Economic implications of altering irrigation scheduling
Carla Muller1, Mark Neal2, MS Srinivasan1 and Richard Measures1
1 National Institute of Water and Atmospheric Research Limited
2 DairyNZ

Abstract

This research forms a part of the New Zealand government-funded Irrigation Insight programme, which aims to maximise the economic benefits of irrigation through improved irrigation scheduling decisions. We developed a desktop model to estimate the environmental and economic impacts of various irrigation scheduling practices. The model simulates soil water balance and pasture growth rates on a daily timestep. Scenario modelling was used to investigate the average annual direct and indirect economic benefits and costs of irrigation scheduling decisions over an 18-year period. The impacts of altering the irrigation infrastructure, particularly irrigation application depth and frequency, were also examined. Direct costs include irrigator maintenance, labour and pumping costs. Indirect costs include changes in pasture growth as a result of water stress, over-watering, as well as wastage and pugging due to soil moisture levels. Results for a case study dairy farm in Rangiora, South Island, New Zealand, demonstrate that on average, there are significant annual economic (+$830/ha) and environmental (226 mm drainage) benefits if irrigation is scheduled based on soil moisture demand rather than following a set frequency (roster). However, for the case study farm, there is not a significant annual economic (+$25/ha) or environmental (79 mm drainage) benefit associated with changing irrigation infrastructure (purchasing an extra irrigation gun) to enable decrease application depths and rotation lengths (35 mm every 9 days rather than 45 mm every 11 days).

Introduction

In New Zealand, as irrigated dairying expanded over the past decade (Corong, Hensen and Journeaux, 2014), there has been concerted effort to improve irrigation application and scheduling practices (IrrigationNZ, 2015). More efficient spray irrigation methods are rapidly replacing less efficient border-dyke systems (Dark, KC and Kashima, 2017). However, further savings are likely to be gained from improved consideration of economic, soil and weather conditions, particularly linking irrigation scheduling to economic and environmental implications. One of the studies that does consider economic impact of marginal irrigation is one by Foundation for Arable Research (2008). Based on data from five farms, this study concluded that the average capital and operating cost of irrigation was $2/mm.ha, though the study included cost components that do not vary with use, e.g. insurance, and did not include changes in pasture or crop growth.

This paper presents an example application of a new hydrological and economic (hydro-econ) model, designed to look at the relative economic and environmental performance for various irrigation scheduling options. It provides the ability to test scenarios such as alternative return periods (irrigation frequency) and application depths. It focuses on operational costs and benefits and excludes capital costs.

Methodology

Within the hydro-econ model, the hydrological model computes changes in root zone (top 40 cm of soil) soil moisture each day using a water balance approach accounting for rainfall, irrigation, evapotranspiration and drainage (Srinivasan et al., in preparation). The model can vary
irrigation frequency and depth based either on soil storage or by applying a pre-set depth at a pre-set frequency irrespective soil moisture conditions.

The hydro-econ model was applied to a commercial dairy farm (“Farm A”) located near Rangiora, New Zealand. Eighteen years of daily climate data obtained from NIWA’s Rangiora weather station (NIWA, 2018), approximately 5 km from Farm A, were used in the model. This is a case study and may not be indicative of other farms. Farm A is a dairy farm of 119 effective hectares, all of which are irrigated. It has two main soil types, both with the same field capacity (FC) (123 mm within the root zone).

For each day the economic implications of the soil moisture are captured. Direct costs include the cash costs incurred for irrigating. Four direct costs were included as part of this model:

- **Pumping cost**, in dollars per m³ of water, is a variable cost incurred from moving water from the farmgate to root zone. Based on Farm A’s historic water use and power costs, this was estimated to be $0.04/m³.
- **Repairs and maintenance (R&M) costs**, in dollars per day of irrigation, are the variable costs associated with repairing and maintaining the irrigation system, including replacing pipes and nozzles. For Farm A, R&M costs were estimated to be $286 per day of irrigation, based on their historic water use and farm accounts.
- **Labour costs**, in dollars per day of irrigation, are based on the hourly wage rate for scheduling and moving the irrigator, and account for the skill level of the person undertaking the work. Farm A spent approximately $87 per day on labour associated with irrigation.

