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Efficiency measures for water management

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Abstract

New Zealand's national and regional water policies aim to improve the efficiency of water use and water allocation. These policies classify water efficiencies (and some aims) as: economic (improved economic outcomes); technical (larger water use as a fraction of water taken from the source); and dynamic (movement of water allocation between users). However, efficiency measures, fundamental to the implementation of water efficiency policies, are rarely used for water management in this country.

Efficiency measures developed from a longitudinal survey of groundwater use, land use and agricultural production in the Lower Confined Aquifer (LCA) zone, Tasman District, in the period 2004/05 to 2007/08 were relevant to water efficiency policy aims. For example, the LCA economic efficiency measure (annual revenue from production divided by annual groundwater use) increased from 4.8 $/m^3 to 16.8 $/m^3 showing improved economic outcomes from water use principally with the conversion of most dairy land to higher-revenue land uses. In addition, LCA allocation efficiency (groundwater use divided by groundwater allocation) for dairy land use increased from 14% to 31% with this conversion.

Uptake of efficiency measures for water management is potentially impeded by the relative complexity of efficiency monitoring and privacy requirements of the productive sector. Future research to reduce these barriers is recommended, with the design and testing of a set of measures that link the needs of water managers (within central and regional government) with those of water users.

Keywords

water use efficiency, efficiency measures, water allocation, Lower Confined Aquifer, Waimea Plains

Introduction

New Zealand's waterways and aquifers are crucial national resources because they provide water for drinking, they underpin the productive sector, and they are integral to the natural environment. Water is crucial to all productive sectors in this country. Consumptive water uses, and approximate rates of use, include drinking water (23 m^3/s, equivalent annual), industry (31 m^3/s), and agriculture (121 m^3/s), (Rajanayaka *et al.*, 2010). Non-consumptive water uses include hydropower, providing approximately 60% of New Zealand's electricity generation (Ministry of Business, Innovation and Employment, 2017) from a water flow of least approximately 4900 m^3/s[1]. Water is also essential to *in situ* uses, such as recreation, amenity (including the quality of urban environments) and social development

1 Estimated water use by 20 power stations in the five major hydropower systems (Waikato, Tongariro, Waitaki, Clutha and Manapouri, that together represent approximately 87% of New Zealand's installed hydroelectric capacity) using published estimates of river flow, flow capacity of canals, assumed utilisation, and power station outflow (e.g., Woods, 2010; Environment Southland and Te Ao Marama Inc., 2011).

(White, 2001; White and Sharp, 2002; White *et al.*, 2016; Green, 2003).

The efficiency of water use is important to the productive sector where efficiency measures, as defined by formulae and units, are commonly applied. Domestic water use efficiency in Tauranga City improved from approximately 750 L/person/day to approximately 500 L/person/day between 1998 and 2008, respectively, due to actions including universal water metering, universal water charging and an education programme (Smith and McDonald, 2009). Efficiency ratings commonly apply to some domestic appliances, e.g., a six-star rating is awarded to full-flush toilet cisterns that operate at no more than 4.7 L/flush (Standards Australia/ Standards New Zealand, 2016). Irrigators have 'a major responsibility for making best use of a limited water supply by reducing water losses and increasing irrigation efficiency' (McIndoe, 2011). 'Water-to-wire efficiency' of power production at the Manapouri power station improved annual generation by 12% with a second tailrace tunnel that increased the hydraulic head at turbines (Pott, 2006).

Water efficiency is an aim of national and regional water management legislation, such as the National Policy Statement for Freshwater Management (NPS-FM; Ministry for the Environment, 2014a, 2014b) and the Tasman Resource Management Plan (TRMP; Tasman District Council, 2014). For example, water allocation efficiency and water use efficiency are objectives of the NPS-FM (Objective B3) and of the TRMP (Policy 30.1.3.22). However, the use of efficiency measures, by water managers, is in its infancy in New Zealand. Typically, water management policies lack a scientific definition of efficiency, as demonstrated by the NPS-FM itself: 'measures of both efficient use and efficient allocation are needed to ensure these are being delivered' (Ministry for the Environment, 2014b). In addition, no published studies demonstrate the application of water efficiency measures to water management in the context of New Zealand water policies.

