Official Journal of the World Water Council
Water Policy

Water Policy Vol 25 No 12, 1125 doi: 10.2166/wp.2023.104

Does irrigation water applied in South Australia increase after the end of the Millennium Drought? Application of the difference-in-differences approach

Koji Noda
Faculty of Economics, Tokyo Keizai University, 1-7-34, Minami-cho, Kokubunji-shi, Tokyo 185-8502, Japan
E-mail: ko_noda@tku.ac.jp

KN, 0000-0002-0443-3247

ABSTRACT

The Millennium Drought drastically reduced the amount of irrigation water applied and triggered modern water reform, such as water market promotion in the southern Murray–Darling Basin (sMDB), Australia. South Australia (SA), located far downstream in the sMDB, occupies a unique and important position because the amount of water supplied for SA is guaranteed under normal weather conditions. The water availability for SA determines whether severe droughts occur in the sMDB. Based on the *Murray–Darling Basin water market catchment dataset* 2021, the causal inference of whether irrigation water applied in the SA Murray water system as the main water system in SA increased after water year (WY) 2011 when the percentage of water allocated to high-reliability water entitlements reached 100% was empirically analysed in this article with a difference-in-differences approach. In this article, the SA Murray water system was adopted as the sole treatment group and WY 2011 was selected as the treatment timing. When control variables and the interaction terms between the dummy variable for post-treatment periods and control variables are included, this article statistically demonstrates that irrigation water applied in the SA Murray water system increased after WY 2011.

Key words: Difference-in-differences, Irrigation water applied, Millennium drought, Murray–darling Basin, South Australia

HIGHLIGHTS

- South Australia (SA) occupies a unique and important position in the southern Murray–Darling Basin as its specified water supply is guaranteed under normal weather conditions.
- To evaluate the increase in irrigation water applied in SA, a difference-in-differences approach, which is a classical empirical strategy, was applied.
- The SA Murray water system increased the irrigation water applied after water year 2011.

1. INTRODUCTION

In the 21st century, the importance of sustainable water reform has increased worldwide. Many authors have considered the current water reform in the southern Murray–Darling Basin (sMDB), which overlaps New South Wales (NSW), Victoria (VIC), South Australia (SA), and the Australian Capital Territory, as this programme, including water market promotion, is recognized as one of the most progressive cases (Hanemann & Young, 2020; Australian Competition and Consumer Commission, 2021; Wheeler, 2022). Since the announcement in 1994 by the Council of Australian Governments (COAG), the commonwealth government and state governments have been involved in reforming water resource management in the MDB (Gardner *et al.*, 2018). The Millennium

Drought (2001–2009) triggered the realization that drastic water reform was needed to manage the water resources in the MDB effectively, efficiently, and sustainably. In 2004, the COAG adopted the National Water Initiative (NWI), which aimed to advance comprehensive and uniform water reforms nationwide to realize sustainable water resource management (Ballard *et al.*, 2014). In September 2007, the Water Act 2007 was enacted nationally. This act aimed to strengthen the institutional framework for the use of water resources in the MDB for their sustainable management from a national interest perspective (Skinner & Langford, 2013). The current water reform in Australia is mainly based on the Water Act 2007.

For water policy in Australia, a water year (WY) denotes the 1-year period from July 1 to June 30 of the next year. For example, WY 2020 is the 1-year period from July 1, 2020, to June 30, 2021. In WY 2019, the share of the volume of water allocation transactions in the sMDB accounted for approximately 85% of the total volume in Australia, and the share of the volume of water access entitlement transactions in the sMDB was approximately 43% (Bureau of Meteorology, 2020). The Australian Competition and Consumer Commission (2021) reported that the cap implementation in 1995 opened transactions into water markets, but the later Millennium Drought drastically increased the volume of temporal water transactions in the sMDB.

In contrast to past studies that analysed how irrigators had adapted due to the Millennium Drought (e.g., Dinh *et al.*, 2017) or examined the efficiency of irrigation water use (e.g., Qureshi *et al.*, 2011), this article focused on the changes in irrigation water use after the end of the Millennium Drought. After a drought, irrigators would naturally increase the amount of irrigation water used within the amount of water permitted for them to recover their economic profits. In fact, the irrigation water applied across the sMDB increased after the end of the Millennium Drought, but it recently decreased again (Figure 1). Namely, the trends of irrigation water applied across the sMDB do not unidirectionally increase. This may reflect that irrigators would select risk-averse decision-making because of current climate change. The actual degree of such changes may vary by water system owing to the diversity of irrigation products across the sMDB (e.g., SunRISE Mapping and Research, 2022). Therefore, it is necessary to empirically study the causal inference of whether irrigators actually increased their irrigation water applied after the end of the Millennium Drought.

When studying this issue, we face a problem related to data availability. For example, the Natural Resource Management (NRM) level has been adopted in the *Water Use on Australian Farms* published by the Australian

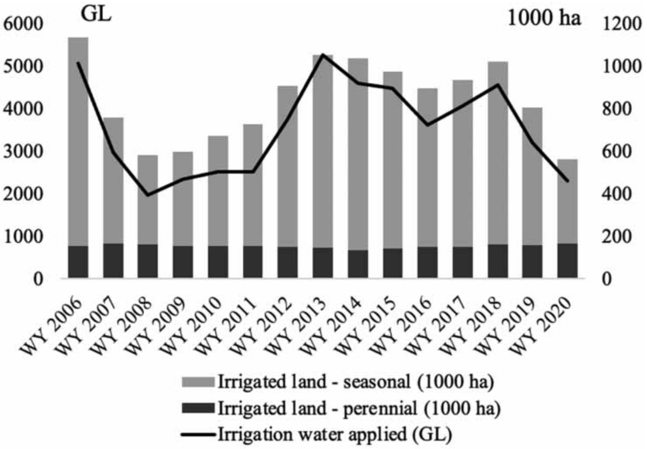

Fig. 1 | Trends in the irrigation water applied and irrigated land in the southern Murray–Darling Basin, WY 2006 to WY 2020. *Source*: Author from the MDBWMC2021-Demand Dataset.

