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A model of water trade and irrigation activity in the southern Murray-Darling Basin

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About

This paper was prepared for the 2018 Australasian Agricultural & Resource Economics Society (AARES) Conference. The paper presents a new economic model of water trade and irrigation activity within the southern Murray-Darling Basin (sMDB), developed by ABARES on behalf of the Department of Agriculture and Water Resources. This model extends a similar model previously developed by ABARES (see Hughes et al. 2016). The model remains under ongoing development, a number of planned improvements to the model are documented in the paper.

This report remains technical in nature and documents the model data sources and assumptions. The only results presented in this paper are provided for the purposes of validating the models performance. The model has a range of potential future applications, such as assessing the effects on sMDB water markets and irrigation industries of: water policy reforms, water trading rules, changes in water availability or changes in perennial plantings.

Abstract

This paper presents a new econometric partial equilibrium model of water trade and irrigation activity within the southern Murray-Darling Basin (sMDB). The model exploits a unique data set detailing water availability, water market outcomes, irrigation activity, climate conditions and commodity prices for the sMDB annually over the period 2002–03 to 2016–17. This data is used to econometrically estimate a set of demand functions for water by region and irrigation activity. These demand functions are placed within a spatial equilibrium framework taking into account constraints on inter-regional water trade across the basin. The model is able to simulate the market prices of water allocations and entitlements by region and inter-regional water trade flows along with water and land use by irrigation activity and region. The performance of the model is demonstrated with in and out-of-sample validation tests. The model provides a basis for separating the effects of historical climate, market and policy shocks on the region and for simulating the effects of potential future shocks.

1 Introduction

The irrigation industry of the southern Murray–Darling Basin (sMDB) has been subject to a wide range of climate, market and policy changes over the last two decades.

Firstly, there have been dramatic variations in water availability including the 'Millennium drought' and subsequent floods, along with a longer-term trend toward reduced winter rainfall in the region related to climate change (CSIRO 2012). In addition, changes in commodity prices have placed adjustment pressure on the industry, leading to a contraction in wine grape plantings and recent expansions in almonds and cotton. At the same time, there have been a number of new government policies, including the Water Act 2007 and Murray–Darling Basin Plan, focused on reallocating water from irrigation to environmental uses.

The other major development during this period has been the continued growth and evolution of water markets. The sMDB water allocation market is now widely regarded as one of the most advanced of its kind in the world particularly given its ability to facilitate large volumes of trade between water users in different river catchments.

Understandably, there remains strong interest from policy makers in models and other tools for analysing water trade and irrigation activity in the sMDB, with the capacity to separate the effects of different historical climate, market and policy shocks, and to simulate the effects of potential future shocks.

This paper presents a new econometric partial equilibrium model of water trade and irrigation activity is presented. This model attempts to reconcile two alternative approaches applied in the literature: reduced form econometric estimation of water demand using historical market price data (see Brennan 2006, Bjornlund and Rossini 2005 and Wheeler et al. 2008) and 'bottom-up' construction of water demand through structural bio-economic optimisation models (see Apples, Douglas and Dwyer (2004) or Qureshi, Ranjan and Qureshi (2010) for a review).

Similar to Brennan (2010) and Hughes et al. (2016) this study involves econometrically estimating a series of short-run (annual) water demand functions which are then placed within a spatial equilibrium framework to simulate water market prices and trade flows across the sMDB. As with Brennan (2010) and Hughes et al. (2016) the model takes into account limits on water allocation trade between regions as defined by prevailing water trading rules. This is significant as in recent years, constraints on interregional water trade have become an important issue within the sMDB. A number of water trade rules, most notably limits on the export of water from the Murrumbidgee have started to affect the market leading to differences in water prices between regions (ABARES 2017).

The model presented in this paper, extends that of Hughes et al. (2016) by including an irrigation component, which estimates demand for irrigation water (and land) by region and activity (i.e., crop type). In this sense, the model provides outputs similar to previous bio-economic models of irrigation in the region, of which there is a long tradition (see for example Hall at al. 1994, Adamson et al. 2007, Hafi et al. 2009, Grafton and Jiang 2011 and Qureshi et al. 2013).

Previous models have employed a range of mathematical programming techniques particularly linear programming, which is subject to number of well documented limitations including "a tendency towards over-specialisation in production and resource allocation" (Qureshi et al. 2013). A range of pragmatic calibration methods have evolved to address these limitations -

including Positive Mathematical Programming (PMP). However, these calibration methods remain subject to their own limitations (Heckelei and Wolff 2003, Doole and Marsh 2014).

The model in this paper does not use calibration techniques, rather the parameters are all estimated econometrically using historical data. The basis for this approach is a unique data set detailing water availability (allocation percentages, entitlement volumes and carryover), market outcomes (prices and trade flows), irrigation activity (water and land use), climate (rainfall) and commodity prices for a consistent set of sMDB regions annually over the period 2002–03 to 2016–17.

This data set combines a variety of data sources, including state government water agencies, the Australian Bureau of Statistics (ABS) and the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). Given inconsistencies between data sets and changes in data collections over time, construction of the data set requires some approximation which creates a risk of measurement error. Despite this the data set is sufficient to generate realistic water demand responses and produce a model which achieves good validation performance both within and out-of-sample.

This paper is structured as follows. Chapter 2 summarises the data set and the key assumptions involved in its construction, with a complete description of the data is provided in Appendix A. Chapter 3 outlines the structure of the model, while Chapter 4 describes the estimation of the parameters. Chapter 5 presents some within and out-of-sample validation tests of the model under a baseline scenario which describes historical market conditions. Finally Chapter 6 outlines some of the strengths and weaknesses of the model and some options for future refinements and application.

2 Data

Data sources and assumptions

The model data is built from number of sources (listed in Table A1). There are two key components; the first is a dataset on water market outcomes (water market prices and trade volumes), water availability (water allocation, carryover and storage volumes) and climate conditions (rainfall) for each of the major sMDB regions for the years 2002–03 to 2016–17, based on data previously collated by Hughes, Gupta & Rathakumar (2016). The second component is a dataset detailing irrigation water and land use on farms in the sMDB (ABS 2016b) drawing on annual ABS agricultural census and surveys between 2002–03 and 2015–16.

The construction of this dataset involved significant effort given the large number of data sources and various inconsistencies between them. In particular, a number of modifications to the original sources were required to compile the data into a consistent set of regional and industry definitions. The assumptions made in constructing the final data set are described in Appendix A and summarised below. Table 1 details the key variables contained in the final data set.

Table 1 Key variables in the final dataset

Variable	Description
Climate	
R_{it}	Average farm rainfall (mm) in region i in year t
Irrigation water use and area	
W_{ijt}	Water use (ML) in activity j in region i in year t
L_{ijt}	Land use (HA) for activity j in region i in year t
Commodity prices	
Y_{ijt}	Output price index for activity j in region i in year t
Water allocations and entitlements	
E_{iht}	Water entitlement volume (ML) in region i for reliability type h in year t **a**
a_{iht}	Allocation percentage (%) for entitlement reliability type h in region i during year t
$c_{it}, \bar{c}_{it}$	Allocation (ML) carried over from previous year / carried forward to next year in region i year t
Δ_{it}	Net inter-region water allocation trade (ML) for region i during year t **b**
P_{it}	Average annual water allocation price ($ / ML) in region i during year t

Note: **a** Entitlement volumes are those available for consumptive use after removing Commonwealth water entitlement purchases for the environment (see Hughes et al. 2016 or Appendix A for detail). **b** Inter-regional trade flows exclude non-market environmental transfers

Regions

In this report the sMDB is defined to include the Murray River, the Murrumbidgee and Lower Darling systems, and the Goulburn, Broken, Loddon and Campaspe systems. The precise regions included in this dataset are detailed in Table 2 and Map 1 below.

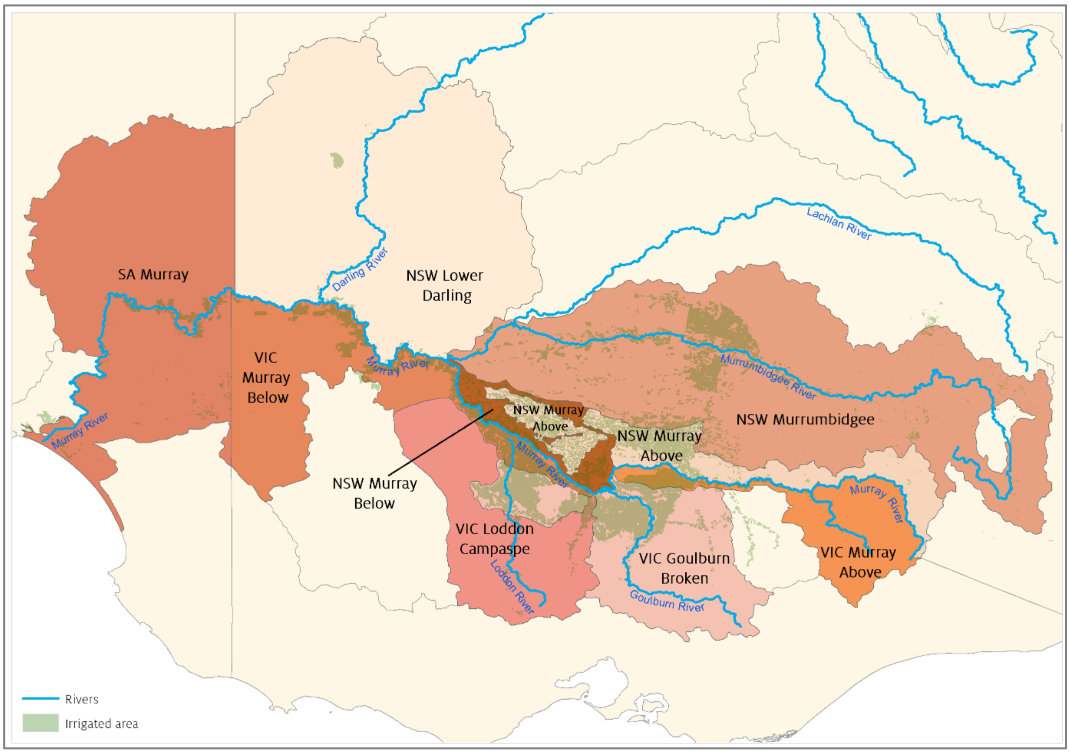
Water allocation and market data (water prices, allocations, carryover, environmental purchases, storage volumes and trade) was available for most of these regions from the previous dataset of Hughes et al. (2016). Some additional work was required to separate the above and below Barmah segments of the NSW and Vic. Murray regions (see Appendix A for detail).

Water use and irrigation area data was available from the ABS at the Natural Resource Management (NRM) region level. In some cases NRM region boundaries closely match the region definitions used in this report (e.g., Murrumbidgee), while in other cases they are substantially different, such as the Victorian (Vic.) Murray. For this study, ABS NRM region data was apportioned to match the regions defined below, using spatial land use mapping data, as described in Appendix A. Prior to 2005–06 ABS data is only available at Statistical District (SD) region level. The same method was applied to map this data to the regions used in this report. Future work could make use of ABS unit record data to construct more precise regional estimates (see chapter 6 for detail).

Table 2 Regions in the sMDB analysed in this report

i	Regions
1	NSW Murray (above Barmah)
2	Vic. Murray (above Barmah)
3	Vic. Goulburn-Broken
4	Vic. Loddon-Campaspe
5	NSW Murrumbidgee
6	NSW Lower-Darling
7	NSW Murray (below Barmah)
8	VIC Murray (below Barmah)
9	SA Murray

Map 1 Southern Murray-Darling Basin water systems and major storages



Irrigation activities

The dataset and model presented in this paper include the irrigation activities shown in Table 3. As the definitions for irrigations activities used by the ABS have changed over time, a complete mapping between ABS activity types and those used in the final data set is presented in Appendix A.

Table 3 Irrigation activities

j	**Irrigation activities**
1	Pastures – Grazing (Dairy)
2	Pastures – Hay
3	Cotton
4	Rice
5	Other cereals
6	Other broadacre
7	Other crops
8	Grapes
9	Fruits and nuts
10	Vegetables

Entitlement types

Following Hughes et al. (2016) only regulated surface water entitlements are accounted for in each region. This includes 'General security' and 'High security' entitlements in NSW regions. 'High reliability' and 'Low reliability' in Victoria and Class 3 in South Australia. For notation purposes entitlement types are indexed by: $h \in \{high, low\}$ (with, for example, NSW General Security referring to type *low*). Data is compiled for entitlement and allocation volumes for these entitlement types and is discussed further in Appendix A.

Time

The dataset contains water allocation and market data on a financial year basis between 2002–03 to 2016–17. As mentioned previously, ABS water and land use data by irrigation activity and NRM region is available from 2005–06. From 2002–03 to 2004–05, data is only available for total water use and land use by SD regions.

The sample used for econometric estimation of water and land use demand functions was limited to the period 2005–06 to 2015–16. Data for the years 2002–03 to 2004–05 and 2016-17 are withheld from estimation and used for out-of-sample model validation.