The base pasture growth rates, $PGR_{base}$, were based on DairyNZ Facts & Figures (DairyNZ, 2017), for the closest measurement location, and while this is likely to underestimate PGRs under perfect irrigation, it provides a proxy to test this model, and these can be altered if better information becomes available. The economic value of pasture is derived from the Forage Value Index (DairyNZ, 2018b), for the Upper South Island, and ranges from $0.13 to $0.42/kgDM depending on the month, these can be changed in the model if there is better information for the farm. Pasture value is calculated based on the final daily PGR multiplied by the economic value of pasture. Indirect costs considered in this study are changes in pasture growth and wastage due to soil moisture levels and reduction in pasture growth from pugging.

- **Soil moisture**, expressed as plant available water (PAW), impacts the daily PGR. In our model we calculate a scaling factor, $F_{\text{moisture}}$, accounting for the effect of soil moisture on $PGR_{base}$, as shown in Equation 1. Pasture growth is assumed to be zero when soil moisture is at or below wilting point, WP. While WP varies with soil type, 20% field capacity (FC) was considered a reasonable generalisation (IrrigationNZ, 2018). When soil moisture is greater than the WP and less than the FC, pasture growth rate is reduced according to the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET) (Doorenbos and Kassam, 1979). This has the effect of reducing pasture growth when soil moisture falls below a threshold ‘wilt point’ (WP) of 50% FC. This threshold can be altered as necessary. Above this threshold pasture growth is not limited by moisture (i.e. AET = PET so $F_{\text{moisture}} = 1$). Soil is considered ‘wet’ when PAW is at or above FC. The impact of wet soil on PGR is based on DairyMod and the SGS Pasture model described in Johnson (2016). Johnson (2016) assumes that $F_{\text{moisture}}$ at field capacity is 100%, and linearly decreases to 50% at saturation point (Sat). Based on the hydrological model used, saturation is assumed to be 120% FC, a point when slow drainage (i.e. drainage through soil matrix) swaps to fast drainage (i.e. overland flow) in the hydrological model.
Pasture wastage represents poor utilisation, and increases, in part, with increasing soil moisture which in turn is affected by irrigation scheduling. Causley (unpublished, cited in Beukes et al., 2013) states that pasture wastage increases linearly up to FC, at which point losses average 16%, and losses continued to increase once soil moisture was above FC. Although wastage impacts pasture utilised, rather than growth per se, in order to aggregate the costs and benefits of irrigation, we treat it as an effect on growth. Based on this and the relationships in Causley (unpublished, cited in Beukes et al., 2013), the hydro-econ model assumed that there was no wastage effect on the PGR at WP, and a 16% reduction in PGR at FC. This linear relationship was extrapolated for soil moisture exceeding FC which resulted in a 22.4% decrease in PGR for soils at Sat (Equation 2).

\[
F_{\text{wastage}} = \begin{cases} 
1, & \text{if } PAW \leq WP \\
1 - 0.16 \frac{PAW - SP}{FC - SP}, & \text{if } PAW > WP 
\end{cases}
\] 

Equation 2:

Pugging is influenced, in part, by soil moisture levels, and pugging can have a significant impact on pasture growth (Betteridge et al., 2003). In our model, the effect of pugging was only considered when soils are at or above FC for at least three consecutive days. The severity of pugging is determined based on Betteridge et al. (2003), who developed severity curves built on the relationship between stock density (stocking rate and rotation length) and grazing duration, which are determined at a monthly level. The time taken for the pugging damage to recover can be varied, but for Farm A was assumed to be 30 days. Pugging is a compounding effect, with multiple pugging events causing a more significant impact. Based on Betteridge et al. (2003) the impact of pugging was calculated according to Equation 3.

\[
F_{\text{pugging}} = \left(1 - \frac{\text{DaysPugging}}{\text{RotationLength}} \times \text{ImpactSeverity}\right)
\] 

Equation 3:

Where: DaysPugging is the number of days in the last 30 days when PAW has been greater than FC for three consecutive days, RotationLength is the stock rotation period in days, and ImpactSeverity is calculated according to Betteridge et al. (2003), taking into account grazing duration and stocking density. If stocking density is zero, then no pugging will occur. For Farm A, ImpactSeverity varied from 0% for June and July when there was no stock, to 56% in May when stocking density was highest.

