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Examining volatility dynamics, spillovers and government water recovery in Murray-Darling Basin water markets

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Abstract

Although participation in water markets is widespread by irrigators in the Murray-Darling Basin of Australia, there has been a lack of study on the dynamics of water markets, in particular price and volume dynamic responses, volatility and spillovers. Questions have also been raised regarding the impact on markets from governments buying back permanent water from consumptive use to return to environmental use. VARX-BEKK-GARCH time-series regression was used to model the water market dynamics of monthly permanent and temporary water market trade from 1997-2017 in one of the largest water markets in the Murray-Darling Basin, the Goulburn. Results suggest that volatility in the permanent water market was less than the temporary market, while persistency in volatility only exists in permanent markets. Unidirectional transmission spillovers exists in both markets from prices to volumes. The main drivers of temporary water prices were water scarcity related, while permanent prices were most significantly influenced by previous permanent water prices and current temporary water market prices. A statistically significant negative impact on temporary volume-traded from government water recovery (e.g. a 1% increase in water recovery resulted in a 0.14% reduction in water volume-traded) was found, but no significant impact was found on temporary water prices, nor on permanent market prices and volumes. However, government water recovery increased the volatility of temporary market prices and volumes, signaling increased issues of risk and uncertainty for irrigators engaging in temporary water markets.

Keywords: water entitlement market; water allocation market; VARX-BEKK-GARCH models; buyback

1. Introduction

Water markets are increasingly being used around the world as a way to reallocate water to more efficient use (Chong and Sunding 2006; Grafton and Horne 2014; Zekri and Easter 2007). In particular, water markets in Australia have developed to a high level of maturity, having been in existence for over thirty years in some areas (Wheeler et al. 2014a). Irrigators can buy and sell water allocations (otherwise known as temporary seasonal water and are traded on an annual basis) or water entitlements (otherwise known permanent trade or water rights and are traded on a permanent basis), and recently there has been further maturation with the development of forward contracts in the water market. However, the use of water markets in Australia has not been without controversy, and there continues to be an ongoing debate over their social and economic impacts and the role that government intervention has played (e.g. Crase 2017).

One of the main advantages of water markets is that it allows water to be traded to its highest possible use, it encourages efficiency and it helps support long-term farm development (Grafton et al. 2011; Grafton et al. 2016). Consumptive users can mitigate their supply risk by purchasing water when it is most needed or selling water if the price of water sale exceeds the use value derived from applying the water in irrigation. It has been widely acknowledged that if water markets had not been present during the Millennium drought of the 2000s in Australia, many more irrigators would have gone bankrupt (Kirby et al. 2014; Wheeler et al. 2014b). Water markets can also benefit urban users by allowing cities to purchase reliable supply for critical human needs during drought or to support urban expansion. Most existing literature on water markets examines price and volume traded, without further investigating their volatility dynamics (including both vulnerability and persistency) and potential volatility spillovers, although these are often studied in financial, commodity and energy markets (e.g. Abdelradi and Serra 2015; An et al. 2016; Lee and Rui 2002). Given the mature stage of Australian water markets, it offers an ideal opportunity to study volatility dynamics and spillovers.

Understanding water markets' vulnerability and persistency helps illustrate market participants' exposure to external shocks. For example, substantial vulnerability to market shocks can increase price uncertainty and risk for future irrigation investors and water users who are reliant on water markets for their water needs. Persistency in a water market refers to whether the current level of volatility is largely dependent upon past volatility. A high level of persistency suggests that external shocks will not dramatically affect volatility. However, because of high persistency, it takes much longer for a large change in price/volume to dissipate compared to the vulnerable but non-persistent case.

The sophistication and development of water markets in the Murray-Darling Basin (MDB) have allowed them to be used as a market and compensation-based approach by federal government to acquire environmental water through the voluntary buyback of consumptive water and returned to the environment. When a water market is used for reallocation from consumptive users to the environment, ecological conditions can benefit when water is bought and used for environmental flows in rivers (Connor et al. 2013). These buybacks have been largely implemented through voluntary reverse auctions with irrigators, and on-farm and off-farm irrigation infrastructure subsidies to recover water (Grafton and Wheeler 2018).

Acceptance of buyback as a policy instrument has not been achieved easily in Australia and the perceived political costs continue to influence federal water policy (Crase 2017).

Given increasing political pressure from irrigator lobby groups who believe government buyback of water has caused significant harm to rural communities, in 2015 a 1,500 GL (gigalitre) cap on total permanent water entitlement buyback was established and in late 2017 the Murray-Darling Basin Authority (MDBA) recommended that buyback be stopped and all future environmental water be recovered from on- and off-farm irrigation infrastructure. This is contrary to considerable evidence from economists that buyback is more cost-effective, has less negative environmental externalities, and that the cost of buyback on rural communities has been overestimated (Crase 2017; Grafton and Wheeler 2018; Wittwer 2011).

This study takes advantage of a unique time-series dataset on Australia’s largest regional water market (analyzing prices and volumes traded on a monthly basis since 1997 in northern Victoria) and seeks to: 1) characterize the vulnerability and persistency of price and volume traded dynamics in temporary and permanent water markets; 2) investigate the transmission of volatility between price and volume in the temporary and permanent water markets; and 3) examine the impact of returning water from consumptive to environmental use (buyback and irrigation infrastructure grants) on both water market prices, volumes and their volatility.

The key findings include that the permanent market is generally less vulnerable than the temporary market; and that persistency in volatility only exists in the permanent market. Unidirectional transmission was found in both markets, with spillovers from prices to volumes only. Although the results suggested a small inelastic response of temporary water volume to government water recovery (a 1% increase in water recovery volume was associated with a 0.14% decrease in the temporary volume traded in the market), the decrease in volume did not translate to a significant impact on temporary prices. Water scarcity factors were the main influence on temporary prices. However, government water recovery did result in a significant small positive impact on the volatility of price and volumes in temporary markets which may need further investigation. Given that water markets are increasingly proposed as a solution for world-wide water scarcity issues (Wheeler et al. 2017), insights gained from analyzing one of the world's most sophisticated and developed water markets provide additional information to the debate.

2. Case Study Area: MDB and Water Markets Background

The MDB is known as Australia's food bowl, and includes regions within Queensland, New South Wales (NSW), Victoria (VIC), South Australia (SA), and all of the Australian Capital Territory. Irrigators within the MDB use more than half of the irrigation water applied nationally. For example, in 2016/17, water application by irrigators in the MDB accounted for 67% of all water applied by Australian farms (ABS, 2018). In particular, water markets have developed significantly in the southern MDB. Water rights (or licences) are defined as the right to access a share or 'entitlement' of water from a consumptive pool (Wheelers et al. 2014a), which can be traded within a number of areas in Australia. Entitlements vary in regards to their reliability and area (entitlement security falls into three main categories: high security (HS); general security (GS) and low security (LS)[1]). Each type of entitlement yields a seasonal volumetric allocation which is the amount that can be extracted by its' owner within the season and put to beneficial use (or traded temporarily).

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[1] HS is available in NSW, Victoria, and SA, GS is mainly in NSW and LS is mainly in Victoria. On average, LS owners are only expected to receive 100% of their water entitlements in 24–35 out of 100 years, GS full entitlements in 64–81 years, and HS 90–95 years (Zuo et al. 2015).

Water markets in the MDB were first established formally within irrigation districts from the 1980s onwards and, over time, trade has been permitted in terms of actual water entitlements and then across districts (MDBA 2010). The 1990s saw continual fundamental water reforms, upon which all current major water policy and institutions evolved, including the unbundling of land and water entitlements (Grafton and Horne 2014; Young 2014). One of the reasons given for the success and adoption of water markets is because of the considerable institutional, governance and property right development that has gone into establishing conditions for water markets. Registers, accounting systems, hydrology basin research, monitoring and management of externalities have continually been developed, updated and refined over time, especially in the southern MDB that has the largest share of water markets in Australia (Young 2014; Wheeler et al. 2017). Institutional arrangements are necessary to enable efficient (water to be moved to its highest use with minimal transaction costs) and equitable (in the sense that water use is monitored and complied with by various stakeholders) water trading (Grafton et al. 2016). Most water trade occurs between irrigators, many of whom use water markets as a risk management strategy (Nauges et al. 2016), although the Commonwealth has become an increasingly significant player with their growing ownership of environmental entitlements (Grafton 2019).

