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MATCHING SOILS AND IRRIGATION AUTOMATION FOR SUSTAINABLE USE OF WASTEWATER

Brian Ellwood[1*], Hamish Lowe[1], Katie Beecroft[1], Cathy Campbell[2]

[1] Lowe Environmental Impact
[2] Fonterra Co-operative Group Limited
**Email: brian@lei.co.nz*

Abstract

Fonterra operated a dairy processing plant at Tuamarina, north of Blenheim within the Marlborough region, whereby dairy plant wastewater (DPW) is produced. The wastewater was predominantly irrigated to farmland at a series of properties surrounding the plant. When soil conditions were not suitable for land application and the Wairau River was above 60 cumecs flow, it discharged to the river. Lowe Environmental Impact (LEI) was engaged by Fonterra to undertake site investigations, and to assess and recommend future irrigation management.

It was found that the soils' field capacity values vary between 12% and 53% moisture content between sites. Available water-holding capacity of the soils across the sites showed large variation mostly due to soil texture. The current irrigation application depth of 25 mm/event (250 m^3/ha) is similar to or less than 50% of most of the soil's Profile Available Water (PAW), which is a normal maximum application criterion for fresh water. However, applying this volume at a high instantaneous rate at two sites with very high soil-saturated hydraulic conductivity (K_{sat}) rates was likely to result in significant macropore bypass flows. This is not appropriate for wastewater application. The K_{sat} values retrieved were moderate to high, while soil unsaturated hydraulic conductivity (K_{-40mm}) values for most sites were low, indicating particle size distribution and the presence of macropores varied across soil types.

These soil findings were used to redesign the irrigation regime, with irrigation customised depending on the property and soils present. Innovative use of automated valves was proposed to upgrade the existing irrigation systems so irrigation application rates could be matched to the soils. Frequent smaller applications during the irrigation day were used to allow time for the soil to absorb the dose volume, minimising bypass flow.

Water balance modelling showed that the total land area available is greater than that required to apply all wastewater sustainably. The revised irrigation application regime and methods allowed the system to operate with no discharge of DPW to the river.

Introduction

Fonterra operated a dairy processing plant at Tuamarina, north of Blenheim within the Marlborough region, whereby dairy plant wastewater (DPW) is produced. The wastewater was predominantly discharged to farmland at a series of properties surrounding the plant. When soil conditions were unsuitable for land application and the Wairau River was above the 60 cumecs flow, it was discharged to the River.

Wastewater was applied to a total of five properties with an irrigable area of 85 ha, and an additional third party farm of about 23 ha was identified to also potentially receive wastewater. The application occurred via irrigation, using a K-Line max system consisting of Senninger 5023 Sprinklers with 6.35 mm nozzles. The individual application rate was approximately 6 mm/hr. Irrigation management indicated that the farms were generally lightly loaded hydraulically, with application depths and long return periods minimising total nitrogen applications. Some paddocks received very little wastewater (0 mm in some years), whereas others received up to five 25 mm application events per year (125 mm), depending on soil moisture status and landowner-specific access constraints.

The resource consent for irrigation onto the farms and to discharge to the Wairau River was due to expire on the 1st of February 2022. To optimise the volume of discharge to land for the new consent, allowing for the reuse of nutrients and reduced environmental effects, modifications to the irrigation management schedule were required. Ideally, this would result in no discharge to the Wairau River by reducing surface water discharge and minimising soil drainage whilst still protecting groundwater quality.

There were multiple constraints to achieving this goal. The system needed to be cost-effective, based on the existing manual K-Line system with limited system capacity. It needed to be flexible to fit in with third-party landowners, who often provided the irrigation operators short notice of access changes for stock and crop rotations, with a mandatory 16-day stand down for grazing after treatment. River flow variability meant levels of acceptable surface discharge would be difficult to predict, and soil variability across the different sites meant irrigation saturation would occur at different times. Finally, the system was required to meet all consent conditions regulating irrigation management.

Lowe Environmental Impact (LEI) was engaged by Fonterra to undertake site investigations and assess and recommend future irrigation management. As part of the technical assistance, LEI carried out field investigations in June 2020 of the soil at the respective sites proposed to receive wastewater. The aim of the field investigations was to get a better understanding of the soils on the farms, their physical and chemical properties, variability and their ability to receive wastewater.

