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Abstract

Water use technical efficiency and three definitions of water use economic efficiency (based on gross, net, and incremental returns) were estimated for the Oldman River Sub-Basin located in Southern Alberta over a five year period -- 2004 - 2008. The average level of water use technical efficiency varied from 4.9 – 8.2 Mt/dam^3. The gross economic value of crop production varied from \$490 - \$710/dam$^{3.}$ The net economic value of crop production varied from \$234 - \$342/dam^3. A third definition of water use economic efficiency was the incremental net value of crop production under irrigation over what it would have been under dry land conditions; that measurement varied from \$176 - \$302/dam^3. The study concludes that although water use technical efficiency is the most commonly used measure of water use efficiency, it does not show changes in the economic well-being of irrigators and thus is not the best measure for decision making by irrigation managers and public policy makers. In addition, variability in water diversions over time can seriously bias calculations of water use technical efficiency. This bias is removed by using financial indicators to measure the increased output that results from irrigated crop production.

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1. Introduction and background

Parts of Southern Alberta lie in semi-arid climate with average annual water deficits in excess of 200 mm, partly the result of a generally dry and sunny climate (Shady, 1964). Irrigation is a necessity in the region, as dry conditions are very frequent. In fact, the largest allocation and use of water in Alberta is for irrigation activities (Figure 1). This region has the largest irrigated area in Canada with 625,000 hectares. Beaulieu et al. (2007) estimated that in 2001, irrigation in Alberta used 2.9 billion m^3 of water, some 66% of total irrigation water in Canada. As irrigation demand for water increases, there is more competition among various uses (AENV, 2008). This results in increasing pressure to reform water management in Alberta to ensure it is allocated and used as efficiently as possible since water supplies are expected to diminish, conflicts increase, and the aquatic ecosystem health become increasingly threatened (Bjornlund, 2010).

As the major user of surface water supplies, irrigators are under increasing pressure to use less water for irrigating crops so that more water would be available for industrial and municipal uses as well as for supporting environmental objectives. Improving the efficiency of water used in irrigation may also help preserve the region's ability to produce high volumes of agricultural products. While much attention has been paid to estimating water use efficiencies at the project or farm levels, effective management of water within a river basin requires knowledge of aggregate water use efficiencies (Haie et al., 2008; AENV, 2008).

The OECD (2001) proposed development of two main indicators of water use efficiency. The first was Water Use Technical Efficiency (WUTE), which was defined as the physical mass of agricultural production (tonnes) per unit volume of irrigation water utlilized. The second was Water Use Economic Efficiency (WUEE), which was defined as the monetary value of agricultural production per unit volume of irrigation water utilized. Calculations of both indicators obviously depend on weather conditions, cropping patterns, and yields. The WUTE measure places greater weight on bulky crops harvested and disregards impacts on irrigators' financial results. The WUEE measure provides for a common base to evaluate the impacts of changes in input and output prices, government policies and other factors that can change year-by-year.

The purpose of this study is to explore the appropriateness of using the above two types of measures for estimating water use efficiencies. Since major changes that could occur in actual water use, cropping patterns, and input and output prices in agriculture, and since these affect water use efficiency, alternative measures of economic efficiency were explored. The study aims to recommend the most appropriate measure for making water management decisions.

2. Conceptual water use efficiency measures

It is clear that the estimated level of water use efficiency depends on the method used to calculate it, which, in turn, depends on available data and scope of measurement (e.g., farm or basin level). Conceptually, several different definitions and concepts for measuring the efficiency of water used in irrigation have been proposed. Some researchers have defined water use efficiency as a dimensionless measure in terms of a ratio or percentage while others have defined it in terms of outputs measured in physical or monetary units per unit of water used. Billi et al. (2007) suggested the use of two main approaches to assess water use efficiency. The first is a hydrological/engineering (technical) approach and the second is an economic or institutional approach. The first measures the yield per unit of water input or diversion needed to achieve required evapotranspiration, and the second estimates social gains from reallocation of water to alternate uses. This approach follows earlier studies by Tollefson et al. (2003) where water use efficiency was defined in terms of physical and economic outputs per volume of water diverted for irrigation, which can more easily be calculated with data commonly found in published sources and government documents such as those by Nitschelm (2010) or IWMSC (2002b). Even though the concept of efficiency generally is perceived in terms of a percentage or a unit-free measure, the WUTE and WUEE (as defined in the previous section following OECD, 2001) provide common sense yardsticks of the opportunity cost of a unit of irrigation water in physical and economic terms.