In the early 2000s, Australian governments started using markets as a way to securing water for the environment. These reforms started partly because of the establishment of the *National Water Initiative* (NWI) in 2004. The NWI was an intergovernmental agreement across states to address over-allocation and achieve environmental objectives in the MDB (COAG 2004). The NWI paved the way for on-going federal water reforms such as the *Water Act (2007)* which sought to establish robust institutions to support the function and regulation of water markets. In 2012 the MDB Plan was passed into law, and it set sustainable diversion limits for consumptive use, which will come into full effect in 2019. A total reallocation target of 2,750GL[2] (e.g. this represented around a quarter reduction in consumptive water use across the Basin) was to be reallocated to the environment by 2019, with an extra 450GL recovered through infrastructure investment expenditure (Grafton, 2019). The *Water for the Future* program in 2008 sought to recover water through irrigation on- and off-farm infrastructure subsidies (AUD$5.8 billion for the *Sustainable Rural Water Use Infrastructure Program* (SRWUIP)), followed by permanent water purchases (AUD$3.1 billion for a program called *Restoring the Balance* (RTB)) (Grafton and Wheeler 2018). Most of the water recovered via buyback has been through using a reverse auction mechanism, although there have also been a number of strategic purchases of large land and water holdings, especially since 2014-15 (DAWR 2019).

However, despite their wide adoption, water markets in the MDB have not been without controversy (e.g. Crase 2017). It is important to note that there are two aspects of this controversy: a) general privatisation and commodification arguments; and b) water recovery impacts on rural communities from using water markets as the instrument for recovery. Grafton et al. (2016) evaluates the privatisation and commodification arguments, and suggests that any evidence for any negative impact of these claims is scarce (albeit appropriate meta-governance and institutional rules and property rights are essential for well-functioning water markets). In relation to the second point about the impacts of water recovery on rural communities, there has been continual pressure since

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[2] In mid-2018 this total figure was reduced by 605GL, due to the MDBA's adjustment mechanism and assessment of the package of supply measures nominated by State Governments could offset water recovery through various water and environmental efficiency projects (Grafton 2019).

the Basin plan passed to try to reduce water recovery. There have been arguments made regarding the impact of buyback on rural communities in terms of: a) reductions in farm production from decreased water use and flow-on impacts on rural jobs; and b) impact on water markets through increased permanent and temporary prices (e.g. see RMCG 2016). These claims have resulted in the current halt on recovering any water via buyback, with all remaining recovery now through on and off-farm irrigation infrastructure, and an adjustment downwards of physical volumes of water recovery (Grafton 2019). Economists have pointed out that this ignores the following issues: 1) as at the beginning of 2018, water recovery through irrigation infrastructure cost at least 2.5 times more per mega-litre than buyback (and this relative difference is increasing); 2) subsidizing irrigation infrastructure reduces return flows into groundwater and surface-water; and 3) subsidizing irrigation infrastructure causes a rebound effect (changing crop mix to often permanent crops and increasing irrigation area). In turn, this increases overall farm water use, reduces diversification across the Basin and places farms at further risk in a future drought (Adamson and Loch 2018; Grafton 2019; Grafton and Wheeler 2018; Perry et al. 2017).

In seeking to understand the dynamics and impacts of water markets, it is first worth working through some theoretical insights about demand and supply in water markets. Water entitlements recovered by the government through buyback and irrigation infrastructure grants reduce the amount of water entitlements owned in an area. Although the law of demand and supply suggests we would expect that if the supply of water goes down in an area, then prices in a water market should increase over time, however, there are a number of considerations that need to be taken into account.

First, there is a difference between: a) water entitlements long-term average annual yield (LTAAY) owned by stakeholders in a region at particular points in time (highest ML); b) water allocations received annually by the region for their entitlements they own (from the 2000s onwards this was lower than ownership and fluctuates widely); and c) water allocations/diversions used in a region by stakeholders (usually lower than b – but dependent upon issues with carry-over and water trade movements – and also fluctuates widely as shown in Figure 1)). Correspondingly, total volume of water supplied in temporary water markets in a region is dependent upon: i) water allocations; ii) total portfolio of permanent water in the region and iii) sellers' willingness/ability to sell water. As previously highlighted, entitlements receive annual water allocations and, depending on drought and rainfall, an allocation within a water season can range from 0% to 100%. Hence, annual water diversions fluctuate considerably year by year (Figure 1). In addition, demand for water in the market is also not linear, due to adaptation, carryover, substitution and underutilization. Wheeler et al. (2014b) found that historically irrigators in the MDB have only used around 70% of their water allocations they receive. Therefore, even if water diversions are reduced, irrigators may not increase their demand for temporary water in the market (because they increase their utilization of water entitlements or adapt to less water correspondingly). Previous research has shown that seasonal factors such as water allocations, drought and low water storages are the critical factors driving temporary water prices (e.g. Wheeler et al. 2008). Given that total portfolio of permanent water ownership in an area only changes slowly over time (given government buyback but also private irrigator permanent trade volumes), Figure One illustrates the growing Federal ownership of entitlements in the Goulburn, while water allocations and diversions fluctuate widely, it is therefore an empirical question over what influences supply in the temporary water market the most (e.g. seasonal fluctuations or increased activity by government in buying water back and taking out a volume of supply).

FIGURE 1

In terms of understanding influences on permanent water markets, it is important to note that total water market trade volumes are dominated by temporary trade (see trade volumes in Figure 2), while a relatively smaller amount of permanent trade is conducted in the MDB. Research has shown that permanent water trading is more related to long-term considerations such as farm and environmental/spatial characteristics, and that participation in permanent trade has increased gradually over time, especially from 2006 onwards (e.g. Wheeler et al., 2010; Zuo et al. 2015; Grafton and Wheeler 2018). Hence, given that current water supply in permanent water markets is very small compared to total water ownership, and that participation in permanent markets has increased over our time-period from 2006 onwards, it is again an empirical question as to what impact overall increasing water recovery plays in permanent water market dynamics where demand is inelastic (e.g. Zuo et al. 2015). The exact impact may also depend on the extent to which the permanent or temporary market plays a price leadership role, and understanding the dynamics of the interactions between permanent and temporary markets will help answer this question.

As such, this suggests it may be hard to theoretically predict the impact of government interventions on the local water markets, both permanent and temporary. Although we have some expectations that water supply ownership by irrigators overall will change, impacts on water market prices and dynamics will depend critically on how much demand and supply *in the markets* are affected, not on how much water ownership is changed because the studied market can be a fraction of total water ownership. Furthermore, the links and substitution between both permanent and temporary surface-water and groundwater utilization and markets, farmer adaptation to less water availability, and other key seasonal water market factors will all influence water market outcomes. It is also worth noting that higher prices in water markets (whether it is due to scarcity factors or government involvement) do not necessarily decrease net social welfare, given that water sellers receive higher prices, while water buyers are paying higher prices. Higher water prices also spur increased innovation and adaptation by irrigators. This is also illustrated by the evaluation of the net social welfare change in Australia from the implementation of water recovery in the MDB, which has shown that the societal benefits outweigh the costs overall (Grafton, 2019).

Within the existing literature, Young and McColl (2008) first suggested that government buyback policy would influence the water market by increasing permanent prices. ABARE (2010) estimated that buyback would result in an increase of 17.5% in permanent water market prices in the southern MDB. Aither (2016) suggested that about a quarter of the increase in temporary water prices was attributable to buyback, with climatic factors being the main driver of variability. RMCG (2016 p. 41) studied the impact of buyback on the Goulburn (the same area studied here), and claimed that the buyback program led to a doubling of temporary water prices, as well as significantly increasing long-term permanent prices. However, these existing studies do not always carefully consider the difference between water market supply and water entitlement ownership, and are significantly constrained by methodology, data availability and assumptions used, as well as only focused on the impact on levels of price and volume without considering volatility impacts. There is therefore a need to properly model and consider all the dynamic adjustment processes and spillover magnitudes within water markets, and to evaluate the potential impact of government water recovery in markets, including both levels and volatilities of price and volume.

3. Literature review on market dynamics

A large number of studies on market dynamics in financial markets focus on the theoretical and empirical relationship between price (or price returns) and trading volume (Gallant et al. 1992; Gündüz and Hatemi-J 2005; Karpoff 1987). Price-volume relationships provide insights into market structure, such as how information flows to the market; dissemination of information and how much market prices convey this information. The sequential information arrival model (e.g. Copeland 1976; Jennings et al. 1981) suggests a positive causal relationship between stock prices and trading volume in either direction. The mixture distributions model (Epps and Epps 1976) proposed that trading volume can be used to measure disagreement as traders revise their reservation prices based on new information arrival into the market, suggesting a positive causal relationship from trading volume to absolute stock returns. In the model by Blume, Easley, and O'Hara (1994), volume traded provides data on the quality or precision of information on past price patterns, while Wang (1994) shows that volume may provide information about expected future returns based on a model with information asymmetry.

