropping pattern and climatic conditions.

The crop component is linked to the economic component based on information for each crop such as the amount of capital required, inputs used, and variable costs of production, yields and return. Although the total amount of water received by a crop during the growing season may be adequate, water stress during the critical season can result in significant yield reductions and environmental impacts. In this way the crops’ demand reflects changing sensitivity to water supply throughout its growing cycle. In order to study the difference in water use application, the variables are estimated on a monthly basis.

Finally, the economic output of the simulation model is the gross margin of irrigation production per megalitre and hectare at irrigation area and catchment levels. This gross margin is calculated in the model as the total return and variable cost that includes fertilizers, seeds and labour. By running the model under various management and resource Scenarios, it can predict how the annual economic outcome will be affected. Also, the model can analyse the tradeoffs between water allocation, agricultural income, environmental performance and equity of water distribution. The water outputs of the model are the flow at each point along the river, the environmental flow at the end of the system, the irrigation diversion and delivery, and the volume of water being traded or stored for further use. All of these components will be described in section 5.3 in detail.

5.2 Limitations of the modelling

In any attempt to model an irrigation system that involves a decision making process, the modeller cannot do anything without first identifying the problems and decision making criteria and constraints (Gladwin, 1989). The main objective of agricultural research and development has expanded from a narrow emphasis on the improvement of productivity through technologies to the enhancement of human and environment welfare, including food security, health and nutrition, and natural resource management. Given the natural resource management focus, it is now recognized that it is important to move from farm to the irrigation area or system scale for evaluation and decision-making.
In the last two decades, many research and development approaches have been used in Australia. These have tried to understand how different technological and economical variables affect development. Green revolution technology, farming systems research and sustainable agriculture were some of the most salient paradigms. For example, the green revolution focused on productivity increases at the plot level, whereas the farming systems approach was concerned with the farm and the household as a unit of management. The sustainable agricultural concept is more irrigation area; catchment and eco-region oriented, and identifies diverse stakeholders and beneficiaries, both on- and off-farm (Rhoades, 1997).

Analysis of farming systems takes into account production, efficiency and sustainability, and can be conducted at different scales. However, bounding farming systems in this way limits analysis of certain important ecological or environmental issues. We need analysis that is more effective in guiding farm management within an irrigation system context. Its applicability to policy-making must be based on its relevance to practical farm needs. This research is based on three assumptions: 1) farmers try to secure their water needs and improve return per region (where each region is modelled as a mixed-use farm), while water policy makers are concerned with improving water productivity per megalitre, 2) the irrigation area is the real world entity that best corresponds to biophysical factors and is the scale most robustly modelled, and 3) even if certain problems are defined at more aggregated or disaggregated scales, remedial action usually needs to take place at the irrigation system level. Decisions of irrigation scientists may be aided by simulation of multiple consequences at the irrigation area scale to evaluate tradeoffs and alternatives. However, the model developed in this study is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly, further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.

There is a large body of literature covering decision making in agriculture and irrigation, both at quantitative and qualitative levels (Smidts, 1990). Quantitative models have performed well in assessing production opportunities, strategies and policies. Qualitative approaches have helped researchers and extension workers improve farmer participation in the research process, provoking a more effective exchange of information. Because these participatory approaches draw farmers into the problem identification process, they have helped create a better framework for technology adoption (Okali et al., 1994; Jeffrey and
However, both qualitative and quantitative approaches suffer from deficiencies when it comes to effective decision making in the extension process. Qualitative approaches tend to fall within settings that are either very complex or involve new circumstances such as new technologies and polices, where farmers cannot draw on past experience (Bebbington, 1994). Quantitative approaches (the type applied in this study), on the other hand, have often been disappointing because the applied mathematical models have not adequately reflected stakeholders’ production contexts or objectives, are not easy to use and requires more data than may be readily available. In addition, most mathematical models are inflexible and complex (Dorward et al., 1997). Their application often hinders effective communication between researchers, extension workers and stakeholders. Thus this study, which uses a system dynamics approach, is quantitative, simple, reflects nonlinearities, is easy to use and requires fewer data.

Simultaneous improvements of irrigation system productivity, gross margins, and environmental and natural resource management at the irrigation area and catchment levels, require more efficient tools for systems analysis and appropriate decision support tools. Any decision support systems should be constructed and made accessible to irrigators, policy makers and catchment managers. Decision support systems are applied to solve irrigation water systems use problems. They are also instrumental in managing the relationship between crop-water production systems and natural resource use to achieve positive economic and environmental outcomes.

This research attempts to identify the decision-making criteria used by most irrigators and water service providers and then incorporates these into a model. The suggestion is to define points in the decision-making process and to determine the appropriate decision variables for the quantitative model (also used in the optimization model) to evaluate consequences of change. In addition, although this research will consider modelling the effects of environmental flow rules, groundwater pumping rules and temporary water trading between irrigation areas on improving the seasonality of flows, it will not thoroughly investigate every aspect, for example, environmental impacts, legal and political issues and long-term policy ramifications. However, this research will present some technical notions of simulation and optimization of water allocation based on economic rationale, and take account of some environmental issues (river flow objectives) by applying a water banking approach.
Some social, or behavioural, factors influence the system. Some of these factors include human treatment of the catchment, irrigation practices, levels of education, irrigator’s migration to the city and legal regulations. Some of these factors are implicitly addressed in through the modelling; however, explicit modelling of social factors is beyond the scope of this study.

One of the research aims was to find decision-making criteria that are useful for water service providers and resource managers and to incorporate these into the simulation model to generate alternatives based on these criteria. Therefore, the allocation of water was evaluated through a quantitative analysis of the relationships between water use and the crop production and return. The most important decision criteria are diversions, water requirements, cost, knowledge and area. These are the minimal conditions required to satisfy decisions for crop-water systems. However, water is allocated based on a priority system for different water uses as described in chapter 2. Water is one of the principle elements of decision-making that causes conflict between different uses such as irrigation and in-stream users. Therefore, serious representation of irrigation and environmental system will be required to test simulated outcomes. This would provide the conditions required to manage the irrigation system in a sustainable way so that water extractions, if possible, could be improved or saved to help the environment or the system in general. Also, if resources are allocated more evenly and efficiently, it is possible to increase the economic, environmental and social value of the crop-water production system.

5.3 Model components

This section presents the rationale, mathematical formulations and input data used for the model components. As stated in chapter 2 this model is based on the view that system dynamics represents the best approach for modelling this complex irrigation system.

What makes using system dynamics different from other approaches used for studying complex systems (such as simulation/optimization) is the use of feedback loops. However, the research approach of this study is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly, further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.

The SD system dynamics tool used in this study to model irrigation demand has four basic building blocks: stocks, flows, connectors and converters. Stocks (levels) are used to
represent anything that accumulates; an example would be water in storage e.g. groundwater banking or dams. Flows (rates) represent activities that fill and drain stocks; examples include releases and inflows. Connectors (arrows) are used to establish the relationships among variables in the model; the direction of the arrow indicates the dependency relationships. They carry information from one element to another element in the model. Converters transform inputs into outputs. Stocks and flows help describe how a system is connected by feedback loops that create the nonlinearity found frequently in complex problems. Figure 5-36 describes the causal loop diagram with some positive (+) feedback and negative (−) relationships. Computer software is used to simulate a system dynamics model of the problem being studied. Running "what if" simulations to test certain policies on such a model can greatly aid understanding of how the system changes over time.

Figure 5-36 Conceptual Structure of the simulation model

The main four components of the simulation model are water, crop mix and environmental and economic factors. The crop component requires information on irrigation and climatic variables, so crop production is a function of available water from both rainfall and irrigation. The dynamic flow of processing within the program is regulated with the TIMESTEP variable on a monthly basis. The conceptual structure of the simulation model is presented in Figure 5-36, which shows the causal loop and relationships between different components as well as factors affecting these components. The positive and negative signs indicate the relationships between different variables and how they influence each other. The two yellow shaded boxes are the main objectives: better economic and environmental outcomes.
Table 5-19 shows all the model components (names and unit) in terms of parameters (inputs/single values), forcing function (input/time series), process (algorithms) and states (output/time series/single function). Because of the size of the model, each component and its subcomponents are presented in separate views (Vensim screens) (see Figure 5-37). Each view displays a sketch showing the relationships and functions among variables for the component. Common or shadow variables link different views. Thus a variable in the first sketch appears as an active variable and in the second appears as a shadow variable. In the following sections, the water use and the amount of irrigation water are described for the water component, which is followed by the crop component. The crop component includes how farmers decide on what crops to grow, the cropping pattern and its production values. Furthermore, the economic component includes the values of variable cost and gross margin, while the environmental component includes an environmental target and allocation.

5.3.1 Water component

Water is the main component of the model that is designed to calculate the water balance under different cropping systems. The water component of the model is based upon the water policy and rules for the Murrumbidgee catchment. Data is based on comprehensive reports by CILI (1999, 2000, 2001, 2002, 2003, 2004 and 2005), on the use, management and distribution of irrigation water and recommendations from the Food and Agricultural Organization of the United Nations (FAO, 1992). Data on the amount of water in the canals system for a 10 year period and on the legal water diversions and licences were collected from DIPNR. Data for crop yields and variable costs is from NSW Agriculture.
<table>
<thead>
<tr>
<th>Name</th>
<th>Unit</th>
<th>Name</th>
<th>Unit</th>
<th>Name</th>
<th>Unit</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seepage factor</td>
<td>mm/d</td>
<td>reach wetted perimeter width</td>
<td>m</td>
<td>Crop Water requirement</td>
<td>ML/ha</td>
<td>Total Area Demand</td>
<td>ML/month</td>
</tr>
<tr>
<td>Evap Losses factor</td>
<td>%</td>
<td>ET0 calculated</td>
<td>mm/month</td>
<td>Effective Rainfall</td>
<td>ML/ha</td>
<td>Total Supply</td>
<td>ML/month</td>
</tr>
<tr>
<td>Losses rate Channel</td>
<td>%</td>
<td>Rainfall</td>
<td>mm/month</td>
<td>Irrigation water need</td>
<td>ML/ha</td>
<td>Sustainability Index</td>
<td>dml</td>
</tr>
<tr>
<td>Loss rate as function in</td>
<td>crop</td>
<td>Diversion</td>
<td>ML/month</td>
<td>Losses</td>
<td>ML</td>
<td>Delivery</td>
<td>ML/month</td>
</tr>
<tr>
<td>diversion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cropped Area</td>
<td>ha</td>
<td>Storage</td>
<td>ML/month</td>
<td>crop variable cost/ha</td>
<td>$/ha</td>
<td>Flow at the weir point</td>
<td>ML/month</td>
</tr>
<tr>
<td>Crop Coefficient Kc</td>
<td>dml</td>
<td>Transmission loss</td>
<td>ML/month</td>
<td>Crop Yield /ha</td>
<td>Tones/ha</td>
<td>End of the system Flow</td>
<td>ML/month</td>
</tr>
<tr>
<td>Effective rain factor</td>
<td>dml</td>
<td>Inflow</td>
<td>ML/month</td>
<td>crop return /ha</td>
<td>$/ha</td>
<td>Water In</td>
<td>ML/month</td>
</tr>
<tr>
<td>Yield</td>
<td>Tones / ha /crop</td>
<td>GW pumping</td>
<td>ML/month</td>
<td>Crop gross margin/ML</td>
<td>$/ML</td>
<td>Water Out</td>
<td>ML/month</td>
</tr>
<tr>
<td>Return</td>
<td>$/ ha/crop</td>
<td>Allocation percentage</td>
<td>dml</td>
<td>Env. Flow Requirement</td>
<td>ML/month</td>
<td>Total area irrigation need</td>
<td>ML/month</td>
</tr>
<tr>
<td>fertilizer cost</td>
<td>$/ ha/crop</td>
<td>Growth Factor GF</td>
<td>days/month</td>
<td>Water deficit</td>
<td>ML/month</td>
<td>Total area irrigation cost</td>
<td>$/ML</td>
</tr>
<tr>
<td>Cultivation cost</td>
<td>$/ ha/crop</td>
<td>ET crop</td>
<td>crop</td>
<td>Total water need</td>
<td>ML/month</td>
<td>Total area gross margin</td>
<td>$/ha</td>
</tr>
<tr>
<td>Sowing cost</td>
<td>$/ ha/crop</td>
<td>Water trading in</td>
<td>ML/month</td>
<td>Crop Irrigation need cost</td>
<td>$/ML</td>
<td>Total area production</td>
<td>Tones/ha</td>
</tr>
<tr>
<td>Harvesting cost</td>
<td>$/ ha/crop</td>
<td>Water trading out</td>
<td>ML/month</td>
<td></td>
<td></td>
<td>Water productivity</td>
<td>Tones/ML</td>
</tr>
<tr>
<td>Water (surface, ground and</td>
<td>$/ML</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Environmental performance</td>
<td>%</td>
</tr>
<tr>
<td>trading) charge cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

dml: dimension less
The water component calculates a water balance for each of the various crops in the irrigation area. The term water balance was used first by meteorologist W. Thonthwaite in the early 1940s to refer to the balance between water inflows from precipitation and outflows by evaporation, groundwater recharge, and stream flow (Dunne and Leopold, 1978). Thonthwaite’s method, which is fundamentally an accounting scheme to calculate soil water storage, evapotranspiration and water surplus, has been modified numerous times to account for specific circumstances and the available technology. Currently, Thonthwaite’s method is used to provide information on water use over geographic regions with limited data on precipitation and evapotranspiration. This is the simplest but most common method used in practice (Hazrat et al., 2000) for crops that are not irrigated.

The inputs for the water balance model include data on climate, inflow, loss, crops, diversion, transmission and groundwater. The climatic data consists of monthly rainfall and potential evaporation obtained from the weather stations through CSIRO Land and Water and SILO. The crop data consist mainly of the cropping, harvesting and sowing dates. Based on these data, the amount of water evaporated is calculated as well as the amount of water needed for irrigation in order to reach maximum yield. Irrigation water use by crops is calculated based on a set of rules. The ratio of actual to potential evapotranspiration is used in the calculation to obtain the yield of the crop (also called the water productivity function). The area of each crop in each irrigation area is impute into the model so cropping decisions are exogenous variables with decisions made by the user of the model or by the crop decision module. The time step of the model is monthly to calculate the water requirement for crops whilst incorporating the effect of water seasonality on agricultural production.

The water component of the model has three subcomponents. The first calculates total water availability within the irrigation system, while the second computes the amount of irrigation water needed and used in each irrigation area. This involves calculating the actual evaporation using the Thonthwaite and Mather (1957) procedure, which is fully described in Dunne and Leopold (1978), and briefly in the section concerning yield response to water. The third subcomponent includes the calculation of the water requirements for crops.

**Total water availability**

Irrigation water is supplied from the main off-take canals through the system: Coleambally main canal, Murrumbidgee main canals (Stuart canal and Murrumbidgee
canal) and from direct river diverters. These canals carry water for the two main irrigation areas within the Murrumbidgee catchment. In addition to surface water, there are licence controls on groundwater use, with some controlled by irrigators within their farm, whilst pumping is managed by water service providers such as CICL and MIA. Groundwater licences are controlled by the DLWC. Moreover, water trading is another mechanism to reallocate water within the system. Data were collected from irrigation companies on the amount of water in the canals, as well as data on transmission losses, delivery, diversion and other commitments to downstream agreements for DIPNR. The model uses the above information to calculate how much water is available within the system on a monthly basis (see equation 5-2). The highest water flow occurs during the summer season while the least amount of water is available during the dry season.

\[ T_{waterAv}(m) = SW(m) + GW(m) + WTin(m) - (WTout(m) + Losses(m)) \]  
Equation 5-2

\( T_{waterAv} \) is the total water available, \( SW \) is the surface water available for month \( m \), \( GW \) is the groundwater available in month \( m \), \( WTin \) is the volume of traded water that enters the area, \( WTout \) is the volume of traded water that leave the area in month \( m \) and \( Loss \) is the loss from transmission and seepage. The transmission losses for the main channels are calculated as a percentage of the total diversion (CIA Report, 2000–05), see equation 5-3.

\[ \text{Irrigation channel losses} = \text{diversion} \times C_{li} \]  
Equation 5-3

The Network Simulation (NSM) Model divides the Murrumbidgee River into five reaches. Each reach has inflow and outflow measured by a gauge station (see Figure 5-38). The data for reach length see Table 5-20 were extracted from Khan et al. (2004a). Each river reach is defined by a water balance (see equation 5-4).

Figure 5-38 shows the river schematic equation
Table 5-20 Reach length, inflow and outflow (1995) (source: Khan et al., 2004a)

<table>
<thead>
<tr>
<th>Reach</th>
<th>Reach name</th>
<th>Reach length (Km)</th>
<th>Average inflow GL</th>
<th>Average outflow GL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dams–Wagga Wagga</td>
<td>250</td>
<td>2764</td>
<td>4165</td>
</tr>
<tr>
<td>2</td>
<td>Wagga – Narrandera</td>
<td>190</td>
<td>4165</td>
<td>3294</td>
</tr>
<tr>
<td>3</td>
<td>Narrandera–Darlington pt</td>
<td>266</td>
<td>3294</td>
<td>2017</td>
</tr>
<tr>
<td>4</td>
<td>Darlington point–Hay</td>
<td>214</td>
<td>2017</td>
<td>1571</td>
</tr>
<tr>
<td>5</td>
<td>Hay–Balranald</td>
<td>280</td>
<td>1571</td>
<td>793</td>
</tr>
</tbody>
</table>

\[ O / In_{flow} = \left\{ In_{flow} + In_{Tri} \right\} - \left\{ O_{Div} + O_{Evap} + O_{Seep} \right\} \]

Equation 5-4

Where \( O / In_{flow} \) is the outflow from a river reach that will be inflow for the following reach, \( In_{flow} \) is the inflow for each river’s reach. For the first reach, \( In_{flow} \) represents the dam releases. A simple water balance has been used to calculate the inflow and outflow of the main two dams (Burrinjuck and Blowing storage) on the Murrumbidgee River. The daily stream flow data used to calculate the monthly flow of the two head dams originates from the sites below (see Table 5-21), and shows data of the year 93/94. The rest of the data appears in Appendix D.

- Murrumbidgee DS Burrinjuck gauge 410008
- Burrinjuck storage gauge 410131
- Tumut DS Blowing (Oddy’s bridge) gauge 410073
- Blowing storage gauge 410102

Table 5-21 Monthly flow in ML (Source: PINNEENA 8 DVD database-DIPNR , 2004)

<table>
<thead>
<tr>
<th>months</th>
<th>BURRINJUCK STORAGE - 410131 monthly</th>
<th>M/BIDGEE D/S B/JUCK 410008 monthly outflow</th>
<th>BLOWERING STORAGE 410102 monthly</th>
<th>TUMUT @ ODDYS BDGE 410073 monthly outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul-93</td>
<td>30,147,449</td>
<td>37,484,882</td>
<td>128,593</td>
<td></td>
</tr>
<tr>
<td>Aug-93</td>
<td>30,382,855</td>
<td>41,654,188</td>
<td>130,047</td>
<td></td>
</tr>
<tr>
<td>Sep-93</td>
<td>30,157,776</td>
<td>41,866,012</td>
<td>156,405</td>
<td></td>
</tr>
<tr>
<td>Oct-93</td>
<td>31,406,807</td>
<td>45,690,460</td>
<td>158,508</td>
<td></td>
</tr>
<tr>
<td>Nov-93</td>
<td>30,540,720</td>
<td>43,323,915</td>
<td>207,925</td>
<td></td>
</tr>
<tr>
<td>Dec-93</td>
<td>30,794,160</td>
<td>42,821,872</td>
<td>162,725</td>
<td></td>
</tr>
<tr>
<td>Jan-94</td>
<td>28,277,263</td>
<td>40,225,304</td>
<td>241,874</td>
<td></td>
</tr>
<tr>
<td>Feb-94</td>
<td>19,860,251</td>
<td>32,830,570</td>
<td>208,921</td>
<td></td>
</tr>
<tr>
<td>Mar-94</td>
<td>20,071,293</td>
<td>33,471,450</td>
<td>238,021</td>
<td></td>
</tr>
<tr>
<td>Apr-94</td>
<td>20,187,649</td>
<td>30,911,627</td>
<td>177,506</td>
<td></td>
</tr>
<tr>
<td>May-94</td>
<td>21,598,988</td>
<td>31,884,389</td>
<td>155,110</td>
<td></td>
</tr>
<tr>
<td>Jun-94</td>
<td>20,935,615</td>
<td>32,490,291</td>
<td>63,292</td>
<td></td>
</tr>
<tr>
<td>Jul-94</td>
<td>21,971,951</td>
<td>38,898,031</td>
<td>67,825</td>
<td></td>
</tr>
</tbody>
</table>

The simple water balance compares the measured change in dam storage level with the measured outflow and computes the difference as total inflow (see equation 5-5).

\[ \text{DamInflow} = (\text{DamStorageVolume}_m - \text{DamStorageVolume}_{m-1}) + \text{outflow} \]

Equation 5-5
Where \( m \) is the month. If this equation is negative it means losses have exceeded gains, i.e. evaporation and infiltration are greater than total catchment inflow. The advantage of the water balance is that it picks up all sources and types of inflows and losses, whereas an inflow gauge would only measures inflow from a particular stream. If equation 5-5 is positive it means gains from rain or overall catchment.

\[ \text{In}_T = \sum \text{In}_T_i \]

Equation 5-6

Where \( \text{In}_T_i \) is the sum of tributary inflow for each reach, as calculated by equation 5-6. The first part of reach1, from the dam’s wall to Gundagai, has 4 tributaries (Jugiong 410025, Muttama Creek at Coolac 410044, Lacmalac 410057 and Adjungbilly Creek at Darbalara 410038) and another 3 tributaries between Gundagai and Wagga Wagga (Adelong Creek at Batlow road 410061, Tarcutta creek at old Borambola 410047 and Kyeamba creek at Book Book 410156). The second reach from Wagga Wagga to Narrandera has only one tributary called Old Man Creek, located at Kywong 410093. The monthly flow data for these tributaries is extracted from PINNEENA 8-DIPNR (2004).

\[ \text{O}_{\text{Evap}} = R_w \times R_L \times \text{Evap} \times F_{\text{Evap}} \]

Equation 5-7

Where \( R_w \) is the top surface reach width, \( R_L \) is reach length, \( \text{Evap} \) is the evaporation data and \( F_{\text{Evap}} \) is the evaporation factor. The evaporation data are collected from the Bureau of Meteorology (BoM) and SILO meteorology for the land (evaporation stations) see Table 5-22. Each river reach’s evaporation data are calculated as average of the nearest evaporation stations. The top width of the reach is calculated through cross section analysis with a ratings table at each inflow and outflow station point along the Murrumbidgee River. The average of the width at the inlet and outlet of the reach is taken to represent the top width of the reach. See Table 5-23 for year 93/94, while the rest of the data may be found in Appendix E.

\( \text{O}_{\text{Seep}} \) is the seepage losses as calculated by equation 5-8. Where \( R_{WP} \) is the reach wetted perimeter, with the main assumption that the river channel is trapezoid. \( R_L \) is reach length, \( F_{\text{Seep}} \) is the average seepage factor in mm/d and \( N_{\text{days}} \) is the number of days. According to Chow (1959), natural channels are usually irregular and ranging from trapezoidal to parabolic. The PINNEENA-8-DVD database (DIPNR, 2004) is used to
generate cross sections of the river channel at inlets and outlets of each reach. The wetted perimeter is then represented as monthly average. Based on flow-stage analysis, see the wetted perimeter data (see Table 5-24 for year 93/94 and Appendix E for the rest of the data).

\[ O_{\text{Seep}} = R_{WP} \times R_L \times F_{\text{Seep}} \times N_{\text{Days}} \]  

Equation 5-8

**Table 5-22 Evaporation stations name and type**

<table>
<thead>
<tr>
<th>Station name</th>
<th>Station number</th>
<th>latitude</th>
<th>longitude</th>
<th>state</th>
<th>type of station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balranald (Silo)</td>
<td>49002</td>
<td>-34.64</td>
<td>143.56</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Gunnedah</td>
<td>55024</td>
<td>-31.03</td>
<td>150.27</td>
<td>NSW</td>
<td>climarc</td>
</tr>
<tr>
<td>Yass (Silo)</td>
<td>70091</td>
<td>-34.83</td>
<td>148.91</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Tarcutta (Silo)</td>
<td>72042</td>
<td>-35.28</td>
<td>147.74</td>
<td>NSW</td>
<td>climarc</td>
</tr>
<tr>
<td>Wagga (Silo)</td>
<td>72150</td>
<td>-35.16</td>
<td>147.46</td>
<td>NSW</td>
<td>climarc</td>
</tr>
<tr>
<td>Burrinjuck dam–Wee Jasper (Silo)</td>
<td>73007</td>
<td>-35.00</td>
<td>148.60</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Gundagai (Silo)</td>
<td>73125</td>
<td>-35.07</td>
<td>148.10</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Narrandera (Silo)</td>
<td>74082</td>
<td>-34.75</td>
<td>146.55</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Finley</td>
<td>74093</td>
<td>-35.57</td>
<td>145.53</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Darlington point</td>
<td>74108</td>
<td>-34.63</td>
<td>146.09</td>
<td>NSW</td>
<td>climarc</td>
</tr>
<tr>
<td>Griffith CSIRO</td>
<td>75028</td>
<td>-34.32</td>
<td>146.07</td>
<td>NSW</td>
<td>climate</td>
</tr>
<tr>
<td>Hay (Silo)</td>
<td>75031</td>
<td>-34.52</td>
<td>144.85</td>
<td>NSW</td>
<td>climate</td>
</tr>
</tbody>
</table>

Climarc: station for rain and climate, Climate: station only for climate data (www.bom.gov.au/silo/)

**Table 5-23 Top reach width (m)**

<table>
<thead>
<tr>
<th>Months</th>
<th>Reach 1 top width</th>
<th>Reach 2 top width</th>
<th>Reach 3 top width</th>
<th>Reach 4 top width</th>
<th>Reach 5 top width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul-93</td>
<td>66.69</td>
<td>65.72</td>
<td>64.125</td>
<td>74.4234</td>
<td>70.29895</td>
</tr>
<tr>
<td>Aug-93</td>
<td>66.8</td>
<td>67.65</td>
<td>67.8</td>
<td>78.245</td>
<td>75.23325</td>
</tr>
<tr>
<td>Sep-93</td>
<td>76.89</td>
<td>76.89</td>
<td>72.93</td>
<td>79.9148</td>
<td>78.53035</td>
</tr>
<tr>
<td>Oct-93</td>
<td>79.58</td>
<td>76.035</td>
<td>70.495</td>
<td>77.1414</td>
<td>81.0009</td>
</tr>
<tr>
<td>Nov-93</td>
<td>65.92</td>
<td>65.35</td>
<td>63.29</td>
<td>70.23475</td>
<td>72.43895</td>
</tr>
<tr>
<td>Dec-93</td>
<td>62.55</td>
<td>60.82</td>
<td>56.895</td>
<td>62.2073</td>
<td>59.301</td>
</tr>
<tr>
<td>Jan-94</td>
<td>65.16</td>
<td>63.11</td>
<td>57.41</td>
<td>60.095</td>
<td>49.0522</td>
</tr>
<tr>
<td>Feb-94</td>
<td>65.16</td>
<td>63.48</td>
<td>59.355</td>
<td>60.506</td>
<td>51.4934</td>
</tr>
<tr>
<td>Mar-94</td>
<td>62.55</td>
<td>61.43</td>
<td>58.88</td>
<td>60.3608</td>
<td>55.658</td>
</tr>
<tr>
<td>Apr-94</td>
<td>59.09</td>
<td>58.27</td>
<td>56.1</td>
<td>58.615</td>
<td>53.3814</td>
</tr>
<tr>
<td>May-94</td>
<td>58.9</td>
<td>57.75</td>
<td>55.17</td>
<td>58.114</td>
<td>48.899</td>
</tr>
<tr>
<td>Jun-94</td>
<td>56.91</td>
<td>56.91</td>
<td>56.365</td>
<td>58.754</td>
<td>49.8648</td>
</tr>
<tr>
<td>Jul-94</td>
<td>55.82</td>
<td>55.27</td>
<td>54.11</td>
<td>56.791</td>
<td>49.9096</td>
</tr>
</tbody>
</table>

**Irrigation water needed and used**

The second sub-component describes in detail the calculations and the data used to calculate the amount of irrigation water needed and used in each irrigation area. The total potential amount of irrigation water used per water year for each irrigation area is expressed in equation 5-9:
The total irrigation water requirement per water year, $T_{\text{Ireq}}$, is calculated as follows:

$$T_{\text{Ireq}} = \sum_{m=1}^{12} \sum_{c=1}^{n} (C_{\text{Ireq}})_{c,m} \times A_{c}$$  \hspace{1cm} \text{Equation 5-9}

Where $T_{\text{Ireq}}$ is the total irrigation water requirement per water year, $C_{\text{Ireq}}_{c,m}$ is the crop irrigation requirement for month $m$, $A_{c,m}$ is the cropped area of crop $C$, $n$ is the number of crops and $m$ is the month of the water year (from 1 to 12).

**Table 5-24 Reach wetted perimeter (m)**

<table>
<thead>
<tr>
<th>Months</th>
<th>Reach 1 WP</th>
<th>Reach 2 WP</th>
<th>Reach 3 WP</th>
<th>Reach 4 WP</th>
<th>Reach 5 WP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul-93</td>
<td>67.2</td>
<td>67.2</td>
<td>65.5</td>
<td>75.8</td>
<td>72.9</td>
</tr>
<tr>
<td>Aug-93</td>
<td>67.3</td>
<td>69.5</td>
<td>68.7</td>
<td>80</td>
<td>78.4</td>
</tr>
<tr>
<td>Sep-93</td>
<td>79.1</td>
<td>79.1</td>
<td>74.7</td>
<td>82.5</td>
<td>81</td>
</tr>
<tr>
<td>Oct-93</td>
<td>81.8</td>
<td>78.6</td>
<td>72.6</td>
<td>79.9</td>
<td>83.6</td>
</tr>
<tr>
<td>Nov-93</td>
<td>67.4</td>
<td>66.8</td>
<td>64.5</td>
<td>72.5</td>
<td>74.6</td>
</tr>
<tr>
<td>Dec-93</td>
<td>63.7</td>
<td>61.8</td>
<td>59.9</td>
<td>63.1</td>
<td>60.3</td>
</tr>
<tr>
<td>Jan-94</td>
<td>66.6</td>
<td>64.1</td>
<td>58.4</td>
<td>61</td>
<td>49.5</td>
</tr>
<tr>
<td>Feb-94</td>
<td>66.6</td>
<td>64.8</td>
<td>60.5</td>
<td>61.6</td>
<td>52</td>
</tr>
<tr>
<td>Mar-94</td>
<td>63.7</td>
<td>62.6</td>
<td>59.8</td>
<td>61.5</td>
<td>56.3</td>
</tr>
<tr>
<td>Apr-94</td>
<td>60.1</td>
<td>59.2</td>
<td>57</td>
<td>59.6</td>
<td>54</td>
</tr>
<tr>
<td>May-94</td>
<td>59.7</td>
<td>58.6</td>
<td>55.9</td>
<td>59</td>
<td>49.5</td>
</tr>
<tr>
<td>Jun-94</td>
<td>57.8</td>
<td>57.8</td>
<td>57.2</td>
<td>59.7</td>
<td>50.4</td>
</tr>
<tr>
<td>Jul-94</td>
<td>56.6</td>
<td>56</td>
<td>54.8</td>
<td>57.5</td>
<td>50.5</td>
</tr>
</tbody>
</table>

**Crop Water Requirements**

Twelve crops are included in the model. They represent the most economic crops within the study area. Their mix is calculated from the crop decision module (CDM) that is described later in this chapter. The two most important factors for determining the amount of irrigation water required for crops are 1) the total water needs of the crop and 2) the amount of rain or water available. Because it was not possible to obtain complete data on crop irrigation requirements, it was necessary to estimate irrigation requirements or biophysical demand (based on climate conditions) using simple calculations from the recommendations of the Food and Agricultural Organization of the United Nations (FAO) provided in a series of papers on irrigation and drainage. Thus, crop water requirement is calculated as follows (see equation 5-10):

$$ET_{\text{crop}} = K_a \times ET_o$$  \hspace{1cm} \text{Equation 5-10}

Where $ET_{\text{crop}}$ is crop evapotranspiration (mm) and $K_a$ is the monthly crop factor ($K_a$). The monthly irrigation water requirement is calculated as follows (see equation 5-11).

$$C_{\text{Ireq}} = \left\{ (ET_{\text{crop}}) \times (GF) \right\} - \left\{ ER \times (GF) \right\}$$ \hspace{1cm} \text{Equation 5-11}

Where $C_{\text{Ireq}}$ is the monthly irrigation water requirement, $GF$ is the monthly growth factor and $ER$ is the effective rainfall (monthly). Taking into account irrigation efficiency, the gross irrigation requirements can now be calculated as follows (see equation 5-12) where $IrrE$, is the irrigation efficiency:

$$G_{\text{Irreq}} = \left( C_{\text{Ireq}} / IrrE \right)$$ \hspace{1cm} \text{Equation 5-12}
The reference crop evapotranspiration ($ET_o$)

The influence of climate on crop water needs is given by the reference crop evapotranspiration ($ET_o$) calculation, which is a measure of the ability of the atmosphere to remove water from the surface through evaporation and transpiration (assuming no limitation in water supply) (Brouwer and Heibloem, 1986). $ET_o$ is usually expressed in millimetres per unit time (mm/month). There are several methods to estimate $ET_o$ through either experimentation or calculation. Theoretical methods involve calculations using measured climatic data, for example, the Penman method recommended by FAO (1992) to calculate the reference crop evapotranspiration. $ET_o$ data for this study were taken from CSIRO land and water Griffith station and SILO stations to get complete data for each river reach.

The growth factor (GF)

The growth factor is the fraction of growth in a given month for a given crop. The percentage of the month that the crop is present differs as the sowing date is different from crop to crop and is not necessary the first day of the month. Thus the growth factor introduced to this calculation to exactly determine the rainfall and evaporation percentage of a month is given by equation 5-13. Its value ranges between zero to one. If it is equal or greater than than zero, it indicates that the crop is growing in this month, while zero indicates the crop is absent.

$$GF_{c,m} = \frac{G_{\text{duration}_{c,m}}}{\text{days}_{(m)}} \quad \text{Equation 5-13}$$

Where $G_{\text{duration}_{c,m}}$ is the growth duration of a crop C in month $m$ and Days is the total days of month $m$.