The WUTE typically is conceptualized in terms of level of irrigation water use and all the productivity is credited to it but measurement of crop water use needs to be adjusted for return flows for accurate estimation. Moreover, the WUTE measure assumes that all crops grown under irrigation have the same impact on the well-being of the irrigator. However, such an assumption is not supported by real situations. Further complications arise from the fact that some irrigated crops are not sold directly in a market but, rather, act as intermediate products for use in another agricultural enterprise.

The WUEE measure removes the major limitation of the technical water use indicator. Higher levels of economic efficiency are associated with maximizing social net benefits when resources are limited (Wichelns, 2002). It is defined as the ratio of total monetary value of agricultural production per volume of irrigation water diverted. However, the total monetary value can be defined as gross revenue, net revenue (after costs of production have been deducted) or incremental increase in revenue (above the revenue that would have been earned if the land had not been irrigated). A major limitation of the WUEE indicator is that it is highly susceptible to changes in several factors, including choice of crops planted, agronomic/cultural practices employed, and crop and input prices. For example, adding more fertilizer to a crop usually increases its yield, and unless market price changes as a result, also increases the gross revenue obtained. This would result in a higher estimated value of

WUEE (if measured on a gross revenue basis) but the change is contributed by factors other than improved water use technical efficiency.

3. Estimating water use efficiencies in Southern Alberta

3.1 Study region

This study calculated levels of water use efficiency for irrigated agriculture in the Oldman River Sub-Basin (ORSB) of southern Alberta (Figure 2). Irrigation in southern Alberta consists of a mixture of technologies including pivot sprinklers, wheel move sprinklers, gravitational applications, and other methods (AARD, 2009). Application efficiencies of these delivery systems vary and are calculated as the ratio of water delivered to the field to the amount available to the crops or the stored soil moisture level divided by the farm diversion amount (IWMSC, 2002a).

3.2 Data and calculations

Water use efficiency in this study was measured by two broad types of measures: (i) Water Use Technical Efficiency (WUTE) and (ii) Water Use Economic Efficiency (WUEE). Three definitions of the second measure were used: WUEE (Gross), WUEE (Net), and WUEE (Incremental). Calculations were made of these four measures in the ORSB for each year of a five-year period, 2004-2008.

Following the OECD (2001), the WUTE was defined as total harvested biomass of the irrigated crops, obtained as the product of yields in tonnes of biomass of each crop harvested and its corresponding area in hectares, divided by the net water diverted in cubic decametres or dam^3 (Mt/dam^3). The WUTE was calculated for each year as in (1):

$$WUTE_t = TM_t \ / \ NWD_t \qquad (t = 2004, 2005, \ldots, 2008) \qquad (1)$$

where: TM_t is total mass in metric tonnes of irrigated crops harvested in the sub-basin in year t (the product of area irrigated for crop i and its yield per unit of area irrigated); and NWD_t, is the net water diverted for irrigation in sub-basin in year t in dam^3.

Three definitions of Water Use Economic Efficiency were calculated for the ORSB in each year. All water use economic efficiency measures result in a benefit of the irrigation water that is expressed in Canadian dollars per net dam^3 of water diverted ($\$/dam^3$) for irrigation in the ORSB in each year. The first measure, WUEE (Gross), was defined as gross revenues of the irrigated crops grown in the ORSB each year, obtained as the product of the biomass harvested and average crop prices, then divided by the net water diverted (as in (2) below):

$$WUEE\ (Gross)_t = GR_t \ / \ NWD_t \qquad (2)$$

where: GR_t is gross revenue of irrigated crops in Canadian dollars in the ORSB in year t (the product of area, yield and price per unit); and other variables are as defined above.