Bureau of Statistics, but the geographic scope of the NRM in NSW drastically changed after 2016–17. In addition, because the geographic scope of the NRM does not match that of the water trading zone, it is necessary to adjust this difference. Thus, it is difficult to adopt and use the long-term and uniform dataset retrieved from the *Water Use on Australian Farms* across the sMDB.

To overcome this problem, the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) published a comprehensive and uniform dataset by water system for the MDB. This dataset was recently revised as the *Murray–Darling Basin Water Market Catchment Dataset 2021*, in which the demand dataset was distinguished from the supply dataset (Walsh *et al.*, 2021). Hereinafter, based on the recent revision, the demand dataset is referred to as the *MDBWMC2021-Demand Dataset*, while the supply dataset is referred to as the *MDBWMC2021-Supply Dataset*.

Based on the MDBWMC2021 dataset, this article aimed to analyse whether irrigation water applied in SA located the most downstream in the sMDB actually increased after the end of the Millennium Drought by comparing the trends of irrigation water applied in other water systems and controlling the impacts of agricultural factors or the current water reform. When inferring causes, the endogeneity bias should be treated as the bias due to the correlation between a given dependent variable and the error term. If the assumption of common trends holds, a difference-in-differences (DD) approach could be used to avoid endogeneity bias. To apply a DD approach, it is necessary to specify a treatment and its timing and to distinguish a treatment group from a control group (Angrist & Pischke, 2009; Wing *et al.*, 2018; Nishiyama *et al.*, 2019).

There are three reasons why the SA Murray water system was adopted as the treatment group and why WY 2011 was adopted as the treatment timing. The first reason involves the institutional feature of the water use in SA in the sMDB. A total of 1,850 giga-litres (GL) per WY is established as the amount of water provided for SA under normal conditions based on the Murray–Darling Basin Agreement (Mooney & Tan, 2012), and it is thus proposed that the water availability in SA partly reflects the water availability across the sMDB. If the percentage of water allocated to high-reliability water entitlements within a given WY (hereafter denoted as the water allocation rate) in SA is less than 100%, this could indicate a relatively severe drought situation across the sMDB. Conversely, if the water allocation rate in SA reaches 100%, it suggests that a severe drought would not occur across the sMDB. The water allocation rate has varied by the water system in SA. Focusing on the SA Murray water system as the main water system in SA, its water allocation rate reached 100% in and after WY 2011 (Department for Environment and Water, Government of South Australia HP, 2023). For the water availability, it could be understood that WY 2011 is the start of the end of the Millennium Drought.

The second reason involves the agricultural feature of SA. Perennial irrigation products such as grapevines, which are not immediately changeable according to changes in the managerial environment, are mainly grown in SA. In contrast to other water systems, irrigation in SA always depends on perennial irrigation products based on the *MDBWMC2021-Demand Dataset* (also refer to Shi, 2021). If the irrigation water applied in SA increased after the end of the Millennium Drought, this would reflect the unique features of the irrigation strategy in SA.

Third and finally, the environmental restoration of the Lower Lakes in SA is required in the current water policy reform, as the flow level has been very low over time. Although there is a controversy over what level should be restored and how much water should be reallocated, there is a consensus that the water environment needs to be restored (Gell, 2020). It is thought that the Lower Lakes issue would have an impact on irrigation water use across the sMDB.

To apply a DD approach, I adopt the SA Murray water system as the sole treatment group and WY 2011 when the water allocation rate of the SA Murray water system reached 100% in SA as the treatment timing. By controlling agricultural factors or the current water reform factors and comparing the trends of irrigation water applied in other water systems in the sMDB, I analyse the causal inference of whether the irrigation water applied in the SA Murray water system actually increased after the end of the Millennium Drought.

2. METHODS

2.1. Water rights system in the southern MDB

The water rights system contents and names vary by state, but the main content of the water rights system in each state was guided by the NWI framework in 2004. In particular, the separation of water rights from land titles and the unbundling of water rights elements are important reform points. Thus, this article refers to the water rights system contents and names according to the NWI reform direction: water access entitlement, water allocation, delivery share, and water-use licence (National Water Commission, 2011). The water rights system in NSW is currently based on the Water Management Act 2000 if a water-sharing plan is implemented and the Water Act 1912 otherwise. The water rights system in the VIC is based on the Water Act 1989. The water rights system in SA is based on the Landscape South Australia Act 2019.

Water access entitlement is defined as a container into which a water access entitlement holder can obtain water within the legally approved scope and features several restrictions, such as priority among holders under normal or emergency conditions. During a dry year, a water access entitlement holder cannot receive the total volume of water specified in the water access entitlement. Priority for water reception is assigned depending on the water access entitlement reliability (Stoeckel *et al.*, 2012; Gardner *et al.*, 2018). The water access entitlement reliability influences the agricultural products produced in the relevant state.

A water allocation is defined as the actual volume of water received by a water access entitlement holder, which depends on the weather conditions during each WY. A delivery share is defined as the right to have water delivered to the location where it is finally consumed, e.g., used for land irrigation. A water-use licence holder is permitted to use the volume of water in the specified area, such as irrigation land. The difference between a water access entitlement and a use entitlement requires that an individual must simultaneously hold both entitlements if he or she wants to use the water received. Generally, several restrictions may be imposed on the transfer of a water-use licence because a water-use licence is recognized as being attached to the land (Stoeckel *et al.*, 2012; Gardner *et al.*, 2018).

Furthermore, the introduction of water access entitlement carryover is an important aspect of water reforms during the considered period. The rule of carryover determines whether and how much water unused during a given WY can be carried over to the next WY. Carryover rules vary between states or between the water systems in a state (Hughes *et al.*, 2013). For example, in the Murrumbidgee water system in NSW, water access entitlement holders with general security are generally allowed to carry over their entitlements. Water access entitlement holders with general security can carry over up to 30% of their entitlements, but the 100% rule is applied. The sum of the carryover and actual volumes of water allocation is constrained to 100% of the water access entitlement at the most; a volume of water over 100% is forfeited (Stoeckel *et al.*, 2012).

