# ON-FARM IRRIGATION EFFICIENCIES – ARE THEY WHAT WE BELIEVE AND WHAT ARE THE IMPLICATIONS BEYOND THE FARM GATE?

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## ABSTRACT

Ten on-farm centre pivot irrigation efficiency evaluations were undertaken using the catch can tests. 70% of the pivots had lower than expected uniformities. The average coefficient of uniformity (CU) and distribution uniformity (DU) were 79% and 68% respectively. Issues affecting efficiency results can be remedied through minor changes to the irrigation systems or operational changes to achieve acceptable average CU and DU values of at least 85% and 75% respectively. For example, the measured pressures on 80% of the pivots were below the optimal design pressures. Dealing with some obvious leaks on 25% of the irrigators could improve performance significantly. The paper further analyses the implications of the low efficiencies at farm level and beyond the farm gate level with respect to water allocation and energy use when (i) the systems are left unchanged to operate at low efficiency levels and (ii) when performance improvements are undertaken to achieve acceptable CUs and DUs. The paper demonstrates that even marginal improvements can have a substantial improvement on water use with up to 46% more water becoming available for other users or expanded irrigation depending on consented allocation and the rainfall season. This paper concludes by illustrating that this aspect of water management could, with further policy attention.



## KEYWORDS

**Irrigation Efficiency, Coefficient of Uniformity, Distribution, Water Use**


## 1 INTRODUCTION

As more than 75% of all abstracted water in New Zealand is used for irrigated agriculture, the need for improved on-farm irrigation efficiency has become more important as pressures on existing water sources start to increase. While on-farm efficiencies will impact directly on the farm management, either through compromised production or on the economic viability of the enterprise, they also have wide regional and national implications. Low on-farm efficiencies mean more water is wasted through runoff and deep percolation. Therefore improving the timing, the amount and uniformity of water application will have a positive effect on the irrigation efficiency.

In this paper, the author makes use of data from 10 centre pivot audits carried out at 10 farms, over the last 5 years. The on-farm audits were carried out using the procedures in the Irrigation New Zealand Irrigation Evaluation Code of Practice (Bloomer, 2006). They were carried out on both new (< 1 year) and old (> 1 year) pivots to achieve the following objectives:

- Evaluate the performance of the new irrigators to confirm compliance with performance criteria promised by equipment suppliers; and,
- Evaluate existing pivots to determine the actual performance of the irrigators as a decision tool to make physical or operational improvements on the irrigation system.

In each case this involved determining the application depths and comparing them to the equivalent water supply depths. This data was used to calculate irrigation uniformities and efficiencies. Given that irrigation abstraction is the largest water user in New Zealand, knowledge of this efficiency and uniformity information has the following practical benefits:

- Assessment of the impacts of poor irrigation efficiency at farm level and potential effects beyond the farm; and,
- Provides knowledge on which to base physical or operational improvements to improve the performance.

The main objective of this paper is to collate and analyse the data from the on-farm audits to:

- Highlight the general uniformities and efficiencies for centre pivots;
- Indentify potential water savings;
- Estimate the cost of poor performance; and,
- Provide recommendations for possible improvements and the likely benefits.

# 2 ON-FARM IRRIGATION EFFICIENCIES

## 2.1 IRRIGATION EFFICIENCY - BASIC DEFINITIONS

Irrigation Efficiency (IE) means different things to different water users and there several often conflicting definitions of what it means. It is basically a measure of how the water applied is effectively used. The more common definition of irrigation efficiency is that it is the amount of water used by plants divided by the total amount of water delivered into the system. IE is further broken down into conveyance efficiency and field application efficiency. These terms are best described by Irrigation Australia using Equations 1, 2 and 3 below.

$$\text{Irrigation Efficiency (\%)} = \frac{\text{Crop Water Use}}{\text{Total Inflow into the Supply System}} \quad \ldots\ldots(1)$$

$$\text{Conveyance Efficiency (\%)} = \frac{\text{Total Outflow from the Supply System}}{\text{Total Inflow into the Supply System}} \quad \ldots\ldots(2)$$

$$\text{Field Application Efficiency (\%)} = \frac{\text{Crop Water Use}}{\text{Water Delivered to the Field}} \quad \ldots\ldots(3)$$

Edkins (2006) reports that attainable application efficiencies for centre pivots in New Zealand range from 75 – 90%. Solomon (1988) has reported similar values in the United States.

