Title: **Modelling the millennium drought in the southern Murray-Darling Basin and subsequent drought in California**

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Abstract

The irrigation regions of Australia's southern Murray-Darling Basin (SMDB) and California's Central Valley provide several contrasts. In the SMDB, reliance on groundwater is relatively limited. In drought, groundwater usage may double but it covers no more than one tenth or so of the shortfall in surface water availability. In the Central Valley, groundwater has compensated for a much larger share of the shortfall in surface water in the prolonged drought which started in 2013.

A common feature of the two irrigation regions is that they both have extensive irrigated infrastructure. But in allocating water, that is where the similarity ends. Ongoing reforms in Australia's water management have resulted in a separation of land and water ownership. With this have come water exchanges and local brokers and hence the ability to move water from annual to perennial activities during drought. In the Californian case, appurtenant water rights have provided a barrier to water trading. Such trading at best proceeds on an informal basis in thin volumes. The lack of water trading has an environmental consequence, with more wells being dug to provide water for existing plantations. This may worsen land subsidence and aquifer depletion.

1. Introduction

Dixon *et al*. (2011) introduced small region representation inclusive of water accounts, farm factor mobility and water trading to a CGE model. This advanced the modelling of the policy implications of Australia's Water Act (Australian Government 2007). Such a model came into being in response to observed data, which implied substantial flexibility in farm production in the Murray Darling Basin.

The Water Act remains controversial. Basin communities continue to struggle with structural change, varying commodity prices and drought. In the political dimension, the Water Act is often perceived of in Basin communities as external interference which is contributing to the undermining of the Basin's economy. This is not consistent with the actions of many farmers, who took the opportunity to sell part of their water entitlements to the Commonwealth government under the Act.

2. The Australian case: dynamic TERM-H2O

TERM-H2O modifications included water accounts, water trading between feasible trading users and regions, farm factor mobility and dynamics. A key part of being able to track large changes in water availability in TERM-H2O is to distinguish between relatively flexible annual crop production and relatively inflexible perennials. Fixed factors in perennials ensure that they become net buyers of water in drought simulations in TERM-H2O.

TERM-H2O was developed initially to model policy and drought scenarios in the SMDB. The need to make substantial modifications to the supply-side of a CGE model that includes water became apparent from water usage data prepared by ABS (2016). In the drought of 2002, water use in rice production dropped by more than 70% relative to the previous year whereas water used on perennials changed little. In 2008, water usage in rice production was only 2% of that in 2006. The challenge was to approximate observed changes in water usage and in water prices in CGE modelling of drought.

Table 1 shows the substantial variation in rainfall and runoff across the Murray-Darling Basin from 2007-08 to 2015-16. Some of the data shown in the table were not available at the time TERM-H2O was constructed. In particular, the relatively wet years of 2010-11 and 2011-12 occurred after the model was devised. The additional years of data serve to illustrate features of TERM-H2O that are useful in both dry and wet years.

2008-09 was the last season of the millennium drought in the southern basin; in the northern basin, the drought broke early in 2008. The water price shown reflects temporary water trades in the southern basin.[1] The water price reflects current water availability, rainfall conditions and farm output prices. For example, in 2007-08 prior to the GFC, a biofuels boom drove up crop prices and the marginal product of water with it. Table 1 (row 13) shows that the water price in 2008-09 was $298/ML with drought still prevailing in the southern basin, whereas in the previous year it was $680/ML prior to the GFC-induced collapse in commodity prices. Rice is the most water-intensive of crops grown in the basin and therefore the most responsive to changes in water price. In the past decade, the volume of water used in rice production has varied from 27 GL in 2007-08 to 1434 GL in 2012-13 (Table 1, row 3).

[1] Temporary water refers to a volume of water allocated in a single season. Permanent trades involve an exchange of a water right. An appendix in Dixon et al. (2011) calculates the asset price of permanent water based on expected temporary water prices.

Table 1 Water use in the Murray-Darling Basin

Year	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16
1Area irrigated ha*10^6	1.0	0.9	1.0	1.2	1.4	1.6	1.6	1.4	
2 Not irrigated ha*10^6	94.6	95.1	94.2	83.8	93.6	88.4	89.1	87.8	
Crop	Water used (GL)								
3 Rice	27	101	205	755	1134	1434	912	876	
4 Cotton	283	793	764	1789	1906	2735	2676	1114	
5 Other annuals	1044	1066	719	537	725	1334	1368	1226	
6 Grapes	434	439	428	303	365	463	415	431	
7 Other perennials	356	374	450	379	475	567	713	502	
8 Pasture, hay, silage	997	719	998	744	1270	2041	1941	2025	
9 Total	3141	3492	3564	4507	5875	8574	8025	6174	
	Source (GL)								
10 Irrigation schemes	NA	1573	1830	1705	2768	4228	3494	3212	
11 Groundwater	NA	1069	989	570	568	686	863	844	
12 Other (dams, creeks,	NA	850	745	2232	2539	3660	3668	2118	
13 Water price	680	298	148	26	16	47	66	118	208

Source: ABS Cat. 4618.0, various years.