Utilised pasture growth, PGR_{revised}, accounting for reductions in growth rate due to moisture, wastage and/or pugging is calculated according to Equation 4. Given that the PGR_{revised} is scaled relative to a PGR_{base}, which is a proxy for perfect irrigation, all three factors in Equation 4 (F_{moisture}, F_{wastage} and F_{pugging}) are between 0 and 1.

\[
PGR_{\text{revised}} = PGR_{\text{base}} \times F_{\text{moisture}} \times F_{\text{wastage}} \times F_{\text{pugging}}
\] 

Equation 4:
This hydro-econ model allows selection of various irrigation scheduling decisions. This paper focuses on demonstrating the impact of some of the key inputs. Other applications, such as the use of forecasting, will be the subject of further research. The inputs varied in this paper are summarised in Table 1.

*Table 1: Hydro-econ model irrigation scheduling variables*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measurement</th>
<th>How often variable is set in the model</th>
<th>Potential options if applicable / notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth per irrigation</td>
<td>mm/day</td>
<td>Monthly</td>
<td>Zero indicates when no irrigation is applied in that month</td>
</tr>
<tr>
<td>Irrigation approach</td>
<td>Selected option</td>
<td>Once</td>
<td>Just in time: Irrigate when soil storage reaches user set threshold</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Always: Irrigate whenever water is available</td>
</tr>
<tr>
<td>Frequency limitation</td>
<td>Selected option</td>
<td>Once</td>
<td>No limit: irrigate whenever it is desired</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minimum return interval: Cannot irrigate until a set number of days after the last irrigation</td>
</tr>
<tr>
<td>Roster/minimum return period of irrigator</td>
<td>Days</td>
<td>Monthly</td>
<td>Roster: Can only irrigate on pre-set days</td>
</tr>
</tbody>
</table>

This paper presents the results for Farm A, in particular, the economic impact if they maintain their current irrigation infrastructure system, or if they include another irrigation gun and reduce application depth and rotation length. These two options are varied by irrigation approach (just in time or always) and frequency limitation (minimum return interval or roster), see definitions of these in Table 1. ‘Just in time’ irrigation approaches check whether the soil moisture levels are below a pre-defined threshold, before checking if the rostered irrigation is available, if both of these conditions are met irrigation is applied. Conversely, if the ‘always’ irrigation approach is selected the model only checks to see if the rostered irrigation is available regardless of the soil moisture levels across a pre-defined irrigation season. ‘Rostered’ and ‘minimum return interval’ frequency limitations represent different types of water supply and infrastructure constraints. Rostered irrigation represents a supply constraint whereby water is only available every so many days. For example, with an 11-day roster water is available on every 11th day and availability is not influenced by whether or not irrigation actually takes place. A minimum return interval limitation represents an infrastructure limitation whereby it takes several days to apply a single application (typically due to the need to move a limited number of mobile irrigators from field to field in rotation). Minimum return interval limitations mean that irrigation cannot be repeated within a set number of days. For example, with a minimum return interval of 11 days, if irrigation occurs on a given day it is not possible to apply more irrigation for the next 10 days.

Farm A is currently using two irrigation guns, applying 45mm irrigation depth with a return interval of 11 days, they have a minimum return interval and use a just in time irrigation approach. Scenarios with two guns received 45 mm per application and had an 11-day rotation length, scenarios with 3 guns, had an application depth of 35 mm per application and a nine-day rotation length.
Results

All results are the average across 18 seasons. Based on 18 irrigation seasons, Farm A on average receives 217mm of rainfall through the irrigation season, which was November to March (inclusive). Table 2 describes the scenarios tested in this paper, the irrigation applied for each scenario and the resulting drainage. Irrigation applied, the number of days irrigated, and the total drainage are lower for scenarios that use a just in time irrigation approach relative to those irrigating whenever water is available.

