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Efficient Water Use for Sustainable Irrigation Industry

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Abstract The aim of this paper is to evaluate the economic efficiency of irrigated agricultural enterprises using a non-radial data envelopment analysis approach. While a number of studies have used radial measures based on data envelopment analysis to obtain efficiency scores for a given production technology, we calculate non-radial measures to understand the efficiency of using individual inputs employed in the production process. In particular, the measures of economic efficiency are decomposed into water use efficiency and managerial efficiency. This decomposition enables us to obtain an efficiency score for the use of water as an environmentally sensitive input in irrigated crop production systems. Treating water input in this way goes beyond traditional measurement of water use efficiency, as the calculated efficiency scores can be used as indicators of sustainability in terms of water withdrawals for irrigation purposes. The results show that the overall efficiency for the considered irrigated enterprises is quite high. This is in contrast to the findings on the water use efficiency scores, which are fairly low. This indicates that while Australian irrigated farms are comparatively more efficient in overall farm activity management, they are not very efficient in managing water resources. In turn, this threatens the sustainability of this industry. There is a substantial variation of water use efficiency scores across irrigated enterprises and across regions. Analysing these variations can provide important insights for current policy and for future efforts to improve water use efficiency that will lead towards more sustainable irrigation industry.

Keywords Irrigation water use · Efficiency measurement · Non-radial DEA

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1 Introduction

The irrigation industry has been creating significant environmental pressures over a long period of time. Excessive water withdrawal for irrigation leaves insufficient water quantities in the rivers and wetlands to support the valuable ecosystems that are dependent on this water resource. Extensive water withdrawals for irrigation activities result in deterioration of many river systems and degradation of wetlands. A recent study found that the long-term average end-of-system flow of the Murray-Darling Basin (Australia's largest river system) was approximately 12,233 gigalitres (GL) before the substantial development of irrigation industry, which had been reduced to 4733 GL with the current level of irrigation development (Grafton et al. 2010). This leads to insufficient flow of water through the Basin to maintain the health of rivers and water dependent ecosystems. There are also a number of environmental pressures that emerge as a consequence of water withdrawal for irrigation, including wetland degradation, salinity and water quality problems, and loss of biodiversity in the complex freshwater ecological systems (Azad 2012). This creates the need for efficient use of the scarce water resources in the irrigated agricultural sector. In the last 20–30 years, the awareness about the need to increase water use efficiency has been present throughout the water industries, and as a result there have been some notable water efficiency gains achieved. Given that the agriculture uses the largest volume of water among all industries in Australia, the importance of having a water efficient irrigation sector is paramount to sustainable water management.

Improving agricultural water use efficiency is a major policy priority in Australia since irrigation water is becoming less available and is competed for vigorously in the water market. Improvements in water use efficiency at farm/enterprise level, as well as more broadly at regional level, are required for maintaining viability and sustainability of the irrigation industry. Sustainable irrigation means increasing agricultural productivity while maintaining environmental services and ecosystem resilience by ensuring that sustainable amount of water is extracted from the river and groundwater systems. The aim of sustainable irrigation and water resource management can be aided by identifying the economic efficiency of water use in agricultural activities. In other words, it would be useful to identify less efficient enterprises that use more water than necessary to produce a given level of output (or economic gain). Increasing the water use efficiency of this type of enterprises would lead to greater water availability for the environment, and it will help to ensure sustainable irrigation industry. Identifying those enterprises that generate high economic benefits per unit of water use, and those that generate small amount of benefits but use significant quantities of irrigation water will provide benchmarks that can serve as models for more efficient water use in the irrigated agricultural production systems, as well as enable policy targeting by government programs aimed at sustainable irrigation water for the environment.

Water use efficiency can be defined at different scales, and it is measured in various ways and from various perspectives (Qureshi et al. 2011). In physical terms, 'water use efficiency' can be defined as the ratio of the amount of water used by a crop to the amount of water applied. In contrast, some agronomic studies dealing with irrigation water management (e.g., El-Wahed and Ali 2013; Wang et al. 2001) define water use efficiency as the ratio of crop yield to the amount of water applied for crop cultivation. However, from an economics point of view, irrigation water use efficiency can be defined in terms of economic return per unit of water used for crop production. We use the economic concept of 'water use efficiency' for this study, and employ the term 'economic efficiency of water use' for it.