Early empirical studies on the price-volume linkage mainly focused on their contemporaneous relationship but rarely investigated the causal relationships (Crouch 1970; Granger and Morgenstern 1963; Karpoff 1987). On the dynamic and causal links between stock prices and volume, Hiemstra and Jones (1994) found uni-directional Granger causality from stock returns to trading volume, while Gallant, Rossi, and Tauchen (1992) found a strong impact from lagged stock returns to current and future trading volume but a weak impact from lagged volume to current and future stock returns. Using bivariate and multivariate vector autoregression (VAR), Lee and Rui (2002) found that volume does not Granger-cause stock market returns and a positive feedback relationship between volume and return volatility existed.

Besides the relationship between price and volume within one market, price transmission across multiple markets has become increasingly the topic for market dynamics studies (An et al. 2016; Esposti and Listorti 2013; Serra and Goodwin 2003). Price transmission can occur both vertically and horizontally. Vertical price transmission refers to linkages along the supply chain (Serra and Goodwin 2003 and An et al. 2016 provide agricultural examples) while horizontal price transmission means linkages among different markets at the same position in the supply chain (Esposti and Listorti 2013).

Price transmission models study either price behavior in levels or on volatility patterns (Assefa et al. 2015). Nonstructural time-series models are usually employed, which has the advantage of only requiring price data for econometric estimation (Serra and Gil 2013). For example, An et al. (2016) use a co-integration test to identify whether export restrictions dampened the price transmission from the wheat to the flour market in Ukraine and an asymmetric VEC-BEKK-GARCH model investigated price spillovers between the two markets.

In the existing water market literature, studies on the relationship between price and volume have focused mainly on estimating the price elasticity of demand or supply (Brooks and Harris 2005; Wheeler et al. 2008; Zuo et al. 2015). Wheeler et al. (2008) analyzed the influences on water temporary and permanent prices in the GMID from

1993-2007 and found that the temporary price was most influenced by short-term water scarcity factors (e.g. drought and water allocations). Although there has been some work in the literature about whether water markets exhibit characteristics similar to other financial markets (e.g. market depth in Brooks, Harris, and Joymungul 2009; price clustering features in Brooks, Harris, and Joymungul 2013 and Zuo et al. 2014; and price leadership in Brooks and Harris 2014), there are many other financial characteristics aspects of water markets that have not been examined. These include a dynamic adjustments process of price and trading volume, volatility of price and trading volume, and spillovers between price and volume volatility. Through studying these dynamic adjustment processes with a unique monthly time-series from 1997 onwards, the vulnerability and persistency of price and volume in water markets can be characterized.

4. Methodology

4.1 Data and study area

A unique historical monthly dataset of temporary and high security (HS) permanent water trade (namely prices and volumes traded) between 1997 and 2017 from the Goulburn trading zone of GMID, northern Victoria is used (total n=227). The majority of irrigated crops in the area in this time-period are annual (pastures and cereals), followed by permanent horticulture. The Goulburn-Murray Irrigation District (GMID) historically is Australia’s largest irrigation district and it has the largest and most active water-trading zone, the Goulburn (i.e. trading zone 1A Greater Goulburn), in terms of trading volume and number of trades (Wheeler et al. 2008; 2009; 2010). For example, in 2017-18, trade within the Goulburn represented 39% of total trades (by number) in the southern MDB.[3]

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[3] Sourced from the water market dashboard, Bureau of Meteorology, available at: http://www.bom.gov.au/water/dashboards/#/water-markets/mdb/at

Brooks and Harris (2014) have also shown evidence that the Goulburn is a price leader across trading zones. As at June 2018, 355.7 GLs (LTAAY) of water were returned from consumptive to environmental use in the Goulburn (DAWR 2019), with the majority of this coming from buyback programs (see Grafton and Wheeler 2018 for more detailed analysis of recovery volumes and costs over time).

The monthly water trade data was supplemented by other monthly data sources of known drivers of water markets (e.g. dairy commodity output and input prices, temperature and seasonal water allocations), previously identified from the literature (e.g. Brooks and Harris 2010; Wheeler et al. 2008; Zuo et al. 2014). In addition, a government water recovery variable was included in the modeling, measured as the accumulative volume of permanent water (LTAAY) recovered for the environment through the Commonwealth government buyback and irrigation infrastructure programs. In addition, alternative specifications of water recovery were also tested.[4]

Table 1 provides the detailed definitions for the dependent and independent variables used in the analysis. Price (Bjornlund and Rossini 2005; Wheeler et al. 2008) and volume (Wheeler et al. 2008) determinants of water markets in the MDB have been well documented in the literature, particularly for the GMID, for example: water scarcity (temperature, water allocations); irrigation agriculture output prices (milk prices as dairy is the biggest irrigation industry in the GMID); and irrigation commodity input prices

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[4] Table A in the Appendix presents similar results with buyback program volumes only. In addition, other testing using a dummy variable to represent the months in which the government was actively buying water entitlements in the market was conducted. However, due to the use of first differences, the dummy variable converted to one in the months when the government started a new tender for buyback, minus one in the months immediately after the tender was closed and zero for all the other months. In total, the non-zero months only represent around 8.8% of the total sample, which is a considerably small proportion and created an identification difficulty in estimating the impact of government buyback dummy on the market. Therefore, the dummy variable specification was not used.

(feed barley for feeding cows as a substitute for watering pasture). In time-series econometrics, parsimonious models can produce more accurate forecasts, given that the information set is extended to include past movements of multiple variables (Verbeek 2012). Therefore, we only include the most relevant independent variables and the government water recovery variable in the models.

TABLE 1

Figure 2 provides an overview of the movements in water market prices and volumes traded in the Goulburn trading zone. Both HS permanent prices and temporary water prices fluctuate greatly. The temporary water market volume has increased substantially while the permanent volume is much smaller, but has increased over time.

FIGURE 2

4.2 Empirical Strategy

Before deciding on the appropriate empirical strategy, we performed the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests and the results (Table 2) indicated that permanent volume was stationary and the two price series were non-stationary. Meanwhile, ADF and PP tests indicated contradictory results for the temporary volume series: ADF suggested non-stationarity while PP suggested stationarity. After transforming the series into first-differenced form, the unit root null was rejected, implying the differenced series were I(0).

To investigate the price-volume interactions as well as volatility spillovers, a multivariate GARCH model, known as the VARX- BEKK-GARCH model was applied (An et al. 2016). VARX refers to a VAR model with exogenous variables. The BEKK-GARCH framework developed by Engle and Kroner (1995) has two attractive empirical properties. First, the model was constructed to ensure positive-definiteness on the conditional variance-covariance matrix of the regression model residuals. Second, the model parameters can directly measure volatility spillovers including the size and direction, which is especially relevant to this study. We used the bivariate BEKK-GARCH instead of a four-variable BEKK-GARCH because of the dimensionality problem associated with the BEKK model (Anthony and Stavropoulos 2012; Zhen et al. 2018). Estimation of a multivariate BEKK-GARCH model involves substantial computations due to the high-dimensional nonlinear optimization nature. The number of parameters is relatively large, especially if we estimate the BEKK variance/covariance equations together with the VARX mean equations as a system to improve efficiency.[5] Because bivariate VARX models can only apply to stationary time-series data unless there is a cointegrating relationship between the two I(1) series, we therefore used the first-differenced logarithm data to investigate volume-price dynamics. For the price transmission model, cointegration was first tested using the Johansen trace test (Johansen 1991). Given the rejection of cointegration, a VARX-BEKK-GARCH model based on differenced data was adopted.