2.2. Outline of the MDBWMC2021 dataset

As explained earlier, because the geographic scope of previous public datasets such as the *Water Use on Australian Farms* has changed several times, it is difficult to adopt and use these datasets directly. Thus, the MDBWMC2021-Demand Dataset, which includes several types of production factors of the irrigation industry from WY 2006 to WY 2020, was adopted in this article. Owing to data availability, this article used data related to nine water systems in the sMDB from WY 2006 to WY 2020: NSW Lower Darling, NSW Murray Above, NSW Murray Below, NSW Murrumbidgee, SA Murray, VIC Goulburn-Broken, VIC Loddon-Campaspe, VIC Murray Above, and VIC Murray Below. Notably, only the SA Murray water system is adopted in SA.

Missing values of irrigation water applied or irrigated land by irrigation product and water system were computed and substituted in the MDBWMC2021-Demand Dataset using several methods, such as linear interpolation or regression modelling. In addition, there were missing values in the MDBWMC2021-Demand Dataset that could not be replaced: the amount of irrigated land and irrigation water applied to vegetables in WY 2019 in the SA Murray water system and the amount of irrigation water applied to almonds in WY 2020 in the NSW Murray Below system. I replaced these missing values with the proxy variables computed using a polynomial approximation method.

Figure 1 shows the changes in the total amount of irrigation water applied (GL) and the total amount of irrigated land (1,000 hectare (ha)) across the sMDB from WY 2006 to WY 2020. Referring to SunRISE Mapping and Research (2022) to reveal the importance of the impacts of the irrigation crop mix and irrigated land on irrigation water use in the sMDB, this article distinguished perennial irrigation products, including only almonds, grapevines, and fruit, from seasonal irrigation products, including cotton, pastures (grazing), pastures (hay), rice, vegetables, and all other crops. As shown in SunRISE Mapping and Research (2022), the increase in irrigated land and irrigation water for almonds on the downside sMDB has recently received attention. In fact, the data related to the number of bearing almond trees to the total number of almond trees are summarized by water system in the MDBWMC2021-Demand Dataset. Thus, almond production is crucial for evaluating irrigation in the sMDB. The total amount of irrigation water applied decreased due to the Millennium Drought but drastically increased after its end. Although this amount repeatedly increased and decreased, it recently decreased again. In addition, the share of irrigation water applied to seasonal irrigation products, not perennial products, accounted for 60% of the total amount.

The changes in irrigated land across the sMDB were similar to those in the irrigation water applied. The total amount of irrigated land decreased under the Millennium Drought but largely increased after its end. Although this amount repeatedly increased and decreased, it recently decreased again. The share of irrigated land for seasonal irrigation products accounted for 70% of the total amount. However, a decrease in irrigated land did not always indicate an absolute decrease in irrigated land, as the share of vacant irrigated land accounted for approximately 20–40% of the total area of the lower sMDB (SunRISE Mapping and Research, 2022).

Figure 2 shows the changes in the amount of irrigation water applied (GL) and the amount of irrigated land (1,000 ha), thereby distinguishing perennial irrigation products from seasonal irrigation products, in the SA Murray water system from WY 2006 to WY 2020 based on the MDBWMC2021-Demand Dataset. In contrast to the total trends across the sMDB, the amount of irrigation water applied in the SA Murray water system first decreased and then gradually increased after WY 2010. Moreover, the share of irrigated land for perennial irrigation products had exceeded 60% over time. The high degree of dependence on perennial irrigation products is a feature of the SA Murray water system. It is suggested that it was difficult for the SA Murray water system to flexibly increase or decrease the amount of irrigation water applied according to the changes in water availability.

2.3. Data

Regarding water availability, SA occupies a unique position in the sMDB. As SA is the most downstream in the sMDB, the amount of water provided for SA under normal conditions, i.e., 1850 GL, is guaranteed based on the Murray–Darling Basin Agreement (Mooney & Tan, 2012). If the water allocation rate for SA reaches 100%, severe droughts do not occur across the sMDB. Furthermore, irrigation in SA always depends on perennial irrigation products based on the *MDBWMC2021-Demand Dataset* (also refer to Shi, 2021). To grow perennial irrigation products, irrigators have to demand water even during droughts. If the irrigation water applied in SA increased after the end of the Millennium Drought, this would reflect the features of the irrigation strategy in SA. Thus, the water availability rate for SA is crucial and specific for evaluating how irrigation was adapted to managerial and environmental changes after the end of the Millennium Drought.

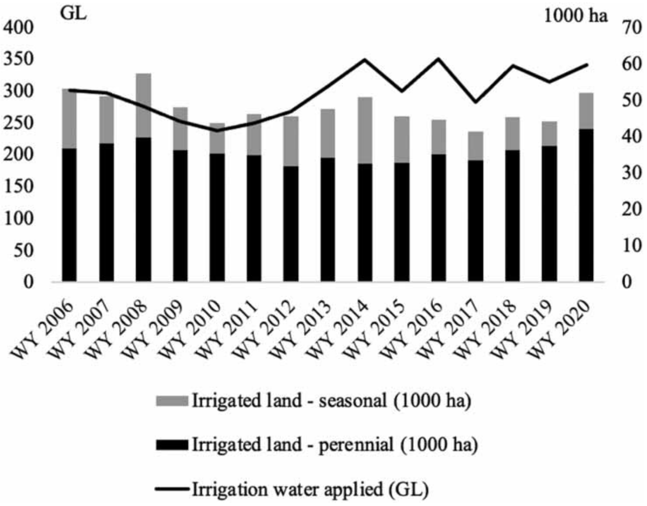

Fig. 2 | Trends in the irrigation water applied and irrigated land in the South Australia Murray water system, WY 2006 to WY 2020. *Source*: Author from the MDBWMC2021-Demand Dataset.