So far, most productivity and efficiency studies have estimated the overall economic efficiency of agricultural enterprises without emphasising the need to determine the contribution of the environmentally sensitive input use (i.e. water use) to the total economic efficiency (Azad 2012). There have been few studies that examined environmentally adjusted economic efficiency measurements of irrigated agricultural enterprises in an Australian context (e.g., Azad and Ancev 2010, 2014). The current state of knowledge does not allow for clear identification of those highly economically water use efficient agricultural enterprises, partly because of the absence of empirical studies that use the appropriate economic efficiency measurement techniques.

Within the literature on productivity and efficiency measurement, there are two broad classes of methods available to compute economic efficiency or performance of a production unit – parametric and non-parametric methods. Parametric methods (such as stochastic frontier analysis) are based on an econometric approach that attempts to distinguish the effects of statistical noise from the effects of productive inefficiency. This approach requires specification of technology (i.e., a production function), which is likely to be restrictive in many cases. On the other hand, non-parametric methods (such as data envelopment analysis (DEA)) use linear programming to construct a non-parametric piece-wise surface over the data, so as to be able to estimate production efficiencies without parameterising the technology. One of the great advantages of using non-parametric methods is that there is no requirement to specify a particular functional form on the technology which enables it to accommodate multiple inputs and outputs (Färe et al. 1996).

While many empirical studies (e.g., Veettil et al. 2013; Ali and Klein 2014, and others) used DEA based on radial efficiency measures as proposed by Debreu (1951) and Farrell (1957), in this study we use a non-radial DEA approach,[1] which has been proposed successively by Färe (1975), Färe and Lovell (1978) and Zieschang (1984). Using a radial DEA approach one can measure the efficiency of a productive unit by estimating the maximum possible proportional reduction in inputs that is compatible with output level. But the limitation of this approach is that this reduction should be the same for all inputs. In contrast, a non-radial approach allows us to reduce various inputs used in the production system in different proportion.

Using the non-radial efficiency measures one can produce fairly robust empirical results, but the same degree of robustness cannot be obtained from the radial measures (Borger and Kerstens 1996). A review of the theoretical intuition and empirical analysis conducted by Ferrier et al. (1994) found that the radial efficiency measure is not a good empirical substitute for the non-radial alternatives, since it scales inefficient observations down to projection points far removed from the efficient subset. In addition, using radial efficiency measures often leads to a situation where a number of production units have the same efficiency score of unity, and hence creates difficulty in ranking the efficiency level of these units only based on their efficiency scores (Zhou et al. 2007).

Non-radial efficiency measures have a higher discriminating power in evaluating the efficiencies of the production units, and these types of models seem to be more effective in measuring economic and environmental performance. Therefore, in recent years, a number of efficiency studies (e.g., Menga et al. 2012; Sueyoshi and Goto 2012; Chiu et al. 2012; Hernández-Sancho et al. 2011; Zhou et al. 2007; Yang and Lu 2006; Sun and Lu 2005) have used the non-radial DEA approach. The present study extends this literature to an application of measuring economic efficiency of water use for irrigated agricultural enterprises.

Although the non-radial DEA approach has been applied in a number of empirical studies, to the best of our knowledge this is the first empirical study that uses the non-

[1] A detailed discussion on radial and non-radial efficiency measures is in the methods and data section.

radial DEA measurement technique to estimate economic efficiency of water use for various types of irrigated enterprises across a number of natural resource management regions. The specific objectives of the study are to measure economic efficiency of water use of irrigated agricultural enterprises using a global efficiency index, and to explore the contribution of water input (irrigation water) in the total efficiency level. This efficiency index is a non-radial type of efficiency measurement technique that is used to decompose the economic efficiency of a productive activity into measures of input use efficiency, and measures of managerial efficiency. The study also examines several variables that contribute to the variation of water use efficiency among the irrigated enterprises.