4.2.1 Volume-price interactions in the permanent and temporary markets

Since preliminary analysis suggested no co-integration between price and volume in both markets, we investigated dynamic adjustments, policy impacts and volatility spillovers by estimating two VARX- BEKK-GARCH models, namely permanent price—volume, and temporary price—volume. To fit any multivariate GARCH model, an appropriate

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[5] In our four-variable case, estimating a VAR(2)-BEKK-GARCH(1,1) model involves estimating 122 parameters simultaneously. Obtaining convergence therefore is difficult because the variance/covariance parameters are nonlinear in nature. We tried the multivariate BEKK-GARCH with different VAR lags, and most models did not converge. In the literature, it is rare to see a BEKK model with more than three variables due primarily to this curse of dimensionality issue. Common practices are bivariate BEKK-GARCH (e.g. Anthony and Stavropoulos 2012) or 3-variable BEKK-GARCH (e.g. Serra et al. 2011).

conditional mean model is required. For the two pair-wise volume-price adjustment processes, the conditional mean model was specified as a bivariate VARX model to quantify policy effects and other influences. The mean model in a VARX-BEKK-GARCH framework was expressed as:

$$\begin{aligned}&\Delta y_t = \alpha + \sum_{i=1}^{p} \beta_j \Delta y_{t-i} + \sum_{j=1}^{q} \theta_j \Delta z_{t-j} + \gamma \Delta Govn_t + \varepsilon_t \\ &\varepsilon_t \mid \Psi_{t-1} \sim (0, H_t)\end{aligned} \qquad (1)$$

where

$$\Delta y_t = \left[\Delta \log\left(\frac{\mathrm{volume_t}}{\mathrm{volume_{t\text{-}1}}}\right) \ \Delta \log\left(\frac{\mathrm{price_t}}{\mathrm{price_{t\text{-}1}}}\right) \right]$$

was a 2×1 vector of the volume and price changes (i.e., the first difference of logarithm), α a 2×1 vector of constants, β_i and θ_j, $\forall i, j = 1,...,n$ are 1×2 parameter vectors associated with lagged dependent variables and additional exogenous variables such as agricultural commodity/input prices and seasonal water allocations. In this study, we are especially interested in estimating γ which represents the impact from government water recovery. The last term ε_t is a 2×1 vector of residuals that depends on past information Ψ_{t-1}. This vector of residuals has zero mean and a conditional variance-covariance matrix H_t:

$$H_t = C'C + A'\varepsilon_{t-1}\varepsilon'_{t-1}A + B'H_{t-1}B + D'D\Delta Govn_t \qquad (2)$$

where H_t is the conditional variance-covariance matrix, and C, A, B, and D are parameter matrices:

$$H_t = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}, \; C = \begin{bmatrix} c_{11} & c_{12} \\ 0 & c_{22} \end{bmatrix}, \; A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \; B = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}, \; D = \begin{bmatrix} d_{11} & d_{12} \\ 0 & d_{22} \end{bmatrix},$$

For equation (2), the first component (*C* matrix) was an upper triangular parameter matrix. The second component was the autoregressive conditional heteroskedastic component and *A* is a matrix of ARCH parameters. The term $\varepsilon_{t-1}\varepsilon_{t-1}^{'}$ was the outer product of residuals from the conditional mean equation (1). The third component allows for a moving average mechanism to the conditional variance, *B* a GARCH parameter matrix and *D* the parameter matrix reflects the impacts of buyback program on price and volume volatility as well as on the covariance between the two. The term $\Delta Govn_t$ reflects the contemporaneous government water recovery.[6] Matrix H_{t-1} is the conditional variance-covariance matrix from the previous period. Specifically, the h_{ii}s are conditional variances for each series *i* and h_{ij}s are the conditional covariances between series *i* and *j*.

Lag structures for the conditional mean model were selected using the Bayesian information criterion. The conditional mean model was estimated simultaneously together with the conditional variance-covariance component using quasi-maximum likelihood methods (i.e., Equations 1 and 2 were estimated as a system) to improve efficiency.

5. Results

5.1 Volume-price interactions in the permanent market

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[6] Correlations between lagged trade volumes/prices and government water recovery were tested and found negligible to cause potential coefficient identification issues for the government water recovery variable.

Table 3 presents the results of the estimated parameters from the bivariate VARX-BEKK-GARCH model for the permanent water market.

TABLE 3

The conditional mean estimations from the first two panels in Table 3 indicate that for the permanent water market in the Goulburn, volume adjustment responds positively to lagged price adjustment, whereas lagged volume adjustment has no significant impact on price adjustment. A 1% increase in the previous month's water price will result in a 0.66% increase in the volume in current month, which may reflect that the supply of permanent water responds to better market opportunities, i.e. higher prices previously. With regard to government water recovery, the results did not suggest a statistically significant impact from buyback on the volume and price traded in the permanent market.

The percentage of seasonal allocations received had a negative statistically significant impact on the permanent water volume traded (a 1% increase in seasonal temporary allocations causes a 0.42% reduction in the total volume traded). Meanwhile, seasonal allocations had no significant effect on traded permanent prices. However, temporary water market prices had a statistically significant positive impact on both price adjustment and volume traded in the permanent market. A 1% increase in temporary water prices resulted in a 0.33% increase in the permanent volume traded and a 0.03% increase in the permanent price.

The conditional variance/covariance estimates are reported in the third panel in Table 3. The diagonal elements of matrix *A* capture own-volatilities resulting from lagged innovations (i.e., market shocks) while the diagonal elements of matrix *B* indicate how persistent the volatilities are. For the volume series, the relative size of *A (1,1)* is compared to that of *B (1,1)*: the permanent water volume traded is not vulnerable to new and unexpected market and/or policy changes (as shown in *A(1,1)*) while the estimated *B(1,1)*) was larger than *A(1,1)* and statistically significant which indicated that volatility in volume adjustment was persistent. Permanent volume trade takes a long time to reduce following a large rise or fall, for example due to policy intervention or adverse weather event. For the price series, *A(2,2)* and *B(2,2)* are about the same in their magnitudes. Therefore, this suggests that permanent prices are moderately vulnerable to new shocks such as new policy announcements and extreme weather events like droughts other than the factors that have been explicitly controlled in the model (i.e., the lagged volatility and the water recovery program). Meanwhile, volatility in price adjustment was moderately persistent and therefore reduces relatively faster than a highly persistent series.

The off-diagonal elements of *A(i,j)* and *B(i,j)* measure spillovers from variable *i* (permanent volume if *i*=1, and permanent price if *i*=2) to variable *j* (permanent volume if *j*=1, and permanent price if *j*=2). The large and significant *A(2,1)* estimate indicates strong spillovers from permanent price adjustment to volume adjustment. Past volatilities in price adjustment continuously contributed to the current and future volatility in the volume adjustment. On the other hand, the insignificant *A(1,2)* and *B(1,2)* estimates indicate no spillovers from the volume traded to price.

In summary, we find evidence of unidirectional volatility transmission from price to volume for the permanent market. In terms of the impact of government water recovery on the volume and price volatility, the matrix multiplication of the last term in Equation 2 (i.e., $D'D\Delta Govn_t$) indicates that $d_{11}{}^2$ represents the magnitudes of the water recovery program on the volatility of volumes and ($d_{12}{}^2 + d_{22}{}^2$) captures the effects of the program on price volatility. The statistically insignificant estimates of $d_{11}{}^2$ and $d_{12}{}^2 + d_{2s}{}^2$ suggests that the government recovery program does not contribute to the uncertainty (volatility) of the permanent water market.

Figure 3 illustrates the results of estimated conditional volatilities. The volatility plots are consistent with the persistency and vulnerability results discussed previously. Volume volatility was more persistent than price volatility. Jumps of price volatility indicate moderate vulnerability to market shocks. Hence, several important implications can be gained from Figure 3. First, the magnitude of volume volatility was much larger than price volatility. Second, the pattern of volatility clustering is close, and the two volatilities tend to move/spike together. This also confirms the results of the volatility spillovers discussed previously. Finally, the strength of volatility, especially for permanent market volumes, has decreased in recent years. Large spikes as occurred in early years are now rare, indicating the increased adoption of permanent trade in our time-period.

FIGURE 3

5.2 Volume-price interactions in the temporary market

Table 4 presents the results of the estimated parameters from the bivariate VARX-BEKK-GARCH model for the temporary water market.[7] The conditional mean estimations indicate that for the temporary market – which was a different result compared to the permanent market - volume adjustment responds negatively to lagged price adjustment. A 1% increase in lagged (by two months) temporary water prices

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[7] The results (Table B, Appendix A) of using buyback volume alone remained the same except that the government water recovery coefficient in the volume equation became insignificant (p-value=0.118), which is largely consistent with Table 4's measure of government water recovery (namely buyback and infrastructure water recovery) where a weak (p-value=0.098) statistically significant coefficient was found.

causes a statistically significant 0.44% decrease in the volume of temporary water traded. This probably reflects reduced water availability in general, or it may indicate that temporary water sellers are able to respond quickly to improved prices and sell in the current month, which consequently reduces the available temporary water for sale in the following months. Given that participation in temporary water markets by irrigators is considerably higher than permanent markets (Grafton and Wheeler 2018), this supports the above finding.