Painter and Carran (1978) and Painter (2009) define the field application efficiency as the ratio of water applied to the soil surface to the water delivered to the irrigator.

Potential application efficiency (PAE) is the ratio of the average lowest 25% irrigation depths to the average depth of water applied across the field (Equation 4). It includes spray drift and evaporation losses though the objective is to keep these to a minimum.

$$\text{PAE (\%)} = \frac{\text{Average Low Quarter of Water Caught}}{\text{Average Depth of Water Applied}} \quad \ldots\ldots(4)$$

PAE values for well designed and managed centre pivot irrigation sprinkler systems should ideally be in the order of 75 – 90% (Clemmens and Dedrick, 1994).

IE is useful to ascertain the amount of water required for irrigation. However, some of its components, in particular the Field Application Efficiency (FAE) are difficult to measure. For this reason, uniformity measures have been developed to describe or quantify the performance of irrigation systems.

## 2.2 MEASUREMENTS OF UNIFORMITIES

The performance of sprinkler systems is a function of the uniformity of water application. Uniformity is measured as either Christiansen's Uniformity Coefficient (CU) or Distribution Uniformity (DU) and this is measured using catch can tests, (Jensen 1983). The main factors affecting uniformity are intrinsic hydraulic design, sprinkler package and size, operating pressure, wind speed (Keller and Bliesner, 1990; Tarjuelo et al., 1999; Howell, 2001).

### 2.2.1 COEFFICIENT OF UNIFORMITY

Christiansen's Uniformity Coefficient (CU) is an indicator of how equal (or unequal) the application rates are throughout the field (Jensen, 1983; Smith et al., 2002). A low coefficient of uniformity indicates that water is distributed unevenly over the irrigated area. Well designed systems are designed to operate at CU of > 85% (Bos et al., 1991; Smith, et al., 2002). Keller and Bliesner (1990) state that a CU of 84% is desirable. Little et al. (1993) consider a sprinkler irrigation system as very good, good, poor, and worst if CU is ≥ 90%, between 80% and 89%, between 70% and 79%, and < 69%, respectively.

The Christiansen's Uniformity Coefficient is calculated as follows:

$$CU = 100\left[1 - \frac{\sum_n |D_x - \bar{D}|}{\sum_n D_x}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Where:

$\underline{D}_i$ is the catch-can depth of application;
D is the mean catch-can depth; and,
N is the number of catch cans.

This method was further modified by Heermann and Hein (1968) for use with centre pivot catch-can data. The equation was modified to include a term representing the distance from the centre to the catch can, $S_i$. The Heermann-Hein $CU_{HH}$ equation is:

$$CU_{HH} = 100\left(1 - \sum_n S_x \left| D_x - \frac{\sum_n D_x S_x}{\sum_n S_x} \right| \Big/ \sum_n D_x S_x \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(6)$$

The following features of CU, and $CU_{HH}$, are important when interpreting the uniformity values obtained:

- The absolute difference between the measured and mean depth of application results in over- and under-irrigation being treated equally. The deviations are represented by magnitude only and not by whether they represent a deficit or excess of irrigation water; and,
- CU is an average measure and as such compares the average absolute deviation to the mean application. Thus, CU indicates, on average, how uniform the application depths are and does not give an indication of how bad a particular area may be.