*http://www.murrayirrigation.com.au/water/water-trade/water-exchange-history/ provides Murray Irrigation weighted sales which are reasonable indicators of average weighted southern MDB trading prices.

Table 1 has embedded in it other aspects of on-farm water management. A La Nina event resulted in two years of record rain surpluses in a substantial part of the basin for the period ending June 2012.[2] This replenished dams under the jurisdiction of irrigation authorities, filled creeks and dams from which farmers extracted water (see Table 1, row 12) and also replenished groundwater supplies. An amendment to the Water Act in 2011 introduced carryover provisions for annual water allocations: these enable irrigators to make on-farm allocation decisions independent of irrigation authorities.[3] Following the wet two year period, some water allocations from those years were used in the three years from 2012-13 to 2014-15.

Another feature of Table 1 is that although groundwater extractions increase when water becomes scarce, they are not sufficient to counter shortfalls in water allocations. For example, in 2008-09 when the southern basin was still in drought, groundwater extractions amounted to 1069 GL. In 2012-13, when total water used was 5000 GL more than in 2008-09, groundwater extractions were only 383 GL less (Table 1, rows 9 & 11). That is, changes in groundwater extractions fall far short of offsetting fluctuations in volumes diverted from other irrigation sources. This contrasts with the California case, in which groundwater extractions make up for a much larger share of the surface water shortfall during drought.

Turning to perennials, water used for grapes dropped below 400 GL only in the La Nina years 2010-11 and 2011-12, when rainfall was sufficiently high to reduce irrigation requirements (Table 1, row 6). The upward trend in water used by other perennials reflects a substantial increase in almond plantings since 2007.[4]

Table 1 also shows water used in pasture, hay and silage (row 8). These feed products are either inputs into livestock production locally, or are sold outside the basin. The table shows a 40-fold difference in the price of water between 2007-08 (i.e., $680/ML) and 2011-12

[2] See http://www.bom.gov.au/jsp/awap/rain/archive.jsp?colour=colour&map= decile&year =2012&month=6&period=24month&area=md (accessed 29 August 2016).

[3] See and http://www.mdba.gov.au/about-us/governance/water-act (accessed 6 September 2016).

[4] See http://growing.australianalmonds.com.au/wp-content/uploads/sites/17/2014/06/ Australian-Almond-Insights-2013-14-LR-WEB.pdf (accessed 29 August 2016).

($16/ML) (Table 1, row 13). Even in drought when the price of livestock feed rises, it is highly probable that a livestock farmer within the basin would gain by selling water to fund feed purchases instead of using scarce water to grow on-farm livestock feed.

2.1 Devising appropriate model theory from observed data

Table 1 points us to the necessary features of our CGE model of irrigation activity, TERM-H2O. First, we require a split between dry-land and irrigated agriculture. The table (lines 1 & 2) indicates that irrigation makes up less than 2% of the land used in agriculture in the basin. ABS (2008) estimate that around 30% of agricultural output in the basin arises from partly or wholly irrigated activity, and exclusively dry-land agriculture accounts for the remaining 70%. Lines 1 & 2 of the table show that the area of dry-land and irrigated agriculture varies from year to year, depending on water availability and output market conditions. This indicates that the theory of our model requires some mobility of irrigable land between irrigated and dry-land technologies.

As mentioned above, line 6 of Table 1 indicates that rainfall variability alters irrigation water requirements. Water availability and rainfall are exogenous in the CGE model, but we need to distinguish between the two. That is, if there is a rainfall deficit, we need to shock water supply in the model, which will lead to substitution away from water in the production function of the irrigated industry. We treat impacts in dry-land agriculture differently, by ascribing production shocks to depict the impact of drought.

Wide variation from year to year in water usage for rice and cotton indicate that we require flexibility in allocation of farm factors for annuals. Line 5 of Table 1 refers to other annuals which are less water-intensive, particularly vegetables. Since water is a smaller share of the total costs of production for other annuals, the responsiveness to changes in the water price is smaller than for rice or cotton. As was the case for grapes, other annuals used less water than usual in 2010-11 and 2011-12 due to above average rainfall. Cotton is split into two technologies, dry-land and irrigated, since it can be grown without irrigation in wet seasonal conditions.