Total water supply and demand

One of the challenges with the dataset is reconciling water supply and demand, given data for each has been obtained from different sources. Water supply is measured in terms of water allocations and reflects the volume available for use against major regulated surface water entitlements. Water use numbers reflect water applied by farmers as reported in surveys. There are a variety of legitimate reasons why historical water allocation and water use numbers may differ (beyond the measurement error present in both data sources), including:

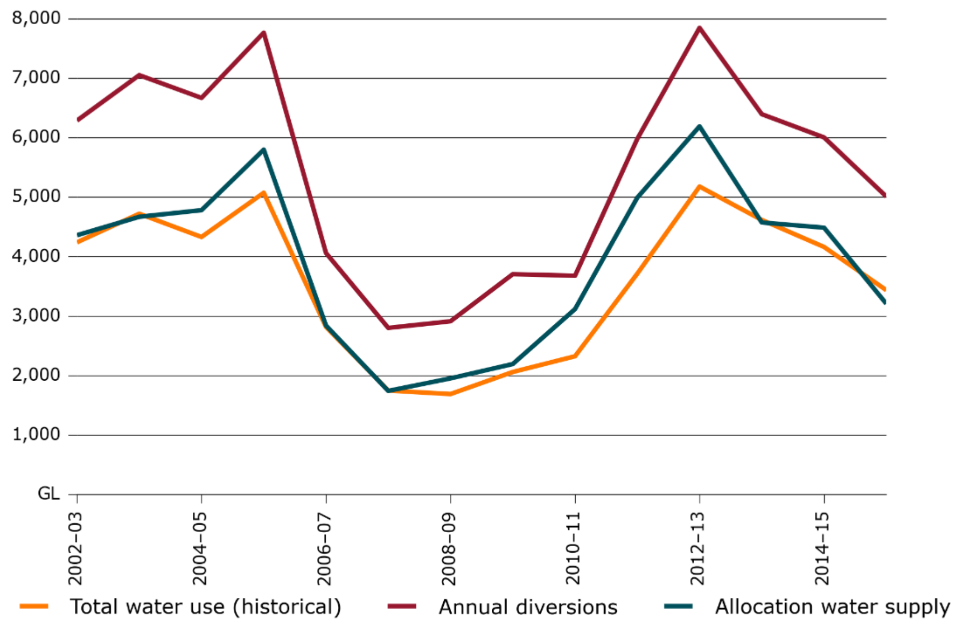
- Additional sources of water supply not included in the allocation data (such as groundwater and unregulated water)
- Non-irrigation water use (such as urban or stock and domestic) against regulated surface water entitlements (although in practice these activities are normally supported by separate entitlements)
- Forfeited water (where allocations are not used, traded or carried over by farmers)

Figure 1 shows total irrigation water use in the sMDB, against water allocations available for use (after accounting for carryover and environmental recovery) as recorded in the dataset. The chart also shows annual diversions (an alternative measure of water demand) as reported by the Murray Darling Basin Authority (MDBA).

Despite the potential for error, water allocation and total water use remain similar over the period. The largest differences are observed during the flood period (2010–11 to 2012–13) where allocations exceed water use (likely due to forfeited allocations). As expected, diversions are higher than water use and allocations, given they include system losses and non-irrigation water use (e.g., urban, stock and domestic etc.). Despite this, diversions are closely related to water use and allocations over time.

The model developed in this study has the flexibility to allow for legitimate sources of difference in measures of water supply and demand (see Chapter 3 for detail). Future research, could help reduce measurement error in each of these (see chapter 6).

Figure 1 Total water use, annual diversions and allocation water supply in the sMDB



3 Model

The model uses a spatial partial equilibrium framework and runs on an annual time step for financial years. Each region has an initial allocation of water (given entitlement volumes and annual allocation percentages), and this water can be traded between activities and across regions subject to defined trading rules. Equilibrium prices are those which maximise the benefits of water use (and equalise the marginal value of water) subject to constraints on trading (Figure 2).

The model has a short-run focus, simulating the demand for water allocations (by region and irrigation sector) in each year given prevailing water availability, rainfall and commodity prices. The model does not attempt to represent longer-term (i.e., between year) industry adjustment. In practice, longer term changes in irrigation water demand (e.g., changes in the mix of perennial vs annual crops,) depend on expectations over future conditions / market prices. Proper representation of these changes requires explicit consideration of risk and uncertainty (see Brennan 2006, Adamson et al. 2017) which remains outside the scope of this study.

Water supply

In this framework, allocation water supply is exogenous and is estimated after accounting for carryover and environmental purchases. Allocations available in region i prior to trade are defined as:

$$A_{it} = \sum^{h \in H} (E_{iht}.\, a_{iht} + c_{iht} - \bar{c}_{iht}) \qquad (1)$$

Here entitlement volumes are those available for consumptive use (after adjusting for environmental purchases), while allocation percentages are 'final' (those prevailing at the end of the financial year). The above equation accounts for carryover from the previous year and carryover into the next year which are both taken as exogenous.

Water demand

Water allocation demand is estimated for each irrigation activity in each region based on the schematic illustrated in Figure 2.

Irrigation land use

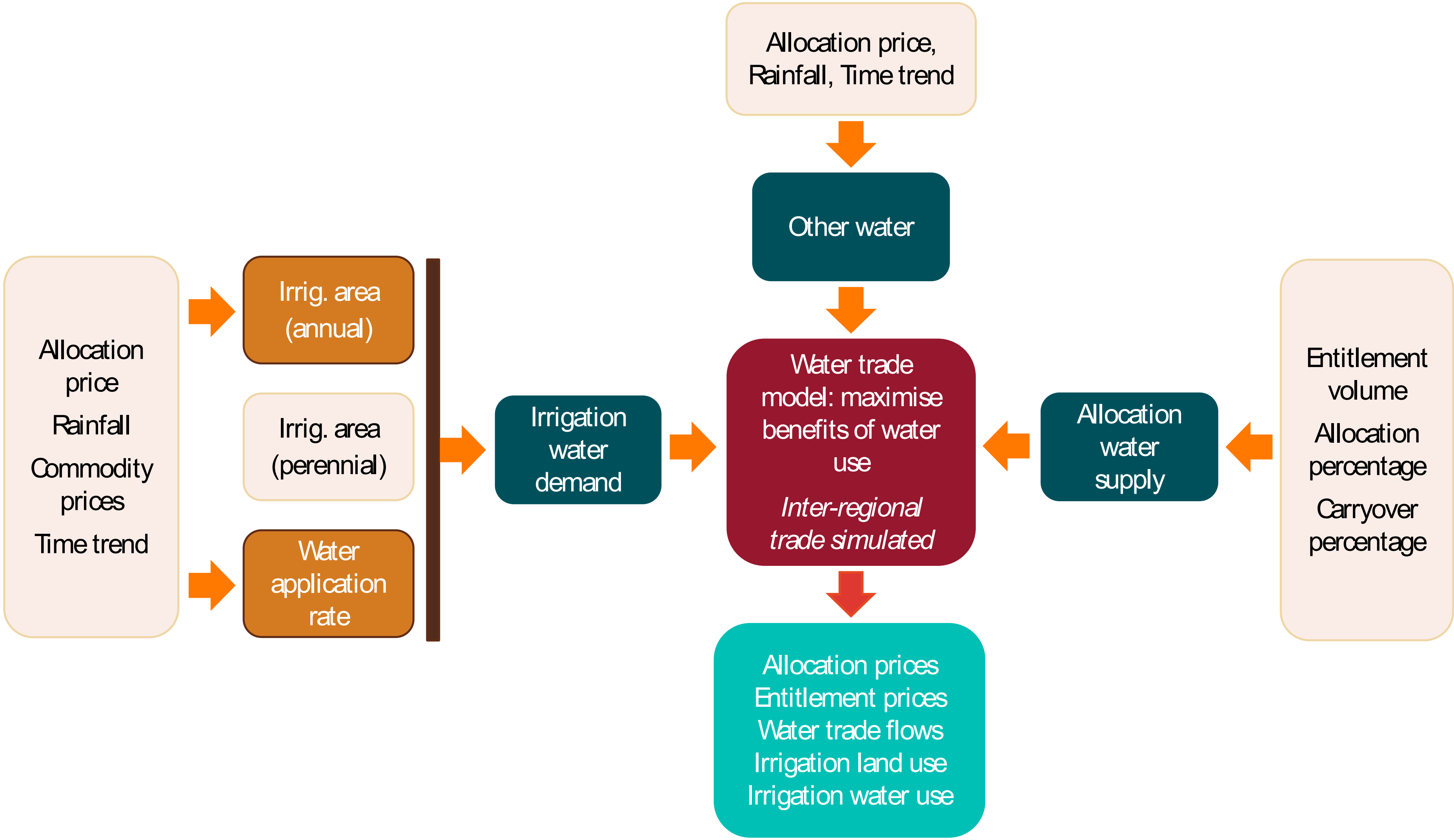
For activities 8 and 9 (grapes and fruit and nuts) land use L_{ijt} is taken as exogenous and set to historical values (based on the prevailing annual land areas in the dataset). Perennial land areas can be varied for the purposes of scenario analysis as discussed further in the conclusions.

For other activities annual land use by region is defined as a function of water allocation prices, rainfall and commodity prices (equation 2) where $\boldsymbol{\beta}_{ij}^{L}$ are parameters to be estimated.

$$L_{ijt} = f^{L}(P_{it}, R_{it}, Y_{jt}, \boldsymbol{t}, \boldsymbol{\beta}_{ij}^{L}) \qquad (2)$$

The exception to this is cotton, where there is insufficient sample to estimate land use functions (because cotton only appeared in the sMDB in 2010–11). To address this, a single function is estimated for the total cotton and rice irrigated area. Individual areas for these activities are then based on the observed historical proportions of rice to cotton in each region.

Figure 2 Modelling framework



Water application rate

The water application rate is defined for each irrigation activity as a function of the water allocation price, commodity price and rainfall (equation 3), where $\boldsymbol{\beta}_{ij}^{W}$ are parameters to be estimated.

$$W_{ijt}/L_{ijt} = f^{W}(P_{it}, R_{it}, Y_{jt}, \boldsymbol{t}, \boldsymbol{\beta}_{ij}^{W}) \qquad (3)$$

Irrigation water use

Together the land use and water application functions (equation 2 and 3) define a water demand function (equation 4), simulating irrigation water use for irrigation activity j in region i in period t:

$$W_{ijt} = d^{W}(P_{it}, R_{it}, Y_{jt}) \qquad (4)$$

For convenience, regional level total water demand functions can be defined as:

$$W_{it} = \sum^{j \in J} d^{W}(P_{it}, R_{it}, Y_{jt}) = D_i(P_{it}, R_{it}, \mathrm{Y}_{it})$$

$$W_{jt} = \sum^{i \in I} W_{ijt}$$

Water supply and demand balance

Other water

As discussed, there are a variety of reasons why estimates of historical water supply in each region $A_{it} + \Delta_{it}$ may differ from total irrigation water use W_{it}.

To address this we define the variable O_{it} as net 'other water' to take into account errors or differences between irrigation water use and allocation water supply:

$$O_{it} = W_{it} - (A_{it} + \Delta_{it})$$

In practice, O_{it} can be either positive or negative. Positive values reflect net additional water supply (i.e., from groundwater or unregulated sources) while negative values reflect net additional water use (i.e., non-irrigation water use or forfeited allocations).

Within the model other water use in region i is defined as a function of the water allocation price and rainfall (assuming that other water is a substitute for allocation water).

$$O_{it} = f^{O}(P_{it}, R_{it}, \boldsymbol{\beta}_{i}^{O}) \qquad (5)$$

Water supply constraint

For each region i and time period t, total water demand must then equal the sum of allocation water supply, net trade for the region and other water use. This is also referred to as the water supply constraint:

$$W_{it} = A_{it} + \Delta_{it} + O_{it} \qquad (6)$$

Water trading constraints

The model has been designed to take into account key historical restrictions on inter-regional water trade in the sMDB including:

- Murrumbidgee import and export limits
- Northern Victoria import and export limits
- Lower-Darling trade limits enforced during drought conditions
- Barmah choke trade limits.

In order to represent these limits, 5 trading zones are defined in the model (Table 4). These trading zones are aggregations of regions, where each region within a trading zone can freely trade with all other regions in the same trading zone.

Table 4 Trading zones, used for simulating inter-regional trade

k	**Trading zones**
1	Murray above Barmah, $I_1 = \{1,2\}$
2	Northern VIC, $I_2 = \{3,4\}$
3	Murrumbidgee, $I_3 = \{5\}$
4	Lower-Darling, $I_4 = \{6\}$
5	Murray below Barmah, $I_5 = \{7,8,9\}$

Note: For the model equations, trading zones are represented by: $k \in \{1, \ldots, 5\}$ and $I_k \subset I$ as listed in Table 2

For each trading zone annual net trade must remain within a predefined lower and upper limit:

$$\underline{\Delta}_{kt} \leq \Delta_{kt} \leq \overline{\Delta}_{kt} \qquad (8)$$

These upper and lower trade limits can be set to reflect prevailing trading rules within the sMDB in each year. The baseline parameters used in this paper are listed in Table 5 and are based on an analysis of historical annual trade flow data (see Hughes et al. 2016).

Table 5 Annual trade constraints for trading zones in southern MDB (GL)

Year	Murrumbidgee		Northern Victoria		Lower-Darling		Murray above Barmah		Murray below Barmah	
	TL	TU	TL	TU	TL	TU	TL	TU	TL	TU
2003	-200	0	no limit	50	0	0	0	no limit	no limit	no limit
2004	-200	0	no limit	50	0	0	0	no limit	no limit	no limit
2005	-200	0	no limit	50	no limit	no limit	0	no limit	no limit	no limit
2006	-200	0	no limit	50	0	0	0	no limit	no limit	no limit
2007	no limit	0	no limit	50	0	0	0	no limit	no limit	no limit
2008	no limit	0	no limit	50	0	0	no limit	no limit	no limit	no limit
2009	no limit	0	no limit	50	no limit	no limit	no limit	no limit	no limit	no limit
2010	no limit	0	no limit	50	-68	0	no limit	no limit	no limit	no limit
2011	-200	0	-150	50	no limit	no limit	no limit	no limit	no limit	no limit
2012	-200	0	-150	50	no limit	no limit	no limit	no limit	no limit	no limit
2013	-200	0	-150	50	no limit	no limit	no limit	no limit	no limit	no limit
2014	-200	0	-150	50	no limit	no limit	no limit	no limit	no limit	no limit
2015	-200	0	-150	50	0	0	-26	no limit	no limit	no limit
2016	-200	0	-150	50	0	0	-26	no limit	no limit	no limit
2017	-200	0	-150	50	no limit	no limit	-37	no limit	no limit	no limit

Note: TL Lower trade limit; TU Upper trade limit.