### 2.2.2 DISTRIBUTION UNIFORMITY

Distribution Uniformity (DU) is usually defined as a ratio of the smallest accumulated depths in the distribution to the average depths of the whole distribution. DU gives an indication of how evenly the irrigator sprinklers are operating or overlapping. The higher the DU, the more evenly water is being distributed. In a perfect system, DU = 100% and each plant would receive exactly the same amount of water.

DU is affected by pressure variations, sprinkler wear, and, with overlapping systems, the sprinkler position. Higher DUs can be achieved but at a higher design and installation cost. The designer and system owner need to weigh the cost benefit of achieving a higher DU. In most cases therefore, irrigation systems with DUs of 80 – 85% are viewed as a reasonable compromise.

The basic equation for calculating DU is given by:

$$DU = \frac{\text{Average depth of lowest 25\% of cans}}{\text{Average Depth of Water Collected}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

The Irrigation Evaluation Code of Practice recommends the use of the distance adjusted collector catch values to account for the greater proportion of area covered by sprinklers (and collectors) at the outer end of the irrigator. This method has been used in this analysis.

Table 1 below gives the generally accepted (Irrigation Evaluation Code of Practice (Bloomer, 2006)) interpretations of DU.

**Table 1 – Interpretation of Distribution Uniformity for a centre pivot irrigator**

| Result | Perfect | Excellent | Good | Fair | Poor |
|---|---|---|---|---|---|
| DU | 100 | 99 – 92 | 89 – 85 | 84 – 75 | < 74 |

## 2.3 THE RELATIONSHIP BETWEEN CU, DU AND PAE

DU values are lower than the CU values for the same set of data. According to Keller and Bleisner (1990) a sprinkler irrigation system with a normal distribution and a CU > 70%, the relationship between CU and DU is expressed by the Equation 8.

CU = 100 - 0.63 (100 - DU)………………………………………………………………………..(8)

The difference between the denominators of DU and PAE is the amount of surface losses i.e. evaporation, runoff and wind drift (Burt et al., 1997). The relationship between the two parameters is represented in Equation 9 below.

PAE = DU x (100 - % Surface Losses)…………………………………………………………...(9)

Most irrigation designs and irrigation extension advice advocate applying enough water (gross application depth) in the drier areas of the field to meet the target or net application depth. Unfortunately, this results in an overwatering of the areas receiving a minimum of their normal depths. The conversion from net depth to gross depth is derived by dividing the former by the field application depth. DU is often used as an acceptable proxy for the PAE and hence the field application depth.

## 2.4 METHOD AND MATERIALS

### 2.4.1 EVALUATION STANDARDS

A number of guidelines are available for evaluating the performance of sprinkler systems. These include:

- ISO standards (a) ISO 15886-3:2004 - Procedure for sprinkler distribution testing for research purposes (ISO, 2004);
- ISO 8224-2:1991 - Procedure for Travelling Irrigator testing and performance recording (ISO, 1991); and,
- ISO 11545:2001(E) – Test procedures for determining the uniformity of water distribution of centre pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles (ISO, 2001).

In New Zealand, the Ministry of Agriculture in collaboration with Irrigation New Zealand has funded a project to develop guidelines for evaluating the performance of different irrigation systems. The result from this work is the Irrigation Evaluation Code of Practice (Bloomer, 2006).

### 2.4.2 PIVOT EVALUATIONS

Data was collected for 10 different pivots from 10 different farms across Canterbury over a period of 5 years. The evaluations were carried using the methods and techniques encouraged in the Irrigation Evaluation Code of Practice (CoP).

At each site visual evaluations were carried out to assess the condition of the site. These evaluations looked at the crop type, ground evaluation, surface water ponding and runoff, wheel rutting, sprinkler packages, sprinkler dropper heights and system leakages which were compared with the design sprinkler charts.

Quantitative data collected included travel speeds (at 2/3rd the pivot length and the end of each pivot), pressure readings along the lengths of the irrigators, flow measurements at the headworks and wind speeds and air temperatures on the day. On a number of occasions evaluations were aborted part way through, to be undertaken on a different day, because of rain and/or wind.

