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The dynamics of groundwater markets: Price leadership and groundwater demand elasticity in the Murrumbidgee, Australia

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ABSTRACT

Groundwater over-extraction is a problem facing many countries around the world. Water pricing and developing property rights to enable groundwater trade are potential demand-based approaches to address the over-extraction of groundwater resources. However, successful implementation of groundwater trading requires knowledge about groundwater demand and its interaction/substitutability with surface-water; and, given the paucity of empirical data on groundwater markets, price elasticity of groundwater demand is rarely estimated in the literature. We analysed 10 years of monthly surface and groundwater temporary market data (July 2008–April 2018) within the Murrumbidgee catchment of the Murray-Darling Basin, Australia, to explore a) the lead-lag relationship between surface and groundwater temporary markets; and b) the price elasticity of groundwater market demand. Results illustrate that surface-water markets show price leadership to groundwater temporary markets, and that groundwater demand is price elastic, with a –1.05 price elasticity estimate in our time-period.

1. Introduction

Water extractions have been increasing worldwide by about 1% per year, and global water demand is expected to increase at a similar rate until 2050 (WWAP, 2019). As a result, over-extraction of groundwater resources is a growing problem and a consequence of a common-pool resource dilemma (Ostrom, 1990). Groundwater overuse represents significant costs to society: it can increase withdrawal costs, as water has to be pumped from a greater depth; it generates cones of depression (Wheeler et al., 2016); and can lead to surface and groundwater depletion, along with significant infrastructure costs (Asci et al., 2017; Silva et al., 2019). Given agriculture extracts 69 % of available freshwater resources in the world (WWAP, 2019), the increased use of irrigation water pricing and property rights has been suggested as a potential mean to cope with water scarcity (Blanco-Gutiérrez et al., 2011). The literature has shown that increased water prices (usually through irrigation water charges) can favour the adoption of water conservation technologies (Caswell and Zilberman, 1985; Caswell et al., 1990) and decrease irrigation groundwater use (Smith et al., 2017).

Groundwater markets often emerge as formal or informal tools to put a price on water and reallocate scarce groundwater resources. Examples of formal groundwater markets are found in Australia (Wheeler et al., 2016), the western United States (Colby, 2000) and China (Zhang and Zhang, 2008); while informal markets exist in countries such as India (Manjunatha et al., 2011) and Pakistan (Khair et al., 2012). Although groundwater markets remain limited in their extent, they have been shown to generate significant benefits in various contexts. Groundwater markets can involve significant gains from trade (Knapp et al., 2003; Gao et al., 2013; Palazzo and Brozovic, 2014), even in the presence of market power (Bruno and Sexton, 2020), with participants becoming more efficient in their water extraction (i.e. generating more outputs with the same amount of water (Manjunatha et al., 2011; Razzaq et al., 2019)). In India, groundwater markets have allowed resource-poor farmers access to irrigation water (Mukherji, 2007).

Little empirical research on the demand elasticities and market dynamics of groundwater markets has been conducted worldwide, largely because operating examples of groundwater markets with sufficient data are rare. Necessary conditions for water markets to be successful include: (i) well defined property rights; (ii) effective and adaptive governance and legislation regarding enabling resources (including a 'cap' on water rights issued); (iii) sufficient knowledge about hydrology and resource constraint, (iv) proper accounting and monitoring of water extraction and consumption; (v) a sufficiently diverse potential market for water, notably in terms of diversity of value-added consumption; and (vi) the existence of institutional arrangements to

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address externalities (Wheeler et al., 2017). Public perception of water markets (Hérivaux et al., 2020) and vested interests (Wheeler and Garrick, 2020) are two other factors potentially influencing the existence of, and participation in, groundwater markets. Allowing trade in the absence of adequate administrative arrangements can endanger water security (Maestu and Gomez-Ramos, 2013; Young, 2014; Wheeler et al., 2017). Where water extraction rights cannot be enforced, the risk of overuse is heightened (Diwakara and Nagaraj, 2003; Zhang, 2007), as is the importance of understanding the connectivity and substitutability between surface and groundwater resources.

Australia provides a rare example of a mature dataset on groundwater markets because of its long-functioning history and development of markets over the past thirty years (Wheeler et al., 2017). In many instances, groundwater markets in Australia coexist with surface-water markets. In cases where both type of water resources are available, the substitutability and connectivity between surface and groundwater is a major water policy issue. For example, understanding the actual impact of irrigation efficiency subsidies requires knowledge about the volume represented by return flows (irrigation surface-water flowing to aquifers following its use) (Grafton et al., 2018; Williams and Grafton, 2019). Furthermore, groundwater pumping in areas close to rivers has been shown to decrease available surface water in nearby streams; and this situation has led to inter-state conflict in the United States (Kuwayama and Brozović, 2013). A well-known substitution phenomenon was also identified between surface and groundwater in the Murray-Darling Basin (MDB) (Haensch et al., 2016). These interactions affect water markets when they coexist in the same area: as noted in California in the 1980 drought, where farmers sold their water to the government and compensated by increasing groundwater pumping (Wheeler et al., 2016). Similar evidence has been found in Australia (Wheeler and Cheeseman, 2013) and China (Zhang, 2007). Therefore, improving the knowledge about the interconnections between surface and groundwater resource management is important (Ross, 2018; Williamson and Grafton, 2019) to design appropriate water markets regulations (Seidl et al., 2020a; Wheeler and Garrick, 2020). This is also because the monitoring of groundwater extraction in the MDB remains weak. For example, in NSW, many bores are not required by law to be metered (for example those termed ‘basic rights’, namely those used for stock and domestic purposes) and all are exempt from the telemetry provisions that were introduced in 2018 (Holley et al., 2020; Nelson, 2019; Wheeler et al., 2020).

Moreover, the appropriateness of property rights and pricing policies in general is conditioned by a sufficiently high elasticity of irrigation water demand. In cases where water demand is inelastic, a water pricing policy targeting a reduction in irrigation withdrawals would need to considerably increase the water price in order to reduce irrigation water consumption, thereby strongly affecting farm income (de Fraiture and Perry, 2007). With a perfectly inelastic groundwater demand, the lack of a rationing mechanism based on the productivity of water consumption has been shown to generate inefficiency (Wang and Segarra, 2011).

Given this context, the interest of this research is twofold. First, this study adds to the literature by providing a rare estimate of groundwater temporary market demand price elasticities, using over a decade of exogenous water price variations from a key groundwater extraction area, the Murrumbidgee, in the MDB, Australia. Second, we examine the dynamics of groundwater temporary markets, by analysing drivers of prices and trade, along with the connectivity and substitutability between surface and groundwater markets. Our results provide insights that can be used to inform pricing and water market policies in the countries choosing to implement such tools.

Studies on the price elasticity of irrigation surface water use (or irrigation water use in general) have often used mathematical programming methodologies. Estimates varied between 0 and 2.81 in absolute value, depending on study characteristics (Shumway, 1973; Frank and Beatie, 1979; Howitt et al., 1980; Pagan et al., 1997; Hooker and Alexander, 1998; Scheierling et al., 2004). Other studies used econometrics to estimate surface-water temporary market demand elasticity, assuming or holding other factors constant. Elasticity estimates range between -3.56 and -0.81 (Schoengold et al., 2006; Brooks and Harris, 2008; Wheeler et al., 2008).

Studies estimating groundwater demand elasticity have mostly focused on groundwater irrigation charges (and pumping costs) only, and estimates have ranged from -0.10 to -0.80 (Nieswiadomy, 1985; Ogg and Gollehon, 1989; Moore et al., 1994; Gonzalez-Alvarez et al., 2006; Hendricks and Peterson, 2012; Mieno and Brozovic, 2016; Badiani-Magnusson and Jessoe, 2019). Apart from this, studies using exogeneous changes in groundwater price to study irrigation groundwater demand elasticity are rare. Alamdarlo et al. (2019) employed mathematical programming to analyse the impact of supply and demand policies in an informal groundwater market framework in the Qazvin plain in Iran, and found groundwater demand elasticities from 0 to -0.17. We could find no other study estimating groundwater demand elasticity using actual groundwater market transactions.