Methods

Site investigations were conducted by LEI staff from 8 - 10 June 2020. The aim of the field investigations was to get a better understanding of the soils on the farms, their physical and chemical properties, and their ability to receive wastewater. In total, there were six farm blocks examined during the field investigation carried out by LEI.

Figure 1: Location of Sites and Test Pits

A desktop and field survey of soil type distribution was undertaken. Surface water flow paths, waterways and wet areas were identified. This desktop investigation was then either modified or confirmed based on field surveys. At each of the proposed sites, a walkover was performed to map surface features and drainage paths, and ten test pits were dug using an excavator across the multiple third-party farms for soil profile descriptions.

Samples taken from test pits at each of the sites were sent to Landcare Soil Physics laboratory for measurements of soil physical properties and were analysed for bulk density, available water capacity (AWC), total porosity and macroporosity. Additional samples were taken at two depths, one within the topsoil, and the other within the underlying subsoil, for phosphorus (P) isotherm analysis to determine the site life with regard to P. Samples taken were analysed for soil fertility, soil P retention, P sorption capacity and C and N species.

Composite soil samples were taken near each test pit site at 0 - 75 mm. Samples taken were analysed for soil fertility, soil P retention, carbon (C) and nitrogen (N) species. Additional test pits were excavated at two properties. These pits were for the purpose of identifying soil boundaries.

Field measurements of both soil saturated (K_{sat})and unsaturated (K_{-40mm}) hydraulic conductivity were undertaken using double-ring metal infiltrometers and glass plate permeameters, respectively. For saturated soil tests, four replicates were taken. Three to four replicates were taken for unsaturated infiltration tests.

Results

Based on the topography present and farm management, 11 sites were identified as suitable and as representative of the investigation area as a whole.

Soils

Soil types and associated characteristics varied both across individual properties, as well as between properties. Soils were dominated by Wairau over-bank deposits near to State Highway 1 and the Wairau River (Thomas property and Woolley/SH1 property); sand dunes intercalated with fine alluvium with higher clay the further away from the Wairau River travelled (Woolley, Campbell, and parts of Pukematai and Pembers Road properties); and a coastal gravel bank close to Neal Road (Pukematai and Pembers Road properties).

Soils across the respective sites were largely in good health. This was determined through both bulk density and macroporosity, which were mostly all adequate (10 - 30% macropores) (Taylor *et al*., 2017). There was no indication that wastewater irrigation had impacted the ability for air and water to enter and drain through the soil. Bulk density values were predominantly between or around the adequate to compact values of 0.9 to 1.25 respectively for a recent soil (Taylor *et al*., 2017), with higher than adequate values likely due to natural processes rather than land uses. This meant that sodium imbalance in the wastewater had not degraded soil structure.

The soil chemistry results do not identify a clear trend in soil fertility which can be attributed to wastewater application on the sites. It is likely that this reflects the comparatively low annual application depths applied. Farm management practices were likely to be the main influence on soil fertility across the investigation area. The measured parameters do not indicate any limitation to a well-managed wastewater irrigation regime.

Field Capacity

The soils' field capacity values varied between 12% and 53% moisture content between sites, indicating that trigger levels to commence irrigation would ideally be customised depending on the property and soils present. Available Water holding Capacity (AWC) of the soils across the sites showed large variation due mostly to the soil texture. Topsoil AWC ranged from 10 to 28% v/v. Subsoil AWC ranged from 8 to 30% v/v.

A water balance shows that the total area (85 ha plus a proportion of an additional 23 ha) is a greater area than that required to apply all wastewater sustainably with no soil moisture constraint and no discharge to the river of wastewater.

Conductivity

A soil's ability to retain or drain applied water is governed by the infiltration rate and permeability of the soil. Soil hydraulic conductivity (K) is a measurement of infiltration and permeability. An understanding of the soil's hydraulic conductivity is needed to enable the development of application rates suitable for the long-term sustainability of an irrigation regime.