Similar to the permanent market, lagged temporary volume adjustment has no significant impact on temporary price adjustment. Meanwhile, permanent prices have a significant positive impact on temporary prices and volumes. A 1% increase in the permanent price results in a 0.85% increase in the temporary volume-traded and a 0.33% increase in temporary prices. Combined with the results from the permanent market, this suggests that price adjustment in the temporary and permanent markets are dependent on each other and adjustments in one market will also affect the other.

As expected, seasonal allocations received by irrigators had a highly positive significant impact on the temporary volume traded and a negative impact on temporary prices. A 1% increase in seasonal water allocations results in a 1.12% rise in the total temporary volume traded and a 0.24% reduction in temporary prices. Government water recovery did not have a statistically significant impact on temporary price adjustment but did have a significant influence on the temporary volume traded. A 1% increase in the government water recovery volume in the Goulburn resulted in a 0.136% decrease in the temporary volume traded.

The results further show that feed barley price (namely a substitution for watering pasture) had a significantly positive effect on the temporary water price (a 1% increase in the barley price raises temporary water prices by 0.63%). Temperature had a significant positive influence on the volume of temporary water traded. Specifically, a one-Celsius degree increase in mean monthly temperature raises temporary volume traded by 6.5%, with no significant impact on temporary water prices.

The conditional variance/covariance estimates in the temporary market are reported in the third panel in Table 4. For the volume series, *A(1,1)* is much larger than *B(1,1)*, suggesting that temporary volume traded was highly vulnerable to shocks, but volatility adjustment was not persistent. For the price series, although neither *A(2,2)* nor *B(2,2)* was statistically significant, the estimate of *A(2,2)* was almost 10 times of that of *B(2,2)*, which suggests that in terms of vulnerability versus persistency, price volatility in the temporary market was much more vulnerable but such volatility adjustment was not persistent. Consistent with the permanent-market results, the volatility spillovers in the temporary markets are also uni-directional and go from price to volume (*A(2,1)*). Regarding the government water recovery effects, our results indicate that 10% increase in water recovered by the government can results in a 0.3% (=0.178^2*10) increase in the volume volatility and a very small increase of around 0.02% (=(0.03^2+0.049^2)*10) in price volatility of temporary trade.

Figure 4 plots the estimated temporary water market conditional volatilities. The volatility plots are abrupt and show little persistency. Temporary volume volatility overall was much higher than price volatility; however, the difference between the two volatilities was smaller than the permanent water trade results in Figure 3. Second, the two volatilities exhibit high co-movement/dependence, and the patterns are almost identical.[8] This also provides evidence to support the results regarding volatility spillovers between the two series.

FIGURE 4

6. Discussion

The findings suggest that in the temporary market, both price and volume are highly vulnerable, while price in the permanent market is moderately vulnerable but volume is not. Substantial vulnerability in the temporary market increases price uncertainty and makes it more difficult to plan production decisions if irrigators rely heavily on the temporary market. Although being vulnerable, volatility in price and volume in the temporary market is not persistent, suggesting buyers may avoid big losses if they can be more flexible in their water requirements (i.e. wait till the abrupt jump in price to dissipate soon; target different months of buying), and likewise sellers may benefit from selling before a volatile price jump disappears.

On the other hand, permanent water market participants can expect this market to be less volatile. Compared to temporary markets, it is easier to predict future uncertainty in the permanent market based on the current and historical levels of uncertainty. However, because risks/external shocks are persistent if they indeed have an effect on volatility, in this case, it takes longer for such changes in prices/volumes to reduce in permanent markets compared to temporary markets.

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[8] One exception is around mid-2008, there was a large drop in price volatility while an increase in volume volatility. This is likely due to large market shocks (the residuals) during this period. The shock contributed positively to volume volatility, but negatively to price volatility (Zhen et al. 2018). Therefore, a large price increase as well as an increased temporary trade volume from the previous month in mid-2008 caused the present month's volume volatility to increase but reduced price volatility at the same time.

Cross-series volatility spillovers were found in both temporary and permanent water markets, in a unidirectional form (from price to volume). This finding suggest that if an external influence initially affects price volatility, it will spill-over to volume; but if an external influence first affects volume volatility, it will not be transmitted to price.

In terms of government policy shocks, after controlling for factors commonly found to influence water prices, such as seasonal water allocations, temperature, and commodity/input prices, contrary to expectations, government water recovery had no significant impact on either permanent or temporary prices. But, water recovery did had a small positive impact on the volatility of monthly temporary prices and volumes. [9] Volatility symbolizes the market's risk and uncertainty, and, like expected returns, can have a crucial effect on traders.

Our results also highlight that previous estimates (e.g. Aither 2016; RMCG 2016) about the impacts of government water recovery on water markets are overestimated. Our findings support other economic studies that have shown that the buyback of water entitlements on rural communities has had far less impact than has been commonly claimed. Reasons for this include the difference between water entitlement ownership and supply of water on the market as previously discussed, but also include demand factors such as farmer adaptation, surplus water use, surface-ground water substitution and farm restructuring following the sale of permanent water by irrigators (e.g., Connor et al. 2014; Kirby et al. 2014; Quiggin et al. 2010; Wheeler and Cheesman 2013; Wheeler

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[9] It should be noted that although increased volatility is an extra cost for irrigators, it does not suggest that environmental water recovery is inefficient. Losses associated with one group of market participants does not mean net social welfare loss.

et al. 2014a; 2014b; Wittwer and Griffith 2011). On the other hand, there is also evidence that current environmental water recovery is insufficient, given significant social welfare costs and over-allocation issues in the MDB (Grafton, 2019). Greater attention to management and institutional reform will be needed.

There are a number of study limitations that need noting. First, given the existence of a rare historical water market monthly dataset, we modelled the most adopted (and highly liquid) water market in the MDB, the Goulburn, and hence the impact of government water recovery may differ in other less liquid water markets. Second, we cannot control for expectations within the water market (for example, irrigators knowing that the government is planning on entering the water market to buy water, or knowing that large-scale irrigation infrastructure grants are going to be made available). Third, we used a cumulative measure of water recovery in the Goulburn, which is different to testing for when government is actually in the market (albeit we tried as many alternative forms as possible). The cumulative measure is not perfect, especially when estimating the extent of buyback through irrigation infrastructure grants, given the lack of detail (plus changing estimates) often provided on this by government departments. Finally, our empirical investigation uses time-series data and methods. Like other research using time-series methods (e.g., An et al. 2016), the policy impact is based upon Granger causality foundation, not the usual causality concept in economic theories. One needs to be cautious when discussing the implications. Nevertheless, our estimates provided the most advanced form of analysis so far on government water recovery in water markets, and further research would be warranted.

7. Conclusion

It has been well established in the literature that irrigators have benefited considerably from the development of water markets in Australia and irrigators now use water markets regularly as a farm adaptation and risk management tool. The results of our study of the Goulburn water trade market from 1997-2017 confirmed how markets allow irrigators to respond to water scarce situations. In particular, our study was the first to explore volatility dynamics in water markets, with findings relevant for traders to better understand the uncertainty and risk in both markets. For example, in order to better cope with future market vulnerability, irrigators may need extra risk alleviation strategies such as futures markets, increased water use adaptation and relevant insurance policies. Market participants need to plan their investment in the permanent market accordingly, since risks/external shocks are persistent if they indeed have an effect on volatility in the permanent markets. Overall, our findings suggest that temporary water trade represents a highly liquid farm asset, while a permanent water trade is more similar to land ownership and is less liquid, hence is heavily influenced by previous values and hysteresis. However, permanent markets also react to the ‘rent’ that is obtained through water ownership (namely the temporary water market price), which is similar to the theory of marginal value product of farmland. Greater information and training about the opportunity costs of water markets for irrigators may be warranted.