Many factors can influence the estimation of groundwater demand elasticity, including the price at which elasticity is estimated, the econometric methodology, temperature and the existence of high value crops in an area (Scheierling et al., 2006); irrigation methods (Frija et al., 2011; Pfeiffer and Lin, 2014); and measurement errors (Mieno and Brozovic, 2016). Besides, there has been some discussion regarding the influences on groundwater markets that can affect prices – and thus the elasticity estimation. Such markets are influenced by traditional surface-water market drivers including rainfall and temperature, allocations received, dam storages, output prices for commodities grown in the area, and seasonal factors (Wheeler et al., 2008). Evidence of price clustering has also been reported (Brooks et al., 2013). In the case of groundwater markets, salinity can also be of influence (Gill et al., 2017). Furthermore, Brooks and Harris (2014) found evidence of price leadership between two surface-water trading zones in the Goulburn-Murray irrigation district. Price leadership is a lead-lag relationship between two indexes, whereby variations in one index can be explained by past variations of another market index. Such lead-lag relationships have been found in various contexts in financial markets, such as between futures and their underlying stocks (Min and Najand, 1999) or between different markets offering similar market products (Roope and Zurbruegg, 2002). However, to the best of our knowledge no study to date has considered the potential lead-lag relationship between surface and groundwater markets. Nevertheless, as it is expected that more liquid markets (such as surface-water markets in Australia) react quickly to new information, the existence of such a lead-lag relationship in the MDB is highly likely.

Therefore, this study analysed in detail the dynamics of groundwater temporary markets between July 2008 and April 2018, in a key groundwater extraction area: the Murrumbidgee in Australia. It investigated the existence of a lead-lag relationship between surface and groundwater temporary markets. It also provided one of the first estimates of groundwater market demand price elasticities using exogenous variations in groundwater price, taking into account a variety of groundwater market dynamics.

Table 1
Groundwater trade count per groundwater system in Australia, 2008-2018.

Groundwater system	State	Total trade count[1]	Temporary trades	Permanent trades	Prop. (All AUS trades)
South East SA	SA	2019	170	1849	10.6
Murrumbidgee Alluvium (GW9)	NSW	1808	1449	359	9.5
Adelaide & Mt Lofty Ranges	SA	1646	220	1426	8.7
Namoi Alluvium	NSW	1531	894	637	8.1
Murray Alluvium	NSW	1467	1087	380	7.7
Condamine-Balonne (GW21)	QLD	1091	436	655	5.8
Burnett Basin	QLD	955	627	328	5.0
Goulburn-Murray	VIC	808	165	643	4.3
Lachlan Alluvium	NSW	673	446	227	3.5
Gwydir Alluvium	NSW	522	444	78	2.8
Other area in Australia		6452	1005	5447	34.1
Australia Total		18,972	6,943	12,029	100.0

Source: BoM water market data, from 2 July 2008 to 20 April 2018. Notes: 1 Many groundwater trades are recorded with a price value of 0. Excluding these transactions reduces the number of trades by 51.7 % (temporary trades) and 75.3 % (permanent trades), although this is most likely to occur in SA water registries. Murrumbidgee Alluvium had 33 % zero priced trades. Reasons for not reporting prices can include: 1) trades without a valid contract (within a single entity, with family or friends…); and 2) not reporting prices during a transaction. Price reporting has been compulsory since 2014, but enforcement is still sometimes lacking (Murray-Darling Basin Authority (MDBA), 2014).

2. Materials and methods

2.1. Study area

2.1.1. Overview

Water markets in Australia's MDB emerged formally in the 1980s and evolved to become the most active water market area in the world (Grafton et al., 2011; Seidl et al., 2020b). Most water trades in the MDB are surface-water transactions, especially in the southern connected system. However, groundwater markets have also been established in various other parts of Australia. The largest Australia-wide groundwater markets (in terms of number of permanent and temporary trades), appear in Table 1.

Between 2 July 2008 and 20 April 2018, 6,943 groundwater temporary trades were recorded Australia-wide in the BoM water market database, along with 12,029 permanent trades. While most groundwater trades occurred in New South Wales; Queensland and South Australia also showed a significant number of transactions. Temporary trade involves the seasonal or temporary transfer of water (known in Australia as water allocation trade) and permanant trade involves the ongoing transfer of the right to an ongoing share of water resources at a given source (known in Australia as water entitlement trade) (Wheeler and Garrick, 2020).

We focused on temporary groundwater markets in the Murrumbidgee region for several reasons. First, trading was generally not allowed between different groundwater systems (as in the Murrumbidgee), which argued for the application of a single water system. Second, permanent groundwater price transactions were relatively scarce, which hampered the creation of consistent time-series data. Third, the Murrumbidgee groundwater market represented 9.5 % of all groundwater trades in Australia but contained a considerably lower proportion of zero priced trades (33 %) than most other regions.

2.1.2. Murrumbidgee

Groundwater extraction for irrigation purposes in the Murrumbidgee started in the early 1960s. Before 1982, groundwater access was unrestricted. Since 2006, new water extraction licences were no longer issued, and licenses became fully tradeable and separated from land titles (Green et al., 2011). The Murrumbidgee catchment (Fig. 1) is the fourth largest catchment in the MDB and covers about 84,000 km^2 (Gilligan, 2005).

The catchment hosts one of the most active groundwater markets in Australia, coexisting with a significant surface-water market. Irrigated agriculture in the Murrumbidgee mainly includes rice and cotton, representing around 65 % of the total agricultural water extractions in 2016 − 17 (ABS, 2018). Other crops includes cereals, pastures, fruits and nuts (Douglas et al., 2016).

Water extraction in the Murrumbidgee is based on an annual accounting system. Along regulated water sources such as the Murrumbidgee river or the Murrumbidgee Alluvium, each water user must own a water license. An initial Available Water Determination is made at the beginning of the year[1], determining the amount of water delivered to each of the shares listed on a user's water license (Green et al., 2011). Water determinations may increase throughout the year, depending on climatic circumstances. Different categories of surface and groundwater licenses exist, defining access to surface or groundwater according to varying levels of priorities (i.e. risk) on the use of surface-water resources. The most common surface-water license in the Murrumbidgee is general security license, or an aquifer access license in the case of groundwater (Douglas et al., 2016).

Groundwater trading has been occurring since 1987, mainly in the Lower Murrumbidgee Deep Water Source. While early trades involved temporary transfers (called allocation transfers), permanent groundwater transfers (called groundwater license entitlement transfers) have been permitted since 2006. They are, however, rarer. Groundwater markets are considerably less active than surface-water markets and are limited to a shared groundwater source (trading between different groundwater sources is not permitted) (Green et al., 2011). Fig. 2 illustrates water market prices and the groundwater volume traded in the Murrumbidgee temporary water markets from 2008 onwards.

Groundwater markets in the Murrumbidgee show higher prices and a higher level of market activity in times of scarcity: between 2008 and 2010, the existence of the Millennium Drought resulted in much higher surface and groundwater prices and an increase in the quantity of water traded. In contrast, flooding in 2010 − 11 led to surface-water prices falling to under AUD$20/ML, while the total quantity of groundwater traded also reduced considerably.

Note that the price of surface-water (median price of AUD$94.62/ML) was consistently higher than groundwater (AUD$22.93/ML), expressed in constant 2018 prices. This reflects the fact that in many areas, irrigators favour surface-water extraction over groundwater extraction. Reasons for this preference include the energy costs of groundwater extraction (Mitchell et al., 2012); greater tradability of surface-water; and frequent presence of malfunctioning bores with high salinity (Gill et al., 2017; Hooker and Alexander, 1998).