Based on the MDBWMC-Supply Dataset, the water allocation rate in almost all water systems in NSW and VIC reached 100% after the Millennium Drought, but there were several cases in which the water allocation rate was less than 100%. For example, the water allocation rate in the VIC Goulburn-Broken water system in fiscal year (FY) 2020 was 79%. This finding could reflect the drought from January 2017 to December 2019 across the MDB (Bureau of Meteorology HP, 2023). However, the water allocation rate in the SA Murray water system always reached 100% in and after WY 2011 to WY 2020 as the end water year in the analysed periods, even under the most recent drought (Department for Environment and Water, Government of South Australia HP, 2023). The Millennium Drought and the recent drought occurred across the sMDB, but the water allocation rate in this water system was decided by considering the differences among the water rights systems and the quantities of water entitlements in NSW, VIC, and SA. If the water allocation rate in the SA Murray water system is less than 100%, a drought occurs across the sMDB because the supply of surface water for SA under normal conditions is legally guaranteed. Conversely, when the water allocation rate in the SA Murray water system is 100%, a drought does not occur across the sMDB. If the water allocation rate in water systems other than the SA Murray water system is less than 100%, it does not always show that drought is occurring across the sMDB. Thus, for water availability, it was reasonable to adopt only the SA Murray water system as the sole treatment group and WY 2011 as the treatment timing despite the occurrence of droughts across the entire sMDB after the end of the Millennium Drought.

The amount of irrigation water applied (*WATER*) (GL) was adopted as the dependent variable. To control a treatment effect, this article adopted three types of dummy variables: a dummy variable with a value of 1 if the SA Murray water system treatment was shown, with a value of 0 otherwise (*DUMMYTREATMENT*); a dummy variable with a value of 1 if WY showed in and after WY 2011 as the treatment timing, with a value of 0 otherwise (*DUMMY2011*); and a dummy variable with a value of 1 if the SA Murray water system implemented treatment after WY 2011, with a value of 0 otherwise (*DUMMYSA*). The SA Murray water system was adopted as the only treatment group, and all other water systems were included in the control group.

The following five variables were adopted as control variables. As explained earlier, the SA Murray water system largely depends on perennial agricultural products, but other water systems depend on seasonal agricultural products. From the MDBWMC-Demand Dataset, both irrigated land for perennial agricultural products (*AREAPERENNIAL*) (ha) and irrigated land for seasonal agricultural products (*AREASEASONAL*) (ha) were adopted in this article to reflect the agricultural features of each water system. As explained earlier, for the three missing values related to irrigation water applied or irrigation land in the original dataset, I replaced these variables with the proxy variables computed using a polynomial approximation method.

To capture the impact of the almond industry as a crucial cash crop in the sMDB, I adopted *BALMOND*, defined as the share of the number of bearing almond trees to the total number of almond trees in a water system. From the MDBWMC-Supply Dataset, to capture the impact of water allocation transactions, this article adopted the three types of variables: the deflated mean value of prices of water allocation transaction implemented from August to May in a WY (*TPRICE*) (AUS$/ML); the total net volume of water allocation transactions in a WY and the transaction shows a net buyer for a water system if the net amount of water allocation transactions was positive (*TRANSACTION*); a dummy variable with a value of 1 if the net amount of water allocation transactions in a WY was positive, with a value of 0 otherwise (*DUMMYNETBUYER*). Finally, because the actual situation of water use largely varies by water system across the sMDB, I attempted to modify such disparity using a probability weights method with the total volume of water access entitlements for a water system (*ENTITLEMENT*).

Table 1 presents descriptive statistics. The standard deviations of *AREAPERENNIAL*, *AREASEASONAL*, and *ENTITLEMENT* are relatively large.

2.4. Empirical strategy: difference-in-differences approach

Based on the DD approach, the time trend of *WATER* in the SA Murray water system after WY 2011 was assessed relative to the time trend of *WATER* in the other water systems. Again, while the SA Murray water system was the sole treatment group, the other eight water systems were treated in the control group. The posttreatment timing was WY 2011 when the water allocation rate in the SA Murray water system reached 100%. The fixed-effects

Table 1 | Descriptive statistics.

Variables	Source	Obs.	Mean	Standard deviation	Minimum	Maximum
WATER (GL)	1	135	394.90	365.01	36.43	1,700.86
DUMMYSA	2	135	0.074	0.263	0	1
DUMMYTREATMENT	2, 3	135	0.111	0.315	0	1
DUMMY2011	2, 3	135	0.667	0.473	0	1
AREAPERENNIAL (ha)	1	135	17,121.98	17,539.15	601.26	60,028.88
AREASEASONAL (ha)	1	135	76,850.26	73,485.14	1,772.75	284,891.8
BALMOND	1	135	0.284	0.366	0.000	0.990
TPRICE (AUS$/ML)	3	135	238.29	227.19	19.36	880.64
TRANSACTION (GL)	3	135	−0.407	79.27	−390.15	336.26
DUMMYNETBUYER	3	135	0.459	0.500	0	1
ENTITLEMENT (GL)	3	135	1,040.60	902.82	72.11	3,197.19

Note: The Source column indicates the data source as follows: 1 for the MDBWMC-Demand Dataset, 2 for the Department for the Environment and Water, Government of South Australia HP 2023, and 3 for the MDBWMC-Supply Dataset.

Source: Author from the aforementioned sources.

regression model in this article can be expressed as follows (Equations (1)–(4)):

$$\begin{aligned} WATER_{it} = {} & \beta_0 + \beta_1 DUMMYSA_{it} + \beta_2 DUMMYTREATMENT_{it} + \beta_3 DUMMY2011_{it} \\ & + \beta_4 AREAPERENNIAL_{it} + \beta_5 AREASEASONAL_{it} + \beta_6 BALMOND_{it} \\ & + \beta_7 TPRICE_{it} + \beta_8 TRANSACTION_{it} + \beta_9 DUMMYNETBUYER_{it} + \gamma_i + \delta_t \\ & + \varepsilon_{it}, (i = 1, \ldots, 9{:}t = WY\ 2006, \ldots, WY\ 2020), \end{aligned} \tag{1}$$