The crop factor ($K_c$)

$K_c$ is the crop coefficient and indicates the degree to which a crop differs from reference with respect to four characteristics: crop height, albedo (reflectance) of the crop-soil surface, canopy resistance and the rate of moisture evaporation from the soil (Allen et al., 1998). The FAO defines four primary stages of growth. The value of $K_c$ increases and then decreases during the rapid growth and late season stages respectively. It is assumed that during these four stages, changes in the value of $K_c$ vary with time (Fipps, 2000). Figure 5-39 shows the length of the crop stages of each crop growth cycle used in the calculations of the irrigation requirements for crops in the study area. In addition, the crop coefficient data for each crop in this study are taken from FAO data
for a semiarid area. Table 5-25 summarizes the values of $K_c$ of each crop used in this study.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oats</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canola</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter pasture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lucerne</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer pasture</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5-39 Crop calendar

Table 5-25 Crop Coefficient data from FAO

<table>
<thead>
<tr>
<th>Water year</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Jan</th>
<th>Feb</th>
<th>march</th>
<th>April</th>
<th>May</th>
<th>June</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barley</td>
<td>0.8</td>
<td>1.0</td>
<td>0.9</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.35</td>
<td>0.5</td>
</tr>
<tr>
<td>Rice</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Wheat</td>
<td>0.9</td>
<td>1.05</td>
<td>1.05</td>
<td>0.8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Maize</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.35</td>
<td>0.5</td>
<td>0.7</td>
<td>0.85</td>
<td>0.85</td>
<td>0.6</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Canola</td>
<td>0.7</td>
<td>0.75</td>
<td>0.75</td>
<td>0.7</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Soybean</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.35</td>
<td>0.75</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Lucerne</td>
<td>0.65</td>
<td>0.65</td>
<td>0.9</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.2</td>
<td>1.2</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Vines</td>
<td>0.4</td>
<td>0.4</td>
<td>0.45</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Win-pasture</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Oats</td>
<td>1</td>
<td>1.05</td>
<td>1.05</td>
<td>0.7</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Actual Crop ET (ET crop)

The crop water need is defined as the amount of water needed to meet the water lost through evapotranspiration. The crop water requirement always refers to a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of disease and with favourable soil conditions (including fertility and water) (Brouwer and Heibloem, 1986). The crop thus reaches its full production potential under the given environment. The crop water requirement mainly depends on 1) the climate, and 2) the crop type—crops like rice need more water than a crop like maize, and 3) the growth stage of the crop: crops approaching maturity need more water than crops that have just been planted. In the model, the crop water need for a given crop during a given month is calculated using equation 5-14 after introduced growth factor.

$$ET_{crop} = GF_{(c,m)} \times K_{a(c,m)} \times ET_{o(c,m)} \quad \text{Equation 5-14}$$

Where $ET_{crop}$ is the crop water need and varies from one to $m$ for each month of the plant’s growth cycle, $ET_o$ is the total reference evapotranspiration during the month $m$, $K_c$
is the crop coefficient corresponding to the appropriate month of crop growth and crop type (Brouwer and Heibloem, 1986), and GF\textsubscript{(c,m)} is the growth factor corresponding to the crop c. The ET\textsubscript{o} evapotranspiration is expressed in millimetres per unit of time (mm/month). The sum of ET\textsubscript{o} throughout the crop’s growth cycle is multiplied by a growth crop coefficient to determine the crop water need.

**Effective rainfall (ER)**

The water needed to meet crop water needs (ET\textsubscript{crop}) can be supplied to the crops by rainfall, by irrigation or by a combination of irrigation and rainfall. Not all rainwater that falls on the soil surface can be used by the crop or plants. Some of the rainwater percolates below the root zone of the plants and some runs off. This deep-percolation water and runoff water cannot be used by the plants. In other words, part of the rainfall is not effective. The remaining moisture is stored in the root zone and can be used by the plants. This remaining water is the effective rainfall (Brouwer and Heibloem, 1986). The amount of effective rainfall is influenced by climate, soil texture, soil structure and the depth of the root zone. If the rainfall is high, a relatively large part of the water is lost through deep percolation and runoff. For this study, effective rainfall in the study area is calculated according to Brouwer and Heibloem (1986) using equations 5-15 and 5-16.

\[
ER = 0.8 \times (R - 25) \text{ if } PP > 75 \text{ mm/month} \quad \text{Equation 5-15}
\]
\[
ER = 0.6 \times (R - 10) \text{ if } PP < 75 \text{ mm/month} \quad \text{Equation 5-16}
\]

Where ER is the effective rainfall or effective precipitation (mm/month) and R is the rainfall or precipitation (mm/month).

**Irrigation Water Requirement**

In the water component, it is assumed that in cases where all the water needed for optimal growth of the crop is provided by rainfall, irrigation is not required and thus the irrigation water need equals zero (Irr\textsubscript{n} = 0). In cases where there is no rainfall during the growing season, all water has to be supplied by irrigation (the irrigation water need equals the crop water need (Irr\textsubscript{N} = ET\textsubscript{crop}). In most cases, however, part of the crop water need (ET\textsubscript{crop}) is supplied by rainfall and the remaining part by irrigation. In such cases the irrigation water need (Irr\textsubscript{N}) is the difference between crop water need and that part of the rainfall that is effectively used by the plants (ER). The final equation for irrigation water need is shown in equation 5-17 after introduced growth factor.

\[
C_{\text{req}} = ET\text{\textsubscript{crop}} - ER \times GF\textsubscript{(c,m)} \quad \text{Equation 5-17}
\]

Where Irr\textsubscript{N} is irrigation water need, expressed in megalitres per unit time (ML/month). For all crops for each month of the growing season, the irrigation water
need is calculated by subtracting the effective rainfall from the crop water need. For those periods during which a crop’s water need exceeds precipitation, it is assumed that there is a water deficit and therefore that the irrigation water need is equal to this difference. The gross irrigation water need of a particular crop must be calculated by dividing the net requirement by an irrigation efficiency factor, as shown in equation 5-18.

\[
\text{gross irrigation requirement: } GI_{\text{req}} = \frac{(C_{\text{req}}/ \text{IrrE})}{\text{Equation 5-18}}
\]

**Irrigation efficiency**

In the study area of this research, before a farmer has the opportunity to decide how much water to apply to a crop, the water must be transported via the canal system from its source to the farmer’s field. Even though farmers have control over the efficiency of water application at the field level through the irrigation techniques they use, there are many other factors outside of the farmer’s control that contribute to the efficiency of water application (water efficiency). These include the infrastructure of the canals, climate conditions, design of the irrigation system, the degree of land preparation, skill and care of the irrigator and the laws and institutions governing water use (Hazrat et al., 2000). Therefore, irrigation efficiency is out of the scope of this study. However, according to a CIA environmental annual report (2001), irrigation efficiency is between 78% and 80% in this district, while in the MIA (MIA annual report, 2002) irrigation efficiency is around 75% to 81%.

**5.3.2. Economic component**

The objective of the model is to quantify and measure the changes in economic productivity from land and water resource use. Annual gross margin is assessed in terms of farm or crop-level economic indicators, which is commonly the mean annual gross margin/ha over a period based on a schedule of costs and sale prices. The values of the gross margin of agricultural production, by income, by area and by total agricultural income are calculated in the model as the difference between revenues or return and variable costs. These variable costs include cultivation, sowing, fertilizer, herbicide, harvest, and levies and insurance. Irrigation cost, (which is based on the volume and source of water (see equation 5-17)), is also taken into account. Gross margin (see equation 5-19) is defined as:

\[
\text{GM} = \text{TR} - \text{TVC} \quad \text{Equation 5-19}
\]

Where GM is the gross margin per area, TR is the total return and TVC is the total variable cost. Total variable cost is calculated by the summation of variable cost plus the
irrigation water cost based on the quantity used from each water source (surface or ground) as shown in equation 5-20.

$$\text{TVC} = \sum_{c=1}^{n} \left( \sum_{v=1}^{m} \text{VC} + \sum_{s=1}^{z} \text{IrrW} \times S_p \right)$$  \hspace{1cm} \text{Equation 5-20}

Where VC in the variable cost for each crop $c$ (which is the summation of the variable cost of variable V and $m$ number of variables such as sowing, machinery, fertilizer, pesticides and etc), IrrW is the amount used for irrigation (ML) from source S (surface water and groundwater), and $S_p$ is the source price ($/ML), z number of water source and $n$ number of crops which could be 1 for field, or $n$ for each irrigation area/node. TR, the total return is calculated by multiply yield of crop $c$ per ha by price of tonnes/ha of crop $c$, as shown in equation 5-21.

$$\text{TR} = \sum_{c=1}^{n} (P_c \times Y_c)$$  \hspace{1cm} \text{Equation 5-21}

Where $P_c$ is the crop selling price ($/tonne) and $Y_c$ is the yield of crop $c$ per hectare (tonnes/ha). Gross margin per ML for each area is calculated by divided total GM ($) by total irrigation water used (ML), as shown in equation 5-22.

$$\text{GM}_{ml(c)} = \frac{\sum_{c=1}^{n} \text{GM}_c}{\sum_{c=1}^{n} \text{CIreq}}$$  \hspace{1cm} \text{Equation 5-22}

Where CIreq is the crop irrigation water used per crop $c$ and GM$_c$ is the gross margin. All the data and variables used are discussed in detail in section 5.3.4 (crop component).

5.3.3. Environmental component

One of the model objectives is to measure and quantify the environmental performance for the base case and each policy option. The environmental component is one of the constraints and water regulation (environmental flow requirement). According to WSP for the Murrumbidgee River 2002, NSW environmental flow rules specify that when surface water allocation is more than 80%, 300 ML/day flow must reach the end of the system. When allocation is less than 80% 200 ML/day must pass into the Murray River at Balranald weir. The recommended monthly volume is accumulated on a monthly basis to calculate the monthly environmental flow target which is then compared with the end-of-system flow.
5.3.4 Crop component (Crop Decision Optimization Module CDOM)

The main driver of the irrigation water demand is the cropping pattern of the irrigation area. Therefore, it is important to understand how farmers decide on their crop pattern and try to capture their planting decisions. These decisions can be captured using an economic approach. Jayasuriya (2004), has used an economic modelling approach to analyse a wide range of policy issues in the past. The most recent application is in the economic evaluation of environmental flows in the Murray River system as part of a larger project coordinated by the MDLC (Eigenraam et al., 2003) and also as an input into state-based policy development processes with respect to the provision of Murray environmental flows (Econ Search and CARE, 2003 a & b).

The objective of the Crop Decision Optimization Module (CDOM) is to capture farmer decisions on crop planning or crop mix by maximizing the gross margin per region (where each region is modelled as a mixed-use farm) within land and water constraints. The model is a program available in a Microsoft Excel spreadsheet framework using the software “What’s Best!” by Lindo Systems, Inc. Version 7.0 (Lindo, 2005). All the mathematical equations and formulation are discussed under section 5.3.6 which deals with water trading module.

Crop Decision Optimization Module structure

The irrigated agriculture area in the Murrumbidgee Valley is covered by an individual Linear Programming (LP) model that is run for a period of ten years (1993–2003) to represent different water years and allocations. The models cover broad acre agriculture, permanent and annual horticultural activities supported by general and high security entitlements. Regional gross margin is aggregated across different enterprises in the region. Gross margin is considered appropriate for measuring economic outcomes as the farmers’ capital cost is linked to their land. Regional gross margin is therefore a measure of the profitability of agriculture in the region and can be used to estimate the impact on the sector of reduced water availability.

This model includes different water-use technologies, alternative crop and production enterprises and allows for the inclusion of variables that reflect different levels of management. Activities represented in the modules include: summer and winter crops, and annual horticulture. Constraints include available land area by soil type and irrigation technology (landformed, non-landformed, raised beds), limits to some crops (such as rice) for environmental and administrative reasons, and volumetric allocation (Figure 5-40). The hydrologic data for the full simulation period was obtained from the CIA annual environmental report and DIPNR-NSW (PENINA 2004). The crop decision module
formulation is discussed in the next section together with the formulation of the water trading module.

![Diagram of Crop Decision Optimization Module CDOM components]

**CDOM Economic Component**

Crop prices used in the model are based on averages calculated over a three year period from 2000–1 to 2002–3 as shown in Table 5-26. Crop yields and variable costs were obtained from a number of sources including research and extension staff within NSW Agriculture Griffith, various departmental publications (Farm Budget Handbooks, technical reports, etc) (NSW Agricultural, CIL annual reports). Yield and variable costs are sourced by soil type (sandy, loam, and clay), irrigation technology (landformed, non-landformed, raised beds) and dry-land enterprises.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Average price between 2000–01 to 2002–3</th>
<th>Gross margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice ($/tonne)</td>
<td>315</td>
<td>1753.5</td>
</tr>
<tr>
<td>maize</td>
<td>220</td>
<td>1206</td>
</tr>
<tr>
<td>soybeans ($/tonne)</td>
<td>450</td>
<td>524</td>
</tr>
<tr>
<td>summer pasture</td>
<td>7</td>
<td>180</td>
</tr>
<tr>
<td>wheat ($/tonne)</td>
<td>150</td>
<td>375</td>
</tr>
<tr>
<td>Barley</td>
<td>150</td>
<td>245</td>
</tr>
<tr>
<td>canola ($/tonne)</td>
<td>370</td>
<td>404</td>
</tr>
<tr>
<td>winter pasture ($/bale)</td>
<td>7</td>
<td>215</td>
</tr>
<tr>
<td>fallow ($/tonne)</td>
<td>165</td>
<td>100</td>
</tr>
<tr>
<td>annual</td>
<td>282</td>
<td>810</td>
</tr>
<tr>
<td>others</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Lucerne</td>
<td>75</td>
<td>187</td>
</tr>
</tbody>
</table>

**Land and soil component**

There are many crop constraints which could affect the farmer’s decision about their crop plan: some are specific for CIA and others for other irrigation areas or nodes (see Table 5-27). Available areas of suitable soil types in different layouts are used to represent constraints on some enterprises, while other constraints (lucerne and grapes) are imposed to represent capital and market constraints.
Table 5-27 Other crop factors that constraint crop decisions.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Constraints</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>rice</td>
<td>• 30% rice by LWMP&lt;br&gt;• following winter cereal or previous rice</td>
<td>CIA Report 2003 and 2004&lt;br&gt;NSW DPI (Murrumbidgee)</td>
</tr>
<tr>
<td>maize</td>
<td>• only for contracted growers. (Secure market before sowing).&lt;br&gt;Rotation with fallow</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>soybean</td>
<td>• commonly the first crop after a rice fallow. Grow on hills or raised beds. Needs capital investment</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>summer pasture</td>
<td>• border checks layouts and slop.</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>wheat</td>
<td>• is the first crop following rice therefore higher land preparation cost&lt;br&gt;• rotation recommended by LWMP&lt;br&gt;• it is susceptible to water logging in wet winter</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>barley</td>
<td>• it is the first crop following a rice fallow.</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>canola</td>
<td>• usually follow winter cereal. Costs are lower if sowing into permanent beds&lt;br&gt;• affected by soil pH &lt; 5&lt;br&gt;• following pasture phase on boarder check land</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>winter pasture</td>
<td>• optimum sowing time march—April&lt;br&gt;• should be fully irrigated</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>oats</td>
<td>• is the second crop following a rice fallow&lt;br&gt;• favoured on difficult soil due to seedling vigour</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>lucerne</td>
<td>• 3–5 years life time&lt;br&gt;• good layout, good drainage and good slope&lt;br&gt;• prices high during drought from $200–600/tonne</td>
<td>NSW Ag (Murrumbidgee)</td>
</tr>
<tr>
<td>other constraints</td>
<td>• water availability during season water entitlement&lt;br&gt;• soil types (restricted, un restricted and marginal)&lt;br&gt;• land formed (border check, Contour bay and no land formed contour bay)&lt;br&gt;• farmer knowledge and experience</td>
<td>NSW Ag (Murrumbidgee)&lt;br&gt;CIA Report</td>
</tr>
</tbody>
</table>

The crop area constraints specified in this module are given in Table 5-28. The choice of farm enterprises varies spatially and seasonally, based on farmers’ capabilities, skills and resources available on the farm, prices of outputs and inputs, and crop sequence constraints. The latter constraints are dealt with in the model by the specification of crop rotations (mostly rice and wheat) while the individual crop areas are constrained to the requirement of rotational activities.

Table 5-28. Crop area constraints (ha)

<table>
<thead>
<tr>
<th>CIA Crops</th>
<th>CIA AREA</th>
<th>MIA AREA</th>
<th>PRD AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual</td>
<td>3400</td>
<td>15000</td>
<td>0</td>
</tr>
<tr>
<td>barley</td>
<td>4000</td>
<td>3500</td>
<td>0</td>
</tr>
<tr>
<td>canola</td>
<td>10000</td>
<td>3000</td>
<td>6000</td>
</tr>
<tr>
<td>fallow</td>
<td>1300</td>
<td>3000</td>
<td>6500</td>
</tr>
<tr>
<td>lucerne</td>
<td>2000</td>
<td>5000</td>
<td>10000</td>
</tr>
<tr>
<td>maize</td>
<td>150</td>
<td>3400</td>
<td>5000</td>
</tr>
<tr>
<td>others</td>
<td>3500</td>
<td>12800</td>
<td>90000</td>
</tr>
<tr>
<td>rice</td>
<td>24633</td>
<td>45000</td>
<td>17000</td>
</tr>
<tr>
<td>soybean</td>
<td>8000</td>
<td>5000</td>
<td>5000</td>
</tr>
<tr>
<td>summer pasture</td>
<td>3000</td>
<td>4000</td>
<td>26000</td>
</tr>
<tr>
<td>wheat</td>
<td>12000</td>
<td>45000</td>
<td>14000</td>
</tr>
<tr>
<td>winter pasture</td>
<td>12000</td>
<td>30000</td>
<td></td>
</tr>
<tr>
<td>total pasture</td>
<td></td>
<td></td>
<td>14000</td>
</tr>
</tbody>
</table>

The actual crop areas for each irrigation area or node are changed each year due to water availability and farmer decisions. The CIA’s crop area was obtained from the CIA annual Environmental Reports (CIL, 2001-2005). The land use of MIA, PRD and CIA
under average climate conditions was obtained from different sources (see Table 4-11, Section 4.1.2 chapter four).

**Soil types**

The CDOM module is specified according to three soil types based on suitability for rice growing. These categories are ‘Suitable Land’ (unrestricted) with a layer of heavy to medium clay soil 6 feet deep; ‘Marginal Land’ with a layer of heavy to medium clay soil 4–6 feet deep; and ‘Unsuitable Land’ (restricted) with sandy soil less than 4 feet deep. These soil types are defined in Singh *et al.*, (2003).

**Layouts**

All nodes and irrigation area modules are specified according to four layouts, namely ‘landformed border check’ (LFBC), ‘landformed contour bay’ (LFCB), ‘non landformed contour bay’ (NLFCB) and ‘dryland’. The land constraints specified in these modules are given below. Land constraints in the Murrumbidgee valley by soil type are presented in Table 5-29.

**Table 5-29 Soil types and land constraints**

<table>
<thead>
<tr>
<th>Farm area (ha)</th>
<th>CIA</th>
<th>MIA</th>
<th>Private Divertive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SL</td>
<td>ML</td>
<td>UL</td>
</tr>
<tr>
<td>LFBC</td>
<td>13%</td>
<td>21%</td>
<td>8%</td>
</tr>
<tr>
<td>LFCB</td>
<td>37%</td>
<td>32%</td>
<td>0</td>
</tr>
<tr>
<td>NLFCB</td>
<td>50%</td>
<td>47%</td>
<td>62%</td>
</tr>
<tr>
<td>Dryland</td>
<td>0</td>
<td>0</td>
<td>30%</td>
</tr>
</tbody>
</table>

Source: Jayasuriya (2004), SL = Suitable Land; ML = Marginal Land; UL = Unsuitable Land PRD 1= From dams to Wagga Wagga PRD 2= From Wagga Wagga to Narrandera PRD 3= From Narrandera to Hay PRD 4= From Narrandera to Balranald

**Water components**

**Licensed entitlements**

The areas serviced by the Coleambally Irrigation Company hold a general security surface water entitlement of 482,000 ML while the areas serviced by the Murrumbidgee Irrigation Company hold a general security surface water entitlement of 928,748 ML. The Murrumbidgee Valley holds a total general security surface water entitlement of 2,032,748 ML. The distribution of these water entitlements is shown in Table 4-13 (section 4.1.2 chapter four). The total general and high water surface security entitlement, allocation volume and usage in the CIA are shown below in Table 5-30.
Table 5-30 General and high Security water entitlement

<table>
<thead>
<tr>
<th></th>
<th>Entitlement</th>
<th>Allocation volume</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS + HS 1998/1999</td>
<td>481651</td>
<td>410629</td>
<td>365783</td>
</tr>
<tr>
<td>GS+ HS 2000/2001</td>
<td>486168</td>
<td>437960</td>
<td>408437</td>
</tr>
<tr>
<td>GS+HS 2001/2002</td>
<td>485992</td>
<td>351794</td>
<td>321257</td>
</tr>
<tr>
<td>GS+HS 2002/2003</td>
<td>485992</td>
<td>289356</td>
<td>283454</td>
</tr>
<tr>
<td>GS+HS 2003/2004</td>
<td>485992</td>
<td>330346</td>
<td>237021</td>
</tr>
</tbody>
</table>

GS= general security and HS= high security

Seasonal water availability

Based on historical data, it is very clear that the seasonal delivery percentage could be represented as a constraint that has an impact on seasonal water availability, see Table 5-31. Farmers have access to their entitlement based on water allocation and this influences their crop decision-making and water availability.

Table 5-31 Seasonal water delivery in CIA ML

<table>
<thead>
<tr>
<th>Total water delivery</th>
<th>Summer season</th>
<th>Winter season</th>
<th>Losses</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80%</td>
<td>15%</td>
<td>5%</td>
<td>100%</td>
</tr>
<tr>
<td>1998/1999</td>
<td>328503.2</td>
<td>61594.35</td>
<td>20531.45</td>
<td>410629</td>
</tr>
<tr>
<td>2000/2001</td>
<td>350368.0</td>
<td>65694</td>
<td>21898</td>
<td>437960</td>
</tr>
<tr>
<td>2001/2002</td>
<td>281435.2</td>
<td>52769.1</td>
<td>17589.7</td>
<td>351794</td>
</tr>
<tr>
<td>2002/2003</td>
<td>231484.8</td>
<td>43403.4</td>
<td>14467.8</td>
<td>289356</td>
</tr>
<tr>
<td>2003/2004</td>
<td>266436.8</td>
<td>49956.9</td>
<td>16652.3</td>
<td>33046</td>
</tr>
</tbody>
</table>

Source: CIA environmental annual reports

Channel constraints

The CIA irrigation area has an old irrigation system that has not been upgraded since 1952. The channel pumping capacities (120,000 ML) are used as a constraint in the water trading module. Other nodes have different channel or pumping capacities, as shown in Table 4-13 (section 4.1.2 chapter four).

5.3.5 Water trading approach

Temporary water trading markets have been developed under the Council of Australian Governments initiative to support efficient use of Australia's water resources. Water trading can serve as a way for solving water sharing problems in the Murrumbidgee River, which can lead to a positive effect on the supply system and on seasonal flow (Hall, 1994, 2001; Appels et al., 2004). Therefore, it is important to understand and evaluate the benefits of water trading and agricultural extraction, which requires integration of hydrology and economics into the modelling process. Moreover, many quantitative models have been developed in Australia, as the type of water market under research has been prevalent in this country for about 15 years. Table 5-32 lists some of these existing trading models.
Table 5-32 Existing trading models in Australia

<table>
<thead>
<tr>
<th>Reference</th>
<th>Basic Approach</th>
<th>Further Comments</th>
<th>Validation comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read Sturgess et al. (1991)</td>
<td>LP</td>
<td>for Victoria irrigation sector</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Hall (1994; 2001)</td>
<td>LP and QP (2001)</td>
<td>for southern MDB irrigation sector, mainly theoretical, little calibration, no validation</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Wijedasa (2004)</td>
<td>priority based reallocation (elasticiy)</td>
<td>based on survey data, marginal value of water not considered, with REALM, in VIC</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Yu (2003)</td>
<td>LP WRAM</td>
<td>CRC-C H research, with IQQM, in NSW</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Weinmann (2003)</td>
<td>LP and SEM (spatial equilibrium modelling)</td>
<td>CRC-C H research, with REALM in VIC</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Zaman et al. (2005a)</td>
<td>econometric approach</td>
<td>GSM Goulburn Broken Authority</td>
<td>Overestimated and underestimated for different seasons</td>
</tr>
<tr>
<td>Kirby et al. (2006)</td>
<td>LP</td>
<td>CSIRO</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Schreider et al. (2003)</td>
<td>classical integration approach</td>
<td>CRC-C H</td>
<td>Overestimated and enough to catch the trend</td>
</tr>
<tr>
<td>Appels et al. (2004)</td>
<td>TERM-Water model</td>
<td>each region is modelled as a separate economy</td>
<td>Overestimated</td>
</tr>
<tr>
<td>Heaney et al. (2004)</td>
<td>NROM developed at ABARE</td>
<td></td>
<td>Overestimated</td>
</tr>
</tbody>
</table>

The MIRVN (Model of the Irrigated Region in Victoria’s North) model was one of the first attempts in Australia to model water trading. It estimated that the gains from regional trading within Victoria in the early 1990s would be around $12m (Read Sturgess and Associates and DCE, 1991). The model was based on linear programming (LP) and its results generated more interest in water trading at the time.

As part of the MDBC’s irrigation management strategy, ABARE developed a spatial equilibrium model to analyse the impacts of water prices and inter-regional water trading on irrigated agriculture (Hall and Poulter, 1994). Each irrigation region incorporated cropping and livestock activities and was modelled using linear programming. The regional sub-models were interlinked by a network model of the (southern) Murray River system. The model’s output included changes to water use, farm incomes and river salinity. Their approach was useful for identifying potential short- to medium-term structural adjustments needed due to water trading. The model attempts to reduce the impact of sleeper licenses (licenses that have not been used previously) by constraining their trading and bidding water away from irrigation to meet increased environmental flows and/or urban demand.

Hall (2001) reformulated a portion of the ABARE by replacing the LP-based production functions with quadratic functions. This model, called IMMS (Integrated Murray Murrumbidgee System), suggests that QP (quadratic programming) may be a more practical approach than LP. Although LP is more established in the literature, QP
offers a more realistic view that farmers will change cropping patterns gradually as water prices increase. An LP model that reflects farm behaviour requires a large amount of data. Moreover, demand and supply functions estimated with LP models are necessarily stepped rather than smooth. The only advantage of QP is that the quadratic programming model is smaller and simpler to specify and that it produces similar results to the linear model, in terms of cropping, trade, and demand for irrigation water (Hall, 2001).

Moreover, Heaney and Beare (2001) modelled the impact of water trading on return flows in the Murray. Beare and Heaney (2002) have also modelled the benefits and costs of water trading and its effects on regional economies in the southern regions of the Murray Darling basin. In other parts of the world, Rosegrant et al. (2000) simulated inter-sectoral water trade in Chile and evaluated the economic benefits through demand management instruments. Mahan et al. (2002) modelled the economic benefits from inter-sectoral water trade in southern Alberta, Canada.

From the discussion so far, it is clear that the most commonly used modelling method is the simple mathematical linear programming approach which optimises one objective, e.g. farmer's gross margin. Hall (2001) reported that in general these models tend to over-estimate traded quantities and volumes. This is not surprising as current water markets are operating in a sub-optimal manner. The main reasons for this are the uncertainty in environmental flow allocations which affect water rights (permanent trading) (Bjurnland, 2003) and poor market information (temporary trading) (Tisdell, 2003). Although all of the economic models used in these studies require agronomic and hydrological data for water demand and water availability, none interact dynamically with hydrological models.

Wijedesa’s (2004) study was one of the first attempts to dynamically link a water allocation model with a water trading module. Trading was modelled on the basis of the water price and the surplus quantity available. A calibrated REALM model for the Goulburn-Broken Catchment (GSM-Goulburn Simulation Model) was used. This is a monthly, network model used by Goulburn-Murray RWA, the main irrigation water supplier in North Victoria. The model output shows mixed results in matching past trading activity. This suggests that factors other than the quantity and price of water are influencing irrigators’ trading behaviour.

The current work undertaken by the CRC Catchment Hydrology by Yu (Yu, 2003) and his team attempts to provide a more dynamic link between the allocation models
and the economic principles behind water trading (WRAM model). Yu (2003) still uses a single-objective LP approach with the shadow price of water to model water trading on annual basis. The extent of trading can be constrained to a fixed number of nodes in the IQQM model of the MIA (Murrumbidgee Irrigation Area) but there is no feedback from the trading module to the allocation model. Weinnmann et al. (2004) link the GSM model to a spatial equilibrium model, which is also driven by an LP function. However, the integrated model operates at an annual time step. As with other programming models, preliminary results from both models tend to overestimate the extent of temporary water trading. Another study by Zaman et al. (2005b) attempts to link the GSM model to a temporary trading economic model using econometric techniques (multi-variable regression analysis) with two-way feedbacks at the irrigation district level. This is expected to be a sophisticated approach to modelling water trading. The results from this study show acceptable levels of agreement with seasonal water trading, and prove also that water price is affected by several factors besides water volume available into the water market.

In general, the common and relatively simple method well established in the literature for modelling water trading is the linear programming approach, which looks to maximize the farm profit. Yu et al. (2003) reported to be able to successfully model the water transfer within system constraints, it is important to adjust crop patterns on an economic basis. Water trade occurs when the buyers recognize a positive return. The trade volume can be given or calculated (availability minus demand) for a given year; if this value is positive this amount will be available for trade, which has a positive impact on the supply system. Taking account of the decision variable (cropped area) and constraints such as water requirements should not exceed the water available.

All the economic models of the benefits and costs of trade to date rely on static exogenous hydrologic constraints. Hydrologic network models are widely used for water resources planning and management. For example, the Integrated Quantity and Quality Model (IQQM) was developed for this purpose. DLWC (1998b) reported IQQM operates on a daily basis and is used to assess the impacts of changes in water management policies on water users and the environment. The model contains complex river management rules that allow it to simulate the delivery and allocation of water resources.

For the past ten years, IQQM has been progressively implemented in all the major river basins of NSW and Queensland. For IQQM and other hydrologic network models, water trade or adjustments to the existing water allocation and crop patterns are treated
as a given rather than an unknown. Recently there have been several attempts to link the water reallocation model (WRAM) with the IQQM. Although water trading has considerable hydrologic implications for resource management, the trading of water entitlements is essentially an economic activity, because water trading is largely driven by economic incentives and for economic gain. Water trade in resource-constrained years will be from the less profitable crops to the higher return crops.

Existing water trading models have had clear limitations in the degree of dynamic linkages between the water trading and network modelling components. Moreover, WRAM (Yu et al., 2003) is very sensitive to low water allocation: the model can’t find the optimal solution for allocation under 60%. However, the economic optimization approach used by Yu (2003) is well accepted by water researchers and gives acceptable results on an annual time scale. Therefore, this study adopts Yu’s (2003) economic optimization approach, to model annual temporary water trading and its impact on the regional economy at the irrigation area and whole-of-catchment scale.

A water trading module (WTM) has been developed and dynamically linked with the network simulation model NSM to simulate crop mix, water demand, and water trading volume, and to integrate and provide this information to the NSM model to simulate the delivery and diversion of water resources. WTM is formulated as a linear programming (LP) problem run on an annual basis to maximize the net benefit subject to a series of constraints considering Yu’s (2003) assumptions (i- the water demand node is represented as a single water trader (buyer or seller), ii- water is demanded by all nodes where water trading is allowed and is within its trade limits, iii- all traders in the market are price takers, iv- all traders possess perfect information, and v- Transaction costs are nil). The linear objective approach to modelling temporary water trading looks to maximize the net benefit of the irrigation area (where each irrigation area is modelled as a number of areas/nodes) after adjusting the cropping plan on an economic basis.

However, this research was not able to validate this approach for water trading on a monthly basis due to the lack of monthly and annually consistent water trading data. Water trading data have been collected from different agencies and water providers companies such as CIA, MIA and DIPNR, although these data are annual and inconsistent. Moreover, most of the available data relate to the annual trading volume in and out without specifying the origin and destination of the trades. In addition, the market water price is less than it could be in the Murrumbidgee catchment due the partial development of the water market (Yu, 2004).
5.3.6 Water trading module (WTM)

Figure 5-41 shows conceptually the general water trading behaviour which might be followed during wet and dry years. During a wet year, some farmers may find that their needs are less than their seasonal allocation and may attempt to trade excess water. In such years there is likely to be a relatively low demand for traded allocation, but a relatively high supply. Therefore prices for traded water in wetter seasons are likely to be lower. In drier seasons it is likely that demand for traded allocation will increase and the price of traded allocations will be higher. In very dry irrigation seasons, such as 2002–3, there is little rainfall with allocation is around 32%. In such dry years, there will be strong competition for traded allocations to augment the reduced seasonal allocation.

![Figure 5-41 Water trading behaviour](image)

The main driver of irrigation water demand is the cropping pattern system in the irrigation area. This is always based on farmers’ perceptions of, and decisions on, economic gains. Therefore, it is important to understand how farmers decide on their annual and seasonal crop pattern, and try to capture most of their decisions on crop planning. These types of decisions could be captured by using an economic optimization approach.

The objective of the Water Trading Module (WTM) is to assess the annual temporary water trading volume by maximizing the gross margin per region (where each region is modelled as a mixed-use farm) within land and water constraints. The WTM module is flexible and can take water trading into consideration if applicable. The module has been implemented in 12 nodes (irrigation areas), as shown in Table 4-14 (section 4.1.2 Chapter Four). Each node is represented by its cropping system, water entitlement, crop water use, crop production and land and water constraints.
Water trading module structure

The Murrumbidgee catchment area is covered by a linear programming (LP) model using the same economic approach used for the crop decision optimization module, CDOM. The model inputs are water allocations from 1993–2002 for each irrigation node. Regional gross margin is defined as gross agricultural income less the variable costs incurred in production, aggregated across different enterprises in each region. Gross margin per area/hectare is considered an appropriate indicator for measuring regional economic gains from the farmers’ perspective, since their capital cost is linked to their land/area. Water policy makers use their gross margin per ML as an indicator of water value and productivity. Regional gross margin per hectare is a measure of the profitability of agriculture in the region and can be used to estimate the regional economic impact of reduced water availability or different water allocations on the sector.

The overall goal of the irrigators is to secure water availability for periods of shortage by trading water to maximize the gross margin of the irrigation areas. Twelve nodes were chosen to represent all the irrigation areas in the Murrumbidgee valley based on the availability water delivery and diversion data from DIPNR-NSW. Each irrigation node is represented by its cropping system, crop water use, crop yield and crop price, water entitlements and its constraints.

Figure 2-5 (Chapter 2 Section 2.1) shows the schematic spatial distribution of the twelve irrigation demand nodes included in the WTM module, their location relative to the river reaches, and their water entitlements and land area. In addition, this module can take into account different water use technologies, alternative crop and production enterprises and allows for the inclusion of variables that reflect different levels of management. Activities represented in the models include summer and winter crops, and annual horticulture. It uses includes the same constraints used in CDM such as land area available by soil type and irrigation technology (landformed, non-landformed, raised beds), limits to some crops (such as rice) for environmental, market and administrative reasons, and also water trading constraints such as volumetric allocation, entitlements and trading percentage. WTM is also used to simulate annual water trading volumes and crop patterns under trading conditions and water and land constraints. This crop pattern is then input into NSM to assess water trading impacts on irrigation diversions and river flows (see Figure 5-42). The hydrology data for the full simulation period is obtained from CIA, the MIA annual environmental report and DIPNR-NSW.
WTM module formulation

From the above and the discussions in chapters two and three, the Yu (2003, 2004) approach (linear programming approach) was adopted and applied to the Murrumbidgee reaches, including the irrigation areas and demand nodes, taking account of maximizing valley-wide net benefit. In this model, the demand node is defined as an area represented in the hydrological network model as a single aggregated water user. This user may grow a mixture of crops of varying area and, as a result, requires certain variable amounts of irrigation depending on climatic conditions.