[1] Water years in Australia begin on July 1st and end on June 30th.

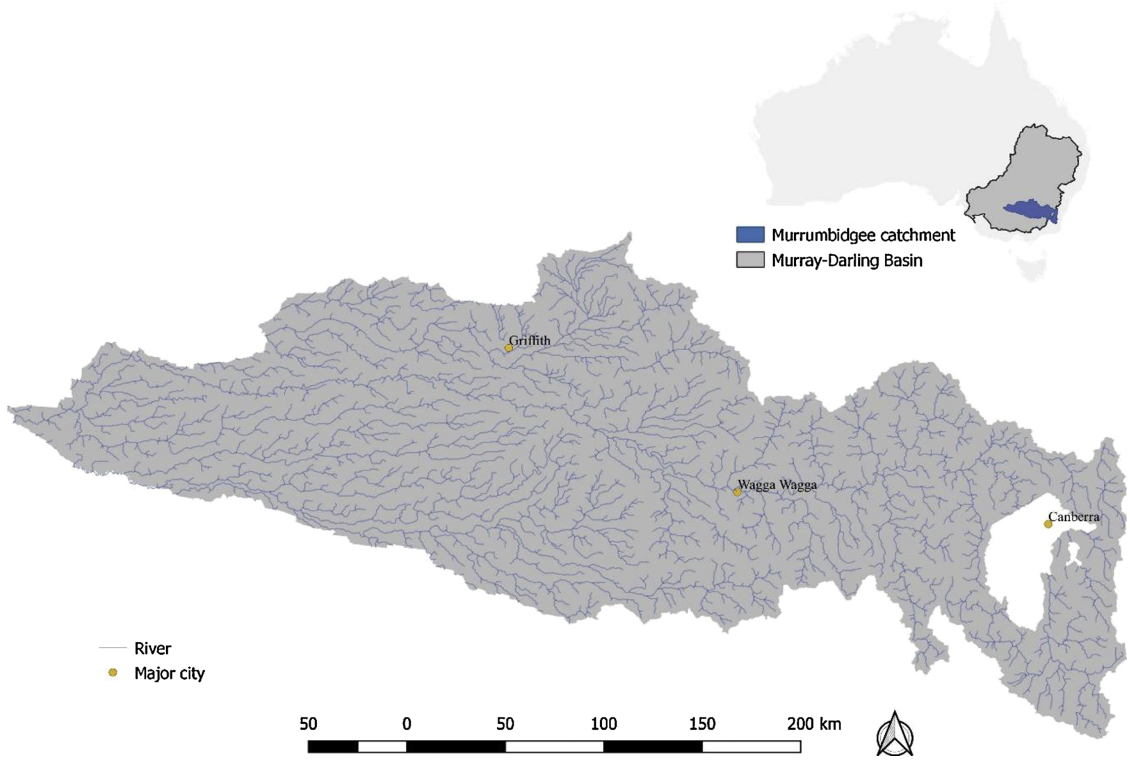

Fig. 1. The Murrumbidgee region.
Source: GIS data collected from the Murray-Darling Basin Authority (Murray-Darling Basin Authority (MDBA), 2013), the OpenStreetMap layer "Places and Boundaries", and the HydroSHEDS project (Lehner et al., 2008). Note: Region represented as defined by the Murrumbidgee surface-water resource management area.

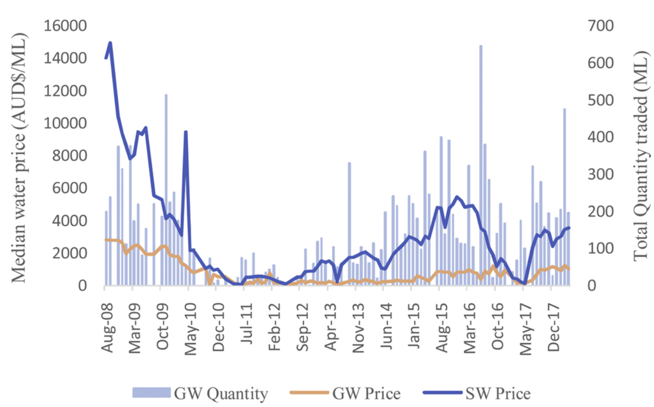

Fig. 2. Median monthly surface and groundwater prices and total groundwater quantity traded in Murrumbidgee temporary water markets, August 2008- April 2018.
Source: BoM water market data.
Note:$0-priced trades are excluded, and prices are adjusted to inflation and are expressed in constant 2018 AUD prices. 16 months where no trade occurred (including July 2008) were not represented.

2.2. Data

The study used 10 years (July 2008-April 2018) of surface and groundwater temporary market trade data in the Murrumbidgee, Australia. Water market data (monthly price and quantity traded – our dependent variables) for this study was extracted from the Australian Bureau of Meteorology's (BoM) national water market database. Independent variables collected included climate variables (rainfall and mean temperature) using BOM's Hay Airport Automatic Weather Station (AWS), located in the Murrumbidgee. Diesel prices were collected from the Australian Institute for Petroleum. Output prices were collected from the Australian Bureau for Agricultural and Resources Economics and Sciences (ABARES). All prices were adjusted using the consumer price index from the Reserve Bank of Australia (RBA)[2], with the base year 2018. Descriptive statistics can be found in Table A1.

Table 2
Results from the Granger causality tests using parameters from the VARX(1) model for key market variables in the Murrumbidgee temporary surface and groundwater markets, 2008–2018.

Lags of	Groundwater (temporary)		Surface-water (temporary)	
	Price	Quantity	Price	Quantity
GW Temporary Price		0.058 (0.810)	0.060 (0.806)	0.621 (0.431)
GW Temporary Quantity	1.775 (0.183)		0.329 (0.566)	0.664 (0.415)
SW Temporary Price	19.949 (0.000)	0.350 (0.554)		0.113 (0.737)
SW Temporary Quantity	0.163 (0.686)	7.163 (0.007)	2.522 (0.112)	

Note: chi-2 reported, p values in parenthesis.

2.3. Methodology

The method followed two stages. First, we modelled the price of temporary groundwater trade, to question the existence of a price leadership relationship between surface and groundwater temporary markets. Second, we modelled the quantity of temporary groundwater traded, in order to investigate the influence of the groundwater price and infer the price elasticity of groundwater demand.

[2] Several other variables were tested but not included in the final analysis, including the Groundwater level and Electricity prices.

Table 3
Results from the VARX(1) estimation for a one percent change in key market variables in the Murrumbidgee temporary surface and groundwater markets, 2008-2018.

	Dependent variables			
	GW Price	GW Quantity	SW Price	SW Quantity
	1	2	3	4
GW Temporary Price	−0.474***	0.042	−0.020	0.109
	(−5.40)	(0.24)	(−0.25)	(0.79)
GW Temporary Quantity	0.061	−0.505***	−0.025	−0.059
	(1.33)	(−5.50)	(−0.57)	(−0.81)
SW Temporary Price	0.504***	−0.134	−0.144	0.060
	(4.47)	(−0.59)	(−1.36)	(0.34)
SW Temporary Quantity	−0.027	0.354***	0.099	−0.011
	(−0.40)	(2.68)	(1.59)	(−0.11)
Monthly rainfall	−0.003*	0.0002	−0.001	−0.001
	(−1.80)	(0.08)	(−0.60)	(−0.38)
Monthly mean temperature	0.027	−0.002	0.016	0.038
	(1.57)	(−0.07)	(1.02)	(1.41)
_cons	−0.009	−0.004	−0.019	−0.007
	(−0.14)	(−0.03)	(−0.33)	(−0.07)
N	100	100	100	100
R-sq	0.352	0.276	0.055	0.046
Chi-sq p.val	0.00	0.00	0.44	0.57

Note: *p < 0.1. **p < 0.05.***p < 0.01; t statistics in parentheses. Water market variables were logged and first differenced, and lagged by one period as independent variables. Climate variables were first differenced.