Examples of the visual observations (a leak and wheel rutting) and quantitative measurements (pressure readings and speed measurements) are shown in Figures 1, 2 and 3 below.

*Figure 1: Example of Visual Observations*

*Figure 2: Pivot Pressure Measurement*

Catch-can tests were used to evaluate the performance of the irrigators using the methodology set out in the Irrigation Evaluation Code of Practice (Bloomer, 2006). Two rows of cans were set out under each pivot. Cans were laid out under the last 80% of each pivot and beyond the length of the pivot as far as the end guns could throw. The inline distance between the cans was 10 m. The distance between the rows was approximately 10 m.

As a control, two cans were filled with water moments before the first line of cans started collecting. The change in water level from the time test began to the finish was measured. Generally, there was no noticeable change and this was attributed to the low temperatures and cloudy conditions during the period the tests were conducted.

The pivots were run with timer setting set at the normal operating setting for the irrigator. As soon as the pivot cleared the catch can lines, the collected volumes were immediately measured, noting the distance of each can from the pivot point.

Photographs of one of the evaluations are provided in Figure 3 below.

*Figure 3 Layout of Catch-cans*

**Figure 3a. –** Pivot run before getting to the cans

**Figure 3b –** Cans laid out from the end of Tower 1

**Figure 3c. –** Pivot has walked past the cans

**Figure 3d. –** Speed Measurements

**Figure 3e.** – Ponding observed in places

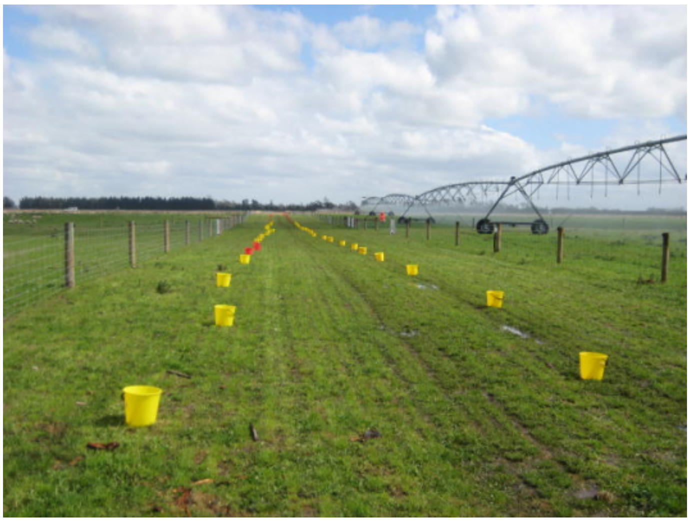


**Figure 3f.** – Volume measurements started from the end of the pivot

## 2.5 RESULTS AND DISCUSSION

Table 2 shows that 50% of the irrigation systems had DUs greater than or equal to 74% (i.e. their performances were fair or better) and 50% had DUs below 74%. This means 50% of the pivots had poor distribution uniformities. This indicates that 50% of the irrigated areas receive less than the target irrigation depth.

Using the grading system of Little et al. (1993), outlined earlier, 20% of the pivots had very good CUs, 50% had good CUs and the remaining 30% either poor or worst. The CU ranged from 63% to 90% with a mean CU of 79% which is poor.