2 Methods and Data

2.1 Methods

Data envelopment analysis, originally proposed by Farrell (1957), and further developed by Charnes et al. (1978), is now a popular nonparametric approach to measure productivity and efficiency of a production unit (i.e., firm, industry, or country). This approach has proven to be lucrative in measuring economic and environmental performance for any type of productive activity (Menga et al. 2012; Emrouznejad et al. 2008; Zhou et al. 2008). DEA can be used with both radial and non-radial efficiency measurement techniques. The efficiency scores obtained from the radial DEA model can often overstate efficiency when non-zero slacks are present because they do not account for the non-radial inefficiency of the slacks (Pastor et al. 1999; Fukuyama and Weber 2009). Moreover, the radial DEA approach can determine the unified efficiency level by measuring an inefficiency score, while the non-radial approach determines the level of unified efficiency by measuring a total amount of slacks,[2] while each slack is able to indicate inefficiency level of a production input (Sueyoshi and Goto 2012; Chiu et al. 2012).

The efficiency of a production unit can be measured by calculating the maximum possible proportional reduction in the use of factors that is compatible with its output level. In case of radial DEA approach this reduction should be the same for all inputs. In this way, one can affirm that radial measures of efficiency use the isoquant curve as a reference and not necessarily the subset of efficient points. As a result, radial-type reductions can lead towards a point on the isoquant curve that does not belong to the set of efficient points, thus enabling greater reductions in at least one input without affecting output. The rationale of a non-radial measure is to find a measure of technical efficiency that makes it possible to qualify an observation as efficient providing it belongs to the subset of efficient points.

As it can be observed in Fig. 1, the efficient subset is made up of points that are situated between X^A, X^B and X^C. Under the assumption of strong disposability, the isoquant curve is made up of the subset of efficient points and the vertical and horizontal extensions that appear in the graph. The radial measures could compare inefficient X' with point X^*, which does not belong to the subset of efficient points. It represents a serious limitation when knowing the maximum possible reduction in each of the inputs without having to sacrifice output (Russell

[2] In case of linear programming problems with more than two variables, each constraint (a linear inequality) needs to be converted into a linear equation. This process is conducted by adding a nonnegative variable, which is called a slack variable to each constraint.

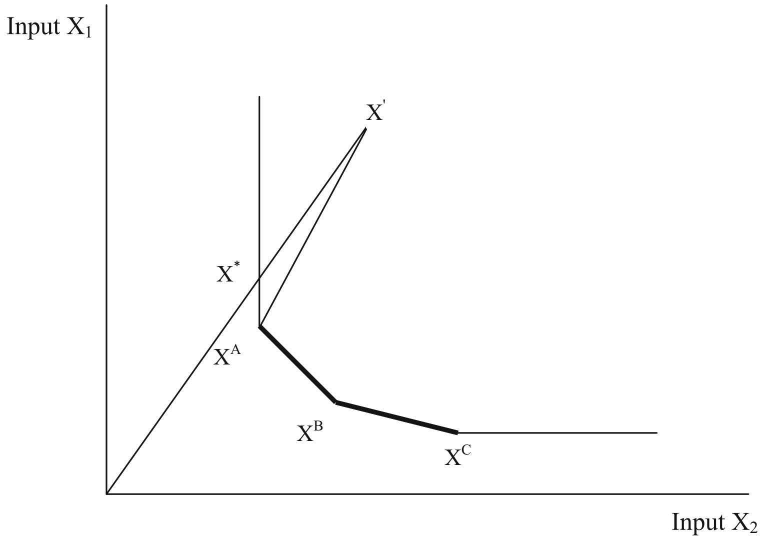

Fig. 1 Radial and non-radial efficiency measures

1985). Using non-radial measures it would not be possible to use point X^* as a reference as if it were chosen, then input X_2 could be maintained at the same level while input X_1 could be reduced to a greater extent until it reaches point X^A. Therefore, the proper minimisation exercise would fix X^A as a reference and not X^*.