Solving for an equilibrium

A solution to the model is given by a set of equilibrium allocation prices P_{it}^* for each region (or equivalently net trade volumes) which maximise water use benefits based on the integral of the demand function:

$$\max_{P_{it}} \sum^{i \in I} \int_{A_{it}+\Delta_{it}} D_i^{-1}(W_{it}, \dots)$$

The solution must also satisfy the market clearing, water demand and water supply conditions and trade constraints:

$$\sum^{i \in I} \Delta_{it} = 0$$

$$\underline{\Delta}_{kt} \leq \Delta_{kt} \leq \overline{\Delta}_{kt}$$

$$W_{ijt} = d^W(P_{it}, R_{it}, Y_{ijt})$$

$$W_{it} = \sum^{j \in J} W_{ijt} = A_{it} + \Delta_{it} + O_{it}$$

Rather than directly computing the integral, a set of equilibrium prices are obtained subject to these conditions using a numerical algorithm which is further described in Appendix B.

Water entitlement prices

The model can also be used to simulate water entitlement prices. Water entitlements are assets which provide annual returns in the form of water allocations. The simplest approach to valuing entitlements (ignoring issues of risk) is to assume that entitlement prices are equal to the discounted expected value of future allocations:

$$V_{ihs} = \sum_{t=s+1}^{\infty} \frac{1}{(1+r)^t} E_s[a_{iht} \,.\, P_{it}]$$

Where V_{ihs} is the price of water entitlement h in region i period s and r is the discount rate parameter.

In the model, the unobservable expectation $E_s[a_{iht}.\, P_{it}]$ is replaced with the sample average for the period 2002–03 to 2016–17. Water entitlement prices can then be approximated as:

$$V_{ihs} = \left(\frac{1}{r}\right) \frac{1}{15} \sum_{t=2003}^{t=2017} [a_{iht}\ P_{it}] \quad (9)$$

This approach assumes that historical water availability and market conditions are a reasonable reflection of future expectations. As such, when attempting to predict current entitlement prices the model baseline is adjusted such that current levels of environmental water recovery are applied from the beginning of the period. A real discount rate of 7 per cent was assumed for this report.

4 Estimation

Parameters for the land use, water application rate and other water use functions (equations 2, 3 and 5) were estimated via linear Ordinary Least Squares (OLS) regression. Regression results are presented below; further detail including standard diagnostic tests are available on request. To ensure theoretically plausible results (including downward sloping demand functions) constraints are applied to model coefficients. However, as shown in the following sections, these are rarely binding.

In testing, a variety of functional forms for these regression models were considered, with simple linear forms ultimately being adopted. Throughout this testing phase, more focus was placed on the performance of model outputs (as measured through validation tests, see chapter 5) than the in-sample fit of the individual regression models themselves. A more formal structural estimation approach (where model equations are estimated simultaneously) remains a potential topic for future research.

Irrigation land use

For equation 2, we fit the following model for each region and activity:

$$L_{ijt} = \beta^L_{0i} + \beta^L_{1ij}.P_{it} + \beta^L_{2ij}R_{it} + \beta^L_{3ij}Y_{it} + \beta^L_{4ij}.t \qquad (10)$$

subject to the following constraints:

$$\beta^L_{1ij} < 0, \beta^L_{3ij} > 0$$

As discussed irrigated area for perennial activities is currently treated as exogenous. Tables 6 – 13 show the results of model estimation for land use for annual irrigation activities in each region. Note that the sample size for each of these models is 11 (2005–06 to 2015–16).

In Tables 6 – 13 omitted variables are the result of parameters not satisfying the constraints set out above. In all cases, except for vegetables in the VIC Goulburn-Broken and VIC Loddon-Campaspe regions, and other broadacre in SA Murray, the parameters for water allocation price have the desired negative sign. Further, the majority of price coefficients are significant at the five per cent level.

Note that while ABS data suggests that rice activity occurs in Victorian regions, it remains close to zero in most years and well below the levels observed in NSW. Based on available ABS and ABARES data, cotton and rice are not grown in the SA Murray, and are excluded from model estimation for this region (Table 13).

Table 6 Regression results for land use by irrigation activity, NSW Murrumbidgee

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	64738.83*	-117.71*			-15.65	2003.03	0.76
	(0.05)	(0.01)			(0.75)	(0.36)	
Vegetables	-9417.51	-3.28	121.13		-2.73	-843.29	0.45
	(0.52)	(0.28)	(0.30)		(0.49)	(0.16)	
Other broadacre	9821.05	-25.4*	90.79		-8.87	-864.44	0.73
	(0.21)	(0.01)	(0.21)		(0.22)	(0.09)	
Other cereals	89672.90	-120.29	484.93		-86.65	-3353.19	0.55
	(0.14)	(0.08)	(0.36)		(0.12)	(0.34)	
Other crops	-966.20	-5.53	41.05		-4.19	-26.74	0.61
	(0.86)	(0.06)	(0.41)		(0.15)	(0.87)	
Pastures - Dairy	54313.64*	-78.97*	326.72		-39.10	-6624.52*	0.87
	(0.04)	(0.01)	(0.18)		(0.10)	(0.00)	
Pastures - Hay	34140.3*	-22.48*			-18.95	-2096.14*	0.78
	(0.00)	(0.02)			(0.12)	(0.00)	

Note: * denotes significance at the 95% level

Table 7 Regression results for land use by irrigation activity, NSW Murray (above the Barmah Choke)

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	49162.31*	-75.81*			-38.60	510.25	0.81
	(0.01)	(0.00)			(0.17)	(0.61)	
Vegetables	1124.67*	-0.77			0.61	-58.95*	0.62
	(0.02)	(0.10)			(0.35)	(0.04)	
Other broadacre	8710.38*	-15.51*	25.74		-13.42*	273.82	0.92
	(0.04)	(0.00)	(0.39)		(0.01)	(0.21)	
Other cereals	79171.99*	-73.96*			-76.06*	410.30	0.79
	(0.00)	(0.00)			(0.02)	(0.68)	
Other crops	-742.82	-0.85	9.97		-0.91	56.47	0.81
	(0.51)	(0.14)	(0.32)		(0.19)	(0.13)	
Pastures - Dairy	129720.75*	-134.46*	133.67		-122.48*	-3018.63	0.83
	(0.01)	(0.00)	(0.66)		(0.02)	(0.20)	
Pastures - Hay	21717.15	-56.02	141.29		-39.18*	-1201*	0.73
	(0.42)	(0.17)	(0.46)		(0.02)	(0.04)	

Note: * denotes significance at the 95% level

Table 8 Regression results for land use by irrigation activity, NSW Murray (below the Barmah Choke)

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	8518.54*	-12.91*			-7.24	31.49	0.83
	(0.01)	(0.00)			(0.13)	(0.85)	
Vegetables	533.12*	-0.36			0.26	-25.42	0.61
	(0.02)	(0.10)			(0.41)	(0.05)	
Other broadacre	1348.98	-2.55*	4.48		-2.11*	30.16	0.89
	(0.08)	(0.01)	(0.43)		(0.03)	(0.45)	
Other cereals	12893.93*	-12.17*			-12.35*	-16.84	0.76
	(0.00)	(0.01)			(0.03)	(0.93)	
Other crops	-162.03	-0.15	1.92		-0.13	8.50	0.81
	(0.41)	(0.14)	(0.28)		(0.29)	(0.18)	
Pastures - Dairy	34568.21*	-33.09*	14.30		-31.76*	-875.77	0.85
	(0.00)	(0.00)	(0.84)		(0.01)	(0.14)	
Pastures - Hay	3350.22	-17.47	52.29		-10.45*	-381.7*	0.75
	(0.59)	(0.09)	(0.28)		(0.02)	(0.02)	

Note: * denotes significance at the 95% level

Table 9 Regression results for land use by irrigation activity, VIC Murray (above the Barmah Choke)

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	276.12*	-0.36*			-0.11	-14.81*	0.77
	(0.01)	(0.00)			(0.24)	(0.01)	
Vegetables	461.15*	-0.13			-0.06	-6.20	0.26
	(0.00)	(0.22)			(0.56)	(0.27)	
Other broadacre	-516.61	-4.11*	22.08*		-1.07	-59.38	0.88
	(0.49)	(0.00)	(0.01)		(0.10)	(0.21)	
Other cereals	1108.39	-1.85			-1.64	363.81*	0.76
	(0.50)	(0.34)			(0.40)	(0.01)	
Other crops	387.30	-0.99	4.17		-0.46	-23.25	0.43
	(0.72)	(0.10)	(0.67)		(0.31)	(0.50)	
Pastures - Dairy	34409.08	-38.45*	119.96		-24.94	-470.25	0.63
	(0.05)	(0.04)	(0.42)		(0.09)	(0.64)	
Pastures - Hay	1498.99	-22.59	88.97		-10.43*	104.48	0.60
	(0.90)	(0.20)	(0.31)		(0.04)	(0.64)	

Note: * denotes significance at the 95% level

Table 10 Regression results for land use by irrigation activity, VIC Murray (below the Barmah Choke)

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	-452.60	-0.20		7.67*	-0.30	-19.50	0.74
	(0.06)	(0.06)		(0.03)	(0.05)	(0.12)	
Vegetables	2670.37*	-1.10			1.30	-27.57	0.26
	(0.04)	(0.43)			(0.47)	(0.73)	
Other broadacre	202.84	-3.96*	17.55		-2.61	46.79	0.79
	(0.89)	(0.04)	(0.21)		(0.12)	(0.62)	
Other cereals	874.27	-14.31	70.98		-11.23	560.33	0.65
	(0.93)	(0.25)	(0.46)		(0.32)	(0.42)	
Other crops	-350.08	-2.05	13.74		-1.56	1.70	0.67
	(0.85)	(0.07)	(0.44)		(0.14)	(0.98)	
Pastures - Dairy	89631.8*	-90.22*			-72.04*	-31.70	0.93
	(0.00)	(0.00)			(0.00)	(0.96)	
Pastures - Hay	2250.72	-38.43	121.47		-23.33	945.34	0.64
	(0.95)	(0.48)	(0.64)		(0.17)	(0.20)	

Note: * denotes significance at the 95% level

Table 11 Regression results for land use by irrigation activity, VIC Goulburn-Broken

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	1066.51*	-1.18*			-0.58	-50.12*	0.78
	(0.00)	(0.00)			(0.09)	(0.02)	
Vegetables	2125.68*				0.49	-20.83	0.26
	(0.00)				(0.20)	(0.30)	
Other broadacre	-339.98	-14.69*	85.19*		-8.02*	-21.15	0.87
	(0.93)	(0.01)	(0.05)		(0.05)	(0.94)	
Other cereals	16018.40	-13.27	3.53		-16.58	1656.24	0.76
	(0.28)	(0.36)	(0.98)		(0.20)	(0.12)	
Other crops	-2304.26	-4.48	53.02		-2.55	-143.11	0.54
	(0.62)	(0.07)	(0.25)		(0.20)	(0.38)	
Pastures - Dairy	226529.75*	-202.98*	389.38		-160.36	-2949.23	0.75
	(0.02)	(0.02)	(0.60)		(0.05)	(0.60)	
Pastures - Hay	35169.81	-73.14	259.72		-60.32	760.24	0.57
	(0.69)	(0.56)	(0.71)		(0.07)	(0.67)	

Note: * denotes significance at the 95% level

Table 12 Regression results for land use by irrigation activity, VIC Loddon-Campaspe

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice	-300.77	-0.08		4.80	-0.12	-11.60	0.63
	(0.09)	(0.19)		(0.07)	(0.14)	(0.21)	
Vegetables	622.00		1.93		0.39	-5.45	0.16
	(0.76)		(0.90)		(0.31)	(0.94)	
Other broadacre	915.45	-1.20	2.25		-1.31*	44.21	0.78
	(0.23)	(0.12)	(0.73)		(0.04)	(0.38)	
Other cereals	2874.03	-3.84	15.36		-3.27	57.09	0.73
	(0.21)	(0.10)	(0.45)		(0.08)	(0.70)	
Other crops	-357.59	-0.83*	8.40		-0.37	-30.85	0.63
	(0.60)	(0.03)	(0.23)		(0.17)	(0.23)	
Pastures - Dairy	31320.08*	-25.9*			-18.86*	4.30	0.86
	(0.00)	(0.00)			(0.01)	(0.99)	
Pastures - Hay	-7832.50	-25.02	118.81		-7.52	150.84	0.69
	(0.56)	(0.22)	(0.30)		(0.09)	(0.59)	