This paper aims to contribute to the development and application of efficiency measures for water management in New Zealand. Firstly, the paper summarises the principles of efficiency measurement with some water-related applications. Then, measures relevant to water management are developed and demonstrated using

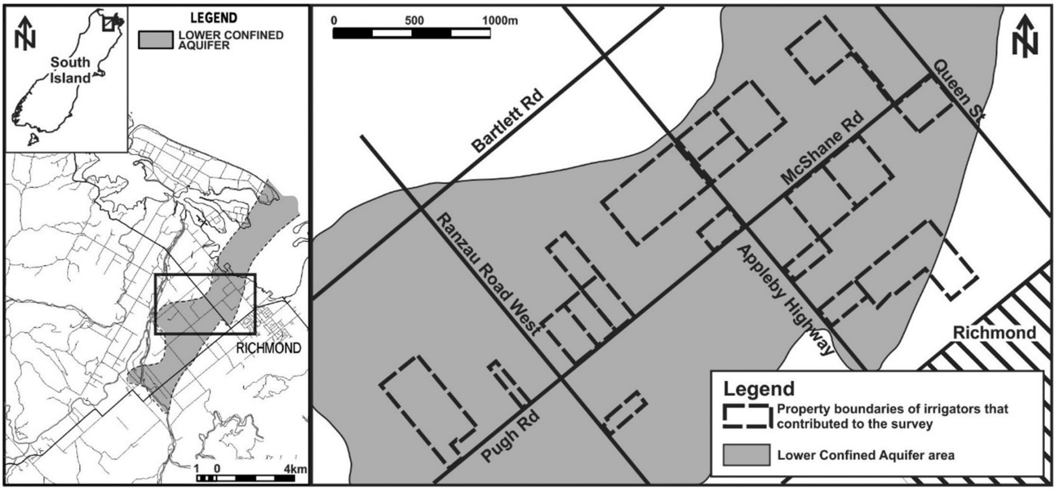

Figure 1 – Location of the LCA zone and irrigators in the LCA study (after White, 2011).

data recorded by a longitudinal survey of irrigators that take groundwater from the Lower Confined Aquifer (LCA) located on the Waimea Plains, Tasman District (Fig. 1). Finally, the Discussion considers how measures address efficiency objectives in the NPS-FM and the TRMP, summarises some barriers to the implementation of water efficiency measures, and suggests potential future directions in water efficiency monitoring and research.

Efficiency measures: principles and examples

Efficiency is commonly defined as the ratio of useful output (O) to consumed resources, or inputs (I):

$$E = O/I \quad (1)$$

The ratio may be represented as a percentage where the units of O and I are the same and as a percentage of an 'ideal', e.g., an engine is 100% efficient where the work done and energy consumption (both measured in joules) are equal. Typically, a larger value of E denotes a higher efficiency.

Water efficiency measures are many and varied because a wide range of outputs depend on water, including municipal water supply, agricultural production and hydro-electric power production.

Water supply efficiency (WSE) by municipalities is:

$$WSE = W_S/W_P \quad (2)$$

Where W_S is water provided to the customer, and W_P is water production, by the municipality. The difference between W_P and W_S is 'unaccounted', e.g., leaks (water lost through the distribution system), theft, flow-data uncertainty and fire-fighting (Green, 2003).

Agricultural irrigation water use efficiency measures are 'usually related to providing monitoring and feedback to achieve effective and productive irrigation systems' (McIndoe, 2011), e.g., field application efficiency (FAE):

$$FAE = W_c/W_d \quad (3)$$

Where W_c is water up-take by crops and W_d is water delivered to the irrigation field.

The efficiency of energy generation by hydro-electric power systems (HPE) would be 100% when $P_A = P_T$, as:

$$HPE = P_A/P_T \quad (4)$$

Where P_A is the actual power generated and P_T is the theoretical power generation provided by hydraulic head and water flow (Odeh, 1999).

LCA water efficiency measures

Tasman District Council (TDC) is responsible for issuing resource consents for the abstraction and use of groundwater in the LCA zone. Each resource consent specifies a weekly allocation, which may be reduced by TDC during times of environmental stress such as very low flow in the Waimea River (Tasman District Council, 2014) (referred to henceforth as the allocation-reduction regime).