*Table 2: Summary of the Audit Results*

| Parameter/Pivot No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Mean |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Pivot Length (m) | 425 | 620 | 516 | 792 | 400 | 456 | 584 | 548 | 725 | 492 | |
| Age of System (years) | < 1 | 2 | 6 | 5 | <1 | 3 | 5 | 3 | 7 | < 1 | |
| CU (%) | 63 | 80 | 84 | 64 | 92 | 82 | 84 | 81 | 77 | 90 | 79 |
| DU (%) | 41 | 75 | 76 | 55 | 85 | 74 | 68 | 70 | 57 | 82 | 68 |
| Application Eff. (%) | 63 | 84 | 85 | 72 | 91 | 84 | 80 | 81 | 73 | 89 | 80 |
| PAE[1] (%) | 39 | 71 | 72 | 52 | 81 | 70 | 65 | 67 | 54 | 78 | 65 |
| Irrigation NZ DU Classification | Poor | Fair | Fair | Poor | Good | Fair | Poor | Poor | Poor | Fair | Poor |

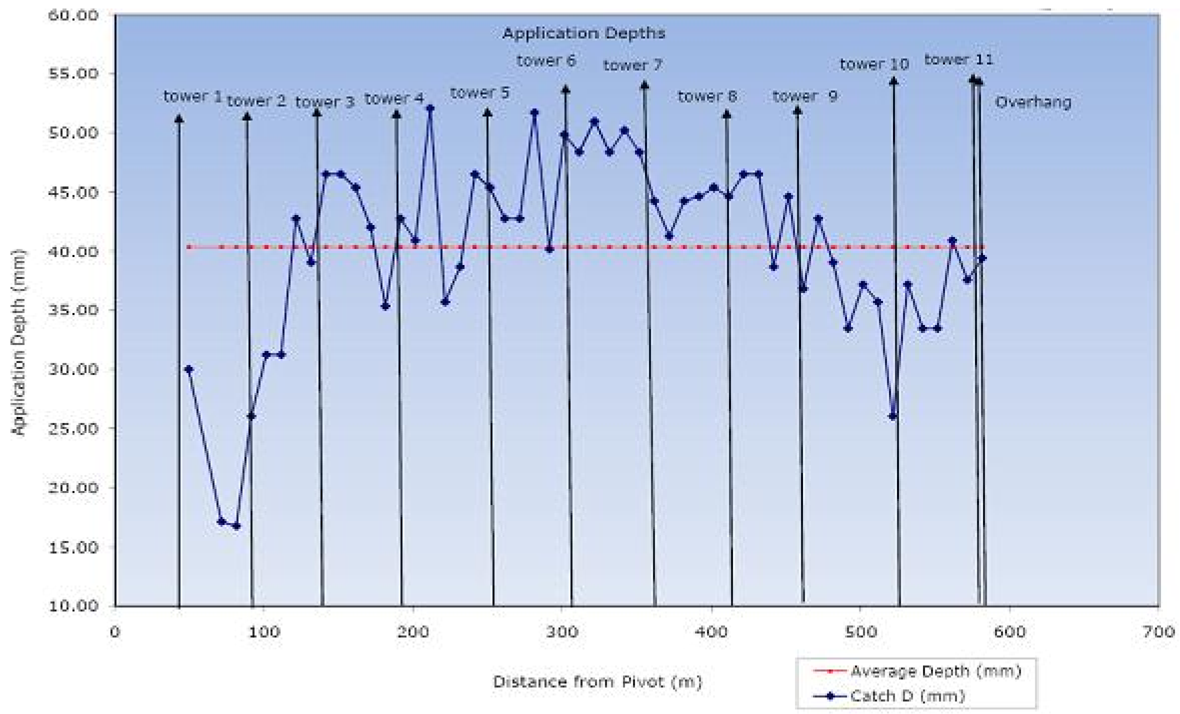
*1- Losses have been assumed to be 5%.*

Clearly, the average performance of the systems is below the expected values as defined in the CoP or by international studies by Pitt et al. (1996) who reported that 80% of the 385 evaluations they carried out resulted in recommendations for improvements.

The application efficiency data look good and ranges from 63 – 91% with 70% of the values greater than 75%. Therefore, relying on the application efficiency alone gives the impression that general performance is above average. It was also clear that well maintained and operated irrigation systems had the highest efficiencies irrespective of age.