Note: * denotes significance at the 95% level

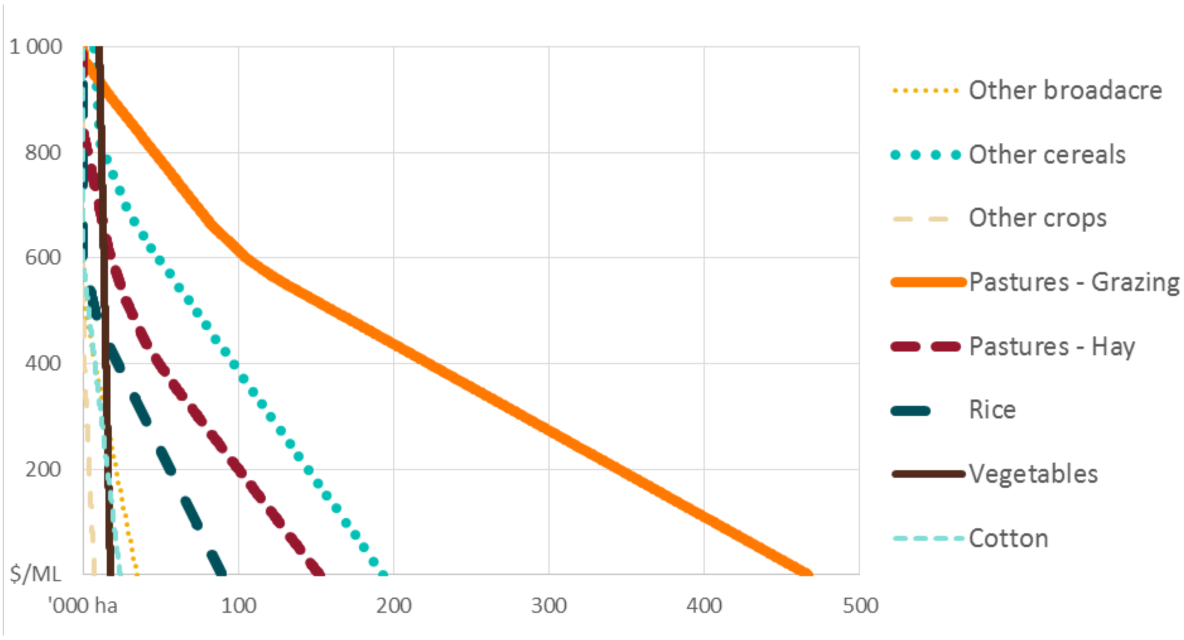
Table 13 Regression results for land use by irrigation activity, SA Murray

Industry	Constant	Price (P)	Output price (Y)	Cotton price (CY)	Rainfall (R)	Time (t)	R^2
Cotton-Rice							0.00
Vegetables	949.34	-1.50	44.37		-2.09	-290.05	0.20
	(0.89)	(0.42)	(0.45)		(0.51)	(0.34)	
Other broadacre	-275.08*		0.97		0.55*	1.03	0.76
	(0.02)		(0.14)		(0.00)	(0.78)	
Other cereals	965.14	-1.32	3.58		-0.80	-80.15	0.23
	(0.47)	(0.35)	(0.73)		(0.66)	(0.31)	
Other crops	-1946.17	-1.26	21.62		-0.05	-36.66	0.50
	(0.20)	(0.13)	(0.13)		(0.96)	(0.44)	
Pastures - Dairy	-349.26	-6.65	79.97		-3.71	-879.83	0.50
	(0.95)	(0.28)	(0.16)		(0.67)	(0.06)	
Pastures - Hay	489.24	-5.83*	21.20		-3.37*	-140.24*	0.79
	(0.75)	(0.05)	(0.11)		(0.02)	(0.00)	

Note: * denotes significance at the 95% level

Figure 3 shows total sMDB irrigated land use by activity against water price, based on the above estimated relationships (given mean rainfall and output prices). As expected, the total area of irrigation contracts as prices increase. Further, higher value activities such as vegetables are less sensitive to changes in price in comparison with lower value activities like pasture.

Figure 3 Annual land use as a function of water allocation price, by irrigation activity



Note: Cotton, Fruits and Grapevines are exogenous and not dependent on the water allocation price.

Water application rate

To estimate the parameters in equation 3 we fit the following regression model by irrigation activity j pooling the data for each region:

$$W_{ijt}/L_{ijt} = \beta_{0j}^{W} + \beta_{1j}^{W}.P_{it} + \beta_{2j}^{W}R_{it} + \beta_{3j}^{W}Y_{it} + \beta_{4j}^{W}.t + \boldsymbol{\beta}_{5j}^{W}.\mathbf{I} \qquad (11)$$

Where $\mathbf{I}$ is a vector of dummy variables identifying the regions i (with the Murrumbidgee region omitted). Any observations with an implied application rate W_{ijt}/L_{ijt} of greater than 20 ML / ha are omitted. In addition the following constraints are applied:

$$\beta_{1ij}^{W} < 0, \beta_{2ij}^{W} < 0, \beta_{3ij}^{O} > 0$$

That is, water demand (for a given land area) must be downward sloping, rainfall must be a substitute for irrigation water and water demand must be increasing in response to an increase in output prices. Results are shown in Table 14.

An additional term was included for the Fruits and nuts industry in VIC Murray: an interaction between the VIC Murray region dummy and time t. This term was included to account for the large exogenous increase in the water application rate observed in this region, likely due to an expansion in almonds (see Hughes et al. 2016). Ideally, nuts would be included as a separate activity in the model. Data is not currently available to support this, but could become available in the future (see chapter 6).

An interaction term between the allocation price and rainfall was used for grapevines and other broadacre irrigation activities. This term accounts for non-linear responses to changes in allocation price during drought or wet years for these activities.

The parameter for allocation price did not meet the constraint for cotton, grapevines, other broadacre, other crops and pastures – hay irrigation activities (Table 14). However water use for these activities remains dependant on allocation price which is an explanatory term for irrigated land use.

Table 14 Regressions results for water application rate by irrigation activity

Industry	Constant	D0	D1	D2	D3	D4	D Fruits	Price (P)	Output price (Y)	Rainfall (R)	I RP	Time (t)	R^2
Cotton	10.962*	-0.981	-4.59E-15		-1.377*	-0.749				-0.006*		0.032	0.60
	(0.00)	(0.11)	(0.00)	(0.00)	(0.00)	(0.15)				(0.00)		(0.65)	
Grapevines	6.982*	-1.767*	-0.741	-0.147	-0.330	-0.290				-0.007*	-6.67E-06	0.104*	0.61
	(0.00)	(0.00)	(0.15)	(0.77)	(0.45)	(0.50)				(0.00)	(0.00)	(0.02)	
Rice	9.806*	-2.259*	1.45E-15	-2.929*	-1.191*	-1.799*		-0.002	0.012*	-0.003*		0.031	0.52
	(0.00)	(0.00)	(0.00)	(0.00)	(0.04)	(0.00)		(0.20)	(0.00)	(0.02)		(0.70)	
Fruits	7.077*	-0.087	2.011*	0.100	0.108	-0.030	0.261*	-0.002*	0.006	-0.007*		0.079	0.47
	(0.00)	(0.88)	(0.00)	(0.86)	(0.82)	(0.97)	(0.02)	(0.02)	(0.57)	(0.00)		(0.20)	
Vegetables	6.392*	-0.617	0.685*	-0.038	0.537	-0.547		-0.001		-0.003*		-0.053	0.57
	(0.00)	(0.07)	(0.05)	(0.91)	(0.07)	(0.07)		(0.14)		(0.00)		(0.09)	
Other broadacre	1.054	-1.301*	-0.647	-1.214*	-1.590*	-1.352*			0.028*		-9.63E-06	-0.171*	0.24
	(0.10)	(0.00)	(0.09)	(0.00)	(0.00)	(0.00)			(0.00)		(0.00)	(0.00)	
Other cereals	3.924*	-1.148*	-1.719*	-1.068*	-1.627*	-1.363*		-0.001*		-0.001*		0.004	0.60
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)		(0.00)		(0.00)		(0.84)	
Other crops	4.881	-0.836	0.517	-0.269	-0.402	0.155			0.017	-0.001		-0.339*	0.66
	(0.21)	(0.34)	(0.57)	(0.76)	(0.63)	(0.84)			(0.58)	(0.34)		(0.00)	
Pastures - Dairy	3.743*	0.852*	1.727*	0.527*	-0.190	0.687*		-0.001*		-0.002*		-0.022	0.57
	(0.00)	(0.00)	(0.00)	(0.03)	(0.36)	(0.00)		(0.01)		(0.00)		(0.34)	
Pastures - Hay	4.103*	-0.559*	0.968*	-0.537*	-0.616*	-0.543*				-0.002*		0.028	0.55
	(0.00)	(0.02)	(0.00)	(0.02)	(0.00)	(0.01)				(0.00)		(0.14)	

Note: **D0** = dummy for VIC Goulburn-Broken, **D1** = dummy for SA Murray, **D2** = dummy for VIC Loddon-Campaspe, **D3** = dummy for NSW Murray, **D4** = dummy for VIC Murray. **D Fruits** = interaction term with time for Fruits in the VIC Murray region. **RP** = interaction term for rainfall and price for Grapevines and Other broadacre. * denotes significance at the 95% level

The water application rate is combined with land use to estimate the corresponding total water use by region and by irrigation activity (equation 4). Figure 4 shows the demand curve for water across all regions for each irrigation activity (holding other predictors at sample average values). As would be expected, rice, other broadacre, other crops and pastures – hay are observed to be relatively price elastic while fruits, grapevines and vegetables are relatively price inelastic.

Figure 4 Total water use as a function of water allocation price, by irrigation activity

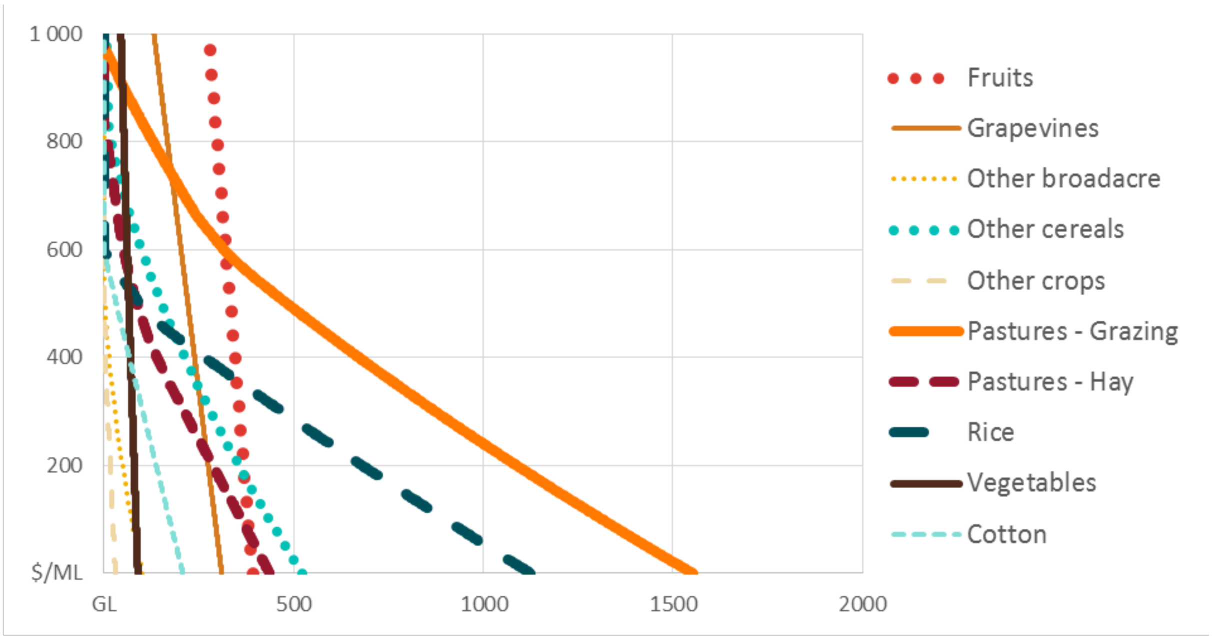
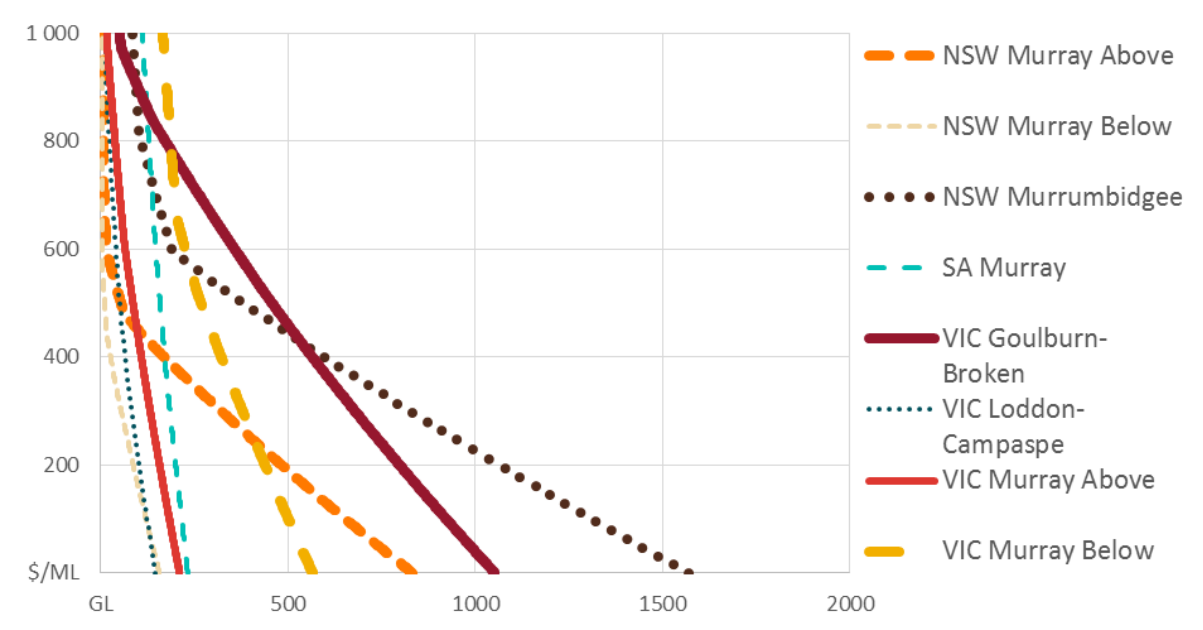


Figure 5 shows the corresponding demand functions for water by region. NSW Murrumbidgee water demand is relatively elastic given the high proportion of Rice, while SA Murray is relatively inelastic given the high proportion of horticultural activity.