In determining economic efficiency of an irrigated enterprise, the study uses a non-radial DEA type approach, which is called global efficiency index (GEI). This efficiency measurement is also known as the 'Russell Measure' as introduced by Färe and Lovell (1978) (for details see Pastor et al. 1999; Färe et al. 1985; Cooper et al. 2007). The Russell measure was originally constructed in an input-oriented form, but Färe et al. (1985) extended it in a new form, by defining it as the "Russell graph measure"—which simultaneously minimizes the input efficiency measure and maximizes the output inefficiency measure. For the purposes of our present study, the *GEI* for each irrigation enterprise (k) can be expressed as:

$$GEI^k(y,x) = \min\left\{\sum_{n=1}^{N} \lambda_n/N : (\lambda_1 x_1, \lambda_2 x_2, \ldots, \lambda_N x_N) \in L(y),\ \ 0 \le \lambda_n \le 1\right\} \tag{1}$$

where, *GEI* refers to the global efficiency index for a representative production unit that uses a vector of inputs $x=(x_1,\ldots,x_N)\in\Re_+^N$ to produce a vector of outputs, $y=(y_1, \ldots, y_M)\in\Re_+^M$.

The *GEI* for each irrigated enterprise can be obtained by minimizing the arithmetic mean of the efficiency scores in input. This index implies that various inputs employed in the production process could be minimized by different proportions, which is in contrast with the radial measure where all inputs are reduced by the same proportion. This degree of flexibility guarantees that *GEI* measure always uses the subset of efficient points as a reference.

The values for the efficiency index for each of the inputs can be obtained by solving the following linear programming optimization problem:

$$
\begin{aligned}
& GEI\left(y^{k'}, x^{k'}\right) = \frac{1}{N} \ \min \sum_{n=1}^{N} \lambda_n \\
& s.t. \\
& \sum_{k=1}^{K} z_k y_{km} \geq y_{k'm} && m = 1, \ldots, M \\
& \sum_{k=1}^{K} z_k x_{kn} \leq \lambda_n x_{k'n} && n = 1, \ldots, N \\
& z_k \geq 0, && k = 1, \ldots, K \\
& 0 \leq \lambda_n \leq 1, && n = 1, \ldots, N
\end{aligned} \tag{2}
$$

In the above equations, each λ_n obtained from the solution of the optimization problem provides the efficiency score for each of the inputs considered in the production model. For the present case study the above optimization problem is solved for K enterprises where, K=1, 2, …,k,…,130 irrigated enterprises. Each enterprise uses a vector x^k=(x_1^k,x_2^k)(2×1) of inputs to produce an output vector y^k=(y_1^k)(1×1), z being a vector of dimension (130×1). Thus the estimated results can be obtained from the 130 optimisation programmes (one for each enterprise).

To provide an applied example of Eqs. 1 and 2, suppose we have a production unit A, which uses two inputs (x_1^A=3, x_2^A=5) to produce one output (y^A=10), therefore we can write GEI for A as:

$$
GEI\left(y^A, x^A\right) = \min\left\{ \sum_{n=1}^{2} \lambda_n / 2 : \left(\lambda_1 x_1^A, \lambda_2 x_2^A\right) \in L\left(y^A\right), \ \ 0 \leq \lambda_n \leq 1 \right\} \tag{3}
$$

The efficiency index for each of the two inputs can be obtained by solving the following optimization problem:

$$
\begin{aligned}
& GEI\left(y^A, x^A\right) = \frac{1}{2} \ \min \sum_{n=1}^{2} \lambda_n \\
& s.t. \\
& \sum_{k=1}^{130} z_k y_k \geq 10 \\
& \sum_{k=1}^{130} z_k x_{k1} \leq \lambda_1 3 \\
& \sum_{k=1}^{130} z_k x_{k2} \leq \lambda_2 5 \\
& z_k \geq 0, && k = 1, \ldots, 130 \\
& 0 \leq \lambda_n \leq 1, && n = 1, 2
\end{aligned} \tag{4}
$$

The global efficiency index accounts for all inefficiencies that the model can indentify, whereas all the radial efficiency models are ‘incomplete’ in that they omit the non-zero input and output slacks, and thus fail to account for all inefficiencies that the model can indentify (Cooper et al. 2007).

