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REDUCING NUTRIENT LOSSES THROUGH IMPROVING IRRIGATION EFFICIENCY

John C Bright, Ian McIndoe and KC Birendra

Aqualinc Research Ltd.
PO Box 20462, Bishopdale, Christchurch 8543.
Email: j.bright@aqualinc.co.nz

Abstract

A desk-top study using data from twelve representative dairy farms located in Canterbury with well-established computer models showed that changing irrigation practices to make more efficient use of both irrigation water and summer-time rainfall reduced N-loss to water by between 4% and 58% (average of 27%). These reductions in N-loss to water were achieved without significantly reducing modelled average annual pasture production.

To achieve this degree of N-loss reduction, changes were made to the irrigation rule used to determine when to irrigate and how much water to apply so that the soil is allowed to dry out more in the shoulders of the irrigation season and reduce the risk of rainfall-induced drainage throughout the season. To apply the new rule it is essential that:

- Soil water content is routinely measured using reputable soil moisture monitoring equipment.
- The irrigation application system can be adjusted to apply relatively small amounts of water.
- The irrigation application system has a relatively short return period.
- The irrigation water supply is very reliable.

Introduction

The National Policy Statement for Freshwater Management 2017 (NPS-FM) requires all regional councils and unitary authorities to set limits on all forms of water use to achieve aquatic ecosystem and human health objectives. If current use, or allocations, in aggregate exceed the relevant limit they must be reduced to comply with the limit within a set time frame.

In some catchments, or freshwater management units, water use has already been judged to be over-allocated in terms of total nutrient loss to water. Examples include the Selwyn-Waihora and Hinds Zones in Canterbury.

Farmers in over allocated areas are having to reduce nutrient loss to water by a prescribed percentage of their baseline loss to water. In some areas this is now a regulatory requirement. In other areas voluntary reductions are being encouraged through education, training and commercial or peer pressure.

Nitrate leaching to groundwater is a significant pathway for N-loss to both groundwater and surface water in intensively farmed areas, particularly if they are irrigated.

The objective of this project was to answer the question "how much could N leaching be reduced by increasing irrigation efficiency?" A case study approach was used that involved twelve dairy farms located in Canterbury, all of which are irrigated using centre-pivot irrigators.

What is "irrigation efficiency"?

There are many different definitions for the generic term "irrigation efficiency". For the purposes of this project we assumed it to be "Irrigation application efficiency". This is the ratio of the volume of water retained in the plant root zone, after drainage has ceased, to the volume of water applied to the land surface. Efficiency is calculated for each irrigation event, and typically varies from event to event. When an irrigation application efficiency value is referred to below it refers to the long-run average of the application efficiency's for all irrigation events.

A "rainfall efficiency" can be calculated in the same way.

It should be noted that in NZ drainage from irrigated lands during the irrigation season will always be higher than under non-irrigated conditions, even if the application efficiency is 100% (ie each and every irrigation event generates no drainage). This is because irrigation maintains a higher soil water content during the irrigation season than occurs without irrigation and therefore there is less capacity to store the rainfall that occurs during the irrigation season. If the rainfall amount exceeds this capacity the excess drains, mostly to groundwater. Rainfall efficiency is lowered by irrigation.

Irrigation rule

Irrigation application efficiency depends on when irrigation occurs and how much water is applied and therefore on how irrigation decisions are made.

It was assumed for this project that the process of determining when to irrigate and how much to apply involved:

- Measuring or calculating soil water content each day.
- Applying an irrigation rule.

The irrigation rule is:

1. Irrigate when the soil water content has dropped below the Irrigation Trigger level, providing the number of days since the last irrigation in this paddock is equal to or greater than the return period. The trigger level is usually expressed as a percentage of the capacity of the plant root zone to hold water (the "size of the bucket"). Current practice is to use a trigger level of 50%. The return period for a centre-pivot irrigator is typically 3 to 5 days. For a travelling irrigator it is typically 8 to 12 days.