2.3.1. Price leadership method

In order to investigate the existence of a lead-lag relationship in various markets, Vector Auto-Regressive (VAR) frameworks have often been used in the literature (Brooks and Harris, 2014; Chordia and Swaminathan, 2000; Chevallier, 2010). Most VAR frameworks are parsimonious (Chevallier, 2010; Brooks and Harris, 2014) in the sense that they only used a few covariates. However, in the case of water markets, climatic variables have been shown to have a clear influence on market price and quantities traded (Wheeler et al., 2008; Brooks and Harris, 2008; Loch et al., 2012). Therefore, we used a VAR-X model including four temporary water market variables (price and quantity traded for surface and groundwater trade) and two climatic variables: rainfall and mean temperature. VAR-X models include endogenous variables, used as dependent and independent variables successively, and exogenous variables that are only used as independent variables. Market variables were defined as endogenous due to the potential interconnections between surface and groundwater trade, while rainfall and mean temperature variables were considered exogenous. Thus, we alternatively used each temporary market variable (price and quantity traded, for surface (SW) and groundwater (GW)) as a dependent variable and regressed it on the past values of other market variables, while controlling for climatic factors.[3]

Augmented Dickey-Fuller and KPSS stationarity tests revealed that most market variables (prices and quantities) were not stationary but became stationary once logged and first differenced. First differences *(D.)* of climatic variables were found stationary. Therefore, market variables have been logged *(log)* and then first differenced, while climatic variables were simply first differenced.

VAR-X frameworks can be applied using a different number of past values for each variable. Indicators such as FPE, Akaike's IC, HQIC or the Schwarz-Bayesian IC were used in order to determine the number of lags to include. Each regression was run using an alternative number of lags, and various information criteria were compared. The Australian water year begins in July and ends in June, where the early months in the season usually show lower trade intensities, as irrigators face higher uncertainty. Therefore, the maximum potential number of lags in these tests was set to be nine. Results showed that the FPE and AIC indicated the use of nine lags, while the HQIC and SBIC suggested the use of one lag. In order to avoid overfitting, we chose to use one lagged value for each variable in our analysis.

The VARX(1) model using logs and first differences estimated the following:

$$\begin{aligned} D.\,logGWPrice_t = {} & \alpha_0 + \alpha_1 D.\,logGWPrice_{t-1} + \alpha_2 D.\,logGWQuantity_{t-1} \\ & + \alpha_3 D.\,logSWPrice_{t-1} + \alpha_4 D.\,logSWQuantity_{t-1} \\ & + \alpha_5 D.\,MonthlyRainfall_{t-1} + \alpha_6 D.\,MeanTemperature_{t-1} \\ & + \varepsilon_t' \end{aligned} \tag{1}$$

[3] Monthly rainfall and mean monthly temperature were used in the final results, although the cumulative three months rainfall was also sensitivity tested, and the results were similar. In addition, surface-water allocation percentage was tested, but was found to be highly correlated with surface-water prices (correlation coefficient = -0.83) and therefore was not included in the final model.

Table 4
Results from the 2SLS estimation for the quantity of groundwater traded monthly in the Murrumbidgee temporary groundwater market, 2008-2018.

	Dependent variables	
	GW Quantity (Second stage)	GW Price (First stage)
GW temporary price (instrumented)	−1.046**	
	(0.455)	
Rice price (instrument for GW Price)		1.076***
		(0.223)
Surface-water temporary price	1.174***	0.549***
	(0.305)	(0.061)
General security surface-water permanent price	2.179**	1.263***
	(0.985)	(0.341)
Diesel price	−1.229	−1.367**
	(1.002)	(0.680)
Mean temperature	0.376	0.587**
	(0.528)	(0.254)
Monthly rainfall	−0.010	0.037
	(0.108)	(0.052)
Early season	0.501	0.346*
	(0.383)	(0.175)
Mid-season	0.048	0.004
	(0.285)	(0.160)
_cons	−4.480	−9.906*
	(10.260)	(5.294)
N	102	102
Centered R^2	0.29	
Kleibergen-Paap rk Wald F stat.[a]		23.284
		(p-value = 0.00)
Weak identification test threshold[b]		16.38
		(p-value <0.05)
Endogeneity test stat.[c]		5.221
		(p-value = 0.02)

Note: Standard errors in parentheses.
[*] p < 0.1.
[**] p < 0.05.
[***] p < 0.01.
[a] Null hypothesis is that our equation is under-identified. Rejection in this case means our equation is not under-identified.
[b] The null hypothesis is that the instrument is weak. The critical value for 10 % maximal IV size at the 0.05 significance level is 16.38 (Stock and Yogo, 2005). Therefore the null was rejected, suggesting the instrument is not weak.
[c] The null hypothesis is that the groundwater price can be treated as exogenous. In this case, the rejection of the null hypothesis suggested that the groundwater price was endogenous.

$$D.\ logGWQuantity_t = \beta_0 + \beta_1 D.\ logGWPrice_{t-1} + \beta_2 D.\ logGWQuantity_{t-1} + \beta_3 D.\ logSWPrice_{t-1} + \beta_4 D.\ logSWQuantity_{t-1} + \beta_5 D.\ MonthlyRainfall_{t-1} + \beta_6 D.\ MeanTemperature_{t-1} + \varepsilon_t^{''} \quad (2)$$

$$D.\ logSWPrice_t = \gamma_0 + \gamma_1 D.\ logGWPrice_{t-1} + \gamma_2 D.\ logGWQuantity_{t-1} + \gamma_3 D.\ logSWPrice_{t-1} + \gamma_4 D.\ logSWQuantity_{t-1} + \gamma_5 D.\ MonthlyRainfall_{t-1} + \gamma_6 D.\ MeanTemperature_{t-1} + \varepsilon_t^{'''} \quad (3)$$

$$D.\ logSWQuantity = \delta_0 + \delta_1 D.\ logGWPrice_{t-1} + \delta_2 D.\ logGWQuantity_{t-1} + \delta_3 D.\ logSWPrice_{t-1} + \delta_4 D.\ logSWQuantity_{t-1} + \delta_5 D.\ MonthlyRainfall_{t-1} + \delta_6 D.\ MeanTemperature_{t-1} + \varepsilon_t^{''''} \quad (4)$$

Following the regression, Granger causality tests were used to identify potential causal relationships between our variables. We then applied Impulse-Response Functions (IRF) and forecast-error variance decomposition in order to understand the duration and extent of the interconnections between surface and groundwater temporary markets.

2.3.2. Price elasticity of groundwater demand method

Given that the groundwater price and the groundwater volume are simultaneously determined, this raised the possibility of endogeneity. Thus, we used an instrumental variables approach. In order to identify the demand equation, a valid instrument must be found for groundwater price: such a variable should impact groundwater supply (e.g. influence water sellers) without affecting groundwater demand (e.g. water buyers). In a water market context, the difficulty in finding a proper instrument is exacerbated by the fact that water sellers can also be water buyers. Several instruments were tested and variables such as the groundwater level, electricity prices, and various agricultural output prices were found to impact demand and hence were unsuitable. However, the rice price was identified as an appropriate instrument for groundwater price. Rice growers tend to own large general security water licenses, grow rice in wet years, and can earn some income by selling water in drought years when water prices are high and water allocations are low (Douglas et al., 2016; Nguyen-ky et al., 2018). Notably, it has been reported that selling water allocations when water prices were greater than AUD\$200/ML was perceived as a better and less risky strategy than growing rice (Loch et al., 2012; Zuo et al., 2015). Therefore, the price of rice can influence water supply on the market, as rice producers are frequent water sellers on the Murrumbidgee water markets, especially in times of water scarcity. Thus, we expect rice prices to mainly influence groundwater supply and to have a limited effect on groundwater demand. This makes it a valid instrument for groundwater price and allows price elasticity of groundwater demand to be properly estimated.