One of the most important results of this study was its finding that the federal government strategy of reverse auction tender mechanisms for water buyback from irrigators was an efficient and effective method, with little price and volume impacts detected from our Goulburn case study analysis. It is worth noting that the recent purchasing methods of the Commonwealth pursued since 2015 (namely only strategically purchasing water entitlements from large corporates and subsidising irrigation infrastructure) warrant increased scrutiny given their marginal value of water and negative externalities. In the context of current water policy reform, this study provides valuable guidance that the impact of government buyback in MDB water markets in general has been overestimated by a number of commentators, however, issues remain regarding the increased volatility from government water recovery for irrigators engaging in temporary water markets. The increased volatility reflects a higher level of risk, which may affect the investment decisions of market participants and also agricultural production decisions. Understanding the impact on volatility is an important aspect of comprehensively measuring policy effects, especially in assessing policy impacts on water markets. At present, public focus has been on the level of price and volume supplied, but with little attention paid to the effects on risk and risk management. Our approach serves as a starting point for future risk and uncertainty research in water markets.

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Tables

Table 1 Variable Definitions and summary statistics

Variable	*Definition*	*Mean*	*Standard deviation*	*Minimum*	*Maximum*
Water temporary price AUD/$ML	Natural logarithm of median real monthly price for temporary water (base year 2012) in Goulburn (all trade price and volume data sourced from Victorian water register and historically from Goulburn-Murray Water)	4.51	1.11	1.73	6.90
Water permanent price AUD/$ML	Natural logarithm of median real monthly price for high security permanent water (water entitlements) in Goulburn (base year 2012)	7.25	0.40	6.40	7.94
Water temporary volume (ML)	Natural logarithm of monthly volume traded for temporary water in Goulburn	10.11	1.12	0	12.43
Water permanent volume (ML)	Natural logarithm of monthly volume traded for high security permanent water in Goulburn	7.94	0.97	0	10.17
Seasonal allocation level (%)	Allocation level (%) for HS permanent water in Goulburn at the beginning of each month (sourced from Goulburn-Murray Water)	71	35	0	100
Temperature (°C)	Monthly mean temperature at Kerang station for GMID (sourced from BOM)	23.72	6.45	13.6	35.3
Feed barley price (AUD/ton)	Natural logarithm of feed barley real export price (base year 2012, sourced from Australian Bureau of Agricultural and Resource Economics and Sciences, ABARES)	5.53	0.23	5.07	6.14
Skim milk dairy powder price (1,000 AUD/$kg)	Natural logarithm of skim milk powder real export price (base year 2012, sourced from ABARES)	1.25	0.21	0.86	1.75
Government policy					
Government Water Recovery Volume (Giga-litre, GL) recovered for the environment	Natural logarithm of monthly accumulative volume of permanent water (LTAAY) recovered for the environment through the Commonwealth Government's Buyback program and irrigation infrastructure programs in Goulburn (sources: DEWHA; DSEWPaC; DEW; DAWR, for various time-periods)	2.52	2.67	0	5.83

Notes: Summary statistics are reported based on the level variables. In the regressions, all variables use first-differences.

Table 2. Unit Root Test Results

	$Volume^P$	$Price^P$	$Volume^T$	$Price^T$
ADF Test	-9.351***	-1.502	-1.826	-2.820
	0 lag	1 lag	12 lags	1 lag
Phillips–Perron Test	-4.053***	-1.726	-4.111***	2.682
	$\Delta Volume^P$	$\Delta Price^P$	$\Delta Volume^T$	$\Delta Price^T$
ADF Test	-6.514***	-17.854***	-4.962***	-13.089***
	11 lags	1 lag	12 lags	0 lag
Phillips–Perron Test	-25.761***	-29.292***	-16.211***	-13.069***

Notes**:** P=permanent; T=temporary.
Numbers in parentheses are p-values, where **$p<0.05$, ***$p<0.01$.
The 1% critical value for the ADF and PP tests was -3.455. The 1% critical value for the Phillips-Perron test was 3.455.

Table 3. VARX-BEKK-GARCH Results for the Goulburn Permanent Water Market

	Variable	*Coeff*	*Std Error*	*T-Stat*	*P-Value*
Mean Model (Permanent Volume)					
1	Permanent Volume lagged by one month	-0.315	0.040	-7.856	0.000
2	Permanent Volume lagged by two months	-0.084	0.046	-1.822	0.068
3	Permanent Price lagged by one month	0.656	0.377	1.739	0.082
4	Permanent Price lagged by two months	0.259	0.388	0.667	0.505
5	Temporary Price	0.329	0.145	2.265	0.023
6	Temperature	0.015	0.010	1.510	0.131
7	Allocation level	-0.415	0.204	-2.035	0.042
8	Feed Barley price	-0.648	0.641	-1.011	0.312
9	Skim Milk price	0.050	0.600	0.083	0.934
10	Government Water Recovery Vol.	-0.026	0.031	-0.840	0.401
Mean Model (Permanent Price)					
11	Permanent Volume lagged by one month	0.002	0.003	0.532	0.594
12	Permanent Volume lagged by two months	0.001	0.003	0.377	0.707
13	Permanent Price lagged by one month	-0.392	0.057	-6.896	0.000
14	Permanent Price lagged by two months	-0.123	0.051	-2.417	0.016
15	Temporary Price	0.026	0.011	2.294	0.022
16	Temperature	-0.001	0.001	-0.745	0.456
17	Allocation level	0.001	0.014	0.060	0.952
18	Feed Barley price	0.020	0.052	0.380	0.704
19	Skim Milk price	-0.109	0.060	-1.823	0.068
20	Government Water Recovery Vol	-0.004	0.006	-0.777	0.437
21	C(1,1)	0.554	0.140	3.973	0.000
22	C(2,1)	0.010	0.023	0.416	0.677
23	C(2,2)	0.027	0.018	1.509	0.131
24	A(1,1)	0.009	0.129	0.070	0.945
25	A(1,2)	-0.009	0.010	-0.859	0.390
26	A(2,1)	1.789	0.821	2.180	0.029
27	A(2,2)	0.795	0.124	6.391	0.000
28	B(1,1)	0.806	0.107	7.546	0.000
29	B(1,2)	-0.007	0.019	-0.361	0.718
30	B(2,1)	-0.402	0.526	-0.764	0.445
31	B(2,2)	0.709	0.081	8.704	0.000
32	D(1,1) = d_{11}	0.003	0.060	0.043	0.966
33	D(1,2) = d_{12}	0.025	0.012	2.085	0.037
34	D(2,2) = d_{22}	-0.006	0.009	-0.690	0.490

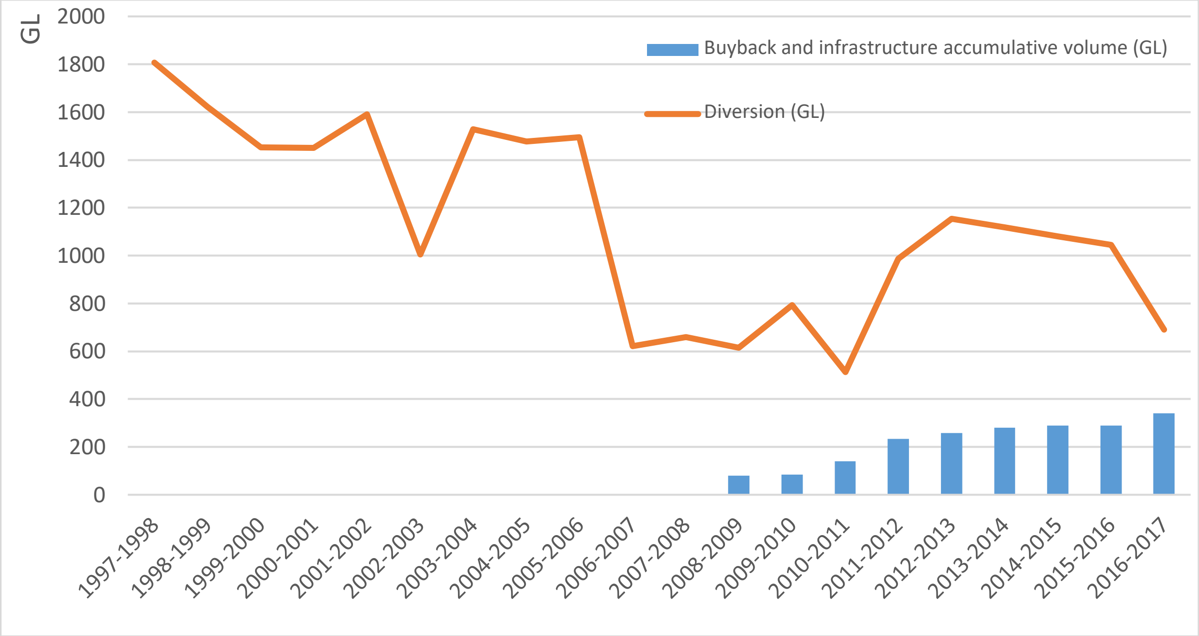
Note: All the variables are first-differenced.