2. Apply the amount of water needed to raise the soil water content to the Irrigation Target level. The target level is also expressed as a percentage of the "size of the bucket".

If the target level exceeds 100%, irrigation will over-fill "the bucket" and the excess will go to drainage. Sometimes this is unavoidable. A number of travelling irrigators, for example, have a minimum application depth and this can result in the target level being greater than 100%.

Method

Overall Approach

The overall approach to the pilot study was to use well-established computer models to simulate irrigation and drainage, pasture production and finally N-loss to water for each of the case study farms under a wide range of irrigation management scenarios. The models were: IrriCalc (irrigation system simulation model) (Bright, 2009), DairyMod (pasture growth model) (Johnson et al, 2008: Johnson 2013), and Overseer™ (nutrient loss model) (Wheeler et al, 2011). IrriCalc provided irrigation application and drainage outputs as daily time series spanning the period 1/7/1972 to 30/6/2016. The irrigation application depth time series was input to DairyMod, which simulated daily pasture growth over the same time period. This was post processed to provide the average annual pasture production. Coupling these models in this way enabled the effect of irrigation management rules on average annual drainage and average annual pasture production to be quantified. The effect of each irrigation management rule on N-loss to water was assessed using Overseer™. Irrigation management in Overseer™ was set up to exactly match that used with IrriCalc to generate the irrigation application time-series for DairyMod.

There were two main reasons for assessing the effects on pasture production of each irrigation management scenario. First, it provided a means of checking whether (or how much) pasture production is being compromised by the pursuit of higher irrigation efficiency. Second, it provided a means of checking that the average annual pasture production achieved at different levels of irrigation efficiency is consistent with the pasture production data used in the Overseer™ analysis.

Case Study Farms

We aimed to analyse twelve case study farms that were pasture-based farm enterprises located on soil types and in rainfall zones broadly representative of those occurring across the Canterbury Plains. Thus farms were sought that had mean annual rainfalls of between 600mm and 800mm, and root zone plant available water (PAW) capacities of between 60mm and 100mm.

Ravensdown and Ballance Agi-Nutrients supplied twelve candidate dairy farms between them for potential inclusion in this study. Overseer™ files were available through these companies for most of these farms. The combinations of soil PAW class and rainfall zone covered by these farms provide good coverage of most of the Canterbury plains. Some of the very deep soils are not represented, but these tend to be less of an issue regarding leaching losses and there are not very extensive areas of these soils on the Plains.

Irrigation management scenarios

There are two main irrigation management parameters to work with to reduce drainage and improve irrigation application efficiency and rainfall efficiency. These are the irrigation trigger level and the irrigation target level. The irrigation management scenarios we analysed were designed to systematically test a wide range of combinations of trigger level and target level – sufficient to traverse the range from a low irrigation application efficiency of 60%, through what is currently considered to be Good Management Practice to extremely ‘severe’ deficit irrigation rules that minimise drainage but also compromise pasture production.

The selection of irrigation trigger levels to test was guided by their expected effects on the risk of pasture production loss and drainage risk. The three sets of trigger levels we tested are set out in the following table.

Table 1: Irrigation trigger levels used in the irrigation scenario analysis (% of soil water holding capacity)

Description	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**
Minimise production risk (Current practice)	50%	50%	50%	50%	50%	50%	50%	50%
Balance risks	20%	40%	50%	50%	50%	40%	30%	20%
Minimise drainage risk	10%	30%	40%	40%	40%	30%	20%	10%

Current practice is to minimise production risk by setting the irrigation trigger level so that there is a very low risk that pasture would experience sufficient soil moisture stress to reduce production (assuming sufficient irrigation system capacity and a very reliable supply of water). Typically this trigger level is 50% of the PAW. Current practice is to use this value throughout the irrigation season.