A practical set of water efficiency measures ('LCA measures') was derived from a longitudinal survey of groundwater use and land use in the LCA zone (White, 2011). The survey included most properties, irrigators and irrigation in the zone; 17 of the 21 LCA groundwater consent holders contributed to the survey with annual questionnaires in the five-year period between 2003/04 and 2007/08. Weekly groundwater pumping was recorded by growers during the irrigation season (within the interval October to May) and these records were obtained from TDC. Little, or no, irrigation occurred outside the season.

Property owners supplied statistics for land use (irrigated and dryland) and production (i.e., type, output, revenue, production costs and product prices). The four main economic activities of these owners were: dairy, apples, horticulture-other (various crops other than apples) and market gardening (various crops). Land occupation changed significantly during the survey and new occupiers were included in the study (White, 2011).

LCA measures were calculated for a subset of groundwater irrigators ('selected properties') where survey statistics could be reasonably attributed to each economic activity, i.e., the main economic activity occupied 75%, or more, of the total irrigated area in each property. The measures were calculated for the study period 2004/05 to 2007/08; statistics from the first year of the LCA survey, 2003/04, were not included because all four economic activities were not represented by the selected properties in that year. Seven selected properties in 2004/05 occupied a total land area of approximately 172 ha, which was most of the land in the LCA zone. Of these, one apple orchard ceased operation in 2005/06; thus six selected properties continued in the study.

Three types of water efficiency measures were defined (i.e., economic, technical and dynamic) following the NPS-FM (Ministry for the Environment, 2014a). The measures were expressed as annual values because the LCA survey recorded annual data. LCA measures were defined so that 'bigger is better', i.e., larger efficiency values mean 'better' outcomes.

The economic efficiency (EE, with unit $\$/m^3$) of LCA irrigation was:

$$EE = V/WU \quad (5)$$

Where V represents revenue from production (with units of \$/year). Groundwater use (WU, m^3/year) assumed (reasonably) that irrigation was zero outside the irrigation season.

Two technical efficiency measures were irrigation efficiency (TE1, ha/m^3) and production efficiency (TE2, output/m^3):

$$TE1 = IA/WU \quad (6)$$

$$TE2 = P/WU \quad (7)$$

Where: IA is irrigated land area (ha/year) and P is agricultural production (output/year); units of output were product-specific, e.g., the units of milk-solid production were kg/year.

Dynamic allocation efficiency was assessed by allocation availability (DE1, %), allocation efficiency (DE2, %) and areal-allocation efficiency (DE3, ha/m^3):

$$DE1 = GAR/GAA \quad (8)$$

$$DE2 = WU/GAR \quad (9)$$

$$DE3 = IA/GAR \quad (10)$$

Where: GAA is groundwater allocation (m^3/year); GAR is available water allocation, i.e., allocation following the application of TDC's allocation-reduction regime (m^3/year); WU is groundwater use (m^3/year, as above); and IA is irrigated area (ha/year, as above).

GAA was annualised by multiplying weekly consented allocation to irrigators (m^3/week) by 52 weeks/year. GAR was annualised by calculating weekly allocation after application of the allocation-reduction regime. The regime applied a step-wise reduction of consented allocation; steps 1, 2, 3 and 4 reduce allocation to 80%, 65%, 50% and 30%, respectively, of the weekly consented rate (Tasman District Council, 2014). Application of the regime was recorded in the study period by TDC (J. Thomas, pers. comm.).

Results

Conversion of dairy land to horticulture-other and market gardening was the predominant land use trend in the LCA during the study period (Table 1). This conversion was driven

Table 1 – Revenue (V), irrigated area (IA) and groundwater use (WU) of the selected properties by economic activity.

Economic activity	Item	2004/05	2005/06	2006/07	2007/08
Dairy	V ($M/year)	0.6	0.6	0.2	0.4
	IA (ha)	92	88	23	20
	WU (000 m^3/year)	224	199	45	58
Apples	V ($M/year)	0.9	0.9	1	1
	IA (ha)	37	21	22	33
	WU (000 m^3/year)	122	73	78	134
Horticulture-other	V ($M/year)	0.1	0.5	2	4.2
	IA (ha)	17	17	32	53
	WU (000 m^3/year)	22	36	70	137
Market garden	V ($M/year)	0.2	0.3	0.8	1.1
	IA (ha)	4	4	41	41
	WU (000 m^3/year)	6	2	84	69
All selected properties (aggregated)	V ($M/year)	1.8	2.3	4	6.7
	IA (ha)	150	130	118	147
	WU (000 m^3/year)	374	310	277	398

by economics (White, 2011) as approximately 72 ha of relatively low-revenue dairy land (average annual revenue of approximately $10,500/ha) was largely replaced by high-revenue land use (i.e., horticulture-other and market gardening with average annual revenues of approximately $44,300/ha and $42,800/ha, respectively; derived from Table 1).