For each assessment the data was graphed to give a visual of the peaks and troughs along the length of the pivot. Figure 4 below presents the data taken for one of the catch-can rows under Pivot 7. Visual representation is important for irrigators and assessors as they can walk the pivot to check for causes of the peaks and troughs. For example, the low application rate on Tower 2 was due to blockages which could easily be rectified.

*Figure 4 Water Distribution Along the Length of Pivot 7*




The low uniformity values at various sites could be attributed to specific factors. For example:

- Poor installation at Pivot 1 where the installed sprinkler package was different to the design sprinkler package;
- Pivot 1 sprinklers were blocked by PVC shavings left over from the installation of the mainline implying that the system had not been adequately flushed;
- The operating pressures along the lengths of 80% of the pivots were 20 – 30% below the design pressures;
- Pivot 9 had some leaking joints where the rubber boots had become worn out;
- Inconsistent dropper lengths;
- Worn out rubber boots between towers causing some leaking;
- Sand traps not tightly sealing; and,
- Poor end gun pressure.

For all the tests wind speeds were low ranging from 0 – 8 km/hr. The air temperature ranged from 12 – 19 $^0$C and under overcast conditions for 90% of the evaluations. Jensen (1983) discussed the effects of wind on evaluations and states that CUs from 70 to 75% were possible at wind speeds of approximately 16 km/h. Bell (1991) reported adequate distribution from wind speeds up to 10 to 15 km/h. Therefore, the effect of wind speeds on the low uniformities measured is minimal, leading to the conclusion that the factors listed above were the main cause of the low CUs and DUs.

While there are a number of factors that contribute to the low uniformities, sprinkler pressure was the main cause of low uniformity of distribution and poor installation was the second major cause.

Definite and practical recommendations to improve the performance of each pivot were documented and provided to the irrigators. 60% of the irrigators have since taken steps to fix the identified issues.

One (Pivot 7) of the six pivots that have been fixed was retested. The primary change made was retrofitting a new sprinkler package. Some seals and gaskets at some joints along the pivot were also replaced. The Nelson Sprays were replaced by Nelson Rotators sized for the design flows and pressures. This reduced the flow and consequently the frictional losses resulting in near perfect pressures along the length of the pivot. As expected the DU increased from 68% to 84%.

Table 3 below shows the effect of the change in DU. Assuming water is not a limiting factor and the target irrigation depth remains constant, water savings of 19% could be achieved. Table 3 also shows the water savings that could be achieved if the other 50% of systems with poor DUs were repaired to achieve DUs of 75% (fair). Systems with DUs > 75% were not to be changed.

*Table 3: Performance Improvements*

| Pivot/Parameter | Target DU | Audited DU | Changed in DU | Water Savings to be Achieved | Comments |
|---|---|---|---|---|---|
| 1 | 75 | 41 | 34.0 | 45.3% | Install correct sprinklers, remove blockages the cost was \$3,500. Because it was still under warranty cost to the irrigator = \$0 |
| 2 | 75 | 75 | 0.0 | 0.0% | No changes |
| 3 | 76 | 76 | 0.0 | 0.0% | No changes |
| 4 | 75 | 55 | 20.0 | 26.7% | Replace sections of the mainline and adjust pump settings to increase pressure or completely change the pump. Install new nozzles. Cost \$30,000 |
| 5 | 85 | 85 | 0.0 | 0.0% | No changes |
| 6 | 75 | 74 | 1.0 | 1.3% | Adjust pump settings. Cost \$500 |
| 7 | 84 | 68 | 16.0 | 19.0% | New sprinkler package, seals Cost \$4,210 |
| 8 | 75 | 70 | 5.0 | 6.7% | Adjust pump settings. Cost \$500 |
| 9 | 75 | 57 | 18.0 | 24.0% | Fix leaking joints and replace rubber boots. Cost \$2,000. Adjust pump settings to increase pressure |
| 10 | 82 | 82 | 0.0 | 0.0% | No changes |
| Mean | 75 | 68 | 6.7 | 8.9% | |

According to Pitt et al. (1996), irrigators will only implement proposed efficiency changes if the benefits out way the costs. In these audits, the cost of raising the efficiency to at least 75% ranged from \$500 to \$35,000. For most of these systems, these costs are low by comparison with costs involved in technological changes from flood irrigation to spray.