Since the main objective of this study is to determine the economics of water use efficiency of irrigated enterprises (economic return per unit of water used for crop production), we have considered two types of inputs: (a) quantity of water use, and (b) production/managerial cost (excluding water use cost). While estimating the global efficiency index using a non-radial DEA approach, we can decompose the efficiency index into two components; 'water use efficiency index' and 'production/managerial cost efficiency index' (using Eq. 2). The water use efficiency index determines the efficiency level of an irrigated enterprise only focusing on water use in the production process, while the production efficiency index measures the scale of efficiency of an enterprise considering the managerial or production costs aspect. Combined, they result with the global efficiency index.

2.2 Data

The Murray-Darling Basin (MDB) has unprecedented economic and environmental importance for agriculture and for the wider public in Australia. A wide range of irrigated agricultural enterprises that represent more than 60 % of total agricultural production in the country are grown in the Basin. Therefore, the MDB is considered as the geographical reference for this paper, and 17 natural resource management areas (NRM) within the MDB have been chosen for the study. The term 'enterprise' is defined in this study as an agricultural activity in its entirety, comprising the technology, type of crops, and also location in this case. Ten types of irrigated enterprises are investigated: cotton, rice, cereal crops (grain/seed), cereal crops for hay, pasture for grazing, pasture for hay and silage, other broadacre crops, vegetables, fruit and nut trees, and grapevine. A particular 'irrigated enterprise' referred to in this study may comprise several irrigated crops; for example, 'other broadacre crops' includes canola, soybean, sorghum, sunflower and chickpea. Even though there are some differences in the production systems among these irrigated enterprises, for the purposes of this paper, a typical representative enterprise is considered as a data point. This is in line with the main focus of this paper, which is to determine the economic efficiency of irrigation water use for a typical irrigated enterprise in a given region, while keeping all other management aspects the same.

The total number of representative irrigated enterprises from 17 NRM areas considered for this study was 130. The term 'representative enterprise' is defined in the study as an enterprise

Table 1 Mean values of inputs and output for the sample irrigated enterprises across 17 NRM regions in the Murray-Darling Basin

Irrigated enterprises	Volume of water applied (GL)	All cost (excluding water) (Million AUD)	Gross revenue (Million AUD)
Cereal crops cut for hay	8.40	1.96	3.52
Cereal crops (grain/seed)	38.41	7.91	17.73
Cotton	103.91	33.46	56.66
Fruit and nut trees	32.03	124.28	184.18
Grapevines	44.39	86.31	132.15
Other broadacre crops	4.82	1.48	3.12
Pasture for grazing	64.46	10.21	23.18
Pasture for hay and silage	28.98	7.22	14.87
Rice	60.27	5.97	20.11
Vegetables	10.28	36.36	44.56
Mean	36.52	30.94	48.74

Table 2 Mean efficiency indices for water use, production cost and global efficiency

Enterprise	Global efficiency index	Water use efficiency index	Production/ management cost efficiency index
Cereal crops for hay	0.468	0.143	0.794
Cereal crops (grain/seed)	0.611	0.272	0.950
Cotton	0.442	0.145	0.739
Fruit and nut trees	0.677	0.359	0.994
Grapevines	0.639	0.279	1.000
Other broadacre crops	0.642	0.372	0.912
Pasture for grazing	0.558	0.152	0.906
Pasture for hay and silage	0.524	0.185	0.862
Rice	0.915	0.830	1.000
Vegetables	0.516	0.209	0.823
Average	0.581	0.255	0.899

which is characterised by an average type of farm from a natural resource management region. The production technology for the irrigated enterprises modeled in this study consisted of two inputs, and one output. The volume of water applied (gigalitres) and all costs (excluding the cost of water) measured in million AUD were treated as inputs, whereas the gross revenue (million AUD) was treated as the output. The mean value of these variables for the 130 representative irrigated enterprises from the 17 NRM regions are presented in Table 1. Data used for this study have been collected from various published sources and research reports such as the Australian Bureau of Statistics (ABS), the Departments of Primary Industry of New South Wales, Victoria and South Australia and from other state departments and related organizations. Data on the considered variables were employed in a production efficiency model to estimate the *GEI*, and the model was solved using the general algebraic modelling system (GAMS).