Figure 5 Total water use as a function of water allocation price, by region



Water demand in the NSW Lower Darling

Given the relatively small amount of irrigation activity in the NSW Lower-Darling region, and problems of measurement error in the available data (see Hughes, et al. 2016) reliable estimates could not be obtained using the models outlined above. Instead a single aggregate demand curve was fit for NSW Lower Darling region. The specification for this is follows Hughes et al. (2016) (equation 12). The resulting model estimation is shown in Table 15.

$$\log P_t = \beta_0 + \beta_1 . A_t + \beta_2 R_t \qquad (12)$$

Table 15 Regressions results for water allocation demand, NSW Lower Darling

Dependant variable	Constant	Allocation water use (A)	Rainfall (R)
log (Price)	4.52	-5.32E-06	-4.01E-04

Other water

Net other water is econometrically estimated according to equation 13:

$$\hat{O}_{it} = \beta^O_{0i} + \beta^O_{1i} . P_{it} + \beta^O_{2i} R_{it} + \beta^O_{3i} . t + e_{it} \qquad (13)$$

$$\beta^O_{1i} > 0$$

$$O_{it} = \widehat{W}_{it} - (A_{it} + \Delta_{it})$$

where e_{it} is the regression residual term and $\widehat{W}_{it}$ is the model predicted water use level for region *i*. Within the model the residual term in this equation is included as a region and time specific constant. This approach is a pragmatic way of maximising the within sample fit of the model for the baseline scenario (in the absence of a more formal structural estimation method). Regression results are presented in Table 16.

Table 16 Regressions results for other water use, by region

Region	Constant	Price (P)	Rainfall (R)	Time (t)	R^2
VIC Murray Above	-555842.2*	492.6*	346.2*	12864.1*	0.79
	(0.00)	(0.00)	(0.01)	(0.01)	
VIC Murray Below	-765222.8*	626.5*	757.7*	50379.5*	0.84
	(0.00)	(0.01)	(0.01)	(0.00)	
VIC Goulburn-Broken	-240955.9	302.3	147.8	28623.6*	0.64
	(0.08)	(0.06)	(0.48)	(0.00)	
VIC Loddon-Campaspe	84946.0*		-67.9	-48.6	0.20
	(0.00)		(0.12)	(0.98)	
NSW Murrumbidgee	717593.5	77.8	-1488.4	-4215.9	0.38
	(0.06)	(0.88)	(0.06)	(0.85)	
NSW Murray Above	-261218.7	536.8	499.2	-5896.9	0.23
	(0.35)	(0.15)	(0.37)	(0.67)	
NSW Murray Below	-334738.2*	351.0*	326.4	-1433.9	0.58
	(0.00)	(0.01)	(0.07)	(0.73)	
SA Murray	-371002.2*	273.6*	213.7	12470.0*	0.78
	(0.00)	(0.00)	(0.11)	(0.00)	

Note: * denotes significance at the 95% level

5 Validation

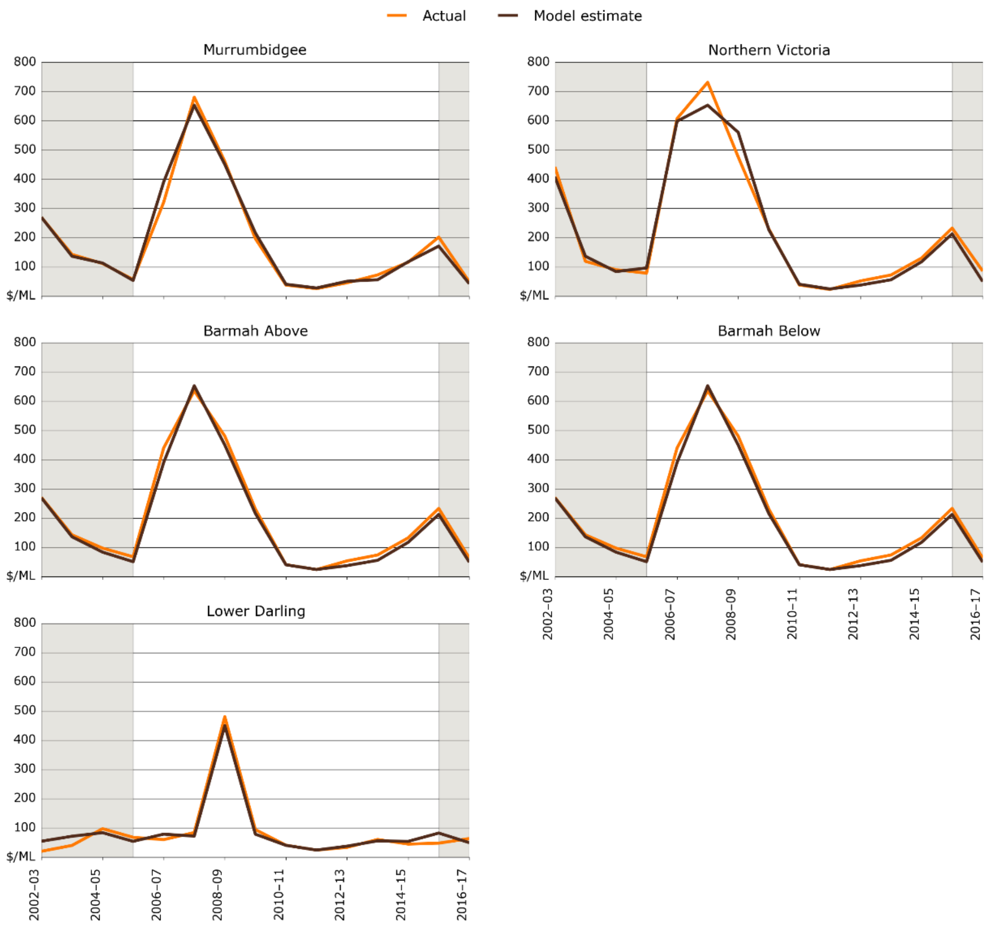
This chapter presents results for the model baseline scenario. In this scenario, model inputs such as water availability (water allocations, entitlements, carry-over), climate (rainfall) and commodity prices are based on historical conditions as defined by our dataset. Note that this scenario includes the effect on water availability of Commonwealth water entitlement recovery associated with the Basin Plan.

As discussed, model estimation uses the time period 2005–06 to 2015–16. However data is also available for all exogenous variables (water availability, climate and commodity prices) for all years 2002–03 to 2016–17. Therefore, model results are presented for the full period 2002–03 to 2016–17, with the years 2002–03 to 2004–05 and 2016–17 being out-of-sample predictions. Note that data is not available on perennial land areas for out-of-sample years, so these are assumed equal to the nearest available year.

Water allocation prices

Model results for water allocation prices accurately capture historical variation over time as well as differences between regions due to trade constraints. For example, the model is able to recreate higher prices in Northern Victoria and lower prices in NSW Lower Darling during drought years (Figure 6). Out of sample results for 2002–03 to 2004–05 and 2016–17 are indicated by the grey shaded bands in the figure.

Figure 6 Actual and modelled water allocation prices, by trading zone, 2002–03 to 2016–17



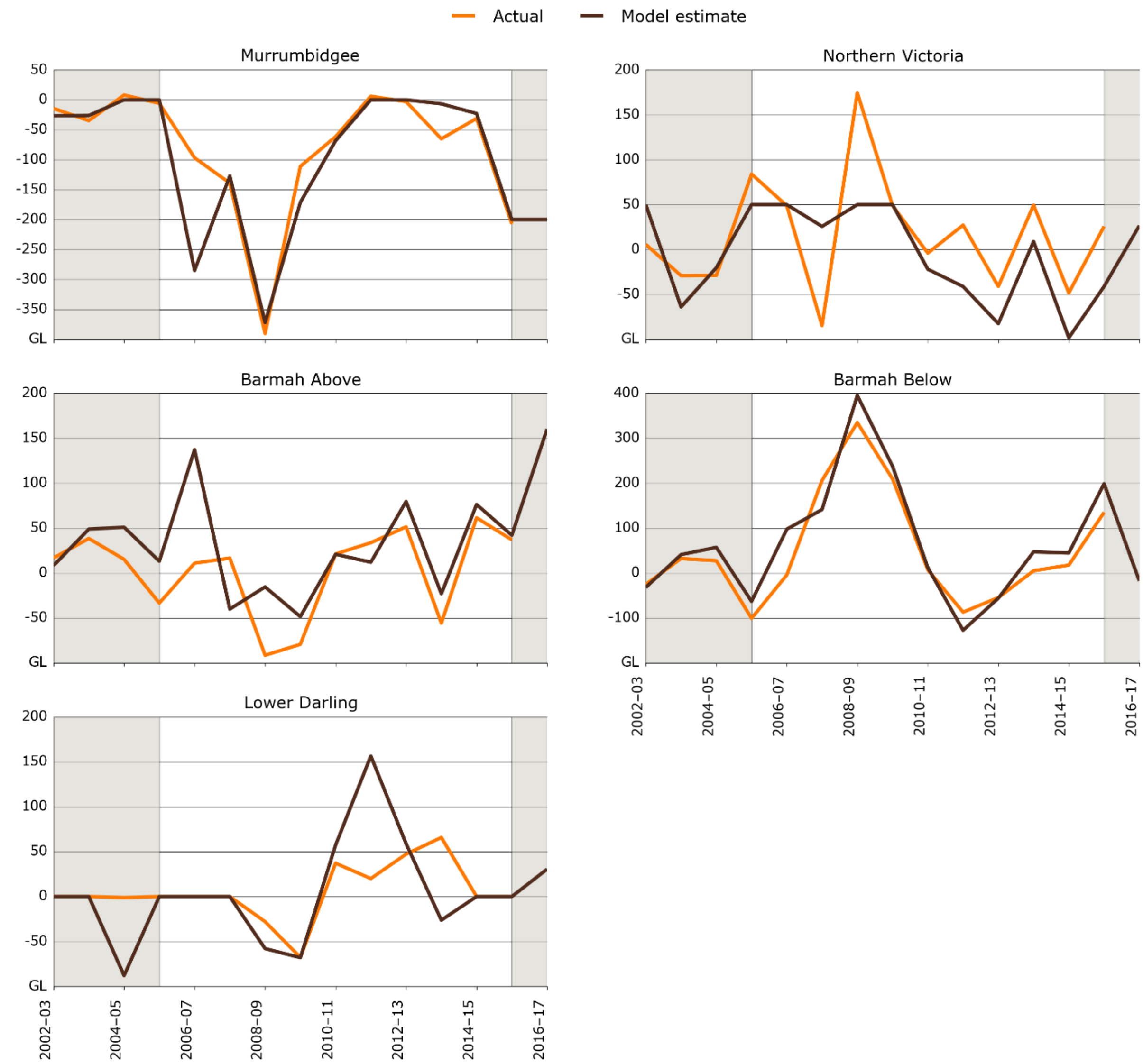
Note: Barmah above is the model trading zone 1; Barmah below is model trading zone 5.

Net trade flows

Replicating historical net trade flows is challenging given the model estimation does not include them as target variable. Further the modelled inter-regional trade flows are sensitive to the assumed trade constraints. While these have been specified to emulate historical trading conditions as much as possible, representing these constraints within the model is difficult given the annual time scale. As noted in previous research (Hughes et al.2016), limits can vary across and within years depending on river operation decisions, and changes in trading rules.

Notwithstanding these issues, the model does a reasonable job of matching historical trading patterns for most zones, including for example water exports from the Murrumbidgee and imports into the below Barmah Murray zone (i.e., SA Murray) during the drought (Figure 7).

Figure 7 Actual and modelled net inter-zonal trade, by trading zone, 2002–03 to 2016–17



Note: Barmah above is the model trading zone 1; Barmah below is model trading zone 5

Irrigation activity

Model results for total water use and land use are shown in Figure 8 and Figure 9. Trends in irrigated land use are reflected in total water use and the model is able to accurately recreate key historical trends. For example, a decrease in irrigated land use and water use during drought years, and an increase in irrigated land use for most years between 2008–09 and 2012–13.

Out of sample results, indicated by the grey shaded bands in each figure. While the out-of-sample performance is reasonable, the model tends to overestimate water use in South Australia and Victoria during the period 2002–03 to 2004–05. However, it is worth noting that for the years 2002–03 to 2004–05 ABS data was only available for Statistical Division (SD) region level (rather than the NRM regions that applied from 2005–06). This creates something of a structural break in the data which could contribute to this poor performance. This data issue could be addressed in future research (see chapter 6).