The linear programming problems consist of three parts: decision variables, linear constraints and the linear objectives function. The water trading module will adjust the cropping pattern based on economic and environmental rationales. Maximizing the net benefits for each irrigation node, while taking account of system constraints and other limitations (such as water requirements should not exceed the water available or allocated for the entire basin and should satisfy environmental flow targets). Water trading will be then be simulated under optimal conditions to calculate the volumes traded in or out between irrigation areas as demand sites on an annual basis. The objective function, constraints and decision variables of the WTM are as follows:

\[
MaxGM = \sum_{i,c} GM_c \cdot A_c - \sum_{i,c} A_c \cdot VC_c - \sum_{i,c} \{IrrN_c \cdot A_c \cdot IrrCost\} - \sum_{c} GWP_c \cdot Pumpcost
\]

Equation 5-23

Where
- \(GM_c\) is gross margin for crop \(c\)
- \(A_c\) is the crop area for crop \(c\)
- \(CIreq_c\) is the irrigation water need for crop \(c\) in month \(m\)
- \(IrrCost\) is irrigation or water cost
GWP\(_c\) is supplementary groundwater pumping for crop \(c\)
Pumpcost is groundwater pumping cost
VC\(_c\) is variable cost per ha for crop \(c\) (fertilizers, herbicides, sowing, etc)

Equation 5-23 represents the aggregated objective function for the irrigation demand nodes which is subject to land and water constraints as follows:

**Land and water constraints**

A. The sum of all cropping areas under each node are equal or less than the irrigation or node area T.Area\(_i\)

\[
\sum_{(c,i)} A_{(c,i)} \leq T.\text{Area}_i
\]

Equation 5-24

B. Total pumping from an irrigation area in any year should not exceed the allowable pumping volume (licensed volume)

\[
\sum GWP_i \leq \text{Pump}_i
\]

Equation 5-25

C. Monthly environmental flow should equal or exceed the target flow

\[
\text{Env.}\text{Flow}_{m} \geq \text{Tar.}\text{Env.}\text{Flow}_{m}
\]

Equation 5-26

D. Market constraints on individual crop areas—another set of constraints that are imposed on the decision variables, based on market considerations (vines-winery contracts)

\[
A_{ic} \leq AC_{ic}
\]

Equation 5-27

Where \(A_{ic}\) is the current area (ha) for growing crop \(c\) in the node \(i\), and is less or equal to the upper limits of crop \(c\) area constraint \(AC_{ic}\) that is allowed in the node \(i\).

E. Water availability constraints are imposed for individual nodes in cases where trade is permitted, as well as on a coalition of nodes or all nodes for which water trading is allowed to take place. In this study the assumption is that the twelve nodes are allowed to trade within trade constraints. Total water use in all irrigation areas should not exceed the total allocation or water availability \(WA\) in a given year for the entire basin.

\[
\sum_{c=1}^{n} \text{CIreq}_c * A_{(c)} \leq WA
\]

Equation 5-28

Where CIreq\(_c\) is the total water demand for crop \(c\) at node \(i\) (ML/ha), and \(WA\) is the water allocation or availability for the whole catchment (ML). Water allocation or availability for nodes is calculated as the sum of the product of the licensed volume (ML) and the level of announced allocation (%) for each node.
Decision variables

Decision variables are the area of land at each node $i$ for growing crop $c$ (ha), denoted as $A_{ic}$ for $i = 1, 2 \ldots n$ and $c = 1, 2 \ldots m$, where $n$ is the number of irrigation node (12 nodes) and $m$ is the number of crops. Thus the water trading volume is simulated, based on optimal crop area. One single aggregate objective function is built to represent farmer cropping decisions by maximizing the gross margin.

The decision variable is the crop area. Based on the optional cropping mix, the WTM module then simulates the annual temporary water trading volume, as shown in equation 5-29.

$$WT_i = WA_i - \sum_{i}^{n} \sum_{c=1}^{m} C_{req} * A_{ic} \text{ under optimal conditions.}$$  \hspace{1cm} \text{Equation 5-29}

The total amount of water required at node or irrigation area $i$ under optimal conditions. $WA_i$ is the volume of water allocated or available at node $i$. If the right hand side is positive (excess water available), this volume is traded out or sold, and if it is negative this volume is traded in.

The water trading volume value is then calculated by:

$$WT_{value} = WT \times AP$$  \hspace{1cm} \text{Equation 5-30}

Where $WT_{value}$ is the total value of the water traded, $WT$ is the water trading volume and $AP$ is the historical average water market price.

Water trading module assumptions

The overall goal of the WTM module is to secure water availability for periods of shortage. This is achieved by water trading to maximize the gross margin of the irrigation areas. Twelve nodes were chosen to represent all the irrigation areas within the Murrumbidgee valley. The main assumption of the WTM module is to allow trade between the irrigation nodes to satisfy the crop water demand resulting from planning decisions made within water trade licence constraints. It is important to note that in this approach all the fields dedicated to rice crops in an irrigation area or node are operated as one farm. Therefore, a reduction in the output of the overall rice area is not necessarily a good estimate of what would happen to the incomes of individual farms that may have a mix of crops including rice.

During a wet year, some farmers may find that their needs are less than their seasonal allocation and may attempt to trade excess water. In drier seasons, it is likely that the
demand for traded allocations will increase, resulting from a low allocation. The price of traded allocations will thus be higher.

5.4 CDOM module validation

Two cases were tested: case one without a seasonal water delivery constraint, and case two with a seasonal water delivery constraint. This means farmers get access to a seasonal entitlement percentage rather than a full entitlement. Figure 5-43 shows the adjustable crop area under the two cases compared with the actual crop area. It is very clear that case two (with a seasonal water constraint) captured the existing maize and annual crops. Case one, however, does not manage to do this.

![Figure 5-43: The optimised crop area in the two cases compared to actual crop area year 1998–9](image)

Figure 5-43 shows the scatter diagram with a linear relationship between the optimised crop area and the actual crop area under both cases. In case two, 92% is represented but in case one (without seasonal water constraints), $R^2$ for the 1998–9 water year is slightly lower. Thus, from these it is apparent that case two (with a seasonal water constraint) can capture the actual crop area better than case one (about 92% of the actual crop variation can be explained or predicted by the CDOM with about +/- 10% uncertainty). Furthermore, with a decreased water allocation such as that of the 2003–4 water year (34% of allocation) case one fails to represent most of the crop pattern such as summer pasture and fallow. However, case two was promising to represent summer pasture, fallow and other crop patterns with an $R^2$ (0.56) better than case one ($R^2 = 0.41$) (see Figure 5-45 for water year 2003–4). The big variation of rice and wheat area can be attributed to water allocation is one of the main factor and constraint into WTM module. Seasonal delivery constraint is able to capture most of summer crops. The five water year results in What's Best! 7.0 Status Report is shown in the Appendix F.
$R^2 = 0.92$

Figure 5-44 scatter plot of the optimised area of case one and two compared with actual crop area

$R^2 = 0.56$

Figure 5-45 the optimised crop area in the two cases compared to actual crop area 2003–4 water year

5.5 Water trading module validation and results

Validation of WTM module results is constrained by lack of sufficient data to perform comparison of the modelled results with observed data. Figure 5-46 (A, B, C, D) shows a comparison of annual total modelled or simulated volume by WTM module of water use in CIA, MIA, PRD and the total catchment. The modelled water use data originate from the IQQM model, while the actual water delivery data is from the DPNIR database (PENINA 2004).
The WTM results are compared with IQQM modelled water use and collected water delivery and diversion data is to gain a better insight and confidence in WTM’s ability to simulate water trading behaviour at an acceptable level. Water delivery data is the total water delivered or used at irrigation area or catchment scale after accounting for irrigation system losses. Water use is accounting for total crop water irrigation need while water diversion is accounting for total water diverted at river supply point/node. It can be observed that the modelled or simulated water use resulted from WTM follows a similar trend to the water delivery data particularly at the catchment scale. Although there are deviations from the observed data over the eight year period, the WTM results are a better representation of reality than the IQQM results, particularly at the whole catchment scale. This could be attributed to the fact that the WTM module is able to distinguish water trading volume from water use and delivery volume, and calculates the optimal cropping pattern to improve regional return. IQQM results, however, do not distinguish between water trading volume and water use, also IQQM takes the crop...
pattern as given. It is also important to note that modelled water uses are not directly comparable to the water diversion and delivery data as these include system water loss and off allocation volumes. These are hard to distinguish as there are no historical data about losses and off-allocation.

The WTM module results are able to capture around 70% from the net water trading behaviour of the CIA and MIA with an $R^2$ of 0.7 and 0.75 respectively. Table 5-33 shows that the comparison between modelled crop area with the actual crop area both at whole of irrigation area level and within irrigation area level is reasonably good. A similar level of agreement is shown for the total crop area. Since there is no available data for each sub-area to compare with the WTM module results, these results (sub-area water use and crop area) are presented in the next section as water trading module results.

### Table 5-33 Modelled crop area versus actual crop area

<table>
<thead>
<tr>
<th></th>
<th>97-98</th>
<th>98-99</th>
<th>99-00</th>
<th>00-01</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelled CIA TOTAL AREA</td>
<td>81527</td>
<td>69121</td>
<td>52226.44</td>
<td>68778.93</td>
<td>67913</td>
</tr>
<tr>
<td>Actual CIA Total Area</td>
<td>71240</td>
<td>68694</td>
<td>54942</td>
<td>79136</td>
<td>68503</td>
</tr>
<tr>
<td>Modelled MIA TOTAL AREA</td>
<td>156566</td>
<td>120698</td>
<td>101380</td>
<td>131499</td>
<td>127536</td>
</tr>
<tr>
<td>Actual MIA Total Area</td>
<td>156605</td>
<td>120000</td>
<td>101400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modelled PRD TOTAL AREA</td>
<td>179500</td>
<td>163316</td>
<td>140297</td>
<td>166453</td>
<td>162391</td>
</tr>
<tr>
<td>Actual PRD Total Area</td>
<td>174835</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Water trading results**

Twelve irrigation nodes and eight years are used to simulate water trading volume between the irrigation nodes after the WTM has been validated. Figure 5-47 shows the results for the eight year time series for ten nodes (the MIA irrigation area is represented by only three nodes for clarity) (MIA 1 2 Water trading = Yanco and Mirrool irrigation area, MIA 3 4 water trading = Tabbita and Benerembah irrigation areas and MIA 5 water trading = Wah Wah irrigation area). It is clear that each water year has different results and also that each irrigation node has a different volume selling out or buying in. Figure 5-48 shows the total net water trading (trade in minus trade out) results for each irrigation area (summation of all sub-areas nodes). It is obvious that the CIA irrigation area is an importer, while MIA is working as an importer and exporter (–ve value indicates selling while +ve indicates buying). On the other hand, total PRD irrigation area is mainly an exporting of water. These results capture around 70% of net water trading behaviour in the MIA and CIA, as discussed previously. The gross margin shows the same trend as water use: when water use increases, the gross margin increases and vice versa (see Figure 5-49). These results are very good indicators of farmer behaviour and perceptions. Farmers believe that when they apply and use more water they will earn more money.
Figure 5-47 Modelled water trading for 10 nodes

Figure 5-48 Modelled total water trading

Figure 5-49 Modelled gross margins versus modelled water use results
5.6 Summary and conclusions

This chapter describes the model’s objectives, assumptions and gives a quantitative description of the simulation model NSM, crop decision optimization module CDOM and water trading module WTM. It also includes the structure of these modules and detailed aspects of biophysical water demand, crop, economic and environment components.

In addition, this chapter includes a description of how the variables for each model component (each representing a feature of agricultural production in the catchment) were calculated. An explanation of the biophysical and economic fundamentals for the model is also given. The calculations of the biophysical demand and economic variables quantify how resources are used in the catchment and irrigation area and quantify the gross margin from agricultural activities in the catchment.

CDOM module validation is discussed and presented. These lead to the main findings of this chapter: that the crop decision module and water trading module are verified and shown that both modules are truly able to represent the reality of the system with a good level of agreement (more than 90% for CDOM and 70% for WTM) (as discussed in section 5.4 and 5.5). In turn, both modules are linked to the NSM model and feed it key data. The NSM model as described in this chapter is capable of simulating alternative management scenarios developed in Chapter 4 to demonstrate the effects of allocation levels and irrigation demand on seasonal flow and environmental performance. The NSM integrated model calibration and validation is presented and discussed in the next chapter (six).
Chapter 6: NSM Model Calibration and Validation Results

A Network Simulation Model NSM was developed to help answer the first research question and achieve the first research objective (see chapter 1, section 1.2). It uses a system dynamics approach to analyse irrigation demand management strategies. This model is designed to operate on a monthly basis to assist managers to analyse system behaviour under various management scenarios. It also demonstrates the effect of climate variability between cropping seasons.

The major drive for understanding the link between irrigation demand, conjunctive water use management and water banking with environmental outcomes, is to determine the change in economic output and environmental impact of various changes in allocation and irrigation demands with a view to modifying the seasonal flow distribution of the river. The model gives priority to meeting environmental demand defined as end-of-system flow and then attempts to satisfy the biophysical crop demand. This is one of the major original contributions of this research. Moreover, the NSM incorporates a wide range of complexities likely to be encountered in water resource management, including surface and groundwater sources, water trading between sources, system constraints (such as maximum groundwater pumping rates), environmental flows and channel capacity.

The NSM is also used to investigate the balance between consumptive use, in-stream demand use and the attainment of economic benefits. This is achieved by examining irrigation demand management, and a water banking approach, which represents the core work of this dissertation.

In this chapter the calibration and validation methods are presented in section 6.1. Section 6.2 presents and discusses the quantitative (i.e. numerical) and qualitative (i.e. visual comparison of a hydrograph) criteria for assessing model performance. Section 6.3 presents and discusses the multi-objective functions used for calibration. Section 6.4 present the calibration and validation results by comparing the discharge for independent gauge stations and using different performance criteria along the Murrumbidgee River. Finally, section 6.5 gives a brief summary of the calibration analysis.

6.1 Calibration methodology

Many studies clearly differentiate between model verification, calibration and validation processes and results (Fishman and Kiviat, 1968; Mihram, 1972; Schlesinger et
al., 1974; Stedinger and Taylor, 1982). According to Schlesinger et al. (1974, p.929) verification is defined as “The certification that the model is implemented on the computer in a manner that truly depicts the idealised model”. Stedinger and Taylor (1982) described the idealised model as a group or series of mathematical equations and logical relations that are used to represent the real system. In a recent study Thacker et al., (2004) posits that verification and validation are the primary processes for quantifying and building confidence (or credibility) in numerical models. They state the definitions of verification and validation: “Verification is the process of determining that a model implementation accurately represents the developer’s conceptual description of the model and the solution to the model” and “Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model”.

In contrast, calibration is the process of estimating selected parameters of a model, assuming that the model is correct. According to Wegmann and Everett (2003), model validation tests the ability of the model to predict future behaviour. Validation requires comparing the model predictions with information other than that used in estimating the model. Validation is typically an iterative process linked to calibration. If the analyst finds that the model output and the independent data are in acceptable agreement, the model can be considered validated. Also, Fishman and Kiviat, (1968) and Stedinger and Taylor (1982) stated that validation tests are used to indicate that a simulation model reasonably represents a real system.

Calibration and validation of integrated models poses difficulties arising from many factors including the complexity of the system under study, lack of data, accuracy of data, different time and space scales of different parts of the model, and policy or other drivers that cannot be replicated and hence cannot be validated (Jakeman and Letcher, 2003; Liu. and Yang, 2005; Letcher et al., 2006). Moreover, Letcher et al. (2006) argued that integrated models should not be developed as prediction tools but as aids to understanding system responses to changes (such as policy changes). Model components should be plausible and explain system outputs (Jakeman and Letcher, 2003) and individual components tested peer reviewed and subject to sensitivity analysis (Letcher et al., 2006). Based on this, calibration and validation processes were conducted on several components by partially validating and testing the CDOM and WTM modules presented in previous chapters and the NSM module presented in this chapter.

Once the model parameters have been estimated the process of calibration and validation begins. Model calibration adjusts parameter values until the predicted values match the observed values within the region for the base case. In the past, calibration
processes were implemented using a trial and error approach to estimate model parameters. However, Madsen et al. (2002) asserted that this approach is time consuming and its efficiency depends on how many parameters the model has and their interdependencies. Furthermore, Madsen et al. (2002) claims that manual calibration is an illogical process because of its complexity when used to quantify the model performance. Thus, much research has been devoted to introduce auto calibration tools that are able to overcome the complexity and time issues.

Over the last decade, the model calibration process has been improved by using computer system technology such as flexibility and better fit between model measurements and real system data. This robust fit can be achieved using optimization tools such as PEST (Watermark Computing, 1994) (Doherty and Johnston, 2003). One of the main advantages of these optimization tools is their ability to identify and measure the uncertainty of the estimated optimization parameters.

Doherty and Johnston (2003) stated that the computer-based tools for auto calibration have performed well for many hydrological models over the past decade. However, many research studies have focused on the development of optimization tools that are better able to estimate the model parameters (Kuczera, 1983; Wang, 1991; Duan et al., 1992; Sorooshian et al., 1993; Sumner et al., 1997).

Several studies have compared these tools' performance (Gan and Biftu, 1996; Cooper et al., 1997; Kuczera, 1997; Franchini et al., 1998; Thyler et al., 1999; Madsen et al., 2002). In addition, many studies have tried to quantify the performance of these tools' output defined by measuring the fit between model measurements and field data (Kuczera, 1983; Gupta et al., 1998; Liong et al., 1998; Yapo et al., 1998; Boyle et al., 2000; Madsen, 2000a; Madsen et al., 2002).

Another avenue of research is measuring the uncertainty generated by the parameters during the estimation processes. This has been attempted in several studies (Beck, 1987; Kuczera and Parent, 1998; Kennedy and O'Hagan, 2001). Where data are lacking, researchers have instead measured the complexity of the models (Jakeman and Hornberger, 1993; Beven, 2000). Analysis of the uncertainty (which is always recommended by stakeholder groups and regulatory agencies) of model validation is considered to be part of the model implementation and structure (NRC, 2001).

Madsen et al. (2002) reported that many research studies compared different automatic algorithms for the calibration of rainfall-runoff models (e.g. Duan et al., 1992; Kuczera, 1997; Franchini et al., 1998; Thyler et al., 1999). They concluded that the most effective
automatic algorithm is the genetic algorithm, in contrast to multi-start local search and pure local search methods. Although many research studies have focused on developing perfect generic research routines, only a few studies have applied these routines to specific models.

The main step in auto calibration is defining the objective function (i.e. search approach). Most automatic calibration routines use a single objective function to compare observed and simulated results, for example, the sum of squared errors. However, a single objective function is not necessarily appropriate for capturing most of the main characteristics of the system (i.e. hydrograph) which are applied by the hydrologist to quantify the performance of the calibrated model.

During recent years automatic calibrations using multi-objective functions have been applied to rainfall-runoff modelling (Lindstrom, 1997a; Lindstrom et al., 1997b; Liong et al., 1998; Madsen, 2000a; Boyle et al., 2000, Madsen et al., 2002). The main advantage of applying multi-objectives calibration is that the solution overcomes the unique parameters problem often present in the single objective approach. Moreover, Madsen (2000b) claimed that using a multi-objective calibration method would result in better parameter estimates and model structure. The multi-objective calibration method is also able to capture different characteristics of the model (Madsen et al., 2002). For these reasons, a multi-objectives method was used to calibrate the NSM model and compare the results under different time cases (by shifting the validation dataset along the dataset to capture the variability see Figure 6-50). An eight year data time series (June 93 to July 01) was used for the auto calibration process with four combination of calibration and validation periods. Each combination includes a different data period used for calibration and validation as shown in Figure 6-50:

- Case I (93-95): uses the period June 93-June 95 for validation and the rest of data for calibration.
- Case II (95-97): Uses the period June 95-June 97 for validation and the rest of data for calibration.
- Case III (97-99): Uses the period June 97-June 99 for validation and the rest of data for calibration.
- Case IV (99-01): Uses the period June 99-June 01 for validation and the rest of data for calibration.
The calibration period was used to find the optimum value for the parameter while the period of validation was used to assess the model performance using the model calibration parameters.

6.1.1 Parameter identification and data

After the model structure and identification stage described in the previous chapter a suitable parameter set was estimated. The process involved adjusting the parameters automatically (auto calibration) until the observed system output and the model output showed acceptable levels of agreement. As explained in chapter 5, the NSM model divided the Murrumbidgee River into five reaches. Each reach has inflow and outflow measured at gauge stations, as shown in Figure 5-38 (Section 5.3.1 in chapter 5 described the water component involved in the NSM model and how evaporation and seepage losses are calculated).

In the calibration process, three parameters were defined: evaporation factor $F_{\text{Evap}}$, seepage rate ($F_{\text{Seep}}$) and channel loss rate ($C_{\text{Ch}}$). These are used to search for the global optimal solution to the objective functions, using Powell’s optimiser (Powell, 1964a, 1964b) (described in detail later in this section).

6.1.2 VENSIM™ Powell’s Optimiser

To perform an optimization using VENSIM™, a set of parameters must be specified to search over and create a payoff that determines the accuracy of an individual simulation. A payoff is a single number that summarizes a simulation. The payoff for a model can be defined by a comparison of model variables with actual data, or as a combination of model variables. These two types of payoffs are known as calibration payoffs and policy payoffs. Calibration payoff which attempts to match model variables with data is implemented in this study. Optimisation is controlled by an optimization domain or control that defines the maximum and minimum range for each parameter. The VENSIM™ optimiser is based on modified POWELL theory.

Powell theory is one of the main techniques used to find the minimum or maximum value of a multivariate function, and can be defined as multidimensional constrained
optimization (Powell, 1964a, 1964b; Chapra and Canale, 2002). According to Chapra and Canale (2002), Powell’s method is one of the best algorithmic methods that capitalize on the idea of pattern directions to find optimum values efficiently. This depends on finding points 1 and 2 (see details later in this section) by searching in the same direction from different starting points (within the boundary of your parameter). The line between 1 and 2, known as the conjugate direction, it should drive to the maximum/optimum value (achieve the objective function), as shown in Figure 6-51.

![Figure 6-51 Conjugate directions (source Chapra and Canale 2002)](image)

Powell’s method initiates the process from different starting points for each parameter within its range (minimum and maximum values). The automatic generated starting point, or the rules used to compute search starting points, under VENSIM™ are different depending on the domain value. This occurs when upper and lower constraints are defined into the model (i.e. min <= parameter <= max). The starting point value for the parameter is determined by equation 6-31.

Parameter = min + X (max − min) \hspace{1cm} \text{Equation 6-31}

A number X will be automatic generated under VENSIM™ by a random method in the range \([0, 1)\) including zero but not including 1. In cases when only a lower constraint is present, the starting point will be calculated by equation 6-32.

Parameter = min + 1/(1 − X) \hspace{1cm} \text{Equation 6-32}

In cases when only an upper constraint is present, the starting point will be calculated by equation 6-33.

Parameter = max − 1/ (1 − X) \hspace{1cm} \text{Equation 6-33}
Powell’s searching process (see Figure 6-52) is briefly described as follows:

1. Assuming, start at point 0 (as initial value of the parameter), it searches in two directions, D1 and D2, until the better value is reached at point 1 in the direction of D1 to the maximum gradient.

2. Next the search starts from point 1 through the D2 direction to find point 2.

3. After that, a new direction, D3, from points 0 and 2 is utilised to find point 3.

4. From point 3, point 4 is found using the previous search direction D2, and so on from point 4 to find point 5 using the D3 direction.

At this time, points 3 and 5 have been allocated by the same direction, D3, from different starting points. Powell’s theory has proved that the new direction D4 along points 3 and 5 is a conjugate direction to D3, which leads directly to the maximum (optimum value of the objective function) (see details in Chapra and Canale, 2002).

![Figure 6-52 Powell’s Method (source Chapra and Canale 2002)](image)

Using the Vensim built in Powell optimiser, the multi-objective functions is formulated into the NSM model. Several model performance criteria are also formulated into the NSM model to determine the best case and result. Mostly the equation with upper and lower constraints has been used to determine the starting point for each parameter into NSM model.

### 6.2 Multi objective functions auto-calibration

A conventional auto calibration method commonly uses the single objective function. This can be quick and objective and its results can produce the behaviour of the time seris (i.e. river flows) based on the selected objective function. The most common single
objective function in the literature is the sum square error. Frequently, hydrologists do not accept the results from a single objective because of their interest in many other aspects of the system hydrographs (i.e. high peak flow events, low peak flow events, minimum flow, etc) (Boyle et al., 2000). Wagener et al. (2003) reported that the single objective function loses information due to the way that model residuals are combined in a single objective function, which could lead to bias in the model’s performance. It could also cause another problem when identifying parameters that do not necessarily affect the objective function (Wagener et al., 2001). For example, Wagener et al. (2003) described an objective function (i.e. the Nash-Sutcliffe efficiency value (Nash and Sutcliffe, 1970)) that focused on matching peak flows. Therefore, selecting multi-objective functions could be more successful in overcoming these shortfalls by its ability to looking for different characteristics of the system hydrograph (i.e. low flow, high flow, frequency, and minimum flow, median and average flow, etc).

Multi-objective algorithm functions are used to find the model parameters values that can fit most of the aspects of the hydrograph (in this study) at different points along the Murrumbidgee River. In this study, four basic objective functions are considered simultaneously to take into account the key characteristics of the hydrograph including (low flow, high flow, frequency, minimum flow, median and average flow and over all volume as shown below:

\[ F_a = \sqrt[N]{\sum_{i=1}^{N} (O_i - S_i)^2} \]

**Equation 6-34**

Where, \( F_a \) measures the model’s overall error in simulating volume by minimizing the overall volume difference between observed and simulated flow. \( O_i \) is the observed volume at time interval \( i \), \( S_i \) is the simulated flow volume at time \( i \) and \( N \) is the number of events.

\[ F_b = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (O_i - S_i)^2} \]

**Equation 6-35**

Where, \( F_b \) is the mean square error which measures the deviation between simulated flows and observed peak flows.

\[ F_c = \sum_{i=1}^{n} (O_i - S_i)^2 \]

**Equation 6-36**

Where, \( F_c \) is the sum of square error between simulated and observed flows. It measures the deviation between observed and simulated flow along the river.
D. Relative RMSE of all flow events

$F_d = \sqrt{\frac{1}{N} \sum_{i} \left( \frac{O_i - S_i}{O_i + S_i} \right)^2}$  \hspace{1cm} \text{Equation 6-37}

Where, $F_d$ is root mean square for high and low flow events only. It measures the deviation between observed and simulated flows.

These mathematical functions are built into the NSM model and are optimised simultaneously (i.e. all are minimized). An eight year data set is used for calibration by using different time periods for calibration and validation as shown in Figure 6-50. The calibration results are also compared visually and numerically using several quantitative performance criteria as explained in the next section

6.3 Assessment criteria for model performance

To measure the model performance for each validation test, a standard set of criteria consisting of seven numerical measures is applied. These criteria were selected to reflect the modelling objectives that are able to simulate monthly river flows at multiple sites along the Murrumbidgee River. The seven selected criteria are as follows:

1. Coefficient of efficiency: It measures the ability to simulate the variation in the flow hydrograph for a particular river gauging station (Nash and Sutchliffe, 1970).
   It is applied for each gauge station along the river. It is define as follows:

   $E = 1 - \frac{\sum (O_i - S_i)^2}{\sum (O_i - \bar{O})^2}$ \hspace{1cm} E = [0, 1]  \hspace{1cm} \text{Equation 6-38}

   where $O_i$ is the observed flow at times step $i$, $S_i$ is simulated flow at time step $i$ and $\bar{O}_i$ is the mean of the observed flow. Values close to 1 indicate that the model is able to capture or accurately simulate the variance of the flows in the river (Nash and Sutchliffe, 1970). Previous studies for Danish river systems (Nielsen and Hansen, 1973; Refsgaard and Knudsen, 1996) and for other international rivers (e.g. Harline. 1991; Linden, 2000; Andersen et al., 2001) have shown that $E$ values for runoff simulation range mostly between 0.5 and 0.95. Andersen et al., (2001) indicated that a value of $E > 0.85$ shows a good model run.

2. Root mean square error RMS (Henriksen et al., 2003) is the root mean square (RMS) $\text{RMS} = [0, \infty]$ see (section 6.2 : Equation 6-35)

3. Water balance error: It is a measure of the ability to simulate the average flow for a particular river gauging station. It is sometimes called the water balance error expressed as the difference between average simulated and average observed flow
normalized by average observed flow (Madsen, 2000a, Madsen et al., 2002; Henriksen et al., 2003).

\[ F_{bal} = \left( \frac{\bar{O} - \bar{S}}{\bar{O}} \right) \times 100 \]  
\% error in water balance \hspace{1cm} \text{Equation 6-39}

where \( \bar{O} \) is the mean of the observed flow and \( \bar{S} \) is the mean of the simulated flow.

4. Percent bias: It is a measure of the bias in the validation results from the observed flow (Hogue et al., 2005):

\[ \% BIAS = \frac{\sum_{i=1}^{N} (S_i - O_i)}{\sum_{i=1}^{N} O_i} \times 100 \]  
\text{Equation 6-40}

where \( O_i \) is observed flow at times step \( i \), \( S_i \) is simulated flow at time step \( i \) and \( N \) is the total number of time steps see Table 6-34 for score range.

5. Low Flow: A measure of the ability to simulate low flow conditions for a particular river gauging station (Wood, 1974; Henriksen et al., 2003). In this study the end of the system station.

\[ F_{low} = \sum_{i=1}^{N} \left( \frac{(O_i - S_i)\bar{O}}{O_i^2} \right)^2 \]  
\text{Equation 6-41}

where \( O_i \) is observed flow at times step \( i \), \( S_i \) is simulated flow at time step \( i \) and \( N \) is the total number of time steps. The low flow measure can be normalized by the minimum environmental flow requirement which is 6,000 ML/month for the Murrumbidgee water sharing plan 2002.

\[ F_{Low-norm} = \frac{F_{Low}}{F_{min-env}} \]  
\text{Equation 6-42}

where \( F_{low-norm} \) is the low flow normalized by minimum environmental flow, \( F_{min-env} \) is the minimum environmental flow.

6. Correlation coefficient: The correlation coefficient was calculated for all river gauge stations to demonstrate the correlation between validated flow and observed flow.
7. Median percentage: It is a measure of the ability to simulate the median monthly flow for a particular river gauging station. Or it is the percentage error of the simulated median monthly flow.

\[
F_{\text{median}} = \left| \frac{O_{\text{median}} - S_{\text{median}}}{O_{\text{median}}} \right| \times 100
\]

Equation 6-43

where \(O_{\text{median}}\) is the median observed flow and \(S_{\text{median}}\) is the validated simulated median flow.

These criteria are not of the absolute fail/pass type, but rather they assess the relative performance of the model considering all the model objectives.

Given that the each measure of performance emphasises a particular flow characteristic and has a unique range of variation, judging the model performance on the basis of the entire set of measures requires an objective criteria. To overcome this problem, a scoring and ranking system used by Refsgaard and Knudsen (1996), Lorup et al. (1998) and Henriksen et al. (2003) for E, \(F_{\text{bal}}\) and correlation was applied. Other rankings were suggested for Percent Bias, FL and RMS/median based on the previous ranked system (see Table 6-34). This ranking system is used to calculate the overall score and determine the acceptable validation case.

<table>
<thead>
<tr>
<th>Points</th>
<th>Rank category</th>
<th>E</th>
<th>(F_{\text{bal}})</th>
<th>Correlation</th>
<th>% Bias</th>
<th>RMS/median</th>
<th>FL</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>excellent</td>
<td>&gt; 0.85</td>
<td>&lt; 5</td>
<td>&gt; 0.85</td>
<td>&lt; 5</td>
<td>≥1–10</td>
<td>0.0–0.01</td>
</tr>
<tr>
<td>4</td>
<td>very good</td>
<td>≥0.65–0.85</td>
<td>≥25–10</td>
<td>≥0.65–0.85</td>
<td>≥25–10</td>
<td>≥10–20</td>
<td>≥0.01–0.02</td>
</tr>
<tr>
<td>3</td>
<td>good</td>
<td>≥0.5–0.65</td>
<td>≥10–20</td>
<td>≥0.5–0.65</td>
<td>≥10–20</td>
<td>≥20–30</td>
<td>≥0.02–0.1</td>
</tr>
<tr>
<td>2</td>
<td>poor</td>
<td>≥0.2–0.5</td>
<td>≥20–40</td>
<td>≥0.2–0.5</td>
<td>≥20–40</td>
<td>≥30–50</td>
<td>≥0.1–0.15</td>
</tr>
<tr>
<td>1</td>
<td>very poor</td>
<td>&lt; 0.2</td>
<td>&gt; 40</td>
<td>&lt; 0.2</td>
<td>&gt; 40</td>
<td>&gt; 50</td>
<td>≥0.15–1.0</td>
</tr>
</tbody>
</table>

An aggregation score system was suggested by giving a score of 1 to 5 point for each interval/class under each performance criteria (see the five intervals/classes for each performance criteria and the corresponding score point for each interval/class in Table 6-34). For example, one of the five gauging stations with a correlation performance equal to excellent (>0.85) was given 5 points while a very good correlation (≥0.65–0.85) gave four points. The overall score to compare each validation case and to determine the best case is calculated by aggregate the individual scale/point of each performance criteria along the river (the five stations). These performance criteria were applied to the results of each time case of the validation period, excluding the calibration period.
6.4 NSM calibration and validation results

In this section, the calibrated and validated results are compared qualitatively (visually) and then quantitatively with the observed data. The steps involved in the calibration process are as follows for Case I (Case 93-95):

1. The NSM model is used to simulate the discharge at several gauging stations along the Murrumbidgee River for 6 water years (June 1995–June 2001).

2. The model results are compared with observed data for each river reach gauge point.

3. The six year flow is calibrated by applying a simultaneous multi-objective auto calibration method to find the optimum value of the parameters.

4. The optimal parameter values are used to run the model for two years (validation period June 93-June 95).

5. The assessment performance criteria is applied to the validation results to assess the model performance.

6. The same steps are repeated with other time cases.

Schlesinger et al. (1974) indicated that model validation concerns the quality of the match between simulated and real data with some interpretation of the appropriateness of the data for validation purposes. As mentioned above, three parameters were used for calibration (evaporation factor, seepage rate and channel losses) using Powell’s method. The range of parameter values are on a literature review and data from local data (Table 6-35). The main assumption here is that the seepage rate along the river is constant.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Initial value</th>
<th>Lower boundary</th>
<th>Upper boundary</th>
<th>Source</th>
<th>Calibration results value 93-95</th>
</tr>
</thead>
<tbody>
<tr>
<td>evaporation factor</td>
<td>0.7</td>
<td>0.5</td>
<td>1</td>
<td>Richard et al., (FAO 56 paper) 1998</td>
<td>0.52</td>
</tr>
<tr>
<td>seepage rate</td>
<td>6 mm/day</td>
<td>2 mm/day</td>
<td>8 mm/day</td>
<td>MDBC 2004b; SKM 2003; Willem et al., 2005</td>
<td>2.1</td>
</tr>
<tr>
<td>channel loss</td>
<td>20 %</td>
<td>15 %</td>
<td>30 %</td>
<td>CIA Report, 2000-05</td>
<td>18.5</td>
</tr>
</tbody>
</table>

For ease of comparison of results for the different cases, the results are shown by gauge location, ordered from upstream to downstream. Each gauge station is assigned four figures covering the four period cases and the performance criteria results.
Wagga Wagga Gauge Station

Figure 6-53 (A, B, C and D) shows the Wagga Wagga monthly flows for the calibration and validation periods. The validation period is represented by two lines, the observed flow and the simulated flow, using the optimum parameters values resulting from the calibration process. Visually it can be seen that the simulated flow is consistent with the observed flow in most cases. There are some discrepancies such as some lower peak flows in case 95–97, for example. The other validation cases (case 93-95, case 97-99, and case 99-01) show more consistency and only one high peak flow does not match during the validation period. This could be attributed to the 95–97 years which were average wet years while the rest of the years were merely dry. In general, the model tends to underestimate the peaks and troughs of the hydrograph. This can be attributed to the complexity of the system, model structure and assumptions about soil types and seepage rate and using three parameters for calibration processes.