The second measure of water use economic efficiency calculated was WUEE (Net), as in equation (3):

$$WUEE\ (Net)_t = NR_t \ / \ NWD_t \quad (3)$$

where: NR_t is net revenue of irrigated crops in the ORSB in year t (the difference between Gross Revenue and Variable Cost of Production) for the irrigated crops in year t; and other variables are as defined above.

The third definition of water use economic efficiency was WUEE (Incremental), which was calculated as (4):

$$WUEE\ (Incremental)_t = IR_t \ / \ NWD_t \quad (4)$$

where: IR_t is incremental net return (i.e., net returns from irrigated crops in the ORSB minus expected net returns if cropland in the ORSB had not been irrigated); and other variables as defined above.

The total production (in metric tonnes) of crops grown in the ORSB was calculated for each of the years from 2004 to 2008 by multiplying the yield in metric tonnes by the number of hectares for each crop in each year. The yield was held constant at the 2000-2004 average to ensure that the annual changes in yields would not affect the calculation of water use efficiencies. Since small changes occur annually in areas planted to each crop under irrigation (in response to changes in output and input prices, rotational considerations and other factors), the total mass produced in the ORSB changes year-by-year.

Tollefson et al. (2003) suggested separating two measures of water used: water diverted and water consumed. The latter is the difference between water diverted and the amount that is returned back to the source (perhaps at another location). The latter procedure (which was used in the present study and was suggested by OECD (2001)) yields a better measure of irrigation water use efficiency. Furthermore, water diversions also reflect water delivery efficiency to producers. Improvements in water delivery efficiencies (such as converting open canals to pipelines) could significantly improve both WUTE and WUEE. Following Tollefson et al. (2003), the denominators of all water use efficiency measures were defined as the net diversions of water for each year over the five-year period

The ORSB contains a number of irrigation districts. For those located in more than one river basin, an apportionment procedure was developed. Gross diversions, return flows and net diversions for the irrigation districts in the ORSB over the five-year period are shown in Table 1, and with totals in Table 2. The calculation of net diversions for sub-basin was obtained by summing the proportions of net diversions for each of the irrigation districts in each sub-basin. The net diverted water in each sub-basin is the amount that was sent through irrigation works and available for the crops.

In a previous study, Yan et al. (2010) estimated the total weight of biomass that was harvested, gross farming revenues, and net farming revenues (above total variable costs) of irrigated cropping activities undertaken in the ORSB during the years 2004-2008. The total biomass of crops produced on irrigated land was derived from the 2000-2004 average yields in metric tonnes for each of the major irrigated crops multiplied by the irrigated crop area in hectares for those years (equation 1). These data are presented in the first column of Table 3 and are the numerators in the calculation of $WUTE_t$.

The second column in Table 3 is the calculation of gross revenues of all major irrigated crops grown in each of the sub-basins during the years 2004-2008. These were obtained by multiplying the number of hectares planted to each of the major crops by its average yield and by its average farm-level price (equation 2) (Yan et al., 2010). This column provides the numerators for the calculation of WUEE $(Gross)_t$.

The third column of Table 3 is the calculation of net revenues of all major irrigated crops grown in each of the sub-basins during the years 2004-2008. These were obtained by subtracting the variable costs of production from the gross revenues (equation 3) (Yan et al., 2010). This column provides the numerators for the calculation of WUEE $(Net)_t$.

Yan et al. (2010) also calculated the expected net revenues that would have been obtained if the irrigated area in the ORSB had no access to supplementary water but, instead, had to rely on rainfall for crop growth. To obtain these, dryland yields were multiplied by the appropriate areas in each sub-basin and by farm-level prices to obtain gross revenues from producing dryland crops. The total estimated variable costs of production for each crop on dryland were subtracted from the gross dryland revenues to obtain estimated net revenues under dryland conditions. Since dryland crop production costs were available by brown, dark-brown, and black soil types for each crop, percentage composition of soils in the ORSB were used as weights to determine total variable costs of production for dryland crops (Yan et al., 2010). Finally, the estimated net revenues under dryland conditions (column 4 in Table 3) were subtracted from the net revenues under irrigated conditions (column 3 in Table 3) to obtain the incremental net revenues from irrigation (equation 4) (column 5 in Table 3). These are the values that become the numerator in the calculation of WUEE (Incremental).