Results of the K_{sat} and K_{-40mm} testing are given in Table . To establish an irrigation rate that can be received by the soil over a long term without causing soil damage, a conversion needs to be made to allow for the application of “enriched” water which has elevated levels of other constituents (cations, anions, complex organic molecules). A value of either 30 % of K_{-40mm} or 10 % of the Ksat is usually adopted in-line with the recommendations of Crites and Tchobanoglous (1998) to provide a recommended irrigation rate that can be applied daily.

Testing Location	**Soil type**	**K_{sat} (mm/h)**	**$K_{-40\ mm}$ (mm/h)**	**Irrigation rate, wastewater (mm/d) based on 10% K_{sat}**	**Irrigation rate, wastewater (mm/d) based on 30% K_{-40mm}**
Thomas (High)	Waimakariri	203 ± 89	2.9 ± 1.8	488	21
Thomas (Low)	Waimakariri	65 ± 17	2.7 ± 0.6	156	19
Pukematai (High)	Rangitata	76 ± 33	1.4 ± 2.9	183	10
Pukematai (Low)	Taitapu	72 ± 91	4.5 ± 4.7	173	32
Campbell (High)	Fereday	120 ± 35	1.5 ± 1.0	288	11
Campbell (Low)	Taitapu	515 ± 267	0.7 ± 0.2	1,237	5
Woolley	Taitapu	69 ± 29	0.6 ± 0.3	165	4
Pembers Road (High)	Taitapu	272 ± 194	0.5 ± 0.3	652	4
Pembers Road (Low)	Taitapu	17 ± 8	0.5 ± 0.4	41	4
SH1	Waimakariri	110 ± 77	1.5 ± 0.9	264	11

Table 1: Soil Hydraulic Conductivity Results

K_{sat} values were moderate to high, while the K-40mm values for most of the sites were low. The difference between the K_{sat} values and K-40mm values is likely reflected by the particle size distribution of the soils, with soils with sand and gravel having the greatest difference between K_{sat} values and K-40mm. K_{sat} values have been used to determine a maximum application depth. The K-40mm values can be used to predict the incidence and duration of surface redistribution that may occur, i.e. short-term very localised ponding (may not be visible) with application rates above this resulting in macropore flow bypass; depending on the application rate, minor surface redistribution would occur in 7 of the 10 sites above.

K_{-40mm} is considered to represent water movement through the entire soil matrix under slow-rate irrigation. However, the maximum rate recommended is based on 10% of K_{sat}, which has been used to determine the technically feasible maximum daily irrigation hydraulic loading rate recommendations. Rates are greater than 41 mm/d across all sites.

The irrigation system’s application rate is based on the Senninger 5023 sprinkler with an individual rate of 6 mm/hr. Based on the soil analysis all sites can accept the sprinkler rate through absorption and infiltration. However, the application rate is greater than the K_{-40mm} rate, therefore some surface redistribution and subsequent macropore bypass flow would occur if the application rate was applied for a long duration. Pukematai Low and Thomas High and Low are likely to have sufficient unsaturated infiltration characteristics to ensure meso and micropore flow. The proposed Pembers Road High and Low, Woolley and Campbell Low sites had low K_{-40mm} rates partly impacted by the soil moisture statues when the testing was undertaken. Pembers Road High and Campbell Low sites have very high K_{sat} rates that are likely to result in significant macropore bypass flows at high instantaneous irrigation rates and volumes.

Profile Available Water, Irrigation Application Depth and Rate

Profile Available Water (PAW) is the difference Field capacity (FC) and wilting point for the top 60 cm, i.e. it is the water available for plants, with water below wilting point too difficult for plants to extract and above FC, not held/stored and is drained.