![Figure 6-53 Wagga Wagga monthly flows under the four cases (A: case 93–95, B: Case 95–97, C: Case 97–99, D: Case 99–01)](image)
The quantitative assessment of model performance is presented Figure 6-54 for the Wagga Wagga stream gauging station under the four time cases. It is very clear that there is no difference between correlation, water balance error and low flow score values between the four time cases. The high E score for case 97-99 is the only clear difference. The root mean square error compared to median flow (RMS/median) show a similar same result: high scores for case 97–99 and 99–01. In addition, the percent bias criteria shows different results, with high scores for cases 93–95, 97–99 and 99–01 and low score for case 95-97. This means that case 95-97 validation result is high deviated from the observed data by over 20% of the time data series. This could be attributed to case 95-97 has received closed to average rainfall while the rest of the data series which have used in calibration are merely dry years.

![Figure 6-54 assessment criteria result of Wagga Wagga station](image)

Figure 6-55 shows the overall average score at Wagga Wagga station under the four time cases. Case 95–97 is the only case that gave a score less than 4 (a very good case), while all other cases gave scores greater than 4 (ranked as excellent). Case 97–99 gave the highest rank score of 4.3 which is the best overall for the Wagga Wagga gauge station for these set of parameter values (evaporation factor=0.51, seepage factor=2.2 and channel losses= 18.6%).
Narrandera gauging station

Figure 6-56 (A, B, C and D) shows the Narrandera monthly flows for the calibration and validation periods. The validation period is represented by two lines: the observed flow and the simulated flow, using the optimum parameter values resulting from the calibration process. By visual comparison, it can be seen that the simulated flow compares very well with the observed flow in most cases except for the 99-01 period. The main deviations are observed during low flows such as in 99–01, for example. This is could be attributed to the fact that the 99-01 period received the lowest rainfall while the rest of the years received average rainfall. Overall, however, there are only small differences in the calibration parameters between the four cases. This can be attributed to model multi-objective calibration processes which for complex systems try to find the optimal combination of the three parameters by compensation between parameters. Figure 6-57 depicts the results of the assessment criteria at Narrandera station for the four time cases. It is apparent that there are no significant differences in correlation, percent bias, water balance error, or low flow score values (5, 2, 5 and 5 respectively) between the four cases. The E values show a lower score in case 99–01 which was the driest period of the data set. The root mean square error to median flow (RMS/median) value shows different results, with a high score for case 97–99. These could be attributed to the model is sensitive to the low flow years which result in high deviation (low score of RMS/median) of the validation results from observed results.
Figure 6-56 Narrandera monthly flows under the four cases (A: case 93-95, B: Case 95-97, C: Case 97-99, D: Case 99-01)

Figure 6-57 assessment criteria result of Narrandera station

In addition, Table 6-36 shows that correlation between observed and modelled flows decreases when moving downstream (from Wagga Wagga to Narrandera stations) under
the four time calibration cases. While case 97–99 demonstrated the highest correlation (0.977) at Wagga Wagga station, case 95–97 showed the highest correlation (0.952) at Narrandera station. This is can be attributed to the high diversion of irrigation water and increasing of measurement errors at downstream stations which is reported 33% (Khan et al., 2006). These errors are attributed to many diversions points upstream in the middle reaches and the connected groundwater system with the river.

<table>
<thead>
<tr>
<th>Table 6-36 Correlation values for Wagga Wagga and Narrandera Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Wagga Wagga Station</td>
</tr>
<tr>
<td>Narrandera Station</td>
</tr>
</tbody>
</table>

Figure 6-58 shows the overall average score at Narrandera station under the four time cases. Case 99-01 is the only case that gave a score less than 3.5 (ranked as a very good case), while all other cases gave higher scores (also ranked as very good cases). In addition, case 97-99 gave the highest rank score of 3.85 (close to excellent) that characterizes it as a very good case and the best case overall at the Narrandera gauge station. This result is similar to Wagga Wagga station, with parameter values of 5.1, 2.2 and 18.6% for evaporation factor, seepage factor and channel losses respectively. Excluding the validation period from the calibration period (which was very dry) made the calibration period better able to estimate the parameters, as it too features average-dry conditions.

![Figure 6-58 over all score of assessment criteria at Narrandera gauge station](image)
Darlington Point gauge station

Darlington Point gauge station is located downstream of Narrandera station. Between Narrandera and Darlington Point station are the main off-take canals for water diversion to the main irrigation areas (Murrumbidgee and Coleambally irrigation areas). Figure 6-59 A, B, C and D show the Darlington Point monthly flows for the calibration and validation periods. The simulated and observed flows compare very well over the validation period for cases 93-95 and 95-97. The 99-07 case shows more deviation between modelled and observed flows. This can be attributed to case 99-01 was the driest period in the eight-year time series. Further, the validation period for this case covers the implementation of the environmental flow plan.

Figure 6-59 Darlington Point monthly flows under the four cases (A: case 93-95, B: Case 95-97, C: Case 97-99, D: Case 99-01)

Figure 6-60 shows the results of the assessment criteria at Darlington Point station under the four time cases. It is clear that there is no significant difference in the assessment criteria for the first two cases (93-95 and 95-97), except for the root mean square median criterion that shows a high score for case 95-97. In general, these cases show better score results than do cases 97-99 and 99-01, except for the root mean square error. All of the assessment criteria ranked between excellent and very good, except for
percent bias and water balance error that ranked as good but close to poor. In addition, Table 6-37 shows that correlation decreases moving downstream (from Narrandera to Darlington Point stations) under the four time calibration cases. While case 95-97 showed the highest correlations, 0.952 at Narrandera and case 93-95 showed 0.944 at Darlington Point station.

<table>
<thead>
<tr>
<th>R² Correlation</th>
<th>Case 93-95</th>
<th>Case 95-97</th>
<th>Case 97-99</th>
<th>Case 99-01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrandera Station</td>
<td>0.95</td>
<td>0.952</td>
<td>0.948</td>
<td>0.918</td>
</tr>
<tr>
<td>Darlington point station</td>
<td>0.944</td>
<td>0.934</td>
<td>0.87</td>
<td>0.79</td>
</tr>
</tbody>
</table>

Figure 6-61 shows the overall average score at Darlington Point station under the four time cases. Case 97-99 is the only case that gave a score less than 3 (good), while all other cases gave higher scores (very good). Case 95-97 gave the highest rank score, 3.5 (very good) which is the best case overall at the Darlington Point gauge station. Parameter values here are 5.2, 2.2 and 18.7% for evaporation factor, seepage factor and channel loses respectively. This result is completely different from the previous, upstream stations (Wagga Wagga and Narrandera).

In general, the overall score for each case at Darlington Point was less than the score for the upstream stations. This can be attributed to the large water diversions estimated in the model according to irrigation activities in this reach and uncertainty in flow measurements. Moreover, high correlation and visual (qualitative) consistency do not usually lead to high performance models. Thus this study is using and applying different performance criteria such as E, low flow, water balance error, %bias and RMS to evaluate and rank the NSM model time cases performance after calibration.
Hay gauge station

Hay gauge station is located further downstream from the Darlington Point station. Figure 6-62 (A, B, C and D) shows the Hay monthly flows for the calibration and validation periods. Based on a visual comparison, the simulated flows appear mostly consistent and have the same trend as the observed flows, especially in case 93-95 and case 95-97. Some peaks flows such as case 95-97 are underestimated. Other cases show less consistent results with the observed flows during the validation period such as case 99-01. Whilst the first two cases generally match the observed flow, this could be attributed to a better estimation of the calibration parameters and good selection of calibration period that is well represented by both dry and average years.

Figure 6-63 shows the results of the assessment criteria at the Hay station under the four time cases. There are significant differences in all cases under each criterion. In general, most of the criteria scores are lower and located between 2 and 3. This could be attributed to the uncertainty in flow measurements that was reported by Khan et al. (2004b) and Pratt Water (2004a) to be around 30–35%. Also, it can be attributed to the connectivity of the surface water system and groundwater system that in the downstream reaches is high.
Figure 6-62 Hay monthly flows under the four cases (A: case 93-95, B: Case 95-97, C: Case 97-99, D: Case 99-01)

Figure 6-63 assessment criteria result of Hay station

The E values sharply decreases from case 93-95 to case 99-01. The results for percent bias and water balance error show two groups of results. Case 93-95 and case 95-97 have higher scores while case 97-99 and case 99-01 have lower scores. This could be attributed to the fact that the first two cases were able to catch the high peak flows. The correlation criterion indicates that the best case is case 93-95 with a correlation score of 4.5. On the other hand, the low flow criterion shows case 97-99 is the best in terms of its ability to
simulate low flows with a score of 5. This result is consistent with percent bias and water balance error results. The RMS median criterion shows the same result with low flow with case 97-99 showing the best score (4). Figure 6-64 shows the overall average score at the Hay station under the four time cases. Case 99-01 is the only case that gave a score less than 2 (poor). Case 93-95 with a rank score of 2.9 (good) is the best case overall at the Hay gauge station. The parameter values for this reach are 5.2, 2.2 and 18.7% for evaporation factor, seepage factor and channel loses respectively. This result is significantly different from the upstream gauge stations results. This can be attributed to the exclusion of years 93-95 (dry years) from the calibration period.

Balranald gauge station

Balranald gauge station is the last gauge station along the Murrumbidgee River, in conjunction with the Murray River. Figure 6-65 (A, B, C and D) illustrates the Balranald monthly flows for the calibration and validation periods. It is apparent that peak flows are less frequent, smaller, and concentrated over the summer months, a feature that can be attributed to irrigation diversions upstream. The visual comparison shows that the simulated flows 97-99 tend to overestimate the peak flows. The other cases, simulated flows show a better matching with measured flows particularly in case 93-95. The model shows more departure from the observed flows in the last two cases. These deviations are consistent with the results of Khan et al. (2004b) and Pratt Water (2004a) that indicate there is a need to validate flows and diversion statistics in the lower reaches because of uncertainty and error in measurements around 35%.

Figure 6-64 over all score of assessment criteria at Hay gauge station
Figure 6-65 Balranald monthly flows under the four cases (A: case 93-95, B: Case 95-97, C: Case 97-99, D: Case 99-01)

The quantitative assessment comparison shows more variable results than the upstream gauge stations (Figure 6-66). There are significant differences in the assessment score for all time cases and measures except for water balance error and percent bias criteria (case 93-95 and case 95-97 show the same score of 4). In general, case 93-95 and case 95-97 show a good score for most criteria; case 95-97 shows particularly high scores except for the correlation criterion. The other two cases, case 97-99 and case 99-01, always show low scores except under the low flow and RMS median criteria, which show similar scores to case 95-97. These results indicate the model is very sensitive to low flow and RMS median at downstream station (Balranald) especially under dry conditions (case 99-01 and case 93-95). These results also point out the difficulty in selecting the case best able to represent the different flows events given the uncertainties in the flow data, the complexity of the system and the model assumptions by using single criteria.
Figure 6-66 assessment criteria result of Balranald station

Figure 6-66 shows the over all average score at Balranald station for the four time cases. Case 97-99 is the only case with a score less than 2 (poor), while all other cases receive higher scores. Case 95-97 gives the highest rank score, 3.4 (very good), and is the best case overall at Balranald gauge station. There calibration parameter values are 5.2, 2.2 and 18.7% for evaporation factor, seepage factor and channel loses respectively. This best case result is different from the upstream gauge stations’ results where other cases were determined as the best case (see Table 6-38). This could be attributed to excluding the calibration period from years 95-97.

Table 6-38 the best case for each station

<table>
<thead>
<tr>
<th>Station name</th>
<th>The best case</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wagga</td>
<td>Case 97-99</td>
<td>4.4</td>
</tr>
<tr>
<td>Narrandera</td>
<td>Case 97-99</td>
<td>3.85</td>
</tr>
<tr>
<td>Darlington Point</td>
<td>Case 95-97</td>
<td>3.5</td>
</tr>
<tr>
<td>Hay</td>
<td>Case 93-95</td>
<td>2.9</td>
</tr>
<tr>
<td>Balranald</td>
<td>Case 97-99</td>
<td>3.4</td>
</tr>
</tbody>
</table>
Overall Assessment

In summary, it is clear that the time case that is best able to represent the flow events for each station is different (See Table 6-38). Furthermore, there is a clear declining trend in the overall score for gauging stations located downstream. The declining quality of fit between modelled and observed flows is more sensitive for the correlation coefficient, E value, low flow and RMS-median criteria. That means the model is sensitive to low flow and dry conditions. However, the balance error and percent bias measures show better results for the downstream stations. This indicates the model is able to simulate the river flow at lower river stations with less deviation from the observed flow data when the model complexity and measurements errors are considered.

Table 6-39 shows the assessment criteria score results for each gauge station under each time case. Most of the criteria show high scores in the upstream gauge stations. The percent bias, especially in case 93-95 at the most downstream station (Balranald), gave the highest score of 4. The balance error gave the same result with case 93-95 and case 95-97. According to Henriksen et al. (2003) the model in the first two cases (case 93-95 and case 95-97) is categorised as very good based on overall score for the whole river (five stations). The other two cases, case 97-99 and case 99-01 could be categorised as poor and good. The maximum RMS result shows that the error is lower than the 35% reported by Pratt Water (2004a) for the downstream reach. The RMS deviation values from the median flow range between 7% and 24% and increases in the downstream reaches. This is because the median flow downstream is less than the median flow upstream, which makes the downstream stations very sensitive to small deviations in the simulated median flow (i.e. high RMS means great deviation between simulated and observed flow).

F treadmill shows the ability to simulate the average flow for a particular river gauging station or the percentage error relative to the average flow. The error percentage for the four cases ranges from 19% to 31%, with an average error percentage of around 24.8%. These errors are within the uncertainty error for the observed flow data. The model gives good results at upstream and downstream reaches, but in the middle reaches the percentage error is higher and the score lower. This could be attributed to the location of irrigation areas and the error in Diethridge wheels water meters. The higher error observed at the middle reach stations could be attributed to the fact that this section of the river is linked to the groundwater aquifer system. This may cause additional factors such as river-aquifer interactions to affect the flow that are not incorporated into the model.
Table 6-39 Assessment criteria results

<table>
<thead>
<tr>
<th>Cases</th>
<th>Performance Indicator validation</th>
<th>E-MO</th>
<th>Fbal-MO</th>
<th>Percent Bias-MO</th>
<th>Correlation - MO</th>
<th>FL norm</th>
<th>RMS/median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wagga-Case 93-95</td>
<td></td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Narrendera-Case 93-95</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Darl Pt-Case 93-95</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Hay-Case 93-95</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Balranald-Case 93-95</td>
<td></td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wagga-Case 95-97</td>
<td></td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Narrendera-Case 95-97</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Darl Pt-Case 95-97</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>Hay-Case 95-97</td>
<td></td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Balranald-Case 95-97</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Wagga-Case 97-99</td>
<td></td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Narrendera-Case 97-99</td>
<td></td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Darl Pt-Case 97-99</td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Hay-Case 97-99</td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Balranald-Case 97-99</td>
<td></td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Wagga-Case 99-01</td>
<td></td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Narrendera-Case 99-01</td>
<td></td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Darl Pt-Case 99-01</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Hay-Case 99-01</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Balranald-Case 99-01</td>
<td></td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

These results are more consistent with the percent bias results which show that the upstream and end of the system stations have high bias. However, the middle reach gauges give low bias, particularly in the last two time cases (case 97-99 and case 99-01). These regional and river reach differences can be attributed to the difficulty in calibrating parameters for these regions where irrigation areas are located and the river-groundwater connections are important.

The low flow criterion measures the model’s ability to simulate low flow conditions for a particular river gauging station. According to Henriksen et al. (2003), there is limited previous experience of the plausible range of FL values for low flow simulation, although this value should be as low as possible or close to zero. Due to the FL sensitivity to small observed flows, this measure can be used mainly as a quantitative assessor and not as a performance criterion. The results for the first two cases (case 93-95 and case 95-97) are reasonable, giving the lowest FL values upstream and increasing further downstream as the uncertainty in the observed flow data increases. These results are consistent with the findings of Khan et al. (2004b) and Pratt Water (2004a) that indicate there is a need to validate flow and diversion statistics in the lower reaches because of measurement and reporting uncertainty.

The median percentage is a measure of the ability to simulate the median monthly flow for a river gauging station and is also the percentage error that occurs in a
simulation of the median monthly flow. It is clear that the upper reaches showed better results with a lower percentage error in simulating the median flow. The highest percentage error was observed at the Balranald downstream station which could be attributed to high uncertainty in measurement (Pratt Water, 2004a). High uncertainty in measurements may be the reason for the bad median flow results downstream as this represents the high deviation of the simulated flow from observed flow.

Based on the above discussion, it is not possible to make an assessment of model performance based on a single criterion or river station. The multiple criteria ranking system discussed above was devised to calculate the average score for each criterion and the best time case for each river gauge. The overall criterion average is used in this study assigns the same weighting to each criterion. This is one of the limitations of this study/model, in addition to the model assumptions (soil types, channel structure and seepage rate).

Table 6-40 shows the ranking and scoring system for the validation results for the four time cases. The scoring results indicate that the model performance varies between very good and excellent for most cases and criteria such as correlation, E value and Fl._norm. For Fbal and percent bias the rank is between poor and good for the last two cases (case 97-99 and case 99-01), while it is close to very good conditions in the first two cases (case 93-95 and case 95-97).

<table>
<thead>
<tr>
<th>Performance Indicator score</th>
<th>E</th>
<th>Fbal</th>
<th>Percent Bias</th>
<th>Correlation</th>
<th>Fl._norm</th>
<th>RMS/median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 93-95</td>
<td>3.8</td>
<td>2.6</td>
<td>2.6</td>
<td>4.8</td>
<td>3.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Case 95-97</td>
<td>3.8</td>
<td>2.6</td>
<td>2.4</td>
<td>4.4</td>
<td>3.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Case 97-99</td>
<td>3.1</td>
<td>1.6</td>
<td>1.6</td>
<td>4.4</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>Case 99-01</td>
<td>2.4</td>
<td>2.2</td>
<td>2</td>
<td>4</td>
<td>4.2</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Furthermore, Figure 6-68 shows the average score for each performance criterion under the different time cases for all gauges stations (whole river), indicating that the first two cases (case 93-95 and case 95-97) give a very good overall score of 3.4 and 3.3 respectively. The other two cases (case 97-99 and case 99-01) give a lower score of 2.9 and 3 respectively, which is ranked as good. The scores indicate that case 93-95 is the best overall case with a score of 3.4 and parameter values of 0.52, 2.1 and 18.5% for evaporation factor, seepage factor and channel loses respectively. Case 93-95 achieved the best result for different performance criteria with a 5.5 to 8% percentage error (due to flow data uncertainty—see chapter four, section 4.4 for details). It is therefore concluded that the set of parameters determined for this case will be used to model the
various water management scenarios. The next chapter is devoted to the simulation and analysis of alternative management scenarios.

![Figure 6-68 Overall Score for Each Case](image)

### 6.5 Summary and Conclusion

A network simulation model (NSM) was developed using the system dynamics approach to analyse irrigation demand management strategies. The NSM monthly model is designed to assist water managers to analyse the system’s behaviour under various management scenarios.

The NSM model was calibrated and validated using an eight year climate and flow time series using a multi-objective auto calibration method. The model calibration comprised three main parameters – evaporation factor, seepage factor and channel losses. The calibration was carried out at five stream gauging stations on the Murrumbidgee River for a combination of four independent calibration-validation time cases - case 93-95, case 95-97, case 97-99 and case 99-01 – in which the years indicate the time period used in the model validation. The independent calibration was carried out on the remaining years of the time series.

The multi-objectives auto calibration method was represented by four separate objectives functions:

a) overall volume error,

b) overall Root Mean Square Error (RMSE),

c) sum of square error (SSE), and;
d) relative RMSE of all flow events.

Seven performance indices were applied to evaluate the overall performance of the validation results and compare the four time cases and five stream gauging stations along the Murrumbidgee River, including: coefficient of efficiency (E value), root mean square RMS, water balance error (\(F_{\text{bal}}\)), percent bias (%Bias), low flow (FL), correlation coefficient (\(R^2\)) and median percentage flow.

A ranking and scoring system (based on literature, see section 6.3) was developed to understand the performance of the NSM model after calibration. Based on the results obtained from the analysis carried out for each stream gauging station and the calibration-validation time periods, the following conclusions can be drawn:

- The model performance exhibits a decline for successive stream gauging stations from upstream to downstream. At the Wagga Wagga and Narrandera gauge station, time case 97-99 shows the best performance with estimated parameters values of 0.51, 2.2, and 18.6 for evaporation factor, seepage factor and channel losses respectively. At Darlington Point, case 95-97 shows the best result with estimated parameters values of 0.52, 2.2 and 18.7 for evaporation factor, seepage factor and channel losses respectively. At the Hay gauging station, case 93-95 shows the best result with estimated parameters of 0.52, 2.1, and 18.5 for evaporation factor, seepage factor and channel losses respectively. At the end of system Balranald gauging station, case 97-99 shows the best results.

- The average ranking results show that case 93-95 is the best calibration performance. Therefore, the optimum parameters values resulting from case 93-95 will be used to simulate the alternative water management scenario developed in Chapter Four. However, more detailed calibration process should be considered for each river reach with specific parameters for each river reach.

- The performance criteria results indicate that case 93-95 is the best model performer. This result is aligned with the result from a MDBC report (2001) about model guidelines: “model calibration acceptability should be judged in relation to each of the performance measures and criteria”. This report also recommends dividing the dataset by 60% for calibration period and the rest for validation period. Moreover, multi-objective auto calibration is able to better calibrate the model, and provide better identifiable parameters and a more well posed model structure (Madsen, 2000b).
The NSM model was calibrated and validated and can represent most of the characteristics of this complex system. However, the NSM does not thoroughly investigate every aspect, for example, environmental impacts, legal and political issues and long-term policy ramifications. The next chapter will describe the use of the NSM model to quantify and analyse the behaviour of the system and economic and environmental outcomes for each alternative water management scenario developed in Chapter Four.
Chapter 7: Scenario Analysis

7.1 Introduction

Scenario analysis is a way to represent and evaluate water demand and supply management Scenarios. Scenarios were investigated in this study to understand the potential for improving water productivity and environmental performance through different management options. The key questions to be answered in this analysis are the second two research questions (from Section 1.2):

- What management options can be used to improve water productivity and river environmental performance (in terms of satisfying end of system flow)?
- What are the implications (economic and social) of these management options?

These questions were answered using the NSM model; discussed in chapters five and six. The NSM model was used to compare several variations of each model Scenario (called a sub-Scenario) as well as understand the sensitivity of individual parameters within the model. These results were then used to determine the implications of uncertainty on the study outcomes. This section contains a large amount of model output and therefore a five step process was used to clearly answer the research questions. Throughout this analysis, Scenarios are compared using a two dimensional figure reflecting the two key criteria of relative economic and environmental performance. A summary of the Scenarios and this performance assessment tool is presented in Section 7.2.

The five step analysis process is:

1. Presentation of model results for each sub-Scenario (grouped by Scenario) to better understand the tradeoffs between sub-Scenarios and demonstrate the overall performance (and sensitivity) of each Scenario (Section 7.3).
2. Selection of the best sub-Scenario in each Scenario for further analysis (Section 7.3). This approach is designed to identify the maximum potential of the management options in the context of model uncertainty.
3. Presentation of model results for each selected sub-Scenario to demonstrate their overall performance (and sensitivity) in terms of total water use, surface and ground water use, gross margin, potential water saving and environmental performance (Section 7.3).
4. Presentation of a sensitivity analysis of the best Scenario output to identify the critical parameters within the model and to demonstrate the level of uncertainty associated with the results (Section 7.4).

5. Comparison of Scenario output in the context of uncertainty, and a discussion of implications for management options (Section 7.5). A summary of the limitations of the research is also provided to facilitate interpretation (Section 7.6).

Using these five processes, the research questions outlined above will be answered (Section 7.7). However, these five processes could lead to exclude some options which may perform better than other options which stay in the assessment and further analysis. These five processes still ok because this study is trying to compare the relative potential of different options and by using the best options, this study is comparing the best possible from each options. Finally, the reason of using these five step process is to provide a clear and succinct approach to the analysis.

### 7.2 Summary of Scenarios and performance measures

This study attempts to investigate and better understand what the potential impacts are if the six scenarios were to be applied. The analysis of the results is based on the assumption that the main concern of farmers is to meet their needs for irrigation water to provide a regular and reliable income. This leads to a water policy that prioritises improving water productivity and environmental performance. Six scenarios, including the base case Scenario (Scenario 1) were identified and developed, based on inputs from the irrigation communities; In addition, each Scenario has several variations called sub-Scenarios (see Chapter 4, Section 4.2). By varying model inputs, it is possible to explore a range of alternatives, but this model is linked with an optimiser that is able to maximise farmers’ crop decisions and water trading behaviours (see Chapter 5, Sections 5.3 and 5.4 for details).

**Scenario 1: Base case** Reflects the main characteristics of each irrigation area or node (12 nodes) of the Murrumbidgee catchment and the current conditions. The base case (Scenario 1) reflects the main characteristics of each irrigation area or node (12 nodes) in the Murrumbidgee catchment and current conditions for a wide variety of situational factors. These factors include current economic margins and profitability, fixed and variable costs for crops under recent water allocations, operational constraints, water trading levels, groundwater and surface water use, cropping system, production and economic return, and environmental conditions. The NSM model includes most of the hydrological, economic, environmental and cropping variables that have influenced
seasonal flows and in turn environmental flows in the Murrumbidgee River over the period of records (June 1993–June 2003).

**Scenario 2:** This Scenario builds on the base case with different crop mixes but using the same water sources and water system constraints. This Scenario simulates changing the crop mix under the same water availability. Under this Scenario four variations were simulated to test their impact on water systems, the environment and agricultural income or productivity. These variations include:

- mixed cropping (balanced mix from summer, winter and annual crops)
- summer Scenario (increasing summer crop area and decreasing winter crop area)
- winter Scenario (increasing winter crop area and decreasing summer crop area i.e. skewed toward winter crops)
- the last variation is an area reduction Scenario that demonstrates the impact of reducing the area of crops that have a high water requirement by 50%.

**Scenario 3:** This Scenario is similar to Scenario 2 (changing crop mix), except that water banking is introduced. This Scenario seeks to understand the efficacy of water banking as a new water management system (regulation) to supply and store water underground by two methods: recharge of groundwater by infiltration into the basin, or through injection by using water wells, either existing or new. Eight sub-Scenarios were modelled under this Scenario: four variations of cropping (described for Scenario 2) were simulated under these two cases of recharge methods to test their influence on water systems, environment and agricultural income.

**Scenario 4:** This Scenario is based on the base case Scenario except that it simulates changing the total water supply by using groundwater as a partial substitute for surface water and shifting the dam release one season (6 months) earlier. Under this Scenario two variations were simulated to test their effect on water systems, environment and agricultural systems.

- The first variation assumes that surface water diversions are reduced by 10% monthly and replaced by groundwater (within monthly groundwater pumping constraints). The assumption here is that 10% of surface water can be allocated to the environment through a market-based approach.
- The second variation assumes that the dam release is shifted forward six months to shift the seasonality of flow, and also allows for groundwater pumping with the same level of delivery to irrigators. Regardless it is impact on hydropower, return flow, dam spill and storage level (as it is beyond the
scope of this study). The main assumption here is water banking is managed by water service provider and the incurred cost will be added on water cost, so the farmer will have equity in sharing water price.

**Scenario 5:** This Scenario builds on Scenario 4 but additionally allows water trading using water banking. This Scenario simulates a situation that introduces water banking (by using infiltration and injection methods of recharge) and allows water trading between water banks in each irrigation area. Effectively this means that the aquifer is used for storage and delivery, rather than relying on the reservoir upstream for storage and the river for delivery. This Scenario could reduce the volume flowing down the river at times when the river would benefit from low flow rates. Under this Scenario the same two variations described under Scenario 4 were simulated to test their effect on the water system, environment and agricultural systems.

**Scenario 6:** This Scenario is based on Scenario 1 (base case), and combines all the best sub-Scenarios (see appendix H). This Scenario was tested under both recharge methods (infiltration and injection) and includes all the best variations from the previous five Scenarios. It entails these changes: crop mix, water banking, conjunctive water use, water trading and shifting dam-flows. It simulates and compares outcomes with the base case to find the most effective option.

All of these Scenarios were compared to the status quo: the base case (Scenario 1). The base case Scenario results or historical data were developed using a “back-casting process”. The back-casting approach allows the model results to be compared with the baseline and can be used to predict how well the proposed policy or Scenario might work. Further information is given in chapter four (section 4.1).

Briefly, the main management options (see Table 7-41) were tested in this study using the following modelling approaches:

- **Crop mix:** changing crop mix area using different cropping pattern systems resulting from CDOM and WTM (see section 5.3 for details) with assumption switching costs are zero.
- **Water banking:** simply redirecting surface water during winter (low demand) to the underground aquifer for storage and re-abstracting groundwater during high demand periods (summer) with assumption losses is zero.
- **Conjunctive water use:** managing surface and groundwater resources as single water source by using and pumping groundwater as substitute for surface water.
- **Water trading**: Allowing water trading between surface and groundwater using the water bank as a mechanism for intermediate storage.
- **Shifting dam release**: Shifting the surface water released from the two main dams (outflow with the same level of delivery to irrigators) by six months to try to mimic the natural flow regime with assumption of water service provider investment and equity sharing water cost between farmers.
- **Surface water restrictions**: reducing surface water use by 10% and directing this saved water to the environment (it could be stored and released according to environmental needs, or released each month).

### Table 7-41 Summary of Scenarios and sub-Scenarios

<table>
<thead>
<tr>
<th>Main Scenarios</th>
<th>Sub Scenario (Scenario variations)</th>
<th>Scenario description and inputs or parameters changed</th>
<th>Impact on</th>
</tr>
</thead>
<tbody>
<tr>
<td>1—base case</td>
<td>none</td>
<td>the main characteristics of each irrigation areas/nodes</td>
<td>demand and supply side</td>
</tr>
<tr>
<td>2—Scenario 1 with different crop mix under different conditions</td>
<td>mixed cropping</td>
<td>crop area (different crop mix from summer and winter crops with equal priority; calculated by CDOM)</td>
<td>demand side</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>increasing the area of the summer crops such rice, lucerne, maize and soybean (calculated by CDOM)</td>
<td>demand side</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>increasing the area of the winter crops such wheat, winter pasture, barley and canola (calculated by CDOM)</td>
<td>demand side</td>
</tr>
<tr>
<td></td>
<td>reduction</td>
<td>rice, wheat and lucerne crop areas are reduced by 50% (calculated by CDOM)</td>
<td>demand side</td>
</tr>
<tr>
<td>3—Scenario 2 with water banking under both artificial recharge methods (infiltration and injection) for each crop mix sub-Scenario</td>
<td>mixed cropping</td>
<td>crop area (different crop mix from summer and winter crops with equal priority; calculated by CDOM)</td>
<td>demand and supply sides</td>
</tr>
<tr>
<td></td>
<td>summer</td>
<td>increasing the area of the summer crops such rice, lucerne, maize and soybean (calculated by CDOM)</td>
<td>demand and supply sides</td>
</tr>
<tr>
<td></td>
<td>winter</td>
<td>increasing the area of the winter crops such wheat, winter pasture, barley and canola (calculated by CDOM)</td>
<td>demand and supply sides</td>
</tr>
<tr>
<td></td>
<td>reduction</td>
<td>rice, wheat and lucerne crop areas are reduced by 50% (calculated by CDOM)</td>
<td>demand and supply sides</td>
</tr>
<tr>
<td>4—Scenario 1 with conjunctive water use (groundwater substitution) under different assumption</td>
<td>reduce surface water by 10%</td>
<td>reduce dam release by 10%</td>
<td>supply side</td>
</tr>
<tr>
<td></td>
<td>shifting dam release</td>
<td>shifting dam release by 6 months</td>
<td>supply side</td>
</tr>
</tbody>
</table>
| 5—Scenario 1 with conjunctive water use and allowing water trading under different assumption | reduce sw by 10% | - reduce dam release by 10%  
- crop area (different crop mix from summer and winter crops with equal priority; calculated by WTM)  
- allowing trading between water banking | supply and demand sides |
|                | shifting dam release                | shifting dam release by 6 months  
- crop area (different crop mix from summer and winter crops with equal priority; calculated by WTM)  
- allowing trading between water banking | supply and demand sides |
| 6—all options Scenario: Scenario 1 with crop mix, water banking and shifting dam release | - crop area, shifting dam release by 6 months  
- crop area (different crop mix from summer and winter crops with equal priority; calculated by WTM) | supply and demand sides |
Results for each Scenario, returned from the NSM model, were provided in a data intensive way, providing information about resources use, crop yields, and gross margin per hectare and megalitre per irrigation area, and for each crop and environmental index (Chapter 4, Section 4.3) for the whole catchment. However, to provide more coherent analysis, the model results are here compared using a trade-off tool that enables assessment along two dimensions: water productivity and environmental outcomes. This tool is shown below in Figure 7-69 and compares the percentage relative change in agricultural income (compared to the base case) on the horizontal axis, and the percentage relative change in environmental index (compared to base case on the vertical axis).

![Figure 7-69 Trade off between agricultural income and environmental performance](image)

The cross point in the centre of the Figure 7-69 is a neutral point of no change (i.e. base case). Therefore, management options that deliver outcomes in the upper right hand segment are considered to deliver positive outcomes on both economic and environmental measures, and therefore are highly recommended. Outcomes in the bottom left segment represent negative impacts for both agriculture and environment and are clearly not recommended. The top left segment represents outcomes where economic outcomes are negative but environmental gains occur, and it is here where government subsidies may make some initiatives feasible and desirable (where the community is prepared to pay the subsidy). The final segment in the bottom right corner represents outcomes where there is a positive economic gain but poor environmental outcomes and these are not seen to be desirable in a context of declining environmental values.
The base case Scenario (Scenario 1) showed that agricultural production and income are affected by irrigation water availability and crop area. Annual gross margin and total water use are linked to irrigated area, cropping system and irrigation water use (surface, groundwater and trading). Also, total water diversion is linked to environmental flow targets (environmental index) with very clear trade-offs between environmental performance and water allocation and agricultural income. The environmental index decreased by 10–20% (environmental flows were not available for 3–6 months) in the last five years when water allocation was about 23–40% due to dryer than average conditions and a reduced water allocation. The three main irrigation areas (as far as total water use and total production) are the MIA, CIA and PRD3. These three irrigation areas use more than 75% of total irrigation water (see appendix G) and are located on a single river reach between Darlington Point and the Hay weir, adding more pressure to this river reach. This increases groundwater pumping, leading to a decline of groundwater levels and opens the opportunity for artificial recharge and use of this aquifer for water banking and storage. These results are consistent with findings by Khan et al. (2004a). The main crops using high proportions of water were rice, lucerne and wheat.