Given the substantial investments that go into establishing vineyards and orchards, we need to depict factor rigidity in perennials. When water is scarce, as was evident in 2007-08 and 2008-09, perennial sectors purchase water from other users in response to diminished water allocations. Even if the water price soars, the costs of destruction to perennial plantations in terms of foregone future income may far exceed the additional water costs in a water-scarce year. Factor rigidity is imposed by including specific capital for perennials, whereas annuals use capital that is mobile between different farm activities.

Specific capital (i.e., the herd) in also used in livestock production. TERM-H2O includes substitutability between irrigated land and feed inputs in livestock production. We can model a similar response by including hay & forage as a substantial input to livestock production. In turn, hay & forage is split into dry-land and irrigated technologies. The specific capital in livestock production ensures that the producer response to worsening water scarcity is to substitute either from irrigated land to feed inputs in the case of TERM-H2O or, as in the modified version of USAGE-TERM outlined in section 3, from irrigated feed inputs on-farm to feed purchased from elsewhere.

Changes in relative output prices alter the allocations of mobile capital, operator labor, dry land and irrigable land between activities. These factors follow a constant elasticity of transformation (CET) form.

Another important feature of TERM-H2O concerns water trading possibilities. The main stylized assumption is that irrigation water is perfectly tradable between irrigation sectors and regions of the southern basin. That is, water is traded at a single price in the southern basin in the model, which has approximated reality. In the northern part of the Murray-Darling Basin, which consists of far-flung tributaries, we assume that water is tradable within a region but not between regions. In the original version of TERM-H2O, a single region depicted the northern basin. This was acceptable if scenarios concentrated on the southern basin and results for the northern basin were not reported, as in Dixon et al. (2011) and Wittwer and Griffith (2011). In subsequent projects undertaken for clients, the northern basin was of interest. In preparation for these projects, TERM-H2O was spilt into catchment regions in the northern basin.

The theoretical modifications of TERM-H2O are documented in Dixon *et al*. (2011; 2012), extending the core theory elaborated in Dixon *et al*. (1982).

2.1 How important is it for a CGE model to track observations?

It is one thing to invest much effort in devising a CGE model for a task such as analyzing irrigation agriculture. But is it important to depict the observed water usage variability between users and implied factor mobility that is shown in Table 1 within a CGE model? One could contend that such a model is crucial in water policy analysis. Without it, exaggerated claims concerning policy measures may prevail without challenge because such claims arise in part from the assumption that farm inputs are rigid.

The 2007 Water Act was legislated late in the Howard government era in an attempt to address over-allocations of irrigation water within the basin. Under the Act, the Murray Darling Basin Authority (MDBA) was formed. The MDBA was assigned a complex array of responsibilities. Here, it is sufficient to mention two, namely water buybacks from farmers and infrastructure upgrades. The prevailing view among economists is that buybacks are a most cost efficient way of addressing sustainable water management than infrastructure upgrades. The latter dominate the costs of the Act, which over its lifetime may exceed AUS$12 billion.

The Act coincided with the middle of a three-year period (2005-06 to 2008-09) in which large areas of the basin and its mountain headlands suffered record rainfall deficits. Water buybacks under the 2007 Act were blamed for job losses in the Murray-Darling Basin. The culprit was drought: TERM-H2O modelling showed that drought-induced job losses were many-fold greater than the job impacts from water buybacks (Dixon et al. 2011; Wittwer and Griffith, 2011). The restoration of some jobs with the end of drought was observable in basin communities. In particular, rice mills which were mothballed for around three years opened again when the millennium drought was superseded by the abovementioned La Nina event.

The end of the millennium drought did not end troubles in the Basin. The mining boom drove the Australia dollar to and above parity with the US dollar around 2011, thereby diminishing the competitiveness of trade-exposed sectors in agriculture, manufacturing and services. At a time when farm competitiveness was being restored with a depreciating Australian dollar in 2014, the downing of a passenger airline over the Ukraine led to a round of trade sanctions with a dramatic adverse impact on the dairy industry.

2.2 Using database weights to compare impacts

One criticism often directed at CGE model results is that they are computed in a black box. The CoPS tradition from the beginning has been to check the veracity of modelled outcomes using back-of-the-envelope calculations, using simplified theory, database weights and shocks.