The two alternate trigger level regimes aim to reduce the risk of drainage occurring by recognising that in the shoulders of the irrigation season the probability of rainfall is higher than in summer and the evapotranspiration rates are lower. The combined effect of these was expected to be lower risk of pasture production loss, even if the trigger level was set lower than current practice. The 'balance risks' trigger levels are based on Hoffman et al (1990) and attempt to achieve a better balance between the risk of production loss and risk of drainage, compared to current practice. The 'minimise drainage risk' trigger levels are uniformly lower than the 'balance risks' levels and were set at a level that was expected to reduce average annual pasture production.

The irrigation target levels used to create the irrigation management scenarios ranged from 140% down to 55% of PAW. The combination of irrigation trigger at 50% of PAW and irrigation target of 140% of PAW results in an average modelled irrigation application efficiency of 55.6%. At the other extreme, the combination of irrigation trigger at 50% of PAW and irrigation target of 55% of PAW results in an application depth of only 5% of PAW (5mm for a soil PAW of 100mm). After each irrigation application the soil water deficit would be 45% of PAW, which leaves significant capacity to store rainfall (45mm for a soil PAW of 100mm). The range of irrigation target levels modelled therefore cover the spectrum from very low irrigation application efficiency to 100% irrigation application efficiency (modelled) and very high rainfall efficiency.

For each of the case study farms we used IrriCalc to model the effects of the many different irrigation management scenarios defined by the combinations of irrigation trigger and target levels on drainage and irrigation over the period 1972 – 2016. The soil-water model built into the current version of IrriCalc does not simulate bypass flow. Therefore if the irrigation target equals 100% of PAW, no drainage is generated and the application efficiency is 100%. If the target is greater than 100% of PAW, drainage is generated and the application efficiency is less than 100%. The application efficiency can never be greater than 100% - all targets of less than 100% of PAW result in an application efficiency of 100%. Irrigation practices that have a target of less than 100% of PAW are referred to as 'deficit irrigation' practices because a soil water deficit remains after each irrigation event. One reason for leaving a soil water deficit after an irrigation event is to leave capacity in the soil to store rainfall that might occur after the irrigation event.

Two other factors that affect irrigation management decisions are irrigation system capacity, an irrigation design parameter, and water supply restrictions. System capacity affects irrigation management decisions through its effect on the irrigation return period. Irrigated dairy farms in Canterbury typically have system capacities that are sufficient to fully meet irrigation need 9 years in 10, on average, and meet a significant proportion of the irrigation need in the shortfall year. We assumed that irrigation system capacity did not adversely affect irrigation management for the case study farms. Irrigation water supplies can be restricted due to equipment failure, electricity supply failure or through take restriction conditions in a resource consent. Exploring the effects on irrigation strategy and drainage of water supply reliability limitations was beyond the scope of this pilot study so we assumed 100% water supply reliability. It should be noted, however, that a common response to limitations in system capacity or water supply reliability is to raise the irrigation trigger and target levels to maintain higher soil water contents than would otherwise be the case. A consequence of responding this way is increased average annual drainage and thus N-loss to water, all other things being equal.

Primary input data

The soil properties data required as inputs to IrriCalc and DairyMod were obtained from S-Map fact sheets (and matched those used for the Overseer^{TM} analysis) and in Lilburne et al (2013). These included soil horizon specific data as well as root zone PAW.

Daily rainfall and reference crop evapotranspiration time-series were developed by Aqualinc for the virtual climate station grid square that best matched each case study farm, using methods described in Kerr (2017). The balance of the climate data required for DairyMod was sourced from NIWA's online climate data portal.

The crop coefficient time-series used for grazed irrigated pasture was derived from Van Housen's (2015) analysis of data collected through Canterbury Regional Council's lysimeter network.

All data inputs required for the Overseer^{TM} analyses was supplied by Ravensdown or Ballance Agri-Nutrients as Overseer^{TM} XML files.