Following Wheeler et al. (2008), a linear log-log specification was used. The instrumental approach used a two stage least squares (2SLS) estimation:

$$GWPrice_t = f(X_t,\ Z_t)$$

Where:

X was a vector of explanatory variables, and Z the instrument (rice price in month t). The estimation used the predicted value of the groundwater temporary price:

$$GWVol_t = f(X_t,\ GW\hat{P}rice_t)$$

Several control variables were included. Given that groundwater markets may be potentially influenced by surface-water markets in the Murrumbidgee, prices of permanent and temporary surface-water entitlements were included. As many irrigators use diesel pumps to extract groundwater, the average annual diesel price[4] was included. Finally, climate variables (rainfall and mean temperature in month), and seasonal dummies were used to consider climatic circumstances and seasonal patterns. Several other control variables were tested[5] but for a variety of reasons (collinearity, continual lack of significance and relevance etc) were not included in the final model. Descriptive statistics are provided in Table A1 and maximum likelihood estimation was used to estimate the model's parameters. The two stage least squares regression was:

Stage 1:

$$lnGWPrice_t = \alpha_0 + \alpha_1 Rice_t + \alpha_2 lnTempSurfacewaterprice + \alpha_3 lnPermSurfacewateprice + \alpha_4 lnDieselprice_t + \alpha_5 lnMeantemperature_t + \alpha_6 lnMonthlyrainfall_t + \alpha_7 Earlyseason + \alpha_8 Midseason + e_t \quad (5)$$

Stage 2:

$$lnGWVol_t = \beta_0 + \beta_1 lnGW\hat{P}rice_t + \beta_2 lnTempSurfacewaterprice + \beta_3 lnPermSurfacewaterprice + \beta_4 lnDieselprice_t + \beta_5 lnMeantemperature_t + \beta_6 lnMonthlyrainfall_t + \beta_7 Earlyseason + \beta_8 Midseason + e'_t \quad (6)$$

3. Results and discussion

3.1. Price leadership

Table 2 illustrates the Granger causality tests and Table 3 the VARX (1) regression results. Granger causality tests and the VARX results suggested the existence of a price leadership phenomenon from surface-water temporary markets to groundwater temporary markets. The percent change in groundwater price is caused by the past change in the surface-water temporary price: the parameter of the surface-water price in regression (1) is positive and highly significant.

Similar evidence was found regarding groundwater temporary allocation quantity traded: the percent change in quantity of groundwater traded can be explained by the past change of surface-water quantity traded. In order to analyse the duration and extent of the interaction between surface and groundwater temporary markets (Roca and Tularam, 2012), orthogonalized impulse-response functions and the forecast error variance decomposition were generated (see Fig. B1). They suggested that a one percent change in the surface-water market generated a response in groundwater temporary price that is positive and significantly different from zero at lag one (See Fig. B1). This response weakens in the second month and disappears four months later. Furthermore, 83.2 % of the error variance for groundwater temporary price was found to be due to groundwater price's own changes and 14.4 % was due to changes in surface-water temporary price.

Note that Table B1 also shows that 84 % of the error variance for surface-water temporary price was due to its own changes and 11.8 % was due to changes in groundwater temporary price, which could suggest that the opposite (groundwater market characteristics impact surface-water markets) could be also true. However, Granger causality tests and regression estimates do not show any impact of the past percent change in groundwater market characteristics, on either surface-water market temporary prices or quantities traded. Impulse response functions also showed no significant response in surface-water temporary price for lags one to eight, following a one percent change in

[4] Due to data availability constraints, we used diesel price in Sydney as a proxy for Murrumbidgee data.

[5] Red wine and cotton prices; rainfall in the last three months; electricity price; the mean groundwater level in six bores over the Murrumbidgee alluvium, the general security surface-water allocation level, a month index.

groundwater price.

Overall, these results suggested that market-sensitive information is first incorporated by the surface-water temporary market, and then transmitted to groundwater temporary markets in the Murrumbidgee. Such a result is coherent with the financial literature, showing that more liquid markets tend to incorporate market information faster (Roope and Zurbruegg, 2002; Brooks and Harris, 2014).

3.2. Price elasticity of groundwater demand

Results from the 2SLS modelling are shown in Table 4. The Durbin-Wu Hausman test confirmed the endogeneity of the groundwater temporary price. Under-identification and weak instrument tests (e.g. Kleibergen-Paap rk LM and Wald F statistics) suggested no under-identification or weak instrument, and our instrument had a significant, positive impact on the groundwater price.

Second stage estimates revealed a groundwater temporary demand price elasticity close to the unit elasticity (-1.05): a one percent increase in the groundwater temporary price led to a 1.05 percent decrease in groundwater demand. This is a relatively high estimate compared to other results in the literature. For example, Mieno and Brozovic (2016) estimate was -0.5 for changes in groundwater extraction in response to changes in pumping costs in the United States. However, greater price elasticities for groundwater trade markets are expected, as found by the surface-water temporary market price elasticity literature (e.g. Wheeler et al. (2008) found a -1.51 temporary surface-water demand elasticity from 1997 to 2007 in the Goulburn, Australia).

Our result suggests that while the groundwater market demand seems generally more elastic than other studies that have focussed on irrigation charges only, it is less elastic than surface-water temporary market demand. This is most likely explained by the fact that surface-water trade volume is much larger, the price is generally higher, the market is more liquid, and the market covers a far greater tradeable area across the southern MDB than the Murrumbidgee groundwater market.

As expected, surface-water temporary and permanent prices statistically significantly (and positively) affected groundwater temporary prices in the Murrumbidgee. This confirmed the existence of a substitution effect between surface and groundwater (Haensch et al., 2016). Diesel prices had a negative impact on groundwater temporary prices: similar to a decrease in farmers' income, an increase in diesel prices shifts the water demand curve to the left as groundwater pumping costs increase. As water demand is reduced, groundwater temporary prices fall. Mean temperature was positively associated with groundwater temporary prices, as evapotranspiration increases crop water demand while not affecting supply. Rainfall had no statistically significant impact. Finally, we found that groundwater temporary prices were slightly higher at the beginning of the water season (i.e. between July and September). This confirmed a seasonal trend already noted in the literature: as uncertainty related to water resources availability is higher, farmers buying water early in the season tend to pay more. This is perceived as an insurance premium, and in the case of groundwater in Murrumbidgee we found that this impact disappeared after October.

This study has focussed on one groundwater region in the MDB, and an analysis of other areas would be warranted. A further limitation of this study is related to its investigation between the full connectivity of surface and ground-water resources. Since our level of analysis is at the trading district level, we cannot control for the distance and/or physical connectivity between a given bore's aquifer and the nearest surface-water body. Future research would be necessary in this space. However, this study's findings of the economic interdependency between surface and groundwater markets is a possible indication of the close physical connectivity between the two resources, that allows for increased substitution between them. Further understanding of this relationship will be crucial for designing appropriate water management policies.

4. Conclusion

This study used a ten-year dataset of monthly groundwater and surface-water market prices and quantity traded in the Murrumbidgee, Murray-Darling Basin and identified two key water policy results. First, we found that there is a significant price leadership phenomenon from surface-water markets to groundwater temporary markets. Surface-water markets are used the most by irrigators in the Murrumbidgee; hence they incorporate market sensitive information first, and this information is then transmitted to groundwater markets. The price of temporary groundwater and its quantity traded were found dependent on the price and quantity of the surface-water traded in the region. This suggested the existence of a substitution effect between surface and groundwater, despite irrigators' preference for surface-water. Therefore, the need for an integrated water policy that applies to both surface and groundwater resources is imperative. Conjunctive management of water resources could offer several benefits in this perspective. If water policies only target surface-water resources, it is likely that irrigators will substitute groundwater for surface-water: and indeed, there is increasing evidence of such behaviour. Furthermore, quantifying return flows is also important, along with the need for greater regulation and monitoring of groundwater extraction in the MDB.