$$\begin{aligned} WATER_{it} = {} & \beta_0 + \beta_1 DUMMYSA_{it} + \beta_2 DUMMYTREATMENT_{it} + \beta_3 DUMMY2011_{it} \\ & + \beta_4 AREAPERENNIAL_{it} + \beta_5 AREASEASONAL_{it} + \beta_6 BALMOND_{it} \\ & + \beta_7 TPRICE_{it} + \beta_8 TRANSACTION_{it} + \beta_9 DUMMYNETBUYER_{it} \\ & + \beta_{10} AREAPERENNIAL_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{11} BALMOND_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{12} TPRICE_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{13} TRANSACTION_{it} \times DUMMYNETBUYER_{it} + \gamma_i + \delta_t \\ & + \varepsilon_{it}, \ (i = 1, \ldots, 9{:}t = WY\ 2006, \ldots, WY\ 2020), \end{aligned} \tag{2}$$

$$\begin{aligned} WATER_{it} = {} & \beta_0 + \beta_1 DUMMYSA_{it} + \beta_2 DUMMYTREATMENT_{it} + \beta_3 DUMMY2011_{it} \\ & + \beta_4 AREAPERENNIAL_{it} + \beta_5 AREASEASONAL_{it} + \beta_6 BALMOND_{it} + \beta_7 TPRICE_{it} \\ & + \beta_8 TRANSACTION_{it} + \beta_9 DUMMYNETBUYER_{it} \\ & + \beta_{10} AREAPERENNIAL_{it} \times \ DUMMY2011_{it} \\ & + \beta_{11} AREASEASONAL_{it} \times \ DUMMY2011_{it} + \beta_{12} BALMOND_{it} \times \ DUMMY2011_{it} \\ & + \beta_{13} TPRICE_{it} \times \ DUMMY2011_{it} + \beta_{14} TRANSACTION_{it} \times \ DUMMY2011_{it} \\ & + \beta_{15} DUMMYNETBUYER_{it} \times \ DUMMY2011_{it} + \gamma_i + \delta_t \\ & + \varepsilon_{it}, (i = 1, \ldots, 9{:}t = WY\ 2006, \ldots, WY\ 2020), \end{aligned} \tag{3}$$

$$\begin{aligned} WATER_{it} = {} & \beta_0 + \beta_1 DUMMYSA_{it} + \beta_2 DUMMYTREATMENT_{it} + \beta_3 DUMMY2011_{it} \\ & + \beta_4 AREAPERENNIAL_{it} + \beta_5 AREASEASONAL_{it} + \beta_6 BALMOND_{it} + \beta_7 TPRICE_{it} \\ & + \beta_8 TRANSACTION_{it} + \beta_9 DUMMYNETBUYER_{it} \\ & + \beta_{10} AREAPERENNIAL_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{11} BALMOND_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{12} TPRICE_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{13} TRANSACTION_{it} \times DUMMYNETBUYER_{it} \\ & + \beta_{14} AREAPERENNIAL_{it} \times DUMMY2011_{it} \\ & + \beta_{15} AREASEASONAL_{it} \times DUMMY2011_{it} + \beta_{16} BALMOND_{it} \times DUMMY2011_{it} \\ & + \beta_{17} TPRICE_{it} \times DUMMY2011_{it} + \beta_{18} TRANSACTION_{it} \times DUMMY2011_{it} \\ & + \beta_{19} DUMMYNETBUYER_{it} \times DUMMY2011_{it} \\ & + \beta_{20} AREAPERENNIAL_{it} \times DUMMYNETBUYER_{it} \times DUMMY2011_{it} \\ & + \beta_{21} BALMOND_{it} \times DUMMYNETBUYER_{it} \times DUMMY2011_{it} \\ & + \beta_{22} TPRICE_{it} \times DUMMYNETBUYER_{it} \times DUMMY2011_{it} \\ & + \beta_{23} TRANSACTION_{it} \times DUMMYNETBUYER_{it} \times DUMMY2011_{it} \\ & + \gamma_i + \delta_t + \varepsilon_{it}, \ (i = 1, \ldots, 9{:}t = WY\ 2006, \ldots, WY\ 2020), \end{aligned} \tag{4}$$

where $WATER_{it}$ is the dependent variable of water system i (No. 1 to 9) at time t (WY 2006–WY 2020), γ_i denotes the individual fixed effects for each water system, δ_t denotes the water year fixed effects, ε_{it} denotes the error terms, and β_1 denotes the average treatment effect and is thus the coefficient of most concern in this article.

Only control variables were included in Equation (1). To control the impact of the excessive demand of water allocations over the maximum volume of water allocations held as the owner of the water allocations, the interaction terms between control variables excluding *AREASEASONAL* and *DUMMYNETBUYER* were included in Equations (2) and (4). *AREASEASONAL* was excluded because irrigators who grow seasonal agriculture products would sell their water allocations through a water market in a drought, as they could adapt to a drought owing to decreasing their irrigation water applied.

In addition, Nishiyama *et al.* (2019) highlight the two types of attention when applying a DD approach. First, it is necessary to properly include control variables to reduce the number of uncontrolled variables included within the error terms. This could contribute to reducing the numerical value of standard errors. Second, by including the interaction terms between the dummy variable to show posttreatment periods and control variables in the analysed model, the impact of control variables during posttreatment periods on the dependent variable could be evaluated; thus, it could be strongly indicated that the common trends would hold if the result computed in such regression is statistically significant. To check the robustness of the results based on Equation (1) or (2), it is indicated that the regression model including the interaction terms between the dummy variable to show post-treatment periods and control variables should additionally be tested based on Equation (3) or (4), respectively.

Because each water system in the sMDB is mutually connected through water markets, it can be predicted that the error terms are heteroskedastic. There is no consensus regarding the corresponding method to resolve heteroskedastic issues when using the DD approach (Angrist & Pischke, 2009; Wing *et al.*, 2018). I attempted to modify the large disparity in the irrigation industry in the sMDB using a probability weights method with *ENTITLEMENT*. Because the application of clustered robust standard errors adjusted for the number of groups in the case of only one treatment group would lead to underperformance, the application of the bias-corrected or cluster–bootstrap method is recommended (StataCorp, 2021). The bias-corrected cluster–robust standard errors method was adopted in this article, as I used a probability weights method simultaneously. Finally, Stata/SE 17.0 and the *xtdidregress* command were used to apply the DD method.