Effects of Irrigation Management on N-Loss to Water

Quantifying the effects of irrigation management on N-loss to water proceeded in stages, as outlined in the previous section. We first examined the effects of a wide range of irrigation management scenarios on average annual drainage, as a key determinant of N-loss to water. We then tested the effects of irrigation management on pasture production to determine when the pursuit of low-drainage irrigation management began to adversely affect pasture production. From this information we selected an irrigation trigger level strategy and then systematically explored the effect of different irrigation target levels on N-loss to water using Overseer™.

Effects of irrigation management on drainage

There is a very large number of combinations of irrigation trigger and irrigation target levels that are feasible. To make the analysis tractable we took the approach of defining three sets of irrigation trigger levels and for each, analysed a wide range of irrigation target levels.

The irrigation trigger levels analysed are shown in Table 1 above. The aim of the changes to the trigger levels was to reduce drainage during the shoulders of the irrigation season. Figure 1 illustrates the effect of the trigger levels on the average drainage depth over the months September to May. These data are for one case study farm and the irrigation target is 100% of PAW. Most of the reduction in drainage achieved by changing the trigger levels from current practice occurs in late summer and autumn.

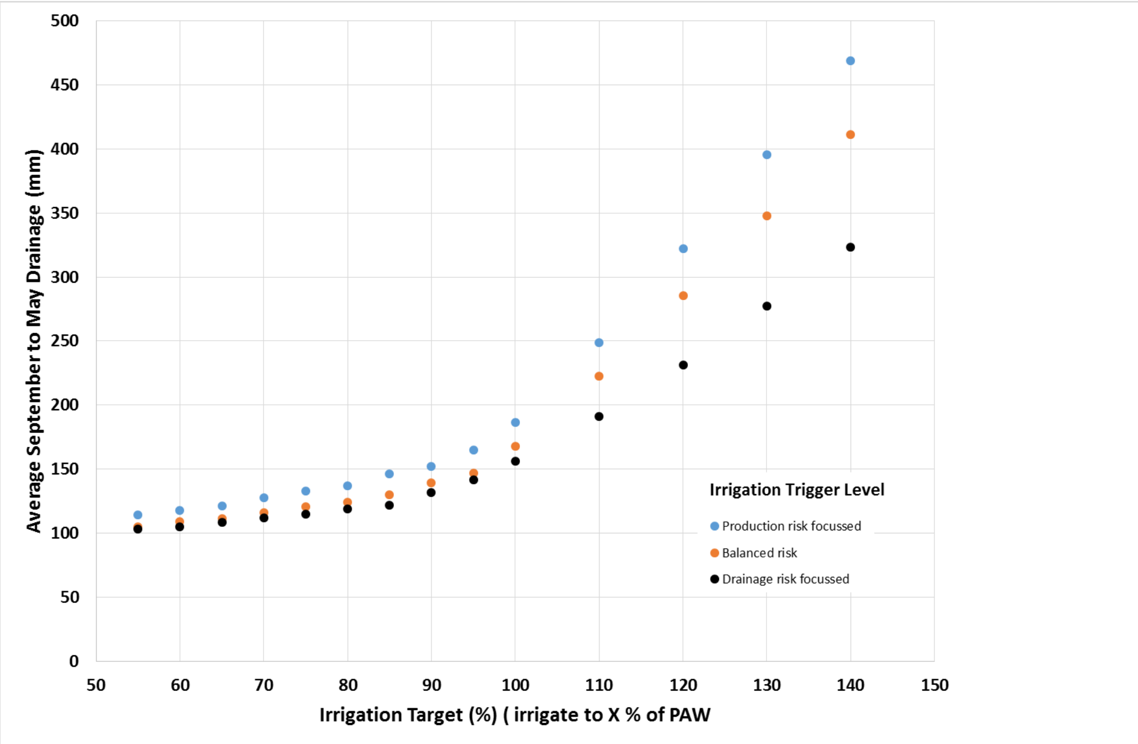

Figure 1: Effect of Irrigation Trigger Level on Average September to May Drainage for one case study farm

Figure 2, below, illustrates the effect on the average drainage depth over the months September to May of changing the irrigation target. The rate of reduction in drainage depth with reducing irrigation target declines as the irrigation target decreases below 100% of PAW. That is, reducing drainage by increasing rainfall efficiency is more difficult than by increasing irrigation application efficiency.