3 Results and Discussion

We applied a non-radial data envelopment analysis model to obtain the global efficiency index of each irrigated enterprise across 17 natural resource management regions. The global efficiency index indicates the overall economic performance (efficiency level) of a productive unit, and it can be decomposed to the efficiency indices for each of the inputs employed in the production model. An efficiency index for each input has been estimated following the linear programming optimization problem (using Eq. 2 in section 2). The mean efficiency scores for the global efficiency index, the water use efficiency index and for the production (or managerial) cost efficiency index for the irrigated enterprises considered in this study are presented in Table 2. The results show that the production/ management cost efficiency index is substantially higher than both global efficiency and water use efficiency indices. Higher production cost efficiency scores, on average, were observed for rice and grapevines, while comparatively lower scores were observed in the case of cotton and cereal crop for hay enterprises. The average efficiency score of about 0.90 for the production/managerial cost implies that the overall production or management efficiency of the major irrigated enterprises in the Murray-Darling Basin is at a satisfactory level.

Water use efficiency index, which is defined and constructed as an indicator for economic efficiency of water use, is a contributing factor into the global efficiency index. Findings reveal that water use efficiency index is significantly lower than the production/managerial cost efficiency index. The average water use efficiency index is only 0.255, indicating that there is substantial room for further improvement of water use efficiency in irrigated agriculture. It is important to mention that the variation in water application rate per hectare among the various irrigated enterprises does not necessarily have impact on water use efficiency level. This is because the efficient performance is measured from an economic point of view — monetary value-added from agricultural output in relation to water used for crop production. For example, the highest water-consuming enterprise, rice, has the greater water use efficiency scores (on average) than some of the low water-consuming enterprises such as cereal crops for grain/seed and cereal crops for hay.

The global efficiency and water use efficiency indices for each irrigated enterprise obtained from the non-radial DEA efficiency model are plotted in Fig. 2. The global efficiency for the irrigated enterprises is significantly higher than the water use efficiency scores. There are a significant number of irrigated enterprises for which the global efficiency levels are between 0.60 and 0.80 across the natural resource management regions, while very few irrigated enterprises are observed with a water use efficiency score of above 0.60. In contrast, nearly 50 % of all considered irrigated enterprises have a water use efficiency index of less than 0.20 (Fig. 2). This result strengthens the finding that water use efficiency is fairly low and can be significantly improved across the NRM regions within the Murray-Darling Basin.

While the water use efficiency is relatively low, the higher scores for the global indices are a result of the high production/managerial efficiency of farms. This suggests that irrigated farms are relatively efficient in overall farm management activities, and relatively less efficient in water resource management. In addition, the high variability in water use efficiency scores indicates great inconsistency in terms of water use efficiency among the irrigated enterprises. While some enterprises have relatively high water use efficiency scores, others have very low scores, which overall translates in a relatively poor water use efficiency performance.

Findings reveal that there is large variation in the efficiency scores for water use compared to global efficiency indices. Table 3 shows that water use efficiency for a particular irrigated

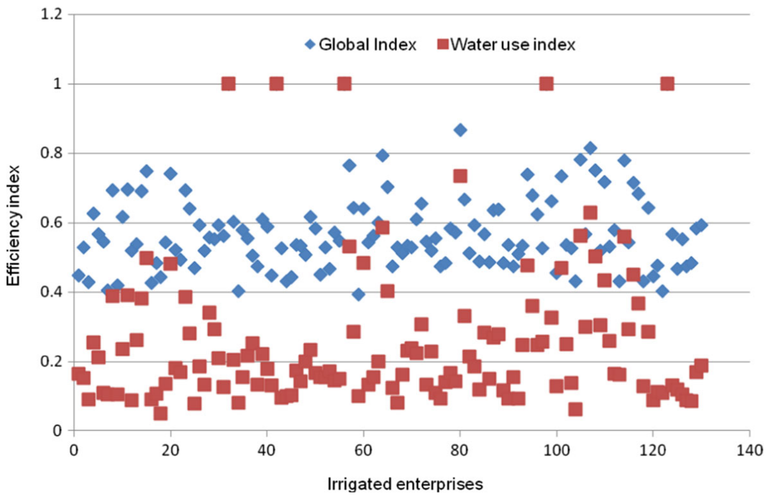

Fig. 2 Comparison between global efficiency index and water use efficiency index

Table 3 Water use efficiency indices of irrigated enterprises across NRM regions within the Murray-Darling Basin