Following calculations of the different water use efficiency measures, bivariate correlations were conducted among the WUTE and the three water use economic efficiency measures to help determine the relative usefulness of the different measures for decision makers.

4. Results

Results for the WUTE measure are shown in Table 4. Over the five-year period, the average level of WUTE was 6.201 Mt/dam^3 for the ORSB. A large percentage of the land in the ORSB (23% average over the five years) was planted to high-yielding, bulky crops: sugar beets, corn silage, potatoes and barley silage (Yan et al., 2010). There were significant variations in calculated values of WUTE throughout the five-year period (Table 4). The standard deviation of WUTE was estimated at 1.229 Mt/dam^3 in the ORSB. Two factors caused this variation. First, the cropping pattern changed annually, which had effects on the numerator. Second, and more importantly, the denominator (net water diverted) changed markedly from year-to-year (Table 2).

The average calculated WUEE (Gross) was \$592.91/dam^3 in the ORSB. The highest WUEE (Gross) occurred in 2005 with the value being \$710.41/dam^3 that year. As noted above, net water diversions for agriculture were the lowest (per hectare) in that year. The average calculated WUEE (Net) was \$268.42/dam^3 in the ORSB. The large population of feedlot cattle that are located in the ORSB provide a ready market for corn and barley silage. Also, two high valued crops (sugar beets and potatoes) are grown in the ORSB. Finally, the average calculated value of WUEE (Incremental) was \$215.80/dam^3 in the ORSB. The WUEE (Incremental) was highest during the 2005 growing season.

The correlation between WUTE and WUEE (Gross) was relatively low (0.65) and statistically insignificant. This suggests that the measure of water use technical efficiency does not closely reflect changes in water use economic efficiency. However, the correlation between the WUEE (Gross) and WUEE (Net) was 0.87, which was statistically significant at the 10% level. Also, the correlation between the WUEE (Net) and WUEE (Incremental) was 0.88, which was statistically significant at the 5% level.

5. Discussion

Both technical and economic measures of water use efficiency were estimated in the ORSB of southern Alberta where a significant amount of irrigation is present. The measures of water use efficiency were defined as either the total weight of agricultural products harvested or the value of the agricultural production divided by the net volume of water diverted. For comparisons over a period of time, these indicators have two major weaknesses. First, moisture to produce a crop comes from two sources: natural rainfall and supplementary irrigation water. In these measures, natural precipitation is ignored. Since some years have above normal rainfall and others may be drought-like, they can produce misleading and even contradictory results. Producers generally adjust the level of supplementary irrigation water for various crops under different weather conditions. For example, 2005 was a year of above average rainfall in Southern Alberta; this resulted in the net diversions of water for irrigation to be much lower than in the other years. Since the net diversions are the divisors in the calculations, this high rainfall year resulted in the highest calculated levels of WUTE and WUEE. Second, the measures, in addition to not being comparable over time, also are not directly comparable across regions due to differences in crop mix, productivity of soils, weather patterns and other factors. Bulky crops, such as forages, generally are higher tonnage crops than are cereals or oilseed crops, thereby distorting the WUTE measure. Third, the numerator in the WUTE measure does not take into account the total amount of biomass produced for all crops. For forages, the amount included in the numerator is the total harvestable biomass whereas only the weight of the seeds harvested is counted for grains and oilseeds.

Results from this study, though based on only five years of data, show that the three measures of water use economic efficiencies -- WUEE (Gross), WUEE (Net), and WUEE (Incremental) -- are all closely related to each other. But, WUEE (Net) and WUEE (Incremental) require much more data to calculate than does WUEE (Gross). The relatively high degree of correlation among the three measures provides confidence that the simplest (to calculate) of these measures -- WUEE (Gross) -- can be considered a good choice for the measurement of water use economic efficiency.