Figure 8 Actual and modelled total water use, by region, 2002–03 to 2016–17

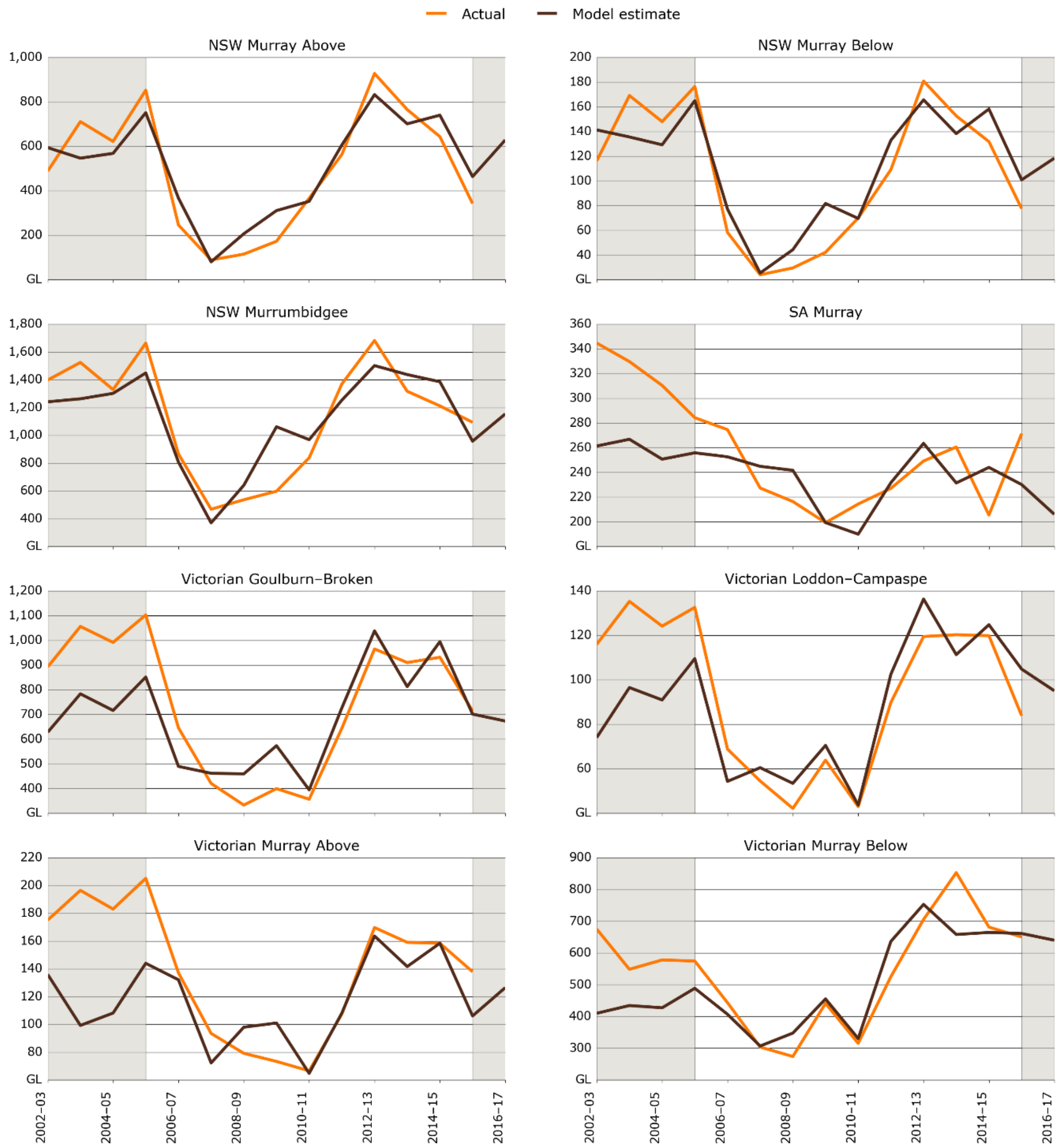
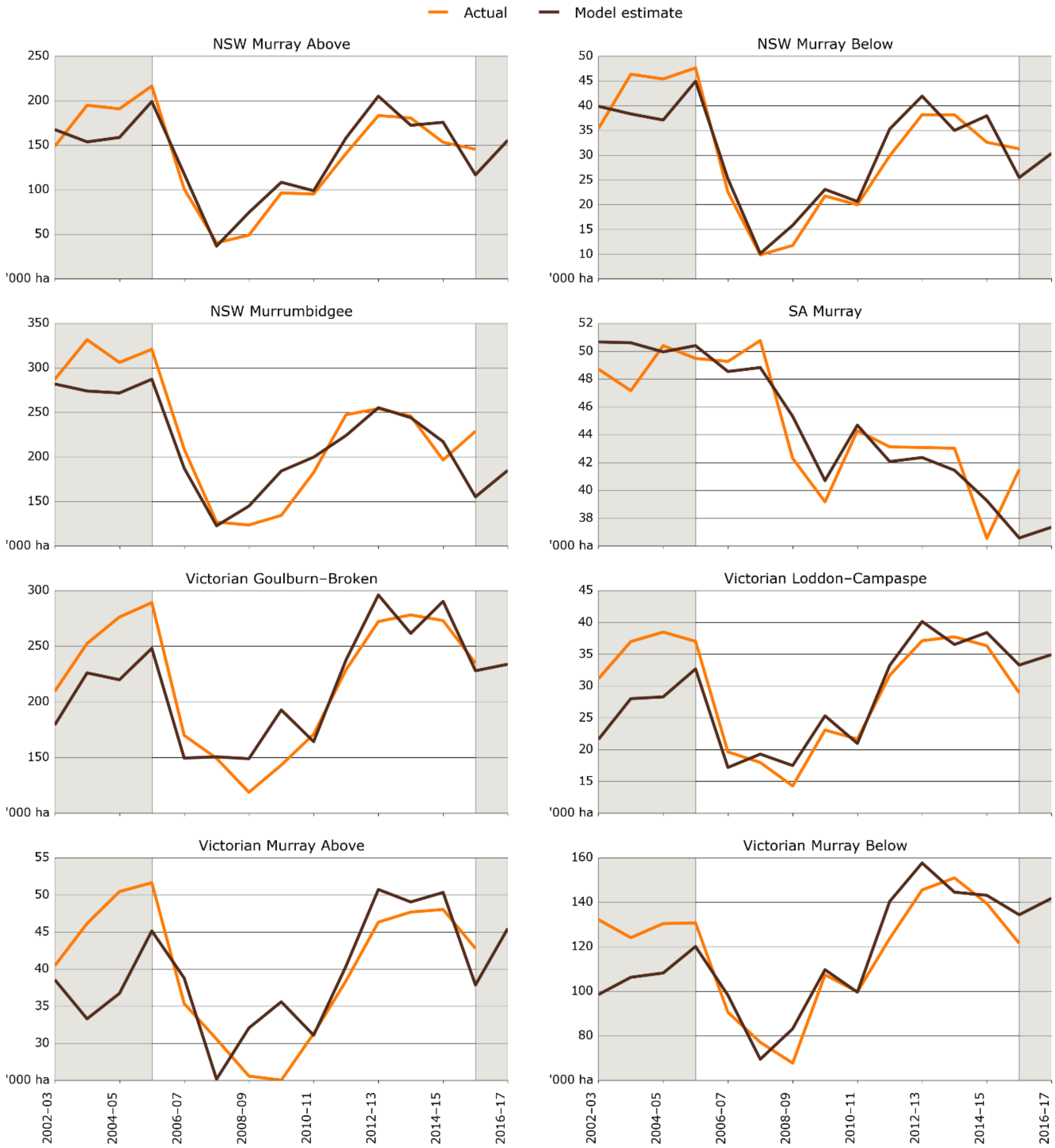


Figure 9 Actual and modelled total irrigated land use, by region, 2002–03 to 2016–17



Entitlement prices

As discussed, entitlement prices are estimated as the discounted value of allocations, based on average allocation prices and percentages over the full model period. In order to predict current water entitlement prices, the model baseline is adjusted such that current levels of environmental water recovery are applied from the beginning of the period, to simulate likely allocation prices going forward.

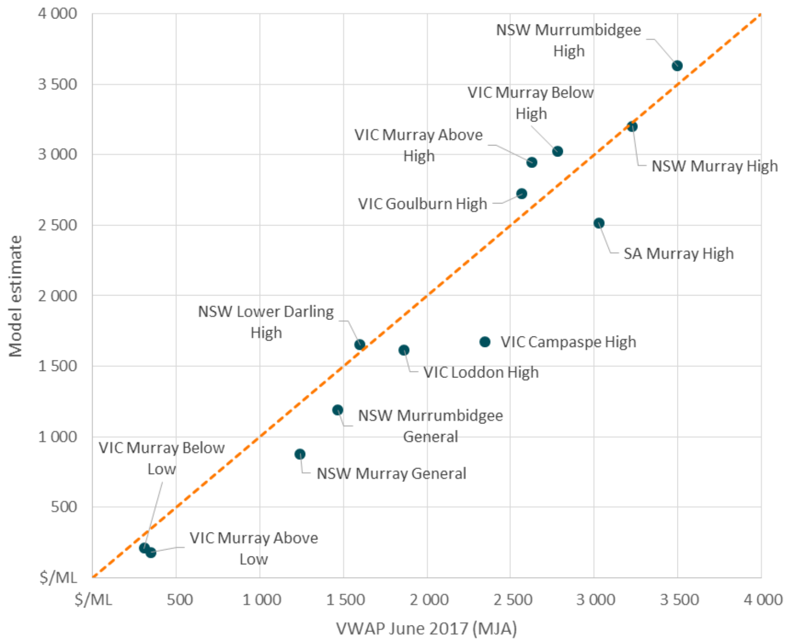
Table 17 shows the estimated entitlement prices for different entitlement types compared with market prices as of June 2017. Figure 10 provides a scatter of actual vs predicted entitlement. The models simple methodology for estimating entitlement prices is able to explain much of the variation in entitlement prices between regions and reliability types. However, it should be noted that the ability of the model to predict changes in entitlement prices over time has not been tested. In practice, predicting future changes in entitlement prices is difficult, given these depend on market expectations of future water supply and demand conditions (including potential changes in irrigated land use, climate and water demand).

Table 17 Actual and modelled entitlement prices, as at June 2016

Entitlement type	Model estimate ($/ML)	Market price – June 2017 ($/ML)
NSW Lower Darling General	1104	
NSW Lower Darling High	1654	1600
NSW Murray General	880	1241
NSW Murray High	3204	3228
NSW Murrumbidgee General	1188	1468
NSW Murrumbidgee High	3631	3500
SA Murray High	2518	3029
VIC Campaspe High	1675	2346
VIC Goulburn High	2723	2567
VIC Loddon High	1613	1862
VIC Murray Above High	2944	2629
VIC Murray Above Low	181	348
VIC Murray Below High	3024	2781
VIC Murray Below Low	201	307
NSW Murray Above High	3165	
NSW Murray Above General	867	
NSW Murray Below High	3244	
NSW Murray Below Low	893	

Note: Historical prices sourced from Marsden Jacobs and Associates (MJA) data provided to the Department of Agriculture and Water Resources. Estimates for NSW Murray entitlement prices are calculated as an average of NSW Murray Above and NSW Murray Below prices.

Figure 10 Modelled entitlement prices compared to actual prices



Performance of the baseline scenario

The correlation between model estimates and actual data for key outputs, measured by the R-squared, is shown in Table 18. Results are presented across regions and irrigation activities for the water allocation price, and irrigated area and water use.

The in-sample results presented in Table 18 correspond to the sample used for econometric estimation: 2005–06 to 2015–16 or 11 years. The out of sample results correspond to the periods 2002–03 to 2004–05 and 2016–17 (4 years) and the full sample refers to the complete modelling period from 2002–03 to 2016–17 (15 years). In general the R-squared values in Table 18 suggest that a high degree of variance in actual data can be explained by the ABARES water trade model for a range of outputs.

Table 18 Correlation between model estimates and actual data for key modelling outputs

Variable	R-squared		
	In-sample	Out-of-sample	Full sample
Water allocation price (by region and year)	0.98	0.97	0.98
Land use (by region, irrigation activity and year)	0.96		
Land use (by region and year)	0.96	0.96	0.96
Water use (by region, irrigation activity and year)	0.92		
Water use (by region and year)	0.93	0.89	0.94

6 Conclusions

This paper presents an economic model of water trade and irrigation activity within the southern Murray-Darling Basin (sMDB). This model combines two previously competing approaches to estimating water demand: econometric analysis of water market data and bio-physical optimisation models. The model is able to simulate the water market prices and water trade flows across regions taking into account constraints on inter-regional allocation trade. The model parameters are estimated econometrically given historical data on water market outcomes and irrigation water demand.

The data-driven approach adopted for this model has a number of advantages:

- The model provides a wide range of outputs including both water market outcomes (prices of allocations and entitlements) and irrigation sector outcomes (water and land use)
- Validation tests demonstrate the model can accurately simulate historical data both within and out-of-sample.
- Water demand responses broadly conform to expert expectations and literature; for example, more elastic responses in broadacre activities and more inelastic responses in horticulture.

The approach adopted in this study also has some limitations. Firstly, the data used in this study are subject to measurement error, given changes within statistical collections across time and differences between data sources. Secondly, given water demand is estimated in reduced form (rather than from a model of farm production) the model is not well suited to extrapolating to price levels or climate conditions significantly outside of historically observed ranges.

Third, the model is short-run in nature simulating annual changes in water demand holding capital investment in the irrigation sector exogenous. As such, the model is not suitable for predicting longer-term structural changes in the industry (such as future changes in the mix of annual and perennial crops), although the model can be used to explore and assess user defined scenarios around these issues (as discussed below).