LCA measures demonstrated features and trends in land use, water use and production. Note that the efficiency measures for market gardening in 2004/05 and 2005/06 were not considered in the following summary of trends because irrigated area was very low (4 ha) for this land use in these years. Aggregated EE showed a large increase over the study period (Table 2), principally due to the conversion

Table 2 – Economic efficiency (EE) of the selected properties by economic activity.

Economic activity	EE ($/$m^3$)			
	2004/05	2005/06	2006/07	2007/08
Dairy	2.7	3.0	4.4	6.9
Apple	7.4	12.3	12.8	7.5
Horticulture-other	4.5	13.9	28.6	30.7
Market gardening	33.3	150	9.5	15.9
All selected properties (aggregated)	4.8	7.4	14.4	16.8

Table 3 – Irrigation efficiency (TE1) of the selected properties by economic activity.

Economic activity	TE1 (ha/000 m^3)			
	2004/05	2005/06	2006/07	2007/08
Dairy	0.41	0.44	0.51	0.34
Apple	0.30	0.29	0.28	0.25
Horticulture-other	0.77	0.47	0.46	0.39
Market gardening	0.67	2.00	0.49	0.59
All selected properties (aggregated)	0.40	0.42	0.43	0.37

Table 4 – Production efficiency (TE2) of selected apple orchards.

Item	2004/05	2005/06	2006/07	2007/08
Apple production (tray-carton equivalent, TCE)	70,000	57,000	59,000	51,000
TE2, aggregated (TCE/m^3)	0.6	0.8	0.8	0.4

of dairy land. EE increased significantly for dairy which was partly due to trends in product price, e.g., the milk-solid price increased by approximately 80% between 2006/07 and 2007/08 (White, 2011).

Horticulture-other and market gardening typically had higher irrigation efficiency, by the TE1 measure, than dairy and apples (Table 3). Apple production efficiency (TE2) increased in 2005/06 (Table 4) as growers reduced the land area of orchards with the removal of poor-producing blocks of trees and closure of one orchard (White, 2011). Irrigation of new apple plantings resulted in low TE2 in 2007/08.

The allocation-reduction regime was sparingly applied as demonstrated by DE1 that was typically at, or close to, 100% (Table 5). Therefore, most of the total allocation (GAA) was available for irrigation. Use of allocation was relatively modest as aggregated DE2 was less than 17% (Table 6) which is partly explained by the annualisation of DE2 (see Discussion). Dairy allocation became more efficient over time, with an approximate doubling of DE2 and DE3 over the study period (Table 6 and Table 7, respectively). By these measures, dairy efficiency exceeded most other economic activities in the period 2005/06 to 2007/08.

Table 5 – Allocation availability (DE1) for the selected properties.

Allocation-reduction regime step	Fraction of GAA (%)	Operation of the allocation-reduction regime (weeks)			
		2004/05	2005/06	2006/07	2007/08
Step 1	80	0	13.1	6.9	3.4
Step 2	65	0	1	0.4	0
Step 3	50	0	0	0	0
Step 4	30	0	0	0	0
DE1, aggregated (%)		100	93	97	99

Table 6 – Allocation efficiency (DE2) of the selected properties by economic activity.

Economic activity	DE2 (%)			
	2004/05	2005/06	2006/07	2007/08
Dairy	14	24	24	31
Apple	14	10	10	17
Horticulture-other	12	21	8	16
Market gardening	9	4	11	11
All selected properties (aggregated)	14	17	11	16

Table 7 – Areal-allocation efficiency (DE3) of selected properties by economic activity.