3. RESULTS AND DISCUSSION

The four models were analysed: Model 1 with control variables (Equation (1)); Model 2 with control variables and interaction terms between control variables and *DUMMYNETBUYER* without interaction terms between control variables and *DUMMY2011* (Equation (2)); Model 3 with control variables and interaction terms between control variables and *DUMMY2011* (Equation (3)); and Model 4 with control variables, interaction terms between control variables and *DUMMYNETBUYER*, and interaction terms between control variables and *DUMMY2011* (Equation (4)). In all models, both water system fixed effects and water year fixed effects were included, and a probability weights method was used.

First, it was necessary to confirm whether the common trend assumption held. The *xtdidregress* command in *STATA* illustrates the common trends during pre-treatment periods computed based on the linear regression and shows the results of the *F* test of the null hypothesis, which states that the pre-treatment time trend of the treatment group coincides with that of the control group (StataCorp, 2021). Figure 3 shows the results computed on the linear regression in Model 2, and Figure 4 shows the results computed based on the linear regression in Model 4. (I omitted the figures in Models 1 and 3 owing to the character limit.) The black line shows the time trend computed for the treatment group, namely, the SA Murray water system, while the grey line shows the time trend

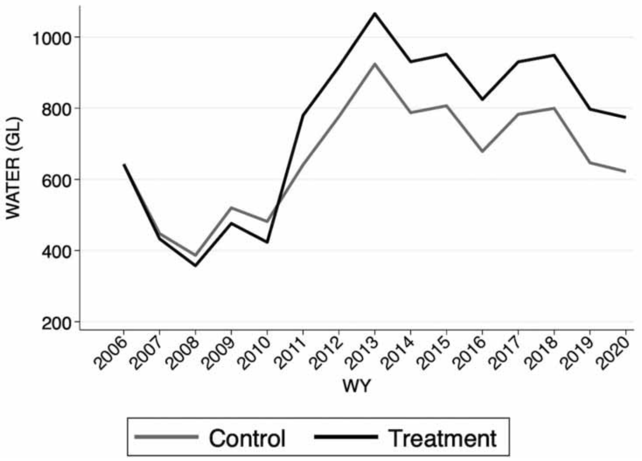

Fig. 3 | The common trends computed based on the regression linear model in Model 2. *Source*: Author.

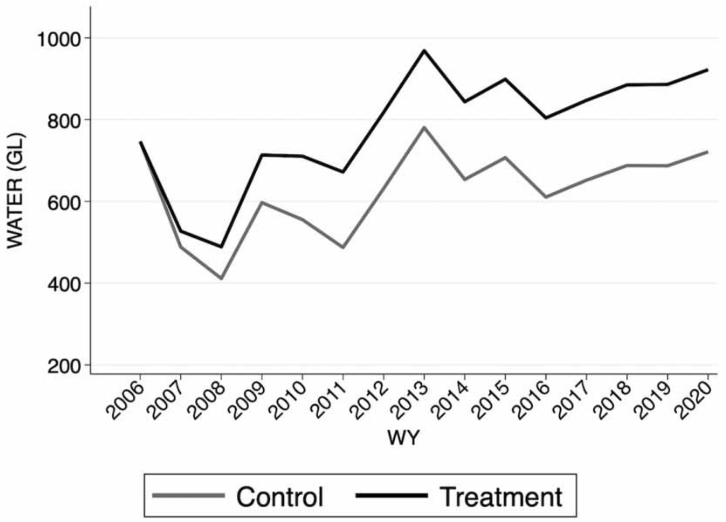

Fig. 4 | The common trends computed based on the regression linear model in Model 4. *Source*: Author.

computed for the control group. I omitted the results computed based on the mean values of observed outcomes, as it is thought that the results would not show that the common trends hold.

Considering the time trends before WY 2011 shown in Figure 3 or 4, it suggests that the common trends would hold in both models. In addition, Table 2 presents the DD results, and the results of the *F*-statistic test of the null hypothesis state that the pre-treatment time trend of the treatment group coincides with that of the control group. Table 2 shows the *F*-statistic value for each model: 0.202 for Model 1, 0.358 for Model 2, 0.161 for Model 3, and 0.295 for Model 4. For all models, the null hypothesis could not be rejected at the 10% significance level. Thus, it is suggested that the common trend assumption for pre-treatment periods would hold.

Table 2 | DD results.

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
WATER	182.315**	167.251**	208.742*	160.147*
	(60.003)	(44.803)	(75.040)	(57.122)
Control variables: *AREAPERENNIAL, AREASEASONAL, BALMOND, TPRICE, and DUMMYNETSELLER*	Yes	Yes	Yes	Yes
Interaction terms between control variables excluding AREASEASONAL and DUMMYNETBUYER	No	Yes	No	Yes
Interaction terms between control variables and DUMMY2011	No	No	Yes	Yes
Water system fixed effects	Yes	Yes	Yes	Yes
Water year fixed effects	Yes	Yes	Yes	Yes
Probability weights	Yes	Yes	Yes	Yes
Observations	135	135	135	135
F test of the assumption of common trends	0.202	0.358	0.161	0.295

Note: The bias-corrected cluster–robust standard errors are provided in brackets. $*p < 0.05$, $**p < 0.05$.
Source: Author.

Table 2 shows the DD results. Regarding Model 1, the average treatment effect on the treated (ATET) was estimated at 182.315 GL, and it was statistically significant at the 5% significance level. Regarding Model 2, the ATET was estimated at 167.251 GL, and it was statistically significant at the 5% significance level. Regarding Model 3, the ATET was 208.742 GL, and it was statistically significant at the 10% significance level. Regarding Model 4, the ATET was 160.147 GL, and it was statistically significant at the 10% significance level. Even when controlling for the difference in the impact of control variables after WY 2011, the ATET was statistically significant, but the value of standard errors was slightly larger than that in Model 1 or Model 3. As explained earlier, it is thought that the common trends for pre-treatment periods would hold in all models. Thus, I could conclude that the irrigation water applied in the SA Murray water system was on average greater than the potential outcome of the SA Murray water system computed based on the time trend of the control group after WY 2011 when the water allocation rate reached 100%.