The second key water policy result was that groundwater temporary market demand in the Murrumbidgee was unitary elastic (-1.05) in our period of study, indicating the price elastic link between groundwater prices and groundwater pumping demand. Other key influences on groundwater temporary prices included diesel cost, rice prices, temperature and early season timing.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

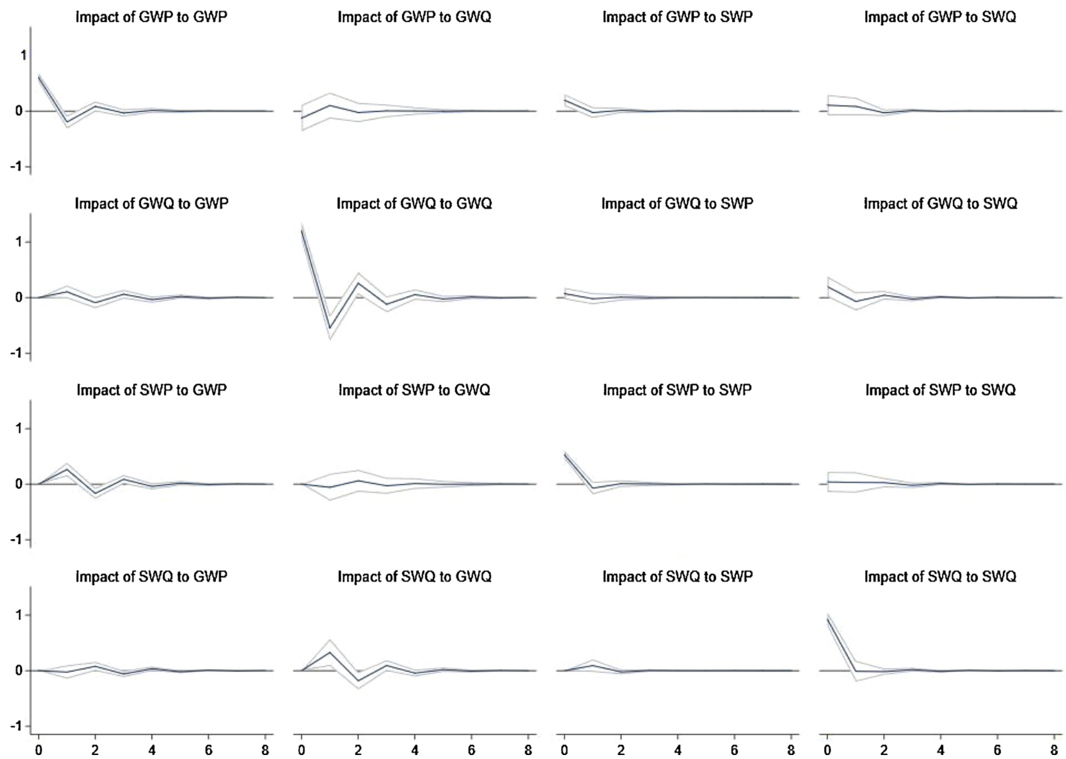

Fig. B1. Orthogonal Impulse Response Functions and Forecast Error Variance Decomposition Results following the VARX(1) estimation: Orthogonalized Impulse-Response Functions and 5% confidence interval following the VARX(1) estimation in the Murrumbidgee temporary surface and groundwater markets, 2008-2018.

Note: Impulse response functions trace the effect of an exogenous shock on one of the endogenous variables in the VARX model to the other endogenous variables. A more detailed explanation on Impulse Response Functions and Variance Decomposition can be found in Roca and Tularam (2012). The duration of the shock is described in the next 8 months (shocks rarely last more than 1 month). The result and the related 5% confidence interval are shown. Abbreviations can be interpreted the following way: GW is Groundwater, SW is Surface-water, P is temporary price, and Q is Quantity temporary traded.

Table A1
Descriptive statistics.

Variable	Description	Used in[a]	Source	Obs	Mean	Std. Dev.	Min	Max
Groundwater temporary price	Median monthly groundwater allocation price in all trading zones of the Murrumbidgee Alluvium, AUD$/ML in constant 2018 prices	PL, E	Bureau of Meteorology water market data[b]	102	33.78	32.74	1.13	122.96
Groundwater temporary quantity traded	Total monthly quantity of groundwater allocations traded (ML) in all trading zones of the Murrumbidgee Alluvium	PL, E		102	3430.35	2874.48	10	14749.60
Surface-water temporary price	Median monthly surface water allocation price $/ML, expressed in constant 2018 prices, in the Murrumbidgee regulated river trading zone	PL, E		102	132.44	129.95	2.84	652.89
General security permanent price	Median monthly price of the general security entitlement ($/ML, constant 2018 prices) in the Murrumbidgee regulated river trading zone	E		102	1056.10	246.49	667.88	1657.66
Rainfall in the last month	Monthly rainfall (mm) at Hay Airport AWS Station, NSW	PL, E	BoM Weather and Climate data[c]	102	30.64	32.96	0	184.80
Mean temperature	Mean temperature (°C) at Hay Airport AWS station, NSW	PL, E		102	18.55	5.77	8.40	27.80
Rice price	Monthly rice price (USD/t, constant 2018 prices)	E	ABARES (2018)	102	540.16	130.59	377.74	871.54
General security allocation level	General security monthly allocation announced for the Murrumbidgee regulated river trading zone water (%)	E	NSW Government, DPI water[d]	102	47.05	30.05	0	100
Diesel price	Mean monthly diesel price (AUD$ cents/litre constant 2018 prices) in Sydney, NSW	E	Australian Institute of Petroleum[e]	102	137.86	20.26	95.75	197.56
Month index	Month index with July = 1 and June = 12	E	–	102	6.57	3.21	1	12
Early water season dummy	Dummy equal to 1 for July, August and September; 0 = otherwise	E	–	102	0.22	0.41	0	1
Mid water season dummy	Dummy equal to 1 for October to January; 0 = otherwise	E	–	102	0.36	0.48	0	1

[a] PL = Price Leadership analysis; E = Elasticity analysis.
[b] Available online: http://www.bom.gov.au/water/dashboards/#/water-markets/national/state/at, accessed on 15th May 2018, data from 01/07/2008 to 30/04/2018.
[c] Available online: http://www.bom.gov.au/climate/data/index.shtml?bookmark=136, accessed on 15th May 2018.
[d] Available online: https://www.industry.nsw.gov.au/water/allocations-availability/allocations/determinations, accessed on 15th May 2018.
[e] Available online: https://aip.com.au/index.php/historical-ulp-and-diesel-tgp-data, accessed on 11th February 2019.

Table B1
Cholesky forecast error variance decomposition after two lags based on VARX(1) estimation for unit percent change in four market variables in the Murrumbidgee temporary surface and groundwater markets 2008-2018.

Share of Variance (%)	Groundwater		Surface-water	
	Price	Quantity traded	Price	Quantity traded
Groundwater temporary price (lag)	83.18	1.38	11.80	1.99
Groundwater temporary quantity (lag)	2.25	92.75	1.66	4.76
Surface-water temporary price (lag)	14.44	0.17	84.07	0.28
Surface-water temporary quantity (lag)	0.13	5.70	2.47	92.97

Note: The Variance decomposition decomposes variations in one of the endogenous variables (first column) in the VARX(1) model into the component shocks to the other endogenous variables (Roca and Tularam, 2012; Reza et al., 2017) in columns 2–5. Variations are expressed in percent of the total variations and indicate the percent valuation that can be attributed to a given variable.

Appendix B. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2020.106204.