Table 2: Scenarios tested for Farm A, irrigation applied and drainage for each scenario per irrigation season (November to March). Data averaged from 18 irrigation seasons. Scenario name represents the number of guns (2 or 3), irrigation approach (J for just in time or A for always) and frequency limitation (M for minimum return interval or R for rostered).

<table>
<thead>
<tr>
<th>Name</th>
<th>Irrigators</th>
<th>Irrigation approach</th>
<th>Frequency limitation</th>
<th>Irrigation applied (m³)</th>
<th>Number of days of irrigation</th>
<th>Total drainage (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-JM</td>
<td>2 Guns</td>
<td>Just in time</td>
<td>Minimum return interval</td>
<td>437,325</td>
<td>90</td>
<td>20.4</td>
</tr>
<tr>
<td>2-AM</td>
<td>2 Guns</td>
<td>Always</td>
<td>Minimum return interval</td>
<td>749,700</td>
<td>154</td>
<td>260.7</td>
</tr>
<tr>
<td>2-JR</td>
<td>2 Guns</td>
<td>Just in time</td>
<td>Rostered</td>
<td>410,550</td>
<td>84</td>
<td>17.7</td>
</tr>
<tr>
<td>2-AR</td>
<td>2 Guns</td>
<td>Always</td>
<td>Rostered</td>
<td>749,700</td>
<td>154</td>
<td>260.7</td>
</tr>
<tr>
<td>3-JM</td>
<td>3 Guns</td>
<td>Just in time</td>
<td>Minimum return interval</td>
<td>425,756</td>
<td>92</td>
<td>17.6</td>
</tr>
<tr>
<td>3-AM</td>
<td>3 Guns</td>
<td>Always</td>
<td>Minimum return interval</td>
<td>708,050</td>
<td>153</td>
<td>225.4</td>
</tr>
<tr>
<td>3-JR</td>
<td>3 Guns</td>
<td>Just in time</td>
<td>Rostered</td>
<td>402,617</td>
<td>87</td>
<td>12.0</td>
</tr>
<tr>
<td>3-AR</td>
<td>3 Guns</td>
<td>Always</td>
<td>Rostered</td>
<td>708,050</td>
<td>153</td>
<td>225.4</td>
</tr>
</tbody>
</table>

Table 3 shows the economic results for the various scenarios. Pasture growth is annual total, and accounts for impact of irrigation on the shoulder seasons to be captured (e.g. pugging).

Table 3: Economic impacts for various irrigation scenarios for Farm A, standard deviation of annual variability in brackets.

<table>
<thead>
<tr>
<th>Name</th>
<th>Total direct costs $/ha/year</th>
<th>Pasture grown* kgDM/ha/year</th>
<th>Pasture value $/ha/year</th>
<th>Total (value of pasture minus direct costs) $/ha/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-JM</td>
<td>$429 (±107)</td>
<td>13,732 (±475)</td>
<td>$3,116 (±128)</td>
<td>$2,688 (±108)</td>
</tr>
<tr>
<td>2-AM</td>
<td>$735 (±0)</td>
<td>11,311 (±1,088)</td>
<td>$2,646 (±217)</td>
<td>$1,911 (±217)</td>
</tr>
<tr>
<td>2-JR</td>
<td>$402 (±106)</td>
<td>13,997 (±417)</td>
<td>$3,172 (±123)</td>
<td>$2,770 (±145)</td>
</tr>
<tr>
<td>2-AR</td>
<td>$735 (±0)</td>
<td>11,311 (±1,088)</td>
<td>$2,646 (±217)</td>
<td>$1,911 (±217)</td>
</tr>
<tr>
<td>3-JM</td>
<td>$431 (±115)</td>
<td>13,960 (±452)</td>
<td>$3,165 (±124)</td>
<td>$2,733 (±125)</td>
</tr>
<tr>
<td>3-AM</td>
<td>$718 (±0)</td>
<td>11,360 (±1,238)</td>
<td>$2,642 (±245)</td>
<td>$1,924 (±245)</td>
</tr>
<tr>
<td>3-JR</td>
<td>$408 (±111)</td>
<td>14,150 (±344)</td>
<td>$3,207 (±101)</td>
<td>$2,799 (±120)</td>
</tr>
<tr>
<td>3-AR</td>
<td>$718 (±0)</td>
<td>11,360 (±1,238)</td>
<td>$2,642 (±245)</td>
<td>$1,924 (±245)</td>
</tr>
</tbody>
</table>

*Interpret PGR as relative to a ‘non-moisture limited’ scenario with no pugging or wastage.