In comparing the impacts of drought and buybacks, we can use an even simpler approach to demonstrate the relative orders of significance. We know that drought affects both dry-land productivity and irrigation water availability. Water buybacks have no impact on dry-land productivity and no impact on rainfall. They are voluntary and fully-compensated at market prices. Indeed, Commonwealth purchases of water drive up the price of water relative to otherwise, which improves the terms-of-trade of farmers.

The point of this simple comparison is to show, contrary to an oft-repeated assertion, that buybacks are nothing like drought in the potential negative impact on farm output. Moreover, buyback proceeds may be used by some farmers to upgrade plant and equipment on their farms, thereby offsetting at least to some extent the negative impact of reduced water availability.

Table 2 Estimates of direct impacts of drought and buybacks on Murray-Darling Basin farming

	Drought 2007-08	Fully implemented buybacks (3500 GL) relative
Dry-land productivity	-20%	0
Irrigation: rain	-37%	0
:water	-37%	-32%
Compensation	No	Full
Process	Involuntary	Voluntary

a Scaled to basin-wide impacts from estimates of southern basin impacts reported in Wittwer (2011).

Little more than half the planned volume of buyback water has been purchased by the Commonwealth up to the present. It is not possible to detect the impact of "half-implemented" buybacks on the water market. Table 1 shows that seasonal conditions are a substantial driver of the water price. Commodity prices are also an important driver. In theory, fully implemented buybacks would remain a second order contributor to fluctuations in the traded water price (Wittwer and Griffith, 2012).

3. The California case: counties of Central Valley as regions in TERM-H2O

USAGE-TERM is a multi-regional CGE model of the US economy in the TERM stable (Wittwer 2017). The state-based master database of the model was modified so as to include 12 counties in and near California's Central Valley as separate bottom-up CGE regions (Figure 1). These counties are Butte, Colusa, Fresno, Glenn, Merced, Kern, Kings, Madera, San Joaquin, Stanislaus, Tulare and Yolo. Wittwer (2015) presents more detail on these modifications.

Figure 1 Bottom-up Californian regions in the water version of USAGE-TERM

In the original version of USAGE-TERM, the representation of farm sectors in the BEA input-output table was amended (see http://www.bea.gov/industry/io_annual.htm). Instead of representing agricultural industries by farm type, they are represented by outputs. This implies that on-farm factors ought to move between crop types as market conditions alter, enabling a given farm type to produce several outputs: the CET functional form provides factor mobility.

Concerning irrigation water, the modified version of the model includes satellite water accounts for irrigation sectors. These are based on USDA agricultural census data. We can impose varying degrees of water tradability within the model. With one closure (that is, choice of endogenous and exogenous variables), water is tradable between all irrigators within a county, but with the exception of Kings and Kern counties, not tradable between counties. To assume that water is tradable within a county is reasonable on engineering grounds, but not on institutional grounds. We can alter the closure to prevent trading between certain types of irrigation activity, thereby mimicking institutional constraints to some extent.

We impose an arbitrarily low initial unit value on water (ie, $50 per acre-foot).[5] Our interest is in how much water prices increase as scarcity worsens. Since the average product of water in production of some crops is only a few hundred dollars per acre-foot, rising water scarcity will induce producers of crops with low average products of water either to switch to different irrigation activities or, assuming water is tradable between farmers, sell their water to willing buyers. USDA data provide us with a set of initial conditions for irrigation water use. Optimal allocations within USAGE-TERM will change as water scarcity worsens and the marginal product of water rises.

[5] Note that in USAGE-TERM, acre-feet are used in satellite accounts for water, not ML as in TERM-H2O, reflecting the respective units of USDA and ABS data. See http://quickstats.nass.usda.gov/.

3.1 Reducing surface water usage by 40 percent and pumping to limit the shortfall to 10 percent

Groundwater accounts for about one-third of California's water requirements in a normal year (Chappelle et al. 2015). Howitt et al. (2015) estimated that groundwater usage rose by 6.2 million acre-feet out and surface water usage fell by 8.7 million acre-feet in 2015 in California relative to a normal year, resulting in reduced water usage of 2.5 million acre-feet or about 10%. In contrast, groundwater's contribution to total irrigation water used in the Murray-Darling Basin may fall below 10% in an average or wet year. During drought, it does not climb above one third (Table 1, rows 9 and 11). This marked difference in water sources has implications for both how a drought scenario is modelled and for a suitable policy plan.