References

ABARES, 2018. Agricultural commodity statistics 2018. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Canberra, Australia. https://doi.org/10.25814/5c07afde3fec3.
ABS, 2018. Water Use on Australian Farms 2016-17 (No. 7503.0). Australian Bureau of Statistics.
Alamdarlo, H.N., Pourmozafar, H., Vakilpoor, M.H., 2019. Improving demand technology and internalizing external effects in groundwater market framework, case study: Qazvin plain in Iran. Agr. Water Manage. 213, 164–173.
Asci, S., Borisova, T., Dukes, M., 2017. Are price strategies effective in managing demand of high residential water users? Appl. Econ. 49, 66–77.
Badiani-Magnusson, R., Jessoe, K., 2019. Electricity prices, groundwater and agriculture: the environmental and agricultural impacts of electricity subsidies in India. In: Schlenker, W. (Ed.), Agricultural Productivity and Producer Behavior. University of Chicago Press Chapter 5.
Blanco-Gutiérrez, I., Varela-Ortega, C., Flichman, G., 2011. Cost-effectiveness of groundwater conservation measures: a multi-level analysis with policy implications. Agr. Water Manage. 98, 639–652.
Brooks, R., Harris, E., 2008. Efficiency gains from water markets: empirical analysis of Watermove in Australia. Agr. Water Manage. 95, 391–399.
Brooks, R., Harris, E., 2014. Price leadership and information transmission in Australian water allocation markets. Agr. Water Manage. 145, 83–91.

Brooks, R., Harris, E., Joymungul, Y., 2013. Price clustering in Australian water markets. Appl. Econ. 45, 677–685.
Bruno, E.M., Sexton, R.J., 2020. The gains from agricultural groundwater trade and the potential for market power: theory and application. Am. J. Agr. Econ forthcoming.
Caswell, M., Lichtenberg, E., Zilberman, D., 1990. The effect of pricing policies on water conservation and drainage. Am. J. Agr. Econ. 72, 883–890.
Caswell, M., Zilberman, D., 1985. The choices of irrigation technologies in California. Am. J. Agr. Econ. 67, 224–234.
Chevallier, J., 2010. EUAs and CERs: vector autoregression, impulse response function and cointegration analysis. Econ. Bull. 30, 558–576.
Chordia, T., Swaminathan, B., 2000. Trading volume and cross-autocorrelations in stock returns. J. Financ. 55, 913–935.
Colby, B.G., 2000. Cap-and-Trade policy challenges: a tale of three markets. Land Econ. 76, 638–658.
de Fraiture, C., Perry, C.J., 2007. Why is agricultural water demand unresponsive at low price ranges? In: Molle, F., Berkoff, J. (Eds.), Irrigation Water Pricing: The Gap between Theory and Practice. CABI Publishing, pp. 94–107.
Diwakara, H., Nagaraj, N., 2003. Negative impacts of emerging informal groundwater markets in peninsular India: reduced local food security and unemployment. J. Soc. Econ. Dev. 5, 90–105.
Douglas, E., Wheeler, S., Smith, D., Overton, I., Gray, S., Crossman, N., Doody, T., 2016. Using mental-modelling to explore how irrigators in the Murray-Darling Basin make water-use decisions? J. Hydrol. Reg. Stud. 6, 1–12.
Frank, M.D., Beatie, B.R., 1979. The economic value of irrigation water in the Western United States: an application of ridge regression. Texas Water Resources Institute.
Frija, A., Wossink, A., Buysse, J., Speelman, S., Van Huylenbroeck, G., 2011. Irrigation pricing policies and its impact on agricultural inputs demand in Tunisia: a DEA-based methodology. J. Environ. Manage. 92, 2109–2118.
Gao, L., Connor, J., Doble, R., Ali, R., McFarlane, D., 2013. Opportunity for peri-urban Perth groundwater trade. J. Hydrol. 496, 89–99.
Gill, B., Webb, J., Stott, K., Cheng, X., Wilkinson, R., Cossens, B., 2017. Economic, social and resource management factors influencing groundwater trade: evidence from Victoria, Australia. J. Hydrol. 550, 253–267.
Gilligan, D., 2005. Fish Communities in the Murrumbidgee Catchment: Status and Trends (Technical Report No. 75). NSW DPI, Narrandera, NSW.. .
Gonzalez-Alvarez, Y., Keeler, A.G., Mullen, J.D., 2006. Farm-level irrigation and the marginal cost of water use: evidence from Georgia. J. Environ. Manage. 80, 311–317.
Grafton, R., Landry, C., Libecap, G.D., McGlennon, S., O'Brien, R., 2011. An integrated assessment of water markets: a cross-country comparison. Rev. Env. Econ. Policy 5, 219–239.
Grafton, R., Williams, J., Perry, F., Molle, C., Ringler, P., Steduto, B., Udall, S., Wheeler, S., Wang, D., Garrick, R., Allen, G., 2018. The paradox of irrigation efficiency. Science. 24, 748–750.
Green, D., Petrovic, J., Moss, P., Burrell, M., 2011. Water resources and management overview: murrumbidgee catchment. NSW Office of Water.
Haensch, J., Wheeler, S.A., Zuo, A., Bjornlund, H., 2016. The impact of water and soil salinity on water market trading in the southern murray-darling basin. Water Econ. Pol. 2.
Hendricks, N.P., Peterson, J.M., 2012. Fixed effects estimation of the intensive and extensive margins of irrigation water demand. J. Agr. Resour. Econ. 37, 1–19.
Hérivaux, C., Rinaudo, J.-D., Montginoul, M., 2020. Exploring the potential of groundwater markets in agriculture: results of a participatory evaluation in five french case studies. Water Econ. Pol. 6, 1950009.
Holley, C., Mutongwizo, Pucci S., Castilla Rho, J., Sinclair, D., 2020. Groundwater regulation, compliance and enforcement: insights on regulators, regulated actors and frameworks in New South Wales, Australia. In: Rinaudo, J.-D., Holley, C., Barnett, S., Montginoul, M. (Eds.), Sustainable Groundwater Management: A Comparative Analysis of French and Australian Policies and Implications to Other Countries. Springer.
Hooker, M.A., Alexander, W.E., 1998. Estimating the demand for irrigation water in the Central Valley of California. JAWRA J. Am. Water Resour. As. 34, 497–505.
Howitt, R.E., Watson, W.D., Adams, R.M., 1980. A reevaluation of price elasticities for irrigation water. Water Resour. Res. 16, 623–628.
Khair, S.M., Mushtaq, S., Culas, R.J., Hafeez, M., 2012. Groundwater markets under the water scarcity and declining watertable conditions: the upland Balochistan Region of Pakistan. Agr. Syst. 107, 21–32.
Knapp, K.C., Weinberg, M., Howitt, R., Posnikoff, J.F., 2003. Water transfers, agriculture, and groundwater management: a dynamic economic analysis. J. Environ. Manage. 67, 291–301.
Kuwayama, Y., Brozović, N., 2013. The regulation of a spatially heterogeneous externality: tradable groundwater permits to protect streams. J. Environ. Econ. Manage. 66, 364–382.
Lehner, B., Verdin, K., Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. Eos, T., AGU 89, 93–94.
Loch, A., Bjornlund, H., Wheeler, S., Connor, J., 2012. Allocation trade in Australia: a qualitative understanding of irrigator motives and behaviour. Aust. J. Agr. Resour. Econ. 56, 42–60.
Maestu, J., Gomez-Ramos, A., 2013. Conclusions and recommendations for implementing water trading: how water trading can be part of the solution. In: Maestu, J. (Ed.), Water Trading and Global Scarcity. RFF Press, pp. 362–375.
Manjunatha, A.V., Speelman, S., Chandrakanth, M.G., Van Huylenbroeck, G., 2011. Impact of groundwater markets in India on water use efficiency: a data envelopment analysis approach. J. Environ. Manage. 92, 2924–2929.
Mieno, T., Brozovic, N., 2016. Price elasticity of groundwater demand: attenuation and amplification Bias due to incomplete information. Am. J. Agr. Econ. 99, 401–426.
Min, J.H., Najand, M., 1999. A further investigation of the lead–lag relationship between the spot market and stock index futures: early evidence from Korea. J. Futures Markets 19, 217–232.
Mitchell, M., Curtis, A., Sharp, E., Mendham, E., 2012. Directions for social research to underpin improved groundwater management. J. Hydrol. 448–449, 223–231.
Moore, M.R., Gollehon, N.R., Carey, M.B., 1994. Multicrop production decisions in western irrigated agriculture: the role of water price. Am. J. Agr. Econ. 76, 859–874.
Mukherji, A., 2007. The energy-irrigation nexus and its impact on groundwater markets in eastern Indo-Gangetic basin: evidence from West Bengal. India. Energ. Policy 35, 6413–6430.
Murray-Darling Basin Authority (MDBA), 2013. Murray-Darling Basin Water Resource Plan Areas - Surface Water (GIS Data). [dataset]. .
Murray-Darling Basin Authority (MDBA), 2014. Fact Sheet: New Basin Plan Water Trading Rules Start 1st July 2014.
Nelson, N., 2019. Water data and the legitimacy deficit: a regulatory review and nationwide survey of challenges considering cumulative environmental effects of coal and coal seam gas developments. Australas. J. Water Resour. 23, 24–34.
Nguyen-ky, T., Mushtaq, S., Loch, A., Reardon-Smith, K., An-Vo, D.-A., Ngo-Cong, D., Tran-Cong, T., 2018. Predicting water allocation trade prices using a hybrid Artificial Neural Network-Bayesian modelling approach. J. Hydrol. 567, 781–791.
Nieswiadomy, M.L., 1985. The demand for irrigation water in the High Plains of Texas, 1957-80. Am. J. Agr. Econ. 67, 619–626.
Ogg, C.W., Gollehon, N.R., 1989. Western irrigation response to pumping costs: a water demand analysis using climatic regions. Water Resour. Res. 25, 767–773.
Ostrom, E., 1990. Governing the Commons: Evolution of Institutions for Collective Actions. Cambridge University Press, Cambridge.
Pagan, P., Fagan, M., Crean, J., Jones, R., 1997. In: Short-Run and Long-Run Approaches to Water Demand Estimation. Presented at the 41st Annual Conference of the Australian Agricultural and Resource Society. Gold Coast, Australia.
Palazzo, A., Brozovic, N., 2014. The role of groundwater trading in spatial water management. Agr. Water Manage. 145, 50–60.
Pfeiffer, L., Lin, C.-Y.C., 2014. Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. J. Environ. Econ. Manage. 67, 189–208.
Razzaq, A., Qing, P., Naseer, M.Aur R., Abid, M., Anwar, M., Javed, I., 2019. Can the informal groundwater markets improve water use efficiency and equity? Evidence from a semi-arid region of Pakistan. Sci. Total Environ. 666, 849–857.
Reza, R., Tularam, G.A., Li, B., 2017. An investigation into the interdependence of global water indices: a VAR analysis. Appl. Econ. 49, 769–796.
Roca, E., Tularam, G.A., 2012. Which way does water flow? An econometric analysis of the global price integration of water stocks. Appl. Econ. 44, 2935–2944.
Roope, M., Zurbruegg, R., 2002. The intra-day price discovery process between the Singapore Exchange and Taiwan Futures Exchange. J. Futures Markets 22, 219.
Ross, A., 2018. Speeding the transition towards integrated groundwater and surface water management in Australia. J. Hydrol. 567, e1–e10.
Scheierling, S.M., Young, R.A., Cardon, G.E., 2004. Determining the price-responsiveness of demands for irrigation water deliveries versus consumptive use. J. Agr. Resour. Econ. 29, 328–345.
Scheierling, S.M., Loomis, J.B., Young, R.A., 2006. Irrigation water demand: a meta-analysis of price elasticities. Water Resour. Res. 42.
Schoengold, K., Sunding, D.L., Moreno, G., 2006. Price elasticity reconsidered: panel estimation of an agricultural water demand function. Water Resour. Res. 42.
Seidl, C., Wheeler, S.A., Zuo, A., 2020a. High turbidity: water valuation and accounting in the Murray-Darling Basin. Agr. Water Manage. 230, 105929.
Seidl, C., Wheeler, S.A., Zuo, A., 2020b. Treating water markets like stock markets: key water market reform lessons in the Murray-Darling Basin. J. Hydrol. 581, 124399.
Shumway, C.R., 1973. Derived demand for irrigation water: the California aqueduct. J. Agr. Appl. Econ. 5, 195–200.
Silva, F., Fulginiti, L., Perrin, R., Schoengold, K., 2019. The effects of irrigation and climate on the high plains aquifer: a county-level econometric analysis. J. Am. Water Resour. As. 55, 1–17.
Smith, S.M., Andersson, K., Cody, K.C., Cox, M., Ficklin, D., 2017. Responding to a groundwater crisis: the effects of self-imposed economic incentives. J. As. Environ. Resour. Economists 4, 985–1023.
Stock, J., Yogo, M., 2005. Testing for Weak Instruments in Linear IV Regression. Identification and Inference for Econometric Models. Cambridge University Press, New York, pp. 80–108.
Wang, C., Segarra, E., 2011. The economics of commonly owned groundwater when user demand is perfectly inelastic. J. Agr. Resour. Econ. 36, 95–120.
Wheeler, S.A., Cheesman, J., 2013. Key findings from a survey of sellers to the restoring the balance programme. Econ. Papers: J. Appl. Econ. Policy 32, 340–352.
Wheeler, S.A., Garrick, D.E., 2020. A tale of two water markets in Australia: lessons for understanding participation in formal water markets. Oxford Rev. Econ. Pol. 36, 132–153.
Wheeler, S., Bjornlund, H., Shanahan, M., Zuo, A., 2008. Price elasticity of water allocations demand in the Goulburn–Murray Irrigation District. Aust. J. Agr. Resour. Ec. 52, 37–55.
Wheeler, S.A., Schoengold, K., Bjornlund, H., 2016. Lessons to be learned from groundwater trading in Australia and the United States. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.-D., Ross, A. (Eds.), Integrated Groundwater Management: Concepts, Approaches, and Challenges. Springer, pp. 493–517.
Wheeler, S., Loch, A., Crase, L., Young, M., Grafton, Q., 2017. Developing a water market