The cost to fix Pivot 7 was \$4,210. The water take consent was 8 years old and did not have annual volume restrictions. In theory, water was not a constraint. However, in reality in some seasons groundwater recharges constrained the availability of sufficient drawdown for the pump to abstract the design flows. Therefore, in seasons when water was not a constraint, the changes meant the volume of water abstracted and power usage could be reduced by more than 19%. In addition to the reduction in flow (from 198 $m^3$/hr to 160 $m^3$/hr), the total pumping head from a 50 m deep bore decreased from 105 m to 101.5 m. The power savings over a 3,000 hour irrigation season is \$10,561 or \$96/ha even with a 2% decrease in pump efficiency under the new pump duty. Therefore, cost of efficiency improvements could potentially be recovered within one irrigation season.

On the other hand, even though the potential water savings that could be achieved by increasing the DU from 55% to 75% under Pivot 4 are approximately 27%, the costs of achieving these gains are considerable. When these were discussed with the irrigator, he was prepared to spend \$2,500 to replace some of the sprinklers that were not consistent with the design sprinkler chart.

Benefits of efficiency improvements go beyond just the power savings discussed above. High uniformities are associated with better crop quality and yield (James, 1993). These economic benefits associated with the changes will shorten the payback period of these changes.

# 3 IMPLICATIONS BEYOND THE FARM GATE

With the water resource reaching full allocation in many parts of the country, implementing effective water management systems will enable the irrigation of a larger area with a limited amount of water. This can be achieved by installing new systems that actually perform with high uniformities. Older systems have to be evaluated to check their uniformities and repaired as necessary.

Many regional water allocation plans now stipulate efficiency targets for irrigation. For example, the Waitaki Regional water Allocation Plan and the Proposed Natural Resources Regional Plan for the Canterbury stipulate target seasonal efficiency values of 80% and water allocation limits are also assessed on that basis. Therefore, uniformities and efficiencies are critical beyond the farm gate.

Table 3 shows that the water savings can be up to 45% for the pivots assessed, with a mean of approximately 9%. The key question that one would ask is what could be done with the saved water? The following two scenarios determine the answer to this question:

- There is enough allocated water to meet the farm's irrigation needs; and,
- The water resource is insufficient to meet all irrigation requirements.

Previous work by Potts ( 2009) on catchment water allocation studies in the Waitaki Catchment and the Morven Glenavy consent application (Brown, 2008) clearly show that farmers will follow one of two paths depending on the adequacy of the available water. When their allocated water is sufficient for crop consumptive uses for the desired level of production they will seek to increase the irrigated area on the farm using the released water. If the water already available is limited, the same water will simply be applied onto that same area to top-up the crop consumptive uses, albeit, more efficiently. In both cases, it is unlikely that the water will be given up for possible use by other irrigators. Only when the farm is fully allocated and fully irrigated will the extra savings be released to others beyond the farm gate.

Table 3 above shows the cost and benefits of undertaking efficiency improvements. These savings may or may not in themselves be sufficient to encourage improvements as demonstrated in the discussion on changes to Pivot 4 and 7. Notwithstanding, changes that bring about large benefits at low cost may find favour with farmers. Collectively these will bring about large benefits beyond the farm gate.

Other factors that have an impact beyond the farm gate are energy use and environmental concerns. Potential water savings were discussed above. These savings translate to energy savings too. The pumping unit for Pivot 7 drew 82.5 kW before and 66.6 kW after the improvements were made. Clearly, such improvements when applied at regional level will have a significant effect on energy use/savings given that irrigation pumping consumes 34% of all energy used on dairy farms (Barber and Pellow, 2005).