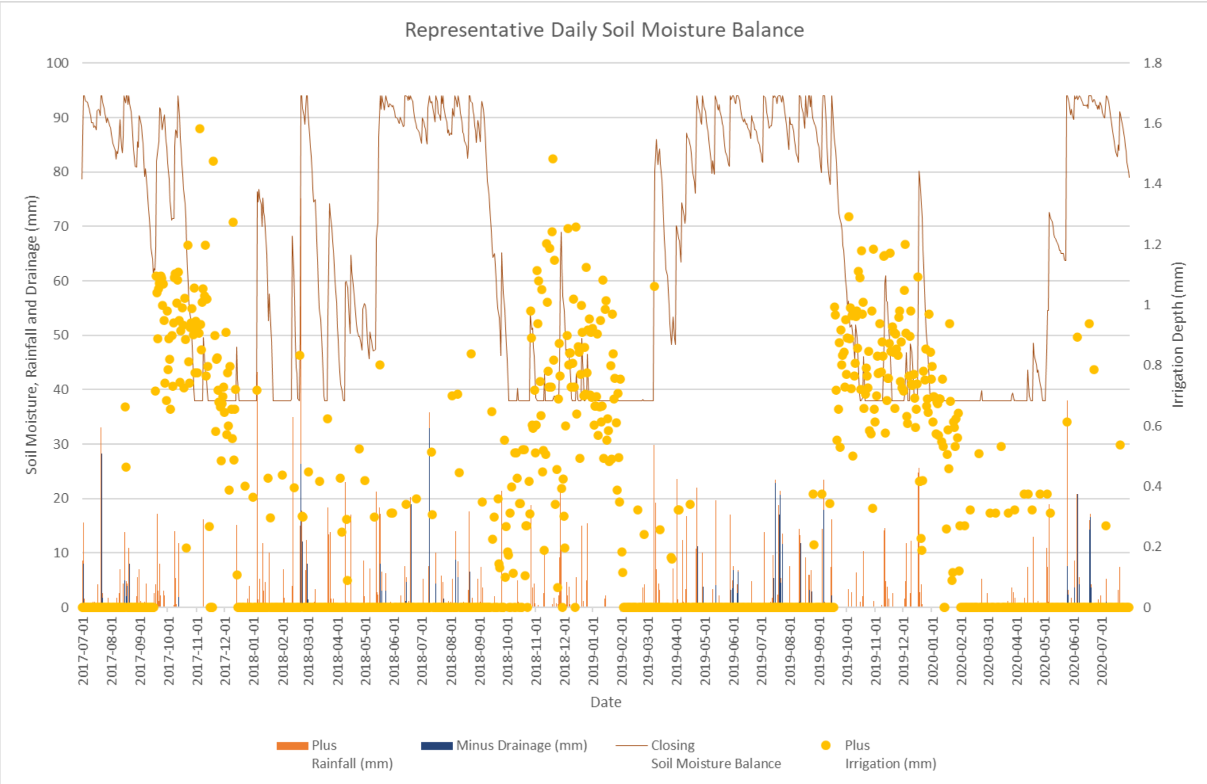

Figure 2: Representative Daily Soil Moisture Balance across Land Treatment Area (2017 to 2020)

Figure shows a daily soil moisture balance for a 56 mm PAW soil receiving the plant wastewater volumes generated between 2017 and 2019. This soil PAW is selected as being representative of Campbell's, Pembers, SH1 and Thomas High soils. The purpose of the soil moisture balance model is to show the average drainage likely to occur due to application of wastewater irrigation. The use of the average area of 39 ha in the water balance model is to reflect the average drainage beneath the whole irrigation area. The actual drainage for an individual block will be different at paddock level with some having lower and higher levels of actual drainage. The water balance uses a 56 mm soil PAW, soils with a higher PAW will have lower drainage and leaching for the same volume of water applied.

Error! Reference source not found. shows that the wastewater irrigation is not causing the soil to be held at field capacity for long periods of time during the spring. This indicates that, provided the application rate does not exceed the soil's infiltration rate, significant periods of forced drainage is not induced by the proposed irrigation regime irrespective of the soil moisture trigger. As shown in Figure , seasonal rainfall is dominating the water balance and soil drainage.

The AWC % of soil volume conversion to PAW based on topsoil depth is shown in Table below. Many of the soil profiles showed fine roots penetrating the subsoils, so PAW could be taken over the top 60 cm of soil rather than the shallower depths that defined the topsoil. This could particularly be the case for Woolley 1 that had fine roots to 54 cm depth.