Future model development

One direction for future work would be to improve the dataset, particularly the irrigation water and land use data. ABARES has recently established an agreement with the ABS (in accordance with ABS legislative provisions) that provides access to unit-record (farm level) data from ABS agricultural census and surveys. This data access provides a number of exciting possibilities: including generation of more accurate catchment level statistics, addition of new industry categories (such as nuts), and even farm level water demand modelling.

A second direction for future work would be to improve the estimation methods, in particular to adopt a structural estimation approach, where all model equations are simultaneously fit to the data (as opposed to the equation by equation OLS approach currently employed).

Third, there are a number of features that could be added to the model some of which are currently under development:

- Output supply responses: predicting irrigation output supply or production (e.g., GVIAP) as a function of water prices, rainfall and output prices.

- Carryover: predicting user carryover behaviour as a function of water prices, rainfall and output prices.
- Extending the model to other regions (such as the northern MDB) and industries (such as nuts) depending on data availability.
- Diversions: including estimates of water diversions by catchment, as a function of farm regional water use, prices and rainfall.

Potential applications

The model has a number of potential applications including:

- **Past and future water policy changes:** the model could be used to examine the effects of historical water policy changes on water markets and the irrigation sector – such as environmental water recovery associated with the Murray-Darling Basin plan.
- **Water availability:** the model could examine the implications of changes in water availability associated with climate variability and change.
- **Inter-regional water trade constraints:** the model could be used to simulate the effects of changes to interregional water trade constraints on water markets – for example the Murrumbidgee IVT rule.
- **Changes in perennial plantings:** the model could be used to simulate the effects of future increases or changes in the mix and location of perennial plantings. For example the model could evaluate the implications of expanded investment in nuts in the Victorian Murray region.
- **Annual projections:** the model could also be used to project future allocation prices and trade flows given assumptions on future allocation and rainfall levels.

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Appendix A: Dataset construction

This appendix details the construction of various datasets used in this report. Table A1 summarises some of the key datasets and their sources.

Table A1 Data variables and sources

Variable	Description	Units	Time period	Source
Rainfall	Average rainfall by region and year	mm	2002–03 to 2016–17	BOM
End-of-period water allocation percentage	Allocation percentages by entitlement type, region and year	%	2002–03 to 2016–17	State governments
Carryover	Carryover percentages by entitlement type, region and year	%	2002–03 to 2016–17	State governments, CEWO
Water entitlement volume	Entitlement volume by type, region and year	ML	2002–03 to 2016–17	State governments, DAWR
Net inter-regional water allocation trade	Allocation trade between water trade model regions	ML	2002–03 to 2015–16	MDBA
Water allocation price	Allocation trade prices by region and year	$/ML	2002–03 to 2016–17	State water registries/ water exchanges
Water use	Total water use by region, industry and year	ML	2005–06 to 2015–16	ABS
Land use	Total land use by region, industry and year	HA	2005–06 to 2015–16	ABS
Commodity prices	Gross unit value or price indices for activities by industry and year	$/ton *or* indexed value	2002–03 to 2016–17	ABARES
Non allocation water use	Primarily groundwater and unregulated surface water use by region and year	ML	2002–03 to 2015–16	ABS

Rainfall

Rainfall estimates are based on average annual rainfall (in millimetres) across national land use and management (NLUM) and catchment-scale land use (CLUM) irrigated areas in each region in the water trade model. Figure A1 shows the average rainfall index (based on irrigated area in each region) across the entire sMDB. The drought years in the sMDB are 2001–02, 2002–03, 2005–06, 2006–07, 2007–08 and 2008–09. The wet years are 2010–11 and 2011–12, which also led to higher storage volumes and allocation announcements in 2012–13 and 2013–14, despite relatively lower rainfall.

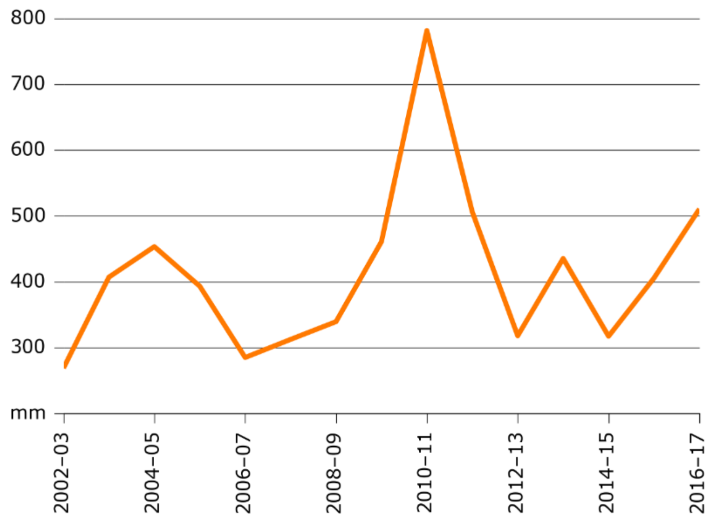
Notes on construction

- The irrigated areas are defined as those 5 kilometre grid cells where at least 10 per cent of the cell contained irrigated land use in at least one of the NLUM (2000–01, 2005–06 or 2010–11) or 2015–16 CLUM areas. The concordance between rainfall, irrigated area and water regions is shown for 2015–16 in Map A1.

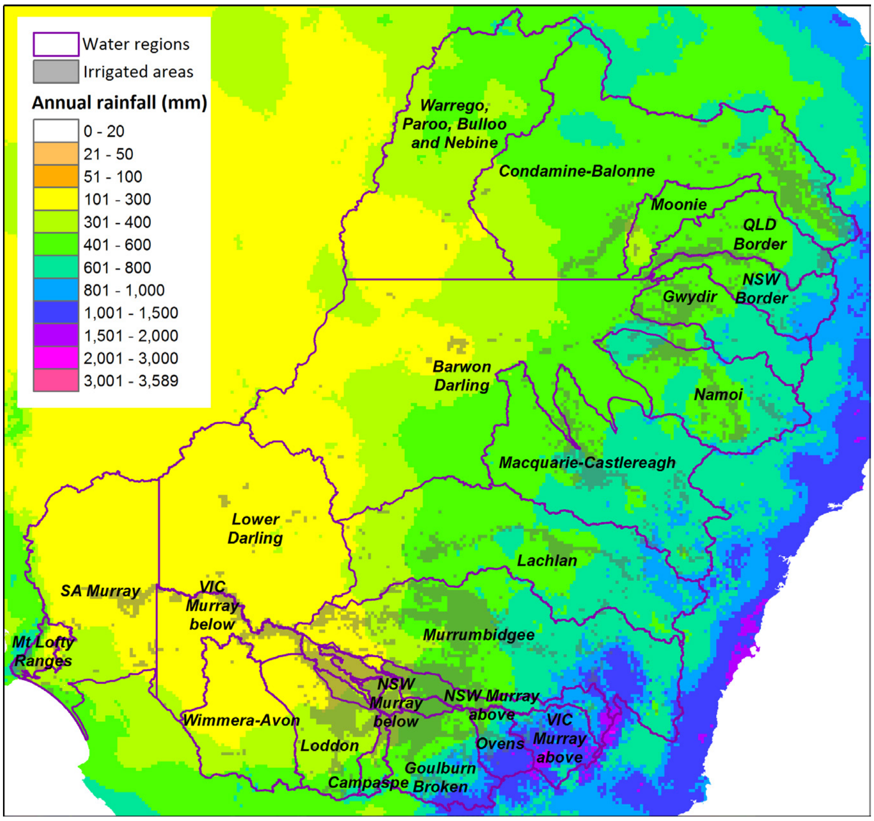
Sources

- Rainfall data available from the Bureau of Meteorology's latest rainfall maps (BOM 2017).
- NLUM/CLUM data available from ABARES land use data page (ABARES 2016a).
- ABARES water regions based on CSIRO Murray-Darling Basin Sustainable Yields Project boundaries (CSIRO 2008), adjusted for trade rules and the Barmah Choke (available on request).

Figure A1 Average rainfall index across the sMDB, 2000–01 to 2015–16



Map A1 Rainfall, irrigated areas and water regions, 2015–16



Allocations and carryover

The allocations dataset used for this report was previously prepared for Hughes, Gupta & Rathakumar (2016) on a daily time step from 1 July 2000 to 30 June 2017.

Data for the Barmah Choke

Entitlement volumes and environmental purchases for the NSW Murray and VIC Murray regions are apportioned above and below the Barmah Choke using the proportion of entitlements on issue (Table A2).

Table A2 Proportion of entitlements on issue above and below the Barmah choke, by type

Entitlement type	Proportion
NSW Murray Above General	0.78
NSW Murray Below General	0.22
NSW Murray Above High	0.14
NSW Murray Below High	0.86
VIC Murray Above High	0.32
VIC Murray Below High	0.68
VIC Murray Above Low	0.32
VIC Murray Below Low	0.68

Sources

- Entitlements, allocations and carryover:
  - NSW Department of Primary Industries - Water (DPI 2017b) water accounting reports,
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- Environmental water:
  - Commonwealth Environmental Water Office (CEWO) Annual carryover reports and website (CEWO 2017),
  - Department of Agriculture and Water Resources (DAWR) Volumes of water entitlements secured by the Commonwealth in the MDB.

Water allocation prices

Monthly water prices were obtained for the Murray, Murrumbidgee, Northern Victoria and Lower-Darling trading zones for the period July 2000 to June 2017. Earlier estimates – in particular before 2007–08 – are sourced from various water exchanges. Annual prices, unless otherwise specified, are calculated as the average of monthly prices. Further detail on the construction of this dataset can be found in Hughes, Gupta & Rathakumar (2016).

ABS data

Water and land use by region, industry and year is taken from ABS agricultural data. The data was first constructed as a time series using annual ABS Agricultural Commodities and Water Use on Australian Farms NRM level data. The ABS data was apportioned from NRM regions to the regions used in the water trade model using geographical data sourced from:

- ABARES water catchment regions based on CSIRO's Murray-Darling Basin Sustainable Yields Project, adjusted for trade rules and the Barmah Choke,
- Irrigation areas from the NLUM and CLUM datasets,
- Victorian Department of Land, Water and Planning (VIC DELWP) trade zones,
- ABS natural resource management (NRM) regions.

Homogenising ABS industry definitions

- ABS agricultural industry definitions have changed over time. ABS agricultural industry data was first homogenised across years using the definitions specified in Table A.
- For use in the water trade model the homogenised time series data was grouped into the irrigation activities listed in Table A3. A detailed breakdown for matching irrigation activities for each ABS survey is listed in Table A4.

Table A3 ABARES industry labels and groupings for water trade model

ABS NRM data industry classification	Water trade model activity
Cotton	Cotton
Fruit trees, nut trees, plantation or berry fruits	Fruits
Grapevines	Grapevines
Nurseries, cut flowers and cultivated turf	Other crops
Other broadacre crops	Other broadacre
Other cereals for grain or seed	Other cereals
Other crops n.e.c.	Other crops
Pastures and cereal for grazing	Pastures - Dairy
Pastures and cereal for hay	Pastures - Hay
Pastures and cereal for silage	Pastures - Hay
Rice	Rice
Sugar cane	Sugar cane (excluded)
Vegetables for human consumption	Vegetables

Note: Alloc

Table A4 ABS agricultural industry definitions and ABARES labels

2011-12 ABS industry definitions	**ABARES labels**
Pastures (incl lucerne) and cereal crops used for grazing or fed off	Pastures and cereal for grazing
Pastures (incl lucerne) and cereal crops cut for hay	Pastures and cereal for hay
Pastures (incl lucerne) and cereal crops cut for silage	Pastures and cereal for silage
Rice	Rice
Other cereals for grain or seed	Other cereals for grain or seed
Cotton	Cotton
Sugar cane	Sugar cane
Other broadacre crops	Other broadacre crops
Fruit trees nut trees plantation and berry fruits	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption	Vegetables for human consumption
Nurseries cut flowers and cultivated turf	Nurseries, cut flowers and cultivated turf
Grapevines	Grapevines
Other crops	Other crops n.e.c.
Total	Total
2010-11 ABS industry definitions	**Final labels**
Total	Total
Pasture for grazing	Pastures and cereal for grazing
Pasture cut for hay	Pastures and cereal for hay
Pasture for seed	Other cereals for grain or seed
Cereal crops cut for hay	Pastures and cereal for hay
Cereal crops for grain or seed	Other cereals for grain or seed
Rice	Rice
Sugar cane	Sugar cane
Cotton	Cotton
Other broadacre crops	Other broadacre crops
Nurseries, cut flowers and cultivated turf	Nurseries, cut flowers and cultivated turf
Fruit trees, nut trees, plantation or berry fruits (excl. grapevines)	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption	Vegetables for human consumption
Vegetables for seed	Other crops n.e.c.
Grapevines	Grapevines
2009-10 ABS industry definitions	**Final labels**
Pasture and cereal crops used for grazing or fed off	Pastures and cereal for grazing
Pasture and cereal crops cut for hay	Pastures and cereal for hay
Pasture and cereal crops cut for silage	Pastures and cereal for silage
Rice	Rice
Other cereals for grain or seed	Other cereals for grain or seed
Cotton	Cotton