Measures of economic efficiency are improvements over measurements of technical efficiency since they more closely match the overall objective of irrigation farmers – improving profitability -- and thereby increasing overall social well-being. The measures of water use economic efficiency effectively weight the physical quantities harvested by their respective economic (social) values and, thus, are more useful for policy makers and water management officials who must make decisions involving water allocations. Results from this study demonstrate that measurements of water use efficiency are not straight-forward and interpretation of calculated values of water use efficiency need to consider factors such as crops grown, output prices, input prices, methods of irrigation and amount of net water used to irrigate, which tends to vary greatly from one year to the next.

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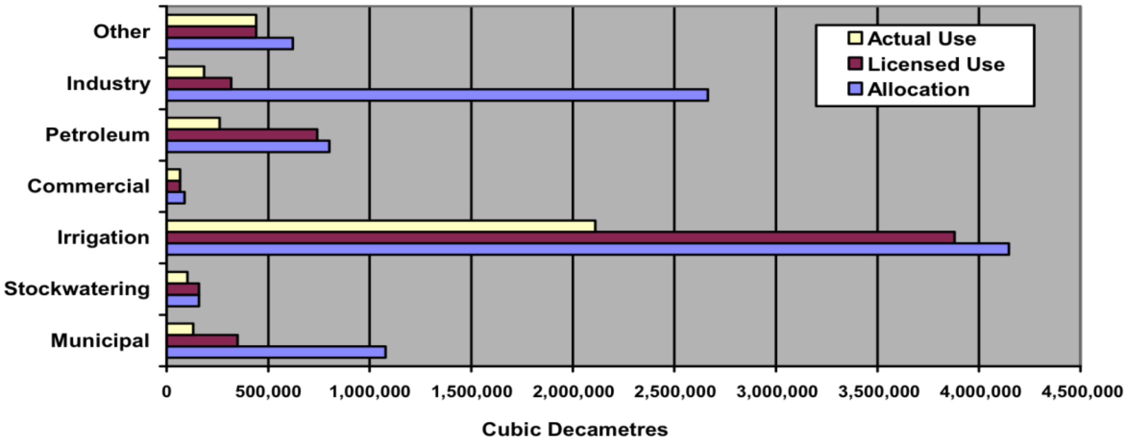
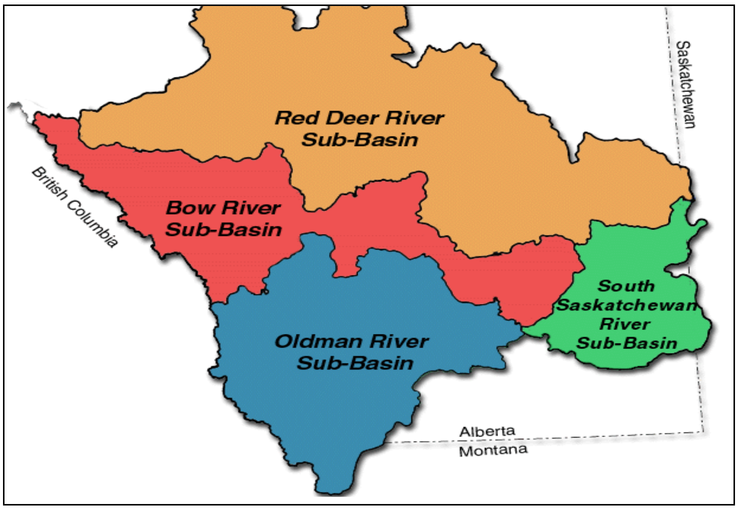
Figure 1. Allocation, Licensed Use, and Actual Use of Water by Sector in Alberta in 2005.



Source: AENV (2007) (p. iv)

Figure 2. Location of the Oldman River Sub-Basin in Southern Alberta.



Source: AENV, 2003.