There is increasing concern over the effects of irrigation on the environment. The effects of run-off and/or deep percolation and the associated nutrient transport is becoming a major consenting issue. Poor uniformities exacerbate nitrate contamination across catchments as fertilisers and dairy effluent percolate into the aquifers below.

Huffaker et al. (2001) discuss the adverse effects of carrying out uniformity improvements on groundwater recharge and on downstream users where water available is supplied to other users as return flow will no longer be available. Huffaker et al. (2001) consider water savings that affect return flows as false water savings on a regional basis due to their effects on downstream appropriators. The performance improvements discussed in this paper will not cause those adverse effects. The changes of irrigation technology from surface systems to centre pivots are more likely to have this effect. For the changes discussed in this paper, where genuine water savings occur and on-farm water allocation is sufficient for crop needs, it is expected that abstraction for the farm will be reduced. This makes more water available for allocation across a catchment for irrigation and other uses.

# 4 WHERE TO FROM HERE?

This paper has focused on the process of carrying out irrigation audits and discussed the results obtained from 10 centre pivot irrigators. Table 2 showed that performance was affected by the age of irrigators to some extent. There is increasing awareness of the need to apply water efficiently. In Canterbury new consents for large schemes are coming with conditions that require management plans to be put in place and water management strategies. These plans stipulate the need for irrigation audits to be carried out regularly. A combination of improving technology and the workstreams being driven by Irrigation New Zealand to certify designers and installers and to promote minimum design standards will go a long way to ensure that these new systems will perform well. Therefore, some policies focusing specifically on improving efficiencies of older irrigators may promote more water savings. Although these have not been assessed in this paper, technological changes from border-dyke to spray systems and in particular centre pivots will produce exponential water savings but are likely to increase energy use.

The assessed centre pivots discussed in this paper are only a fraction of the total number of irrigation audits that have been carried over the years by other parties. It would be beneficial if all this data could be collated at a central repository, at catchment or regional level, to be used to:

- Collect data on the on-farm performance and operation of irrigation systems;
- Track the water savings from uniformity improvements;
- Study and improve irrigation scheduling strategies;
- Understand and improve crop responses and crop water use efficiencies;
- Develop models for trading water savings or seasonal surplus requirements within catchments; and,
- Develop policies to be used to improve water use and management.

One of the challenges associated with preparing this paper has been to obtain crop production and profitability data as owners of this data, rightly so, consider it to be highly confidential. No doubt other similar studies have suffered from the same challenge. The central repository could also provide a way of collecting this data while maintaining the confidentiality desired by owners of the data. This data would be useful for estimating water use and economic efficiencies and would also be beneficial to irrigators as it will give them benchmarks for their production systems.

# 5 CONCLUSIONS

In this paper irrigation audit results from 10 pivots have been discussed. The large percentages of farms that fall short of the benchmark suggest the problem could be wide spread. Improved irrigation efficiency can lead to lower energy costs, availability of more water, better use of nutrients and more income. The paper also demonstrates that significant changes can be achieved by making minor changes to the existing systems rather than major technological changes or new infrastructure. These changes can be relatively simple and inexpensive. For the type of improvements that are recommended for the systems investigated, for all but Pivot 4, the cost of improvements can be recouped during the first season.

Where water availability is inadequate, for on-farm crop consumptive use, any savings achieved by uniformity improvements will be redistributed within the farm and will not necessarily be available beyond the farm gate. Ideally, the efficiency improvements should benefit the wider community with savings becoming available for use beyond the savers farm gate. Therefore, those tasked with allocating water should create an environment that allows efficient water users to profit from their gains in efficiency.

Due to lack of data, the effect of efficiency on crop yields and economic efficiencies has not been determined. These issues can be studied in more detail if more data was available. A central repository for all efficiency audits would be a good step forward towards understating water use on-farm and beyond the farm gate.

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