16,121kgDM/ha/year
Figure 1 illustrates the relative value from each of the scenarios tested as well as the components of the direct economic costs for Farm A. The direct economic costs are a negative, whereas the value from pasture is a positive and the total value per hectare per year is also included.
Discussion

There is not a significant difference between the top four options (scenarios 3-JR, 2-JR, 3-JM, 2-JM). These top four options include two systems with additional irrigation infrastructure (3-JR and 3-JM) and two with the existing infrastructure (2-JR and 2-JM). Of these four top options, two use a roster to schedule irrigations and two use a minimum return period between irrigation, all four are based on a just in time irrigation approach. The distinction between roster and minimum return interval is driven by infrastructure restrictions on most farms, and while using a roster was slightly better economically, it was not significantly different across these top four scenarios. This indicates that there is no significant economic benefit in purchasing additional irrigation infrastructure. There is however, significant economic and environmental benefits in using a just in time approach relative to irrigating whenever water is available. The top four scenarios economically also had lower total drainage, indicating a positive environmental outcome. Based on this, the results for Farm A show the best option is to purchase the new irrigation gun and reduce their irrigation application depth and return length, and utilise a just in time irrigation approach (only irrigate when soil moisture indicates it is required) under a roster system (rather than minimum return).

Irrigation scheduling is limited by the flexibility of the irrigation infrastructure, at both a farm and a scheme level. At a farm level, irrigation scheduling decisions are constrained by the rotation lengths and application depth. Where this hydro-econ model can help improve outcomes, is by comparing how economic and environmental outcomes can change when these infrastructure limits are altered. The benefit of using a just in time irrigation approach rather than irrigating whenever water is available is to be expected (Srinivasan et al., in preparation). However, the lack of significant difference in total value and drainage between reducing irrigation application depth by 10mm and rotation length by two days, illustrated that Farm A should not necessarily invest in new infrastructure. This suggests that a commonly held view of irrigating smaller amounts more frequently can be beneficial for some farm situations, but there will be diminishing economic and environmental returns to investment in irrigation investment, so it will not always be the case.

A key assumption in this hydro-econ model is that water is available whenever the model decision rules wants to apply it. Another assumption is that labour and R&M costs are fully variable costs. In reality these are likely to be lumpy costs (Hall and Lieberman, 2012), and will not scale proportionally with each reduced irrigation day. In addition, this model does not address application uniformity and distributional accuracy, both of which can influence irrigation efficiency. Application uniformity is examined in depth in studies such as Hedley, Yule and Bradbury (2010), whilst distributional accuracy is examined by tools such as ‘bucket tests’ (DairyNZ, 2018a).

The hydro-econ model provides a way to compare economic and hydrological impacts of various irrigation scheduling decisions at a seasonal level, but it is not a marginal decision-making tool. There is currently not a tool in New Zealand which provides farmers with a predicted economic and environmental impact of each marginal irrigation scheduling decision, i.e. if they should turn the irrigator on today, and if so how much should they apply (if application depth can be varied). Access to this information is likely to help improve irrigation decision making both economically and environmentally. This hydro-econ model provides a starting point for a marginal decision-making tool for irrigation scheduling. Other areas for future research should consider, use of weather
forecasts for irrigation decision making, varying soil types, partially variable labour and R&M costs and the economic impact of nutrients in any drainage water.

**Conclusion**

Application of a hydro-econ model to Farm A shows that there is a significant positive economic and environmental benefit from using soil storage-based scheduling rather than a rostering system. The lack of significant difference between reducing irrigation application depth by 10mm and rotation length by two days, illustrated that Farm A should not necessarily invest in new infrastructure. The results have a number of underlying assumptions that need further examination. This research provides an important first step in understanding the economic impact of marginal irrigation scheduling decisions.

**References**