Economic activity	DE3 (ha/000 m^3)			
	2004/05	2005/06	2006/07	2007/08
Dairy	0.06	0.10	0.12	0.11
Apples	0.04	0.03	0.03	0.04
Horticulture-other	0.09	0.10	0.04	0.06
Market garden	0.05	0.06	0.05	0.07
All selected properties (aggregated)	0.06	0.07	0.05	0.06

Discussion

LCA measures and efficiency objectives in water management legislation

Efficient allocation and efficient use

National water policy objectives include to 'improve and maximise the efficient allocation and efficient use of water' (Ministry for the Environment, 2014a; Objective B3). LCA measures of dynamic allocation provide useful information on the state and trends of allocation. The high values of the allocation availability measure (DE1) indicate most allocation was available for use because the allocation-reduction regime was little-used in the study period (Table 5). Existing allocation was sufficient to support irrigation during the study period because allocation efficiency (DE2) was much less than 100% for all land uses (Table 6). Alternatively, seasonal allocation could be used to calculate DE2. For example, 'seasonal' DE2 was 58% for dairy in 2007/08 indicating that allocation was not substantially greater than use. Allocation efficiency by dairy increased considerably (i.e., DE2 and DE3; Table 6 and Table 7, respectively), due to the 'movement' of allocation to higher-revenue land uses.

As well as demonstrating water allocation efficiency, the LCA measures are relevant to economic and technical water use efficiency. The EE measure showed how the economic efficiency of water use improved with the conversion of dairy land (Table 2). TE1, aggregated for all selected properties, was similar through the period (Table 3).

Water use efficiency measures can be relevant to the productive sector and to water managers. For example, TE2 (Table 4) could be used by apple orchardists as a sector benchmark to improve business practice and by water managers for water-use planning.

Promotion of water use efficiency during the LCA study is consistent with Tasman District Council (2014) Policy 30.1.3.22di:

'…provision of information… to water users about how to reduce water use.' Each irrigator in the LCA survey received an annual report that included their efficiency measures and a summary of measures aggregated by their sector. Growers used these reports to compare their water use with best-practice water use. Growers were enthusiastic to compare EE across economic activities as demonstrated by the attention given to one landowner (a market gardener) with consistently large values of EE. The grower was not identified, to other growers or by this paper, because of his request for privacy in relation to his (legal) crop type. Dairy farmers were happy to see that their efficiency (i.e., TE1, DE2 and DE3) was mostly higher than that of apple orchardists because this result is generally counter to the public's understanding of water consumption by the dairy sector.

Movement of water allocation and water use

The transfer of allocation and use across economic activities is implicit in the aims of efficiency policy, i.e., 'to enable optimum economic outcomes (e.g., allocating water to the uses which have the highest value to society…)' (Ministry for the Environment, 2014b) and "water to be used for the highest social or economic values" (Tasman District Council, 2014, Policy 30.1.3.22b). The movement of water allocation and water use to higher economic values is demonstrated by the large increases in EE over time. However, it is notable that LCA agricultural land did not convert into land with the 'highest' economic value, which is urban (White, 2011), possibly because the TRMP Objective 6.2.2 (which aims for 'urban growth that avoids or mitigates the loss of land of high productive value') can restrict the conversion of farm land to urban use.

Tasman District Council (2014, Policy 30.1.3.22bii) aims to encourage the transfer of permits within the same water management zone. LCA measures (DE2 and DE3, Table 6 and Table 7, respectively) are suitable to address this policy because they track the movement of groundwater allocation, between economic activities and irrigators, over time. However, LCA allocation was 'static' in the study period, i.e., the ownership of allocation did not change and consent holders retained their rights to water. Static allocation was possibly due to land leasing or to the value of the consent. Leasing was the predominant mechanism of land use change (White, 2011) and does not involve transfers of freehold title. The value of the consent is large in the Waimea Plains (e.g., the average value of Waimea Plains irrigation consents was $212,000, or 28% of the consent holders' property values, in 1999; White *et al.*, 2001) and irrigators may wish to preserve this value.

Drivers of water use

The TRMP aims to promote water efficiency research, e.g., with 'investigations into what economic decisions affect water use and how these may be managed to improve water use and water allocation efficiency' (Tasman District Council, 2014, Policy 30.1.20.4i). The LCA study is consistent with this policy as it shows the impacts of economics on cultivation and irrigation (White, 2011). LCA measures vary over time, responding to the drivers of water use including crop type, as demonstrated by the conversion of dairy land, and farming practices exhibited by apple orchards in response to apple prices.

Efficiency measures: benefits and barriers to implementation

Benefits of efficiency measures to water resources, identified by water managers (TDC and Marlborough District Council), include provision of water and land information, such as measured in the LCA survey, that will be valuable for statutory reviews of water policy. The information is also relevant to addressing 'under-utilisation' of water, as consent holders retain their allocation for non-productive purposes, or 'over-use' of water, where sustainable limits are exceeded.