7.3 Comparison of sub-Scenarios
In order to maximise the outcomes of management options for water supply and demand it is preferable that model results fall in the top-right corner of the matrix shown in Figure 7-69. Figure 7-70 to Figure 7-74 below show the results of comparing the sub-Scenarios for each Scenario in turn. The detailed main model outputs from each Scenario are given in appendix H. These figures compare the final values of sub-Scenarios with water productivity and environmental outcomes. This analysis was used to select the best sub-Scenarios under each Scenario (see Table 7-41 for details) that were then compared to determine which ones represent the best-case options for final analysis. The main model outputs of these sub-Scenarios (best sub-Scenario only under each Scenario) compared all together on an annual average basis can be seen in the following four figures (Figure 7-75 to Figure 7-78).

Figure 7-70 shows the performance of Scenario 2 (changing crop mix with four sub-Scenarios) compared to the base case Scenario as threshold (point 0, 0). It can be seen that the mixed cropping sub-Scenario is in the top right segment, giving a positive environmental result that is 7% better than the base case. This means that the model predicts that this sub-Scenario can improve environmental flow above the status quo (in fact, providing environmental flows 2–5 months longer than the base case per year during dry years and low allocation periods). Also, the mixed cropping Scenario shows a
13% positive benefit in agricultural income compared to base case. This translates to an additional $12–26 million in gross margin (at base case prices and costs) with less water use by 80–100 GL (see appendix H for detailed analysis). The water productivity is $137/ML compared to the base case $116/ML. Obviously, there are implications for the marketability of production and other enterprise constraints. However, such positive results warrant further investigation into barriers to switching crops.

It can be seen that one other sub-Scenario, the summer variation, increases economic benefit (giving a 3% or $4–6 million improvement in agricultural income), but it reduces environmental performance. Clearly, such an outcome does not fit the definition of success for this research project. All other sub-Scenarios (winter and area reduction) under Scenario 2 fall in the top left segment with positive environmental performance but with a negative impact on agricultural income. From this analysis, the mixed cropping sub-Scenario is the best and recommended sub-Scenario as the best management option under Scenario 2 (changing crop mixes).

![Figure 7-70: Trade-off for the best variation under Scenario 2](image)

Figure 7-70 shows the trade-off for Scenario 3 (changing the crop mix with water banking under both infiltration and injection recharge with four changing crop mixes sub-Scenarios) compared to the base case Scenario (point 0, 0). Again, the mixed cropping sub-Scenario falls in the top right segment, with either system of water banking. This variation has a positive benefit on the environmental indicator of 8% with infiltration, and 10% with injection. This means it can increase environmental flow above the base case by providing environmental flows 3–7 months longer. Also, this option has
a positive economic benefit of 3% ($4–6 million) with injection and 9% ($10–15 million) with infiltration, compared to the base case. Overall, this means the use of water banking under a mixed cropping sub-Scenario may increase gross margin to farmers but still deliver water savings of 80 GL (see appendix H for detailed analysis).

Compared to Scenario 2, the winter and reduction sub-Scenarios (Figure 7-70) fall in the top left segment with improved environmental performance, but have a detrimental effect on agricultural income. However, the summer sub-Scenario with water banking (Scenario 3) is moved from the bottom right to the top left segment, giving 0.5% improvement in environmental performance with infiltration and 1% improvement with injection. Effect on agricultural income is negative under both recharge methods. Water banking can improve environmental performance under the summer sub-Scenario compared to the same Scenario without water banking (see Figure 7-70) but has only a 1% negative impact on agricultural income for infiltration water banking and 6% for injection water banking. From this analysis a mixed cropping sub-Scenario with water banking under infiltration and injection is the best and recommended sub-Scenario.

![Figure 7-71: Trade-off for the best variation under Scenario 3](image)

Figure 7-71 shows the trade-off for Scenario 4 (conjunctive water use by managing surface and groundwater as a single resource with two sub-Scenarios: reduced surface water by 10% and shifting dam release. These variations were compared to the base case Scenario (point 0, 0). Both sub-Scenarios fall in the top left segment. The surface water restriction sub-Scenario, which reduced surface water by 10%, improves environmental performance compared to the base case by almost 5% (1–2 months provide environmental flows per year more than the base case). It had a negative impact on
agricultural income by 3–6% ($5.6–11.5 million) compared to the base case Scenario. However, it gives better water productivity by $123/ML compared to the base case $116/ML. The shifting dam release sub-Scenario enhanced environmental performance by 22% compared to the base case (it provided environmental flows 2–6 months per year more than base case) and also by 17% when compared to the other sub-Scenario (reduced surface water by 10%). However, it had a negative impact on agricultural income of 1–3% ($1.5–5.6 million) when compared to the base case with water productivity $127/ML.

Based on these results, the second sub-Scenario (shifting dam release with conjunctive water use) could be an attractive alternative for improving seasonal and environmental flows; although caution is required as it reduces agricultural income by 1–3% ($1.5–5.6 million). Given the potentially significant positive impact on the environment, the relatively minor reduction in economic performance could be overcome by government or community intervention. Therefore, this option should be examined further. From this analysis, the shifting dam release sub-Scenario with conjunctive water use is the best and recommended sub-Scenario.

Figure 7-72: Trade-off for the best variation under Scenario 4

Figure 7-73 shows the trade-off of Scenario 5 (conjunctive water use by managing surface and groundwater as single source, with water banking under two artificial recharge methods to facilitate water trading, with two sub-Scenarios including reduced surface water by 10% and shifting dam release). As before these Scenarios are compared to the base case Scenario (point 0, 0). All four sub-Scenarios under both recharge
methods fall in the top left segment with a positive environmental impact and a negative effect on agricultural income. The Scenario of 10% reduced surface water increased environmental performance by 12% (with infiltration) and 13% (with injection) under both recharge methods when compared with the base case. They were able to provide environmental flows 2–4 months per year more than other Scenarios. However, this Scenario had a negative effect on agricultural income of 8% or $12 million with infiltration and 10% or $15 million with injection when compared to the base case. The shifting dam release sub-Scenario showed a better environmental performance by 16% for infiltration and 17% for injection. It provided environmental flows for 3–6 months per year longer than the base case and was also better than the reduced surface water sub-Scenarios. However, it had a negative impact on agricultural income of 4% or $6 million with infiltration and 13% or $19 million with injection. These differences in income under both sub-Scenarios can be attributed to the difference in the cost of pumping and recovery, which depends on groundwater depth, aquifer recharge methods and the operation cost.

![Trade-off for the best variation under Scenario 5](image)

These results indicate that allowing water trading through water banking reduced environmental performance by almost 5% compared to the same sub-Scenarios under Scenario 4 (see Figure 7-72). Another reason is that water banking using infiltration could lose water through evaporation, which in turn would reduce the environmental performance. However, under the injection recharge method, there are still losses through the channels, which could be minimized and become close to zero with
automated channel lining. The performance of the infiltration basin method is likely to be more cost effective than the injection recharge method providing that it is possible to implement it. From this analysis, the shifting dam release sub-Scenario under infiltration recharge with conjunctive water use and water trading was found to be the best and recommended sub-Scenario as best management option under Scenario 5.

Figure 7-74 shows the trade-off for Scenario 6 (all options/combined Scenarios) including all the best options from the crop mix, water banking, conjunctive water use, water trading and shifting dam flows Scenarios. These were analysed for two recharge sub-Scenarios (infiltration and injection) and compared to the base case Scenario. There is quite a significant difference between both sub-Scenarios. In the first sub-Scenario, all options under infiltration, falls in the top right segment with a positive impact on agricultural income and an improved environmental performance, while the second sub-Scenario, the all options under injection method, is in the top left with a positive environmental impact and a slightly negative effect on agricultural income. The all options under infiltration sub-Scenario improved environmental performance by 21% when compared to the base case. It is able to meet the environmental flow target 3 to 7 months more than the base case. It is also has a positive impact on agricultural income of 3–4% when compared to the base case, or $3–6 million.

The all options (scenario 6) under the injection sub-Scenario shows a 23% better environmental performance when compared to the base case. Also, this variation compares favourably to the first sub-Scenario (all options under infiltration), which reduced agricultural income by almost 2% or $2–3million compared to the base case.
These differences in income under both sub-Scenarios can be attributed to the difference in the cost of pumping and recovery, which depends on groundwater depth, the type of aquifer recharge methods and the operational cost. These results indicate that the performance of the infiltration basin method is likely to be cost effective better than injection recharge method. There are a number of limitations of this option that need to be considered in future studies. These include as soil profile, evaporation rate and losses, climatic zone, location of infiltration basins and infiltration rate. From this analysis the all option Scenario under infiltration sub-Scenario is the best sub-Scenario under Scenario 6 (crop mix, water banking, conjunctive water use, water trading and shifting dam flows).

7.3.1 Best Scenario analysis
From the above analysis, five management options (sub-Scenarios) were selected for further analysis to be compared together and with the base case. These include:

1. Scenario 2: mixed cropping under changing crop mixes
2. Scenario 3: mixed cropping with water banking under infiltration and injection recharge methods
3. Scenario 4: conjunctive water use with shifting dam release
4. Scenario 5: conjunctive water use with shifting dam release, water banking to allow water trading under infiltration and injection recharge
5. Scenario 6: all options: crop mix, water banking, and shifting dam release.

7.3.2 Water use analysis
A simple comparison of the sub-Scenarios highlights their relative performance. Figure 7-75 shows the average total water use for the best sub-Scenario (the above options) for each Scenario compared to the base case at a catchment level. It is clear that all sub-Scenarios used less water than the base case, except for Scenario 4 (conjunctive water use with shifting dam release). This Scenario used the same cropping system as the base case, but it used a different mix of surface and groundwater. Scenario 5 (conjunctive water use with allowing water trading with water banking) gave the second lowest average total water use under both recharge methods infiltration and injection (saving 290 GL and 293 GL respectively). It also used 60% more groundwater than the base case. The lowest total water use sub-Scenario was all options combined (Scenario 7) under both infiltration and injection recharge methods. While it had the highest groundwater use, this Scenario was able to save around 350 GL, which could be attributed to the different crop mix, conjunctive water use, allowing water trading with water banking, and shifting dam release.
Allowing water trading can result in new cropping patterns that in turn will change the crop biophysical demand based on water allocation and the climatic conditions for each river reach and irrigation area. Shifting dam release changes the timing and quantity of surface water availability. This in turn affects the time and quantity of groundwater demand and water use, and also the level of water trading. In reality, this Scenario could be difficult to implement given the enormous cooperation required from governments and water authorities. However, these results highlighted the great potential for this option to be effective, and the relatively minor impact on economic output.

Scenarios 5 and 6 show that water banking could facilitate the management of surface and groundwater as a single resource. In addition, the mixed cropping sub-Scenario under Scenarios 2 and 3 (with water banking) gave the same level of total water use (less than the base case Scenario by around 80 GL or 5–7% of total water use). This is attributed to the crop mix applied in these Scenarios, which was different from the crop mix in the base case. Not surprisingly, Scenario 5 (conjunctive water use with shifting dam release) showed the lowest groundwater use (see Figure 7-75). This is attributed to the effect of shifting dam release on the time and quantity of surface water available to meet crop demand which, in turn, influences the time and quantity of groundwater demand and use.

Figure 7-75: Average total water use, surface water use and ground water use

7.3.3 Gross margin analysis

Figure 7-76 shows the average gross margin for each of the best sub-Scenarios when compared to the base case (Scenario 1). It is very clear that the mixed cropping sub-Scenario under Scenario 2 gives the highest gross margin by 10–15% ($20–30m) compared to all other Scenarios and the base case. This can be attributed to the level of water use and, in turn, total water cost, and also to the crop production and market price.
of crops in the mixed cropping sub-Scenario. The second best sub-Scenario is the mixed cropping sub-Scenario under Scenario 3 (crop mix with water banking) with infiltration recharge method: 8% better than the base case. The lowest gross margin is Scenario 5 (conjunctive water use and allowing water trading and water banking) under both recharge methods infiltration and injection (–8% and –13% respectively). This is can be attributed to water banking establishment and operation costs. In Scenario 6 (all options: crop mix, conjunctive water use, water trading, water banking and shifting dam release) infiltration gives a better gross margin than the base case and Scenario 5 (conjunctive water use, water trading, water banking and shifting dam release) by 4% and 12% respectively. This can be attributed to the impact of improved crop mix management in recovering the loss in gross margin that resulted from the implementation of other management options in Scenario 5.

Figure 7-76: Average gross margin for each best variation under each Scenario compared with baseline Scenario

7.3.4 Water saving analysis

Figure 7-77 shows the average potential water saving for each of the best sub-Scenarios when compared to the base case. Potential water savings ranged from 70 GL to 350 GL per year (using the base case as a threshold 0 GL saving). This potential for water saving depends on the management option used and external conditions. Scenario 4 (conjunctive water use with shifting dam release) has the potential to generate savings of around 30 GL (about 70% of this water came from reduced groundwater use, see Figure 7-75) by managing surface water and groundwater as a single resource. Allowing water trading through water banking can facilitate water management and trading, leading to potential saving of 250—280 GL under infiltration and injection recharge methods.
However, adding crop mix option to the previous combination of management options in Scenario 5 leads to potential water saving of 340–355 GL. Crop mix (Scenario 2) by itself is able to save around 70—78 GL while crop mix with water banking (Scenario 3) is able to save around 78—83 GL under infiltration and injection recharge methods.

**Figure 7-77: Average of potential water saving for each best variation only compared with baseline Scenario**

### 7.3.5 Environmental impact analysis

Figure 7-78 depicts the average environmental benefit index percentage (how many months the system is able to satisfy environmental flow requirement at end of the system on top of the base case) (see Chapter 4, Section 4.3 for details), for each of the best sub-scenarios, compared to the base case Scenario as threshold. It is clear that improving environmental performance depends on the potential water saving resulting from each Scenario.

**Figure 7-78: Average environmental benefit percentage of each best variation only compared to the base line Scenario**
Scenario 4 (conjunctive water use with shifting dam release) improves the environmental outcome by 22% when compared to the base case. This is attributed to managing surface and groundwater as a single resource together with shifting dam release and was better able to provide water for the environment during demand times and to satisfy environmental water requirements. This Scenario also gives better results when compared to Scenario 5 (conjunctive water use with water trading through water banking and shifting dam release). This may be due to two factors: firstly, water trading, which can reduce the environmental benefits of conjunctive water use management with shifting dam release; secondly, water banking with infiltration and injection induces water losses through evaporation and channel losses. When adding a crop mix management option (Scenario 6) to the previous management options in Scenario 5, it was able to improve environmental benefits by 24% above the base case. To sum up, different demand management options are able to improve environmental performance from 5%-25% above the base case (3–8 months per year).

From the previous results it is clear that there are different environmental and economic trade-offs for each management option or scenario. Presentation of a sensitivity analysis of the best Scenario output to identify the critical parameters within the model and to demonstrate the level of uncertainty associated with the results is discussed in the next section.

7.4 Sensitivity and uncertainty analysis

The results of the six Scenarios have been discussed with respect to water productivity, economic and environmental outcomes. The five best sub-Scenarios were selected for further analysis. Due to the complexity of irrigation demand management and system analysis, uncertainty is one of the key factors that influence irrigation demand management.

Uncertainty has been extensively studied by many authors who have classified it in many different ways. However, a recent study by Refsgaard et al. (2007) classified uncertainty in terms of Source, Types and Nature. Refsgaard et al. (2007) reviewed 14 methods representing the most commonly applied tools (details can be seen in Refsgaard et al., 2005). The main conclusion of this study is that uncertainty should be considered from the beginning of the study and not at the end after calibration and validation of the model, particularly in integrated water resource management. In this study, achieving this is particularly challenging given the complexity of the system, the feedback loops throughout the system and the availability of data. These issues led to a decision to select
a deterministic model structure and use an analytical process to estimate the extent and effect of uncertainty.

Refsgaard et al. (2007) defined three main sources of uncertainty: context — at the initial stage of the study such as external economic, environmental, political, social and technological boundaries; inputs — such as external or internal data driving the model and model — the model structure, the technicalities of software or bugs, and model parameters values. In addition, they further classified nature into epistemic (such as inadequate knowledge and information) and stochastic (such as climatic variability). In further classification of uncertainty, the third dimension of uncertainty is statistical uncertainty, and recognised ignorance. Finally, an uncertainty matrix can be developed from these three main categories to form an overview of the various sources of uncertainty (Refsgaard et al., 2007).

Taking this uncertainty matrix into consideration, the uncertainties associated with this complex study (irrigation demand management) can be categorised as follows: (1) inherent uncertainties in economic, social, and environmental systems arising mainly from social and economic development such as changing crop area or the decision variable, irrigation technology and irrigation efficiency; (2) exterior uncertainties caused by the environmental factors beyond the users’ control, such as climatic changes (rainfall and evaporation), and market price; (3) uncertainties associated with raw data (such as flow measurements which showed about 33% error in flow measurements at downstream stations (Pratt Water, 2004); and (4) uncertainties arising from anthropogenic effects (Jamieson, 1996; Hamed and El-Beshry, 2004), as opposed to effects or processes that occur in the natural environment without human influence.

There are several reasons for incorporating uncertainty into irrigation demand management and water system analysis. First, water system planning involves long planning horizons (e.g. several decades). Secondly, accurate long-term projections are generally difficult to make. Thirdly, there are inaccuracies in data measurements and model parameters. Therefore, there is a need to incorporate uncertainty measurements and analysis into the system. For these kinds of uncertainties, system dynamics programming approaches offer a convenient framework for planning and decision making with sensitivity analysis processes. Besides imprecision, water and irrigation demand management is also inherently multiple objective in nature, mainly due to the nature of irrigation management. Farmers make joint water and land use decisions for economic purposes, based in part on water availability and reliability of supply. An understanding of the risks associated with better agricultural production and
environmental performance requires accounting for the uncertainty of climate, environmental policy, markets, water allocations, environmental flow requirements and intensive cropping systems.

To sum up, there are many uncertainties that can affect model outputs. Therefore sensitivity analysis is conducted to understand the relative importance of the parameters (model inputs) and to quantify their effect on model results. To understand the potential impact of uncertainty on NSM results, a sensitivity analysis was made by changing each of the model inputs of the base case only (tested as changing each input one at time) by ±10% (Refsgaard et al., 2007). This analysis is able to capture the uncertainty due to parameters and data uncertainty and not due to model structure. However, given that a system dynamics approach was selected to enable a highly flexible and non-prescriptive model structure, it was determined that this limitation was a reasonable and pragmatic decision designed to determine the most important variable to assess within the uncertainty testing. The main model inputs that were changed, based on the level of uncertainty for the base case Scenario (detailed discussion later below), are:

- **Water allocation**: Allocation rules (water and environmental); for this analysis surface water allocations were reduced or increased by 10%. The reduction in MDBCA and state water availability, especially in NSW, was based on rather tenuous assumptions. Allocation rules could be changed to attempt to maintain entitlement flows into the Murrumbidgee. This could imply a smaller irrigation allocation. Alternatively if an attempt was made to follow the intent of the National Water Initiative, to ensure that the environment does not bear the risk of reduced flows under climate change, the reduction in irrigation water allocation could be even greater.

- **Rainfall and evaporation rate**: Changes in rainfall and evaporation; for this analysis the same frequency of low and high rainfall events was assumed, affecting water availability and allocation. Also, the same assumption was made for evaporation.

- **Seepage rate and Channel losses rate**: Channel losses and seepage rate; for this analysis low and high losses from irrigation delivery channels were assumed. This is has a direct effect on water availability. A different low and high seepage rate assuming the same soil types along the river would result in reduced or increased surface water flow and groundwater in the connected system.

- **Crop area, Changes in main crops area**: for this analysis an increase or decrease in the main crop area would lead to changes in gross margin, crop water demand and water available for environment. Main crops area changed by ±10%.
• **Dam release**: for this analysis low and high dam release were introduced by plus of minus 10% which can affect river flow and water availability for irrigation.

• **Environmental legislation**: for this analysis an increase or decrease in the environmental flow requirement would lead to changes in irrigation allocation and agricultural revenue.

Figure 7-79 shows a summary of the sensitivity analysis results of the model for changes in selected model inputs by ±10%. For a better understanding, this figure assumes four levels of sensitivity to better understand the sensitivity level of each input on agricultural income and environmental performance, see Table 7-42.

<table>
<thead>
<tr>
<th>Sensitivity level</th>
<th>Environmental performance (+/-)</th>
<th>Agricultural income (+/-)</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0% to 2.5%</td>
<td>0% to 5%</td>
<td>seepage rate, channel losses, barley</td>
</tr>
<tr>
<td>Moderate</td>
<td>&gt;2.5% to 6%</td>
<td>&gt;5% to 10%</td>
<td>wheat, environmental legislation, evaporation rate, rainfall</td>
</tr>
<tr>
<td>High</td>
<td>&gt;6% to 10%</td>
<td>&gt;10% to 20%</td>
<td>environmental legislation, evaporation rate, rainfall, dam release, water allocation</td>
</tr>
<tr>
<td>very high</td>
<td>&gt; 10%</td>
<td>&gt; 20%</td>
<td>rice, vines +10%</td>
</tr>
</tbody>
</table>

It is clear that model is highly sensitive to the area planted to rice; it is outside the very high sensitivity square for environmental performance and agricultural income, while the model agricultural income results are more sensitive to area of vines than the area of rice because the total vine area is only a small proportion of the rice area. There is group of inputs that the model outputs is less sensitive to them, such as seepage rate, channel losses and barley area. The evaporation rate, environmental rule and rainfall located between moderate and high sensitivity levels with an average of 10% uncertainty. Reduced water allocation is categorised as a highly sensitive input to the model results with more than 10% uncertainty in agricultural income and less than 10% in environmental performance. Results demonstrate the effects of water availability and allocation, rainfall, evaporation rate, environmental legislation, and changing crop area (depend upon which crop) on economic and environmental performance.

The upshot of these uncertainties is that the outputs of the NSM model should be treated with considerable caution. It should be assumed that any of the model outputs is accompanied by a degree of uncertainty, both of greater and lesser impact, within which could be the most likely future outcomes. This study does not claim that these model
outputs represent the best results. Rather, they represent an estimate of the most likely and reasonable results of management options with an average of 15% uncertainty in economic performance and an average of 6% uncertainty in environmental performance. The use of this calculated level of uncertainty to compare the best management options (sub-Scenario) that resulted from the previous analysis are demonstrated in the next section.

7.5 Comparison of management options

Based on the previous section (section 7.2), five best case Scenarios were identified. Additionally, the sensitivity analysis has shown that a 10% level of uncertainty in the inputs (quite a modest level of uncertainty), leads to an average of 15% uncertainty in economic performance and an average of 6% uncertainty in environmental performance. Comparisons between management options will be made on the basis that this level of uncertainty is not an unreasonable minimum expectation. It should be noted that this level of uncertainty in the results does not represent the whole uncertainty associated with the model since neither measurement uncertainty nor model structure uncertainty have been considered. However, it is argued that both of these uncertainty sources are ubiquitous to all options and applied equally and would not alter the relativity. Therefore, it should be noted that actual uncertainty will likely be larger, not smaller, than these average bands, and they should thus be treated as a minimum level.

Figure 7-80 shows the trade-off between agricultural income and environmental performance for the best sub-Scenario for each Scenario compared to the base case within the uncertainty level (each box represent the level of uncertainty ±6% environmental performance and ±15% economic performance). It is obvious that there is a clear trade-off between improved seasonal flow, environmental flow and agricultural income depending on which option is used to manage demand. Results indicate that within the level of uncertainty, all the selected options show positive environmental performance; except for the mixed cropping sub-Scenario (Scenario 2) where there is potential for 0.25% negative environmental impact. Also, it is very clear there is an overlap between all these sub-Scenarios when uncertainty is taken into account. In other words, the same result could be achieved by different Scenarios with different levels of probability or chance to occur. From Figure 7-80, any point close to the boundary has the worst of best result to occur with lowest probability under uncertainty level.
Figure 7-79 Summary of sensitivity analysis
Figure 7-80 trade-off for the best variation under each Scenario
By using the base case as a threshold, the mixed cropping sub-Scenario (Scenario 2), gives very good results and has a positive effect for agricultural income per area and per ML (10–15% and 12–16% respectively) when compared to the base case. It also shows savings around 75–78 GL as an annual average (see appendix H for more details) which can be allocated to the environment, while the environmental index is improved by around 5–10% (3–6 months per year more than base case) over the base case Scenario. However, there is a potential for negative effects on environmental performance if the level of uncertainty is considered, plus a 1% potential negative impact on agricultural income of low probability.

The worst option is the shifting dam release sub-Scenario (Scenario 5—conjunctive water use with water banking and water trading under injection recharge method), it has a very positive environmental impact with potential water saving of about 290 GL (10% to 15% environmental improvement) while having the largest negative effect on agricultural income of 18%. This option also shows that the uncertainty circle lies in the negative economic impact region. However, the same option using the infiltration recharge method shows a potential positive impact on agricultural income with a low uncertainty level. This option could be attractive to water policy makers as it has a positive impact on water economic productivity or gross margin per megalitre of around 1% to 3%, however more feasibility study is required. This matches the water policy makers’ desire to maximize the return per unit water applied. All these Scenarios are in the second group (top left segment) and need more consideration and support from the government, water authority and farmers.

Water banking shows positive effects when it is combined with mixed cropping sub-Scenario (Scenario 3) under both infiltration and injection recharge methods. It was able to save around 75–80 GL on average per annum, with a positive impact on agricultural income of 4% to 10% under the infiltration recharge method and a 3–5% improvement in agricultural income under the injection method. However, when it is compared with Scenario 2 and considering the level of uncertainty, water banking still shows very positive environmental performance but has the potential for negative effects on agricultural income.

Conjunctive water use with a shifting dam release sub-Scenario (Scenario 4), shows very positive effects on the environmental performance of over 20%, and has around 3% negative impact on agricultural income. Considering the level of uncertainty, there is no possibility of negative environmental performance while there is greater probability of negative impact on agricultural income.
Crop mix is considered to be one of the best options. In Scenario 6 (combined option-crop mix, conjunctive water use, water trading and water banking with shifting dam release) altering the crop mix can improve the environmental outcome of Scenarios 4 and 5 with a potential for water saving of 330–350 GL. It also has a positive impact on environmental performance of more than 22% when compared to the base case. Without doubt, this option needs further research in order to be proved to be a viable possibility, particularly in terms of economic policies or industry assistance that might facilitate useful outcomes. In particular, changes in cropping require problems with market availability to be overcome (and potentially accompanying processing capability) as well as technical barriers in enterprises. Additionally, there may need to be changes in operations, management, behaviour and trade policies.

Finally, to understand further the implications of these findings, other output measures from the NSM model need to be considered. Table 7-43 shows the behaviour of the main components of the system for each of the five Scenarios. This shows that Scenario 6 (combined Scenario) has the highest potential for water saving (350 GL) and shows a 23% improvement in environmental river performance. However, there is either a positive or negative impact on agricultural income depending on which artificial recharge method chosen. Crop mix (mixed cropping sub-Scenario) Scenario 2 has a potential to save 75—78 GL of water and has a potential positive impact on agricultural income of $25–27 million. Introducing water banking to mixed cropping (Scenario 3 under both infiltration and injection methods), shows potential water savings of 78–82 GL with a $6 million to $17 million improvement in agricultural income under injection and infiltration recharge respectively. Conjunctive water use management with shifting dam release (Scenario 4) shows a very high potential improvement in environmental performance with over 29 GL water saving and a negative impact on agricultural income by 3% ($4–6 million). Scenario 5, which allows water trading through water banking and conjunctive water use, shows potential water savings with a loss of agricultural income. The combined Scenario (Scenario 6) shows the highest potential water saving. Overall, improving the river environmental performance using demand management options is mainly rely on the potential of water savings under each options. Therefore, environmental performance or seasonal flow should be considered as policy variable taking into account its potential impact on the system economic productivity.
Table 7-43 main components behaviour analysis for the best variations under each Scenario

<table>
<thead>
<tr>
<th>Economical Water analysis</th>
<th>Total Water use (GL)</th>
<th>Ground water use (GL)</th>
<th>Surface water use (GL)</th>
<th>Gross Margin $(m)/ha</th>
<th>Loss or Benefit % to Gross margin/ha</th>
<th>Loss or Benefit % to Gross margin/ML</th>
<th>Benefit % to Env-Index</th>
<th>Potential Water saving (GL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>base case (Scenario 1)</td>
<td>1876</td>
<td>190</td>
<td>1686</td>
<td>210</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>mixed cropping (Scenario 2)</td>
<td>1798</td>
<td>181</td>
<td>1617</td>
<td>237</td>
<td>13%</td>
<td>16%</td>
<td>7%</td>
<td>78</td>
</tr>
<tr>
<td>mixed cropping -- water banking;-inf (Scenario 3)</td>
<td>1798</td>
<td>181</td>
<td>1617</td>
<td>227</td>
<td>8%</td>
<td>11%</td>
<td>7%</td>
<td>78</td>
</tr>
<tr>
<td>mixed cropping -- water banking;inj (Scenario 4)</td>
<td>1798</td>
<td>181</td>
<td>1617</td>
<td>216</td>
<td>3%</td>
<td>6%</td>
<td>10%</td>
<td>80</td>
</tr>
<tr>
<td>SGTW-WB-shifting dam release (Scenario 4)</td>
<td>1876</td>
<td>163</td>
<td>1686</td>
<td>204</td>
<td>-3%</td>
<td>-3%</td>
<td>22%</td>
<td>29</td>
</tr>
<tr>
<td>SGTW-WB-shifting-inf (Scenario 5)</td>
<td>1586</td>
<td>311</td>
<td>1274</td>
<td>202</td>
<td>-4%</td>
<td>2%</td>
<td>20%</td>
<td>290</td>
</tr>
<tr>
<td>SGTW-WB-shifting-inj (Scenario 5)</td>
<td>1586</td>
<td>311</td>
<td>1274</td>
<td>183</td>
<td>-13%</td>
<td>-7%</td>
<td>20%</td>
<td>293</td>
</tr>
<tr>
<td>all options Scenario-inf (Scenario 6)</td>
<td>1519.56</td>
<td>340</td>
<td>1179.56</td>
<td>218</td>
<td>3.90%</td>
<td>13%</td>
<td>23%</td>
<td>356</td>
</tr>
<tr>
<td>all options Scenario-inj (Scenario 6)</td>
<td>1519.56</td>
<td>340</td>
<td>1179.56</td>
<td>206</td>
<td>-1.90%</td>
<td>4%</td>
<td>23%</td>
<td>356</td>
</tr>
</tbody>
</table>

7.6 Limitations of the study

This research takes a holistic view of the economic and environmental values provided by water. However, clearly a modelling study is an idealised representation of reality and this creates limitations in the nature and application of this research (Table 7-44 also see details in section 5.2 chapter 5). In particular, since considerable uncertainty exists around the magnitude and nature of variables and physical processes, modelling results need to be viewed as presenting the potential of various options given current best understanding. Therefore, further studies of key processes would be vital to test assumptions before actual implementation.

In terms of modelling assumptions and limitations, crop price was assumed and was based on the historical average price, and unreliable cost information of water banking was used, since most water banking studies have been done on a small scale rather than a catchment scale or irrigation area scale. Also, any artificial recharge water banking approach needs to consider both elastic and inelastic recovery behaviour of clay layers and related land subsidence issues, losses from infiltration basin and infiltration rate. This research did not take into consideration the cost involved in changing crop mix such as land preparation and irrigation schedules and the technology required. One of the main limitations of this research was that it did not consider the social aspect of water banking. It was assumed that water banking would be managed by the irrigation company or water...
service provider. However, introducing the concept of water banking to farmers is as critical as its actual design and operation.

Table 7-44 Model assumptions and limitations

<table>
<thead>
<tr>
<th>Model Assumptions</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop price</td>
<td>The model used the average historical price.</td>
</tr>
<tr>
<td>Water banking Cost</td>
<td>Cost has been used from available reports.</td>
</tr>
<tr>
<td>Water banking scale</td>
<td>The model assumed water banking on catchment scale; however, most of the literature used the approach for farm or small irrigation area.</td>
</tr>
<tr>
<td>Water banking with artificial recharge</td>
<td>Need to consider elastic and inelastic of clay layers. Land subsidence Infiltration rate</td>
</tr>
<tr>
<td>Water banking evaporation</td>
<td>The assumption is stored water in the aquifer underground with zero evaporation. Also, this is working with releasing water from the high dam early in the season without using on-farm storage.</td>
</tr>
<tr>
<td>Changing crop mix</td>
<td>Establishment cost is not involved in terms of land preparation and technology.</td>
</tr>
<tr>
<td>Social aspect of water banking</td>
<td>Is not involved, however, introducing the concept of water banking to the farmer is critical and important as its design and operation.</td>
</tr>
<tr>
<td>Water banking management</td>
<td>It was assumed that each irrigation area had its own water banking (or share of the aquifer) and could mange it for pumping, recharge and trade.</td>
</tr>
<tr>
<td>Seepage rate from the river</td>
<td>Assumes the same soil type and river channels are trapezoid with 6 mm/day seepage rate</td>
</tr>
<tr>
<td>Drought/climate change</td>
<td>Increasing/decreasing rainfall and evaporation by 10%</td>
</tr>
<tr>
<td>Water allocation</td>
<td>Using historical data</td>
</tr>
<tr>
<td>Water irrigation cost (surface water and groundwater)</td>
<td>Use average historical price</td>
</tr>
<tr>
<td>Water trading price</td>
<td>Use average historical price</td>
</tr>
<tr>
<td>Irrigation efficiency</td>
<td>Use between 70–85% according to irrigation area data</td>
</tr>
<tr>
<td>Irrigation area</td>
<td>Is the real entity and best response to any biophysical changes</td>
</tr>
<tr>
<td>Remedial action</td>
<td>Aggregated and disaggregated according to the level/scale of interest</td>
</tr>
<tr>
<td>Channel losses</td>
<td>Using 20% of diversion within irrigation system</td>
</tr>
<tr>
<td>Lack of data</td>
<td>Considering the complexity of the system</td>
</tr>
<tr>
<td>Evaporation rate</td>
<td>From literature 0.7</td>
</tr>
<tr>
<td>Yield</td>
<td>Using average historical, no yield penalty function used</td>
</tr>
<tr>
<td>Legal and political aspect</td>
<td>Not considered related to environmental issues/rules</td>
</tr>
<tr>
<td>Environmental flow rules</td>
<td>Only consider end of system flows to be the main factor or attribute to measure and represent environmental performance in the Murrumbidgee river since it is the only clear quantity or volume figured out in the environmental flow rules. This is limits the analysis of certain important ecological or environmental issues.</td>
</tr>
</tbody>
</table>

Another assumption is that the seepage rate is uniform along the Murrumbidgee River and that river channels are trapezoid. One more assumption is about increasing or decreasing a particular crop area, which is sometimes dictated by irrigation area rules or catchment rules, and farmers’ behaviour and skills. Finally, the error in flow measurements (one of the main input parameters in the NSM model) is reported to be approximately 33% in flow measurements at downstream stations (Pratt Water, 2004a).