Several issues are discussed. First, it is thought that the main reason why the common trends assumption would hold in all models was to include control variables and the interaction terms between control variables and the dummy variable for the net buyer of water allocations. By including such a dummy variable, I could capture the impact of the excessive demand for water allocations over the maximum volume of water allocations held as the owner of the water allocations. In addition, comparing the result of Model 3 with that of Model 4, the inclusion of the interaction terms between control variables and the dummy variable to show the post-treatment periods would contribute to fitting a model more reasonably. Note that the pre-treatment time trend for the treatment group is located lower in Figure 3, but the pre-treatment time trend for the treatment group is located higher in Figure 4. This suggests that the interaction terms between control groups and the dummy variable for the post-treatment periods have an impact on the results of the time trends computed. Thus, the introduction of such a dummy variable would be significant for evaluating the relationships between the treatment group and the control group.

Second, neither cotton nor rice was cultivated in the SA Murray water system from WY 2006 to WY 2020. The share of irrigated land for perennial irrigation products such as almonds and fruit in the SA Murray water system persistently accounted for more than 60% of the total amount, and the amount of irrigation water applied in the

SA Murray water system increased after WY 2010, not WY 2011 (Figure 2). The high degree of dependence on perennial irrigation products of the SA Murray water system could explain this result.

Third, even after the end of the Millennium Drought, irrigators used water markets or carryover rules to adapt to changes in their managerial risks, and the commonwealth government and state governments implemented several policies to realize environmental restoration, such as buyback programmes or on-farm irrigation infrastructure programmes. Because the Millennium Drought triggered modern water reform progress, including water markets, it could be presumed that several experiences gained under extreme drought could have contributed to implementing smarter irrigation water uses (Wheeler, 2022). At the same time, it has been shown that the number of irrigators in the sMDB who are wary about becoming involved in the water market has increased (Australian Competition and Consumer Commission, 2021). It has been reported that irrigators involved in on-farm infrastructure programmes have rebounded to use more irrigation water after involvement (Wheeler *et al.*, 2020). Although water allocation transaction prices were controlled for, the impacts of water markets on each irrigation strategy by water system should also be investigated.

Since WY 2012, the Murray–Darling Basin Authority has annually published a report on the water use by the sustainable diversion limit (SDL) resource unit in the MDB, which can include data related to carryover, water allocation transactions, and the actual volume of water for consumptive water uses, including irrigation, since WY 2017. Because the geographical range of the SDL resource unit differs from that of the water system adopted in the MDBWMC2021 dataset, the two datasets cannot be directly compared. The water lawfully received for consumption excluding interceptions can be defined as follows: carryover from a previous WY + water allocations + net allocation trades (positive if the water allocation transactions bought match or exceed the water allocation transactions sold, negative otherwise) + others. Regarding the SA Murray SDL resource unit, the actual rate of water obtained, which is defined as the actual water obtained (excluding interceptions) to the water lawfully received for consumption excluding interceptions, was very high: 90.2% in WY 2019 and 95.6% in WY 2020 (Murray–Daring Basin Authority, 2021, 2022).

Considering that the SA Murray SDL resource unit occupies a large share of irrigation in SA, it is suggested that irrigators in the SA Murray water system use almost all water institutionally available with not only their water allocations but also their carryover or water markets. Namely, it could be concluded that the irrigation water applied in the SA Murray water system returned to the state before the Millennium Drought. However, as the net allocation trade in WY 2019 reached −10.68 GL, the SA Murray water system has not always been a net importer of irrigation water. It is necessary to analyse more carefully how irrigators in the SA Murray water system have adapted to changes in their water availability.

Fourth, an additional issue highlighted by the results is that the irrigation water applied in NSW or VIC in the sMDB might not increase more than expected even after the end of the Millennium Drought. Would irrigators in NSW or VIC in the sMDB change how they use their irrigation water? For instance, in both WY 2019 and 2020, the Murrumbidgee SDL resource unit in NSW was the net seller of water allocations, and the share of carryover to the total water lawfully received for consumption excluding interceptions reached approximately 14% (Murray–Daring Basin Authority, 2021, 2022). After the end of the Millennium Drought, irrigators in the Murrumbidgee SDL resource unit might have strengthened their motivation to use their water as a commodity rather than for growing irrigation agriculture products. To study the reason why the irrigation water applied in water systems in NSW or VIC would not truly increase, it is necessary to directly analyse the impacts of water markets or carryover on irrigation water use in NSW or VIC. To do so, it is necessary to create a uniform dataset including agricultural factors, such as irrigation water use, water markets, and carryover by water system.

Fifth and finally, to strengthen the conclusions, water productivity should be estimated in monetary terms, which is defined as the ratio of the monetary value of irrigated agricultural products to that of the irrigation water applied, as the fundamental motivation among irrigators is the acquisition of profits. Considering that the actual rate of water obtained approaches 100% in the SA Murray water system, it is predicted that its water productivity is higher than that of other water systems. Conversely, if the water productivity in the SA Murray water system is not so high, it is necessary to focus more on factors other than water availability, such as water markets or carryover.

4. CONCLUSIONS

By using the DD approach, this article analysed whether the irrigation water applied in the SA Murray water system increased after the end of the Millennium Drought. SA is a unique state for the evaluation of the degree of drought across the sMDB, as it is located the most downstream. Since control variables such as irrigated land and water allocation transaction prices and the interaction terms between the dummy variable for posttreatment and control variables were included, it is revealed that the average amount of irrigation water applied in the SA Murray water system would be larger than that determined based on the time trend of other water systems after WY 2011. Conversely, in other water systems in NSW or VIC, the irrigation water applied might not increase after the end of the Millennium Drought. This suggests that the actual situation over the usage of irrigation water applied in the sMDB would be more complicated after the end of the Millennium Drought. Finally, considering the importance of dryland agriculture in the MDB, it is necessary to evaluate the change in the relationship between dryland farms and irrigation after the Millennium Drought in future studies.