In modelling drought, we also account for rainfall deficits. To illustrate, every inch of effective rainfall below average is equivalent to a water shortfall on every 12 acres of one acre-foot. Rainfall shocks in the scenario are based on estimates of rainfall deficits shown in Table 4 for July 2014 to June 2015. In addition to the modelled rainfall deficit, the shortfall of 2.5 million acre-feet is allocated among counties in proportion to annual crop water requirements of a normal year. The other shocks imposed in the scenario are to depict increased pumping costs arising from the extraction of an addition 6.2 million acre-feet of water. At $100 per acre-foot (Howitt et al., 2015), these additional costs total $620 million. In order to depict limited water trading possibilities, hay & forage and other agriculture water in each region are not transferable to other agricultural activities.

Table 4 Effective Rainfall Deficit & Irrigation Cuts by County

	Average effective rain (inches)	**Effective July 2014-June 2015 (inches)**	**Deficit (inches)**	**Irrigation cuts ('000 acre-feet)**
ButteCA	25	10	15	41
ColusaCA	10	9	1	79
FresnoCA	7	4	3	263
GlennCA	13	10	3	54
MercedCA	6	2	4	142
KernCA	6	1	5	182
KingsCA	2	2	0	136
TulareCA	5	1	4	117
YoloCA	17	6	11	51
SanJoaquinCA	10	3	7	116
StanislausCA	7	3	4	94
MaderaCA	6	1	5	33
Rest of Calif.	13	5	8	1191

Source: http://www.usclimate.com (accessed 28 August 2015).

Table 5 Macroeconomic Impacts on 12 Counties and Terms-of-Trade Impacts, "Observed" Scenario
(% change from base case)

12 counties	Macro results	Terms-of-trade by region		Water trading price $/ac-ft
Real consumption	-0.51	ButteCA	2.9	278
Real investment	-0.04	ColusaCA	0.7	107
Real GDP	-0.83	FresnoCA	0.3	337
Employment	-0.37	GlennCA	0.1	119
Real wage	0	MercedCA	2.1	571
GDP deflator	0.04	KernCA	0.4	259
CPI	-0.30	KingsCA	0.4	259
		TulareCA	0.8	361
		YoloCA	0.2	490
		SanJoaquinCA	0.5	452
		StanislausCA	-0.2	690
		MaderaCA	1.0	713

Table 5 shows the macroeconomic impacts. The macro impacts are relatively modest, with real GDP falling by 0.83% and real consumption, boosted by varying terms-of-trade gains across the 12 counties, lessening the losses in spending power. There are two types of cost associated with groundwater extractions that are not included in this scenario. First, additional groundwater extractions have required substantial investments in new or deeper wells. Only the marginal pumping costs are included in the scenario. We would expect present period investment to result in foregone consumption in the future, in order to service the debt incurred in financing the investment. But this version of USAGE-TERM was run in comparative static rather than dynamic mode. Consequently, the model does not account for dynamic linkages between investment and capital, and between international trade balances and net foreign liabilities.

Dynamics would also have been useful in the Californian context, to capture some of the longer term impacts of investment in well boring in response to the four year drought. But even a dynamic model would not have told the full story of the response. The other type of cost not modelled is the impact on sustainability: the more existing groundwater is pumped, the higher will be the costs of extracting more water as aquifer levels fall. Groundwater pumping is causing land subsidence, thereby damaging property and the environment.

3.2 Why water pricing and trading would help in California

In 2015, there was some optimism in California that an El Nino would end the drought. By early in 2017, finally there was a sense that the drought had well and truly broken. But it would appear that policy problems remain. What benefits, for example, might arise from water metering and trading? If all water used in irrigation activity were metered, including groundwater, it would contribute to water being rationed according to scarcity. The task of moving water from users with low average products of water to users with higher average products would be encouraged through metering and other reforms that enable water trading. In addition, metering of groundwater may have reduced investments in perennials. In many irrigation regions around the world, there are physical constraints to trade, but in much of California's irrigation areas, the main constraints appear to be institutional. Metering would be most effective if the total groundwater extractions were limited to a volume that enables aquifers to be replenished in wetter years and drawn down in drier years, as proposed by Howitt and M'Marete (1991) a generation ago. A potential incentive that faces irrigators at present who invest in a new well is that instead of using it in dry years, they may perceive that they increase their return on the investment by using it in all years, to the detriment of sustainable management.

Not all welfare-enhancing measures arise from price mechanisms. It would appear that the town of East Porterville, CA, for example has suffered excessively from drought due to wells drying up. Prior to the prolonged drought, no authority recognized the vulnerability of the town's water supply. Various state and utility authorities planned to connect dry homes to mains water supply, and this finally happened in August 2016 (Stevens 2016). This is an appropriate response given that universal service obligations should take precedence over pricing mechanisms.

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