NRM regions	Cereal crops for hay	Cereal crops (grain/seed)	Cotton	Fruit and nut tress	Grapevines	Other broadacre crops	Pasture for grazing	Pasture for hay and silage	Rice	Vegetables
Border River-Gwydir	0.090	0.152	0.165	-	-	0.110	0.254	0.212	-	-
Central West	0.104	0.388	0.104	0.380	0.498	0.087	0.235	0.390	-	0.263
Lachlan	0.049	0.107	0.091	0.386	0.282	0.182	0.136	0.481	-	0.170
Lower Murray Darling	-	0.079	-	0.210	0.125	0.341	0.186	0.134	-	0.292
Murray	0.080	0.205	-	0.221	0.178	0.253	0.155	0.216	1.000	0.134
Murrumbidgee	0.101	0.096	0.130	0.223	0.167	0.143	0.103	0.173	1.000	0.200
Namoi	0.172	0.155	0.154	0.531	0.287	1.000	0.146	0.151	-	-
Western	-	0.483	0.100	0.155	0.201	-	0.134	-	-	-
Goulburn Broken	0.123	0.403	-	0.223	0.307	0.230	0.082	0.163	0.587	0.239
Mallee	0.228	0.134	-	0.166	0.144	-	0.109	0.093	-	0.141
North Central	0.214	0.332	-	0.270	0.279	0.283	0.185	0.119	0.734	0.149
North East (VIC)	0.117	-	-	-	0.477	0.092	0.094	0.155	-	0.247
Wimmera	-	0.360	-	1.000	0.327	-	0.248	0.257	-	-
Border River (QLD)	0.251	0.470	0.128	0.630	0.503	0.562	0.139	0.061	-	0.299
Condamine	0.259	0.434	0.304	0.451	0.368	0.559	0.164	0.161	-	0.293
Maranao Balonne	0.089	0.286	0.129	-	0.132	1.000	0.111	0.110	-	-
SA Murray Darling Basin	0.119	-	-	0.169	0.187	-	0.104	0.087	-	0.086

"-" indicates that there are no values for water use efficiencies of enterprises, since inputs data are not available for the respective NRM regions enterprise varies significantly across the NRM regions within the Murray Darling Basin. Some irrigated enterprises have reasonable water use efficiency scores in some regions, but very low scores in other regions. For instance, cotton has a highest water use efficiency score (0.304) for Condamine, but very low efficiency score (0.091) for the Lachlan region. In contrast, the scale of water use efficiency for pasture for hay and silage was comparatively higher in Lachlan than that in the Condamine region (Table 3). The variation in water use efficiency of the irrigated enterprises across the NRM regions can provide an important insight for policy in particular for less efficient enterprises.

The Kruskal-Wallis non-parametric tests[3] are used to verify whether the differences between the efficiency scores among the sample groups (i.e. type of irrigated enterprises, and NRM regions) are statistically significant. The test results show that there is significant difference in water use efficiency scores among the irrigated enterprises (Table 4). The Kruskal-Wallis was also run across the natural resource management regions, and the test results reveal that there is significant variation in water use efficiency of irrigated enterprises across the regions within the Murray-Darling Basin.