Table 1. Water Diversions to Irrigation Districts Located in the Oldman River Sub-Basin

Irrigation districts	Diversions (dam^3)	2004	2005	2006	2007	2008
	Gross	4,243	4,934	4,540	3,990	4,421
Aetna	diversion	1,895	2,339	2,529	1,479	2,302
	Return flow	2,349	2,595	2,012	2,511	2,119
	Net diversion					
	Gross	284,709	225,504	259,945	316,410	293,569
Bow River*	diversion	69,161	111,061	62,464	58,027	63,310
	Return flow	215,547	114,442	197,482	258,384	230,259
	Net diversion					
	Gross	205,098	165,395	204,452	290,275	220,485
Lethbridge	diversion	32,169	46,378	49,232	N/A	55,121
Northern	Return flow	172,929	119,017	155,220	290,275	165,364
	Net diversion					
	Gross	15,284	10,927	17,409	22,496	15,615
Magrath	diversion	5,115	4,437	5,112	5,173	4,137
	Return flow	10,169	6,491	12,298	17,323	11,478
	Net diversion					
	Gross	3,281	2,550	4,918	4,441	3,218
Mountain	diversion	900	1,129	1,164	1,394	1,409
View	Return flow	2,381	1,421	3,753	3,047	1,810
	Net diversion					
	Gross	34,814	33,361	45,699	58,371	42,368
Raymond	diversion	12,163	18,780	18,045	27,489	20,698
	Return flow	22,650	14,581	27,655	30,881	21,670
	Net diversion					
	Gross	453,305	390,027	412,106	486,855	470,203
St. Mary's**	diversion	33,933	87,830	40,810	24,725	41,593
	Return flow	419,371	302,197	371,297	462,130	428,610
	Net diversion					
	Gross	79,435	89,411	101,698	124,467	104,132
Taber	diversion	11,607	28,946	25,840	19,858	20,339
	Return flow	67,828	60,465	75,858	104,609	83,793
	Net diversion					
	Gross	26,643	16,920	25,151	39,226	25,970
United	diversion	1,994	3,810	2,491	1,992	2,297
	Return flow	24,649	13,110	22,660	37,234	23,673
	Net diversion					
	Gross	140,617	148,615	88,811	83,877	104,846
Western	diversion	78,745	83,224	49,734	46,971	58,714
	Return flow	61,871	65,391	39,077	36,906	46,132
	Net diversion					

* Only 48% of these values belong to the Oldman River Sub-Basin

** Only 40% of these values belong to the Oldman River Sub-Basin

Notes: Except for United and Western Irrigation Districts, all data were obtained from Nitschelm (2010). Gross diversions for those two irrigation districts were taken from AARD (2009, pp. 10). Return flows for United Irrigation District were estimated using the ratio of gross and return flows of St. Mary's Irrigation District. Return flows for Western Irrigation District were estimated using the 1997-2000 average return flow of 56% (IWMSC, 2002a, p.79).

Table 2. Net Diversions of Water for the Oldman River Sub-Basin, 2004-2008

Year	Amount in dam^3
2004	573,941
2005	393,337
2006	542,554
2007	504,285
2008	591,643

Table 3. Biomass and Revenues for the Oldman River Sub-Basin, 2004-2008

Year	Biomass of irrigated crops (Mt)	Gross revenues of irrigated crops (M $)	Net revenues of irrigated crops (M$)	Net revenues of dryland crops (M$)	Incremental revenues (M$)
	(1)	(2)	(3)	(4)	(5)
2004	3,134,680	281.25	140.24	32.58	107.65
2005	3,207,185	279.43	134.69	15.77	118.92
2006	3,283,402	284.50	127.41	13.32	114.08
2007	3,230,662	310.01	128.59	26.74	101.85
2008	2,916,678	369.75	157.09	52.46	104.63

Source: Compiled from Yan et al. (2010), various tables.
Note: Mt = metric tonnes; M$ = Million Canadian dollars

Table 4. Water Use Technical Efficiency (WUTE) and Water Use Economic Efficiency (WUEE) for the Oldman River Sub-Basin, 2004-2008

Year	WUTE (Mt/dam^3)	WUEE (Gross) ($\$/dam^3$)	WUEE (Net) ($\$/dam^3$)	WUEE (Incremental) ($\$/dam^3$)
2004	5.462	490.03	244.34	187.57
2005	8.154	710.41	342.43	302.33
2006	6.052	524.36	234.83	210.27
2007	6.406	614.75	255.00	201.96
2008	4.930	624.96	265.52	176.85
Mean	6.201	592.91	268.42	215.80
Std. dev.	1.229	87.455	42.937	50.060

Note: Mt = metric tonnes; $ = Canadian dollars; dam^3 = cubic decametres