Sample Name	**Soil Type**	**Depth (cm)**	**Measured AWC (%)**	**Calc'd PAW (mm)**	**Total PAW for Soil (mm)**	**Calc'd 50% of PAW (mm)**
Campbell High	Fereday	10-20	20	40		
Campbell High	Fereday	30-40	8	16	56	28
Campbell Low	Taitapu	10-20	10	20		
Campbell Low	Taitapu	30-40	17	34	54	27
Pembers High	Taitapu	5-15	23	35		
Pembers High	Taitapu	20-30	12	12	47	24
Pembers Low	Taitapu	10-20	28	56		
Pembers Low	Taitapu	30-40	25	50	106	53
Pukematai Low	Taitapu	10-20	22	44		
Pukematai Low	Taitapu	30-40	23	46	90	45
SH1	Waimakariri	10-20	24	48	48	24
Thomas High	Waimakariri	10-20	26	52	52	26
Thomas Low	Waimakariri	10-20	27	54		
Thomas Low	Waimakariri	30-40	30	60	114	57
Woolley 1 [a]	Taitapu	10-20	18	36	36	18

a. See comment above about using 54 cm rooting depth, giving 97 mm PAW.

Table 2: Soil Profile Available Water

The difference between FC and porosity is the amount of water that can be absorbed by the soil before ponding occurs, with the amount entering above FC forcing drainage out of the soil profile under gravity. This shows that all soils, in theory, have the ability to accommodate wastewater (more than double the event depth) applied above field capacity without ponding occurring. However, forced drainage will occur for high application depths, and surface redistribution would occur that would result in localised ponding (this may not be visible depending on the soil and location of depressions).

It is accepted good freshwater irrigation practice is to apply less than half the soil's PAW per application event. As shown in Table , 50% of the PAW of all sites is in the general order of 25 mm or greater with the exception of Wooley 1 at 18mm. The current application event depth of 25 mm, or 250 m^3/ha, is considered acceptable for normal irrigation (application to bring near to FC) and is applied in one application. However, for applications that result in soil moisture above FC, it is not optimal for ensuring the whole application depth is attenuated through the soil to remove nutrients and minimise the potential for localised ponding.

A future irrigation regime is proposed where the daily irrigation volume is applied in pulses over the day so that the average irrigation rate in mm/hr is reduced and more closely matched to the soils unsaturated hydraulic conductivity.

Discussion

The total irrigable area (85 ha plus a proportion of an additional 23 ha) is greater than that required to apply all wastewater sustainably with no soil moisture constraint and no discharge of wastewater to the Wairau River. The application rate of the K-Line Max Senninger 5023 sprinklers is in the order of 6 mm/hr, assuming no wear and tear on the nozzles. The typical line set-up of 25 m between the pods means with normal operation, there is no overlapped application. Based on the saturated hydraulic conductivity testing undertaken, all sites could accept the sprinkler rate through absorption and infiltration. However, the application rate is greater than the K_{-40mm} rate, therefore some surface redistribution and subsequent macropore bypass flow, as well as isolated ponding in low spots, may occur in some soils. Pukematai Low and both Thomas High and Low are likely to have sufficient unsaturated infiltration characteristics to ensure meso and micropore flow at the expected sprinkler rates. The Pembers Road High and Low, Woolley and Campbell Low sites have low K_{-40mm} rates and the Pembers Road High and Campbell Low sites have very high K_{sat} rates that are likely to result in significant macropore bypass flow if high dose volumes are applied. The cycling of applications over the day increases the soil's capacity to receive the dose volume without bypass flow. The use of frequent smaller applications (20 minute irrigation events once every hour) would allow time for the soil to absorb the dose volume minimising bypass flow.

Based on the soil testing hydraulic conductivity testing, application depth of up to 30 mm being less than 10 % of K_{sat} has been adopted here as being sustainable and can be safely applied across all soil types. This depth considers the long-term protection of soil health and the protection of groundwater, which is shallow across the lower-lying areas. As a result, the actual wastewater irrigation regime should be a combination of return period based on nutrient loading and design of the irrigation application based on matching the application depth to the hydraulic loading to the soil. Limiting the application rate up to 30 mm per event, which is less than 10 % of K_{sat}, helps avoid bypass flow and drainage of recently applied wastewater below the root zone.

It is accepted good freshwater irrigation practice is to apply less than half the soil's PAW per application event. 50% of the PAW of all sites is in the general order of 25 mm or greater. The current application event depth of 25 mm, or 250 m^3/ha, is considered acceptable for normal irrigation (application to bring near to FC) and is applied in one application. However, for applications that result in soil moisture above FC, it is not optimal for ensuring the whole application depth is attenuated through the soil to remove nutrients and minimise the potential for localised ponding. It is proposed that the daily irrigation is applied in short cycles and at a dose depth of 10 or 15 mm/day and the event depth is limited to 20 or 30 mm (i.e. two days of irrigation before a minimum 16 day return period) depending on the soils unsaturated hydraulic conductivity.