Most of the uncertainty parameters such as (water allocation, rainfall, evaporation rate, seepage rate, loss rate of channel, dam release, crop area, environmental legislation) have been tested by the sensitivity analysis technique and represented in the calculated uncertainty level of the model outputs. This uncertainty analysis is able to capture the
uncertainty due to parameters and data uncertainty and not due to model structure. This study does not claim that these model outputs represent the most accurate results. Rather, they represent an estimate of the most likely and reasonable results of different recommended management options on a system level (complex system) with an average of 15% uncertainty in economic performance and an average of 6% uncertainty in environmental performance due to available information at the time of analysis. Thus, these model results may provide useful information about the sensitivities, the consequences and the possible responses of different management options under climate change. However, there may be circumstances, which, like the present drought, will prove immensely challenging for the management of irrigation water supply and environmental flows.

Finally, NSM is not a detailed catchment hydrology model, but NSM model is a tool developed in this study using a system dynamic approach which has the potential to help and aid stakeholders simulate and optimise the system and test different future scenarios by evaluating and analysing key decision variables. Also, the NSM model and scenarios helped to prove that what is good for one year or season, such as cropping pattern or demand management, is not necessarily appropriate for the next season or water year according to changes in water allocations and climatic change. Indeed, this model can be extended and applied to simulate various policy Scenarios.

7.7 Summary and conclusion

This section analyses the outcomes of the main Scenario options modelled in this study and the importance of the uncertainty associated with this modelling. The main aim of this chapter is to use the NSM model to evaluate the proposed alternatives/options that are defined by water availability and demand. The evaluation of each alternative is based on water productivity, and economic and environmental outcomes recommended by irrigation communities. The relevance of the model is illustrated by its application to the Murrumbidgee River catchment and its irrigation areas. The model was used to evaluate and identify the change in economic and environmental performance of various water management strategies that result in improved seasonality of flows and environmental flows. The economic and environmental performance was measured by a set of indicators that included the use of land and water resources, resources productivity, economic and environmental indicators.

The model was used to simulate the baseline condition and to evaluate five other alternatives of supply and demand management options, taking into account farmers’ crop decisions. These Scenarios were compared to the base case Scenario that reflects the
system status quo. Uncertainty of results was analysed by applying 10% level of uncertainty of inputs, which translates into ±6% environmental performance and ±15% economic performance.

This analysis indicates that there is a clear trade-off between agricultural income and environmental performance to improve the seasonality of flows. The best option for each Scenario that showed an improvement in environmental performance and water productivity are:

- mixed cropping under (Scenario 2)
- water banking with mixed cropping (Scenario 3) under infiltration and injection
- conjunctive water use with shifting dam release (Scenario 4)
- conjunctive water use with water banking and shifting dam release (Scenario 5)
- all options (Scenario 6) seems not to be possible since it needs changes in management, operations, behaviours and policies all at the same time.

Finally, these results indicate that the NSM model tool developed in this study using system dynamics can provide system overviews of water uses. It also can provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods to be predicted. It is not a detailed catchment hydrology model, but a tool that has the potential to help stakeholders simulate and optimise the system, by evaluating and analysing key decision variables. However, it is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly, further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.
Chapter 8: Conclusions and Further Research

The aim of this chapter is to present and discuss the general conclusions of this study. A discussion of future research needs will follow, considering this study’s outcomes and findings, which can provide a foundation for further study to improve river water productivity and environmental performance. Section 8.1 presents a brief background about the research statement, questions, objectives and methodology. In Section 8.2 the key nine messages and implications are discussed. Section 8.3 presents recommended future research directions.

8.1 Research statement, questions and methodology

The overarching goal of this research was to use a systems analysis approach to improve river water productivity and environmental performance in the Murrumbidgee River by testing different irrigation demand management strategies. Using the recommendations from irrigation communities; the main goal was to better understand the link between irrigation demands, conjunctive water use management and water banking with environmental outcomes; to measure and identify the change in economic outputs and environmental impacts of various allocations and demands from irrigation on modify river flows while enhancing the overall productivity of the irrigation system/areas. Under this goal, three research questions were formulated.

- How can the available knowledge be integrated within a model in an effective way to provide useful understanding of the current system in terms of economic outcomes and environmental performance (end of system flows) at catchment and irrigation area scale?
- What management options can be used to improve water productivity and river environmental performance (in terms of satisfying end of system flow)?
- What are the implications of these management options (different demand and supply managements including water banking)?

To answer these questions, three main objectives were identified as follows:

- Propose and develop an integrated (hydrological, economic and environmental) modelling framework that incorporates hydrological, economic and environmental constraints. The framework was designed to simulate and optimise irrigated area demand management by considering both demand side and different water resource options.
- Evaluate the current economic, environmental performance and seasonality of flows situation by employing the developed integrated framework on three levels
of analysis (crop/field, irrigation area and catchment) within the Murrumbidgee catchment.

- Evaluate and compare the proposed future demand management Scenarios (various allocation and demand) under different climatic conditions.

The methodology of this research was based on a system analysis (system dynamics approach), a type of feedback-based approach (Simonovic, 2000). System dynamics is based on system theory and a set of tools for representing complex systems and analysing their dynamic behaviour. This method generates the system behaviour from the system structure.

Through the application of a system dynamic approach, an integrated framework model (named the Network Simulation Model—NSM) was developed. It was used to identify and measure the effects of various irrigation allocations and demand Scenarios on economic and environmental indicators. NSM incorporates a wide range of complexities (hydrological, agronomic and environmental components) likely to be encountered in irrigation system management. The model uses VENSIM™ as a software development tool to configure the water balance network model. The outputs of the NSM model are different indicators such as total cost, total yield, total return, irrigation demand, gross margin, losses, surface water used and groundwater pumping.

The NSM model was linked to a Crop Decision Optimization Module (CDOM) and water trading module (WTM). Both modules simulate the effect of farmers’ crop decisions and water trading on several constraints such as irrigation technology, seasonal water availability, trading limits, channel capacity and soil types. Moreover, the NSM model has the potential to help stakeholders simulate and optimise the system by evaluating and analysing key decision variables. However, it is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly, further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.

Based on the recommendations from irrigation communities and stakeholders in the two workshops, several options were suggested and evaluated. The key criteria for success of the irrigation demand management options were demonstrable water savings and clear reduction in peak summer water demand. These options were basis and the main drivers for the six Scenarios and their sub-Scenarios, including the base case. The Scenarios investigated gained wide acceptance from irrigation community members in the attendance groups. However, attendance groups did not represent all stakeholders involved in the industry and the number of participants was quite few. Therefore, the
social aspect of this study was not seriously addressed, and was one of the limitations of this research. Another limitation was the uncertainties in the collected river data and water trading data. These limitations could be overcome by a pilot study approach or infrastructure such as flow measurement meters.

To sum up, the response to the first research question was the development of the NSM model, integrating hydrological, economic and environmental variables (chapter 5). The NSM model was calibrated and validated as discussed in chapter 6 and tested for the current case (base case Scenario 1) in chapter 7.

8.2 Key messages and findings

The purpose of the model was to help us understand how the current pattern of cropping system, irrigation demand, environmental demand, seasonal flow and water demand can be altered to jointly maximize the agricultural income and environmental benefits at catchment and irrigation area scales. The model was able to reflect different production conditions and demonstrated what would happen under the six Scenarios including the base case suggested by the irrigation community. The second research question was addressed using five options within the NSM model, analysed with an estimated minimum uncertainty boundary (±15% of agricultural income and ±6% environmental performance). The Scenarios considered were i) mixed cropping (Scenario 2), ii) water banking with mixed cropping (Scenario 3) under infiltration and injection, iii) conjunctive water use with a shift of dam release time (Scenario 4), iv) conjunctive water use with water banking and a shift of dam release time (Scenario 5) and v) all options (Scenario 6).

In summary, the main recommended management options based on their outcomes are in the following order:

1. Changing the crop mix to spread water demand
2. Introducing water banking combined with changing the crop mix under both recharge methods (infiltration and injection)
3. All options (combine all changes)
4. Conjunctive surface and groundwater use together with shifting the dam release time (single water source)
5. Water trading between surface and groundwater, facilitated by a water banking mechanism.

The analysis of these five options (see chapter seven for details) leads to eight key messages as follows:
**Message 1:** There are clear trade-offs between changing seasonal flows, improving environmental performance and agricultural income, depending on the type of management options and cropping mix. Also, seasonal flow is not decision policy variable.

Each options has its cost and benefit in terms of improve seasonal flow and agricultural income. Changing crop mixes scenario was able to secure around 75–78 GL on average annually for environmental purposes with a positive impact on agricultural income of about 11–15% (average $20 million/year). However, the water banking approach (underground storage and recovery water system, Scenario 3) uses infiltration and artificial injection recharge methods with changes to the crop mix (mixed cropping sub-Scenario), was able to improve agricultural income by 3% to 10% with potential water savings of about 76–80 GL for environmental purposes. Using conjunctive water use combined with shifted dam release was able to improve seasonal flow and the environmental index by about 19–22% (29 GL/year) while decreasing agricultural income by 2% to 4%. Also, conjunctive water use and water trading through water banking (between surface and ground water, Scenario 5) leads to an improved environmental performance and river flow by securing about 272–290 GL for environmental purposes while can reduce agricultural income under both recharge methods (infiltration and injection) by 4–13%. Therefore, seasonal flow or environmental performance should be considered as decision policy variable.

**Message 2:** Changing the crop mix to spread water demand was found to be the most cost-effective irrigation demand management option for changing the seasonality of flow and improve water productivity and environmental performance.

Changing crop mix (mixed cropping sub-Scenario, Scenario 2) was able to spread water demand throughout the season and the year. It can also decrease groundwater use by 3% to 6%. However, changing crop mixes needs to be encouraged with consideration of soil types, irrigation technology and climatic conditions. The crop mix should depend upon less water intensive crops and more winter crops. On the other hand, this option needs to be supported by market development for these alternatives and some incentives to offset structural adjustment costs. This cost could also be met by encouraging corporate farms that have more access to capital compared to the individual or traditional farm. These results indicate that water productivity and water use vary by irrigation area and cropping system. Moreover, agricultural productivity is affected by the amount of irrigation water used and consequently, farmers’ decisions vary by climatic zone of the catchment and level of water available.
**Message 3:** Using water banking combined with changing the crop mix under both recharge methods (infiltration and injection) is another attractive option. The infiltration method was able to improve seasonal and environmental flow without a negative impact on agricultural income. Also, complementary studies into the hydro-geological structure, economics and social impacts should be encouraged.

The water banking approach (underground storage and recovery water system, Scenario 3) uses infiltration and artificial injection recharge methods with changes to the crop mix (mixed cropping sub-Scenario), was able to improve agricultural income with potential water savings of about 76–80 GL for environmental purposes. Also, it can reduce groundwater use by about 4% to 8%. The infiltration recharge method is likely to be more cost effective than injection when it is feasible, depending on the river and aquifer connection system. The associated capital and operating cost of water banking could be recovered by a positive environmental impact which could lead to tourism and recreation activities with an annual value around $20–21 million (Khan et al., 2006). This option is also considered a feasible demand management option. While knowledge of groundwater systems and their connectivity with surface water systems has increased in recent years, many of these systems remain poorly understood. Where this is the case, as in this study area, it would be prudent for policy makers to be conservative and to consider additional aspects such as improved water quality, prevention of saltwater intrusion and nutrient reduction in agriculture for future research.

**Message 4:** All options (combine all changes) is considered another possible option to improve water productivity and environmental performance taking into account it needs changes in management, operations, behaviours and policies at the same time.

All options scenario combines all the changes (changing crop mix, conjunctive water use, water banking and shifting dam release). It has the potential to save 350 GL of water and has a positive impact on environmental performance and agricultural income. However, this option is difficult since it needs all water system stakeholders (government, irrigators and other users) to work together to achieve these outcomes. It requires ability and willingness to foster changes in management, operation, behaviour and demand.

**Message 5:** Conjunctive surface and groundwater use together with shifting the dam release time (single water source) is another feasible option to make additional surface water available for the
environment during the summer season. Also, complementary studies into the dam operation and simulation should be encouraged.

Conjunctive water use management is also considered one of the feasible options for irrigation communities to pursue. Using conjunctive water use combined with shifted dam release is able to improve seasonal flow and the environmental performance by about 19–22% (29 GL/year) while decreasing agricultural income by 2% to 4%. The economic effect of this alternative would depend on the linkage between groundwater and surface water systems. This result is consistent with Miller (1995). He claimed that in areas where the linkage is significant, and where agriculture is the primary user of groundwater (such as in this Murrumbidgee River case study), crop rotations, the crops grown and the crop management practices might need to be altered. Any of these actions could significantly impact farm and agricultural income.

**Message 6:** Water trading between surface and groundwater, facilitated by a water banking mechanism, is also able to change seasonal flows and secure water for the environment. This option should be promoted with a clear understanding of water quality and salinity issues.

Conjunctive water use and water trading through water banking (between surface and ground water, Scenario 5) leads to an improved environmental performance index and river flow by securing about 272–290 GL for environmental purposes. Caution should be taken as this option can reduce agricultural income under both recharge methods (infiltration and injection) by 4–13%. The infiltration case has a positive impact on return per megalitre of about 2–4% and leads to increasing groundwater use. This option requires a better understanding of the connectivity between all water systems. Increasing demand for irrigation water and reduced access to surface water could result in the activation of groundwater licenses that are currently unused or partially used. The activation of these licenses could lead to an increase in groundwater pumping. If this occurred in connected water systems such as the Murrumbidgee River, it could lead to a reduction in surface water flows. These results are consistent with Sinclair Knight Merz (2003) who estimated that a 550 GL per year increase in groundwater pumping to the fully allocated rate of 2450 GL per year across the Murray Darling Basin could lead to a 330 GL a year reduction in surface water flow. In general, about 60% of increased groundwater use originates indirectly from surface water or river flow.

**Message 7:** This study is considered one of the first attempts to discuss the water banking concept with farmers—a critical step in its design and operation.
Water banking refers to delivering water earlier than it is required and storing it as groundwater so it is available to be pumped when required. In other words, redirecting surface water to sub-surface water until it is required with zero evaporation losses. Water banking is a new management approach to managing water resources with ability to test and assess the impact of options for the allocation of limited water resources between agricultural production and the environment. Water banking is able to better manage biophysical demand, and enhance in-stream flows that are biologically and ecologically significant. Water bank could help in: i) adding flexibility in conjunctive water management, ii) enhancing in-stream flows that are biologically and ecologically significant, iii) reducing water use in over appropriate areas, iv) reducing impact of water pumping on to streams, and v) facilitating the legal transfer and market exchange of various types of surface, ground water and storage entitlement. Therefore, this study attempted to present and investigate the concept of water banking for farmers, as it is critical as its design and operation before put it into action.

**Message 8:** The integrated modelling framework NSM (hydrological-economic and environmental) can be considered adequate for estimating potential water savings, associated costs and levels of seasonal and environmental flow improvements under each promising demand and supply management option.

The developed integrated modelling framework (NSM) is a useful policy and planning tool for catchment managers, water supply irrigation authorities, policy and decisions makers and irrigators. It is not a detailed catchment hydrology model, but a tool that has the potential to help stakeholders simulate and optimise the system by evaluating and analysing key decision variables. It is not a program that only computes one optimised solution, but a tool that can simulate long term management scenario. Using the NSM model as described in chapter five facilitates the manipulation of the alternative scenarios developed in the chapter (four) to study the effects of various allocations and demand from irrigation on seasonal flow and environmental impact. Also, the analysis indicates that NSM model tool developed in this study using system dynamics can provide system overviews of water uses. It also can provide a basis for examining the impact of physical changes to the system and for interactions with agricultural productivity, economics and livelihoods to be predicted. However, it is limited to the assessment of options from a policy perspective and does not seek to undertake an engineering assessment of the feasibility of certain proposals. Certainly,
further work would be required to ensure the engineering feasibility of preferred policy initiatives or options.

Following the potential options and results for changing seasonal flow and improving environmental performance with positive economic outcomes, it is valuable to consider the following recommendations prior to implementation.

- Introduce water and land policy incentives especially for those who are going to invest in water saving technologies by improving system efficiency (farmers, water service providers). This will help remove the barriers to the adoption of new irrigation technologies which in turn will reduce local and regional environmental impacts and secure water for a better ecological future.

- The NSM model is one of many tools available; however, the use of these tools still remains largely in the research domain. This case study demonstrates the potential of the system dynamics approach as a decision support tool for improving stakeholder and decision-maker involvement and confidence in modelling. However, further investigation could be undertaken into incorporating further sources of uncertainty (e.g. measurement uncertainty) into a system dynamics model.

Given these results on water use and demand and their effect on agricultural income and the river environment, there is a need for further research to be undertaken into several issues. These are discussed in detail in the next section.

8.3 Future research

Future research in this area would need to achieve two diverse objectives, the practice and theory of developing improved seasonality of flows and total system harmonization by considering these findings as a foundation. The future research recommendations based on the previous findings are:

1. A complete environmental cost and benefit analysis to quantify all recommended options. In particular, the application of water banking needs a detailed study to determine the best technological applications and to quantify the additional environmental costs and benefits associated with different suggested level of management (irrigation area, catchment).

2. Potential for artificial recharge sites using infiltration basins should be explored in detail to provide knowledge of evaporation-free, secure underground water dams. A detailed investigation into the hydrogeology of the connections between the river, the shallow aquifer and the deep aquifer must be considered. Also, any
artificial recharge water banking approach needs to consider both elastic and inelastic recovery behaviour of clay layers and associated land subsidence issues.

3. Detailed social studies with irrigation communities about changing the seasonality of flows. Further social study is required to determine who will invest in water saving options such water banking, who will manage and operate and who will collect the benefits. How farmers are introduced to the concept of water banking is as critical as the actual design and operation.

4. Additional economic water analysis needs to determine the water value under each use, such as environment, agriculture and industry. Other uses must be properly estimated with clear water accounting. Also, there is a need to investigate leasing water to non-agricultural users. The associated economic and social impacts must be considered, as it may lead to a diminishing demand for agricultural labour. Leaving land without water as fallow fields may encourage invasive weed infestation which will need weed control and incur additional cost.

5. Adding the rain (as it is the global water resource) and soil moisture water (which exhaled during plant growth as vapour flow from the land to the atmosphere) dimensions to integrated catchment management and IWRM opens a broader perspective with new degrees of freedom for water use to support both direct and indirect water needs. These could be facilitated by using a water banking approach to capture and manage different water resources with zero evaporation losses. Hydrological consideration of capacity, automated flow measurements and canal infrastructure (which may be concrete-lined and consolidated), is also required.

Ultimately, the research outcomes address policy Scenario options and introduce the water banking concept to farmers and water policy makers to achieve:

- modified river flows in the Murrumbidgee River
- restored environmental flow
- enhanced water security.

These will need to integrate crop science, demand management and ecological sciences. Finally, the implications and conclusions of this study are of relevance not only to the Murrumbidgee River catchment, but to any catchment facing the challenges of increasing equity in the water allocation between different users, agricultural productivity and food security.
Chapter 9: References


COAG (Council of Australian Governments), (2004). Intergovernmental Agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory.


Hall, N., and D. Poulter, (1994). ABARE model of irrigation farming in the southern Murray-Darling Basin. [Canberra], ABARE.


Kumar, B. (2002). Review of groundwater Use and groundwater Level Behaviour in the Lower Murrumbidgee groundwater Management Area 002, Ground- water status report number 6, Department of Land and Water Conservation, Murrumbidgee Region, May


Powell D., (1964a). An efficient method for finding the minimum of a function of several variables without calculation derivatives’ The computer journal vol.7, 155-162.


...


Wegmann, F. and J. Everett, (2005). Minimum Travel Demand Model Calibration And Validation Guidelines For State Of Tennessee, The University of Tennessee, Center for Transportation Research, Knoxville, Tennessee


Winpenny, J. (1994), Managing water as an economic resource. London: Rout ledge for the Overseas Development Institute


http://www.toolkit.net.au/WRAM


Appendixes

Appendix A: Murrumbidgee Environmental and River Flow Objective

Rule 1: Dam transparency

Dams on rivers tend to change the quantity and timing of water flow and consequently involve changes to the river environment. ‘Dam transparency’ refers to ensuring that the amount of water flowing into the dam is equal to the amount flowing out during certain periods. In the case of the Murrumbidgee, the rule has been put in place to protect low flows in the river immediately downstream of the Burruijuck and Blowering dams. The rule states that flows into Burruijuck at rates of up to 615 ML/day are passed through the dam and into the river. If the inflow is greater than 615 ML/day, the rate of outflow is limited to 615 ML/day. For the Blowering Dam, all the inflows up to 560 ML/day are passed through, with an upper limit of 560 ML/day.

Rule 2: End of system flows

This flow rule is aimed at achieving a certain flow target at the end of a river system. The flow rule in the Murrumbidgee addressing end of system flows is that once irrigation allocations exceed 80 per cent, a target flow of 300 ML/day at Balranald will be maintained during the year. This is calculated as an average daily flow for each month. If the allocation is less than 80 per cent, 200 ML/day at Balranald will be maintained.

Rule 3: Dam translucency

‘Dam Translucency’ means that part of the inflow is allowed to flow through the dam. The translucency rule takes effect from the moment the dam begins to store water. In the Murrumbidgee, this rule has been put in place to ensure that, to some degree, natural flow and variability is restored downstream of Burruijuck Dam. Both daily inflows and outflows to and from the Dam are examined to determine how to increase the outflows to match and mimic the inflows. Currently, early winter storms are retained in storage and later storms fill the dam to overflowing. In other words, the dam builds up storage as quickly as possible and is maintained full for the irrigation season. There are some constraints on the volume of water that can be released under the translucency rule. While, Burruijuck Dam is below a threshold of 30 per cent, up to a maximum of 50 per cent of inflows will be released as translucent water when catchment conditions are ‘wet’ or ‘average’. While Burruijuck is between 30 and 50 per cent of its capacity there is a maximum of 50 per cent translucency when catchment conditions are ‘average’. There is no constraint to releases when conditions are dry.

Rule 4: Environmental contingency allowance / provisional storage

(a) Environmental contingency allowance
An ‘environmental contingency allowance’ is a quantity of water set aside for future use to meet specific environmental objectives. In the Murrumbidgee under current rules, 25 GL of high-security water is set aside each year in Burruinjuck to be used for environmental contingencies that may arise such as bird breeding, fish migration or blue-green algae outbreaks. Until allocations reach 60 per cent, this 25 GL is included as part of the resource available for allocation. Allocations are not permitted to exceed 60 per cent until this ‘borrowed’ water is returned and is again available for environmental use.

(b) Provisional storage

Provisional storage involves the retention of water in storages to meet future irrigation commitments. In the Murrumbidgee, the operation of provisional storage in Burruinjuck and Blowing dams helps the river environment by allowing the dams to spill earlier in the following year, providing more natural flows in the river. Provisional storage reserves also help the irrigation industry by reducing the impact in dry years. At the start of the water year, 25 GL is set aside as provisional storage. When the allocation exceeds 80 per cent, the amount of water stored increases linearly from 25 GL at 80 per cent allocation to 200 GL at 100 per cent allocation. The provisional storage only becomes available to the environment in the advent of dam spills.

Murrumbidgee River Flow Objectives

This section explains each of the river flow objectives (RFOs). The RFOs recommended for each part of the Murrumbidgee River and Lake George catchments are listed down. The river flow objective process links with water quality objectives, the work of the Healthy Rivers Commission, the Stressed Rivers program, the fixing of water access and use rights and, in the Murray Darling Basin, the interim cap on diversions. Other related reform areas are country town water services, and preparing flow and water quality management plans to achieve agreed objectives.


The flow of NSW streams is naturally very variable being characterized by extremes of flood and drought. The volume and velocity of flow at any time determines the amount of habitat and food available to the plants and animals of the rivers and wetlands, as well as influencing water quality. The variability of flows as evidenced by frequent changes in water levels and changes in the wetted area is critical for maintaining biological productivity, triggering fish and water bird breeding and the regeneration of wetland plants.

The river flow objectives seek to identify the characteristics of flow in each river which are necessary to maintain or restore river health and biodiversity. These objectives are forming the basis for action to protect or improve river flows. In the regulated rivers such as Murrumbidgee River where natural flow has been supplemented though releases from dams, the objectives will
guide the review of the interim environmental flow rules which are part of the Government’s water reform package.

The objectives have required the Department of Land and Water Conservation, which is responsible for managing users’ access to water and operating irrigation dams and weirs, together with other bodies responsible for dams and weirs, to change their management practices so that the flow volume and variability is improved to better accommodate the needs of river ecosystems. Given the link between river flow objectives and the access rights of irrigation and other water dependent industries, as well as to the ongoing productivity of the fish and shellfish industry and the quality of recreation and tourism, the determination of river flow objectives will need significant community involvement. In total, there are eleven inland interim river flow objectives, each objectives dealing with a critical element of natural river flows.

Flow patterns in many rivers have been significantly altered and will not return to natural flow regimes. The NSW Government is not attempting to restore completely natural flow patterns where the community significantly benefits from altered flow patterns. Communities and the Government have identified important areas where we can make adjustments to maintain or improve river health while continuing to benefit from water use.

Environmental flow rules for regulated rivers

As part of these water reforms, in 1998 the Government established environmental flow rules for the regulated parts of rivers (Gwydir, Namoi, Macquarie, Lachlan, Murrumbidgee and Hunter rivers) and the Barwon-Darling, after consideration by the RMCs. These rules will apply for five years and be reviewed annually by the committees.

The rules cover some interim RFOs and, therefore, the Government will not be recommending interim RFOs on regulated rivers until the end of the five years. It is important for the committees to use the RFO framework, when considering river flow management.

Protect pools in dry times: Protect natural water levels in pools of creeks and rivers and wetlands during periods of no flows

During dry times, some streams stop flowing and form pools. Pools and wetlands are refuges for aquatic plants and animals. Pumping water from these areas can make it more difficult for many species to recover after a drought.

Protect natural low flows

Water extraction and storage are high in dry times and impose long artificial droughts that increase the stress on aquatic plants and animals.

Protect important rises in water levels: Protect or restore a proportion of moderate flows ('freshes') and high flows
Rain causes peaks in river flows. This 'pulsing' of flows, including their duration, may trigger migration of animals and reproduction of plants and animals; provide over-bank flows to wetlands and floodplains; shape the river channel; and control water quality and nutrients. Water storage and extraction can alter or remove freshes, inhibiting these vital processes. The height, duration, season and frequency of higher flow events are all important.

**Maintain wetland and floodplain inundation:** *Maintain or restore the natural inundation patterns and distribution of floodwaters supporting natural wetland and floodplain ecosystems*

Floodplain and wetland ecosystems develop in response to flow patterns and the landscape between the river and wetlands or floodplains. Floodplain works can change the flooding patterns, which will lead to changes in habitat and vegetation. These changes can be expected to result in reduced or different species diversity and abundance, particularly reduced numbers of native fish, and water quality problems.

**Mimic natural drying in temporary waterways:** *Mimic the natural frequency, duration and seasonal nature of drying periods in naturally temporary waterways*

Continuous or seasonal water releases from water storages can mean streams and wetlands can sometimes be 'wetter' than natural. In streams and wetlands that naturally dry out, this can create problems in maintaining habitat, vegetation, nutrient cycling and signals for breeding. It can also lead to a high watertable and associated salinity problems. Natural wetting and drying cycles produce diversity of habitat and, therefore, high species diversity.

**Maintain natural flow variability:** *Maintain or mimic natural flow variability in all streams*

Australia's rainfall and river flows are naturally variable. The way we currently store and divert river water can reduce natural pulsing of water down rivers and maintain artificially high or stable river heights. Hydro-electric releases can vary unnaturally between day and night. In urban areas and other places where the ability of the land to absorb or detain rainfall is reduced, more water runs off rapidly, so water levels will rise higher. These changes often create problems with streambank stability, biodiversity and signals for breeding and migration.

**Maintain natural rates of change in water levels:** *Maintain rates of rise and fall of river heights within natural bounds*

Shutting off dam releases, or starting many pumps together, can drop river levels too quickly. If water levels fall too fast, water does not drain properly from riverbanks and they may collapse. Migration of aquatic animals may also be restricted by such sudden falls in river height.

**Manage groundwater for ecosystems:** *Maintain groundwater within natural levels and variability, critical to surface flows and ecosystems*
Some shallow groundwaters are directly linked to flows in streams and wetlands. They may provide base flows in rivers during dry periods and may be primary sources of water for wetland, floodplain and riparian vegetation. Seriously depleting groundwater in dry times may lead to unnatural recharge of groundwater from surface waters during the next flow.

**Minimise effects of weirs and other structures: Minimise the impact of instream structures**

Most instream structures (e.g. weirs) convert flowing water to still water, thus altering habitat and increasing the risk of algal blooms or other water quality problems. Barriers prevent passage of plant propagules (e.g. seeds) and animals.

**Minimise effects of dams on water quality: Minimise downstream water quality impacts of storage releases**

Many dams release water from the bottom of reservoirs where temperatures and dissolved oxygen are low and nutrient concentrations are high. These changed water quality conditions can affect the river downstream for hundreds of kilometres. For instance, many native fish will not breed in colder water.

**Make water available for unforeseen events: Ensure river flow management provides for contingencies**

River systems can sometimes be affected by unforeseen or irregular events—such as algal blooms or the start of bird-breeding seasons. As river flows are a major determinant of many of these processes, we can sometimes alleviate a water-quality or environmental problem by better managing river flows.
Appendix B: Catchment definitions

- The area drained by a stream, lake or other body of water. Frequently used to refer to areas which feed into dams. May also refer to areas served by a sewerage or storm water system. [www.sydneywater.com.au/](http://www.sydneywater.com.au/)


- The area of land feeding water to a drainage system of rivers, creeks etc. Continental shelf: The shallow area of sea that is around any continent. Usually extending to an average width of 70km, and becoming deeper towards the seaward edge, usually to about 130m. [www.amcs.org.au/periodic/glossary](http://www.amcs.org.au/periodic/glossary)

- The catching or collecting of water, especially rainfall. (2) A reservoir or other basin for catching water. (3) The water thus caught. (4) A watershed. [www.tpwd.state.tx.us/texaswater/rivers/](http://www.tpwd.state.tx.us/texaswater/rivers/)

- Describes the area of land which contributes runoff to a particular creek, river lake or ocean. [www.reefed.edu.au/](http://www.reefed.edu.au/)

- The area contributing flow to a point on a drainage system. [www.ciria.org/suds/glossary.htm](http://www.ciria.org/suds/glossary.htm)

- The physical or surface area from which rainfall flows into a river, lake or reservoir. [www.unep.or.jp/ietc/publications/](http://www.unep.or.jp/ietc/publications/)

- A land area determined by topographic features within which rainfall provides runoff to streams. [www.gtasa.asn.au/glossary/gloss_c.htm](http://www.gtasa.asn.au/glossary/gloss_c.htm)

- That area of land defined by the ridges of the terrain and where surface water flows towards a river or stream. [www.horizons.govt.nz/](http://www.horizons.govt.nz/)

- the surface of land that collects rain which then flows into a waterway [www.wrc.wa.gov.au/](http://www.wrc.wa.gov.au/)

- The resource area around an archaeological site which is within convenient walking distance. [www.californiaprehistory.com/glossary.html](http://www.californiaprehistory.com/glossary.html)

- An area of land defined by ridges and hills in which all water flows to a common point. [www.members.optushome.com.au/](http://www.members.optushome.com.au/)

- Formation where impervious rock underlies a zone of fractured rock or alluvium that serves as a reservoir for infiltrated water; a catchment can be a special type of aquifer. [www.adtdl.army.mil/](http://www.adtdl.army.mil/)
Appendix C: General Scenario Drivers

(a) Demand for agricultural products

Worldwide, the demand for agricultural products comes from demand for food to feed a growing population, evolving dietary preferences and demand for higher quality foods in high environmental standard. Most growing population will be in the developing countries. According to Pinstrup A. et al. 1999, the recent projections from the International Food Policy Research Institute (IFPRI) predict a globally a 40% increase in cereal consumption by humans and livestock. According to Dunlop, M et al (2002), this will help and activate cereal imports, mainly from the developed countries such as Australia to pacific countries. They have predicted, Australia is predicted to experience a 38% increase in cereal exports from 1995 to 2020, and remain a relatively small player, with about 10% of the market. In addition, Dunlop and Foran (2001) reported, most of Australian horticultural crops, including citrus, apples and vegetables, are traded internally, thus their demand growth is mainly depend on Australian population growth and demand.

These predictions represent diverse assumptions about increases in demand, productivity, area cultivated and trade for those crops. Moreover, these projections represent the rationale and drivers that could enforce or encourage farmers to choose from these crops in the future when they are planning their farm such as cereals and vegetables according to their future markets. This could be changing the constraints in the crop decision module.

(b) Water resources and Irrigation

Worldwide, the main concern is about rapidly increasing demand for water to feed the world's growing population. This demand is largely due to the dependence on irrigated cereal production for food (Seckler et al. 1998, van Hofwegen and Svendsen 2000). Although Australia does not have the same level of concern about water security to meet its food demand, the country still faces a number of significant water resource issues affecting both irrigated and dryland agriculture Dunlop M, et al 2002.

In many areas of Australia, including the Murrumbidgee, issues related to water allocation, the volume used and water infrastructure have led to environmental and economic problems. The current set of water allocation procedures, which are being revised, encourages the liberal use of water and restricts transfer of water to higher value uses such industry (Dunlop and Foran 2001). According to NLWRA (2001b), water extraction is either close to or above sustainable levels in 26% of surface water basins (mainly in the Murray-Darling Basin) and 30% of ground water management units. Moreover, water markets are currently expected to be the body who can revise water allocation. They can help and facilitate the movement of water to higher value crops within a local region. However, this could raise many environmental, social, and economic issues.

In addition, recently, the health of the ecosystems affected by water trading and water movement came to the people concern. Of course the issue is not only water extracted, but also the flow regimes and modifications to river channels and wetlands. Nowadays, particularly
attention paid of the land-water interface for river health, in particular riparian strips and the condition of vegetation upstream, and new “systems approaches” which are examining the linkages between different elements in catchments. These lead to introduce environmental flow, which has impacted water allocation to the irrigators by 4%-5%, Khan S. et al (2004a).

According to NLWRA 2001b, water use has increased dramatically over the last decade, total water use increased by 65% between 1984 and 1997, surface water use increased by 58% (mainly in NSW, Qld and Vic), groundwater use increased by 88% (mainly in WA, NSW and Qld), and water use for irrigation increased by 76%. These promote the use of water licences that have not previously been used. One of the main commitments of water researcher is developing irrigation system which can be able to handle drought conditions. Indeed, annual variations in allocations due to climate variability may leave some irrigators more exposed to risk due to the higher cost base of irrigated farming. These indicate the importance to study the impact of climatic condition on water availability.

One potential source of water savings is improved water distribution and irrigation infrastructure. It is reported by Khan S. et al (2004a) there is potential opportunity of saving water from Murrumbidgee system by 10%-15%. The volume of water losses varies considerably between irrigation areas depending on the age and type of infrastructure such as in CIA 45-60 GL/yr and MIA 104-125 GL/yr Khan S. (2006). Moreover, excessive leaking of water and nutrients past the root zone causes many land degradation problems in farming systems while Crop yields are frequently less than their potential based on available rainfall (Cornish and Murray 1989, van Rees 1996, Cornish et al. 1998, Coventry et al. 1998, Armstrong et al. 2001, Lodge et al. 2001, NLWRA 2001a).

According to NLWRA (2000b) estimated that 23% of water that is diverted is lost to evaporation or leakage before it reaches the end users (irrigators) on national level. Improvements to infrastructure include upgrading of irrigation systems, metering and monitoring of distribution systems, lining of irrigation channels, and using more pipelines instead of channels and streams to distribute irrigation water could achieve considerable amount of water saving. Such water saving volumes could be used to provide water for increased environmental flows or to provide increased irrigation allocations.