The current Good Management Practice for irrigation, from a water allocation perspective, aims to achieve an irrigation application efficiency of 80%. This is equivalent to setting the irrigation target at about 112% of PAW, assuming an irrigation trigger of 50%.

Reducing the irrigation target to 100% of PAW from this GMP point is expected to reduce the average September to May drainage by about 20%, depending on the PAW and rainfall. If the irrigation target is reduced still further, for example to 80% of PAW, the average September to May drainage on these case study farms is reduced 30% to 40% below that at GMP.

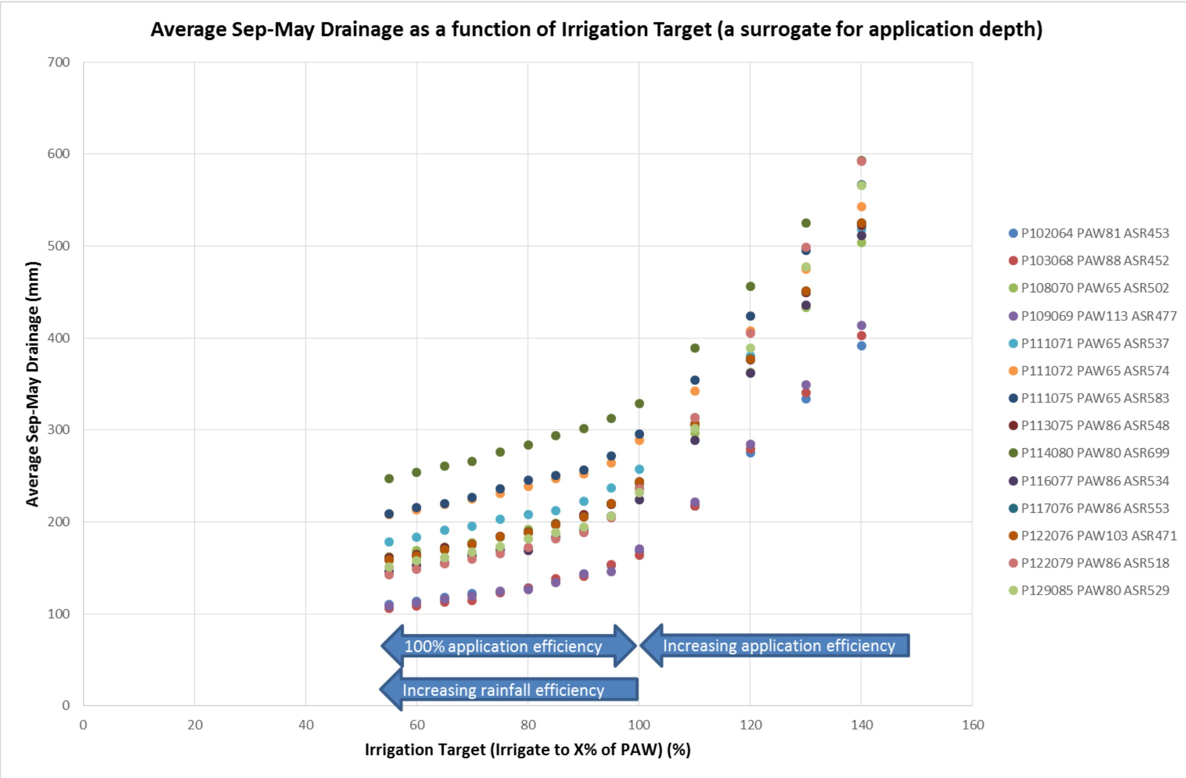

Figure 2: Effect on September to May drainage of irrigation target for all case study farms

These graphs demonstrate that substantial reductions in drainage can be achieved by reducing the irrigation target soil water content to a value of less than 100% of PAW, thus increasing the modelled irrigation application efficiency to 100% (this is reached in the modelled scenarios when the irrigation target is 100% of PAW).