Table 4: VARX-BEKK-GARCH Results for the Goulburn Temporary Water Market

	Variable	*Coeff*	*Std Error*	*T-Stat*	*P-Value*
Mean Model (Temporary Volume)					
1	Temporary Volume lagged by one month	-0.159	0.086	-1.854	0.064
2	Temporary Volume lagged by two months	-0.122	0.062	-1.953	0.051
3	Temporary Price lagged by one month	-0.069	0.267	-0.259	0.796
4	Temporary Price lagged by two months	-0.435	0.215	-2.018	0.044
5	Permanent Price	0.854	0.489	1.745	0.081
6	Temperature	0.065	0.014	4.720	0.000
7	Allocation level	1.118	0.215	5.207	0.000
8	Feed Barley price	0.798	0.765	1.043	0.297
9	Skim Milk price	0.054	1.040	0.052	0.959
10	Government Water Recovery Vol	-0.136	0.082	-1.652	0.098
Mean Model (Temporary Price)					
11	Temporary Volume lagged by one month	0.021	0.019	1.080	0.280
12	Temporary Volume lagged by two months	0.006	0.017	0.336	0.737
13	Temporary Price lagged by one month	0.079	0.068	1.153	0.249
14	Temporary Price lagged by two months	0.155	0.067	2.298	0.022
15	Permanent Price	0.334	0.193	1.727	0.084
16	Temperature	0.008	0.005	1.439	0.150
17	Allocation level	-0.244	0.073	-3.318	0.001
18	Feed Barley price	0.630	0.277	2.270	0.023
19	Skim Milk price	-0.186	0.278	-0.670	0.503
20	Government Water Recovery Vol	0.000	0.009	0.021	0.983
21	C(1,1)	0.584	0.193	3.023	0.003
22	C(2,1)	0.031	0.047	0.652	0.515
23	C(2,2)	0.264	0.018	14.365	0.000
24	A(1,1)	0.636	0.122	5.217	0.000
25	A(1,2)	-0.037	0.045	-0.814	0.415
26	A(2,1)	0.895	0.297	3.016	0.003
27	A(2,2)	0.145	0.193	0.752	0.452
28	B(1,1)	0.202	0.195	1.039	0.299
29	B(1,2)	-0.069	0.042	-1.665	0.096
30	B(2,1)	-0.781	1.704	-0.458	0.647
31	B(2,2)	0.014	0.228	0.063	0.949
32	D(1,1) = d_{11}	0.178	0.099	1.797	0.072
33	D(1,2) = d_{12}	0.003	0.014	0.222	0.824
34	D(2,2) = d_{22}	-0.049	0.022	-2.198	0.028

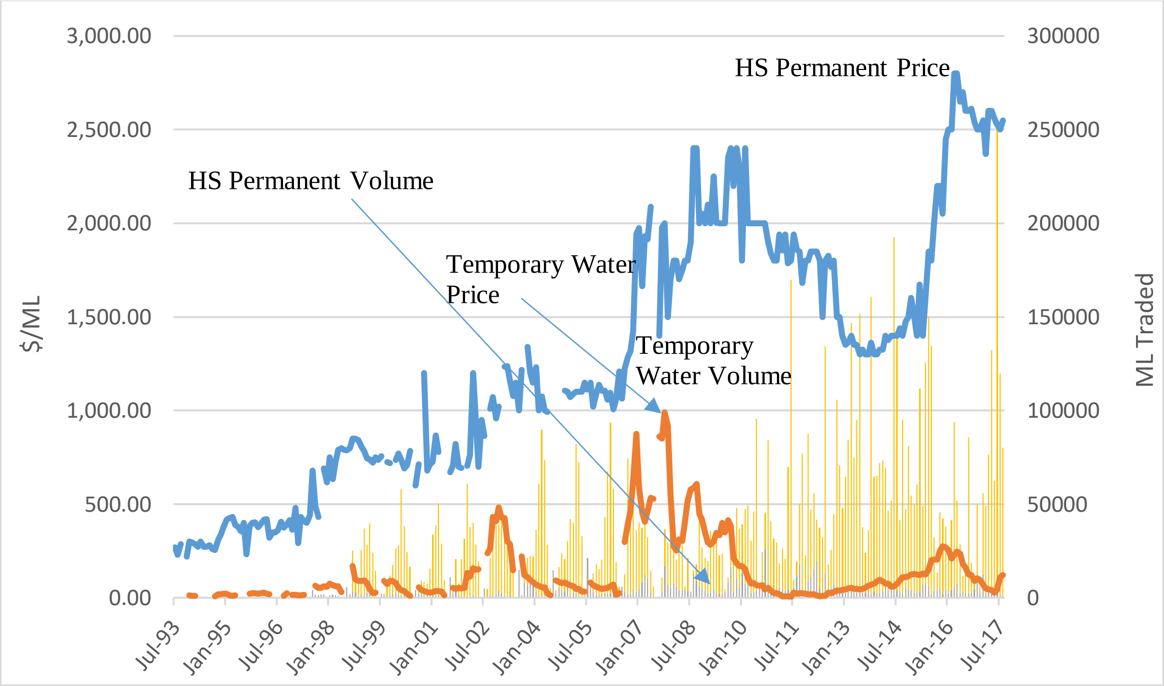
Note: All the variables are first-differenced.

Figure 1. Goulburn annual water diversions and accumulative government buyback and infrastructure program water recovery volumes



Sources: DEWHA, DSEWPAC, DEW; and DAWR, for various time-periods. MDBA (2018) and MDBA (various years).

Figure 2. Monthly price (nominal) and volume of temporary and high security (HS) permanent water trade in the Goulburn



Sources: Historical datasets and the Victorian water register.