The study has identified NRM regions where there is a greater scope to increase water use efficiency for particular enterprises. Every region has a best and a worst performing irrigated enterprise with respect to water use efficiency. We calculated the efficiency distance between the least water efficient (worst) irrigated enterprise in a given NRM region and the globally highest efficiency score, which is assigned to the enterprises on the frontier, and therefore has a value of unity (Table 5). Similarly, the efficiency distance between the most water efficient irrigated enterprise in a given NRM region and the globally highest efficiency score was calculated. A relatively short distance from the globally highest efficiency score indicates better performance of an enterprise in relation to water use, and hence relatively lower opportunity to further increase water use efficiency. In contrast, a relatively long distance from the globally highest efficiency score implies that there is a greater scope to increase water use efficiency. Results reveal that water use efficiency scores of both best and worst performers in certain NRM regions are fairly far away from the global frontier. Examples of those NRMs are the Border River-Gwydir, Mallee, and South Australia Murray-Darling Basin (Table 5). This finding implies that some enterprises in those regions could be prioritised by water use efficiency improvement policies.

4 Conclusions

The non-radial efficiency measure is a special type of efficiency estimation technique through which the efficient performance with respect to individual inputs employed in the production process can be measured. This particular type of efficiency model allows non-proportional reduction in inputs used in the production system. Non-radial efficiency measures have a higher discriminating power in evaluating the efficiencies of the production units, and these types of models seem to be more effective in measuring economic and environmental performance. In case of irrigated agriculture, this measurement technique enables us to obtain an efficiency score for the use of water as an environmentally sensitive input in irrigated crop production systems.

[3] Kruskal-Wallis is a non-parametric test for which any specific form for the distribution of the population is not required. It is used to compare between the medians of two or more samples to determine if the samples have come from different populations.

Table 4 Comparison in water use efficiency across irrigated enterprises and the Kruskal-Wallis test result

Enterprise	Number of enterprises	Mean water use efficiency	Maximum	Minimum
Cereal crops for hay	14	0.143	0.259	0.049
Cereal crops (grain/seed)	15	0.272	0.483	0.079
Cotton	9	0.145	0.304	0.091
Fruit and nut trees	14	0.359	1.000	0.155
Grapevines	16	0.279	0.503	0.125
Other broadacre crops	13	0.372	1.000	0.087
Pasture for grazing	17	0.152	0.254	0.082
Pasture for hay and silage	16	0.185	0.481	0.061
Rice	4	0.830	1.000	0.587
Vegetables	12	0.209	0.299	0.086
Kruskal-Wallis test	0.0001			

Using a non-radial DEA approach the study has estimated water use efficiency scores for the major irrigated enterprises in the Murray-Darling Basin. It was observed that overall the irrigation enterprises in the MDB are fairly efficient production units. They are well managed and in general, use inputs efficiently. But there is significant difference between the efficiency in managing water input, and in managing other inputs (e.g. machinery, labour). The evidence suggests relatively poor management of the water input in comparison to the management of the other inputs in the production process. There are significant opportunities to improve water management in the irrigated enterprises in the MDB. This is documented by the relatively large

Table 5 Efficiency distance comparison in water use efficiency of irrigated enterprises across the NRM regions

NRM regions	Efficiency distance from the globally highest efficiency score	
	Least efficient irrigated enterprise	Most efficient irrigated enterprise
Border River-Gwydir	0.910	0.746
Central West	0.913	0.502
Lachlan	0.951	0.519
Lower Murray Darling	0.921	0.659
Murray	0.920	0.000
Murrumbidgee	0.904	0.000
Namoi	0.854	0.000
Western	0.900	0.517
Goulburn Broken	0.918	0.413
Mallee	0.907	0.772
North Central	0.881	0.266
North East (VIC)	0.908	0.523
Wimmera	0.752	0.000
Border River (QLD)	0.939	0.370
Condamine	0.839	0.441
Maranao Balonne	0.911	0.000
SA Murray Darling Basin	0.914	0.813

differences between most and least water efficient enterprises, suggesting that many enterprises have quite a bit of catching up to do with the best practice peers.

The variation of water use efficiency scores across irrigation enterprises and across NRM regions can provide an important insight for the current policy and future efforts to improve water use efficiency as well as to ensure sustainable irrigation industry in Australia. Measuring the efficiency of irrigated enterprises using the non-radial DEA approach offers important insights about water use efficiency of the irrigation industry. The findings of this study point to the need for improvement of efficiency in using water in the irrigated sector, which will be critical for the long-term sustainability of the industry.

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