Effects of Irrigation Management on Pasture Production

The irrigation trigger levels were chosen to provide a range from production focussed to drainage focussed, and a 'balanced' middle ground. The production focussed trigger level is current practice. Given the rationale behind the other sets of trigger levels, one would expect they'd have some effect on average annual pasture production.

Both sets of irrigation trigger levels that are alternatives to current practice (production risk focussed) reduce average annual pasture production. In the case of the 'balanced risk' trigger level in the above figure, pasture production is 2% to 3% lower than under current practice across most of the irrigation target levels analysed. For the more severe trigger level set (drainage risk focussed) the pasture production is 6% to 8% lower than under current practice.

Given the relatively small reduction in average annual pasture production of the 'balanced risk' trigger levels, the pasture production results presented below illustrate the effect of the irrigation target level used in conjunction with the 'balanced risk' trigger level set. In each case the average annual pasture production has been normalised by dividing it by the average annual pasture production achieved using an irrigation target of 100%.

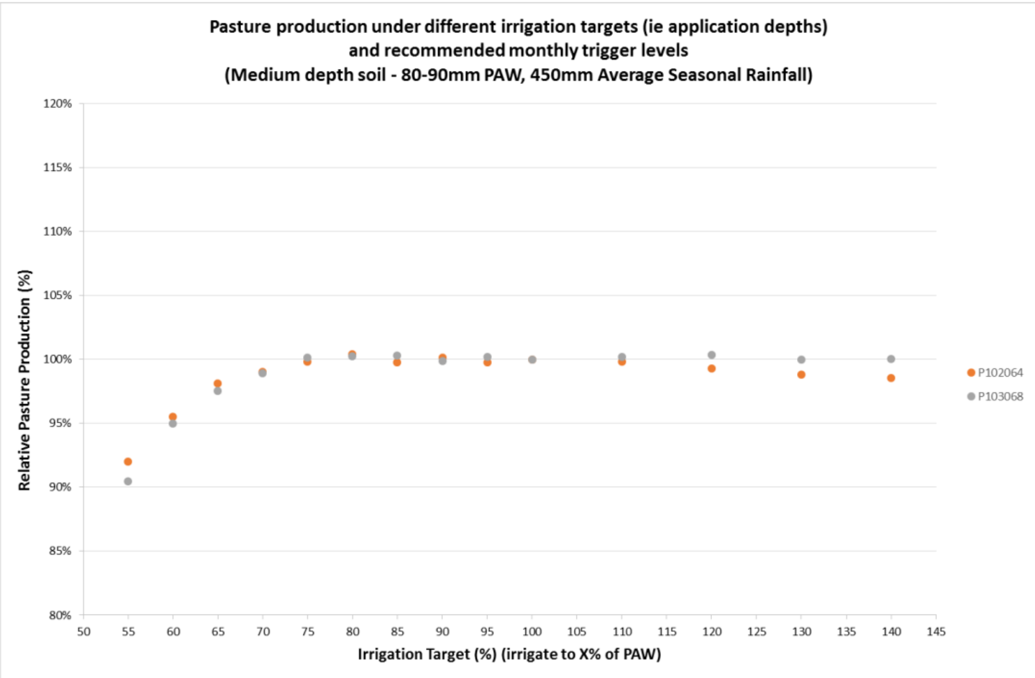

Figure 3: Effect of irrigation target on pasture production for farms on medium soils and with 450mm average seasonal rainfall

These results demonstrate that for these farms there is little variation in pasture production as the irrigation target drops from 140% down to about 75%. For the shallower soils or drier climates, dropping the irrigation target below 75% reduces pasture production to an increasing degree.