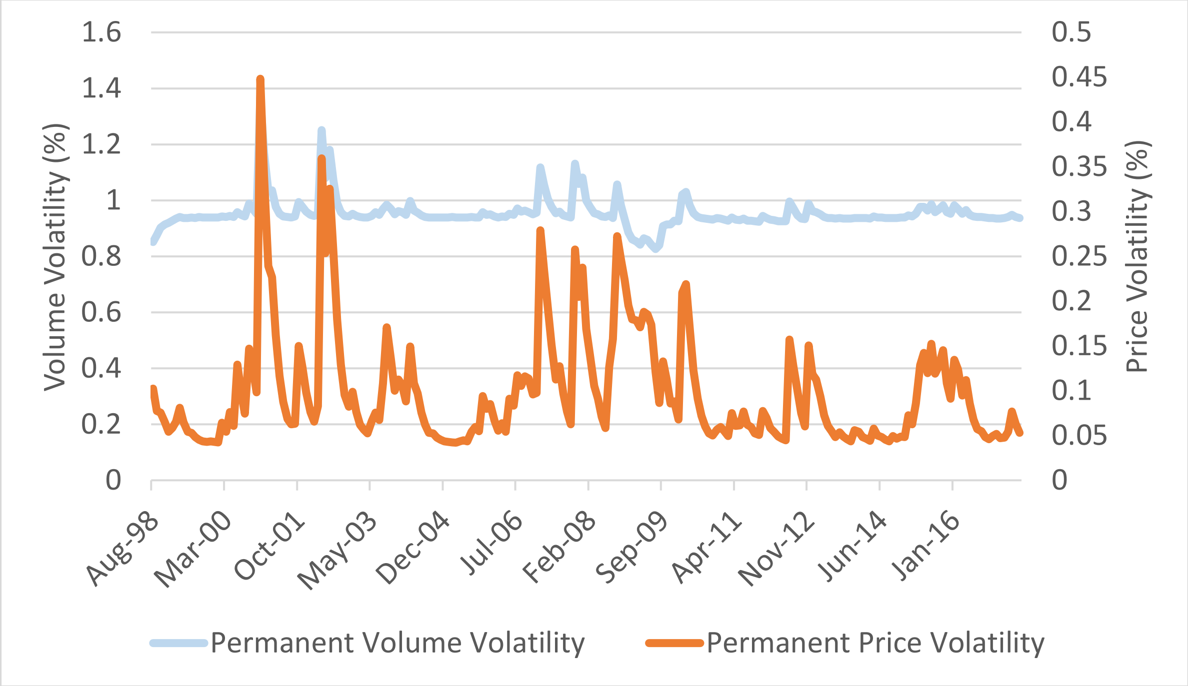


Figure 3. Volatility for the Goulburn permanent water market

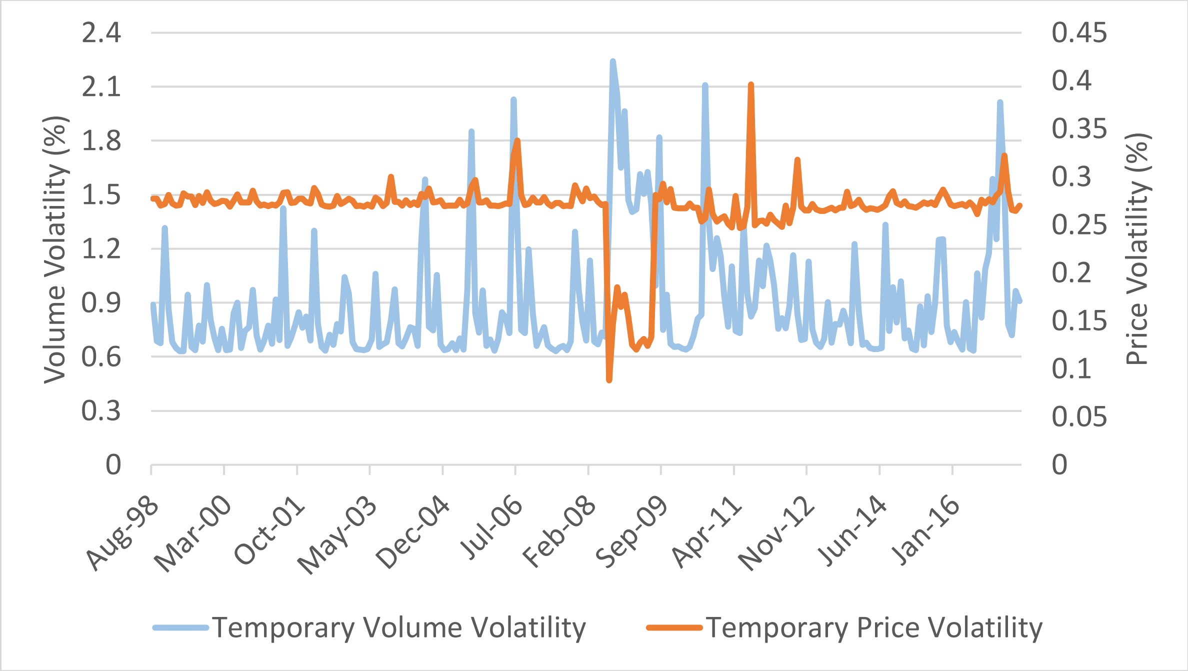


Figure 4. Volatility for the Goulburn temporary water market

Appendix A. Robustness checks for the government water recovery measurement

Table A. VARX-BEKK-GARCH Results for the Goulburn Permanent Market, using Buyback water volumes only

	Variable	*Coeff*	*Std Error*	*T-Stat*	*Signif*
Mean Model (Permanent Volume)					
1	Permanent Volume lagged by one month	-0.315	0.041	-7.736	0.000
2	Permanent Volume lagged by two months	-0.084	0.045	-1.850	0.064
3	Permanent Price lagged by one month	0.660	0.398	1.661	0.097
4	Permanent Price lagged by two months	0.276	0.394	0.701	0.483
5	Temporary Price	0.338	0.139	2.437	0.015
6	Temperature	0.015	0.010	1.500	0.134
7	Allocation level	-0.425	0.201	-2.115	0.034
8	Feed Barley price	-0.672	0.648	-1.037	0.300
9	Skim Milk price	0.033	0.604	0.055	0.956
10	**Government Water Recovery (buyback only)**	**-0.030**	**0.030**	**-1.005**	**0.315**
Mean Model (Permanent Price)					
11	Permanent Volume lagged by one month	0.002	0.003	0.563	0.574
12	Permanent Volume lagged by two months	0.001	0.003	0.387	0.698
13	Permanent Price lagged by one month	-0.388	0.063	-6.178	0.000
14	Permanent Price lagged by two months	-0.120	0.055	-2.172	0.030
15	Temporary Price	0.026	0.011	2.404	0.016
16	Temperature	-0.001	0.001	-0.744	0.457
17	Allocation level	0.001	0.014	0.064	0.949
18	Feed Barley price	0.021	0.052	0.404	0.687
19	Skim Milk price	-0.109	0.062	-1.767	0.077
20	**Government Water Recovery (buyback only)**	**-0.005**	**0.005**	**-0.875**	**0.382**
21	C(1,1)	0.567	0.142	3.983	0.000
22	C(2,1)	0.014	0.020	0.690	0.490
23	C(2,2)	0.025	0.021	1.147	0.252
24	A(1,1)	0.026	0.130	0.204	0.839
25	A(1,2)	-0.008	0.011	-0.768	0.442
26	A(2,1)	1.754	0.801	2.191	0.028
27	A(2,2)	0.797	0.130	6.131	0.000
28	B(1,1)	0.797	0.114	7.013	0.000
29	B(1,2)	-0.010	0.018	-0.546	0.585
30	B(2,1)	-0.402	0.501	-0.801	0.423
31	B(2,2)	0.712	0.082	8.688	0.000
32	D(1,1) = d_{11}	-0.005	0.058	-0.091	0.928
33	D(1,2) = d_{12}	0.023	0.012	2.013	0.044
34	D(2,2) = d_{22}	-0.006	0.010	-0.600	0.548

Note: All the variables are first-differenced.

Table B. VARX-BEKK-GARCH Results for the Goulburn Temporary Water Market, using Buyback volumes only

	Variable	*Coeff*	*Std Error*	*T-Stat*	*Signif*
Mean Model (Temporary Volume)					
1	Temporary Volume lagged by one month	-0.164	0.084	-1.969	0.049
2	Temporary Volume lagged by two months	-0.123	0.060	-2.037	0.042
3	Temporary Price lagged by one month	-0.083	0.251	-0.331	0.741
4	Temporary Price lagged by two months	-0.428	0.190	-2.254	0.024
5	Permanent Price	0.841	0.479	1.755	0.079
6	Temperature	0.066	0.013	4.867	0.000
7	Allocation level	1.131	0.168	6.715	0.000
8	Feed Barley price	0.823	0.764	1.077	0.281
9	Skim Milk price	0.041	0.984	0.042	0.967
10	**Government Water Recovery (buyback only)**	**-0.137**	**0.087**	**-1.565**	**0.118**
Mean Model (Temporary Price)					
11	Temporary Volume lagged by one month	0.020	0.017	1.125	0.261
12	Temporary Volume lagged by two months	0.005	0.018	0.294	0.769
13	Temporary Price lagged by one month	0.083	0.058	1.432	0.152
14	Temporary Price lagged by two months	0.163	0.070	2.338	0.019
15	Permanent Price	0.324	0.186	1.745	0.081
16	Temperature	0.007	0.005	1.355	0.175
17	Allocation level	-0.245	0.070	-3.514	0.000
18	Feed Barley price	0.635	0.270	2.348	0.019
19	Skim Milk price	-0.193	0.282	-0.686	0.493
20	**Government Water Recovery (buyback only)**	**0.000**	**0.009**	**0.024**	**0.981**
21	C(1,1)	0.598	0.145	4.129	0.000
22	C(2,1)	0.033	0.042	0.787	0.431
23	C(2,2)	0.264	0.017	15.195	0.000
24	A(1,1)	0.628	0.128	4.901	0.000
25	A(1,2)	-0.033	0.043	-0.784	0.433
26	A(2,1)	0.867	0.318	2.726	0.006
27	A(2,2)	0.115	0.176	0.653	0.514
28	B(1,1)	0.219	0.201	1.093	0.274
29	B(1,2)	-0.067	0.029	-2.295	0.022
30	B(2,1)	-0.667	1.589	-0.420	0.674
31	B(2,2)	0.021	0.214	0.097	0.923
32	D(1,1) = d_{11}	0.178	0.095	1.862	0.063
33	D(1,2) = d_{12}	0.003	0.012	0.271	0.786
34	D(2,2) = d_{22}	-0.054	0.017	-3.123	0.002

Note: All the variables are first-differenced.