In practice, the return period is longer than 16 days at 19 – 58 days (or occasionally longer), due to dynamic paddock availability. The longer return period helps to more widely spread the wastewater nutrients, avoid biological growths on the soil surface and limits areas of soil drainage. The low irrigation rates are not equivalent to a normal pastoral irrigation system, meaning that less than optimal grass growth occurs and may also cause hydrophobic soils (soil's rejection of water). The automation of the K-Line strings allows cycling of irrigation doses to soils exhibiting hydrophobicity. Allowing a lower applied depth more often can help to mitigate the effect of water repellence. This is particularly appropriate for the Pembers Road Low farm that has low infiltration characteristics.

Currently, the low application volume applied per year mitigates the majority of the potential for adverse effects on the soils and the receiving environment. However, the high daily discharge volume dose rates do increase the soil drainage rates. The land treatment system is also constrained by restrictions of the application based on soil moisture status if greater than 85% of field capacity. This forces the discharge to the River or trucking off-site to the District Council wastewater treatment system.

To reduce the daily volume applied per hectare, it is recommended that the operation of individual existing K-Line Max irrigation pod lines could be automated with the addition of programmable actuated valves on each K-Line string immediately after the hydrant. The control valves would allow the system to irrigate on and off for short periods during the day, rotating the water application around a number of connected pod lines. Depending on the number of additional lines, these would be shifted on a minimum of every second day, with the application pulsed to minimise nutrient loss and land-owner disturbance. It is suggested that the system is remotely controlled using a handheld controller system programmer and linked to an Internet-enabled monitoring system. Each actuator valve can communicate to the other valves within a 1 km radius allowing for system and irrigation scheduling changes to be uploaded.

The automated system can be set up to pulse apply the wastewater or rotate around a set series of lines. With the controller, the operator can connect to soil moisture monitoring probes if needed. The internet reporting can show what lines are irrigated, the time this occurred and its duration. Given that the valves would move when the K-Line is shifted or attached to a new hydrant, operator input would be required for accurate reporting of location/area irrigated. It is proposed that automated irrigation is utilised across all soil types to provide low rate intermittent application of the wastewater. In the example provided in Table 3, the cycle length has been set at 20 minutes to allow water to be applied when the soils are at field capacity whilst allowing the cycle volume to infiltrate and be absorbed on the soil surface.

Parameter	Input Assumption	Units
Days per between shifts	2	days
Average application rate	2	mm/hr
Cycle depth	2	mm
Dose depth	10	mm/day
Event depth	20	mm

Table 3: Irrigation System Assumptions

The long return period between irrigations means that the risk of irrigation induced drainage of wastewater directly to groundwater is avoided. Drainage induced by irrigation is only likely to occur during spring, forcing soil pore water into the aquifer. The minimum return period is 16 days, and the average return period is greater than 20 days. The application of water in a pulse fashion without a soil moisture constraint will mean that bypass flow and drainage is avoided.

With the addition of automation and additional lines enabling 600 m^3 per day to be applied across 6 ha, the full daily wastewater volume can be discharged to land under all soil conditions while also minimising drainage and avoiding the need for direct surface water discharges. The automation would allow the existing system to operate without changes to the pumping or mainline network.

Conclusion

The soils are in good physical and chemical health and wastewater irrigation does not appear to have caused a discernible difference on them, with differences more likely to be due to land use. Some soils have low unsaturated hydraulic characteristics and need to be treated carefully to limit ponding and bypass flow. Saturated hydraulic conductivities are generally high, as is absorbance above field capacity, i.e. the soils are suitable to receive limited wastewater above field capacity. The current application depth of 25 mm, even applied at <85% of FC, has the potential to be forcing drainage and resulting in localised ponding on some soils. Adopting simple irrigation automation that does not require high operator input and that allows pulsing of small irrigation doses, even as little as 20 minutes on, will minimise ponding, drainage and allow a better spread of nutrients.

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