However, as the target is reduced the risks associated with not being able to irrigate increase. Suppose, for example, the irrigation target is 80%, the trigger is 50% and the root zone PAW is 50mm. These parameters result in an irrigation application depth of 15mm. Under typical Canterbury summer conditions irrigation will need to be occurring every three days to keep up with evapotranspiration. If the irrigator breaks down at the end of its run, it needs to be fixed in three days to prevent soil moisture stress occurring. If the target was 60% the application depth would be five millimetres and irrigation would need to occur every day. There would be no lee-way to cope with equipment breakdowns, for example. Many centre pivots irrigating light soils operate on a 50% trigger and 15mm every three days regime. This suggests that the level of risk associated with an irrigation target of 80% of PAW is acceptable.

The results of the drainage and pasture production analyses suggest that there is benefit, in terms of reducing drainage, in reducing the target irrigation application depth to 80% of PAW and that this can be done without adversely affecting average annual pasture production, for a given trigger level set.

Effects on N-Loss to water

The effects on average annual N loss to water of changing irrigation management has been modelled using Overseer™ for the ten farms for which we received Overseer™ files. No changes were made to the Overseer™ files supplied, apart from changing the irrigation management rules.

The analysis assumed the use of the balanced risk trigger level set because of the drainage reduction it achieves at very small cost in terms of average annual pasture production.

Figure 4 below illustrates the effect on average annual N loss to water of varying the irrigation target.

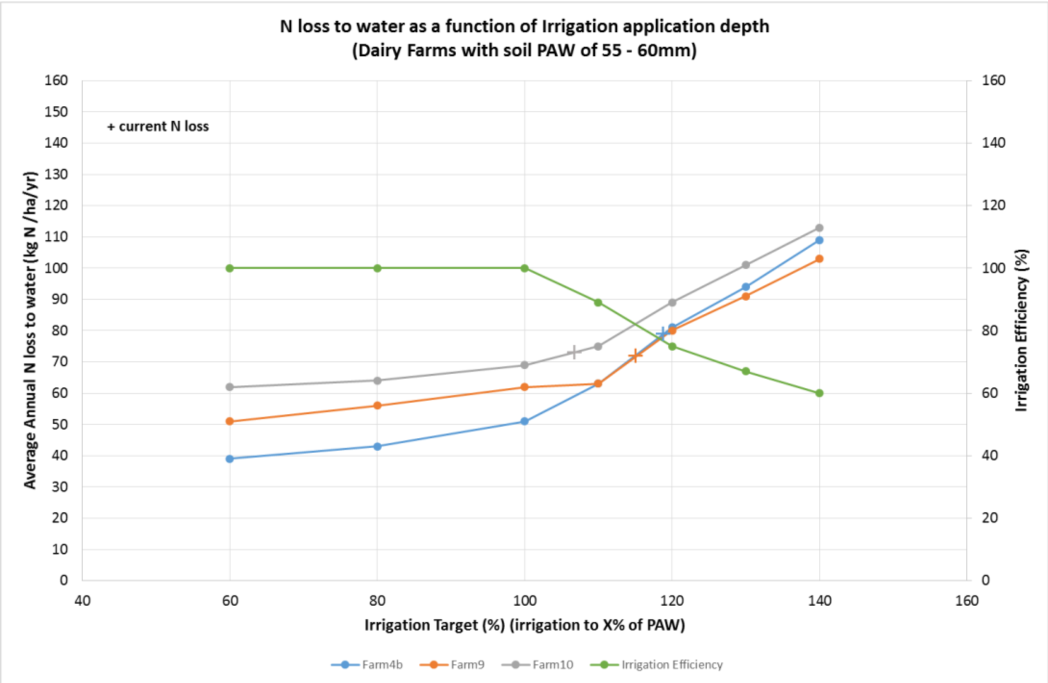

Figure 4: N-loss to water as a function of irrigation target – shallow soils

Leaving aside the obvious variation between farms, the pattern of reducing N loss as the irrigation target is reduced follows the same pattern as reducing drainage – as one would expect.