In practice, the application of efficiency measures by water managers is uncommon in New Zealand. Barriers to their application may include: the lack of efficiency targets in national, and regional, policies; the relative complexity of efficiency monitoring compared with current water-use monitoring; requirements for data privacy; and the general lack of focus on water economics (e.g., resource economics and production economics) by water policy-making organisations.

Multiple efficiency targets for producers could contribute to the uptake of efficiency-related policies and sustainable management of the water resource. For example, dual efficiency targets (e.g., EE and TE1) will cause irrigators to improve water-use efficiency by balancing two outputs (V and IA) and one input (WU). In contrast, single efficiency targets may provide perverse incentives to waste water, e.g., a TE1 target, without an EE target, may encourage consent holders to pump water, but not produce efficiently, as they seek to retain the value of their water consent. Efficiency monitoring requires a wide variety of data, as demonstrated by the LCA survey, and is therefore more complex than water-use monitoring (solely) that is typically required by current consents (e.g., Glubb and Durney, 2014). In addition, long-term monitoring may be required to assess variable water requirements through the life cycles of crops. Efficiency monitoring may not place an undue burden on the productive sector because landowners commonly collect efficiency-related data as part of their business.

Protection of individual privacy will be required by efficiency monitoring because some measures are developed from commercially-sensitive information. The reporting of efficiency measures will benefit from an understanding, by water managers, of economics as related to the water resource and to production (e.g., White *et al.*, 2001; White, 2011).

Further research

Further research is required on the barriers to the implementation of water efficiency measures. Research could build on the LCA measures described in this paper to design and test measures that link the efficiency needs of water managers (within national and regional government) to those of the productive sector and *in situ* users. Upskilling water managers and consent holders should be part of the research, particularly improving understanding of water-economics techniques (e.g. White *et al.*, 2001) as related to the analysis of policy and productive-sector behaviours. The development of *in situ* measures will be particularly challenging because data collection typically requires field-based surveys that are relatively complex to design (e.g., White *et al.*, 2001) and are relatively expensive to conduct on an on-going basis.

Conclusions

Efficiency measures are relevant to water management in New Zealand because water allocation and use efficiency objectives are part of national and regional water legislation such as the NPS-FM and Tasman District's TRMP. However, measures are rarely applied to water management; they lack scientific definitions, as equations and units, by the NPS-FM and the TRMP and have not been the subject of published studies.

This paper defined LCA efficiency measures that were broadly related to water management, from a longitudinal survey of irrigators in the Lower Confined Aquifer (LCA) zone, Tasman District. The survey recorded annual statistics (including land use, water use, production by type and value, and allocation) from the four main economic activities by agriculture (i.e., dairy, apples, horticulture-other and market gardening) in the study period 2004/05 to 2007/08. For example, economic efficiency (EE) increased significantly over the study period with the conversion of most dairy pasture (i.e., approximately 72 ha) to relatively high-revenue land uses (i.e., horticulture-other and market gardening). The production efficiency (TE2) of apples increased in 2005/06 (Table 4) as growers reduced the land area of orchards with the removal of poor-producing blocks of trees and the closure of one apple orchard (White, 2011).

LCA efficiency measures were relevant to water efficiency objectives of the NPS-FM and the TRMP. Water allocation and water use efficiency objectives were measured by: EE, which varied significantly over time and across the four land uses; TE2, which responded to changes in cultivation practices; and DE2, which showed that existing allocation was sufficient to support irrigation during the study period. Movement of water allocation and water use to higher economic values was demonstrated by LCA measures. Large increases of aggregated EE, and DE2 for dairy, were principally due to the movement of water allocation to relatively high-revenue land uses. The promotion of water use efficiency was addressed during the LCA study by annual efficiency reports that were individualised for each grower. These reports, favourably-received by growers, allowed comparison with best-practice sector efficiency.

Barriers to the uptake of efficiency measures for water management include: extensive data requirements for efficiency monitoring that are certainly greater than current monitoring with its focus on water use; data privacy requirements by the private sector; and the general lack of focus on water economics by water policy-making organisations. Uptake of the measures may be assisted by future research that links the efficiency needs of water managers (within central and region government) and water users; the LCA efficiency measures described in this paper should provide a good basis for this research.

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