It is expected in the coming future there will be reduction in water use for lower value products as water prices increase, there will be increases in higher value production as water trading increases, and there will be increases in irrigation in some regions and decreases in others. The rate and extent of these changes will depend largely on the level of stimulation from governments and demand from the community.

(c) Land use

The availability of arable land, its productivity and land degradation all present significant constraints to future growth in agricultural production. According to Dunlop et al. 1999, only small areas of Australia have soils with very good physical characteristics for growing crops. Australian landscapes were developed and changed to farming system by European people.
These changes have frequently had negative impacts and led to various forms of land degradation. The most common degradation includes dryland salinity, rising water table (such the case in CIA some areas less than 2 m, CIA report 2003, 2004 and 2005), soil acidification, soil fertility decline, soil structural decline, soil erosion and irrigation salinity.

Land degradation has several impacts on farm such direct losses in crop and pasture yield, pollution of ground and surface water, adjustments to management, changes in crop or pasture choice, and abandoning land for agriculture. According to NLWRA 2001a, 2001b, 2001c, despite much research and experience on land degradation, there is considerable uncertainty about the impacts of land degradation on agriculture at the national scale. The Scenarios developed in this study include land use changes as a result of degradation could be represented by suggested decrease the total irrigation area by 10% and changing the cropping system with some incentive like discarded or decreased rice crop area as reported by CIA environment report, CIA is willing to give incentive$ 50000 maximum per farm to changing from flood irrigation to row cropping or pressurized irrigation ,establishing permanent plantings ,converting from annual crops/pastures to perennial crops/pastures ,costs associated with converting from cropping to grazing enterprise e.g. fences, yards, stock watering systems ,declassification of rice ground could be included by the landholder as part of the package ,purchase of seed and transportable infrastructure/capital (stock, portable pumps, trucks / machinery, etc.) are not eligible activities for this incentive.

(d) Intensification

Another aspect in agriculture is increasing intensity of production. This is defined as increases in inputs to a given system, eg increasing use of fertiliser, irrigation, stockfeed and machinery, and replacement of less intensive land uses by more intensive ones. Intensification is usually driven by the higher profits associated with increases in productivity and inputs. Dunlop et al. 1999 claimed the soils in most Australian cropping regions are relatively low in productivity and resilience, compared to the Darling Downs or European and North American cropping regions. However, some people argue that the increased profits of more intense production systems will allow many farmers to undertake soil amelioration, fencing of streams and other actions that are needed for environmental sustainability.

According to Poole 1998, Angus 2001, high grain prices, new rotations and other technology have led to increases in the frequency of cropping. This means shorter pasture phases in rotations, an increase in continuous cropping, and expansion of cropping such as new legume and oilseed crops, as well as winter cereals. Poole (1998) reported intensification can also have environmental benefits: eg, Lucerne increases soil fertility and reduces recharge in crop rotations as well as producing a valuable product. These show the importance of some crops such as Lucerne, wheat and oilseeds.

Moreover, intensive animal production is also increasing by focus on animal intensification, in the dairy industry; herds of 1000 cows fed on irrigated pasture are replacing the traditional 200 cow herds. Dunlop and Foran 2001 reported, with this change, dairying industry is moving from
the higher rainfall regions to irrigation and cropping areas. They claimed, the use of irrigated pasture for beef and sheep grazing is likely to fall significantly, as the price of irrigation water increases and trading allows water to move to higher value uses. These give the rationale for farmers or grazers to grow more pasture now and in the future.

(e) Technology

New technology and better use of technology have helped and facilitated increases in crops yield, improvements in quality and environmental benefits. According to H. A. and Chapman (2000), adoption of improved technology in Australia particularly in the grains industry helped achieve annual productivity increases of 3.6% over the last 20 years. Moreover, Dunlop M et al 2002, reported new technology has allowed crop diversification with more than 30 grain crops in production, including rapidly expanding areas of oilseed crops, and the establishment of cotton as an important rotation crop with cereals. These are helping crop mix change as many divers crops available o farmers to choose from.

Pool 1998, has claimed crop intensification in the low and medium rainfall (such as median and lower Murrumbidgee river reaches) has been facilitated by the new rotation and farming systems. The new technology such as genetic improvements and new crops and varieties, larger and more sophisticated machinery, more use of herbicides and pesticides, improved tillage systems, increased use of fertiliser especially nitrogen, and “cropping packages” , all of these help the farming system and could enforce farmer to choose oilseeds and grains crops to grow.

The future technologies and farming systems may overcome some issues such declining soil fertility, increasing saline and acidic soils, rising water tables, soil structural decline, erosion, droughts, floods, water logging, pests and pathogens, the off-site effects of exported water, nutrients and salt, and any emerging new opportunities and threats (Poole 1998). Dunlop M, et al 2002, claimed without continuing significant technological advances, Australian agriculture is very unlikely to be able to maintain the productivity increases necessary to ensure the economic sustainability of agricultural production in many regions.

Thus new technology could help to return some declined or retired farm to the irrigation system again in the future and in consequence increase the total irrigation area which should taken into account, this is tested in the Scenario by testing increase the total area by 10%.

(f) Biotechnology

According to Poole (1998), Conway and Toenniessen (1999), and Miflin (2000), biotechnology can deliver to agriculture in two main ways: the use of genetic markers to enhance conventional breeding, and in the production of transgenic organisms. These techniques can be used to improve yields, quality, pest increased tolerance to drought, low pH, salinity and herbicide resistance. In addition biotechnology can help in the optimisation of farming systems using the new crops. Dunlop M, et al (2002), claimed everywhere in the world including Australia, biotechnology gains much concern and investment, but no one can judge whether the gains for agriculture will be good or bad. While Miflin (2000), suggested success will depend on genomics and scientists if can actually develop new crop varieties. In conclusion, biotechnology
and new technology could be a good driver to foster farmer’s crop plan by produced new crop varieties able to resist drought, water shortage, saline water and some other soil condition, these open the opportunity for farmers to choose between different crops or recultivate some retired land according to soil degradation.

(g) Ecosystem services

Biodiversity has got much attention within scientific and wider communities as one of the most beneficiary to the system, (Binning et al. 2001) which is called ecosystem services. Dunlop M et al (2002) have defined the “ecosystem services” as the role that nature plays in supporting human activities, from providing clean air and water, through to assimilating wastes. Ecosystem services are also becoming more policy relevant, as natural resource management policy increasingly seeks whole-of-system solutions. Ecosystems are obviously very important for agriculture and for providing fresh water. The most likely consequence of understanding ecosystem services is that increased attention and recommended policy for greater environmental flows in rivers, better protection of native vegetation, better controls on the externalities of agriculture and other economic activity, and better use of natural predators and soil organisms in agriculture. These could be test by increase the environmental flow allocation and test its impact on irrigation sector.

(h) Grain crops and yields

According to Pingali (1999), the most important technological factors that help grain yield were the introduction of semi-dwarf, high-yielding, rust-resistant wheat varieties, an unrestricted global wheat research system, and investment in fertilisers, irrigation and transport infrastructure. In addition, Dunlop, M et al, (2002) claimed Australian wheat yields have improved in the last 100 years, with an average increase of about 13 kg/ha/yr but in the last 10-15 years, another rise in yield, averaging more than 30 kg/ha/yr has occurred. This could be attributed to increased use of nitrogen fertiliser (new technology) and rotations with canola (Poole 1998, Angus 2001).

A review by Clements et al. (1992) suggested genetic improvements for wheat have contributed between one third and one half to overall yield improvements, although the introduction of semi-dwarf varieties may have contributed more than this. Nevertheless, Godden and Brennan (1988), and Hamblin and Kyneur (1993) argue that farmers regularly make other agronomic changes at the same time as introducing new crop varieties, making it very difficult to accurately identify the reason of yield increase according to introduce new varieties.

Although the average wheat yield in Australia about 2 t/ha but in many areas are less than could be expectable depend on available rainfall (French and Shultz 1984, Cornish and Murray 1989, NLWRA 2001a). This could be attributed to poor adoption of new technology and management and declining soil fertility (Hamblin and Kyneur 1993, Cornish et al. 1998). In summary, this highlight wheat crop as one of the crops gains much improvement which could encourage farmers to decide to grow. This could be tested by increase the wheat area in winter Scenario.
(i) Information and Precision agriculture

Collecting and analysing spatial data as a new technique at paddock scale is helping in crop management with potential for higher yields and better environmental outcomes. Moreover, such technology can linked with geographic information systems and remote sensing to provide and offer detailed within-paddock crop management. This will overcome some problem such as seeding rates, fertiliser and soil conditioner application and spraying, and strategic retirement of economically unproductive or environmentally unsuitable patches of land. This technology is relatively new plus laser guiding is also used to allow more precise machinery operations, with considerable savings in soil disturbance, fuel and chemicals (Poole 1998). These technologies improve the efficiency of the farmer system and could be tested by increase the efficiency by 10% or 20% percent.

Moreover, information and communication technology has brought vast new capacity to many aspects of land and water management. Precision agriculture is one good example. Another example is the use of climate analysis and long term weather forecasts to help manage drought and risk. Other example, J.langford under CRC evater projects, the research taken to test and develop irrigation sensors for more precision irrigation. In general, farming system management tools allow better monitoring of performance and planning of farm operations which can lead to better outcomes.

Increasing adoption of the new technology and using information available with new monitoring and information technology in irrigation can provide increased water use efficiency through more precise timing and volume of water application at the crop scale (Hutchinson and Stirzaker 2000), through to water delivery at the regional scale and to achieving better environmental outcomes. Again, this could be tested into the Scenario by increase the water use efficiency level by 10% or more optimistic by 20%.

(j) Oil consumption

Oil is the only cheap source of energy in Australia and evidence suggests that supplies will begin to be constrained over the coming decades (Magoon 2000, Powell, G. 2001, Akehurst 2002). A large increase in the price of oil, before the widespread adoption of alternative fuel technologies would have significant impacts on the cost of agricultural operations. Dunlop M, et al (2002), reported the agricultural sectors with a high energy dependency, due to high use of irrigation, fertiliser or machinery, will be more affected than lower intensity sectors. According to Foran and Crane 2000, Australia has significant potential to produce biofuels as other source of energy from sugar, oilseed crops and biomass crops. If this is the case in the nearest future, these could enforce or open new market price of oilseeds crops and in consequence farmers could start to grow these crops intensity more than other low value crops. These could be tested by increase the area of oilseeds crops by 20% as one constraint in the crop decision module.

(k) Social issues

In any Scenarios tested under the study, stockholders are the main driving component. Not the number of stockholders, but the decisions they make. These decisions are the consequence of
numerous physical and economic factors, many of them have been discussed above, and also social issues and aspirations. Three main social issues are the aging farming population, a migration of young adults (especially women) to urban areas where more opportunities are available, and the amalgamation of farms. The impact of these changes on regional communities will depend on the extent to which the regions experience economic growth in non-agricultural sectors, indeed off-farm income is an important part in total farm income. According to Barr (2000), and NLWRA (2002), levels of education, rates of adoption of new management practices, and the tendency of different groups to leave and enter farming are also likely to be significant drivers of change in agriculture. The aspirations and lifestyle choices in the cities as well as in rural areas will directly affect decisions about future land and water use and it might end by more retired farms, which is tested by decreased total farm area by 10%.

(l) Regional and Research development

According to Sefton (2001), many regions in Australian are facing significant pressures such as a growing rural-urban divide, declining services, declining economic importance of agriculture, growing issues of natural resource management, increased responsibility for delivering on state and federal natural resource policy, an aging workforce and movement of young people, especially women, to the cities. One of the indicators of rural decline, a decreasing number of farms, may actually signal an opportunity in regional Australia. The amalgamation of small family farms into larger agribusinesses may be a key to sustainability and more viable agriculture economic development which might increase or decrease the irrigation area. These issues are tested within the Scenario by assuming increase or decrease the total area by 10%.

Globally there is a marked increase in privately funded R&D in the agricultural sector by industry not only the government. One of the most important funded research, systems thinking and analyses that integrate across traditional disciplines and scales are becoming popular areas of research that are promising to deliver substantially better natural resource management and regional development.

(m) Climate change

Inter-annual climate variability is a significant feature of agricultural, water policy and planning in Australia. Global climate change is likely to have some significant effects on both water resources and agricultural productivity. Potential sources of the impacts include changed rainfall patterns (average rainfall, the intensity of rainfall events, seasonality of rainfall), plant water use (CO2 concentration, potential evaporation) and catchment yields of surface water (evapotranspiration in the catchments). In turn, these could affect the amount of water available for irrigation, domestic industrial uses and environmental flows, crop and pasture growth. Although climatic changes research is more developed but still allied with high level of uncertainty, which should be taken into account in the Scenario development process.

Climate change is expected to have significant impacts on the hydrological cycle at both a global and regional scale. This will in turn, affect the availability of, and demand for, water resources and the way the resources are most effectively managed. According to Beare.S and
A. Heaney (2002), A number of future emission Scenarios have been developed to explore the links between global warming and economic development, population growth and technological progress. According to IPCC, (2000) global warming Scenarios, the Atmospheric Research Division of Australia’s Commonwealth Scientific and Industrial Research Organization (CSIRO) has run global and regional climate models to develop long term projections for a variety of climatic variables such as precipitation, temperature and potential evaporation for Australia regions particularly Murray Darling Basin, Beare,S and A. Heaney (2002). They have concluded the projected declines for rainfall in 2050 and 2100 are 5% and 5-10% respectively. In addition to rainfall or precipitation, climate change has an impact on other parameters such evaporation, it is predicted evaporation future projection is likely to increase by 10-20% overall the MDB basin.

Climate change will also affect agriculture indirectly through any attempts to reduce greenhouse gas emission. The major contributors for emission are land clearing and animal production. This study does not explore the impacts of climate change. However, the Scenarios developed will be used as a basis for quantifying some climate change impacts. These issues could be recovered by altered water allocations. While it is very hard to quantify how the climate will change and what the impacts will be, but there is need for agricultural and water use institutions to be flexible enough to be able to overcome these issues of water availability and demand. These uncertainty is tested in this study by examine dry and wet conditions impact on irrigation demand and seasonal flow. For dry conditions assuming evaporation will increase by 10 percentages and rainfall will be decrease by 10 percentages for extreme dry. While for wet conditions, assume the rainfall increase by 10% with decreasing evaporation by 10% for extreme wet conditions.
## Appendix D: Water Monthly Flow Data ML

<table>
<thead>
<tr>
<th>Months</th>
<th>BURRINJUCK STORAGE - 410131 monthly</th>
<th>M/BIDGEE D/S B/JUCK 410008 monthly outflow</th>
<th>BLOWERING STORAGE 410102 monthly</th>
<th>TUMUT @ ODDYS BDGE 410073 monthly outflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul-93</td>
<td>30,147,449</td>
<td>212,221</td>
<td>37,484,882</td>
<td>128,593</td>
</tr>
<tr>
<td>Aug-93</td>
<td>30,382,855</td>
<td>164,842</td>
<td>41,654,188</td>
<td>130,047</td>
</tr>
<tr>
<td>Sep-93</td>
<td>30,157,776</td>
<td>323,992</td>
<td>41,866,012</td>
<td>156,405</td>
</tr>
<tr>
<td>Oct-93</td>
<td>31,406,807</td>
<td>253,389</td>
<td>45,690,460</td>
<td>158,508</td>
</tr>
<tr>
<td>Nov-93</td>
<td>30,540,720</td>
<td>100,687</td>
<td>43,323,915</td>
<td>207,925</td>
</tr>
<tr>
<td>Dec-93</td>
<td>30,794,160</td>
<td>67,303</td>
<td>42,821,872</td>
<td>162,725</td>
</tr>
<tr>
<td>Jan-94</td>
<td>28,277,263</td>
<td>206,859</td>
<td>40,225,304</td>
<td>241,874</td>
</tr>
<tr>
<td>Feb-94</td>
<td>19,860,251</td>
<td>178,646</td>
<td>32,830,570</td>
<td>208,921</td>
</tr>
<tr>
<td>Mar-94</td>
<td>20,071,293</td>
<td>28,140</td>
<td>33,471,450</td>
<td>238,021</td>
</tr>
<tr>
<td>Apr-94</td>
<td>20,187,649</td>
<td>13,354</td>
<td>30,911,627</td>
<td>177,506</td>
</tr>
<tr>
<td>May-94</td>
<td>21,598,988</td>
<td>17,526</td>
<td>31,884,389</td>
<td>155,110</td>
</tr>
<tr>
<td>Jun-94</td>
<td>20,935,615</td>
<td>22,176</td>
<td>32,490,291</td>
<td>63,292</td>
</tr>
<tr>
<td>Jul-94</td>
<td>21,971,951</td>
<td>21,399</td>
<td>38,988,031</td>
<td>67,825</td>
</tr>
<tr>
<td>Aug-94</td>
<td>22,203,505</td>
<td>18,482</td>
<td>42,653,184</td>
<td>140,489</td>
</tr>
<tr>
<td>Sep-94</td>
<td>21,845,907</td>
<td>10,859</td>
<td>41,433,154</td>
<td>226,433</td>
</tr>
<tr>
<td>Nov-94</td>
<td>18,853,302</td>
<td>71,203</td>
<td>34,694,609</td>
<td>237,497</td>
</tr>
<tr>
<td>Dec-94</td>
<td>16,453,153</td>
<td>194,518</td>
<td>32,590,115</td>
<td>272,715</td>
</tr>
<tr>
<td>Jan-95</td>
<td>13,603,744</td>
<td>121,726</td>
<td>26,996,468</td>
<td>245,158</td>
</tr>
<tr>
<td>Feb-95</td>
<td>16,471,308</td>
<td>62,032</td>
<td>20,178,986</td>
<td>236,723</td>
</tr>
<tr>
<td>Mar-95</td>
<td>16,373,772</td>
<td>50,727</td>
<td>17,272,979</td>
<td>240,026</td>
</tr>
<tr>
<td>Apr-95</td>
<td>15,248,976</td>
<td>10,622</td>
<td>14,128,132</td>
<td>106,323</td>
</tr>
<tr>
<td>May-95</td>
<td>17,108,453</td>
<td>14,339</td>
<td>16,410,116</td>
<td>15,661</td>
</tr>
<tr>
<td>Jun-95</td>
<td>19,605,987</td>
<td>10,829</td>
<td>22,195,992</td>
<td>5,086</td>
</tr>
<tr>
<td>Jul-95</td>
<td>25,841,899</td>
<td>83,762</td>
<td>30,904,478</td>
<td>4,995</td>
</tr>
<tr>
<td>Aug-95</td>
<td>30,457,752</td>
<td>61,662</td>
<td>38,609,599</td>
<td>4,766</td>
</tr>
<tr>
<td>Sep-95</td>
<td>30,314,471</td>
<td>81,661</td>
<td>42,153,116</td>
<td>62,142</td>
</tr>
<tr>
<td>Oct-95</td>
<td>30,454,611</td>
<td>173,693</td>
<td>43,863,408</td>
<td>157,237</td>
</tr>
<tr>
<td>Nov-95</td>
<td>30,113,969</td>
<td>40,196</td>
<td>43,020,605</td>
<td>150,377</td>
</tr>
<tr>
<td>Dec-95</td>
<td>31,636,090</td>
<td>269,145</td>
<td>44,952,598</td>
<td>192,414</td>
</tr>
<tr>
<td>Jan-96</td>
<td>30,290,465</td>
<td>103,028</td>
<td>40,927,979</td>
<td>236,397</td>
</tr>
<tr>
<td>Feb-96</td>
<td>26,083,279</td>
<td>108,231</td>
<td>33,074,421</td>
<td>239,659</td>
</tr>
<tr>
<td>Mar-96</td>
<td>26,958,107</td>
<td>11,734</td>
<td>31,625,058</td>
<td>156,952</td>
</tr>
<tr>
<td>Apr-96</td>
<td>26,070,967</td>
<td>22,329</td>
<td>29,836,293</td>
<td>101,908</td>
</tr>
<tr>
<td>May-96</td>
<td>27,386,405</td>
<td>14,639</td>
<td>31,659,735</td>
<td>64,837</td>
</tr>
<tr>
<td>Jun-96</td>
<td>27,100,905</td>
<td>14,660</td>
<td>33,058,451</td>
<td>58,118</td>
</tr>
<tr>
<td>Jul-96</td>
<td>30,060,137</td>
<td>86,648</td>
<td>38,422,507</td>
<td>18,812</td>
</tr>
<tr>
<td>Aug-96</td>
<td>31,155,268</td>
<td>246,906</td>
<td>45,284,818</td>
<td>137,833</td>
</tr>
<tr>
<td>Sep-96</td>
<td>30,273,637</td>
<td>156,710</td>
<td>43,676,669</td>
<td>173,055</td>
</tr>
<tr>
<td>Oct-96</td>
<td>31,520,950</td>
<td>358,516</td>
<td>49,820,884</td>
<td>170,371</td>
</tr>
<tr>
<td>Nov-96</td>
<td>30,054,338</td>
<td>82,830</td>
<td>47,385,396</td>
<td>232,192</td>
</tr>
<tr>
<td>Dec-96</td>
<td>29,455,140</td>
<td>169,139</td>
<td>45,856,174</td>
<td>255,296</td>
</tr>
<tr>
<td>Jan-97</td>
<td>23,101,847</td>
<td>257,113</td>
<td>39,928,830</td>
<td>265,603</td>
</tr>
<tr>
<td>Feb-97</td>
<td>15,673,279</td>
<td>138,720</td>
<td>31,786,376</td>
<td>246,877</td>
</tr>
<tr>
<td>Mar-97</td>
<td>15,068,217</td>
<td>24,305</td>
<td>31,249,598</td>
<td>238,642</td>
</tr>
<tr>
<td>Apr-97</td>
<td>14,427,263</td>
<td>9,700</td>
<td>26,633,107</td>
<td>171,286</td>
</tr>
<tr>
<td>May-97</td>
<td>14,865,690</td>
<td>9,282</td>
<td>26,005,882</td>
<td>66,069</td>
</tr>
<tr>
<td>Jun-97</td>
<td>14,723,348</td>
<td>6,734</td>
<td>27,684,432</td>
<td>17,145</td>
</tr>
<tr>
<td>Jul-97</td>
<td>20,686,285</td>
<td>8,131</td>
<td>33,445,250</td>
<td>40,583</td>
</tr>
<tr>
<td>-------</td>
<td>---------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
</tbody>
</table>
### Appendix E: River Reach Width and Wet perimeter

<table>
<thead>
<tr>
<th>months</th>
<th>reach 1 width</th>
<th>reach 2 width</th>
<th>reach 3 width</th>
<th>reach 4 width</th>
<th>reach 5 width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jul-93</td>
<td>66.69</td>
<td>65.72</td>
<td>64.125</td>
<td>74.4234</td>
<td>70.29895</td>
</tr>
<tr>
<td>Aug-93</td>
<td>66.8</td>
<td>65.65</td>
<td>67.8</td>
<td>78.245</td>
<td>75.23325</td>
</tr>
<tr>
<td>Sep-93</td>
<td>76.89</td>
<td>76.89</td>
<td>72.93</td>
<td>79.9148</td>
<td>78.53035</td>
</tr>
<tr>
<td>Oct-93</td>
<td>79.58</td>
<td>76.035</td>
<td>70.495</td>
<td>77.1414</td>
<td>81.0009</td>
</tr>
<tr>
<td>Nov-93</td>
<td>65.92</td>
<td>65.35</td>
<td>63.29</td>
<td>70.23475</td>
<td>72.43895</td>
</tr>
<tr>
<td>Dec-93</td>
<td>62.55</td>
<td>60.82</td>
<td>56.895</td>
<td>62.2073</td>
<td>59.301</td>
</tr>
<tr>
<td>Jan-94</td>
<td>65.16</td>
<td>63.11</td>
<td>57.41</td>
<td>60.095</td>
<td>49.0522</td>
</tr>
<tr>
<td>Feb-94</td>
<td>65.16</td>
<td>63.48</td>
<td>59.355</td>
<td>60.506</td>
<td>51.4934</td>
</tr>
<tr>
<td>Mar-94</td>
<td>62.55</td>
<td>61.43</td>
<td>58.88</td>
<td>60.3608</td>
<td>55.658</td>
</tr>
<tr>
<td>Apr-94</td>
<td>59.09</td>
<td>58.27</td>
<td>56.1</td>
<td>58.615</td>
<td>53.3814</td>
</tr>
<tr>
<td>May-94</td>
<td>58.9</td>
<td>57.75</td>
<td>55.17</td>
<td>58.114</td>
<td>48.899</td>
</tr>
<tr>
<td>Jun-94</td>
<td>56.91</td>
<td>56.91</td>
<td>56.365</td>
<td>58.754</td>
<td>49.8648</td>
</tr>
<tr>
<td>Jul-94</td>
<td>55.82</td>
<td>55.27</td>
<td>54.11</td>
<td>56.791</td>
<td>49.9096</td>
</tr>
<tr>
<td>Aug-94</td>
<td>59.09</td>
<td>57.455</td>
<td>52.975</td>
<td>54.294</td>
<td>45.5219</td>
</tr>
<tr>
<td>Sep-94</td>
<td>60.31</td>
<td>58.335</td>
<td>53.96</td>
<td>54.20905</td>
<td>40.9977</td>
</tr>
<tr>
<td>Oct-94</td>
<td>64.78</td>
<td>62.21</td>
<td>56.47</td>
<td>55.07905</td>
<td>43.308</td>
</tr>
<tr>
<td>Nov-94</td>
<td>62.55</td>
<td>60.55</td>
<td>56.025</td>
<td>55.20335</td>
<td>45.22565</td>
</tr>
<tr>
<td>Dec-94</td>
<td>65.54</td>
<td>63.27</td>
<td>57.615</td>
<td>56.748</td>
<td>45.44695</td>
</tr>
<tr>
<td>Jan-95</td>
<td>64.78</td>
<td>62.92</td>
<td>58.43</td>
<td>58.3566</td>
<td>44.8659</td>
</tr>
<tr>
<td>Feb-95</td>
<td>61.8</td>
<td>60.175</td>
<td>56.16</td>
<td>56.938</td>
<td>42.60195</td>
</tr>
<tr>
<td>Mar-95</td>
<td>61.8</td>
<td>59.9</td>
<td>54.76</td>
<td>55.013</td>
<td>40.6341</td>
</tr>
<tr>
<td>Apr-95</td>
<td>56.36</td>
<td>55.065</td>
<td>51.785</td>
<td>54.553</td>
<td>42.1527</td>
</tr>
<tr>
<td>May-95</td>
<td>56.91</td>
<td>56.655</td>
<td>55.8</td>
<td>58.452</td>
<td>44.3356</td>
</tr>
<tr>
<td>Jun-95</td>
<td>58</td>
<td>58.275</td>
<td>58.175</td>
<td>60.947</td>
<td>48.3492</td>
</tr>
<tr>
<td>Jul-95</td>
<td>68.97</td>
<td>68.4</td>
<td>66.565</td>
<td>64.697</td>
<td>56.0066</td>
</tr>
<tr>
<td>Aug-95</td>
<td>61.8</td>
<td>63.1</td>
<td>64.25</td>
<td>62.475</td>
<td>61.3173</td>
</tr>
<tr>
<td>Sep-95</td>
<td>59.64</td>
<td>58.545</td>
<td>55.605</td>
<td>55.74555</td>
<td>56.8342</td>
</tr>
<tr>
<td>Oct-95</td>
<td>64.4</td>
<td>63.1</td>
<td>59.375</td>
<td>58.512</td>
<td>52.7544</td>
</tr>
<tr>
<td>Nov-95</td>
<td>61.06</td>
<td>60.075</td>
<td>57.455</td>
<td>59.13</td>
<td>48.4564</td>
</tr>
<tr>
<td>Dec-95</td>
<td>67.07</td>
<td>65.925</td>
<td>62.165</td>
<td>60.599</td>
<td>45.23795</td>
</tr>
<tr>
<td>Jan-96</td>
<td>64.78</td>
<td>63.29</td>
<td>59</td>
<td>58.125</td>
<td>43.9691</td>
</tr>
<tr>
<td>Feb-96</td>
<td>64.02</td>
<td>61.83</td>
<td>56.925</td>
<td>56.35</td>
<td>42.7379</td>
</tr>
<tr>
<td>Mar-96</td>
<td>59.09</td>
<td>58.27</td>
<td>56.025</td>
<td>56.525</td>
<td>43.1973</td>
</tr>
<tr>
<td>Apr-96</td>
<td>56.91</td>
<td>57.315</td>
<td>53.96</td>
<td>53.94975</td>
<td>43.7287</td>
</tr>
<tr>
<td>May-96</td>
<td>55.82</td>
<td>55.025</td>
<td>52.965</td>
<td>54.70765</td>
<td>43.7366</td>
</tr>
<tr>
<td>Jun-96</td>
<td>55.27</td>
<td>55.27</td>
<td>54.785</td>
<td>56.375</td>
<td>43.66685</td>
</tr>
<tr>
<td>Jul-96</td>
<td>61.8</td>
<td>60.445</td>
<td>58.255</td>
<td>57.951</td>
<td>48.236</td>
</tr>
<tr>
<td>Aug-96</td>
<td>70.1</td>
<td>73.495</td>
<td>73.145</td>
<td>63.957</td>
<td>56.1562</td>
</tr>
<tr>
<td>Sep-96</td>
<td>65.92</td>
<td>65.73</td>
<td>64.08</td>
<td>60.939</td>
<td>60.52495</td>
</tr>
<tr>
<td>Oct-96</td>
<td>76.89</td>
<td>73.12</td>
<td>67.825</td>
<td>62.795</td>
<td>60.9242</td>
</tr>
<tr>
<td>Nov-96</td>
<td>64.4</td>
<td>63.475</td>
<td>59.975</td>
<td>58.357</td>
<td>54.10505</td>
</tr>
<tr>
<td>Dec-96</td>
<td>65.92</td>
<td>63.86</td>
<td>58.45</td>
<td>57.579</td>
<td>45.86155</td>
</tr>
<tr>
<td>Jan-97</td>
<td>66.69</td>
<td>65.355</td>
<td>59.93</td>
<td>57.953</td>
<td>45.3818</td>
</tr>
<tr>
<td>Feb-97</td>
<td>64.4</td>
<td>62.73</td>
<td>58.43</td>
<td>57.937</td>
<td>47.2552</td>
</tr>
<tr>
<td>Mar-97</td>
<td>61.8</td>
<td>60.445</td>
<td>56.91</td>
<td>57.018</td>
<td>49.11715</td>
</tr>
<tr>
<td>Apr-97</td>
<td>58</td>
<td>56.91</td>
<td>54.785</td>
<td>56.124</td>
<td>47.3685</td>
</tr>
<tr>
<td>May-97</td>
<td>55.27</td>
<td>54.995</td>
<td>52.935</td>
<td>54.808</td>
<td>45.0609</td>
</tr>
<tr>
<td>Jun-97</td>
<td>52.99</td>
<td>53.375</td>
<td>53.23</td>
<td>55.579</td>
<td>46.4381</td>
</tr>
<tr>
<td>Jul-97</td>
<td>53.76</td>
<td>52.66</td>
<td>51.48</td>
<td>55.325</td>
<td>47.74</td>
</tr>
<tr>
<td>Aug-97</td>
<td>55.82</td>
<td>55.82</td>
<td>54.785</td>
<td>56.908</td>
<td>46.7724</td>
</tr>
<tr>
<td>-------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Months</td>
<td>Reach 1</td>
<td>Reach 2</td>
<td>reach 3</td>
<td>Reach 4</td>
<td>Reach 5</td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Jul-93</td>
<td>67.2</td>
<td>67.2</td>
<td>65.5</td>
<td>75.8</td>
<td>72.9</td>
</tr>
<tr>
<td>Aug-93</td>
<td>67.3</td>
<td>69.5</td>
<td>68.7</td>
<td>80</td>
<td>78.4</td>
</tr>
<tr>
<td>Sep-93</td>
<td>79.1</td>
<td>79.1</td>
<td>74.7</td>
<td>82.5</td>
<td>81</td>
</tr>
<tr>
<td>Oct-93</td>
<td>81.8</td>
<td>78.6</td>
<td>72.6</td>
<td>79.9</td>
<td>83.6</td>
</tr>
<tr>
<td>Nov-93</td>
<td>67.4</td>
<td>66.8</td>
<td>64.5</td>
<td>72.5</td>
<td>74.6</td>
</tr>
<tr>
<td>Dec-93</td>
<td>63.7</td>
<td>61.8</td>
<td>59.9</td>
<td>63.1</td>
<td>60.3</td>
</tr>
<tr>
<td>Jan-94</td>
<td>66.6</td>
<td>64.1</td>
<td>58.4</td>
<td>61</td>
<td>49.5</td>
</tr>
<tr>
<td>Feb-94</td>
<td>66.6</td>
<td>64.8</td>
<td>60.5</td>
<td>61.6</td>
<td>52</td>
</tr>
<tr>
<td>Mar-94</td>
<td>63.7</td>
<td>62.6</td>
<td>59.8</td>
<td>61.5</td>
<td>56.3</td>
</tr>
<tr>
<td>Apr-94</td>
<td>60.1</td>
<td>59.2</td>
<td>57</td>
<td>59.6</td>
<td>54</td>
</tr>
<tr>
<td>May-94</td>
<td>59.7</td>
<td>58.6</td>
<td>55.9</td>
<td>59</td>
<td>49.5</td>
</tr>
<tr>
<td>Jun-94</td>
<td>57.8</td>
<td>57.8</td>
<td>57.2</td>
<td>59.7</td>
<td>50.4</td>
</tr>
<tr>
<td>Jul-94</td>
<td>56.6</td>
<td>56</td>
<td>54.8</td>
<td>57.5</td>
<td>50.5</td>
</tr>
<tr>
<td>Aug-94</td>
<td>60.1</td>
<td>58.3</td>
<td>53.6</td>
<td>55</td>
<td>46.4</td>
</tr>
<tr>
<td>Sep-94</td>
<td>61.4</td>
<td>59.2</td>
<td>54.7</td>
<td>54.9</td>
<td>41.5</td>
</tr>
<tr>
<td>Oct-94</td>
<td>66.1</td>
<td>63.5</td>
<td>57.5</td>
<td>55.8</td>
<td>44.1</td>
</tr>
<tr>
<td>Nov-94</td>
<td>63.7</td>
<td>61.6</td>
<td>56.9</td>
<td>56</td>
<td>46.3</td>
</tr>
<tr>
<td>Dec-94</td>
<td>67</td>
<td>64.5</td>
<td>58.7</td>
<td>57.5</td>
<td>46.4</td>
</tr>
<tr>
<td>Jan-95</td>
<td>66.1</td>
<td>64</td>
<td>59.2</td>
<td>59.3</td>
<td>45.7</td>
</tr>
<tr>
<td>Feb-95</td>
<td>62.9</td>
<td>61.1</td>
<td>56.9</td>
<td>57.8</td>
<td>43.4</td>
</tr>
<tr>
<td>Mar-95</td>
<td>62.9</td>
<td>60.9</td>
<td>55.5</td>
<td>55.9</td>
<td>41</td>
</tr>
<tr>
<td>Apr-95</td>
<td>57.2</td>
<td>55.9</td>
<td>52.7</td>
<td>55.1</td>
<td>43.1</td>
</tr>
<tr>
<td>May-95</td>
<td>57.8</td>
<td>57.5</td>
<td>56.6</td>
<td>59.3</td>
<td>45.5</td>
</tr>
<tr>
<td>Jun-95</td>
<td>58.9</td>
<td>59.1</td>
<td>59</td>
<td>62</td>
<td>48.7</td>
</tr>
<tr>
<td>Jul-95</td>
<td>70.9</td>
<td>70.2</td>
<td>68</td>
<td>65.9</td>
<td>56.9</td>
</tr>
<tr>
<td>Aug-95</td>
<td>62.9</td>
<td>64.1</td>
<td>65.3</td>
<td>63.9</td>
<td>62</td>
</tr>
<tr>
<td>Sep-95</td>
<td>60.7</td>
<td>59.4</td>
<td>56.4</td>
<td>56.4</td>
<td>57.6</td>
</tr>
<tr>
<td>Oct-95</td>
<td>65.7</td>
<td>64.1</td>
<td>60.4</td>
<td>59.5</td>
<td>53.4</td>
</tr>
<tr>
<td>Nov-95</td>
<td>62.2</td>
<td>61</td>
<td>58.3</td>
<td>60.2</td>
<td>48.9</td>
</tr>
<tr>
<td>Dec-95</td>
<td>68.7</td>
<td>67.4</td>
<td>63.4</td>
<td>61.6</td>
<td>45.8</td>
</tr>
<tr>
<td>Jan-96</td>
<td>66.1</td>
<td>64.5</td>
<td>60</td>
<td>59</td>
<td>44.3</td>
</tr>
<tr>
<td>Feb-96</td>
<td>65.3</td>
<td>62.9</td>
<td>57.9</td>
<td>57.2</td>
<td>43.1</td>
</tr>
<tr>
<td>Mar-96</td>
<td>60.1</td>
<td>59.1</td>
<td>57.1</td>
<td>57.4</td>
<td>44.1</td>
</tr>
<tr>
<td>Apr-96</td>
<td>57.8</td>
<td>58.1</td>
<td>54.6</td>
<td>54.7</td>
<td>44.5</td>
</tr>
<tr>
<td>May-96</td>
<td>56.6</td>
<td>55.8</td>
<td>53.6</td>
<td>55.4</td>
<td>44.9</td>
</tr>
<tr>
<td>Jun-96</td>
<td>56</td>
<td>56</td>
<td>55.4</td>
<td>57.2</td>
<td>44.2</td>
</tr>
<tr>
<td>Jul-96</td>
<td>62.9</td>
<td>61.6</td>
<td>59.1</td>
<td>58.6</td>
<td>48.9</td>
</tr>
<tr>
<td>Aug-96</td>
<td>72.2</td>
<td>75</td>
<td>74.7</td>
<td>65.2</td>
<td>56.9</td>
</tr>
<tr>
<td>Sep-96</td>
<td>67.4</td>
<td>67.1</td>
<td>65.3</td>
<td>61.8</td>
<td>61.6</td>
</tr>
<tr>
<td>Oct-96</td>
<td>79.1</td>
<td>74.9</td>
<td>69.6</td>
<td>63.9</td>
<td>61.9</td>
</tr>
<tr>
<td>Nov-96</td>
<td>65.7</td>
<td>64.6</td>
<td>60.9</td>
<td>59.1</td>
<td>54.8</td>
</tr>
<tr>
<td>Dec-96</td>
<td>67.4</td>
<td>64.8</td>
<td>59.3</td>
<td>58.5</td>
<td>46.5</td>
</tr>
<tr>
<td>Jan-97</td>
<td>68.3</td>
<td>66.8</td>
<td>61</td>
<td>58.7</td>
<td>46.1</td>
</tr>
<tr>
<td>Feb-97</td>
<td>65.7</td>
<td>63.9</td>
<td>59.3</td>
<td>58.6</td>
<td>47.9</td>
</tr>
<tr>
<td>Mar-97</td>
<td>62.9</td>
<td>61.5</td>
<td>57.8</td>
<td>58</td>
<td>49.7</td>
</tr>
<tr>
<td>Apr-97</td>
<td>58.9</td>
<td>57.8</td>
<td>55.4</td>
<td>57</td>
<td>47.8</td>
</tr>
<tr>
<td>May-97</td>
<td>56</td>
<td>55.7</td>
<td>53.4</td>
<td>55.5</td>
<td>45.5</td>
</tr>
<tr>
<td>Jun-97</td>
<td>53.6</td>
<td>54.1</td>
<td>54.1</td>
<td>56.2</td>
<td>46.9</td>
</tr>
<tr>
<td>Jul-97</td>
<td>54.4</td>
<td>53.1</td>
<td>52</td>
<td>56.1</td>
<td>48.1</td>
</tr>
<tr>
<td>Aug-97</td>
<td>56.6</td>
<td>56.6</td>
<td>55.5</td>
<td>57.8</td>
<td>47.2</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Month</td>
<td>Mar-02</td>
<td>Apr-02</td>
<td>May-02</td>
<td>Jun-02</td>
<td>Jul-02</td>
</tr>
<tr>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td></td>
<td>62.9</td>
<td>57.5</td>
<td>56</td>
<td>54.4</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>61</td>
<td>57.5</td>
<td>55.4</td>
<td>54</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>56.9</td>
<td>56.3</td>
<td>53</td>
<td>54</td>
<td>55.8</td>
</tr>
<tr>
<td></td>
<td>57</td>
<td>56.8</td>
<td>53.2</td>
<td>54</td>
<td>57.6</td>
</tr>
<tr>
<td></td>
<td>46.9</td>
<td>44.6</td>
<td>45.4</td>
<td>44.1</td>
<td>48.1</td>
</tr>
</tbody>
</table>
Appendix F: What’s Best! 7.0 Status Report