N loss reduces relatively quickly as the irrigation target reduces from 140% to 100% of PAW. This corresponds to increasing irrigation application efficiency from 60% to 100%. N loss reduces at a lower rate as the irrigation target decreases below 100% of PAW.

Based on these case studies, almost all of the gains in terms of N loss reduction are achieved by using an irrigation application depth that refills the soil profile to 80% of PAW. The irrigation trigger level set (i.e. soil moisture content as a % of PAW at which irrigation is initiated) used in these analysis was the balance risk set in which the trigger varies from month to month as follows:

Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
20%	40%	50%	50%	50%	40%	30%	20%

The average annual pasture production graphs show that with these trigger levels and an irrigation target of 80% of PAW there is only a minor production penalty on average, relative to the current practice trigger level of 50%.

Potential N-loss Reductions on Case Study Farms

For most farms, important (given they're located in Canterbury) reductions in N-loss to water are achievable by varying the irrigation trigger level and adopting an irrigation target that leaves a soil moisture deficit after each irrigation event. The recommended irrigation target, based on these results, is 80% of PAW. The reductions in N-loss to water achieved by making these changes to irrigation management are summarised in the following table.

Table 2 Modelled potential N-loss reductions on the case study farms:

Farm	Current N Loss	N Loss with 'optimum' irrigation	N loss Reduction	
	(kg N /ha/yr)	(kg N /ha/yr)	(kg N /ha/yr)	(%)
1	57	48	9	16%
2	67	62	5	7%
3	131	92	39	30%
4a	45	19	26	58%
4b	79	43	36	46%
5	71	42	29	41%
6	78	75	3	4%
7	37	29	8	22%
8	84	56	28	33%
9	72	56	16	22%
10	73	62	11	15%

As noted above, these modelled N-loss reductions are based on the use of an irrigation trigger level that varies from month to month and a constant irrigation target of 80% of PAW. This means that the irrigation application depth varies from month to month because the depth is a function of the difference between the trigger level and the target.

In practice most farmers find it simpler to operate on a fixed-depth basis. Thus the trigger level would vary from month to month, following the ‘balanced’ trigger levels, and the application depth would be fixed. This depth would be set so that in summer it did not raise the soil water content above the 80% target as recommended. Fixing the application depth means that the target would vary from month to month, as the trigger level varied. In the shoulders of the irrigation season the target would be less than 80% of PAW, assuming typical application depths, thus providing more capacity to store rainfall. The N-loss reductions would potentially be greater than those shown above – further analysis is required to test this, and assess effects on production.

Conclusions

Overseer^{TM} modelled N-loss to water can be reduced by 27% (~19 kg N/ha/year), on average, by changing irrigation practices to make more efficient use of both irrigation water and irrigation-season rainfall on the twelve case study farms analysed in this pilot. The percent reduction ranges from 4% to 58%. These reductions in N-loss to water can be achieved without significantly reducing modelled average annual pasture production.

Changes to both the irrigation trigger level and the irrigation target level are beneficial for making more efficient use of irrigation water and rainfall.

Changes to the irrigation trigger level have more effect on average annual pasture production than do changes to the irrigation target level, unless the target level is reduced to less than about 70% of PAW. Care should therefore be exercised around the setting and application of the trigger level.

Regular soil moisture measurements are essential to ensure that the soil water content does not drop below the irrigation trigger level in order to reduce the risk of pasture production losses.

Further refinement of the irrigation rule may lead to lower N-loss to water estimates than those presented above and eliminate the current (very small) reduction in pasture production – the huge number of possible combinations of irrigation trigger and target have not been exhaustively tested.

A high proportion of the irrigation systems on the Canterbury plains are capable of being managed according to the irrigation strategy developed through this pilot study. Greater understanding of the value proposition of changing to this strategy is a key to reducing N-loss to water.

Acknowledgements

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