ROLE OF THE FUNDING SOURCE

This study was financially supported by the Japan Society for the Promotion of Science KAKENHI (Grant No. 17K00672).

ETHICS STATEMENT

I accept the IWA Publishing Ethics Statement for authors.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Angrist, J. D. & Pischke, J. S. (2009). *Mostly Harmless Econometrics: An Empiricist's Companion*. Princeton University Press, New Jersey.

Australian Competition and Consumer Commission (2021). *Murray–Darling Basin Water Markets Inquiry Final Report*. Available at: https://www.accc.gov.au/publications/murray-darling-basin-water-markets-inquiry-final-report (accessed 3 April 2023).

Ballard, C., Garland, N. & Foreman, J. (2014). Management of drought in the Southern Murray-Darling Basin, Australia, from 1996/1997 to the present. *Irrigation and Drainage 63*(2), 254–262.

Bureau of Meteorology, Australian Government (2020). *Australian Water Markets Report 2018–19*. Bureau of Meteorology. Available at: http://www.bom.gov.au/water/market/documents/TheAustralianWaterMarketsReport2018-19.pdf (accessed 3 April 2023).

Bureau of Meteorology, Australian Government HP (2023). *Previous Droughts*. Available at: http://www.bom.gov.au/climate/drought/knowledge-centre/previous-droughts.shtml (accessed 3 April 2023).

Department for Environment and Water, Government of South Australia HP (2023). *Current Allocations*. Available at: https://www.environment.sa.gov.au/topics/river-murray/water-allocation/current-allocations (accessed 3 April 2023).

Dinh, H., Daly, A. & Freyens, B. (2017). Farm adjustment strategies to water-related challenges in the Murray-Darling Basin. *Policy Studies 38*(5), 482–501.

Gardner, A., Bartlett, R., Gray, J. & Nelson, R. (2018). *Water Resources Law*, 2nd edn. LexisNexis Butterworths, Australia.

Gell, P. A. (2020). Watching the tide roll away – contested interpretations of the nature of the Lower Lakes of the Murray Darling Basin. *Pacific Conservation Biology 26*, 130–141. https://doi.org/10.1071/PC18085_CO.

Hanemann, M. & Young, M. (2020). Water rights reform and water marketing: Australia vs the US West. *Oxford Review of Economic Policy 36*(1), 108–131.

Hughes, N., Gibb, C., Dahl, A., Tregeagle, D. & Sanders, O. (2013). *Storage Rights and Water Allocation Arrangements in the Murray–Darling Basin (ABARES Technical Report 13.07)*. ABARES. Available at: https://apo.org.au/sites/default/files/resource-files/2013-01/apo-nid165806.pdf (accessed 3 April 2023).

Mooney, C. & Tan, P. -L. (2012). South Australia's river Murray: Social and cultural values in water planning. *Journal of Hydrology 474*, 29–37.

Murray–Daring Basin Authority (2021). *Annual Water Take Report 2019–20*. Available at: https://www.mdba.gov.au/sites/default/files/pubs/annual-water-take-report-2019-2020.pdf (accessed 3 April 2023).

Murray–Daring Basin Authority (2022). *Annual Water Take Report 2020–21*. Available at: https://www.mdba.gov.au/sites/default/files/pubs/annual-water-take-report-2020-21.pdf (accessed 3 April 2023).

National Water Commission (2011). *Water markets in Australia: A short history*. National water Commission. Available at: https://apo.org.au/sites/default/files/resource-files/2011-12/apo-nid27438.pdf (accessed 3 April 2023).

Nishiyama, Y., Shintani, M., Kawaguchi, D. & Okui, R. (2019). *Econometrics: Statistical Data Analysis of Emperical Economics*. Yuhikaku, Tokyo. (in Japanese)

Qureshi, M. E., Grafton, R. Q., Kirby, M. & Hanjra, M. A. (2011). Understanding irrigation water use efficiency at different scales for better policy reform: A case study of the Murray-Darling Basin, Australia. *Water Policy 13*(1), 1–17.

Shi, T., (2021). Building up resilience and sustainability. In *The Palgrave Handbook of Climate Resilient Socities*. Brears, R. C., (ed.). Palgrave Macmillan, Switzerland, pp. 631–657.

Skinner, D. & Langford, J. (2013). Legislating for sustainable basin management: The story of Australia's Water Act (2007). *Water Policy 15*(6), 871–894.

StataCorp (2021). *Stata Treatment-Effects Reference Manual: Release 17. Statistical Software*. StataCorp LLC, College Station, TX.

Stoeckel, K., Webb, R., Woodward, L. & Hankinson, A. (2012). *Australian Water Law*. Thomson Reuters, Australia.

SunRISE Mapping and Research (2022). *Irrigated Crop Area Data for the Lower Murray-Darling 2003 to 2021 – Including Analysis of the Edward/Kolety and Wakool River System*. Murray-Darling Basin Authority. Available at: https://www.mdba.gov.au/sites/default/files/pubs/irrigated-crop-area-data-for-the-lower-murray-darling-2003-to-2021.pdf (accessed 3 April 2023).

Walsh, J., Westwood, T. & Gupta, M. (2021). *Murray-Darling Basin Water Market Catchment Dataset 2021 (ABARES Technical Report 21.11)*. ABARES. Available at: https://www.agriculture.gov.au/abares/research-topics/water/mdb-water-market-dataset (accessed 3 April 2023).

Wheeler, S. A. (2022). Debunking Murray-Darling Basin water trade myths. *Australian Journal of Agricultural and Resource Economics 66*(4), 797–821.

Wheeler, S. A., Carmody, E., Grafton, R. Q., Kingsford, R. T. & Zuo, A. (2020). The rebound effect on water extraction from subsidising irrigation infrastructure in Australia. *Resources, Conservation and Recycling 159*, 104755.

Wing, C., Simon, K. & Bello-Gomez, R. A. (2018). Designing difference in difference studies: Best practices for public health policy research. *Annual Review of Public Health 39*(1), 453–469.

First received 9 May 2023; accepted in revised form 15 November 2023. Available online 27 November 2023