readiness assessment framework. J. Hydrol. 552, 807–820.
Wheeler, S., Carmody, E., Grafton, R.Q., Kingsford, R., Zuo, A., 2020. The Rebound Effect on Water Extraction from Subsidising Irrigation Infrastructure in Australia. Resour. Conserv. Recycl. 159, 104755. https://doi.org/10.1016/j.resconrec.2020.104755.
Williams, J., Grafton, R.Q., 2019. Missing in action: possible effects of water recovery on stream and river flows in the Murray–Darling Basin, Australia. Australas. J. Water Resour. 23, 78–87.
WWAP, 2019. The United Nations World Water Development Report 2019: Leaving No One Behind. UNESCO World Water Assessment Programme, Paris.
Young, M., 2014. Trading into trouble? Lessons from Australia's mistakes in policy sequencing. In: Easter, K.W., Huang, Q. (Eds.), Water Markets for the 21st Century. Dordrecht, pp. 203–214.
Zhang, J., 2007. Barriers to water markets in the Heihe River basin in northwest China. Agr. Water Manage. 87, 32–40.
Zhang, J.-L., Zhang, F.-R., 2008. Mutual monitoring in a tradable water rights system: a case study of Zhangye City in Northwest China. Agr. Water Manage. 95, 331–338.
Zuo, A., Nauges, C., Wheeler, S.A., 2015. Farmers' exposure to risk and their temporary water trading. Eur. Rev. Agric. Econ. 42, 1–24.