This is example of the What'sBest! 7.0 Status Report of crop decision optimization module CDOM

What'sBest! 7.0 Status Report  12/7/05 5:19 PM
Solver memory allocated: 16384
Linear solver: Primal simplex
Model Type: LINEAR
The smallest and largest coefficients in the model were:

0.80000000E-04   437960.00

The smallest coefficient occurred in constraint cell: '2003-2004'!D35
on optimizable cell: '2003-2004'!B35
The largest coefficient occurred in constraint cell: '2000-2001'!F38
on optimizable cell: <RHS>

CLASSIFICATION STATISTICS  Current /  Maximum

-----------------------------------------
Numeric                      3705 /  10000
Adjustable                   60 /  300
Constraints                  85 /  150
Integers                     0 /  30
Optimizable                  360
Nonlinear                    0 /  30
Coefficients                 750

Tries: 57  Infeasibility: 0  Objective: 52.84451
Solution Status: GLOBALLY OPTIMAL.
Solution Time:  0 Hours  0 Minutes  1 Seconds
End of report.
Appendix G: Base Case and Crop mix Scenarios Results

Table A Base case Scenario 10 years average

<table>
<thead>
<tr>
<th>Average 10 years</th>
<th>water use %</th>
<th>gross margin $/ML</th>
<th>gross margin $ (m)/ha</th>
<th>Irr WUI</th>
<th>Yield %</th>
<th>water use/ha</th>
<th>gross production % tonnes/ha</th>
<th>total area %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA</td>
<td>21.4</td>
<td>92.5</td>
<td>55.9</td>
<td>1.7</td>
<td>17.7</td>
<td>8.7</td>
<td>15.4%</td>
<td>19.1</td>
</tr>
<tr>
<td>MIA</td>
<td>40.6</td>
<td>88.4</td>
<td>101.4</td>
<td>1.8</td>
<td>35.9</td>
<td>8.8</td>
<td>16.5%</td>
<td>35.7</td>
</tr>
<tr>
<td>PRD 1</td>
<td>2.8</td>
<td>53.5</td>
<td>4.2</td>
<td>2.8</td>
<td>3.7</td>
<td>6.0</td>
<td>17.0%</td>
<td>3.6</td>
</tr>
<tr>
<td>PRD 2</td>
<td>11.8</td>
<td>50.2</td>
<td>16.9</td>
<td>2.6</td>
<td>14.7</td>
<td>6.4</td>
<td>16.9%</td>
<td>14.3</td>
</tr>
<tr>
<td>PRD 3</td>
<td>18.3</td>
<td>46.4</td>
<td>24.3</td>
<td>2.5</td>
<td>21.9</td>
<td>6.7</td>
<td>17.0%</td>
<td>21.4</td>
</tr>
<tr>
<td>PRD 4</td>
<td>5.1</td>
<td>47.4</td>
<td>7.0</td>
<td>2.4</td>
<td>6.1</td>
<td>6.8</td>
<td>16.8%</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table B Base case Scenario crop water use and gross margin percentage of total catchment

<table>
<thead>
<tr>
<th>Irrigation area</th>
<th>CIA</th>
<th>MIA</th>
<th>PRD 1</th>
<th>PRD2</th>
<th>PRD3</th>
<th>PRD4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water use %</td>
<td>gross margin %</td>
<td>Water use %</td>
<td>gross margin %</td>
<td>Water use %</td>
<td>gross margin %</td>
</tr>
<tr>
<td>Maize</td>
<td>0.03</td>
<td>0.05</td>
<td>0.90</td>
<td>1.50</td>
<td>0.10</td>
<td>0.19</td>
</tr>
<tr>
<td>Rice</td>
<td>11.87</td>
<td>18.92</td>
<td>18.84</td>
<td>31.83</td>
<td>0.45</td>
<td>0.83</td>
</tr>
<tr>
<td>wheat</td>
<td>2.47</td>
<td>2.14</td>
<td>5.17</td>
<td>5.18</td>
<td>0.27</td>
<td>0.36</td>
</tr>
<tr>
<td>Canola</td>
<td>1.02</td>
<td>1.22</td>
<td>0.33</td>
<td>0.45</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>Lucerne</td>
<td>1.24</td>
<td>0.12</td>
<td>3.33</td>
<td>0.34</td>
<td>0.59</td>
<td>0.07</td>
</tr>
<tr>
<td>soybean</td>
<td>1.49</td>
<td>1.11</td>
<td>1.12</td>
<td>0.87</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Winter pasture</td>
<td>1.63</td>
<td>1.09</td>
<td>2.70</td>
<td>2.06</td>
<td>0.05</td>
<td>0.06</td>
</tr>
<tr>
<td>Barley</td>
<td>0.74</td>
<td>0.42</td>
<td>0.52</td>
<td>0.34</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fallow</td>
<td>0.12</td>
<td>0.23</td>
<td>0.26</td>
<td>0.20</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>sum past</td>
<td>0.00</td>
<td>0.00</td>
<td>1.56</td>
<td>0.27</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Others</td>
<td>0.61</td>
<td>0.13</td>
<td>2.85</td>
<td>0.42</td>
<td>1.12</td>
<td>0.26</td>
</tr>
<tr>
<td>Annual</td>
<td>0.23</td>
<td>1.12</td>
<td>3.01</td>
<td>4.69</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Table C Crop mix Scenario 10 years average

<table>
<thead>
<tr>
<th>Average 10 years</th>
<th>water use %</th>
<th>gross margin $/ML</th>
<th>gross margin $/m²/ha</th>
<th>Irr WUI</th>
<th>Yield %</th>
<th>water use/ha</th>
<th>gross production % tonnes/ha</th>
<th>total area %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA</td>
<td>21.1%</td>
<td>101.20</td>
<td>58.7</td>
<td>1.98</td>
<td>19.9%</td>
<td>8.3</td>
<td>18.0%</td>
<td>19.2%</td>
</tr>
<tr>
<td>MIA</td>
<td>39.9%</td>
<td>98.61</td>
<td>108.2</td>
<td>1.96</td>
<td>38.3%</td>
<td>8.6</td>
<td>18.5%</td>
<td>35.3%</td>
</tr>
<tr>
<td>PRD 1</td>
<td>2.8%</td>
<td>73.66</td>
<td>5.6</td>
<td>2.49</td>
<td>3.3%</td>
<td>5.9</td>
<td>15.9%</td>
<td>3.6%</td>
</tr>
<tr>
<td>PRD 2</td>
<td>12.0%</td>
<td>67.45</td>
<td>22.5</td>
<td>2.28</td>
<td>13.2%</td>
<td>6.4</td>
<td>15.9%</td>
<td>14.4%</td>
</tr>
<tr>
<td>PRD 3</td>
<td>18.9%</td>
<td>62.54</td>
<td>33.0</td>
<td>2.16</td>
<td>19.8%</td>
<td>6.7</td>
<td>15.9%</td>
<td>21.5%</td>
</tr>
<tr>
<td>PRD 4</td>
<td>5.3%</td>
<td>62.72</td>
<td>9.3</td>
<td>2.12</td>
<td>5.5%</td>
<td>6.8</td>
<td>15.9%</td>
<td>6.0%</td>
</tr>
</tbody>
</table>

Table D Crop mix Scenario crop water use and gross margin percentage of total catchment

<table>
<thead>
<tr>
<th>Irrigation area</th>
<th>CIA</th>
<th>MIA</th>
<th>PRD 1</th>
<th>PRD2</th>
<th>PRD3</th>
<th>PRD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 10 years</td>
<td>Water use %</td>
<td>gross margin %</td>
<td>Water use %</td>
<td>gross margin %</td>
<td>Water use %</td>
<td>gross margin %</td>
</tr>
<tr>
<td>Maize</td>
<td>0.05</td>
<td>0.07</td>
<td>1.33</td>
<td>1.91</td>
<td>0.16</td>
<td>0.25</td>
</tr>
<tr>
<td>Rice</td>
<td>13.05</td>
<td>17.90</td>
<td>20.94</td>
<td>30.48</td>
<td>0.66</td>
<td>1.06</td>
</tr>
<tr>
<td>Wheat</td>
<td>1.67</td>
<td>1.33</td>
<td>4.88</td>
<td>4.51</td>
<td>0.41</td>
<td>0.48</td>
</tr>
<tr>
<td>Canola</td>
<td>1.58</td>
<td>1.61</td>
<td>0.49</td>
<td>0.57</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Lucerne</td>
<td>0.68</td>
<td>0.06</td>
<td>1.99</td>
<td>0.17</td>
<td>0.43</td>
<td>0.04</td>
</tr>
<tr>
<td>Soybean</td>
<td>0.76</td>
<td>0.49</td>
<td>0.68</td>
<td>0.45</td>
<td>0.14</td>
<td>0.10</td>
</tr>
<tr>
<td>Winter pasture</td>
<td>2.00</td>
<td>1.16</td>
<td>3.24</td>
<td>2.08</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Barley</td>
<td>0.38</td>
<td>0.19</td>
<td>0.29</td>
<td>0.16</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Fallow</td>
<td>0.18</td>
<td>0.31</td>
<td>0.23</td>
<td>0.15</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Summer past</td>
<td>0.00</td>
<td>0.00</td>
<td>0.92</td>
<td>0.14</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Others</td>
<td>0.37</td>
<td>0.07</td>
<td>1.51</td>
<td>0.19</td>
<td>0.74</td>
<td>0.15</td>
</tr>
<tr>
<td>Annual</td>
<td>0.35</td>
<td>1.49</td>
<td>3.45</td>
<td>4.65</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Appendix H: Scenarios Results

In the preceding chapters, a model was established as a tool for analysis to represent the current conditions in the Murrumbidgee catchment and this model was used to study the current system of irrigation water management. In this section, the model is used to analyse the effects of other alternatives of water supply and demand with respect to water productivity, economic and environmental outcomes. Six Scenarios have been identified in chapter four including the base case Scenario (the first Scenario). Each Scenario also has several variations (sub-Scenarios), for this reason the results of the Scenarios and their variations are presented in this section by each Scenario and its variations compared to the base case Scenario. In addition, all of these Scenarios and their variations are presented under different climatic conditions.

Scenario two (changing crop mix/improvement)

This Scenario simulates a situation of changing crop mix for ten years period under the same level of water supply or availability. Under this Scenario four variations have been simulated to test their consequence or impact on water system, environment and agricultural income/productivity. The results of these variations are presented in comparison with the base case Scenario at catchment and irrigation area levels in terms of land and water resource use, crop yields, and gross margin for the catchment, irrigation area and for each crop by hectare and mega litre and environmental index.

Catchment level analysis

Figure 7-81 describes total water use per year at catchment level under the four variations of Scenario two (changing crop mix) compared to the base case Scenario. It is clear summer Scenario is the highest water use option compared to all others variations under Scenario two. It is higher in water use by 5-10% (143-287GL) compared to the base case. These can be attributed to different crop mixes in each variation under Scenario two without changing the total irrigation area; summer variation includes more summer crops which are the highest water use crops.

While crop mix, winter and cutting variations (sub Scenarios) are using irrigation water less than base case and summer Scenarios. The crop mix variation gives the highest gross margin per area compared to all other variations and always better than base case Scenario in gross margin per area by 7-15% ($12 – $26 million) (see Figure 7-82). Also, it spreads the demand frequency along the year. These can be attributed to different cropping system under crop mix variation (increase crop area of wheat, canola, lucerne and fallow and decreased rice crop area) which lead to shifting the peak demand to winter months.
Figure 7-81 Total water use for Scenario two and its variations compared to the base case

Moreover, the same trend between average water use and average water production per megalitre are observed (see Figure 7-83) between different variations (highest water use Scenario is lowest water production Scenario related to tonnes/ML). Figure 7-84 shows the environmental index for the four Scenarios variations compared to the base case Scenario. It is clear crop mix, cutting and winter variations achieved better environmental index compared to the base case and summer Scenario, which means they are able to provide environmental flow better than base case and summer Scenario. While in the last three years crop mix variation gives better results than base case, cutting and winter Scenarios by 10%-15% (this means crop mix Scenario is able to provide environmental flows 2-5 months more than base case per year during these drying years and low allocations).
Figure 7-83 water use and water productivity for Scenario two and its variations compared to the base case

In addition, crop mix variation is used groundwater less than the base case Scenario and summer variation due to its cropping system which requires and uses less water with low annual variability see Figure 7-85. It is clear, there is a clear annual variation in groundwater use; crop mix variation has the lowest annual variation compared to all other Scenarios, this annual variation resulted from different crop mixes and climatic conditions. Also, it is able to free more water for environment and groundwater ecosystem about 70-78GL.

Irrigation area analysis

At the irrigation area level the same results of water use are observed, crop mix variation, winter and cutting Scenarios variations have used water less than base case Scenario and summer variation; while summer variation is the highest water use variation (see Figure 7-86) under all the irrigation areas. This trend of water use under each variation can be attributed to different crop mixes which in turn lead to different irrigation water demand in time and quantity. Table 7-45 shows the proportion of water use (GL) per irrigation area under each variation, it is clear there is clear difference around 50GL-150 GL between each variation at the irrigation area level.
and in turn at the catchment level different. Under each Scenario, the highest water use areas in order are MIA, CIA and PRD3.

![Groundwater use](image)

**Figure 7-85 Average groundwater use per Scenario**

![Average water use](image)

**Figure 7-86 Average water use for ten years at irrigation area levels**

**Table 7-45 Average water use GL per irrigation area**

<table>
<thead>
<tr>
<th>Average water use percentage</th>
<th>cutting Scenario</th>
<th>winter Scenario</th>
<th>summer Scenario</th>
<th>crop mix Scenario</th>
<th>base case Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIA</td>
<td>482</td>
<td>541</td>
<td>640</td>
<td>589</td>
<td>616</td>
</tr>
<tr>
<td>MIA</td>
<td>1002</td>
<td>1038</td>
<td>1217</td>
<td>1118</td>
<td>1167</td>
</tr>
<tr>
<td>PRD 1</td>
<td>69</td>
<td>71</td>
<td>83</td>
<td>77</td>
<td>79</td>
</tr>
<tr>
<td>PRD 2</td>
<td>296</td>
<td>305</td>
<td>353</td>
<td>336</td>
<td>338</td>
</tr>
<tr>
<td>PRD 3</td>
<td>463</td>
<td>476</td>
<td>550</td>
<td>529</td>
<td>527</td>
</tr>
<tr>
<td>PRD 4</td>
<td>130</td>
<td>134</td>
<td>154</td>
<td>149</td>
<td>148</td>
</tr>
</tbody>
</table>

Figure 7-87 shows the gross margin per hectare at the irrigation area level for Scenario two (changing crop mix) and its variations compared to base case Scenario. It is clear the same trend of highest return of crop mix variation is observed compared to all other Scenario variations at the irrigation area. MIA produces 45% ($96 million) of total gross margin under crop mix variation which better than base case Scenario by average ($8 million) 6.8%. CIA produces 24% ($51.6 million) average, which is better than the base case Scenario’s gross margin by average 4.2% ($3 million). While PRD irrigation areas give better gross margin compared to the base case by almost 20% average ($6 million).
Figure 7-87 Average gross margin of Scenario two and base case Scenario at the irrigation area level

Based on the (Appendix G, Table C, D) describes average proportion of gross margin and water use percentage of total catchment per each crop under each irrigation area for each variation. In MIA the greatest average amount of irrigation water used applied to rice 559 GL (20.9%) of total water used by catchment which produces ($64.5 million) 30.5% of the average total gross margin per catchment; followed by wheat use 5% (134 GL) of total irrigation water which produces ($10 million) 4.5 % of total gross margin, although annual crops used (97 GL) 3.45% and produces ($10.4 million) 4.6% of the total gross margin.

In CIA area/node, the greatest irrigation water applied to rice 364GL (13%) of total water use which produces 18% ($39 million) of total gross margin and winter pasture used 56GL (2%) of total water use which produces ($3.5 million) 1.6 % of total gross margin, while wheat used 47.5 GL (1.67%) and produces $3 million (1.4%) and annual crops used 10 GL (0.35% of total water use) and produces $3.2 million (1.5 %) of total gross margin. In PRD 3 irrigation area, the main crops used water, are rice, lucernes, wheat and vegetables.

Again, the same observations, results and trade off, of significant differences in the irrigation water productivity and land and water economic productivity (Agricultural income per ha and ML) are observed between each crop under each irrigation area and its contribution to the whole catchment water use and gross margin. Also, different gross production is also observed between each irrigation areas and for each crop within each irrigation area. These can be attributed to different water allocation and climatic conditions which have impacts on farmer’s crop decisions about their cropping system, which inturn lead to different irrigation water demand in time and quantity. To sum up, managing environmental impacts in terms of environmental flows at catchment level is very sounds and highly impacted by irrigation area water demand which inturn has impact on agricultural productivity at irrigation area level.

Scenario three (changing crop mix and water banking)

This Scenario simulates a situation of changing the crop mix, which is similar to Scenario two but with introduced water banking by two recharge or fill cases (methods) of the water banking
by infiltration basin or injection by using water wells already existing in the area or introduced new wells. Figure 7-88, shows crop mix variation under water banking approach still use water less than summer variation and base case Scenario but use water more than winter and cutting variations. It is clear there is overlapping between annual variations under each variation, the minimum and maximum of crop mix variation still less than minimum and maximum of the summer variation. While crop mix variation also shows the highest gross margin per hectare along the ten years compared to all other variations and base case Scenario under both cases of recharge methods (see Figure 7-89).

![Total water use](image1)

**Figure 7-88** Total water use for Scenario three and its variations compared to the base case Scenario

![Average total gross margin](image2)

**Figure 7-89** Average total gross margin of Scenario compared to base case Scenario under infiltration and injection recharge methods

These results can be attributed to the different crop mixes and the difference in the cost of pumping and recovery of water banked which depend on ground water depth and the type of aquifer recharge methods (infiltration and injection). The estimated cost of ground water extraction only without water banking is 35.29$/ML (department of primary industry, 2005) and the estimated cost of ground water extraction and artificial storage/recharge and recovery (groundwater with water banking) for the area between Narrendera and Balranald under infiltration and injection are 57$/ML and 116$/ML respectively (Pratt Water: Feasibility of aquifer Storage and Recovery report 2004b).
These estimated costs indicate that performance and cost of infiltration basin method is likely to be costly effective (if it is possible) better than injection recharge method under different cropping pattern Scenarios. All the results of Scenario four and its variations show less gross margin per hectare with water banking approach compared to the base case, except crop mix variation. These could be attributed to crop mix variation gives gross margin ($3.6-$8 million) 3%-8% better than base case Scenario which is able to recover the increasing in the ground water cost due to both recharge methods with water banking approach. In addition, Figure 7-90 shows the gross margin per mega litre for the four variations under Scenario four compared to the base case Scenario. These differences perceived in water use and gross margin (per ha and ML) are likely due to crop mix variation is used groundwater and surface water less than all other variations. Up to this point, these results seem to indicate an infiltration recharge method is cost effective compared to injection recharge method, if it is possible because it does not need high operation and capital cost, although it needs more considerations of the geographical characteristics and river and aquifer connections and silt/clay deposit rate.

Figure 7-90 Average gross margins per ML under both recharge methods for Scenario three

Figure 7-91 shows the environmental index for Scenario four (changing crop mix with water banking) and its variations compared to the base case Scenario. It is clear the index results are different from index values resulted in Scenario two without water banking. Under Scenario four, crop mix variation gives better values compared to all other variations under Scenario four and base case Scenario for the last 6 years, while during the previous four years from 93/94 to 96/97 gives better results than base case and summer variation.
Along the ten years simulation period, crop mix variation shows better environmental index than base case Scenario by about 8% to 20% improvement in environmental performance (able to provide environmental flows 3-6 months per year more than base case). In addition, crop mix variation is used groundwater less than base case Scenario and summer variation, also it is able to free more water for environment and groundwater ecosystem about 75GL-80GL as the groundwater system is connected to the river. These results are consistent with Beddek R. et al (2005), mentioned different crop mixes result with different groundwater use particularly in the connected river–aquifer system such as Murrumbidgee River in this study. The same trend of water use and agricultural income are observed at the irrigation area level with the same trade off between saving water for environment and improve agricultural income from irrigation areas. Also, still the highest irrigation areas water uses in order are MIA, CIA and PRD 3, 39%, 20% and 18.5% (1090 GL, 559 GL and 517 GL) respectively of total water use.

**Scenario four (base case with conjunctive water use)**

This Scenario (conjunctive water use) simulates a situation of changing total water supply by using and allowing ground water pumping as substitute water source with using surface water for ten years period. Under this Scenario two variations have been simulated: The first variation is reduced surface water by 10% and the second variation is shifted the dam release one period of six months with also allowing groundwater pumping. Figure 7-92 describes average total water use at catchment level under the two variations of Scenario five (conjunctive water use) compared to the base case Scenario. The first variation (reduced surface water by 10%) under Scenario five is used water less than the base case Scenario and the other variation. While the second variation (shifting dam release) shows the same level of total water use compared to the base case Scenario with clear annual variation particularly of ground water use see Figure 7-93. Shifting dam release variation shows, most of the years are used groundwater less than base case Scenario by 40GL-100GL, while around 50% of its groundwater use results are less than the other Scenario variation (reduced surface water by 10%) by 10GL-45GL. These could be
attributed to the difference in time and quantity of surface water availability for crops biophysical demand which in turn impact on time and quantity of groundwater demand and use.

![Figure 7-92 Average total water use for Scenario four and its variations compared to the base case](image1)

![Figure 7-93 Annual ground water use for Scenario four and its variations compared to the base case](image2)

Figure 7-94 shows the average gross margin results per hectare and water use at the catchment level. It is clear the average total gross margin per hectare (agricultural income) of reduced surface water by 10% variation Scenario is decreased by about 3% to 6% ($5.6 - $11.5 million) from the base case Scenario while, the second variation (shifting dam release) decreased by about 1% to 3% ($1.5 - $5.6 million) from base case Scenario and gives better result compared to the first variation Scenario (reduced surface water by 10%), while gives less gross margin per megalitre compared to the base case.
Figure 7-94 Average gross margin per ha and ML for Scenario four and its variations compared to the base case.

In addition, Figure 7-95 shows environmental index values under each variation of Scenario five compared to the base case Scenario. Again, shifting dam release one period of six months gives better environmental index than base case Scenario along the ten years simulation period by about 16%-40% improvements (provide environmental flows 2-6 months per year more than base case). Although, the second variation under Scenario six (reduced surface water by 10%) shows the lowest index value compared to the first variation (shifting dam release) but, also still shows better results compared to the base case Scenario by about 5%-10% (1-2 months provide environmental flows per year more than the base case). Moreover, the same trend of total water use, groundwater used, gross margin per area and water productivity are observed at the irrigation area level. These represent the trade off between improve the environmental flow, the seasonal flow and agricultural income for this Scenario and its variations compared to the base case Scenario.

Figure 7-95 Environmental index for Scenario four and its variations compared to the base case.
Scenario five (base case with water banking and water trading)

This Scenario (Water banking-conjunctive water use and water trading) simulates a situation of introducing water banking approach (by using infiltration and injection methods of recharge) and allowing water trading between water banks for each irrigation Figure 7-96 describes average total water use and its annual variations at catchment level under two variations of Scenario six (water banking and water trading) compared to the base case Scenario. Allowing water trading resulted in new cropping patterns which in turn change the crop biophysical demand based on water allocation and the climatic conditions for each river reach and irrigation areas. The first variation (reduced surface water by 10% under Scenario six) shows less water use compared to the base case Scenario and the other variation (shifted the dam release). While the second variation shifting surface water release shows the same level of total water use compared to the base case Scenario with clear annual variation of ground water use see Figure 7-97. Shifting dam release variation, more than 70% of its groundwater use result is less than base case Scenario groundwater use by 20GL-40GL, while 90% of its groundwater use results are less than the first variation (reduced surface water by 10%) by 50GL-200GL. These could be attributed to differences in the crop mixes and the time and quantity of surface water availability for crop biophysical demand which inturn impact the time and quantity of groundwater demand, use and also the level of water trading.

Figure 7-96 Average total water use for Scenario five and its variations compared to the base case

In contrast, the results of agricultural income (gross margin per area) are different from water use level (see Figure 7-98), as the first variation (reduced surface water by 10%) gives better income compared to the second variation (shifting dam release), while still gives less gross margin results by 5% to 11% ($10-$20million) along the ten years compared to the base case Scenario under both cases of recharge methods. These differences in income under both variations attributed to the difference in the cost of pumping and recovery which depend up on ground water depth, the type of aquifer recharge methods and the operation cost. These results indicate that the performance of the infiltration basin method is likely to be cost effective better than injection recharge method by 3% to 5%($5-$11 million) under both Scenario variations. All the
results of Scenario six’s variations show less gross margin with water banking approach and allowing water trading by 5%-17% ($8-$35million) compared to the base case Scenario. Not surprising, the agricultural income in the second variation of shifting dam release is less than reduce surface water by 10% variation as it is also involved operation cost.

![Annual groundwater use](image1)

**Figure 7-97 Annual ground water use for Scenario five and its variations compared to the base case**

![Total Gross margin $/ha](image2)

**Figure 7-98 Average total gross margin of Scenario five and its variations compared to base case Scenario under infiltration and injection recharge methods**

In addition, Figure 7-99 shows the gross margin per megalitre for the two variations under Scenario six compared to the base case Scenario. These results indicate that, infiltration recharge method is cost effective compared to injection recharge method; if it is available/possible according to river and aquifer connection. Also, these variations show better gross margin per megalitre in comparison to the base case Scenario which could be preferred and attractive option for water policy makers as their main concern about how much can be earn/return per megalitre of water use while farmers or irrigators are concerned about how much can be earn/return per hectare or land area because all their capital cost is associated with their land area not with their water licences/volume.
Figure 7-99 Average gross margin per megalitre of Scenario five and its variations compared to base case Scenario under infiltration and injection recharge methods

Figure 7-100 shows the environmental index value under Scenario six variations compared to the base case Scenario. The second variation of Scenario six (shifting dam release) gives a better results compared to the first variation (reduce surface water by 10%) during most of the years by almost 15% to 20% better (i.e. able to provide environmental flows 3-5 months per year more than other Scenario). While shows better results about 70% of all its results (frequency of years) better than base case Scenario index values particularly in the last five years (driest year). These could be attributed to changing the time of flows which in turn changing the demand behaviour of ground water and surface water by using water banking which is able to manipulate crop water demand and allowing more water for environment.

Figure 7-100 Environmental index for Scenario five and its variations compared to the base case

At the irrigation area level under Scenario six, again the same trend of surface water use and ground water use are observed, reduced surface water by 10% variation used water less than other variation and base case Scenario. While achieved better water productivity compared to the other variation and base case Scenario. Different gross production is also observed between each irrigation areas and for each crop within each irrigation area from base case Scenario. These results attributed to the trade off between improve environmental performance and water productivity with changing seasonal flow.
**Scenario Analysis and climatic conditions**

Again, in this section, the model is used to analyse the effects of different climatic conditions for the same alternative of water supply and demand (six Scenarios including base case) with respect to water productivity, economic and environmental outcomes. The hypothesis here, it is expected the climate conditions will impact the way of water use and availability, during the dry conditions water availability is going to be highly restricted and reduced due to decreased rainfall and increased evaporation while the crop will needs more water for evapo-transpiration according to high temperature. In wet season or year, water is available and plant water needs is reduced. In turn, these assumptions have several impacts on land and water productivity and water economics. Therefore, the results are examined under these conditions in respect to water use, water economic and land and water productivity.

Figure 7-101 shows annual water use for base case Scenario compared with Scenario two (changing crop mix) and its variations under different climatic conditions (average, wet and dry). It is clear the results matched the expected trend of water use. Water use increased under dry conditions due to increased crop water requirements while water use decreased under wet conditions due to reduced crop water needs for each Scenario with increased rainfall. Summer Scenario is the highest water user under all the climatic conditions. While cutting, winter and crop mix variations are used less water compared to the base case and summer Scenario. In turn, average gross margin per megalitre shows different trend and results. Crop mix variation gives higher gross margin per megalitre compared to all other variations, around 10% to 16% ($6-$22 per megalitre) better than base case Scenario, and summer Scenario; around 12% to 18% ($8-$25 per megalitre) better than winter Scenario and around 16% to 24% ($22-$28 per megalitre) better than cutting Scenario.

These results are in a reverse trend with average water use per hectare. Crop mix, cutting and winter variations are used water per hectare less than base case and summer Scenarios. While crop mix variation gives better environmental index than base case and summer Scenarios. Winter Scenario gives a better environmental index compared to all other variations, using less water and free more water for environmental but less in gross margin see Figure7-102. These results indicate climatic variability have clear impact on the environmental performance and agricultural productivity.
At the irrigation area level, the same trend of results are observed and also the same level of water use percentage by each irrigation area, CIA irrigation area is used between 18-21% of the total water use under the same Scenario under different conditions which produces between 24-27% of total gross margin, MIA irrigation area is used around 39-41% of total water use under different Scenarios and conditions which produces between 45-48% of total catchment income. It is obvious there is clear relationship and trade off between water use and economic productivity.

In general, the hypothesis of climatic conditions dry and wet is observed, these climatic conditions have impacted/influenced the way of water use and availability, during the dry condition water availability for crops is reduced and became highly restricted while the crop needs is increased according to high temperature which in turn increased water needs for evapotranspiration and also increased water cost. While, in wet season or year, water available for crops increased due to increased rainfall and decreased evaporation which lead to decreased crop biophysical demand. In turn, these assumptions have impacted water productivity and water economic. The same trends of these results in terms of water use are observed under the rest of Scenarios compared to the base case Scenario.
Therefore, this section is not further discuss the rest of the results under different climatic conditions, while the main message/point pull through of this discussion is the question of difficulties to evaluate and compare these results for six Scenarios and its variations. Thus, further analysis is presenting for each Scenario and its variation compared to the base case which supposed to able to overcome these difficulties with clear description of the trade-off between agricultural income and environmental performance (see chapter 7, section 7.3).