Sugar cane	Sugar cane
Other broadacre crops	Other broadacre crops
Fruit trees, nut trees, plantation or berry fruits	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption	Vegetables for human consumption
Nurseries, cut flowers and cultivated turf	Nurseries, cut flowers and cultivated turf
Grapevines	Grapevines
"2009-10"	Total
2008-09 ABS industry definitions	**Final labels**
Pasture for grazing	Pastures and cereal for grazing
Pasture cut for hay	Pastures and cereal for hay
Pasture cut for silage	Pastures and cereal for silage
Pasture for seed production	Other cereals for grain or seed
Cereal crops cut for hay	Pastures and cereal for hay
Cereal crops harvested for grain or seed	Other cereals for grain or seed
Cereal crops not harvested for grain seed or cut for hay	Pastures and cereal for grazing
Rice	Rice
Sugar cane	Sugar cane
Cotton	Cotton
Other broadacre crops	Other broadacre crops
Fruit trees, nut trees, plantation or berry fruits	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption	Vegetables for human consumption
Vegetables for seed	Other crops n.e.c.
Nurseries, cut flowers and cultivated turf	Nurseries, cut flowers and cultivated turf
Grapevines	Grapevines
"2008-09"	Total
2007-08 ABS industry definitions	**Final labels**
Pasture, cereal and other crops used for grazing	Pastures and cereal for grazing
Pasture, cereal and other crops cut for hay	Pastures and cereal for hay
Pasture, cereal and other crops cut for silage	Pastures and cereal for silage
Rice	Rice
Other cereals for grain or seed	Other cereals for grain or seed
Cotton	Cotton
Sugar cane	Sugar cane
Other broadacre crops	Other broadacre crops
Fruit trees, nut trees, plantation or berry fruits	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption or seed	Vegetables for human consumption
Nurseries, cut flowers and cultivated turf	Nurseries, cut flowers and cultivated turf
Grapevines	Grapevines
2006-07 ABS industry definitions	**Final labels**
Pasture for grazing [incl. subcategories]	Pastures and cereal for grazing

Pasture harvested for hay (including lucerne), silage or seed	Pastures and cereal for hay
Cereal crops harvested for grain or seed	Other cereals for grain or seed
Cereal crops cut for hay or for grazing or fed off	Pastures and cereal for hay
Rice	Rice
Sugar cane	Sugar cane
Cotton	Cotton
Other broadacre crops	Other broadacre crops
Fruit trees, nut trees, plantation or berry fruits	Fruit trees, nut trees, plantation or berry fruits
Vegetables for human consumption or seed	Vegetables for human consumption
Nurseries, cutflowers or cultivated turf	Nurseries, cut flowers and cultivated turf
Grapevines	Grapevines
2005-06 ABS industry definitions	**Final labels**
Cereal crops cut for hay	Pastures and cereal for hay
Cereal crops for grain or seed	Other cereals for grain or seed
Cereal crops not for grain or seed	Pastures and cereal for grazing
Cotton	Cotton
Fruit trees, nut trees, plantation or berry fruits	Fruit trees, nut trees, plantation or berry fruits
Grapevines	Grapevines
Nurseries, cutflowers or cultivated turf	Nurseries, cut flowers and cultivated turf
Other broadacre crops	Other broadacre crops
Other crops	Other crops n.e.c.
Pasture for grazing	Pastures and cereal for grazing
Pasture for hay and silage	Pastures and cereal for hay
Pasture for seed production	Other cereals for grain or seed
Rice	Rice
Sugar cane	Sugar cane
Vegetables for human consumption	Vegetables for human consumption
Vegetables for seed	Other crops n.e.c.

Apportioning ABS NRM regional data

ABS water use and land use data is publically available by NRM region. ABARES apportioned this data into regions used in the water trade model

Changes in NRM boundaries

The NRM regions used by the ABS change over time. To apportion the ABS NRM regional data into water trade model regions, the following NRM boundaries were used for ABS water and land use data:

- 2008 NRM boundaries for the years 2007–08, 2008–09, 2009–10, 2010–11 and 2011–12;
- 2010 NRM boundaries for the year 2012–13;
- 2012 NRM boundaries for the years 2013–14, 2014–15 and 2015–16.

The only significant change between these regions is the dissolving of the Lower Murray Darling NRM region which does not appear in the 2012 boundaries and is largely replaced with the Western NRM region.

Methodology for apportioning NRM data

The values are calculated from the concordances of NRM regions to the regions used in the water trade model. The proportion of total irrigated area in a NRM region (according to the NLUM/CLUM areas for the relevant year) that overlaps with each water trade model region is calculated. Similar proportions are calculated for irrigated cropping area, irrigated horticultural area and irrigated pasture area for each of the 2008, 2010 and 2012 NRM regional boundaries.

As an example, the 2012 concordances are listed in Table A5 where the percentages indicate the proportion of water and land use in each NRM region that is captured in each water trade model region.

Irrigation activities (as defined in Table A3) were mapped to NLUM/CLUM land use categories as follows:

- Cotton - irrigated cropping area,
- Other broadacre - irrigated cropping area,
- Other cereals - irrigated cropping area,
- Other crops - irrigated cropping area,
- Rice - irrigated cropping area,
- Fruit - irrigated horticultural area,
- Grapevines - irrigated horticultural area,
- Vegetables - irrigated horticultural area,
- 'Pasture - Hay' - irrigated pasture,
- 'Pasture - Dairy' - irrigated pasture.

Notes on construction

- Irrigated pasture for grazing was assumed to be for the Dairy industry as it predominantly occurs in the dairying areas around the VIC Goulburn-Broken, VIC Loddon-Campaspe and VIC Murray regions.
- Pastures for hay and silage were combined due to their substitutability.
- ABS NRM data included a very small amount of sugar cane in the NSW Murray area, which was excluded from the model.
- In 2009–10 there is no data available from the ABS for irrigated area or water applied for grapevines in the SA Murray Darling Basin NRM region. This may relate to changes in survey methods for this year (Caboche T, Shafron W, Gunning-Trant C, Lubulwa M, Martin P, 2013). In the absence of this data ABARES has estimated land and water use for grapevines in SA Murray as follows:
    - For irrigated land use, a substitute value (23195.12 ha) was calculated by applying the percent decrease in land use for grapevines across the whole state (-5.5 per cent) to land use in 2008–09 (24428.77 ha).
    - For total water use, a substitute value (88141.46 ML) was calculated by applying the 2010–11 application rate (3.8 ML/ha) to the land use estimate given above.

Sources

- ABS Agricultural Commodities (Cat. No. 7121) for 2001–2016 (ABS 2017a).
- ABS Water Use on Australian Farms (Cat. No. 4618) for 2006–2016 (ABS 2016b).
- ABARES water regions based on CSIRO Murray-Darling Basin Sustainable Yields Project, adjusted for trade rules and the Barmah Choke (available on request).

Table A5 Percentage of irrigated area in NRM regions contained within water trade model regions, 2012 NRM boundaries

Water trade model region NRM Region	**Irrigated cropping area**	**Irrigated horticultural area**	**Irrigated pasture area**	**Total irrigated area**
Goulburn-Broken				
Goulburn Broken	78.57%	79.67%	80.24%	81.00%
Murray	0.00%	0.02%	0.00%	0.00%
North Central	54.10%	27.07%	46.73%	48.51%
North East	0.21%	0.21%	0.04%	0.12%
Port Phillip and Western Port	0.00%	0.00%	0.13%	0.05%
Loddon-Campaspe				
Corangamite	0.00%	0.32%	0.00%	0.06%
Glenelg Hopkins	0.00%	0.00%	0.05%	0.04%
Goulburn Broken	0.01%	0.07%	0.00%	0.01%
Mallee	1.79%	0.33%	0.45%	0.86%
North Central	17.66%	33.96%	14.13%	19.06%
Port Phillip and Western Port	0.15%	0.00%	0.00%	0.01%
Lower Darling				
Mallee	0.02%	0.02%	0.02%	0.02%
Murray	0.76%	50.36%	1.44%	4.52%
Murrumbidgee	0.00%	0.04%	0.03%	0.01%
Western	22.34%	58.84%	39.38%	25.58%
Murrumbidgee				
ACT	100.00%	100.00%	100.00%	100.00%
Lachlan	0.01%	0.00%	0.14%	0.04%
Murray	15.07%	7.39%	11.56%	14.57%
Murrumbidgee	99.95%	99.90%	99.92%	99.93%
Southern Rivers	0.00%	0.00%	0.01%	0.01%
NSW Murray Above				
Goulburn Broken	0.01%	0.00%	0.00%	0.00%
Murray	72.14%	28.82%	69.54%	65.36%
Murrumbidgee	0.00%	0.00%	0.00%	0.00%
North East	0.26%	0.00%	0.21%	0.19%

NSW Murray Below	Irrigated cropping area	Irrigated horticultural area	Irrigated pasture area	Total irrigated area
Goulburn Broken	0.00%	0.00%	0.00%	0.00%
Mallee	0.02%	0.00%	0.03%	0.01%
Murray	11.99%	13.28%	17.41%	15.49%
Murrumbidgee	0.04%	0.00%	0.00%	0.03%
North Central	0.03%	0.03%	0.05%	0.04%
SA Murray				
Adelaide and Mount Lofty Ranges	0.00%	0.01%	0.00%	0.01%
Northern and Yorke	0.00%	2.05%	0.79%	1.46%
SA Murray Darling Basin	55.64%	76.55%	40.82%	67.51%
South East	0.13%	0.38%	1.34%	0.89%
VIC Murray Above				
Goulburn Broken	21.41%	20.17%	19.75%	18.96%
Murray	0.01%	0.00%	0.01%	0.01%
North East	41.51%	25.78%	55.35%	45.95%
VIC Murray Below				
Mallee	85.66%	97.38%	91.65%	92.27%
Murray	0.02%	0.13%	0.04%	0.04%
North Central	27.94%	38.17%	38.93%	32.08%
SA Murray Darling Basin	0.00%	0.02%	0.01%	0.02%
Wimmera	1.09%	14.81%	0.00%	2.19%

Commodity prices

Annual commodity prices were sourced from the quarterly ABARES Agricultural Commodities publications. Given that in most cases the model activities capture a number of similar crop types, indexes are used to measure of commodity prices (taken from 'Indexes of prices received by farmers - Australia Table 1'). In the case of some specific crop types, commodity prices are measured as the gross unit values of farm products (taken from 'Gross unit values of farm products - Table 10').

The activities included in the model along with the corresponding source of commodity price data are listed in Table A6.

Notes on construction

- The 'total grains' price index is used for both cereals and broadacre activities as it includes both grains such as wheat, barley and sorghum as well as other broadacre crops such as lupins and canola. There are no separate indices for broadacre excluding cereals. However the prices of these crops are generally highly correlated through time.
- Prices for commodities are assumed to be the same across regions.

Sources

- ABARES commodity price indices and gross unit values available from ABARES Agricultural Commodities (ABARES 2017a).

Table A6 ABARES commodity price sources and model activity groups

Activity	ABARES commodity grouping	Units	Source table
Cotton	cotton	index	Table 1
Fruits	fruit	index	Table 1
Grapevines	wine grapes	gross unit value given in dollars per ton	Table 10
Other broadacre	total grains	index	Table 1
Other cereals	total grains	index	Table 1
Other crops	other crops	index	Table 1
Pastures - Dairy	milk	index	Table 1
Pastures - Hay	hay	index	Table 1
Rice	rice	gross unit value given in dollars per ton	Table 10
Vegetables	vegetables	index	Table 1

Source: ABARES agricultural commodities publications

Appendix B: Solution algorithm

Recall from chapter 3, that a solution to the model is defined by a set of equilibrium prices for each region P_{it}^{*} (or equivalently set of net trade volumes) which maximise water use benefits subject to satisfying the market clearing, water availability and water demand conditions:

$$\max_{P_{it}} \sum^{i \in I} \int_{A_{it}+\Delta_{it}} D_i^{-1}\,(W_{it}, \dots)$$

subject to:

$$W_{ijt} = d^{W}(.)$$

$$W_{it} = \sum^{j \in J} W_{ijt} = A_{it} + \Delta_{it} + O_{it}$$

$$\sum^{i \in I} \Delta_{it} = 0$$

$$\underline{\Delta}_{kt} \leq \Delta_{kt} \leq \Delta_{kt}$$

In equilibrium we know that for regions within a trading zone prices must be equal:

$$P_{kt} = P_{it}$$

for all i in I_k.

Secondly, we know that prices between trading zones must be equal if trade constraints are non-binding. We define the unrestricted market price P_t^{u} as the price applying in all regions where trade limits are non-binding. Further, we know (by assumption) that there is always at least one trading zone (i.e., Murray below Barmah) where net trade is unrestricted.

Next note that for any P_t^{u} we can compute net trade Δ_{kt} for each trading zone in the model:

$$\Delta_{it}^{u} = D_i(P_t^{u}, \dots) - O_{it} - A_{it}$$

$$\Delta_{kt}^{u} = \sum^{i \in I_k} \Delta_{it}^{u}$$

$$\Delta_{kt} = \min\{\max\{\Delta_{kt}^{u}, \underline{\Delta}_{it}\}, \overline{\Delta}_{kt}\}$$

A solution to the model is then given by the P_t^{u} which clears the market, such that

$$\sum^{k \in K} \Delta_{kt} = 0$$

Given the above conditions, P_t^{u} is obtained numerically in the model with a route finding algorithm.

Once P_t^{u} is obtained, prices for all other trading zones and regions can be determined. All unrestricted zones take P_{kt}^{u}

$$P_{kt} = P_t^u \text{ for } k \text{ where } \underline{\Delta}_{kt} < \Delta_{kt} < \overline{\Delta}_{kt}$$

For restricted trading zones prices can be computed as:

$$W_{kt} = A_{kt} + \Delta_{kt} + O_{kt}$$

$$P_{kt} = D_k^{-1}(W_{kt}, \ldots)$$

where P_{kt} is computed numerically by solving the following with a route finding algorithm:

$$W_{kt} = D_k(P_{kt}, \ldots)$$